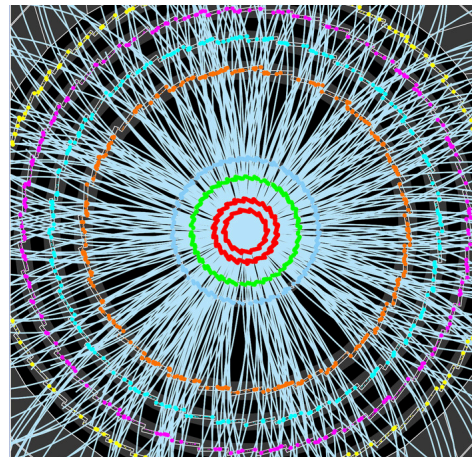
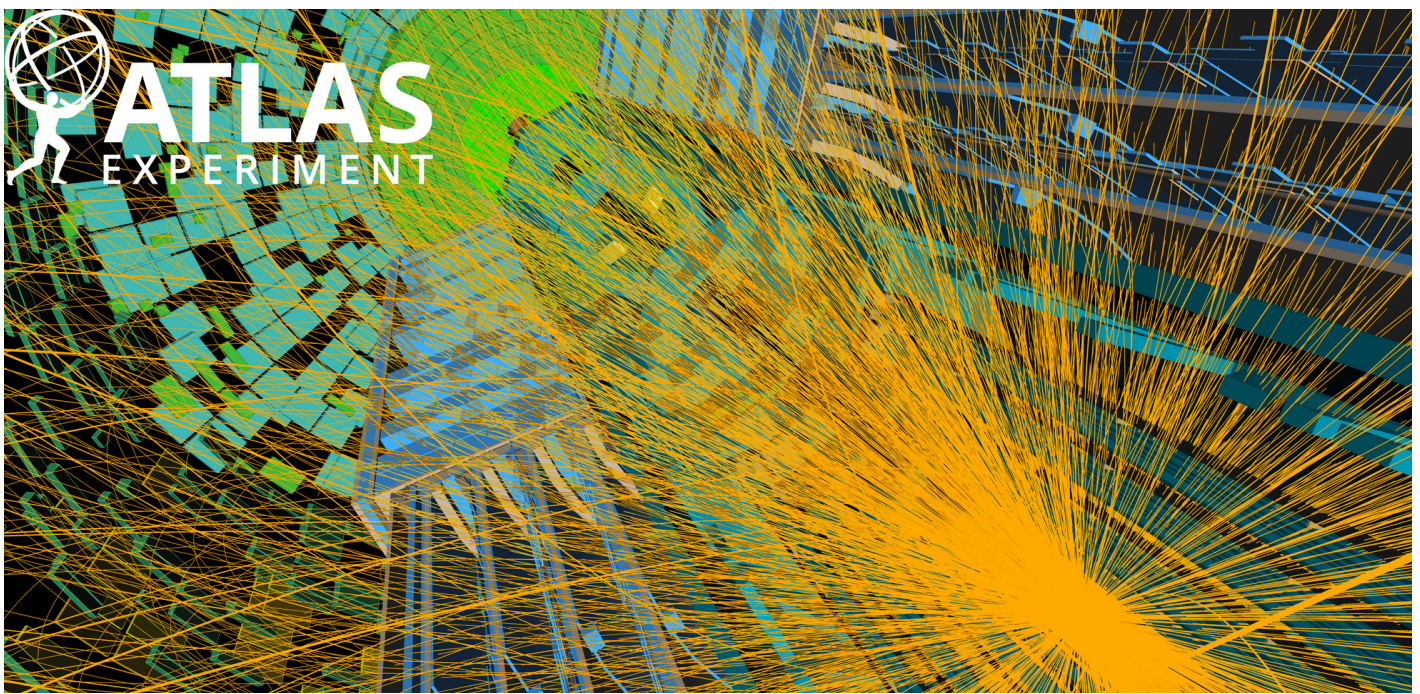


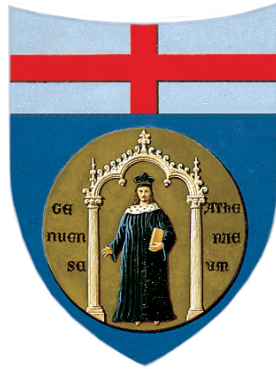


The ATLAS Pixel detector and its use in a Search for Metastable Heavy Charged Particles



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PHD THESIS

The ATLAS Pixel detector and its use in a Search for Metastable Heavy Charged Particles



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Wir müssen wissen, wir werden wissen

— David Hilbert

Abstract

Thomson's discovery of the *electron* in 1897 demonstrated that the atom can be split into smaller parts, opening a new era of discoveries. The modern concept of atom emerged in 1911 as a result of Rutherford's experiments. He showed that the atom is composed by a nucleus surrounded by an electron cloud. In the thirties, the Chadwick's discovery of the *neutron* removed all doubts that the building blocks of the nuclei were *protons* and *neutrons*. In the same years Anderson confirmed the Dirac's theory observing the *positron*, a positively charged twin of the electron. In the following seventy years many discoveries improved our knowledge of the fundamental structure of matter. The Standard Model (SM) of particle physics, developed in the mid-sixties included quantum electrodynamics, the Glashow-Weinberg-Salam theory of electroweak processes and quantum chromodynamics. The SM has unified strong, weak and electromagnetic interactions, has explained experimental results and predicted with amazing precision many particle physics processes.

The Large Hadron Collider (LHC) located at CERN (Conseil Européen pour la Recherche Nucléaire) with its $\sqrt{s} = 13$ TeV centre of mass energy is the most powerful collider ever built. The LHC aims to challenge the SM under energy condition never created before on Earth. Four main experiments are distributed around the LHC ring: ALICE (A Large Ion Collider Experiment), ATLAS (A Toroidal LHC ApparatuS), CMS (Compact Muon Spectrometer), and LHCb (Large Hadron Collider beauty experiment).

The discovery of the Higgs boson, the missing piece in the Standard Model puzzle, at the electroweak scale in 2012 by the ATLAS and CMS experiments, closed an important season of particle physics and a search lasted 50 years. Even though the discovery of the Higgs boson is a great achievement, the Standard Model is incomplete, since it does not include the gravitational field and can not explain some experimental measurements such

as the dark matter observed in galaxy studies and the matter and anti-matter asymmetry observed in the universe. The experiments at LHC have the exciting goal to give answers to the SM open questions and make available the hint or the evidence that may allow to proceed beyond it. An introduction on the Standard Model and the LHC is provided in Chapter 1 where the ATLAS detector is also described.

ATLAS is the largest of the detectors placed along the LHC ring and is able to detect products from pp and heavy ion collisions. The detector has a cylindrical geometry around the interaction point. The inner part of the ATLAS detector reconstructs trajectories of the charged particle that cross it, the position of the proton-proton collision and eventually the secondary vertices due to particle decays (e.g. b -hadrons). The silicon Pixel Detector is the innermost component of the tracker and is located few centimetres away from the interaction region. It provides at least three high accuracy space-point measurements per track and plays a crucial role for tracking, vertexing, and b -tagging capabilities of ATLAS. The reader can find some useful information on the interactions of the particles in matter and on semiconductor tracking detectors in Chapter 2. The LHC first beam circulated in 2008. To increase discovery potential, the luminosity¹ of the machine has been boosted constantly and the detector has been improved to cope with the new luminosity conditions. During the first LHC long shutdown (LS1) in 2014, to maintain ATLAS performance, the Pixel Detector has been upgraded to a 4-layer detector with the addition of the Insertable B-Layer (IBL). IBL is a new detector installed between the existing pixel detector and a new beam-pipe of smaller radius in order to ensure and maintain excellent performance of tracking, vertexing and jet flavor tagging. My Master Thesis and part of my first Ph.D. year have been focused on the production, characterization and on the study of IBL modules. IBL uses different sensors and readout electronics than the old 3-layer detector. A description of IBL and some results from production are reported in the first part of Chapter 3.

Particle interacts with matter mainly with inelastic collisions according to a quantum-mechanical probability. In 1932 a relation (so-called *Bethe-Bloch formula*) to describe the energy loss of heavy charged particles was derived by Bethe, using quantum mechanical perturbation theory. In the ATLAS Pixel Detector, the charge produced by a charged particle that crosses a silicon sensor is measured in the electronics via the Time over Threshold (ToT) technique. The Time over Threshold is the duration of the signal above the discriminator threshold and the front-end electronics is designed to make it proportional to the amount of charge deposited in each silicon pixel. ToT is converted to charge through

¹The luminosity is a measurement of the number of collisions that can be produced in a detector per unit of cross section and per second. LHC is designed to produce a luminosity $L \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

devoted calibration scans in which a known charge is injected into the pixel electronics. The ionization released by a charged particle, that crosses a silicon pixel sensor, can be spread amongst few pixels. The charges of the individual pixels are summed in a cluster energy release. Clusters of these hit pixels are reconstructed and associated to the particle track. In Chapter 4 the *track* dE/dx is presented, as a measurement of the ionisation associated to a charged particle. It is defined as an average of the individual cluster dE/dx measurements (charge collected in the cluster, corrected for the track length), for all the Good Clusters² associated to the track. To reduce the Landau tails due to δ -rays, the average is evaluated after having removed the cluster(s) with the highest charge. The different accuracy of IBL readout electronics and the different behaviour for large energy releases requires a non trivial *track* dE/dx calculation algorithm. I have developed a new *track* dE/dx computation algorithm that includes the IBL information. It has been validated and integrated in the ATLAS reconstruction framework (Athena), showing improvement in the dE/dx resolution and reducing the residual amount of high- dE/dx tails. A fit has been also performed with an empirical 5-parameters *Bethe-Bloch formula* based on Blum and Rolandi studies for the ALEPH TPC. It describes how the Most Probable Value of the specific energy loss ($MPV_{dE/dx}$) depends on the particle $\beta\gamma$. I worked also to increase the performance of the dE/dx observable, developing a dE/dx path correction thus correcting its dependence on the track pseudorapidity η ³.

The Pixel *track* dE/dx can be used to detect massive, highly ionizing particles such as charged R -hadrons (sparticles formed by squarks or gluinos and ordinary quarks) and charginos. These particles are predicted in many extensions of the Standard Model and they appear, for example, in both R -parity conserving and violating supersymmetry (SUSY) models and in universal extra dimensions theories. R -hadrons and charginos can be stable, or metastable⁴. If produced at the Large Hadron Collider, such heavy particles will be moving non-relativistically and therefore they will be identifiable through the measurement of an anomalously large specific energy loss or time of flight in various ATLAS subdetectors, including the Pixel Detector. If the particles are metastable and

²The local position of the cluster is constrained not to be at the edge of the module or in any region where the charge may not be completely collected.

³ATLAS has a cylindrical geometry so it is useful to define a cylindrical coordinate system (z, R, ϕ) where z is the position in the direction along the beam axis, R is the radius in the xy plane measured from the nominal interaction point, ϕ is the azimuthal angle measured around the beam axis, while the relation between R and z is defined by the polar angle θ . The pseudorapidity η is defined as:

$$\eta = -\ln(\tan(\frac{\theta}{2})) \quad (1)$$

⁴If a particle decays inside the detector volume is considered metastable

decay before reaching the muon spectrometer, but live enough to have an associated track reconstructed, these particles may still be identified using the Pixel Detector only. Given the $track\ dE/dx$ and momentum, the heavy particle mass is reconstructed starting from a Bethe-Bloch calibration obtained with low mass SM particles.

The tracker-only approach has sensitivity to metastable particles, with a lifetime ranging from a fraction of a nanosecond to several tens of nanoseconds.

After LS1 the LHC collision energy has been increased from 8 TeV to 13 TeV, thus enhancing the cross-section to generate heavy particles through the gluon-fusion mechanism. The larger the mass, the larger the cross section increase. As an example the pair production of 1.5 TeV gluinos is boosted by a factor close to 50, while the background increases much less (a factor between 2 and 3). Results on a search for massive charged long-lived particles performed with LHC $\sqrt{s} = 13$ TeV data with an integrated luminosity of 3.2 fb^{-1} are shown in Chapter 5.

The Large Hadron Collider is working beyond expectations in terms of delivered instantaneous luminosity. The *in time pile-up* produced by the multiple collisions in the same bunch crossing is problematic for the Pixel readout electronics, in particular in terms of readout bandwidth saturation. At the end of 2013, the number of Pixel Detector disabled modules were increased from an initial 2% to 5%. For these reasons during LHC LS1 the pixel data transmission system was completely renewed: new data cables, new electrical-to-optical converter boards, and new data fibres were installed. During the 2015-2016 LHC Winter Shutdown, the Pixel off-detector electronics (described in the second part of Chapter 3) has been also upgraded. In this contest, the last part of Chapter 3 is devoted to a description of the test developed to qualify the IBL Readout Driver (IBL-ROD) for the Pixel System, to which I have contributed.

Finally Chapter 6 describes the last part of my work and shows some results and studies on the ATLAS Pixel Detector technologies for LHC upgrade in 2025, called High Luminosity LHC (HL-LHC). Here, the experiment will accumulate integrated luminosity up to 3000 fb^{-1} and the inner (outer) pixel layers will be exposed to fluence close to $1.7 \times 10^{16} n_{eq} \text{ cm}^{-2}$ ($1.4 \times 10^{15} n_{eq} \text{ cm}^{-2}$). The HL-LHC luminosity conditions are too extreme for the current ATLAS tracking system. Therefore it will be completely replaced by a new system called Inner Tracker (ITk), an all-new all-silicon tracker to be built using only strip and pixel detectors. Three possible sensor types are considered for the pixel detector upgrade: Planars, 3Ds, CMOS. I have tested new 3D and CMOS sensors and I have studied new hybridization technologies, such as bump bonding at high density or capacitive coupling. For this purpose I have developed a laser setup, that has allowed the measurement of the charge collection inside the pixel cell with few μm resolution.

Table of contents

List of figures	xi
List of tables	xxv
1 The ATLAS Experiment at the Large Hadron Collider (LHC)	1
1.1 The Large Hadron Collider (LHC)	1
1.2 ATLAS (A Toroidal LHC ApparatuS)	6
1.2.1 Coordinate System and Nomenclature	7
1.2.2 The Inner Detector	8
1.2.2.1 The Pixel Detector and the Insertable B-layer	8
1.2.2.2 The SemiConductor Tracker (SCT)	10
1.2.2.3 Transition Radiation Tracker (TRT)	11
1.2.3 The Calorimetric System	12
1.2.4 The Muon Spectrometer	12
1.2.5 The Magnetic System	13
1.2.6 The Trigger	14
1.2.7 Event Reconstruction	16
1.2.7.1 Jets	16
1.2.7.2 Electrons	17
1.2.7.3 Muons	18
1.2.7.4 Missing Transverse Energy	19
1.3 Physics at the ATLAS Experiment	19
1.3.1 The Standard Model (SM) and the Higgs Boson	19
1.3.2 The hierarchy problem, naturalness and a possible solution	23

1.3.3	The Minimal Supersymmetric Standard Model	24
1.3.3.1	R-parity	25
2	Interactions of Particles in Matter and Semiconductor Tracking Detectors	27
2.1	Interactions of Particles in Matter	27
2.1.1	Passage of Massive Charged Particles Through Matter	29
2.1.2	Energy deposition of photons	32
2.2	Semiconductor Tracking Detectors	34
2.2.1	Charge Transport and Collection in Semiconductor Detectors	34
2.2.2	The <i>pn</i> Junction	38
2.2.3	Semiconductor Detector Geometries: Strips and Pixels	40
2.2.3.1	Strip Geometry	40
2.2.3.2	Pixel Geometry	41
2.2.4	Detector readout processing	43
2.2.5	Pixel Semiconductor Sensors	44
2.2.5.1	Planar Sensors	44
2.2.5.2	3D Sensors	45
2.2.5.3	Diamond Senors	46
2.2.5.4	Towards New Pixel Technologies: HV and HR-CMOS	47
2.2.5.5	Towards New Pixel Technologies: Monolithics	49
2.3	Hybridization: From sensors to modules	50
2.3.1	The bump-bonding technique	50
2.3.1.1	Solder based bump-bonding process	50
2.3.1.2	Indium based bump-bonding process	51
2.3.2	Capacitive Couplings	52
2.3.3	Through Silicon Vias	55
2.4	Radiation Damage in Silicon	56
2.4.1	Surface Damage	56
2.4.2	Bulk Damage and Changes in Detector Properties	57
2.4.2.1	The NIEL Hypothesis	58
2.5	Tracking Detectors Parameters	59
2.5.1	Charged particle trajectories in magnetic fields	60
2.5.2	Impact parameter	60
2.5.3	Vertex resolution	61
2.5.4	Multiple scattering	62

3	The Insertable B-Layer (IBL) and the Pixel Readout Upgrade in LHC Run 2	63
3.1	The Insertable B-Layer (IBL)	64
3.1.1	Motivations	65
3.1.2	IBL Modules	66
3.1.3	Front-End Electronics: FE-I4	67
3.1.3.1	FE-I4 Low Voltages	71
3.1.4	Sensors	72
3.1.4.1	Planar Sensors	73
3.1.4.2	3D Sensors	74
3.1.5	IBL Modules Production and Integration	76
3.1.6	IBL Performance during LHC Run 2	80
3.2	Pixel Off-Detector Readout Upgrade in LHC Run 2	83
3.2.1	Interlude: The Module Controller Chip (MCC)	84
3.2.2	A VME system: SBC, TIM, ROD and BOC	87
3.2.3	The IBL Readout Driver (<i>IBL-ROD</i>)	91
3.2.3.1	ROD Architecture and Data path	92
3.2.4	The TDAQ and PixelDAQ framework	93
3.2.5	Qualification Procedures for New Pixel Readout	95
4	A 4-layers Pixel detector: Charge collection, Cluster properties and Track Pixel dE/dx	103
4.1	Charge Measurement in Pixels	103
4.2	The Pixel Track dE/dx	106
4.2.1	The ATLAS Pixel dE/dx Calculation Algorithm	110
4.2.2	Stability of Track dE/dx during LHC Run 2	115
4.2.2.1	dE/dx path correction and η dependence	117
4.2.2.2	Bethe-Bloch Fit	120
5	Search of massive charged particles unsing the <i>Track</i> dE/dx	125
5.1	Theoretical Overview	126
5.1.1	Production and Decay	127
5.1.2	Interaction of Massive Charged Particles	128
5.1.2.1	Mass spectrum	130
5.2	Search for metastable heavy charged particles with large ionisation energy loss in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment	131
5.2.1	Analysis Strategy	132
5.2.2	Simulation: Montecarlo Samples	133

5.2.3	dE/dx MPV drift due to IBL Front-End decalibration	136
5.2.4	Data Sample and Event Selection	138
5.2.5	Signal Selection Efficiency	141
5.2.6	Background Estimation	142
5.2.7	Results	146
5.3	Analysis Improvements and Discovery prospectives with LHC 2016 Data . .	151
6	Towards the HL-LHC: Pixel detector technologies for the Inner tracker (ITk)	153
6.1	The High-Luminosity LHC Upgrade and Deficiencies of the existing <i>ATLAS</i> Inner Detector	154
6.1.1	Inner Tracker (ITk) Layout	155
6.2	Pixel Technologies for the HL-LHC	156
6.2.1	Hybridization Technologies	157
6.2.1.1	High Density Bump Bonding	157
6.2.1.2	Capacitive Coupling	160
6.2.2	Sensors	168
6.2.2.1	New FBK 3D Sensors	168
6.2.2.2	Results	169
6.2.2.3	HV-CMOS detectors in BCD8 technology	172
6.3	A Laser Setup to Measure the Hit Efficiency	178
6.3.1	Laser System	178
6.3.1.1	USBPix and read-out	180
6.3.1.2	Charge Injection	181
6.3.2	Results	183
	Conclusions	187
	Appendix A	191
	References	193

List of figures

1.1	Acceleration stages of LHC	2
1.2	Evolution of energy, luminosity and beam size during the filling sequence. The beams are kept separated until the Physics stage is reached [1]	3
1.3	Integrated and peak luminosity collected by LHC experiments in pp collisions during 2016.	4
1.4	The maximum number of inelastic collisions per beam crossing (μ) during stable beams for pp collisions at $\sqrt{s}=13$ TeV is shown for each fill in 2016. The number of interactions shown is averaged over all colliding bunch pairs, and only the peak value per fill during stable beams is shown. LHC is working beyond expectations: to have a reference, the maximum mean number of events per BC in machine design is 19.	5
1.5	The ATLAS Detector.	6
1.6	xyz Right handed coordinate system with Z in the beam direction of the ATLAS experiment at LHC.	7
1.7	The ATLAS Inner Detector.	9
1.8	Schema of the current ATLAS 4-Layer Pixel Detector. From the inner part to the outer part the layers are: IBL, B-Layer, Layer-1, and Layer-2. At the bottom, the radial placement of the barrel layers including the beam pipe is depicted [2].	10
1.9	A barrel SCT module.	11
1.10	The TRT detector.	11
1.11	A computer generated image of the ATLAS full calorimeter.	13
1.12	The ATLAS Muon system.	14

1.13	The magnet system is composed of barrel solenoid and outer toroid magnets.	15
1.14	Schematic layout of the Run-2 ATLAS trigger and data acquisition system [3].	16
1.15	View of ATLAS sub-detector system.	17
1.16	The elementary particles of Standard Model.	21
1.17	Graph of the potential of the field ϕ in the case of $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right). $V(\phi) = \frac{1}{2}\mu^2\phi\phi^* + \frac{1}{4}\lambda(\phi\phi^*)^2$ in the form of a Mexican hat (right) leads to spontaneous symmetry breaking.	21
1.18	Feynman diagrams of Higgs boson production modes. a) gluon-gluon fusion via heavy quark loops; b) vector boson (Z or W) fusion; c) radiation of a Higgs (Higgstrahlung) from a W or Z boson; d) Higgs production in association with top quarks.	22
1.19	Cancellation of the Higgs boson quadratic mass renormalization between fermionic loop and scalar squark tadpole Feynman diagrams in a supersymmetric extension of the Standard Model.	23
1.20	Particles predicted by the MSSM. On the left there are the particles existing in the SM and further four new Higgs bosons predicted by MSSM. On the right their superpartners are reported.	25
2.1	Energy loss or stopping power for muons penetrating copper as a function of $\beta\gamma$. The dashed lines for $\beta\gamma > 1$ illustrate the energy loss for heavy charged particles as described by the Bethe-Bloch formula with and without density correction. The solid line for $\beta\gamma > 1$ illustrates the Bremsstrahlung losses which becomes dominant at high momentum for light charged particles. Vertical bands indicate boundaries between different theoretical approximations or dominant physical processes [4].	30
2.2	Landau distributions [4] for various thickness of silicon. For reference the ATLAS Pixel Detector sensors are $250\ \mu\text{m}$, instead the IBL ones are 230 (3D) and 200 (Planars) μm thick.	31
2.3	The sketch shows the schema of electromagnetic interaction a) the photoelectric effect, b) the scattering Compton and c) the pair production	32
2.4	Silicon is an indirect bandgap semiconductor so there is a long tail in absorption out to long wavelengths. The data is graphed on a log scale.	33
2.5	A pn -junction and its band diagram	38

2.6	The space resolution improves with the segmentation. In the first case 1 dimensional space coordinates for single sided strip detector is reported, in the second picture a 2 pseudo dimensional space coordinates for a double side strip detector and finally in the last a full 2 dimensional space coordinates as it is for pixel detectors.	40
2.7	In this sketch from is reported the evolution of pixel and strip detectors surfaces for different experiments [5]. As we have seen in Chapter 1, experiments at collider, like ATLAS, have high precision semiconductor detectors close to the interaction region.	41
2.8	A pixel cell is the basic building block of a hybrid pixel detector. In the picture a cross section of a single hybrid pixel readout channel is reported. Here the sensor at the bottom (for signal generation) the bump connection in the middle (for the interconnection) and the readout electronics (for the signal amplification and data processing) are shown. When ionizing particle crosses into the sensor, it generates charges that move in the depletion region under the action of an electric field producing the signal.	42
2.9	A scheme of a basic detector acquisition chain is here reported. The sensor converts the energy deposited by a particle to an electrical signal. This low-level signal is first integrated in a pre-amplifier then fed to a pulse shaper and finally digitized.	43
2.10	In the picture the cross section of a n-in-p pixel silicon detector is reported. On the left is possible to see the depletion region growth and on the right the drift of charge carriers generated by an ionizing particle	45
2.11	Layout of a 3D silicon sensors produced with a double sided process. The n^+ -doped electrodes penetrating from the pixel side of the sensor are used as read-out electrodes. The p^+ -doped columns are in contact with the back side metallization to bias the sensor.	46
2.12	Sketch of a generic HV-CMOS pixel structure from [5]. Dimensions are not to scale.	48
2.13	In this sketch from [6] the process flow in the PbSn (solder) bump deposition process (a)–(e) and flip-chip of the electronics die (with UBM and bump) to the sensor (with UBM only) (f)-(g) are reported	52
2.14	In this sketch from [7] the In bump deposition process is reported.	53

2.15	The basic process for capacitive coupling is shown. First the SU8 spacers are built on one of the chip surface. After the glue is deposited on the same side. Finally the alignment of the two chip and the glue curing is performed. An exploded axonometric view of a capacitive structure flip-chipped is also reported. In light and dark grey the top and bottom metal layer are respectively reported together with the SU8 spacers in the middle.	54
2.16	A side view of a TSV structure assuming a uniform circular cross section of copper surrounded by an oxide inside a silicon substrate.	56
2.17	Schematic illustration of the introduction of fixed positive oxide charges in SiO_2 [8]	57
2.18	Determination of the impact parameter d_0 of a track generated from a secondary vertex [9].	61
2.19	Sketch of a simple vertex detector in a collider experiment is reported. . . .	61
3.1	a) IBL layout $r\phi$ view: the IPT, the IBL detector and the IST are visible b) The Insertable B-Layer during its insertion in the ATLAS Pixel Detector c) Schematic of and IBL stave: 12 planar sensors are placed in the central region and 8 3D sensors in the forward region (4 for each side).	65
3.2	a) A picture of the last IBL stave being integrated on surface b) Photographs of a dressed IBL single chip module on the left a double chip and on the right a single chip module.	66
3.3	Comparison between the $20.2 \times 18.8 \text{ mm}^2$ FE-I4 and the $7.6 \times 10.8 \text{ mm}^2$ FE-I3 used in the Pixel Detector.	67
3.4	Analog section of a single pixel inside the FE-I4 readout chip.	68
3.5	Organization of the 4-pixel region, focusing on a schematic of the digital region.	69
3.6	Digital threshold mechanism	69
3.7	The regulator output voltages for analog and digital supply voltages as a function of the tune DAC ($V_{refAnTune}$ and $V_{refDigTune}$) for an IBL module is shown.	72

3.8	Figures a) and b) show the analog Regulator output (VDDA) distribution for maximum (255) and minimum (0) <i>VrefAnTune</i> register value for IBL module production. The maximum and minimum VDDA values correspond to 1.46 and 1.27 (RMS 0.03) V. Figures c) and d) show the digital Regulator output (VDDD) distribution for maximum (255) and minimum (0) <i>VrefDigTune</i> register value for the modules accepted and sent to the stave assembly site for loading. The maximum and minimum VDDD values correspond to 1.47 and 1.01 (RMS 0.03) V.	73
3.9	Comparison of the edge region of the current ATLAS Pixel design (upper) and the IBL planar sensor design (lower) [10].	74
3.10	Sketch and SEM micrographs of 3D etched columns of the CNM pixel sensor design [10].	75
3.11	Sketch and SEM micrographs of 3D etched columns of the FBK pixel sensor design [10].	75
3.12	V_{bd} measured on assembly level (ASSY), versus V_{bd} measured on the 3D guard ring at wafer level (before dicing) for a subset of CNM production. Measurements at assembly level were done with a current compliance of 100 μ A. A better agreement between the breakdown voltage at the wafer and module level for FBK a) than for CNM b) is shown.	77
3.13	Yield of IBL module production for sensor types of Planar (PPS) and 3D per production batch group. In the top panel for failure modules, “B.B. Fail.” stands for large bump-bonding failure, “Bare Fail”. stands for the module not assembled due to mainly mechanical damages, and “Other Fails”. stands for both electrical and sensor failures discovered after assembly. Within the same batch group, similar configuration of the laser condition and the bump bonding was applied. In the bottom panel, the first batch group was excluded from the average yield in the plot because they were largely affected by bumpbonding problems that were fixed in the following batches. The total average bad module fraction for PPS, CNM, FBK is 0.36, 0.50, 0.44, respectively. If the first batch is excluded, the fraction are 0.27, 0.37 and 0.38 respectively.	78

3.14 Production Trend - The Green line shows the number of modules accepted or lower quality sent to the stave assembly site for loading. a) 62% of 3Ds satisfied the IBL requirements. b) 75% of Planars satisfied the IBL requirements. These percentages are calculated adding those modules accepted for loading and spare modules divided by all the assembled (excluding the first batch).	79
3.15 xy -view of the Pixel Detector from the distribution of hadronic interaction vertex candidates in data (a). In (b) it is possible to distinguish the innermost part the beam pipe, IPT, IBL staves and IST [11].	80
3.16 Comparison of the radial distribution of hadronic interaction candidates between data and simulation in $20 < r < 45$ mm region [11].	81
3.17 Unfolded transverse impact parameter resolution measured from data in 2015, $\sqrt{s} = 13$ TeV, with the Inner Detector including the IBL, as a function of p_T , for values of $0.0 < \eta < 0.2$, (a) and η and for values of $0.4 < p_T < 0.5$, (b) compared to that measured from data in 2012, $\sqrt{s} = 8$ TeV. The data in 2015 is collected with a minimum bias trigger. The data in 2012 is derived from a mixture of jet, tau and missing E_T triggers.	81
3.18 The light-flavour jet rejection in bins of jet p_T (a) and $ \eta $ (b) for the MV1c b -tagging algorithm using the Run-1 detector and reconstruction software (blue) compared to the MV2c20 b -tagging algorithm using the Run-2 setup (red). In each p_T or $ \eta $ bin the b -tagging cut value has been chosen in such a way to yield a constant b-jet efficiency of 70% [12].	82
3.19 The ATLAS Pixel Module.	85
3.20 Data format and timing for event transmission from FE to MCC. (a) Hit frame is 26-bit long, (b) EoE frame is also 26-bit long.	85
3.21 Event Data format at the MCC output. Some Examples of data stream are reported.	86
3.22 MCC protocol - Real data coming from one MCC during ATLAS datataking at ROD level.	86
3.23 Pixel DAQ Crates in USA15. A crate can contain 16 boards (enumerated from 5 to 21). In slot 13 is always located the TTC Interface Module (TIM) to propagate the timing properly on its left and right crate side.	88
3.24 Overview of the VME crate structure for the data readout of the ATLAS Pixel Detector.	88
3.25 A scheme of the functional blocks of <i>SiROD</i> is shown [13].	90

3.26	Comparison between the old <i>SiROD</i> and <i>IBL-ROD</i> . The data are emulated at BOC level, setting 20 hits per channel. Since the old <i>SiROD</i> has a lower bandwidth available, it saturates with higher frequency than the <i>IBL-ROD</i> . The data-taking of <i>SiROD</i> shows also more drops in trigger rate due to the Busy creating to compensate the bandwidth saturation.	91
3.27	Overview of the main components of the ATLAS Pixel Read-out chain using the new <i>IBL-ROD</i>	93
3.28	Block scheme of the Firmware of Layer 2 ROD Slave. Only one slave is shown.	94
3.29	The functional blocks of the TDAQ and PixelDAQ data acquisition software.	95
3.30	Tool to monitor IS variables.	98
3.31	ROS parameters as are shown in IS. A comparison between problematic a) and a good b) firmware version is shown.	98
3.32	An example of ROD violation protocol.	100
3.33	An example of two problematic firmware versions. On the left it is shown one of the first version running at 40 (top) and 80 (bottom) Mbit/s. On the right an intermediate firmware version running at 40 (top) and 80 (bottom) Mbit/s. The fraction of NotDeleted fragments of the ROS links grows with different slopes when increasing the trigger rate at different readout speeds. This problem was due to a bug in the firmware. In the final version used for ATLAS data-taking the fraction of bad fragments was close to 0.	100
4.1	Time over threshold (TOT) mean values vs injected charge for a FE-I4 module	104
4.2	Different scenarios of charged particles traversing a silicon sensor [14]: (a) a single charged particle traversing the silicon sensor producing a cluster with a width of two pixels. (b) a merged cluster produced by two close-by particles that both deposit charge in the second pixel. The fourth pixel is not read-out as the charge is below the read-out threshold. (c) a large cluster created from a single charged particle due to a δ -ray produced in the silicon.	105
4.3	In the cartoon a particle that is crossing more pixels generating the specific cluster energy loss is shown.	107
4.4	The cluster ToT and Charge in IBL and in the three layers of the "old" pixel detector for pp collisions in 2016 is reported. IBL is tuned to have the MIP peak of 16 ke^- at 8 BC, instead the b-Layer and Layer-1(2) are tuned at 20 ke^- with a ToT peak at 18 and 30 respectively.	108
4.5	A comparison between harmonic, geometric and truncated mean is reported for pp collision data at $\sqrt{s}=13\text{ TeV}$	110

- 4.6 The cluster dE/dx distribution in logarithmic scale is shown before and after having applied the Good Cluster cuts for Pixel Barrel and EndCap (a) and IBL (b). 111
- 4.7 Distribution of the dE/dx computed with the Pixel algorithm in data (black dots) and Pixel without IBL (red triangles) for minimum bias event tracks selected as in Ref. [15], with the additional requirements of a momentum $p > 3$ and at least two associated pixel clusters. The corresponding dE/dx distributions for simulation with and without the IBL are also plotted, respectively, as dashed and dotted lines. The simulation overestimates the dE/dx , which is taken into account in the systematic uncertainty evaluation. The addition of IBL clusters reduces the tails at both low and high dE/dx . The fraction of tracks with $dE/dx < 0.5$ (> 1.8) $\text{g}^{-1} \text{cm}^2$ decreases with the use of the IBL charge information from 0.065% to 0.018% (from 0.89% to 0.44%) [16]. 113
- 4.8 Number of pixel good cluster associated to the selected tracks. The red distribution corresponds to the Pixel only algorithm, while the dots are the Pixel+IBL good clusters. As observed in the plot, the new algorithm has on average one good cluster more. 113
- 4.9 The track dE/dx MPV over luminosity is reported for all the data-taking runs used in the analysis of 2015 and 2016. In dark green dashed line is reported the B-layer new threshold set at 5000 electrons. The points at the left of the dashed blue line represents the datasets used in 2015 analysis where a variation of the dE/dx MPV due to the ToT drift of the IBL electronics was present. The other points show a drop of dE/dx MPV over luminosity for 2016 data. The MPV of simulation for 2015 and 2016 are reported with red dashed and blue dash-dot lines respectively. 116
- 4.10 The plot shows the dE/dx MPV over luminosity for the clusters associated to a track for the different pixel layers. The dashed lines without points represent the dE/dx MPV for 2015 simulation. A strong drop of B-layer dE/dx MPV between the start of 2016 data-taking and its threshold change, in accordance to Fig. 4.9 are shown. A drop is also visible for the other layers, this is currently under investigation by the pixel online and offline groups. . 116
- 4.11 Variation in the truncated track dE/dx due to geometrical effects. 118
- 4.12 Variation of the truncated track dE/dx due to geometrical effects (*Truncated*). Using the logarithmic term in the cluster dE/dx computation the effect is strongly reduced (*Truncated Corr*). 118

4.13	Variation of the cluster dE/dx in the different ATLAS Pixel Detector layers due to geometrical effects (<i>Truncated</i>). Using the logarithmic term in the cluster dE/dx computation the effect is strongly reduced (<i>Truncated Corr</i>).	119
4.14	Truncated track dE/dx (<i>Truncated</i>) in comparison with the truncated after the cluster path correction described in Eq. 4.14 (<i>Truncated Corr</i>). The distribution width is independent of the path correction, instead the most probable value scales with path length as shown in Fig. 2.2.	119
4.15	dE/dx distribution in 16 slices of momentum $p \in [0.2, 1]$ GeV in which the three peaks of pions, kaons and protons (π , K and p) are clearly visible for positive charged particles. In red is reported an example of the fit performed with the Crystal Ball function.	121
4.16	Two-dimensional distribution of dE/dx versus charge signed momentum (qp) for minimum-bias event tracks compatible with a primary vertex, which has the same data selection as in Ref. [15]. The distributions of the most probable value for the fitted probability density functions of pions, kaons and protons are superimposed [16].	122
4.17	Distribution of the Most Probable Value of the dE/dx distribution for pions, kaons and protons fitted with function 4.15 for 2015 ATLAS minimum bias data.	123
4.18	Distribution of the the mass estimate m obtained from 2015 Minimum Bias data having a measured specific energy loss $dE/dx > 1.9 \text{ MeV } g^{-1} cm^2$. The solid lines: shows positive tracks instead dashed lines the negative ones. $numberOfUsedHitsdEdx = 2$ (red), $= 3$ (green), > 3 (blue).	123
4.19	Fitted peak mass for Deuteron using positive tracks and all $nUsedHitsdEdx$ categories, from (a) minimum bias simulation and (b) data 2015. The mass value of the deuteron in simulation is $1884 \pm 7 \text{ MeV}$, while in data $1847 \pm 8 \text{ MeV}$, compatible with the expected value (1876 MeV) within $\sim 20 \text{ MeV}$	124
5.1	R -hadron scattering of a proton. (a) Elastic scattering, (b) Inelastic scattering leading to baryon and charge exchange, (c) Inelastic scattering leading to charge exchange, (d) Resonance formation [17].	130
5.2	Two-dimensional distribution of dE/dx versus signed momentum for 800 GeV and 1600 gluino R -hadron with a lifetime of 3 ns and 10 ns respectively, decaying to $q\bar{q}$ plus a light neutralino of mass $m(\tilde{\chi}_0)=100 \text{ GeV}$ (red and blue dots), and for 2400 GeV stable gluino R -hadrons. Good events are selected with at least one high- p_T track matched to a true R -hadron particle.	136

- 5.3 The track dE/dx MPV over time is reported for all the runs of 2015 data-taking used in the analysis (blue dots). They show a variation of the dE/dx MPV due to the ToT drift of the IBL electronics. The red dots show the dE/dx MPV after the run-by-run rescaling. 137
- 5.4 The proton mass versus grouped continuous run numbers (arbitrary units, from data periods D and E) before (red dots) and after (blue dots) the track dE/dx rescaling is shown. The runs with a dE/dx MPV difference $<0.01\%$ have been merged in a single dot. In violet the proton mass from low $<\mu>$ runs is also reported. 137
- 5.5 Ionization MPVs as a function of $|\eta|$, obtained from $CR2$ tracks for each η interval. The distribution is overlapped with a third order polynomial function. 144
- 5.6 Expected mass distribution from background events in the signal region for the metastable R -hadrons, before the ionization requirement is imposed. Data are superimposed. The ratio of data to expected background is shown in the lower panel with statistical uncertainties only. 145
- 5.7 Mass distribution for data and background for stable (top) and metastable (bottom) particle searches. The yellow band around the background estimation includes both the statistical and systematic uncertainties. Also shown are two examples for signals as expected for gluino R -hadrons in the explored mass range. 147
- 5.8 cross-section as a function of mass for gluino R -hadrons with lifetime $\tau=10$ ns, decaying to $q\bar{q}$ plus a light neutralino of mass $m(\tilde{\chi}_0) = 100$ GeV. Theoretical values for the cross-section are shown with their error. The expected upper limits (UL) in the case of background only is shown by the solid black line, with its $\pm 1\sigma$ and $\pm 2\sigma$ bands, green and yellow respectively. The observed 95% UL is shown as a solid red line. The cross-section for the same process and the corresponding 95% UL measured at $\sqrt{s} = 8$ TeV [18] are shown as dashed lines. 149
- 5.9 Excluded range of lifetimes as a function of gluino R -hadron mass. The expected lower limit (LL), with its experimental $\pm 1\sigma$ band, is given with respect to the nominal theoretical cross-section. The observed 95% LL obtained at $\sqrt{s} = 8$ TeV [18] is also shown for comparison. 150
- 6.1 Status of the LHC baseline programme including the HL-LHC run. 154

6.2	Simulated hit positions on the R-z plane for a simulated <i>ATLAS</i> Inner Tracker layout with extended inner barrel layers, optimized for measuring at least 9 space points on tracks up to $ \eta < 3.2$ or $ \eta < 3.4$ for $ z_0 < 150$ mm. Pixels (blue), short strips (light red) and long strips (dark red) are shown.	156
6.3	a) The bump deposition and the flip-chip has been performed using two different bump sizes: 12 and 16 μm bumps. b) A picture of the bump deposition before flip-chip. Some probing pads to test the resistive chains are also shown. As example pads numbered as 1 and 2 can be used to check missing bumps (dark red pads), instead 2 and 3 for merged ones (green pads).	158
6.4	Measurements of bumps dimension before the flip-chip, done in Genova using KLA-Tencor P7 mechanical profilometer. Picture a) and b) shows 12 and 16 μm bumps size.	159
6.5	Four corner X-ray images of a silicon dummy assembly showing the good level of planarity reached by the flip-chip process for both bump size chosen, confirmed also by the uniformity of the resistance measurements.	159
6.6	a) Distribution of the resistance of single bump after the breaking of the indium oxide. The mean values obtained with a gaussian fit are compatible: 24.8 ± 0.5 and $24.4 \pm 0.7 \Omega$ for 12 and 16 μm bumps respectively. b) Trend of single bump after resistance for 12 and 16 μm bumps after several HV cycles. 160	
6.7	Dummy chains on 12-inch wafer. a) On the wafer are present 62 dummy chip and sensor tiles with a dimension of $\sim 1.92 \times 2.08 \text{ cm}^2$ respectively. On each tile is present a pixel matrix of 400×336 , close to the final RD53 FE chip. b) Zoom of a portion of tile and sensor, this layout was chosen to avoid electric arc between 2 adjacent bumps between two contiguous rows. c) Sketch of chain after the flip chip between the dummy chip and sensor. . . .	161
6.8	GDSII project and a picture of the corresponding tile on quartz. a) 24 capacitors with a single plate surface of $1.5 \times 1.5 \text{ mm}^2$ b) 32 capacitors with a single plate surface of $0.5 \times 1.5 \text{ mm}^2$ c) 48 capacitors with a single plate surface of $0.5 \times 1.5 \text{ mm}^2$	162
6.9	The equivalent electric circuit of the one tile after the assembly is reported. C_{glue} is the goal capacitance to measure. The other three capacitances are parasitic and should be made as small as possible. C_{Ox} and C_{Si} are the capacitance between two plates in the oxide and the silicon respectively. C_{Sub} is the capacitance from one plate to the biased substrate.	163
6.10	Value of C_{meas} for different substrate resistivity using HyperLynx 3D EM Design is shown.	163

6.11 C-V measurement for frequencies from 1kHz to 5MHz taken with a B1500A Semiconductor Device Analyser of Keysight performed on a tile assembled with Araldite 2020 at 25 °C.	164
6.12 a) The tile assembled with ARclad 5913 shows a good uniformity the capacitor heights with a difference of $\sim 1 \mu\text{m}$ between the upper and the lower part of the tile. ARclad has a declared height of $25 \mu\text{m}$, before the assembly. b) The tile assembled with Araldite 2020 shows a worse uniformity the capacitor heights with a maximum variation of $\sim 4 \mu\text{m}$. This is due to a lower control of the glue during the flip-chip process in comparison with the tape. The quoted error is 2 % of the height value shown.	165
6.13 a) Picture of a 48 capacitors FE-I4 size tiles assembled with Araldite 2011. b) Estimated equivalent height in μm . The quoted error is 2 % of the height value shown.	165
6.14 Stability of the capacitance value versus temperature for different glues (Araldite 2020 and 2011) for various capacitor positions in the tile. The quoted error includes the negative thermal expansion of the aluminium plates.	166
6.15 In the plot a pillar measurement for the $3 \mu\text{m}$ case is shown. The height measurement was performed using the KLA-Tencor P7 mechanical profilometer.	167
6.16 Schematic cross-section of 3D sensors on on SiSi DWB substrate.	169
6.17 On the wafer are present different pixels dimensions: $50 \times 50 \mu\text{m}^2$, $25 \times 100 \mu\text{m}^2$ and some sensors with ATLAS IBL pixel size $50 \times 250 \mu\text{m}^2$	169
6.18 In the new FBK production several wafer have been produced. In the sketch the yield of first FBK 3D wafer is reported (FBK - W76). The colour scale defines the quality of the sensor (9 - good to 0-very bad). The pixel dimensions and the V_{BD} values are also reported. Sensors number 9,11,12 and 13 have been rejected for either early breakdown or too-large leakage current.	170
6.19 An example of assembled module.	170
6.20 Example of two device with different pixel size. a) A device assembled with W76-6 ($50 \times 50 \mu\text{m}^2$ pixel size) sensor shows a noise mean of $89.7 \pm 0.04 \text{ e}^-$ b) A device assembled with W76-8 ($50 \times 250 \mu\text{m}^2$ pixel size) sensor shows a noise mean of $100.9 \pm 0.05 \text{ e}^-$	171
6.21 An example of Source Scan in false colour for a 3D module (W76-8). In white are represented the disconnected bumps. The shadows (in black) are the SMDs components of the module.	172
6.22 The test beam setup used SPS H6A beam line.	173

6.23	The layout of a) the complete chip b) the active and passive diodes. In b) is possible to observe the four passive diodes in the corners and the the 8 active pixels in the centre and on the edges.	174
6.24	An example of a) I-V curve b) C-V curve for one passive diode, fitted with Eq. 6.3.	175
6.25	Peak of from γ - rays at 59.5 keV of ^{241}Am at different V_{Bias} for a passive diode. The spectrum measurement has been performed using two different bias voltaged of -30 and 50 V. The shaping time of the amplifier has been set to 5 μs	175
6.26	The complete chip layout of KE15AA.	176
6.27	Preamplifier scheme of a KE15A active pixel.	177
6.28	C-V curve for one $50 \times 250 \mu\text{m}^2$ passive diode of KE15A fitted with Eq. 6.3. The depletion depth extrapolated from the fit corresponds to $24 \pm 1 \mu\text{m}$. . .	177
6.29	The sketch shows the main communication chains in the lab setup.	179
6.30	Signals in the laser test system. A measurement starts with the laser-trigger which causes a laser-pulse. The deposited charge is amplified by the preamplifier and digitised by the discriminator of the front-end. Finally, the read-out trigger requests data within the time window (green).	179
6.31	The USBpix Readout system (left) with the Adapter card (Right) to analyse one module per time.	180
6.32	Schematic of USBpix test system.	181
6.33	The power of the laser measured at different intensities for several trigger frequencies.	182
6.34	A laser MIP-like energy release example for a module with a sensor thickness of $200 \mu\text{m}$ tuned at $1 \text{ ToT} = 2000 \text{ e}^-$ and a threshold of 3000 e^-	184
6.35	Laser Scan 2D of a planar sensor.	185
6.36	The collected charge for a planar sensor with a depletion region of $100 \mu\text{m}$. The comparator threshold was tuned at 2500 e^- and the tuning point set to $1 \text{ ToT} = 1000 \text{ e}^-$	185
6.37	a) 2D Laser Scan 2D of a 3D sensor with $50 \times 250 \mu\text{m}^2$ pixel size. The scan is in agreement with expected pixel geometry (superimposed). b) Projection along x and y direction. The dimension of the pixel is in agreement with expectations.	186

List of tables

1.1	LEP, Tevatron and LHC colliders comparison.	1
1.2	Higgs decay branching ratios, given a mass of 125.4 GeV	22
2.1	Material properties of Silicon and Diamond	47
2.2	Glues currently under evaluation as capacitive medium. In the table the critical parameters (air bubbles, pot life and the curing time) for the process are reported. Some glues can degas during the curing creating air bubbles. If they are present the relative permittivity of the coupling medium could be not constant. The pot life is the period for which two (or more) mutually reactive chemicals remain usable when mixed. This one with the curing time are critical parameters to develop a fast and repeatable process. At the moment are currently in evaluation also glues with ultraviolet (UV) curing.	55
3.1	Summary of Layout Parameters of ATLAS IBL.	64
3.2	Comparison between FE-I4 and FE-I3.	70
3.3	Extrapolated link occupancy for Pixel Readout at different number of pile up events and trigger rate of 75 (100) kHz.	84
3.4	Pixel Detector and IBL readout components.	87
3.5	List of TTC signals.	89
3.6	Comparison between <i>SiROD</i> and <i>IBL-ROD</i>	90
3.7	Test performed in SR1 to validate the ROD firmware. The tests are repeated using different masks for disabled modules.	97
3.8	The ROD data format for ROS.	99

4.1	Comparison between Geometric, Harmonic and Truncated Mean $\langle dE/dx \rangle$. The Truncated mean has a better resolution, and lower fraction of tracks at low ($dE/dx < 0.5 \text{ MeV g}^{-1}\text{cm}^2$) and high ionization ($dE/dx > 2 \text{ MeV g}^{-1}\text{cm}^2$) tails than the other means.	110
4.2	x_{loc} and y_{loc} are the local coordinates of the cluster barycentre with respect to the geometrical centre of the module. d_L denotes a shift to take into account the Lorentz angle and is set to $50/0 \mu\text{m}$ in the Barrel/EndCap	111
4.3	Removed Cluster(s) in the mean computing in presence of IBL Overflow dE/dx Clusters for some different good clusters values. The Pixel and IBL cluster(s), that are not in overflow, are labeled sorting them in descending order of dE/dx ($C_i > C_{i+1}$, where $i=0,1,\dots$). C_{IBL} is the dE/dx value associated to the overflow IBL cluster. To underline that the IBL overflow cluster is always removed by the truncated mean, while in the case of a number of good cluster = 3,4 the greatest cluster (C_0) is removed only if its value is greater than the C_{IBL} value.	112
4.4	Resolution of the truncated mean ($\text{MeV g}^{-1} \text{cm}^2$) for the new and old algorithm. The resolution is computed as the RMS of a Gaussian fit to the distribution of the dE/dx for tracks with momentum larger than 3 GeV and have ≥ 6 SCT clusters.	114
4.5	Fitted peak mass m_i (where $i = K, p$) for the K and proton peaks, obtained on a 10^8 minimum bias simulation and data events . The quoted error on m_i is the one obtained from the fit and does not include any systematic contribution. For each fit category ($q = \pm e$, $n_{\text{UsedHitsdEdx}} = 2, 3, 4+$) the residual Δm_i ($i = K, p$) of the fitted peak mass w.r.t. the nominal one is also shown.	124
5.7	Observed and expected 95% CL lower limit on mass is listed for gluino R -hadrons that are either stable or decaying to $q\bar{q}$ plus a light neutralino of mass $m(\tilde{\chi}_0) = 100 \text{ GeV}$. The stable selection is more efficient for lifetimes of 50 ns or more.	148
6.1	Summary of the measured voltage breakdown at wafer and before and after the assembly. They have been measured with a current limitation of $10 \mu\text{A}$	171

The ATLAS Experiment at the Large Hadron Collider (LHC)

1.1 The Large Hadron Collider (LHC)

The Large Hadron Collider (LHC) is a circular accelerator for charged particles with a total length of 26.7 km placed in the tunnel constructed for the Large Electron-Positron collider (LEP) in 1989 at about 100 m under the surface. It is located at CERN (European Centre for Nuclear Research) in Geneva and operates by colliding two beams of protons obtained from ionization of hydrogen gas or, in alternative, lead ions ($^{208}_{82}\text{Pb}^{82+}$). In Table 1.1 a comparison between LHC, LEP and Tevatron colliders is reported.

Table 1.1 LEP, Tevatron and LHC colliders comparison.

	LEP	Tevatron 2020	LHC
Beam type	e^+, e^-	$p, \bar{p}$	p, p
Beam energy [GeV]	104	1000	6500
Circumference [km]	26.7	6.85	26.7
Luminosity [$\text{cm}^2 \text{s}^{-1}$]	10^{30}	10^{32}	$10^{33}-10^{34}$
Years of operation	1989-2000	1986-2011	2008-

LHC consists of over 1600 superconducting magnets cooled by liquid helium in superfluid state to a temperature of 1.9 K. The bending magnetic field generated is about 8 T, necessary to keep in orbit the hadron beam. The collider is divided into eight cryogenically independent sectors, where each sector consists of an 3.3 km long arc with a cold mass of 4500 tons. In 2015 the accelerator reached the maximum collision energy of 13 TeV in the centre of mass. The energy is transferred to the beam through stages of acceleration.

The hadrons are extracted with an energy of 100 keV and preliminary accelerated to 750 keV using an RF frequency. The second stage is a 80 m long linear accelerator (LINAC2)

that brings the hadron energy up to 50 MeV. After this stage the protons are then injected into Proton Synchrotron Booster (PBS), that increases their energy up to 1.4 GeV. From the PBS the particles go into Proto Synchrotron (PS) and Super-Proto Synchrotron (SPS) reaching respectively the energies of 26 GeV and 450 GeV. After the SPS stage the hadrons are injected into the LHC where the final energy is reached. In LHC, the collisions between packets occur on average every 25 ns, for a total of 40 million collisions per second. The LHC RF frequency f_{rf} is 400.79 MHz and the revolution frequency for protons is 11.245 kHz, this gives a chain of 35640 RF-buckets around the machine which could potentially be filled with bunches. As seen the packets are spaced by 25 ns, therefore only 3564 slots are available. Each of them is tagged by a unique bunch crossing identifier (BCID). For security reason a $3\ \mu\text{s}$ gap is kept free, in order to abort safely the LHC beam. In 2016, for several safety reasons the number of bunches in pp collisions has reached a maximum of 2240.

The two beams collide in four distinct crossing points where four experiments are placed: ATLAS (**A Toroidal LHC ApparatuS**) [19], CMS (**Compact Muon Solenoid**) [20], LHCb [21] and ALICE (**A Large Ion Collider Experiment**) [22]. The LHC acceleration stages and the position of the four experiments located along the ring are shown in Fig. 1.1.

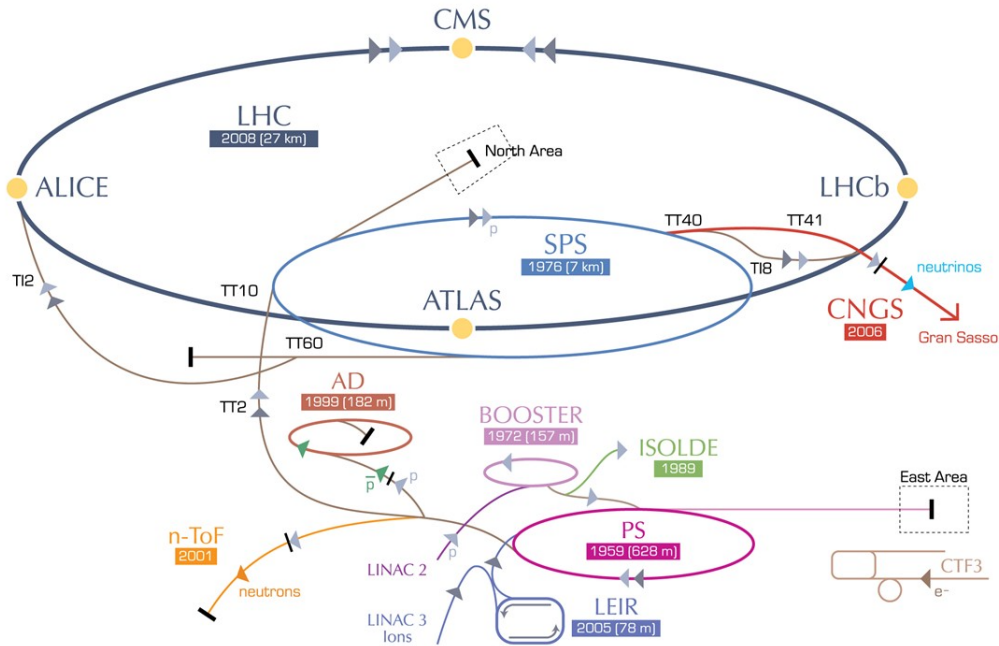


Fig. 1.1 Acceleration stages of LHC

In Fig. 1.2 the evolution of the main beam parameters during a physics fill is schematically shown. The beams are injected at a β^{*1} of 11 m in IP1 and IP5 and 10 m in IP2 and IP8 [1, 23]. The beams are ramped to high energy, squeezed at the interaction points to a smaller β^* value, in 2016 for example β^* was 0.55 m. During ramping the longitudinal momentum of the particles increases, while the transverse component is left unchanged.

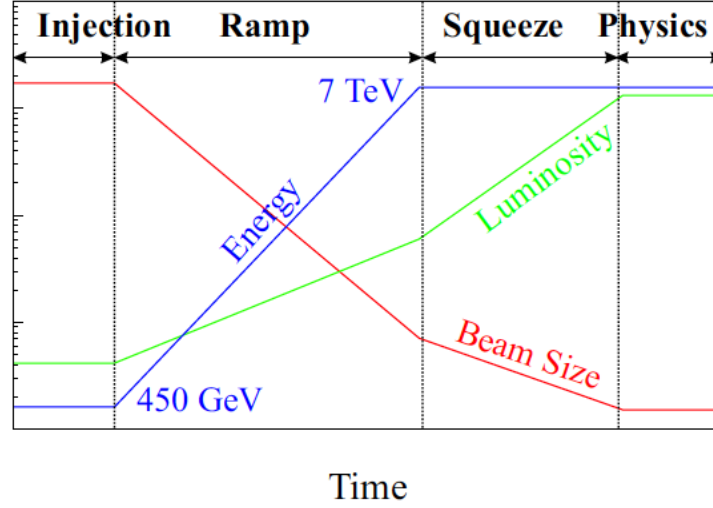


Fig. 1.2 Evolution of energy, luminosity and beam size during the filling sequence. The beams are kept separated until the Physics stage is reached [1]

LHC was designed to reach a luminosity (L) of $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at 14 TeV for the proton-proton (pp) collisions and of $L \sim 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ at 5.5 TeV for the heavy ions. The high value of L allows to study processes with low cross sections, such as the production of the Higgs boson. It may be useful to recall that the luminosity L is defined as:

$$L = F \frac{f N_A N_B}{4\pi\sigma_x\sigma_y} \quad (1.1)$$

Where:

- N_i is the number of particles per packet,
- f is the frequency of collision of packets of the two bunches,
- F is a factor that takes into account the non perfect collimation of the two beams, is equal to 0.9,

¹ β is the betatron function, coming from the solutions of Hill equation for betatron motion and it is defined by the arrangement of the magnets along the design orbit. The betatron function at the interaction point (IP) is denoted as β^* and is usually given in unit m [23].

- σ_x e σ_y are the Gaussian profiles of the packages in the transverse direction.

In terms of beam parameters the instantaneous luminosity can be expressed as:

$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F \quad (1.2)$$

where N_b is the number of particles per bunch, n_b is the number of bunches per beam, f_{rev} the revolution frequency, γ_r is the relativistic gamma factor ϵ_n is the transverse beam emittance, β^* is the beta function at the collision point and F is a geometrical reduction factor due to the introduced crossing angle at the interaction points.

The number n of events expected for a process having cross section σ , over a given (T_1, T_2) time interval, is then given by:

$$n = L \sigma \quad (1.3)$$

where L is the integrated luminosity, measured in unit of inverse-barn, in the time interval, defined as:

$$L = \int_{T_1}^{T_2} L dt \quad (1.4)$$

As example 1 fb^{-1} corresponds to 70×10^{12} pp collisions. During 2016 in pp collisions LHC delivered more than 40 fb^{-1} reaching a peak luminosity of $\sim 1.55 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, as shown in Fig. 1.3.

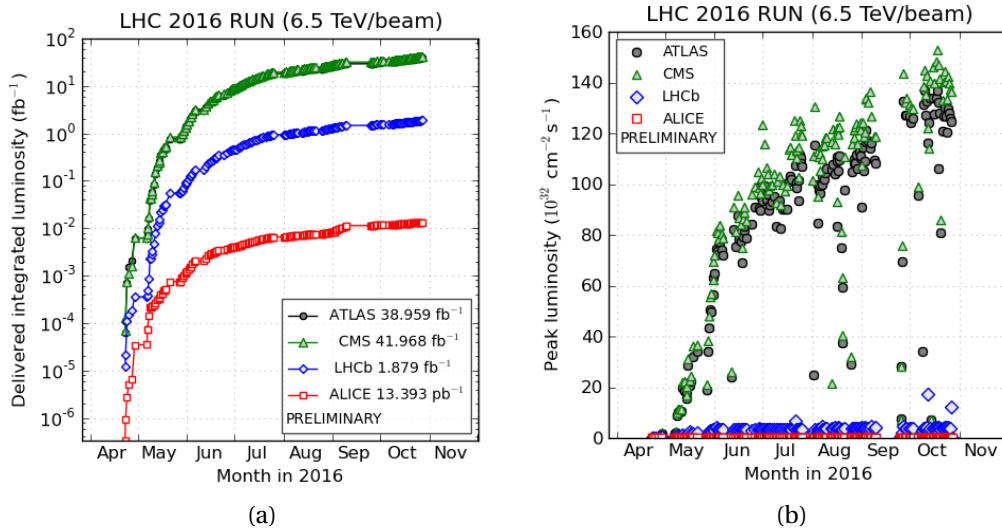


Fig. 1.3 Integrated and peak luminosity collected by LHC experiments in pp collisions during 2016.

If the number of bunches in the LHC beam is high, and therefore high luminosity is delivered, multiple collisions in the same bunchcrossing can occur. This is so-called *in time pile-up* ($\langle \mu \rangle$). If the collisions takes place immediately before and after the considered collision, is called *out of time pile-up*. The *in time pile-up*, the more problematic of the two and is expressed by the mean number of interactions per bunch crossing:

$$\langle \mu \rangle = \frac{L_{bunch} \times \sigma_{inel}}{f_{rev}} \quad (1.5)$$

where $L_{bunch} = L/n_b$ is the per bunch instantaneous luminosity and f_{rev} is the LHC revolution frequency of 11.245 kHz. This overlap is a real a challenge for readout-electronics and the reconstruction algorithms where finding the correct vertex for each secondary particle is really crucial to estimate the missing energy and invariant masses. In Fig. , the average number of interactions for 2016 data per bunch-crossing is shown.

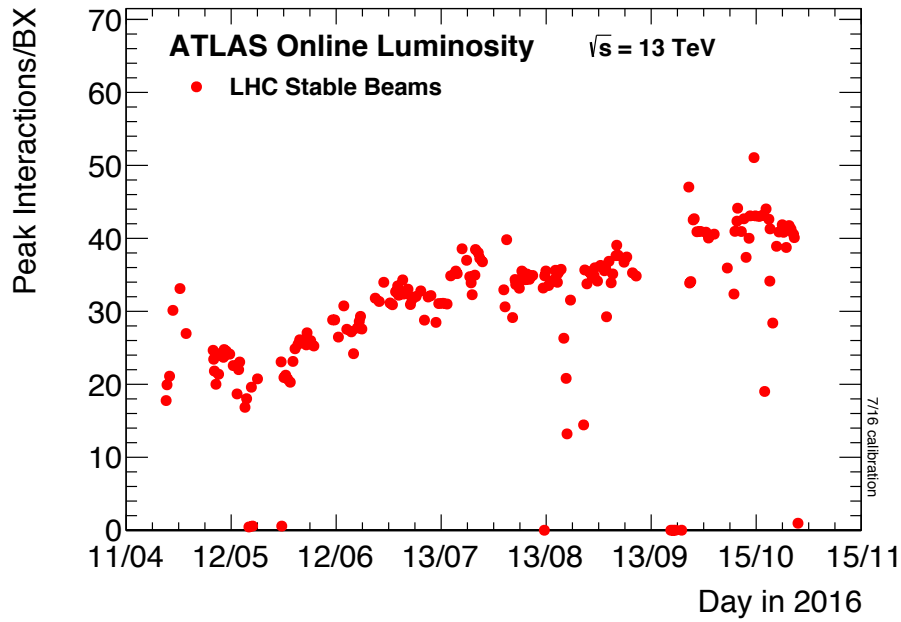


Fig. 1.4 The maximum number of inelastic collisions per beam crossing (μ) during stable beams for pp collisions at $\sqrt{s} = 13$ TeV is shown for each fill in 2016. The number of interactions shown is averaged over all colliding bunch pairs, and only the peak value per fill during stable beams is shown. LHC is working beyond expectations: to have a reference, the maximum mean number of events per BC in machine design is 19.

1.2 ATLAS (A Toroidal LHC ApparatuS)

ATLAS (acronym for "A Toroidal LHC ApparatuS") is the largest of the detectors placed along the LHC ring and is able to detect products from pp and heavy ion collisions. The apparatus has a size of 25 m in height and 44 in length, with a total weight of over 7000 tons. The section of the ATLAS detector is shown in Fig. 1.5.

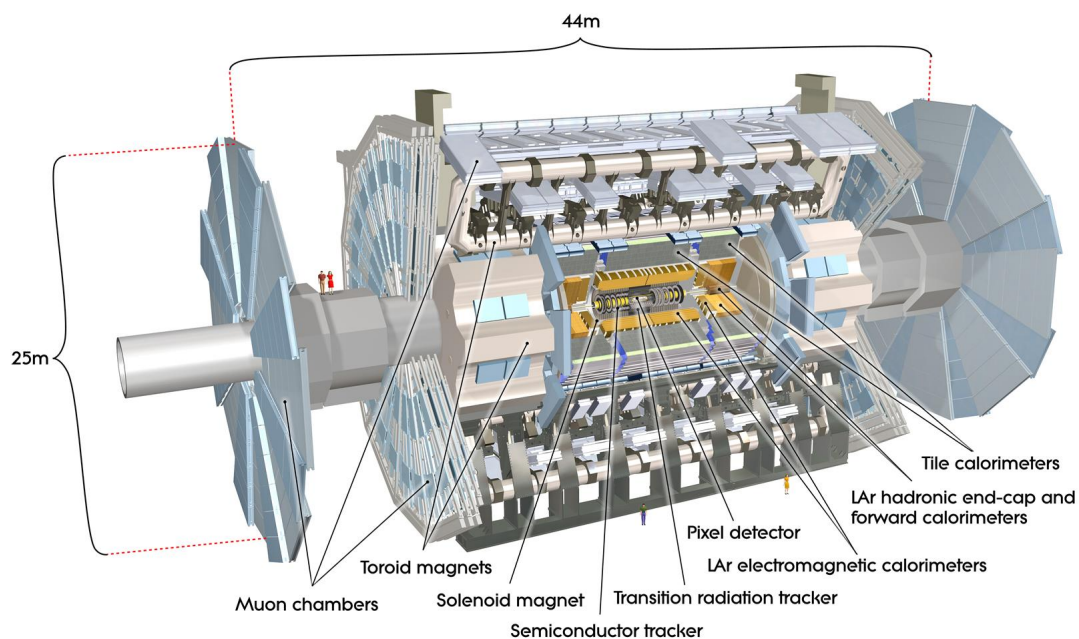


Fig. 1.5 The ATLAS Detector.

The ATLAS detector is constituted by a series of concentric cylinders around the point of interaction. Starting from the inside, is mainly composed of four parts:

1. Inner detector: reconstruct of charged particle trajectories;
2. The calorimetric system: composed of an electromagnetic calorimeter and a hadron calorimeter measures the energies carried by the particles;
3. The muon spectrometer: identifies and measures the momentum of the muons escaping the calorimeters;
4. The magnetic system: bends the charged particles in order to enable the measurement of their momentum.

In the following paragraphs the main characteristics of each subdetector component, paying particular attention to the description of the Inner Detector (ID).

1.2.1 Coordinate System and Nomenclature

The coordinate system and nomenclature used to describe the ATLAS detector are summarized here and they are used throughout this work. The z -axis is defined by the beam direction, while the xy plane is transverse to the beam direction. The positive x -axis is defined as pointing from the interaction point to the centre of the LHC ring and the positive y -axis is defined as pointing upwards. The side-A of the detector is defined as that with positive z and side-C is that with negative z (Right handed coordinate system). Fig. 1.6 provides a schematic representation of the detector position.

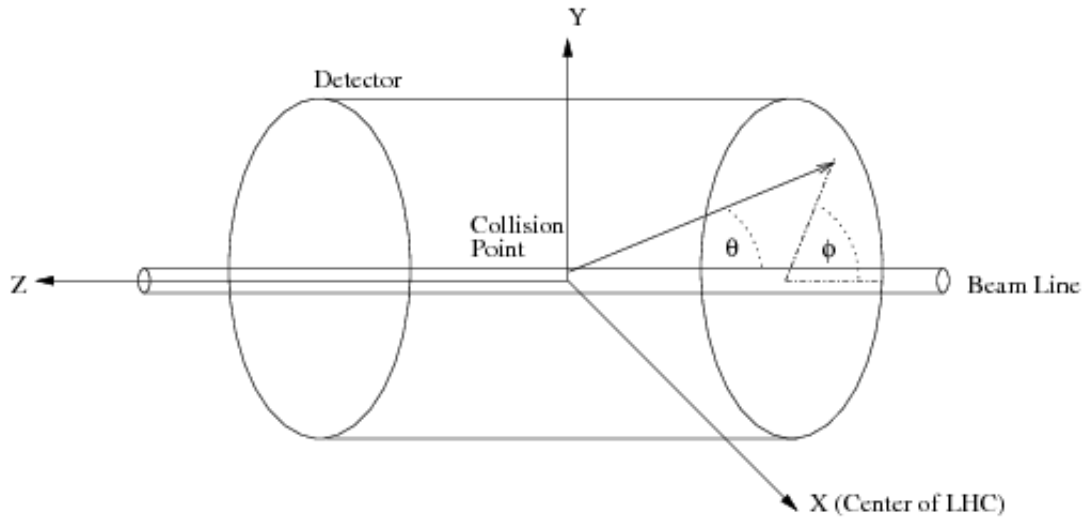


Fig. 1.6 xyz Right handed coordinate system with Z in the beam direction of the ATLAS experiment at LHC.

ATLAS has a cylindrical geometry (as it is shown in Fig. 1.6), so it is useful to define a cylindrical coordinate system (z, R, ϕ) where z is the position in the direction along the beam axis, R is the radius in the xy plane measured from the nominal interaction point, ϕ is the azimuthal angle measured around the beam axis, while the relation between R and z is defined by the polar angle θ or the pseudorapidity η .

$$R = \sqrt{x^2 + y^2} \quad (1.6)$$

$$\phi = \arctan\left(\frac{y}{x}\right) \quad (1.7)$$

$$\theta = \arccos\left(\frac{z}{\sqrt{R^2 + z^2}}\right) \quad (1.8)$$

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right) \quad (1.9)$$

η is usually used to identify the central region and forward region of the ATLAS detector. It can be divided approximatively in reality it depends from the subdetectors extension. in three parts: the Barrel ($|\eta| < 1.05$), the Extended Barrel ($1.05 < |\eta| < 1.4$) and the Endcap ($|\eta| > 1.4$).

Other useful observables are the transverse momentum p_T and the transverse energy (E_T^{miss}), calculated from energy deposits in the calorimeter. They are defined as:

$$p_T = \sqrt{p_x^2 + p_y^2} = p \sin(\theta) \leftrightarrow |p| = p_T \cosh \eta \quad (1.10)$$

$$E_T = \sqrt{m^2 + p_T^2}; \quad E_T^{miss} = -\sum p_T \quad (1.11)$$

1.2.2 The Inner Detector

The purpose of the inner tracking system of ATLAS, the reconstruction of secondary vertices of interaction or decay and the reconstruction of charged particle tracks trajectories that cross it.

The precision tracking detectors cover the pseudorapidity region $|\eta| < 2.5$, and has to face an expected flux of about 1000 particles per collision, i.e. every 25 ns. The Inner Detector (ID, Fig. 2.4) has a length of 6.8 m and a outer diameter of 2.3 m, it is immersed in a solenoidal field of 2 T. It is composed by three distinct subsystem a silicon pixel tracker, a silicon strip detector (SCT) and a straw-based transition radiation detector (TRT) as Fig. 1.7 shows.

The transverse momentum resolution of the ID is:

$$\frac{\sigma_{p_T}}{p_T} = 0.05\% p_T (GeV) \oplus 1\% \quad (1.12)$$

1.2.2.1 The Pixel Detector and the Insertable B-layer

The Pixel Detector [24] is the innermost component of the ATLAS experiment and it is therefore located very close to the interaction region. The pixel tracking system consists of three concentric barrel layers (with mean radii of 50.5 mm, 88.5 mm and 122.5 mm) and six disk layers, arranged in two endcaps with three disks each. It provides at least three high accuracy space-point measurements per track for pseudo-rapidity $|\eta| \leq 2.5$, as needed for track and vertex determination. The innermost pixel layer (so-called B-Layer)

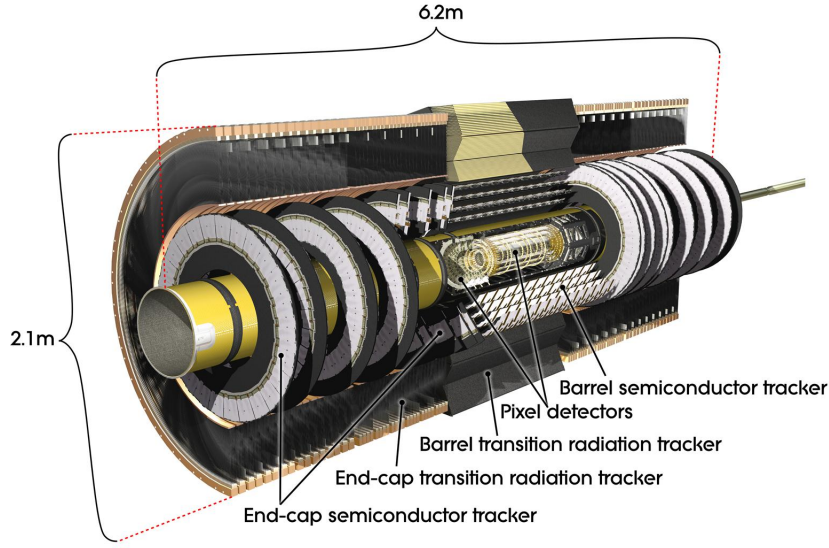


Fig. 1.7 The ATLAS Inner Detector.

plays a crucial role for tracking, vertexing, and b -tagging capabilities of ATLAS. The Pixel Detector is composed by 1744 modules in total. Each module consists of a $16.4 \times 60.8 \text{ mm}^2$ planar n-in-n silicon sensor tile, $250 \text{ }\mu\text{m}$ thick, with 47232 pixels (size of $50 \times 400 \text{ }\mu\text{m}^2$), connected to 16 front-end (FE-I3) integrated circuits. The detector has been designed to face a TID² of 50 MRad (expected at 300 fb^{-1}), a NIEL³ of $1 \times 10^{15} \text{ 1 MeV n}_{eq} \text{ cm}^{-2}$ and a peak luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. In 2014 the Insertable B-Layer (IBL) has been added to the Pixel Detector between the beam pipe and the B-layer, at an average sensor radius of 33 mm. To make the insertion of IBL possible, the beam pipe has been replaced by a new one, with reduced radius (from $R=29 \text{ mm}$ to $R=24 \text{ mm}$), built of Beryllium. IBL consists of 14 staves (64 cm long, 2 cm wide), tilted in ϕ at 14° to guarantee hermeticity and optimize charge collection. Each carbon-fibre IBL stave carries and provides cooling to 32 FE-I4 [25] read-out chips, which are bump-bonded to silicon sensors. In the IBL two different silicon sensor technologies have been used: planar n-in-n and 3D with passing through columns. Each IBL stave is populated with planar pixel technology (12 double chip modules) in the central region and 3D technology (4+4 single chip modules) in the forward region. The IBL has been built to sustain high radiation levels, up to a NIEL of $5 \times 10^{15} \text{ 1 MeV n}_{eq} \text{ cm}^{-2}$ and a dose of 250 MRad. An detailed description of the IBL will be given in Chapter 3. In Fig. 1.8 a scheme of the ATLAS Pixel Detector is shown.

²Total Ionizing Dose

³Non Ionizing Energy Loss, where 1 MeV n_{eq} is the number of particles with a non-ionizing energy loss of a 1 MeV neutron, see Chapter 2

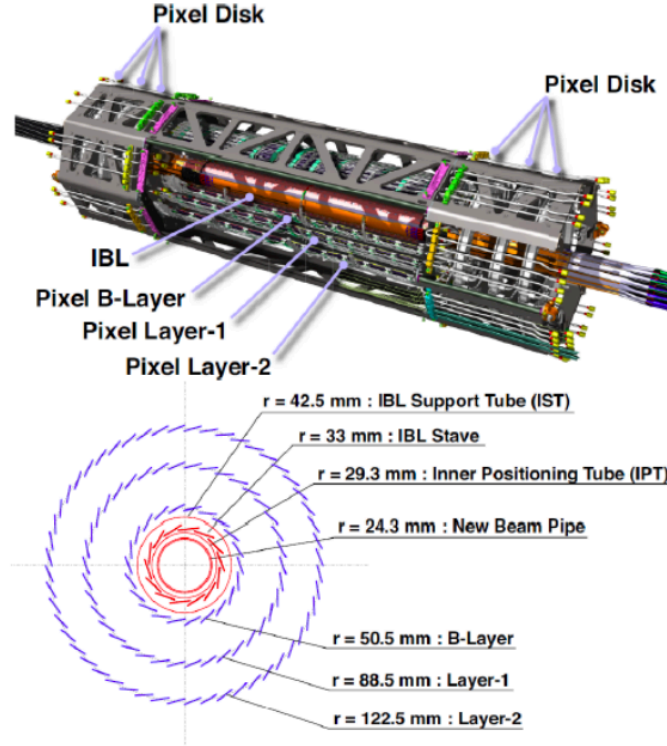


Fig. 1.8 Schema of the current ATLAS 4-Layer Pixel Detector. From the inner part to the outer part the layers are: IBL, B-Layer, Layer-1, and Layer-2. At the bottom, the radial placement of the barrel layers including the beam pipe is depicted [2].

1.2.2.2 The SemiConductor Tracker (SCT)

The SemiConductor Tracker consists of 4 088 modules of silicon-strip detectors arranged in four concentric barrels (called ID layers 3-6) and two end-caps of nine disks each. The modules cover a surface of 63 m^2 of silicon [26]. It is designed to provide precision measurements of the tracks to determine momentum, vertex position and impact parameter. The average strip pitch is $80 \text{ }\mu\text{m}$, two sensors are daisy chained in such a way that each effective strip is $\sim 12 \text{ cm}$ in length. The intrinsic resolution of the SCT is $17 \text{ }\mu\text{m}$ in the $xy - \phi$ direction and $580 \text{ }\mu\text{m}$ in z . It provides typically eight measurements (four space-points) for particles originating in the beam-interaction region. The strips are read out by radiation-hard front-end readout chips, each chip reading out 128 channels, for a total number of 6.3 readout channels.

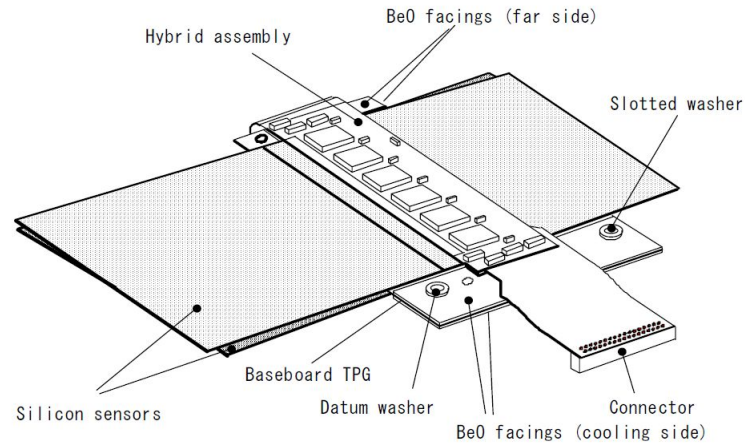


Fig. 1.9 A barrel SCT module.

1.2.2.3 Transition Radiation Tracker (TRT)

The Transition Radiation Tracker (Fig. 1.10) is a gas detector with a sensitive volume that covers radial distances from 563 mm to 1066 mm. The detector consists of 298304 proportional drift tubes (straws), 4 mm in diameter, read out by 350 848 channels of electronics. Each tube is filled with a gas mixture of $Xe : CO_2 : O_2 = 70 : 27 : 3$ with 5-10 *mbar* over-pressure and a gain of 2.5×10^4 . The straws in the barrel region are arranged in three cylindrical layers and 32 sectors; they have split anodes and are read out from each side. The barrel is 156 cm long and each end-cap is 191.7 cm in length. The single straw position resolution is $130 \mu\text{m}$ and a track is on average associated with 30 TRT measurements. More information can be found in [27].

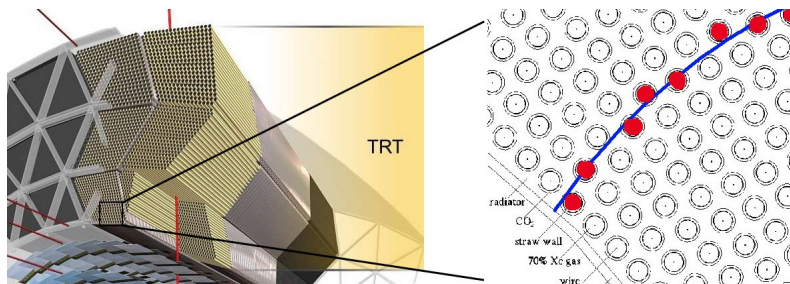


Fig. 1.10 The TRT detector.

1.2.3 The Calorimetric System

A calorimeter detector measures the energy that a particle deposits when it passes through the material of the detector. The physical principle behind the function of a calorimeter is the formation of a shower of particles which propagates until it is completely absorbed in the calorimeter volume. The particles produced are converting into an electrical signal. Calorimeters, thus, perform a destructive measurement on particles.

The ATLAS calorimeters (Fig. 1.11) are constituted of a number of detectors with full ϕ -symmetry and coverage around the beam axis. ATLAS has two type of calorimeters: one electromagnetic and one hadronic. The electromagnetic calorimeter uses lead absorbers in liquid Argon while the hadronic one uses iron absorbers with scintillator plates staggered in planes perpendicular to the beam axis.

The calorimeters, that are closest to the beam-pipe are housed in three cryostats: one barrel and two end-caps.

Different calorimeter parts cover different pseudorapidity regions: Electromagnetic Barrel Calorimeter (EMB) $|\eta| < 1.475$, the Electromagnetic End-Cap Calorimeter (EMEC) $1.375 < |\eta| < 3.2$, the Hadronic EndCap Calorimeter (HEC) $1.5 < |\eta| < 3.2$, the Tile Calorimeter (TileCal) $|\eta| < 1.7$ and the Forward Calorimeter (FCal) $3.1 < |\eta| < 4.9$. The expected total energy resolution for the electromagnetic calorimeter is:

$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E(\text{GeV})}} \oplus 0.7\% (|\eta| < 3.2) \quad (1.13)$$

While for the hadronic one is:

$$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E(\text{GeV})}} \oplus 3\% (|\eta| < 3.2, \text{Barrel}) \quad (1.14)$$

$$\frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E(\text{GeV})}} \oplus 10\% (3.1 < |\eta| < 4.9, \text{End Caps}) \quad (1.15)$$

1.2.4 The Muon Spectrometer

The muon spectrometer forms the outer part of the ATLAS detector, its radius R is in the range between $4.5 < R < 11$ m and its length is 46 m. It is designed to detect charged particles exiting the barrel and end-cap calorimeters and to measure their momentum in the pseudorapidity range $|\eta| < 2.7$.

The muon spectrometer is designed to provide a standalone measurement of the muon momentum with an uncertainty in the transverse momentum varying from 3% at

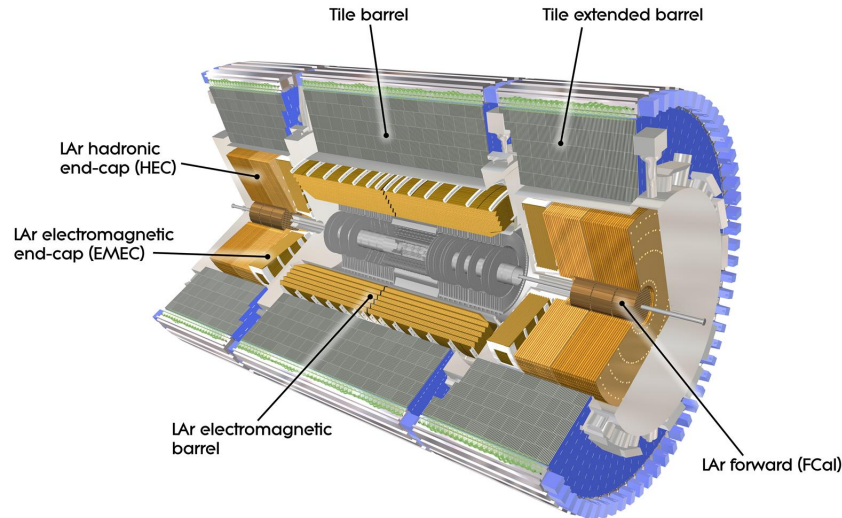


Fig. 1.11 A computer generated image of the ATLAS full calorimeter.

100 GeV to about 10% at 1 TeV, and to provide a trigger for muons with varying transverse momentum thresholds down to a few GeV.

The muon spectrometer is divided into:

- **High precision tracking system:** Monitored Drift Tube chambers (MDT's) and Cathode-Strip Chambers (CSC's) that are important to measure the spatial coordinates in two dimensions.
- **Muon trigger system:** Resistive Plate Chambers (RPC's) and Thin Gap Chambers (TGC's) that determine the global reference time and the muon track coordinate in both directions.

In Fig. 1.12 the layout of the muon system is shown.

1.2.5 The Magnetic System

The ATLAS magnet system (Fig. 1.13) consists of:

- **A central superconducting solenoid:** operating at a temperature of 4.5 K, which is aligned on the beam axis and provides a 2 T axial magnetic field for the inner detector, while minimizing the radiative thickness in front of the barrel electromagnetic

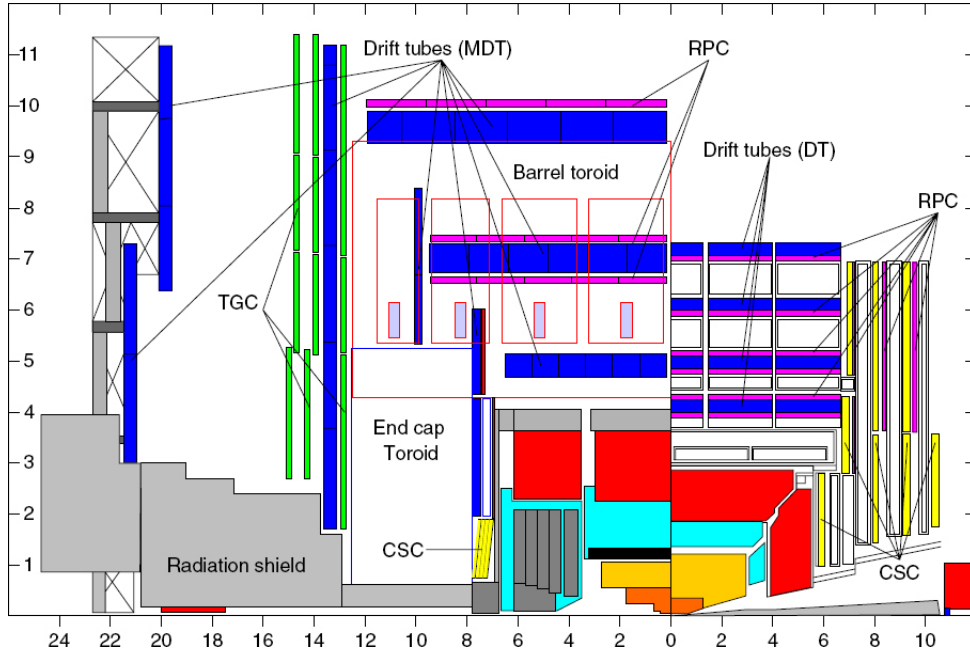


Fig. 1.12 The ATLAS Muon system.

calorimeter. It has a length of 5.3 m, with an inner diameter of 2.44 m and an outer diameter of 2.63 m. For hard-track in TeV-range, given the magnetic field $B = 2$ T and the transverse momentum p_T , the sagitta⁴ s of the track is roughly:

$$s = \frac{p_T}{0.3B} \left(1 - \cos\left(\frac{0.3BL}{p_T}\right)\right) \sim 10^{-4} m \quad (1.16)$$

- **Barrel toroid and two end-cap toroids:** which produces a toroidal magnetic field of approximately 0.5 T and 1 T for the muon detectors in the central and end-cap regions, respectively. The barrel toroid extends over a length of 25 m with an inner diameter of 9.4 m and outer diameter of 20.1 m. The two end-cap toroids, inserted at the two ends of the barrel, have a length of 5 m; inner and outer diameter are respectively 1.6 m and 10.7 m.

1.2.6 The Trigger

LHC is designed to produce a luminosity $L \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, leading to over 23 interactions per bunch crossing; this, multiplied by the bunch crossing rate (40 MHz), corresponds to

⁴Geometrically it is the distance from the center of the arc to the center of its base

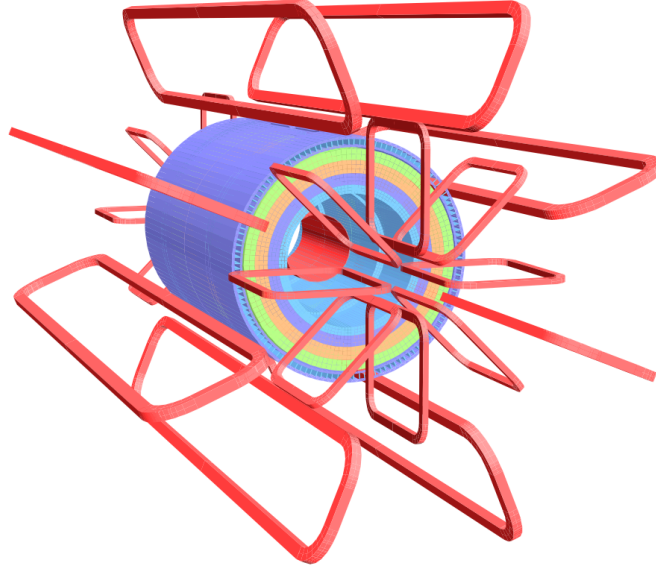


Fig. 1.13 The magnet system is composed of barrel solenoid and outer toroid magnets.

a data volume of $\sim 4 \times 10^4 \text{ GB/s}$. The trigger system is able to reduce this rate from 40 MHz to 100-200 Hz, corresponding to $\sim 10^2 \text{ MB/s}$ recorded. The trigger system consists of a hardware based first level trigger (Level-1) and a software based high-level trigger (HLT). The Level-1 trigger determines Regions-of-Interest (RoIs) and it is implemented in custom electronics. At Level-1 only information of the muon spectrometer and calorimeters are used. It is designed to operate at maximum pass rate of 100 kHz and has $2.5 \mu\text{s}$ of latency to process its decision. The RoIs are passed to the HLT, in which reconstruction algorithms using full granularity detector information are ran. This processing takes a time of 0.2 s. The output of HLT is $\sim 1 \text{ kHz}$. A schematic overview of ATLAS trigger and data acquisition system is shown in Fig. 1.14.

The signals from the electromagnetic and hadronic calorimeter detectors are processed by Level-1 calorimeter sub-system that provides trigger signal inputs to the central trigger processor (CTP). The inner end-cap muon chambers, which are in front of the end-cap toroid magnets, and from the extended barrel region of the Tile calorimeter are used in timing coincidences with the Level-1 muon system information. All Level-1 information, coming from different systems, is combined in the CTP which forms the final Level-1 trigger decision

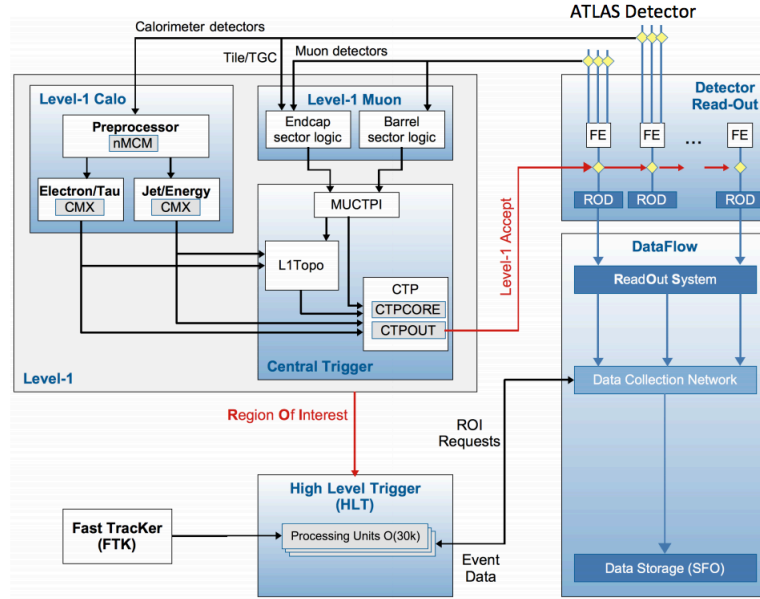


Fig. 1.14 Schematic layout of the Run-2 ATLAS trigger and data acquisition system [3].

1.2.7 Event Reconstruction

All the information coming from the detector signals about the particles (e.g. their position or energy) that cross the ATLAS detector are reconstructed with a software called *ATHENA*. The following subsection describes the methods used to identify and reconstruct jets, electrons and muons. These algorithms are essential to understand properly the terminology used in the analysis described below in Chapter 5. Fig. 1.15 shows how each sub-detector responds to different types of particles.

1.2.7.1 Jets

The hadronization of a gluon or quark produces particles that form a narrow cone (*Jet*) that approximately travels in the same direction. The energy deposition is mainly in the electromagnetic and hadronic calorimeters system. The ATLAS calorimeters have a high granularity: the large energy deposits in the cells are grouped into clusters using the anti- k_t [28] jet clustering algorithm with a distance parameter $R = \sqrt{x^2 + y^2}$ of 0.4. The anti- k_t algorithm belongs to the sequential recombination class, where jets are built by pair-wise clustering of the initial constituents. The algorithms define a distance measure between objects and also some condition upon which clustering should be terminated. For each measured object i with an associated four-momentum, the quantities d_{ij} and

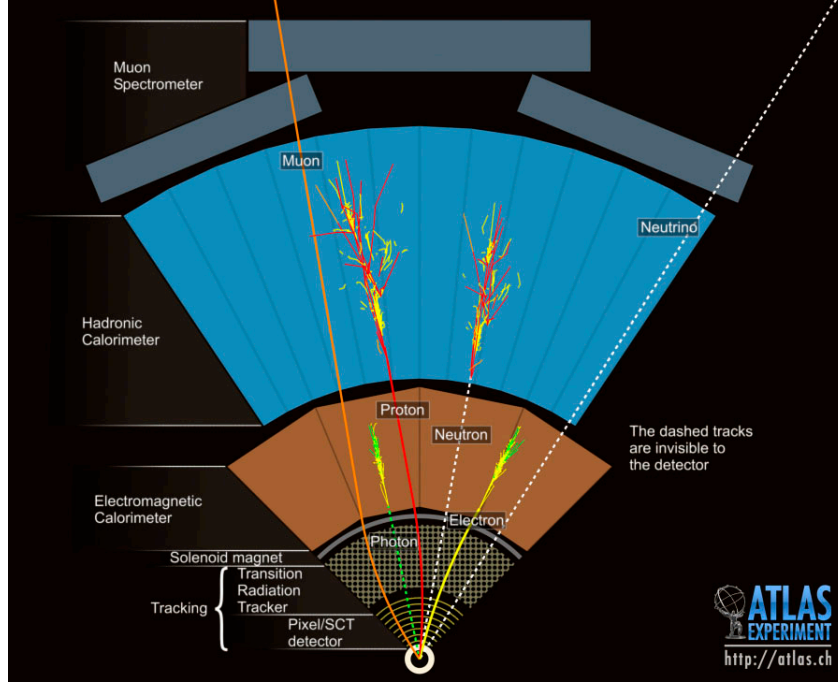


Fig. 1.15 View of ATLAS sub-detector system.

d_{iB} are defined and evaluated as follows:

$$d_{ij} = \min(p_{Ti}^{2p} p_{Tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \quad (1.17)$$

$$d_{iB} = p_{Ti}^{2p} \quad (1.18)$$

where $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and y_i is the rapidity of the object i and p_{Ti} i object transverse momentum, instead d_{ij} is the distance between two objects and d_{iB} is the distance between the object and the beam. The jet candidates are calibrated to account for effects of the calorimeter response and inhomogeneities using calibration factors which depend on the energy and η of the jets. Jets containing b-hadrons (b-jets) are identified based on both impact parameter and secondary vertex information using the *MVI* b-tagging algorithm [29].

1.2.7.2 Electrons

The electrons are reconstructed from energy deposits (clusters) in the electromagnetic calorimeter. The reconstructed objects in the calorimeter have as requirement their matching with a track from a charged particle reconstructed in the Inner Detector. The

electron identification algorithm relies on variables which deliver good separation between isolated electrons and fake signatures from *QCD* jets. Electrons are classified using a set of cuts: following these requirements they are consequently tagged as loose, medium and tight.

- *Loose*: only the information from the calorimeters is used where a simple electron identification is performed. The cuts are applied on the hadronic leakage and on shower-shape variables, derived from the middle layer of the EM calorimeter only. It provides excellent identification efficiency, but poor background rejection.
- *Medium*: these cuts improve the background rejection quality, adding cuts on the energy deposits in strips in the first layer of the EM calorimeter and on the tracking variables. The tracking variables include the number of hits in the pixels, the number of silicon hits (pixels plus SCT) and the transverse impact parameter. The identification efficiency is $\sim 4\%$
- *Tight*: In addition to the criteria used in the *Medium* identification, cuts are also applied to reject electrons from conversions to reject the dominant background from charged hadrons. The identification efficiency is $\sim 70\%$

1.2.7.3 Muons

The muons can be reconstructed and identified in four different ways:

- *Stand-alone*: only the hits from Muon Spectrometer are combined into segments to form a track. The muon momentum is measured using this track and then it is corrected for the parametrized muon energy loss in the calorimeter, to obtain its momentum at the interaction point.
- *Combined*: *stand-alone* muons are combined with an Inner Detector track. The muon parameters are derived from a combined track fit to the hits in the two sub-detectors.
- *Segment tagged*: the reconstruction algorithm searches a track in the Inner Detector and associates it to a track segment in the muon spectrometer
- *Calorimeter tagged*: In this reconstruction, built starting from an Inner Detector track, that is identified as a muon if energy depositions compatible with the minimum ionizing particle hypothesis.

1.2.7.4 Missing Transverse Energy

In pp collision is impossible to use the momentum conservation along the z axis since the interacting parton momentum is unknown. The momentum conservation can be used instead in the transverse plane where the total momentum is zero summing over all particles involved in the event, including non interacting particles (e.g. neutrinos). The missing transverse momentum (p_T^{miss}) is calculated from high quality tracks originating from the primary vertex and it is defined as:

$$p_T^{miss} = - \sum_{electron} p_T - \sum_{muon} p_T - \sum_{jet} p_T - \sum_{soft-track} p_T \quad (1.19)$$

The missing transverse energy (E_T^{miss}) is defined as:

$$E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2} \quad (1.20)$$

where $E_x^{miss} = -\sum E_x$ and $E_y^{miss} = -\sum E_y$ are the energies measured in the detector.

A correction is then applied to take into account dead or inactive detector components, since an extremely precise measure of E_T^{miss} is fundamental for the study of many physics channels, e.g. W decay, H and event discovery in SUSY models.

1.3 Physics at the ATLAS Experiment

In this section an overview of the theoretical framework needed to understand the importance of some goals of the ATLAS experiment is presented.

1.3.1 The Standard Model (SM) and the Higgs Boson

Standard Model (SM) is the name given in 1970s to the Quantum Field Theory providing the best description of elementary particles and their interaction. The SM describes the electromagnetic, weak and strong interactions, by means of the Glashow-Weinberg-Salam (GWS) Theory and Quantum Chromo Dynamics (QCD), without including the gravitational interactions. The Standard Model is a re-normalizable gauge theory based on: fermions with half-odd integer spin, bosons with integer spin and a scalar boson. The model is based on the symmetry.

$$SU(2) \otimes U(1) \otimes SU(3) \quad (1.21)$$

where $SU(3)$ is the group associated to strong interaction, while $SU(2) \otimes U(1)$ represents the group of unified weak and electromagnetic interaction.

The elementary particles, which constitute the matter we are surrounded, are composed by two types of fermions with spin $1/2$:

- *Leptons* (with their corresponding antiparticles), organized in three families:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

- *Quarks* (with their corresponding antiparticles), divided in three families:

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

The quarks and leptons are considered point-like and there is no experimental evidence of any internal structure. The six types of quarks (u, d, c, s, t, b) are also known as six type of flavour. The quark t (top) is the heaviest one and was the last that has been observed (1995, FermiLab Tevatron).

The quark electric charge Q is fractional: $+2/3$ for quarks u, c, t and $-1/3$ for quarks d, s, b . Nevertheless, there is no evidence of any free fractional charge in nature, as quarks are confined into integer charge combinations of three quarks (baryons) or two quarks (mesons). Particles with spin 1, called gauge bosons, are exchanged in the interactions between fermions. These bosons are:

- Electro-weak gauge bosons ($W^\pm$, Z_0 and γ), exchanged in electroweak interactions
- Gluons (g), exchanged in strong interactions.

In Fig. 1.16 a summary of the Standard Model elementary particles is reported. To each particle corresponds an antiparticle with the same mass and spin but opposite charge.

In order the SM to be a renormalizable theory no explicit particles mass terms are introduced in its Lagrangian. The Higgs mechanism is the “trick” that, retaining the renormalization property of the theory, allows the introduction of the mass.

The Higgs mechanism adds an additional scalar field to the Lagrangian exploiting the so-called the process of spontaneous symmetry breaking.

We can consider a toy model in which a scalar field is introduced in the Lagrangian as follows:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}\mu^2 \phi \phi^* - \frac{1}{4}\lambda(\phi \phi^*)^2, \text{ with } \lambda > 0 \quad (1.22)$$

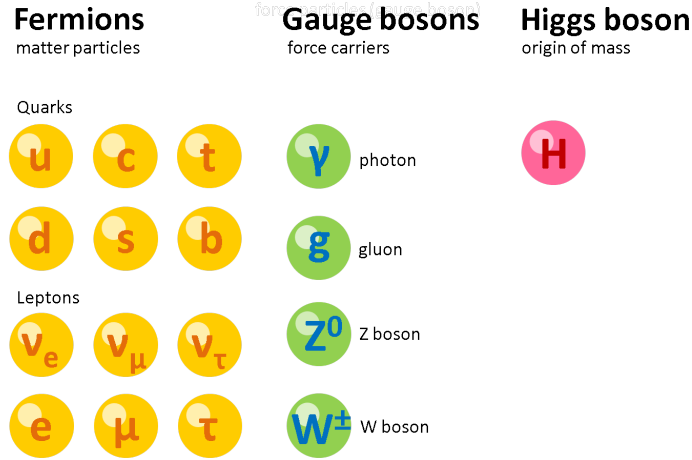


Fig. 1.16 The elementary particles of Standard Model.

There are no odd terms in ϕ as the Lagrangian must be invariant under the transformation $\phi \rightarrow -\phi$ while the term in ϕ^4 is needed in order the theory to be renormalizable.

Depending on the sign of μ^2 , the potential can have a single minimum or various minima as shown in Fig. 1.17.

If $\mu^2 > 0$ the Lagrangian describes a field with mass μ and four-particle self-interaction with the coupling constant λ . The ground state (or vacuum state) corresponds to $\phi = 0$.

If $\mu^2 < 0$ a perturbation expansion should be performed around a true vacuum, for example around a state with minimum energy. For $\mu^2 < 0$ the minimum energy state corresponds to $\phi = \pm v$ where $v = \sqrt{-\mu^2/\lambda}$.

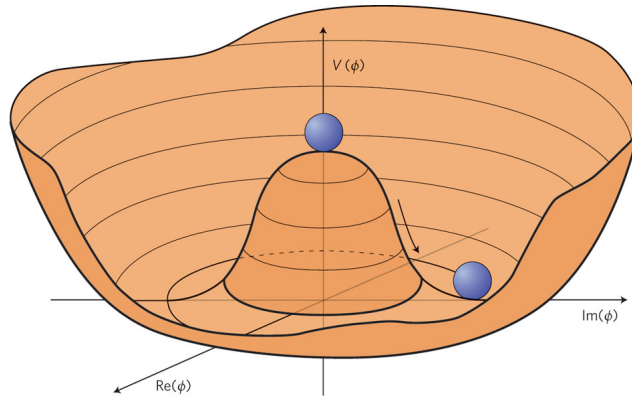


Fig. 1.17 Graph of the potential of the field ϕ in the case of $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right). $V(\phi) = \frac{1}{2}\mu^2\phi\phi^* + \frac{1}{4}\lambda(\phi\phi^*)^2$ in the form of a Mexican hat (right) leads to spontaneous symmetry breaking.

In the Higgs mechanism, four additional degrees of freedom are introduced, which end up in three Goldstone bosons (that are massless and are absorbed to build up the

longitudinal components of the massive W and Z bosons) and one physical scalar particle: the Higgs boson (H).

The mass of the Higgs boson, depends on a free parameter of the theory, the coupling constant λ .

The Large Hadron Collider has been designed to probe the existence of the Higgs boson over a large mass range. On July 4, 2012, ATLAS and CMS experiments announced the discovery of a particle with Higgs-like properties, with a mass of about 125 GeV [30]. The main H production channels are illustrated in Fig. 1.18, instead in tab. 1.2 the decay branching ratios (given a Higgs with mass 125.4 GeV) are reported.

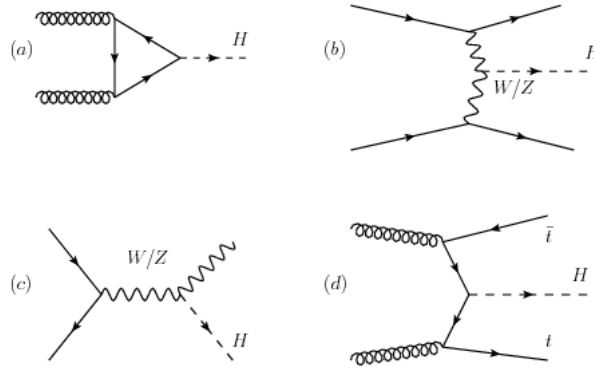


Fig. 1.18 Feynman diagrams of Higgs boson production modes. a) gluon-gluon fusion via heavy quark loops; b) vector boson (Z or W) fusion; c) radiation of a Higgs (Higgstrahlung) from a W or Z boson; d) Higgs production in association with top quarks.

Table 1.2 Higgs decay branching ratios, given a mass of 125.4 GeV

Decay Mode	Branching ratio (%)
$H \rightarrow b\bar{b}$	57.1
$H \rightarrow WW$	22.1
$H \rightarrow \tau\tau$	6.25
$H \rightarrow ZZ$	2.74
$H \rightarrow \gamma\gamma$	0.228
$H \rightarrow Z\gamma$	0.157
$H \rightarrow \mu\mu$	0.021
$H \rightarrow other$	11.4

The measurement of the properties of the newly discovered Higgs boson and its comparison with theoretical predictions are a crucial part of LHC program in the coming years.

1.3.2 The hierarchy problem, naturalness and a possible solution

Despite its success, the Standard Model (SM) of particle, describes with very good prediction phenomena below an energy scale of the order of 100 GeV. It is not capable to account for physics at shorter distances than the Planck scale ($\Lambda_{Planck} \approx 10^{19}$ GeV), where the gravity must be fully quantized, or for some other experimental evidence (e.g. the dark matter) that seems to require an extension of this framework. The difference between the energy scale in which the SM theory works properly and the Plank scale is known as *hierarchy problem* and is deeply related to the structure of the scalar field produced by the Higgs boson. Renormalisation of higher order loop corrections requires the definition of a cut-off scale Λ of the order of 10^{16} GeV (Λ_{GUT}). Any fermion in SM have a coupling with the Higgs boson (H) with a lagrangian term $-\lambda H f \bar{f}$ as Fig. 1.19 shows. From loops corrections where the Higgs particle radiates and reabsorbs a virtual particle pair, its physical mass is given by:

$$m_H^2 = m_0^2 - \frac{|\lambda_f|^2}{8\pi^2} \Lambda^2 + \mathcal{O}(\ln(\frac{\Lambda^2}{m_f^2})) \quad (1.23)$$

where m_0 is the bare Higgs mass and λ_f is the the Yukawa coupling of fermions. Λ^2 is the ultraviolet cut-off, we can observe that the Higgs boson mass diverges quadratically in Λ , hence the corrections needed to keep the mass of $m_H \sim 125$ GeV are $\mathcal{O}(\Lambda_{GUT})$.

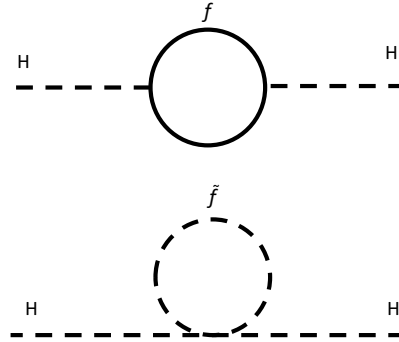


Fig. 1.19 Cancellation of the Higgs boson quadratic mass renormalization between fermionic loop and scalar squark tadpole Feynman diagrams in a supersymmetric extension of the Standard Model.

Theories have to provide natural explanations of experimental observations, but the balance between the numbers discussed in eq. 1.23 means that m_0^2 must be known at least with ~ 20 digits. This fine tuning sounds to be *unnatural*, for this reason new theories have been developed to take care of the *hierarchy problem*. The hierarchy problem is solved

when considering the supersymmetric theory or other theories such as technicolor-like models. The Supersymmetry (SUSY) is a theory that associates a fermionic (bosonic) partner to each SM boson (fermion) thanks to the generator Q . It was developed in its final form by Haag, Lopuszanski and Sohnius in 1975 [31].

$$Q|Fermion\rangle = |Boson\rangle, \quad Q|Boson\rangle = |Fermion\rangle \quad (1.24)$$

The generators of this new symmetry are the Majorana spinors Q_α ($\alpha = 1, \dots, 4$). Q and its hermitian conjugate $Q^\dagger$ are called supercharges. These fermionic generators satisfy the following relation:

$$\{Q_a^\dagger, Q_b\} = (\bar{\sigma}^\mu)_{ab} P_\mu \quad (1.25)$$

where σ^μ are the usual 4×4 Pauli matrices and P_μ is the four-momentum operator.

We can solve the SM hierarchy problem, assuming the existence of a heavy scalar particle S with mass m_S that couples to the Higgs with a Lagrangian term $-\lambda_S |H|^2 |S|^2$ and that gives a contribution to the Higgs mass of:

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} \Lambda^2 + \dots \quad (1.26)$$

where the first term diverges quadratically in Λ . In the comparison between 1.26 and 1.23, we can observe that the quadratic divergences cancelled each other independently of the masses and of the magnitude of the couplings. The reason is that every Standard Model fermion f has two scalar SUSY partners S , that also couple to the Higgs, contributing with a mass correction. The simplest supersymmetric extension is the MSSM (Minimal Supersymmetric Standard Model), that will be discussed in the following subsection (1.3.3).

1.3.3 The Minimal Supersymmetric Standard Model

The minimal supersymmetric extension of the Standard Model is referred to as the *Minimal Supersymmetric Standard Model* (MSSM). It was originally proposed in 1981 to stabilize the weak scale, solving the hierarchy problem and it is the most general supersymmetric extension of the SM. MSSM is interesting from a phenomenological point of view since it represents many of the dominant effects of SUSY with its ~ 100 free parameters. The corresponding field content of the MSSM and its Gauge quantum numbers are shown in Fig. 1.20.

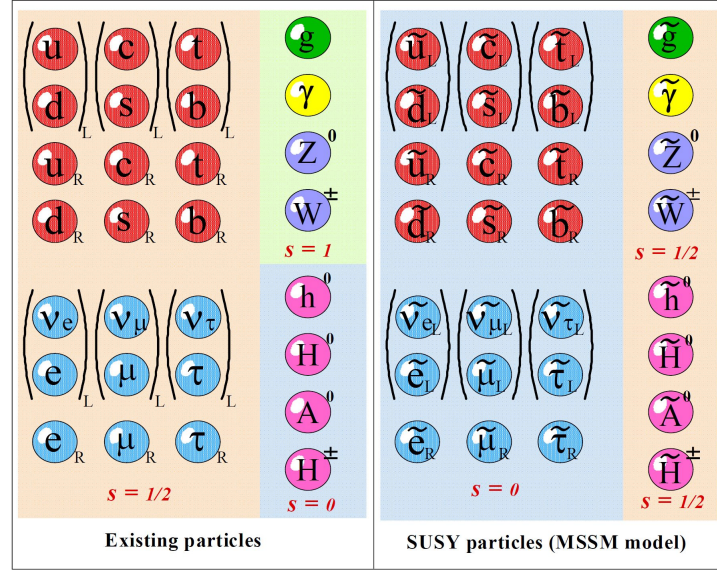


Fig. 1.20 Particles predicted by the MSSM. On the left there are the particles existing in the SM and further four new Higgs bosons predicted by MSSM. On the right their superpartners are reported.

The interactions of SUSY particles are obtained from the Standard Model ones, by replacing any two lines in a vertex by their SUSY partners. A complete reference can be found in [32].

1.3.3.1 R-parity

In the Standard Model Lagrangian, baryon and lepton number are conserved. In supersymmetric theories like MSSM, these conservation numbers can be violated. The main consequence of this violation is the predicted proton rapid decay ($\sim 10^{-2} \text{ s}$)⁵, that is in clear contrast with observations [33]. To avoid this theoretical problem a conserved quantity called R-parity has been introduced in which either B or L, but not both, is conserved to prevent proton decay:

$$R = (-1)^{3(B-L)+2S} \quad \text{or} \quad R = (-1)^{3B+L+2S} \quad (1.27)$$

where B and L are baryon and lepton numbers respectively and S is the particle spin. Hence all SM particles have $R = +1$, while SUSY particles have $R = -1$. If R-parity is conserved then each vertex involves an even number of sparticles, and hence [34]:

⁵Depending on the chosen model.

- The lightest superpartner (LSP) is stable since it can not decay to light quarks as this would lead to an odd number of sparticles at that vertex.
- Each sparticle other than the LSP should decay to an odd number of LSPs plus additional SM particles.
- High-energy collider reactions always produce an even number of sparticles.

Searches at the LHC have not found superpartners yet, but continue to set lower limits on their masses in various scenarios.

Interactions of Particles in Matter and Semiconductor Tracking Detectors

Tracking and vertexing detectors are indispensable tools for the study of many phenomena at LHC since many crucial parameters for physics analyses depend on them. Precise tracking is performed using solid state detectors and in particular pixel silicon detectors. The aim of this chapter is to introduce the reader to the Interactions of Particles in Matter and Semiconductor Tracking Detectors.

2.1 Interactions of Particles in Matter

The goal of this section is to give an overview of the different ways in which subatomic particles interact with matter. For reference to the original literature see [35], [4], [36]. When a charged particle (e.g., electron, pion or proton) penetrates in matter, it interacts with the electrons and nuclei present in the material through the electromagnetic force. Charged particles are sources of the electromagnetic field and the recipients of its effects and their electromagnetic properties depend on their electric charge and magnetic moments. Classically Maxwell theory fully describes the macroscopic *electromagnetic field* going towards the concept of *electromagnetic waves*. In the microscopic realm, however, the field obeys quantum laws and in certain cases, we may regard as intuitive by thinking of electromagnetic field as a flux of *photons*. Rigorously we should always treat the interactions between two particles in terms of the electromagnetic field set up by the particles and the effects of these fields on the particles themselves. If we look at the corpuscular aspect of the electromagnetic field, we may say that the electromagnetic interactions should always be described by as processes of photon emission and absorption. However many cases arise in the classical electrodynamics where one can calculate the interaction

of the two charged bodies in terms of the relatively simple Coulomb forces acting between their charges, rather than in terms of the more general electromagnetic field. We briefly proceed with a classification of the elementary electromagnetic phenomena that are of importance in the high-energy radiation quanta interactions with matter, while a deeper description will be given in the following paragraphs.

We can consider to start, a *charged particle* that passes in the neighbourhood of an atom. This processes are usually called *collision loss process* or *electronic energy-loss*. If the distance between the particle and the atom is large compared with the dimension of the atom, this reacts as a whole to the variable field set up by the passing particle with an *excitation* or an *ionization*. We can consider the passing particle as a point charge, neglecting the magnetic moment ¹ and treat the phenomenon by ordinary methods of quantum mechanics without direct reference to radiation.

If the interacting distance is of the order of the atomic dimensions, the interaction involves the atom as a whole due to electromagnetic field interaction. As a consequence of the interaction, one of the orbital electrons can be ejected from the atom with considerable energy. If the energy acquired by the emitted electron is large compared with the binding energy, the phenomenon can be treated as an interaction between the passing particle and a quasi-free electron, but at this stage we can't neglect the magnetic moments or the spins of interacting particles. Fast electrons resulting from ionization processes are called *δ -rays*.

The last option available is an interacting distance smaller than the atomic radius. In this case the deflection of the trajectory of the incident particle due to the electric field of the nucleus becomes the most relevant effect. From a classical [quantistic] point of view we have an emission of a weak electromagnetic radiation [photons] with a continuous frequency spectrum for every deflection. This phenomenon takes the name of *bremsstrahlung*. For few cases one photon can be emitted with an energy comparable with the incident particle.

Now we will focus our attention on the interaction of the *photons* with matter. We can split this possibility in three cases: interaction of a photon with an atom as a whole, interaction of a photon with a free electron and interaction of a photon with the Coulomb field of the nucleus. The interaction of a photon with an atom as a whole takes the name of *photoelectric effect*, but this phenomenon is negligible at high energies. In following sections, the described ionisation interaction will be examined with more attention.

¹The forces associated with magnetic moment decrease as the third power of the distance, whereas the Coulomb forces decrease as the square of the distance

2.1.1 Passage of Massive Charged Particles Through Matter

The collision process induced by massive charged particles - with a mass well above the electron rest mass ($M \gg m_e$) - was studied by Bethe (1930), and Bloch (1933), who determined the resulting energy lost by charged particles traversing a medium [35]. The goal of all tracking devices is the detection of the free charges resulting from the ionization of a medium due to a passing charged particle. This is described by the Bethe-Bloch formula [4] Eq. 2.1 :

$$-\left\langle \frac{dE}{dx} \right\rangle = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A\beta^2} \left[\frac{1}{2} \ln\left(\frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2}\right) - \beta^2 - \frac{\delta(\gamma)}{2} - \frac{U}{2} \right] \quad (2.1)$$

where:

- $\frac{dE}{dx}$ is the energy loss of the particle per unit path length.
- N_A is the Avogadro's Number, 6.022×10^{23} atoms·mole⁻¹.
- $r_e = \frac{e^2}{m_e c^2}$ is the classical electron radius, 2.817×10^{-15} .
- m_e is the rest mass of electron.
- c is the speed of light.
- z is the charge of the traversing particle in units of the electron charge.
- Z is the atomic number of absorption medium (14 *for silicon*),
- A is the atomic mass of absorption medium (28 *for silicon*),
- $\beta = v/c$.
- $\gamma = 1/\sqrt{1 - \beta^2}$ is the Lorentz factor.
- I is the excitation energy, given by phenomenological expressions $I \approx 11.5 \cdot Z \cdot 10^{-6} [MeV]$ (173 eV in silicon)
- δ is the density effect correction.
- T_{max} is the maximum kinetic energy which can be imparted to a free electron in a single collision.
- U is the so-called shell correction term - related to the non-participation of electrons of inner shells (K, L, ...) in the collision loss process, when (in an absorber with atomic number Z) the incoming velocity is no longer much larger than that of the bound atomic electrons. The estimated values for protons traversing metals are lower than 0.1 when $\beta > 0.05\sqrt{Z}$

In the *Bethe–Bloch formula* the $1/\beta^2$ term is dominant for low energies and the stopping power decreases with increasing energy and at a particle's velocity β of about 0.96 ($\beta\gamma \approx 3$) a minimum is reached. A particle with an energy loss corresponding to the minimum of the *Bethe–Bloch formula* is called a *Minimum Ionizing Particle (MIP)*.

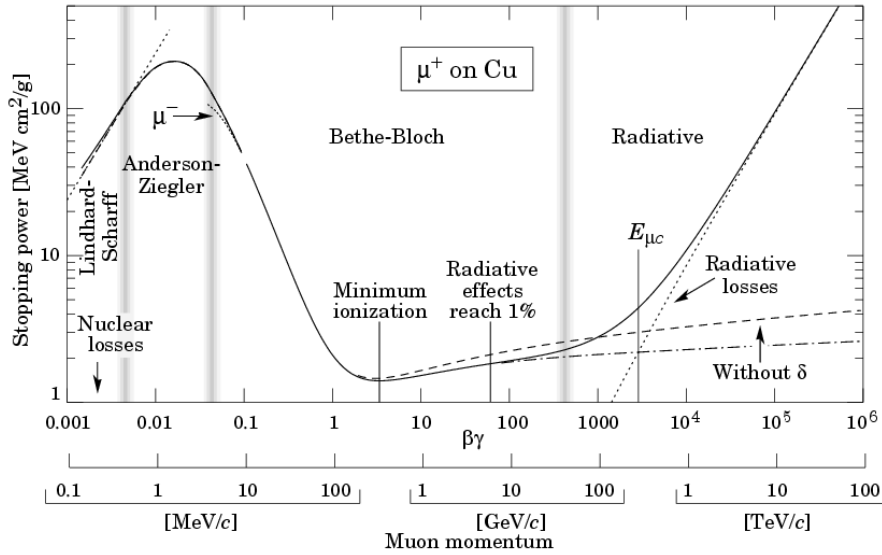


Fig. 2.1 Energy loss or stopping power for muons penetrating copper as a function of $\beta\gamma$. The dashed lines for $\beta\gamma > 1$ illustrate the energy loss for heavy charged particles as described by the Bethe-Bloch formula with and without density correction. The solid line for $\beta\gamma > 1$ illustrates the Bremsstrahlung losses which becomes dominant at high momentum for light charged particles. Vertical bands indicate boundaries between different theoretical approximations or dominant physical processes [4].

In silicon, the average energy needed to create an electron-hole pair is 3.65 eV, i.e. three times larger than *Si* band gap (1.12 eV): this difference of energy generates phonons, which in the end will be degraded into thermal energy.

A MIP penetrating into a detector is responsible of a uniform ionization along its path. Usually Silicon wafer has a thickness of 300 μm and the signal generated in it by a *MIP* is typically around 23000 e^- : so the detector itself must be able to detect a charge of 3.6 fC.

The Bethe-Bloch formula predicts the average value of the energy deposition loss distribution per unit path length, but is essentially useless in describing the behaviour of a single particle because of the stochastic nature of energy losses. The distribution of the energy loss is successfully modelled by a *Landau distribution* that properly includes the statistical fluctuation in the number of collisions around energy transfer per occurred scattering.

It also includes the rare but important effect of the so-called δ – *electrons* generation which obtain enough energy by the interaction to become ionizing particles themselves. δ – *electrons* are responsible for an asymmetry in the collected spectrum, with a longer tail toward higher energies, leading to a spectrum described by a Landau distribution having the most probable value 30% below than the average value.

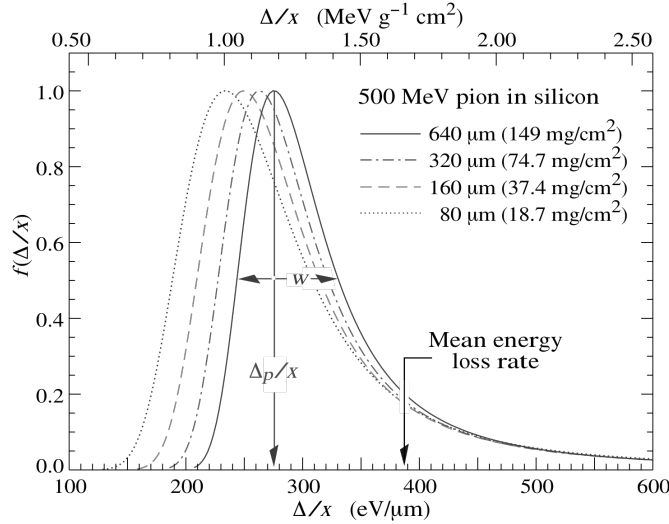


Fig. 2.2 Landau distributions [4] for various thickness of silicon. For reference the ATLAS Pixel Detector sensors are 250 μm , instead the IBL ones are 230 (3D) and 200 (Planars) μm thick.

In Fig. 2.2, we can observe that the most probable energy loss lower than the mean energy loss as reported in Eq. 2.1 for moderately thick mediums. For a thin layer of the stopping material (as silicon particle detector are) and high-energy charged particles the Vavilov equation (Eq. 2.2) is much more appropriate than Eq. 2.1, since the Most Probable Value (MPV) is much lower.

$$\Delta_p = \xi \left[\ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I}\right) + \ln\left(\frac{\xi}{I}\right) + j - \beta^2 - \delta(\beta\gamma) \right] \quad (2.2)$$

Where $K = 4\pi N_A r_e^2 m_e c^2 = 0.307 \text{ MeV g}^{-1} \text{ cm}^2$, $\xi = (K/2 < Z/A > (x/\beta^2)) \text{ MeV}$, $j = 0.200$.

The form of the Landau distribution is not easily parametrisable, but it is approximated with a MPV from Eq. 2.2 and a width of 4ξ as:

$$f(\Delta/x) = \frac{1}{2\pi} \exp\left[-\frac{1}{2}\left(\frac{\Delta/x - a(\Delta/x)_{MIP}}{\xi}\right)^2\right] + e^{-\left(\frac{\Delta/x - a(\Delta/x)_{MIP}}{\xi}\right)} \quad (2.3)$$

2.1.2 Energy deposition of photons

Photons interact with matter mainly via three different processes sketched in Fig. 2.3:

- **Photoelectric effect:** This can happen when the energy of the incident photon E_γ is slightly higher than the ionization energy of the atom E_b . The photon is absorbed by the atom. Consequently an electron is ejected from the atom with a kinetic energy $E_e = hf - E_b$ where $h = 4.136 \times 10^{-15}$ eV is the Planck constant and f the frequency of the atomic electron.
- **Compton effect:** It is based on the corpuscular behaviour of incident radiation and is an incoherent scattering process on individual atomic electrons. In the Compton effect, an incoming photon of momentum $\frac{h\nu}{c}$ interacts with a (quasi-)free electron quasi at rest. The outcome is a deflected photon and recoiling electron.
- **Pair production:** If the incoming photon has an energy at least twice the energy corresponding to the electron rest mass ($2m_e c \sim 1.02$ MeV) the production of an electron and positron pair becomes possible. Pair production can only occur close to a charged massive object, like a nucleus. This takes away the amount of momentum needed to preserve momentum conservation.

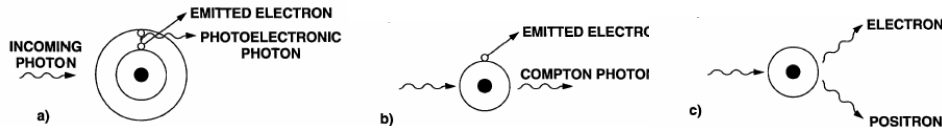


Fig. 2.3 The sketch shows the schema of electromagnetic interaction a) the photoelectric effect, b) the scattering Compton and c) the pair production

In the photoelectric absorption and pair production modes, the photon is completely absorbed while in Compton mode is scattered by a large angle. The characteristic amount of matter traversed by high-energy photons is called the radiation length X_0 , usually measured in g cm^2 . It is $7/9$ of the mean free path for pair production by a high-energy photon [4].

A monochromatic photon beam penetrating through a material is attenuated according to the Lambert-Beer law 2.4:

$$I(x) = I_0 e^{-x/\mu} \quad (2.4)$$

with I_0 the beam intensity before the interaction with the medium, $I(x)$ after traversing a material of thickness x and μ the attenuation length that is a material property.

The absorption coefficient coefficient μ can be expressed by the cross sections σ of the different interactions:

$$\mu = \mu_{Photo} + \mu_{Compton} + \mu_{PairProd} = \frac{\rho}{uA} (\sigma_{Photo} + \sigma_{Compton} + \sigma_{PairProd}) \quad (2.5)$$

where ρ is the density of traversed material, u is the atomic mass unit and A is the atomic mass of traversed material.

In Fig. 2.4 the absorption coefficient of silicon as a function of the wavelength is shown².

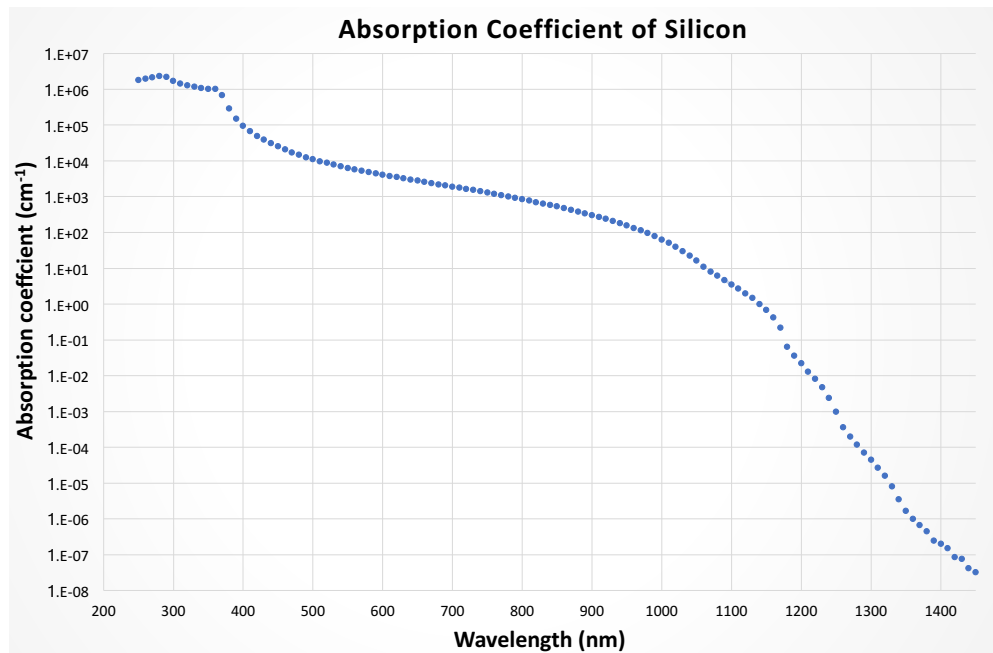


Fig. 2.4 Silicon is an indirect bandgap semiconductor so there is a long tail in absorption out to long wavelengths. The data is graphed on a log scale.

²The optical properties of silicon measure at 300 K are taken from *M. A. Green and Keevers, M. J., "Optical properties of intrinsic silicon at 300 K", Progress in Photovoltaics: Research and Applications, vol. 3, pp. 189 - 192, 1995.*

2.2 Semiconductor Tracking Detectors

The aim of this section is to introduce the reader to an overview of semiconductor tracking detectors. In semiconductor detectors (SD), the information carriers are electron-hole pairs, which are produced along the path taken by the charged particle through the detector. By collecting electron-hole pairs, the detection signal is formed. SD have been used in spectroscopy applications since the 1960s because they require lower energy to produce an electron-hole pair respect to ionization chambers (e.g for Silicon is 3.6 eV versus 26 eV of a gasFor Argon case.). In the 1970s, the use of semiconductor detectors for charged particle tracking became relevant; these were mainly based on silicon, since it is very cheap and can be found in great abundance, thus being the most studied semiconductor. Nowadays other semiconductor materials are available (e.g. Diamond) which might offer better radiation hardness than silicon, even if they are not currently available in large wafers or their quality is not yet as good.

2.2.1 Charge Transport and Collection in Semiconductor Detectors

Silicon, as every other semiconductor, has a forbidden region in the energy band structure, the so-called band gap. The number of free electrons n can be calculated by multiplying the density of states in the conduction band $N(E)$ with the probability of their occupation given by the Fermi–Dirac function. A complete introduction can be found here [6]

$$n = \int_{E_C=0}^{\infty} N(E)F(E)dE \quad (2.6)$$

where E_C is the energy of the lower bound of the conduction band arbitrarily set to zero. The density of states in the conduction band can be calculated as:

$$N(E)dE = 4\pi\left(\frac{2m_n}{h^2}\right)^{2/3}\sqrt{E}dE \quad (2.7)$$

where m_n is the effective mass of electrons and h the Planck constant. The Fermi level E_F is usually located close the centre of the band gap.

The Fermi function can be approximated by an exponential function in the conduction band:

$$F(E) = \frac{1}{1 + e^{(E-E_F)/k_B T}} \approx e^{-(E-E_F)/k_B T} \quad (2.8)$$

where k_B is Boltzmann constant and E_F is the Fermi level. Substituting and solving the integral 2.6, it is possible to obtain the concentrations of free charge carriers in the material:

$$n = 2 \left(\frac{2\pi m_n k_B T}{h^2} \right)^{3/2} e^{-(E_C - E_F)/k_B T} = N_C e^{-(E_C - E_F)/k_B T} \quad (2.9)$$

$$p = 2 \left(\frac{2\pi m_p k_B T}{h^2} \right)^{3/2} e^{-(E_F - E_V)/k_B T} = N_V e^{-(E_F - E_V)/k_B T} \quad (2.10)$$

where n and p are the concentrations of free electrons and holes, m_n and m_p are the masses of electrons and holes, E_C and E_V are the energies of the conduction and valence bands. N_C and N_V are called effective density of states in the conduction and valence band.

The product of concentrations of electrons and holes is independent of Fermi Level, it depends only on temperature:

$$np = n_i^2 = N_C N_V e^{-(E_C - E_V)/k_B T} \quad (2.11)$$

where n_i is the *intrinsic concentration* and the difference $E_C - E_V$ is called energy gap E_g .

The amount of free electrons in an intrinsic semiconductor (always equals to the amount of free holes) at ambient temperature of $T = 300\text{ K}$ is

$$n_i = 1.01 \times 10^{10} \text{ cm}^{-3} \quad (2.12)$$

The silicon generally shows a low intrinsic conductivity that must be artificially increased in order to be used in devices. This reason for, additional states are inserted in the forbidden band gap so that a lower energy is required for hole or electron excitation. This procedure is known as "*doping*".

Silicon has four valence electrons and so is located in the IV Group of the periodic table. In order to modify its conductivity, usually elements from III Group (i.e. Boron) or V Group (i.e. Phosphorus, Arsenic), having respectively one valence electron less (*p-type*) or more (*n-type*) than silicon, are used. The latter ones release their "extra" electron easily into the conduction band and are therefore called donors. Donor levels are very close to the conduction band. For phosphorus the difference is 0.045 eV and for arsenic 0.054 eV [6]. In turn materials from III Group are called acceptors as they accept the extra electrons from silicon.

The current conduction in a semiconductor depends on the number of free charges as, in presence of an external electric field, the charge carrier is accelerated between two random collisions. It is possible to define the conductivity (σ) and resistivity (ρ) of doped semiconductors as:

$$\sigma = (e\mu_n n + e\mu_p p) = \frac{1}{\rho} \quad (2.13)$$

where e is the elementary charge (negative define for electrons), μ_n and μ_p are the mobilities of electrons and holes respectively.

The mobility is generally defined as:

$$\mu = \frac{|\vec{v}_D|}{|\vec{E}|} \quad (2.14)$$

where $|\vec{v}_D|$ is the drift velocity and $|\vec{E}|$ is the electric field.

In a typical (not irradiated) silicon detector the applied voltage is in the order of 150 V and the average field is about 5000 V/cm, which is about the value where the mobility starts to drop.

The low field mobility for intrinsic silicon at 300 K is given as [6]:

$$\mu_n = 1415 \pm 46 \text{ cm}^2 / (\text{Vs}) \quad (2.15)$$

$$\mu_p = 480 \pm 17 \text{ cm}^2 / (\text{Vs}) \quad (2.16)$$

The current density can be expressed as:

$$\vec{J} = \sigma \vec{E} \quad (2.17)$$

From Eq. 6.13 is possible to have the drift current per unit areas $\vec{J}_{drift}$ for electrons and holes:

$$\vec{J}_{drift} = \vec{J}_{n,drift} + \vec{J}_{p,drift} = e(\mu_n n + \mu_p p) \vec{E} \quad (2.18)$$

The random movement of the charge carriers implies that in case of a gradient in the carriers concentration it is more probable that a carrier from a high-concentration region arrives at a low-concentration region than vice-versa. This effect, which spreads the distribution, is called diffusion and it is expressed by Fick's Law:

$$\vec{J}_{n,diff} = -D_n \vec{\nabla} n = \frac{kT}{e} \mu_n \vec{\nabla} n \quad (2.19)$$

$$\vec{J}_{p,diff} = D_p \vec{\nabla} p = -\frac{kT}{e} \mu_p \vec{\nabla} p \quad (2.20)$$

where $\vec{\nabla} n$ and $\vec{\nabla} p$ are the gradients of the electron and hole concentration, instead the diffusion constants $D_{n,p}$ are related to the mobilities through the Einstein equation.

Considering both drift and diffusion contributions, the total current density in a semiconductor becomes:

$$\vec{J}_n = e\mu_n n \vec{E} + \frac{kT}{e} \mu_n \vec{\nabla} n \quad (2.21)$$

$$\vec{J}_p = e\mu_p p \vec{E} - \frac{kT}{e} \mu_p \vec{\nabla} p \quad (2.22)$$

If the semiconductor is in thermal equilibrium, without exchanges with the external world, the charge carrier concentration is constantly balanced by generation and recombination. The thermal generation rate of carriers (G) does not depend on carriers concentration and is equal to:

$$G = \frac{n_i}{\tau_g} \quad (2.23)$$

where τ_g is the generation lifetime.

In the case of low level injection, the recombination is in fact limited by the concentration of the minority carriers. The thermal recombination rate R of charge carriers does not depend on the concentration, and it is defined as:

$$R = \frac{\Delta n}{\tau_{r,p}} \text{ for p - material} \quad (2.24)$$

$$R = \frac{\Delta p}{\tau_{r,n}} \text{ for n - material} \quad (2.25)$$

where $\tau_{r,n/p}$ is the recombination lifetime in n-type and p-type silicon.

Finally considering the continuity equation for the charge:

$$\frac{\partial p(\vec{r}, t)}{\partial t} + \vec{\nabla} \cdot \vec{J} = S \quad (2.26)$$

the entire process can be described through 2.23:

$$\frac{\partial (p(\vec{r}, t)/n(\vec{r}, t))}{\partial t} + \vec{\nabla} \cdot \vec{J}_{p/n} = G - R \quad (2.27)$$

2.2.2 The pn Junction

In an intrinsic silicon substrate there is a density of about 10^{10} free charge carriers on cm^3 . As seen in the previous section 2.1, the passage of a MIP induces about 2×10^4 electrons and the signal would be lost in the larger number of free charge carriers, so it is very important to reduce them by several orders of magnitude. To achieve this, it is used a p -type and n -type silicon in combination in a reverse-biased pn -junction configuration. The reversely biased pn -junction is the basic element of silicon sensors. As an example, a pixel sensor can be seen as a reversely biased pn -diode.

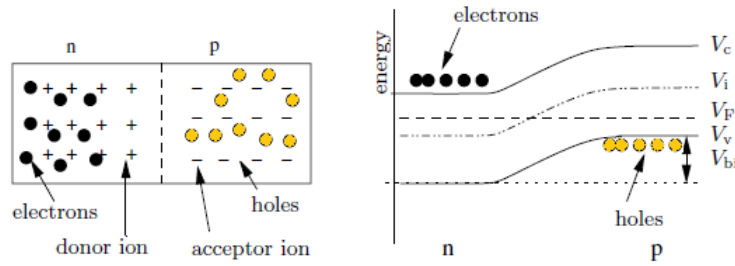


Fig. 2.5 A pn -junction and its band diagram

In presence of a transition between n -doped and p -doped material, some of the majority charge carriers will diffuse from one side into the differently doped side. They will recombine with the majority carriers producing a region close to the junction which is depleted from free charge carriers. In the vicinity of the junction, donor and acceptor ions are left without their balancing charges, causing this region to be electrically charged and be often referred to as Space Charge Region (SCR), see Fig. 2.5.

The SCR causes an electrical field counteracting the diffusion that can be characterized by the so-called *built-in voltage* V_{bi} :

$$V_{bi} = \frac{k_B T}{e} \ln\left(\frac{N_D N_A}{n_i^2}\right) \quad (2.28)$$

where N_D and N_A are the concentrations of donors and acceptors.

An external voltage applied in the same direction as the built-in voltage will further remove majority carriers from either side and will extend the SCR. The junction is now reversely biased. The width of the depletion zone, the electric field, and the potential as

function of the applied voltage can be calculated by solving the one-dimensional Poisson equation:

$$W = x_n + x_p = \sqrt{\frac{2\epsilon_0\epsilon_{Si}}{e} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) (V_{bias} + V_{bi})} \quad (2.29)$$

where W is the total width of the depletion zone, x_n and x_p its part on the n - and p -side respectively, and V_{bias} the externally applied voltage.

In silicon detectors a junction is generally realized by low-doped material ($N_D \approx 10^{12} \text{ cm}^{-3}$) in which are implanted electrodes that are generally very doped ($N_A > 10^{18} \text{ cm}^{-3}$). Assuming an n -doped bulk material it is possible to neglect the $1/N_A$ in Eq. 6.14. In addition, V_{bi} is of the order of 0.5 V, small compared to typical operation voltages exceeding in most cases 50 V and can therefore also be neglected.

So we obtain:

$$W \approx \sqrt{\frac{2\epsilon_0\epsilon_{Si}}{eN_D} V_{bias}} \quad (2.30)$$

The maximum electric field value inside a typical pn-junction device, is located at the junction and is equal to:

$$E_{Max} = \frac{2V_{bias}}{W} \quad (2.31)$$

Increasing the bias voltage to high values will cause the electric field at the junction to reach the critical value thereby triggering the so-called avalanche breakdown effect. This effect is related to the kinetic energy gained by free carriers thermally generated inside the material: a free electron under the influence of a strong electric field will be accelerated to a very high speed gaining enough energy to break the covalent bond of another electron in the silicon lattice when colliding with it. If the field is high enough, this avalanche effect is self sustained and leads to a large increase in the reverse current of the device.

It is possible to calculate the maximum operating voltage (V_B) for a silicon device:

$$V_B \approx \frac{\epsilon_{Si}}{2eN_D} E_B^2 \quad (2.32)$$

E_B is the critical electric field for avalanche multiplication in silicon at $T = 300 \text{ K}$ and its value is $E_B = 4 \times 10^5 \text{ V/cm}$.

2.2.3 Semiconductor Detector Geometries: Strips and Pixels

A simple semiconductor diode with only two electrodes can only detect the passage of a particle, but not its position. This information can be obtained by segmentation of one or both electrodes. We have three main different sensor geometries, sketched in Fig. 2.6:

- Strip Geometry: single side
- Strip Geometry: double side
- Pixel Geometry

A single sided strip detector can provide only an one dimensional position information. To have the availability of two dimensional position information both electrodes have to be segmented into non parallel strips.

In trackers and vertex detectors several layers of pixel and strip detectors are used to reconstruct the tracks of traversing *MIPs*. During high energy physics (HEP) era, the surface used for trackers and vertex detectors has been increased to cope with the increasing of track densities due to higher luminosities of colliders as Fig. 2.7 shows.

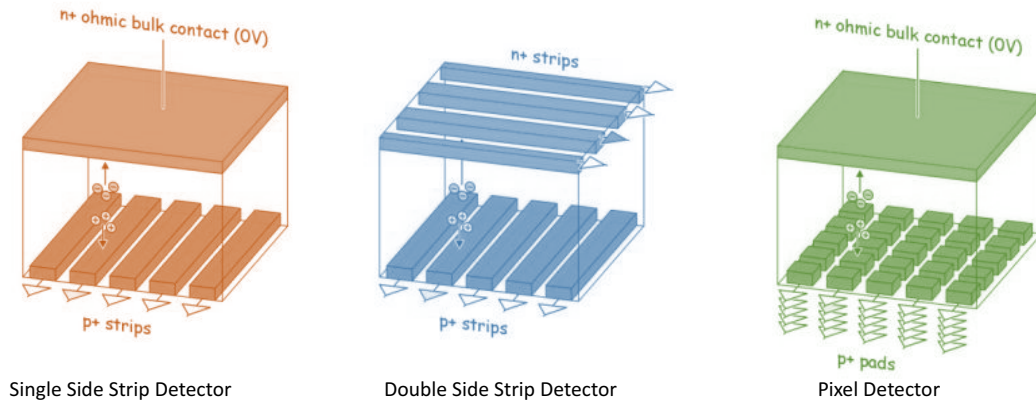


Fig. 2.6 The space resolution improves with the segmentation. In the first case 1 dimensional space coordinates for single sided strip detector is reported, in the second picture a 2 pseudo dimensional space coordinates for a double side strip detector and finally in the last a full 2 dimensional space coordinates as it is for pixel detectors.

2.2.3.1 Strip Geometry

A strip detector is an arrangement of strip-like shaped implants acting as charge collecting electrodes. Placed on a low doped fully depleted silicon wafer these implants form a

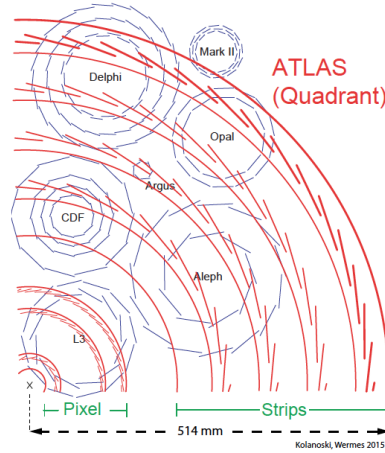


Fig. 2.7 In this sketch from is reported the evolution of pixel and strip detectors surfaces for different experiments [5]. As we have seen in Chapter 1, experiments at collider, like ATLAS, have high precision semiconductor detectors close to the interaction region.

one-dimensional array of diodes. By connecting each of the metallized strips to a charge sensitive amplifier a 1D position sensitive detector is built. Two dimensional position measurements can be achieved by applying an additional strip like doping on the wafer backside by use of a double sided technology (see Fig. 2.7). This configuration is useful to detect two coordinates and is relatively simple, but it leads to ambiguities when the detector is operated with high hit densities in fact each hit generates both an X and Y coordinate.

In case n hits occur in a short time, n pair of coordinates will be generated, simulating a total of n^2 hits, $n^2 - n$ of which are fake. A way of overcoming this is to use a stereo angle α between opposite side strips instead of 90° . The speed of a strip detector is only limited by the carriers charge drift time, thus the achievable time resolution is in the range of 10 ns. If there are multiple events within one readout period a strip detector is not able to assign the hit positions unambiguously. This inherent drawback results from the long electrode shape. If the hit occupancy becomes too large, for example, close to the interaction point of colliders, ambiguities occur and another category of sensor elements, pixels, have to be used.

2.2.3.2 Pixel Geometry

To avoid ambiguities for high particle fluxes, for electrodes must be segmented in both directions: this geometry is adopted in the so-called pixel detectors. The main limitation to pixel size usually comes from the electronics, because a large amount of circuitry must

be fit in a single read-out pixel with complexity changing depending on the adopted type of read-out. In these years different sensor pixel technologies have been developed, we have mainly three different types of pixel detectors [37]:

- **Hybrid pixel detectors:** The pixels of the sensor have to be connected to the read-out chip (Front-end) through small solder bumps (Fig. 2.8). This technology has many advantages as proven radiation hardness (beyond $10^{15} n_{eq}/cm^2$) and good spatial resolution ($\sim 10 \mu m$). The hybrid form of these detectors is also their main disadvantage, since usually a large material budget contribution (typically more than 3% X_0 per layer in ATLAS and CMS) and the module production, including bump-bonding and flip-chipping (see 2.3.1) is complex and laborious [37].

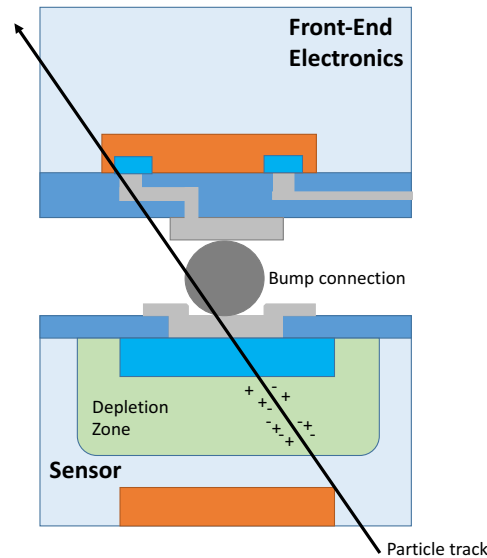


Fig. 2.8 A pixel cell is the basic building block of a hybrid pixel detector. In the picture a cross section of a single hybrid pixel readout channel is reported. Here the sensor at the bottom (for signal generation) the bump connection in the middle (for the interconnection) and the readout electronics (for the signal amplification and data processing) are shown. When ionizing particle crosses into the sensor, it generates charges that move in the depletion region under the action of an electric field producing the signal.

- **Active hybrid pixel detectors:** The so-called semi-monolithic detectors are still hybrid detectors. In this case amplifier stages are implemented in the sensor part (see Sec. 2.2.5.4). The increased signal size after amplification provides more options of interconnection using a capacitive medium like a glue layer (see Sec. 2.3.2). This should allow interconnection without bump-bonding. This possibility is currently under investigation, some results will be shown in Chapter 6.

- **Monolithic pixel detectors:** It is possible to integrate parts or the entire front-end electronics in the sensor, obtaining the so-called monolithic detectors. They are standard for the detection of visible light, in HEP this type of detectors could offer many advantages in terms of production costs, assembly and integration. Unfortunately the readout speed usually is very slow and some technologies (e.g. MAPS) result sensitive to radiation damage. A more accurate description can be found in Sec. 2.2.5.5.

2.2.4 Detector readout processing

The sensor converts the energy deposited by a particle to electrical signal. This signal is processed by the electronic readout chain that can be located in the same piece of silicon (monolithic approach) or in a different tile of silicon (hybrid approach). In this section will be given a brief introduction since a detailed description is out of the scope of this thesis, extensive descriptions can be found in [6, 38]. The readout electronics usually consist of an analogue part to amplify and shape the signal and a digital data processing logic.

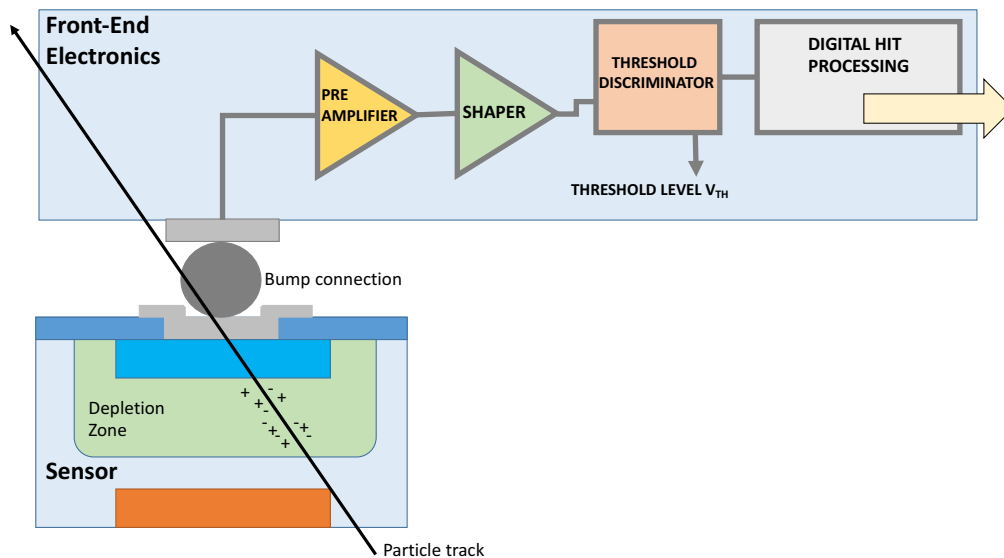


Fig. 2.9 A scheme of a basic detector acquisition chain is here reported. The sensor converts the energy deposited by a particle to an electrical signal. This low-level signal is first integrated in a pre-amplifier then fed to a pulse shaper and finally digitized.

As shown in Fig. 2.9 the first two basic blocks of an ideal front-end are the pre-amplifier and the shaper. The pre-amplifier is needed since the signal charge can be small, in the order of $\sim 4fC$ ($4 \cdot 10^{-15} C$) in a typical HEP tracking detector, for this reason the signal

must be amplified. After this stage a pulse shaper is situated, that is basically a band-pass filter to improve the signal-to-noise ratio.

Following the readout chain after the first two stages the threshold discriminator is situated. Here a discriminator compares the shaper output to a threshold value which is distributed globally to all pixels. Usually the threshold is set to low values in order to maximize the detection efficiency, but high enough to keep the rate of noise hits at an acceptable level. Finally the discriminator output signal is routed to the digital readout chain and the digital readout logic stores the hit information in buffers. In the case of ATLAS pixel modules, the hit information stored consists of a time-stamp to associate the hit to the correct LHC bunch crossing, the pixel address and the digitized TOT information. A detailed description of the IBL readout chip will be provided in Chapter 3.

2.2.5 Pixel Semiconductor Sensors

In this section an overview on the most important sensor pixel technologies will be given. This section will be mainly focused on sensors for hybrid and active hybrid detectors (Planars, 3Ds, Diamonds and HR and HV-CMOS) since they are the most used in LHC experiments or, as for HR/HV-CMOS sensors in very advance R&D stages. In the last section (Sec. 2.2.5.5) new monolithic pixel technologies will be discussed where R&D programs started only few years ago.

2.2.5.1 Planar Sensors

Planar Sensors are the oldest technology, but radiation hardness has been proven and mass production capabilities are well established with several international vendors. Traditionally are $p-in-n$ or $n-in-n$ sensor. For $p-in-n$ type the undepleted region of the sensor is shorting the p^+ -pixel implants and making an under-depleted operation impossible. $N-in-n$ sensors, on the other hand, have the depletion zone growing from the n^+ -pixel implants and the drifting charge carriers are still seen by the individual electrodes. The undepleted portion of the sensors just does not contribute any more to the charge collection. Before *type inversion*³ the $n-in-n$ sensor has to be operated fully depleted. Test-beam results have shown that this type of sensors can operate at fluences of more than $10^{16} \text{ n}_{eq}\text{cm}^{-2}$. After $2 \times 10^{16} \text{ n}_{eq}\text{cm}^{-2}$, a bias voltage of 1.5 kV is required for a MIP signal of 6000 electrons. Radiation tolerance sufficient has been also demonstrated for 100 μm thin $n-in-p$ sensors after a received fluence of $5 \times 10^{15} \text{ n}_{eq}\text{cm}^{-2}$ at an applied

³The effective doping decreases with irradiation and the material becomes intrinsic at a specific value of irradiation fluence (that depends on the original doping concentration). Above this value the doping becomes effectively p-type (this is called *type inversion*) and eventually rises linearly with the fluence.

bias voltage of 500V and for $150\ \mu\text{m}$ thick sensors after $1 \times 10^{16}\ \text{n}_{eq}\text{cm}^{-2}$ at a bias voltage of 1.2 kV.

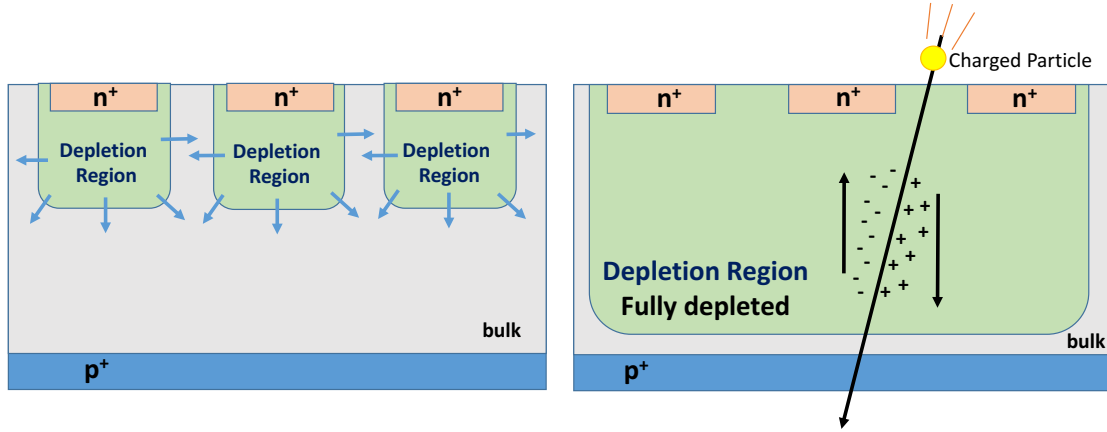


Fig. 2.10 In the picture the cross section of a n-in-p pixel silicon detector is reported. On the left is possible to see the depletion region growth and on the right the drift of charge carriers generated by an ionizing particle

2.2.5.2 3D Sensors

3D Sensors architecture was proposed for the first time in 1996 by Parker and collaborators [39]. They are characterized by cylindrical electrodes perpendicular to the surface and etched into the bulk material. To realize this kind of structures micro-machining processes used in the production of Micro-Electro-Mechanical-Systems (MEMS), as it is the Deep Reactive Ion Etching (DRIE), are necessary. Different designs in a single sided and a double sided process (see Fig. 2.11) have been studied and produced [40].

The 3D concept preserves the bulk thickness for charge generation while reducing the electrode spacing. When a MIP crosses a 3D sensor, the same amount of charge of a planar sensor with the same substrate thickness will be generated. The main difference between the two technologies is that for planar device the inter-electrode distance is equal to the wafer thickness, instead for 3D detectors the distance can be optimized and it is possible to reduce it to very low values (less than $50\ \mu\text{m}$). Compared to planar detectors, the benefits regarding radiation damage are a shorter drift length for the charge carriers and therefore a much decreased depletion voltage.

3D sensors require a relatively low depletion voltage even after high irradiation dose, but are currently more expensive due to the more complex technology. During the IBL sensor qualification period (see Chapter 3), 3D pixel modules irradiated to $5 \times 10^{15}\ \text{n}_{eq}\text{cm}^{-2}$, were operated with excellent hit reconstruction efficiency with a bias voltage of

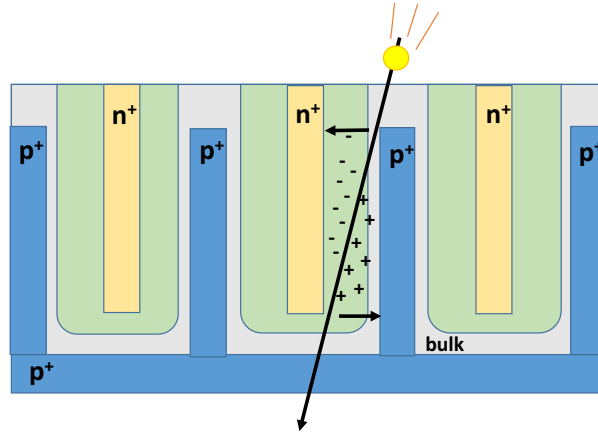


Fig. 2.11 Layout of a 3D silicon sensors produced with a double sided process. The n^+ -doped electrodes penetrating from the pixel side of the sensor are used as read-out electrodes. The p^+ -doped columns are in contact with the back side metallization to bias the sensor.

160 V and moderate cooling requirements. Furthermore, the 3D technology has been proven to be operational at fluences of $10^{16} \text{ n}_{eq} \text{ cm}^{-2}$ [41]. Designs with thickness of 100 to 200 μm , with 5 μm diameter columns are currently being investigated for the HL-LHC upgrades (see Chapter 6).

Unfortunately, 3D sensors have also some functional disadvantages [41] because of their peculiar structure. The signal response is non-uniform due to the presence of low/null field regions between electrodes of the same doping type, and within the electrodes themselves. Efficiency of 3D sensors has been evaluated at several test beam campaigns, e.g. for Insertable B-Layer (Chapter 3) unirradiated 3D sensors have shown near 100% efficiency and after an irradiation dose of $5 \times 10^{15} \text{ n}_{eq} \text{ cm}^{-1}$, the efficiency reaches 99.0% [42].

2.2.5.3 Diamond Sensors

Today the majority of sensors are made with silicon, but it isn't the only material used and some sensors are done with diamond. In Table 2.1 the Silicon and Diamond properties and characteristics are summarized.

Diamond sensors promise lower capacitance and a high radiation hardness in terms of dark current and so do not require cooling. With its large band gap of 5.5 eV diamond behaves more like an insulator than a semiconductor. The electrodes can be metallized directly on the surfaces without the need for implantation, that could be dangerous for the diamond integrity. The intrinsic carrier concentration is extremely low ($< 1 \text{ cm}^{-3}$) and the

Table 2.1 Material properties of Silicon and Diamond

Property	Silicon	Diamond	Units
Atomic Number (Z)	14	6	
Density (ρ)	2.33	3.52	g/cm^3
BandGAP (E_g)	1.12	5.48	eV
Electron Mobility (μ_n)	1450	1800	cm^2/Vs
Hole Mobility (μ_p)	505	1000	cm^2/Vs
Resistivity at 300 K (ρ)	10^3	0.5	$k\Omega cm$
Voltage Breakdown (V_B)	0.3	0.5	MV/cm

thermally generated leakage current is negligible. A diamond sensor has no *pn-junction* and this absence allows for charge collection even at low bias voltages. The mobility for electrons and especially for holes is much higher than the silicon value.

The charge in the sensor is collected over the full bulk thickness as long as the biasing voltage is high enough to collect the charge carriers before they recombine or get trapped. This is especially important as diamond for sensor applications is predominately available as polycrystalline material.

Artificial diamond wafers are industrially produced by chemical vapour deposition (CVD).

The crystalline structure and the impurities inherent to such material cause trapping and recombination centers in the material and this limits the charge carrier life time. For a High quality **p**CVD (where **p** stays for **p**oly-crystalline) the mean charge deposited of a *MIP* in a 300 μm of detectors is around 11000 e^- .

These results on Diamond performance mainly come from studies performed by the *RD42* [43] and *ATLAS-DPix* collaborations on single-chip size samples. High quality pCVD diamonds have been irradiated to a fluency of 1.8×10^{16} per 24 GeV protons/ cm^2 . After the irradiation, the deposited energy corresponds to an average charge of 7500 electrons and a most-probable charge of 5500 electrons, independent of operating temperature.

In the last years the diamond quality and purity have been significantly improved. Polycrystalline material suitable for sensor applications is commercially available at the 10 cm diameter wafer scale.

2.2.5.4 Towards New Pixel Technologies: HV and HR-CMOS

Complementary Metal–Oxide–Semiconductor (CMOS) electronics uses in its simplest form only n- and p-channel enhancement transistors as active devices. These complementary transistors are insulated from each other by putting one of them into a well with

opposite doping to the original bulk material. Such a well is usually produced by diffusion or by implantation and following drive-in diffusion [44].

CMOS Pixels Sensor technology employing a HV technology was first implemented by I. Peric in 2006 [45] using a 350 nm feature size. The high voltage technology allowed to apply up to 100 V for biasing the diode. This technology is called High Voltage CMOS (HV-CMOS). In Fig. 2.12 the pixel cross section of a generic HV-CMOS structure is reported.

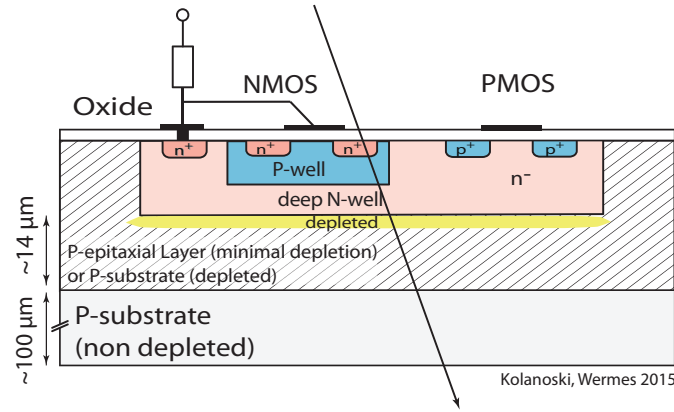


Fig. 2.12 Sketch of a generic HV-CMOS pixel structure from [5]. Dimensions are not to scale.

The deep n-well in a p-substrate is used as the charge-collecting electrode in each pixel cell. It is reversely biased with respect to the substrate. The entire CMOS pixel electronics (amplifier, discriminator, control logic) is placed inside the pixel cell with a reverse bias voltage of 100 V. Signal charge collection occurs mainly by drift and should be radiation hard due to extremely thin sensor depth. The achievable depletion depth is expected around 10–20 μm , but measurements on prototypes suggest even larger values.

After irradiation with low energy protons with a fluence of $10^{15} \text{ n}_{eq} \text{ cm}^{-2}$ and 300 MRad the signal from beta-particles is clearly visible above the noise at moderate temperature.

Another approach is the High Resistivity CMOS (HR-CMOS), that has been produced in different technologies. The idea is to use p-substrate with High Resistivity and a depletion layer to collect signal by drift under application of HV. The HR-CMOS technology [46] is based on High Voltage CMOS technology with the difference that high resistivity silicon can be modified to have different depletion depth in the substrate according with Eq. 2.33⁴ from [47]:

$$d \approx 0.3 \cdot \sqrt{V_{bias} \cdot \rho_{sub}} \quad (2.33)$$

⁴Assuming a simple pn diode mode

where V_{bias} is the reverse bias voltage and ρ_{sub} is the substrate resistivity ($[\Omega \cdot \text{cm}]$).

The CMOS-based sensors are an industrial process and they promise a higher production yield and cheaper sensors than passive hybrid technology, ongoing R&D. Capacitively (via glue bonds) coupling between the pixel cells and the front-end electronics could also reduce production costs with respect to traditional bump-bonding.

2.2.5.5 Towards New Pixel Technologies: Monolithics

The *Monolithic detectors* integrates the sensor matrix and readout in one piece of silicon. This type of device is at the moment the standard for the detection of visible light. In HEP, they could offer an advantage in terms of production costs and detector assembly. Unfortunately detectors for HEP, as seen, have different requirements from those for traditional CMOS visible light sensors, because photons in the visible spectrum generate signal within a depth of few microns in silicon. In the past several functional monolithic detectors on high resistivity silicon were developed, but often required very complicated fabrication steps, incompatible with high volume manufacturing in standard semiconductor foundries [48]. In other experiments with less harsh requirements than ATLAS in terms of radiation hardness and detection timing, Monolithic Active Pixel Sensor (MAPS) or Depleted P-Channel Field Effect Transistor (DEPFET) have been chosen as mainstream technology for STAR [49], ALICE [22] and Belle-II [50] respectively. These devices usually collect the signal charge by diffusion over a very limited depth, which makes them sensitive to radiation damage and results in relative slow signal collection. As we have seen, two mechanisms exist to collect charge generated in silicon by ionizing radiation: diffusion and drift. The diffusion process takes up to several hundred ns (in comparison of few nanoseconds of traditional HEP sensors) and therefore increases the chance for the signal charge to be captured by defects or traps in the material and its possibility to be reduced. In traditional MAPS the charge is collected primarily by diffusion, and radiation tolerance therefore does not exceed fluences of 10^{12} – 10^{13} neutrons/cm². Monolithic detectors are not yet installed at the Large Hadron Collider high luminosity experiments (ATLAS and CMS), but they are under consideration for their upgrades and for detectors in new accelerators like the Compact Linear Collider (CLIC) [51]. Many ATLAS R&Ds at the moment are investigating monolithic technology as good candidate for outer layers of the ITk upgrade. A good candidate at the moment seems to be the CMOS on Silicon on Insulator (SOI)⁵ which provides a buried oxide layer (BOX) which separates the CMOS

⁵In Silicon-On-Insulator (SOI) technologies, a thin silicon layer on top of an insulator is created by, for example, high energy, high intensity implantation of oxygen followed by recrystallization of the top silicon layer. This top layer is then structured so that each transistor is built on its own island of silicon. A potential

electronics from the substrate layer. First prototypes show a signal peaks at about 1700 e corresponding to a depletion depth of 31 μm for a beam of 120 GeV pions [2, 37].

2.3 Hybridization: From sensors to modules

This section describes how the sensors and the electronics are put together to form a hybrid module. In particular, various hybridization technique like bump-bonding (Sec. 2.3.1), capacitive coupling (Sec. 2.3.2) and finally through silicon vias (Sec. 2.3.3) are presented.

2.3.1 The bump-bonding technique

Through the Bump Bonding and Flip-Chip process, each pixel of sensor is connected to the corresponding FE chip [6]. The interconnect process between chip and sensor usually is based on soldering, thermo-compression bonding and adhesive bonding. Many different bump metallurgies are used ranging from pure Au, Cu, Sn, or In to alloys such as eutectic or high-melting PbSn, AuSn, AgSn, SnCu, and AgSnCu depending on the application [52]. Concerning pixel detectors, two main technologies are well established and developed. They use either electroplated solder bumps or indium bumps deposited by evaporation. The bump deposition is performed at wafer level, instead the flip-chip is normally carried out on single dices. A brief description of both techniques will be given in the following subsections.

2.3.1.1 Solder based bump-bonding process

The first, and the original type of flip-chip interconnect structure, was introduced by IBM in 1964, in response to the need for a relatively large number of highly reliable input/output connections in semiconductor devices. It was based on bumping high-melting temperature, high Pb-Sn solder (3-5 % Sn and 97-95 % Pb) on chip and subsequently joined to a ceramic carrier at a temperature greater than 320 $^{\circ}\text{C}$. This technique was called Controlled Collapse Chip Connection (C4). The maximum bump pitch reachable in this process was 250 μm or higher, not acceptable for most high energy physics applications. This limitation was overcome in the past years thanks to the use of eutectic solder (e.g. 37Pb/Sn)

problem is due to the undefined conditions on the buried Si/SiO_2 interface and on the side edges of the silicon islands. These problems can, however, be avoided by proper design of the circuit elements. More details can be found in [44]

The basic information of the solder based process can be summarized in six steps as reported in Fig. 2.13:

1. From the aluminium contact pad on the IC wafer, first a thin Ti/W adhesion layer (200 nm) and a diffusion barrier are sputtered before the Cu plating base (≈ 300 nm). A wettable $1 - 5 \mu\text{m}$ thick Cu Metallization follows. This set of layers is known as *Under Bump Metallization* (UBM). The UBM has to provide a low contact resistivity to the chip pad and the solder, good adhesion to the chip metallization and the chip passivation and a hermetic seal between the UBM and the IC pad.
2. A photo-resist is spin coated and developed to realize the bump pad openings.
3. The bump deposition process is performed and the metal is deposited through electroplating.
4. The remaining photo-resist is stripped and a wet etching of the plating base is performed leaving only small cylinders.
5. The PbSn cylinders are turned into $25 \mu\text{m}$ diameter spheres by the re-flow process performed at temperatures ranging between $250 - 350^\circ\text{C}$.
6. The UBM is also grown on the sensor wafer with the addition of Ni and Au layers for better wettability. The flip-chip is performed and the subsequent re-flow process is performed at temperatures never exceeding 350°C .

This technique had been chosen for the production of the Insertable B-Layer modules. During this production in 2012 the vendor observed some problems of unconnected and merged bumps. The problem was due to the surface size of the front-end chip ($2 \times 2 \text{ cm}^2$) used. It was thinned down to $150 \mu\text{m}$ developing an unacceptable high deflection during the high temperature reflow soldering. This led an high fraction of unconnected bumps especially in the outer areas of the assemblies. To avoid this chip deflection a $500 \mu\text{m}$ thick glass carrier chip was temporally mounted to the read-out chip and removed again after the reflow soldering, using an UV laser (248 nm).

2.3.1.2 Indium based bump-bonding process

The Indium based bump-bonding technology was developed for infrared sensor arrays connected to CCD readout chips, which require good mechanical and electrical connection properties down to liquid nitrogen temperatures [6]. The indium bump deposition process is sketched in Fig. 2.14. With this technique the bump pitches can be as low as $30 \mu\text{m}$, but the bump height is limited to $10 \mu\text{m}$. Bumps must be deposited both on

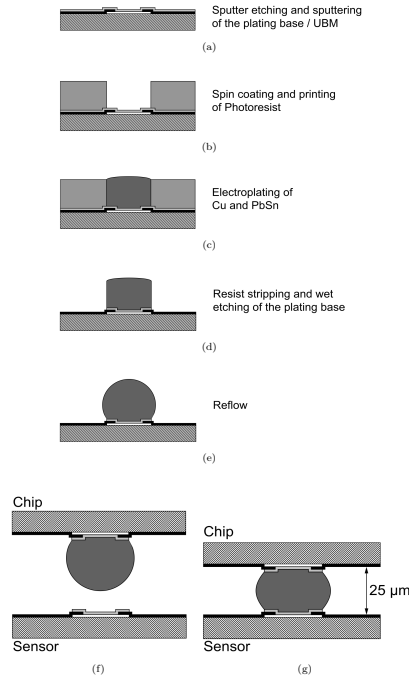


Fig. 2.13 In this sketch from [6] the process flow in the PbSn (solder) bump deposition process (a)–(e) and flip-chip of the electronics die (with UBM and bump) to the sensor (with UBM only) (f)–(g) are reported

the sensor and on the electronics because the connection is obtained by In–In thermo-compression. Indium belongs to the third group of the periodic table of elements. It oxidises, very easily forming an insulating In_2O_3 layer, which is difficult to break. Applying a low voltage (~ 500 mV) is sufficient to break the oxide layer and restore a low (~ 10 Ω) contact resistance. The flip-chip operation can be performed at room temperature, but the best results are obtained at around 100 $^{\circ}C$. The connection between the sensor and FE is obtained applying a pressure of about 2000 N/cm². This technology was used in the assembly of the ATLAS pixel detector. The quality control is typically performed using laser interferometry or X-ray machines able to estimate misalignments or merged bumps. The yield for this technology is well established with a defect rate of about 10^{-4} – 10^{-5} at wafer level and 10^{-3} – 10^{-4} after flip chip [53].

2.3.2 Capacitive Couplings

Capacitive couplings could be a good option to reduce costs and simplify the hybridization process for semi-monolithic detectors. This type of sensors are currently in evaluation for HL-LHC and Compact Linear Collider (CLIC) detectors. In this case, a coupling

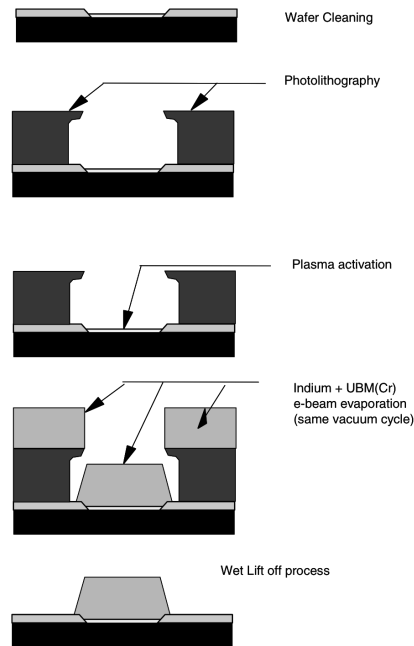


Fig. 2.14 In this sketch from [7] the In bump deposition process is reported.

medium (typically glue) is used to connect the FE and the sensor without using metallic connections. The process consists in a deposition of a coupling medium at tile level. Unfortunately wafer to wafer processes are excluded: FE wafers are typically 12", instead semi-monolithic sensors are 8". A R&D process is ongoing with the following requirements:

1. Check the uniformity and repeatability of the R&D production steps and their reproducibility at industrial level,
2. Evaluation of radiation tolerance of the coupling medium (glues),
3. Control of the coupling medium thickness by adding spacers between the sensor and the FE,
4. Evaluation of cost effectiveness, including the time used for chip assembly.

In 2015, this technology was extended to CCPD (Capacitively Coupled Pixel Detector) with a successful capacitive coupling between a front-end (FE-I4) and a small High Voltage CMOS (HV-CMOS) sensor. The capacitive coupling can be done through metal pads (typical values are about 18 μm), present on the facing HV-CMOS and on the FE chip. The thickness needed in the assembly can be roughly estimated by requiring the coupling capacity to transfer 1 V of signal (typical output of a HV-CMOS pixel cell) and 1.6 fC

(10 ke^-) of charge⁶. Considering as dielectric an epoxy material e.g. Araldite 2011 (see Table 2.2 for the glues in evaluation at the moment), the relative permittivity (ϵ_r) is of the order of ~ 3.2 . The described system can be approximated as a planar capacitor and the needed thickness of the dielectric can be easily calculated (with chosen values is $\sim 5 \mu\text{m}$ ⁷). Having the thickness uniform and defined over the whole surface can be achieved by patterning some spacers on the surface of one of the two surfaces. To build the spacers, SU-8 [54], a negative epoxy based photoresist has been used. SU-8 was formulated at IBM in 1982, it consists of multifunctional highly branched polymeric epoxy resin, dissolved in an organic solvent along with photoacid generator. It is photo imageable to near UV (365 nm) radiation, allowing the fabrication of relatively thick structures since it can be spin-coated in a conventional spinner from 0.5 to 300 μm thickness. Once the spacers are produced an amount of the glue is deposited and the two chips are joined together until the spacers are in contact, limiting the minimum distance, the alignment is done using a flip-chip machine opportunely modified. Fig. 2.15 shows the gluing and alignment process.

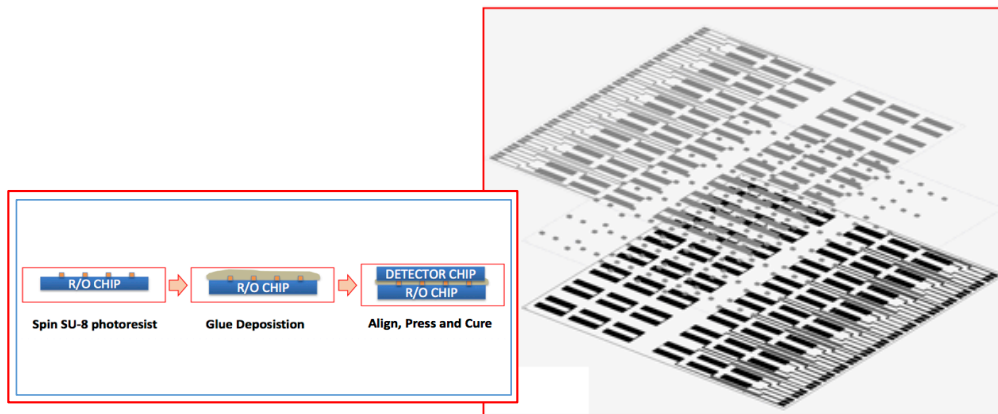


Fig. 2.15 The basic process for capacitive coupling is shown. First the SU8 spacers are built on one of the chip surface. After the glue is deposited on the same side. Finally the alignment of the two chip and the glue curing is performed. An exploded axonometric view of a capacitive structure flip-chipped is also reported. In light and dark grey the top and bottom metal layer are respectively reported together with the SU8 spacers in the middle.

Some results from R&D are shown in Sec. 6.2.1.2.

⁶When a minimum ionizing particle (MIP) crosses a silicon pixel sensor approximately 80 electron-hole pairs per micrometer of thickness are generated. The active region of a HV-MOS is about 15-20 μm , but its output is amplified

⁷It can be lower in case of sensors with low amplification gain

Table 2.2 Glues currently under evaluation as capacitive medium. In the table the critical parameters (air bubbles, pot life and the curing time) for the process are reported. Some glues can degas during the curing creating air bubbles. If they are present the relative permittivity of the coupling medium could be not constant. The pot life is the period for which two (or more) mutually reactive chemicals remain usable when mixed. This one with the curing time are critical parameters to develop a fast and repeatable process. At the moment are currently in evaluation also glues with ultraviolet (UV) curing.

	Araldite 2011	Araldite 2020	Epotek 301-2	EPOLITE FH-5313	Master Bond (V15DC80LV)
Viscosity [Pas]	30÷45	0.15	0.22÷0.45	1.97	0.15÷0.5
Relative dielectric constant (ϵ_r)	3.4 (50 Hz) - 3.2 (1 kHz) - 3.2 (10 kHz)	No Info available	3.8 (1 kHz)	4.06 (100 Hz)	3.49 (60 Hz)
Pot life [min]	100	40÷50	480	30	-
Curing time [min]	30 (at 60 °C)	90 (at 60 °C)	180 (at 80 °C)	60 (at 65 °C)	UV Curing + 40÷60 (at 80 °C)
Air bubbles	Many	Some	None	Many	To test
Rad-hardness	3 MGy	3 MGy	No infos	10 Mrad	To test

2.3.3 Through Silicon Vias

The first generation of hybrid pixel detectors that are currently in operation at the LHC were implemented using a commercial CMOS 250 nm technology with custom enclosed layout transistors (ELT) to achieve radiation tolerance above 50 Mrad (Si) [55, 56]. The ability to use linear transistors increase in radiation hard logic density going from 250 nm to 130 nm for FE used in the ATLAS Insertable B-layer upgrade of 2013. For future hybrid pixel detectors an analogue scaling between 130 nm and 65 nm is currently ongoing. For the future upgrades of pixel detectors at LHC experiments, a 3D conception of the read-out chip appeared as an interesting solution since a critical parameter for pixel readout chips is the circuit density that can be achieved in a radiation hard process. A good option seems to be through silicon via (TSV), in which sensor and the functional blocks of the front-end can be split in different layers. TSV is a vertical electrical connection (via) passing completely through a silicon wafer or die. The general structure of a TSV (Fig. 2.16) is typically a cylinder with a uniform circular cross section of a conducting material (copper) surrounded by an insulator (silicon dioxide) which is intended to prevent leakage and resistive coupling through the substrate (silicon) [57].

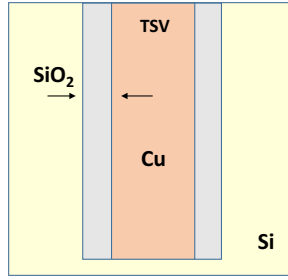


Fig. 2.16 A side view of a TSV structure assuming a uniform circular cross section of copper surrounded by an oxide inside a silicon substrate.

2.4 Radiation Damage in Silicon

Silicon detectors in HEP experiments are progressively affected mainly by two classes of radiation damages: surface and bulk damage. These damages can limit the lifetime of silicon detectors. In this section an overview on most common damages due to the passage of particles is given, also discussing the radiation tolerance for silicon devices. A complete reference can be found in [58].

2.4.1 Surface Damage

When a ionizing particle or a photon crosses into the dielectric layer (usually SiO_2) that covers the silicon detectors, it can cause the build-up of trapped positive charge. The passage produces an e-h pairs that can recombine or move in the oxide electric field (electrons towards SiO_2-Si interface, the holes toward the metallic contact). The electrons with higher mobility ($\mu_e \approx 20 \text{ cm}^2/\text{Vs}$) can escape from recombination processes and can be injected into the silicon bulk in a typical time of 100 ps [58]. The holes, which have a much smaller mobility ($\mu_h \approx 2 \times 10^{-5} \text{ cm}^2/\text{Vs}$), are instead trapped in the SiO_2-Si interface. This causes an increase of the oxide positive space charge with degradation of its quality. In Fig. 2.17 the process that leads to permanent damage in the oxide is shown. The trapped charge causes also the production of new energy levels in the band gap at the SiO_2-Si interface, that can be occupied by electrons or holes (depending on the position of the Fermi level at the interface). The defect described alters the performance mainly of the electronics read-out chain elements (above all the transistors) and every part of the sensor which contains SiO_2 .

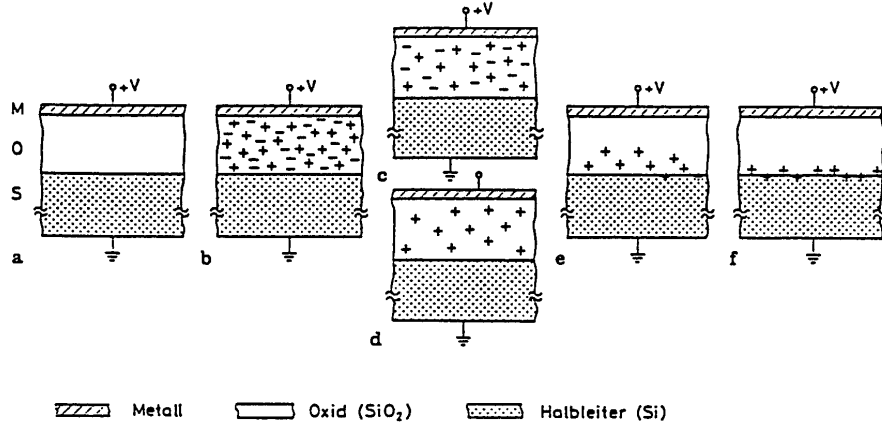
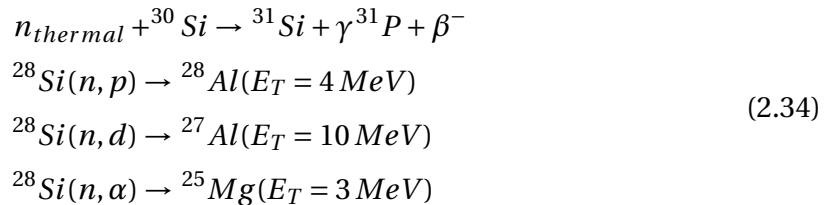


Fig. 2.17 Schematic illustration of the introduction of fixed positive oxide charges in SiO_2 [8]

2.4.2 Bulk Damage and Changes in Detector Properties

Hadrons, like e.g. neutrons or protons, could cause pointlike (a single silicon atom is displaced from its lattice site) or cluster (high concentrations of damages in a restricted volume) defects in the silicon crystal structure. The displaced atom is called a Primary Knock-on Atom (PKA). The necessary energy to displace an atom from its lattice site (displacement threshold) is $E_d \approx 25$ eV. The generated vacancies and interstitials (e.g. the Frenkel pair) are mobile at room temperature. The minimum energy for particles with mass 1 u, required to create a Frenkel pair is ≈ 110 eV (for electrons is ≈ 260 keV) [58]. The impinging radiation through nuclear reaction of silicon nuclei is another mechanism of damage in silicon.

In nature the abundance of ^{28}Si is 92.2%, 4.7% for ^{29}Si and 3.09% for ^{30}Si . In environment with neutrons, various nuclear reactions can take place with the different Si isotopes, such as:



where n_{thermal} is a thermal neutron and E_T is the threshold energy of the specific reaction [58].

From operational point of view for silicon sensors, these damages cause relevant changes in the full depletion voltage (V_{dep}) and in the reverse current (I_R), also afflicting the signal height. Silicon used for sensors is not completely pure, some impurities are usually presents (e.g. carbon or hydrogen). These ones can interact with the defects generated by the passage of a particles, forming new structures with different electrical nature and stability. The *annealing* process changes the electrical properties of the detectors and is function of time and temperature. The depletion and the reverse current can be expressed as a function of irradiation and time after irradiation. As seen in Eq. 2.30 the depletion voltage V_{bias} is proportional to the concentrations of donors and acceptors (N_{eff}) (Eq. 2.35):

$$V_{dep} = \frac{eW^2|N_{eff}|}{2\epsilon_0\epsilon_{Si}} \quad (2.35)$$

$$N_{eff}(\phi) = N_D e^{-c\phi} - N_A e^{-d\phi} + (\beta_D - \beta_A)\phi$$

where as seen N_D [N_A] is the initial donor [acceptor] concentration, c and d are removal constants, β_A and β_B take care of the introduction of acceptor or donor-like defects. The first two terms describe the exponential removal of the initial doping, instead the second one describes the linear changes with radiation fluence ϕ . The reverse current I_R increases linearly with the fluence and is proportional to the detector volume V :

$$\Delta I_r = \alpha_T \phi V \quad (2.36)$$

α_T is called *damage factor* and depends from the annealing (temperature and time after irradiation). The usual value of the leakage current for a typical pixel sensor in ATLAS is about 400 nA before irradiation. After a fluence of $6 \times 10^{15} \text{ n}_{eq} \text{ cm}^2$ the leakage current increased to about 50 μA (at 120 V) [59]. The current of an irradiated sensors depends from temperature, as Eq. 2.37 describes:

$$I_R \propto T^2 \exp\left(-\frac{E_{gap}}{k_B T}\right) \quad (2.37)$$

where E_{gap} as usual is the silicon energy gap (1.12 eV).

2.4.2.1 The NIEL Hypothesis

The radiation damage produced in a silicon device depends from the type of the particles that pass through it and their energies. The bulk damage scales with the Non Ionising Energy Loss (NIEL) in silicon. The assumption of NIEL hypothesis is that the radiation

damage in silicon can be traced back to point and cluster defects and therefore the damage can be normalized to the damage created by a reference particle. The reference particle being usually used are 1 MeV neutrons. The hardness factor k is defined for that purpose, for neutrons its value is 1 and it is possible to express an equivalent fluence ϕ_{eq} (Eq. 2.38). If the NIEL is normalized to the fluence is called 1 MeV neutron equivalent (n_{eq}).

$$\phi_{eq}^{1MeV} = k\phi \quad (2.38)$$

k (hardness factor) is defined as:

$$k = \frac{EDK}{EDK(1\text{ MeV})} \quad (2.39)$$

with EDK the energy spectrum averaged:

$$EDK = \frac{\int \phi(E)D(E) dE}{\int_E \phi(E) dE} \quad (2.40)$$

where $\Phi(E)$ is the differential flux and

$$D(E) = \sum_k \sigma_k(E) \int dE_R f_k(E, E_R) P(E_R) \quad (2.41)$$

is the damage function for the energy E of the incident particle, σ_k the cross section for reaction k , $f_k(E, E_R)$ the probability of the incident particle to produce a recoil of energy E_R in reaction k and $P(E_R)$ the partition function (the part of the recoil energy deposited in displacements). Integrating over the whole energy range gives $EDK(1\text{ MeV}) = 95\text{ MeV mb}$.

2.5 Tracking Detectors Parameters

A pixel detector is a crucial part in every HEP experiments, since an efficient identification of primary electrons and muons is necessary to separate new possible phenomena from the QCD background. The main goal is the measuring of the position of the particles when they traverse its layers, giving a resolution of primary and secondary vertices. The pixel detector contributes also to momentum resolution, b -tagging and reconstruction of tracks in jets. Pattern recognition algorithms are used to reconstruct the particle tracks starting from its position in the different layers. In this section an overview of the basic driving properties for the design of an inner tracking system are reported. A complete reference can be found in [60].

2.5.1 Charged particle trajectories in magnetic fields

The inner detectors are immersed in a magnetic field as seen in Chapter 1. The trajectory of a particle with momentum p and charge q passing in a static magnetic field $\mathbf{B}(\mathbf{r})$ is bent by the Lorentz force and it is given by differential equation 2.42:

$$\frac{d^2\mathbf{r}}{ds^2} = \frac{q}{p} \frac{d\mathbf{r}}{ds} \times \mathbf{B}(\mathbf{r}) \quad (2.42)$$

where $ds=vd t$ is the path length along the trajectory. The trajectory can be approximated in the plane containing the magnetic field with a straight line $f(z)=a+bz$ for large momentum particles, where a is the intercept and m the slope at the origin. For not too low momenta the trajectory can be approximated with a parabola $y=a+bx+(c/2)x^2$ in the plane perpendicular to the magnetic field⁸. The parameter of the quadratic term c is equal to $-1/R$ and describes the radius R of the curvature and the transverse momentum p_T . Fitting of a straight line in this plane is sufficient to obtain the impact parameter (subsection 2.5.2).

2.5.2 Impact parameter

The impact parameter is the closest distance of a track to the primary vertex of an interaction. The determination of the impact parameter is illustrated in Fig. 2.18 for a jet with a hadron containing a b -quark and thus decaying at a distance off the primary vertex [9].

To determinate the impact resolution measurement uncertainty, we have to start considering $N+1$ coordinates measured equally distributed along z axis with an error σ and in which L denotes the distance between the first and the last layer ($L=r_N - r_0$). For a straight line case the impact parameter d_0 will be:

$$d_0 = f(-z_c) = a - m \cdot z_c; \quad z_c = (z_N - z_0)/2 \quad (2.43)$$

The impact parameter resolution error $\sigma(d_0)$ without considering the multiple scattering can be expressed as a simple error propagation of σ_a and σ_m :

$$\sigma_{d_0}^2 = \sigma_a^2 + \sigma_m^2 z_c^2 = \frac{\sigma^2}{N+1} + \frac{\sigma^2}{N+1} \frac{12N}{N+2} \frac{z_c^2}{L^2} \quad (2.44)$$

From the Eq. 2.44 is possible to observe that a fine layer segmentation achieves good impact parameter resolution and a large value of L reduces the error on the slope.

⁸In solenoid magnetic fields this plane is the transverse plane.

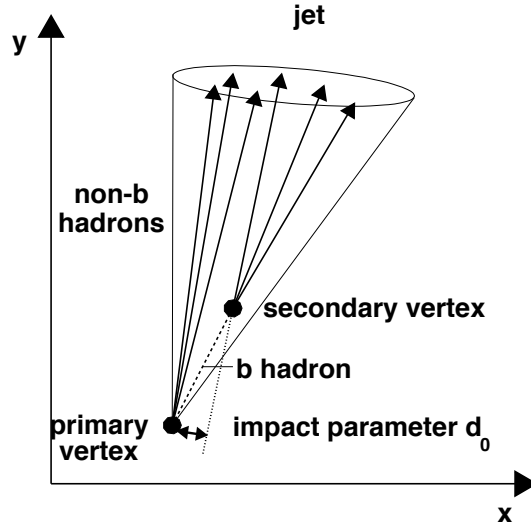


Fig. 2.18 Determination of the impact parameter d_0 of a track generated from a secondary vertex [9].

2.5.3 Vertex resolution

To determine the position of a primary or secondary vertex is necessary to have a finely segmented detector layers, as close as possible to the beam pipe and consequently to the interaction point. As example, the simplest detector module is considered: two segmented layers of radii r_1 and r_2 with $r_2 > r_1$ as Fig. 2.19 shows.

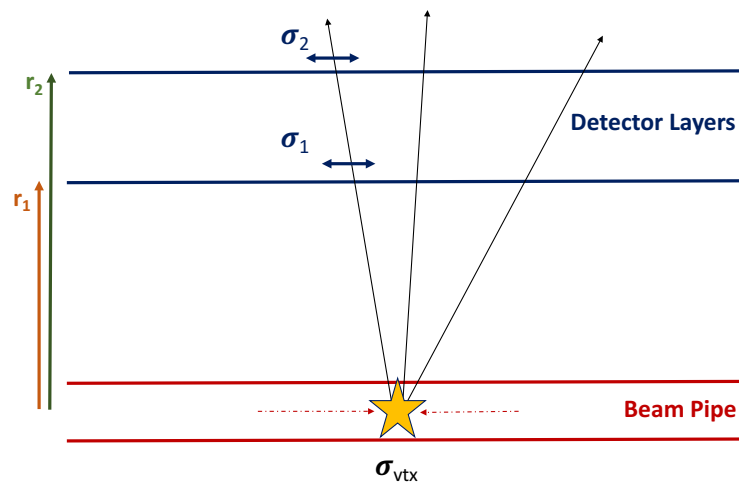


Fig. 2.19 Sketch of a simple vertex detector in a collider experiment is reported.

We assume first that $\sigma_2 = 0$ and $\sigma_1 \neq 0$ to calculate σ_{vtx} the resolution in the position of reconstructed vertex. Using geometrical considerations we obtain:

$$\sigma_{vtx} = \frac{r_1}{r_2 - r_1} \sigma_1 \quad (2.45)$$

In similar way we can consider $\sigma_2 \neq 0$ and $\sigma_1 = 0$ obtaining:

$$\sigma_{vtx} = \frac{r_2}{r_2 - r_1} \sigma_2 \quad (2.46)$$

The total vertex resolution is a quadratic combination of both contributions. In this simple model we have to take in account of the contribution from multiple scattering in the beam pipe (with radius r_0), this contribution add an additional degradation to the layers resolution.

$$\sigma_{vtx}^2 \approx \frac{r_1^2}{(r_2 - r_1)^2} \sigma_1^2 + \sigma_2^2 + (2r_1 - r_0)^2 \frac{(13.6 \text{ MeV})^2}{p^2} \frac{d_0}{X_0} \quad (2.47)$$

From Eq. 2.47 is possible to observe a dependency from $\frac{1}{(r_2 - r_1)}$ which shows the benefit of a large lever arm of the vertex detector for high momentum tracks. The factor $\frac{1}{p}$ shows the dominance of multiple scattering for low momentum tracks. To have a good resolution the first layer has to be as close as possible to guarantee a good vertex resolution.

2.5.4 Multiple scattering

The uncertainty of the track parameters is affected by the so-called *Multiple Scattering*. A charged particle, traversing any medium, encounters large field gradients owing to the nuclear charges. These gradients cause the so called "Coulomb scattering". On traversing a block of material, a particle suffers a large number of small Coulomb deflections. The additive effect of such small collisions constitutes multiple Coulomb scattering. The scattering angle after many interactions, roughly follows a Gaussian distribution with an RMS value of:

$$\theta_{plane} = \frac{13.6 \text{ MeV}}{\beta p c} z \sqrt{\frac{x}{X_0}} [1 + 0.038 \ln(\frac{x}{X_0})] \quad (2.48)$$

where θ is the angle expressed in rad, p is the momentum of the particle in MeV, β is the velocity of particle expressed in natural units, z is the charge number of the considered particle and x/X_0 is the thickness of the absorption medium in units of radiation length. The radiation length X_0 of silicon is 9.36 cm. As an example, the pixel detectors operating in the LHC experiments, have an overall thickness leading to changes in the trajectory of a 1 GeV particle of an angle of about 0.1 rad.

The Insertable B-Layer (IBL) and the Pixel Readout Upgrade in LHC Run 2

This third chapter is devoted to the upgrades that the ATLAS Pixel Detector had during the LHC Long Shutdown 1 in 2013-2014 and the Winter Shutdown in 2015-2016.

In the first part an overview on the Insertable B-Layer (IBL) is given. IBL is a new pixel layer inserted into the Pixel detector in April 2014. The work done during my Master Thesis [61] and the preliminary part of my first Ph.D. year were focused on the production, characterization and the study of IBL modules. In that contest I have improved the experimental setup in Genova to test IBL modules and I have contributed to develop software tools, qualification and analysis procedures. This has allowed to increase the module production rate and to improve its quality, making it more automatic. In Sec. 3.1.5 the final yield of the production is reported, together with a description of some problems that I have observed during the production, such as the low agreement between module and wafers voltage breakdown measurements for 3D sensor produced by CNM.

The second part is instead focused on the Pixel off-detector electronics, in particular on the extension of the IBL back-end electronics to the Pixel system. The update was necessary because the Pixel Detector was close to a bandwidth limitation due to the high instantaneous luminosity in LHC Run 2. In Sec. 3.2 the Pixel off-detector electronics will be detailed to give to the reader an overview of the data acquisition chain complexity. The back-end electronics is a crucial part in the acquisition system and well structured tests are needed to qualify the new components. For this reason in the last part of this section (Sec. 3.2.5), the attention of the reader will be focused on the tests and tools that I have developed and performed during 2015 and 2016 LHC Winter Shutdown to qualify the IBL Readout Driver (IBL-ROD) for the Pixel System.

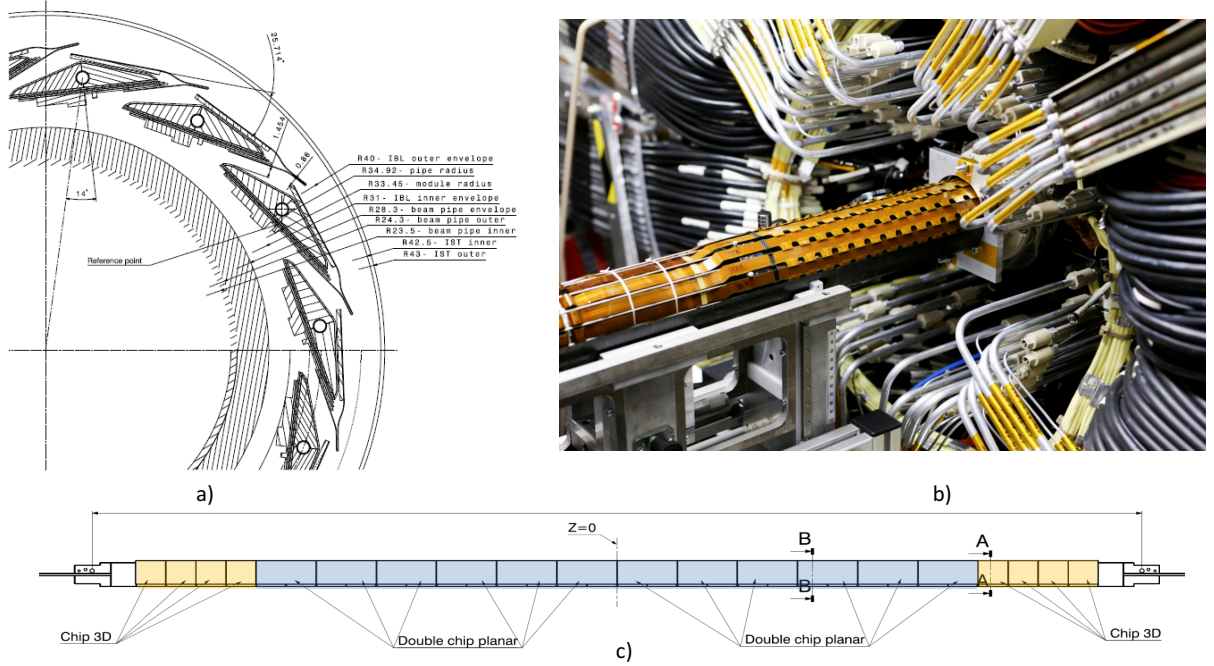
3.1 The Insertable B-Layer (IBL)

The Insertable B-Layer (IBL) [62] consists of a cylindrical layer of 0.64 m active length and 3.5 m full length including the support structure and services on each side. It is not accessible once integrated inside the ATLAS Inner Detector. The IBL volume is placed between an external Inner Support Tube (IST) fixed on the Pixel structure and the Inner Positioning Tube (IPT), an external carbon fiber skin at a radius of 42.5 mm. The central part of the ATLAS beam pipe (radius of 23.5 mm) is slipped inside the IPT tube and fixed to it. The IBL layout parameters are summarized in Tab. 3.1. The IBL sensors are at a mean radius of 33.25 mm (compared with 50.5 mm for the Pixel B-Layer). Sensors have been arranged longitudinally along a supporting and cooling structure called stave. A total of 14 staves with a length of 0.74 m has been mounted inside the IBL ring providing full azimuthal (ϕ) hermeticity for high transverse momentum particles. Each one of the 14 staves has been equipped with 32 Front-End (FE) read-out chips in 130 nm CMOS technology: 12 planar n-in-n sensors, placed in the central region of the stave and 8 3D sensors in the forward region (4 for each side). The planar sensor with a length of 40.9 mm is bump-bonded to two front-end readout chips while the 3D sensor of about half that size is connected to a single front-end chip. The staves are inclined by 14 degrees with respect to the radial direction in order to achieve an overlap of the active area between staves. This tilt should also compensate for the Lorentz angle of drifting charges in the case of planar sensors. The IBL was inserted into the Pixel Detector in April 2014. In Fig. 3.1 the IBL layout and a picture of its insertion in the Pixel Detector are respectively shown.

Table 3.1 Summary of Layout Parameters of ATLAS IBL.

Number of staves	14
Number of Modules per Stave	
Single (3D)	8
Double (Planar)	12
Module active size $W \times L$	
Single (3D)	$16.8 \times 20.4 \text{ mm}^2$
Double (Planar)	$16.8 \times 40.8 \text{ mm}^2$
Coverage in η , no vertex spread	$ \eta < 3$
Coverage in η , $2\sigma (= 112 \text{ mm})$ vertex spread	$ \eta < 2.58$
Sensor thickness	
Single (3D)	$230 \mu\text{m}$
Double (Planar)	$200 \mu\text{m}$

Fig. 3.1 a) IBL layout $r\phi$ view: the IPT, the IBL detector and the IST are visible b) The Insertable B-Layer during its insertion in the ATLAS Pixel Detector c) Schematic of an IBL stave: 12 planar sensors are placed in the central region and 8 3D sensors in the forward region (4 for each side).



3.1.1 Motivations

The IBL acts as a fourth pixel layer of the Pixel detector improving tracking and vertexing performance. A fundamental requirement for LHC experiments is the ability to distinguish jets arising from the production of different quark flavours. The jets from light quarks (u, d, s) cannot be distinguished but those from bottom (b -jets) can be identified by exploiting the lifetime of the B-mesons and baryons presented in the jets.

A precision vertex system capable of tagging b -jets with high efficiency and excellent rejection of light quarks jets, including additional jets from QCD or $t\bar{t}$ production, is essential. Besides it is very important to have an apparatus that has improved vertex resolution and that it is able to distinguish the primary vertex from nearby secondaries in a high luminosity environment.

The ATLAS Pixel Detector was to face a TID¹ of 50 MRad (expected at 300 fb^{-1}), a NIEL² of $1 \times 10^{15} \text{ 1 MeV } n_{eq} \text{ cm}^{-2}$ and a peak luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Given the present

¹Total Ionizing Dose

²Non Ionizing Energy Loss, where $1 \text{ MeV } n_{eq}$ is the number of particles with a non-ionizing energy loss of a 1 MeV neutron

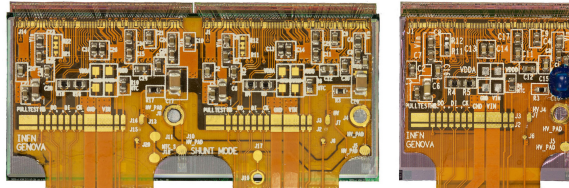
LHC schedule, the peak luminosity should reach $2\text{--}3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in the operation, thus generating some inefficiency in the B-Layer where the occupancy is higher. For this reason a program of upgrade has been arranged.

3.1.2 IBL Modules

IBL staves are composed with a *mixed scenario* in which, double chip (DC) planar sensors are installed in the central region, while 3D single chip (SC) modules populate the forward regions, in order to benefit from the vertical electrode orientation in terms of better z -resolution after heavy irradiation. In Fig. 3.2 a picture of the last IBL stave being integrated on surface and fully dressed 3D single chip and a planar double chip module are shown.



(a)



(b)

Fig. 3.2 a) A picture of the last IBL stave being integrated on surface b) Photographs of a dressed IBL single chip module on the left a double chip and on the right a single chip module.

The choice between double or single chip modules is related to the different yields of the planar and 3D fabrication processes, in fact the planar process is well established and able to deliver double chip sensors with relatively high yields, while the 3D process is more complex and the yield is lower. Producing smaller area sensors, like single chip, allows to get a higher yield per device. The pixels of SC and DC sensors are connected to the

corresponding readout pixel cell in the front-end chip (FE-I4) through the *bump bonding process* (as described in Sec. 2.3.1). When connection between sensor and electronics is performed the so-called *bare module* is done. The *bare modules* are dressed by gluing a flex hybrid circuit on the sensor side: two similar circuits are available for single or double chip assemblies. The module flex comes with a pigtail and a test connector that are cut away before the stave loading, at which stage wirebondings connect the FE to the external services. On the module flex several passive components are present for decoupling and filtering of the read-out chips and for terminations of the signal traces. The module temperature is remotely monitored via a Negative Temperature Coefficient (NTC) thermistor added on the module flex.

3.1.3 Front-End Electronics: FE-I4

The ATLAS Pixel detector is built with 16-chip modules of $7.6 \times 10.8 \text{ mm}^2$ size with 2880 pixel each. The front-end electronics used is called FE-I3, with a pixel granularity $400 \times 50 \text{ mm}^2$ in a 250 nm feature size bulk CMOS process (Fig. 3.3). The limitations of the FE-I3 concern in particular radiation hardness and the ability to cope with high hit rates. For this reason, a brand new chip was designed: the FE-I4 [62, 63]. With respect to previous Front-End generations the FE-I4 shows an increased tolerance to radiation, being rated for a 250 Mrad Total Ionizing Radiation (TID) dose and high efficiency versus luminosity.

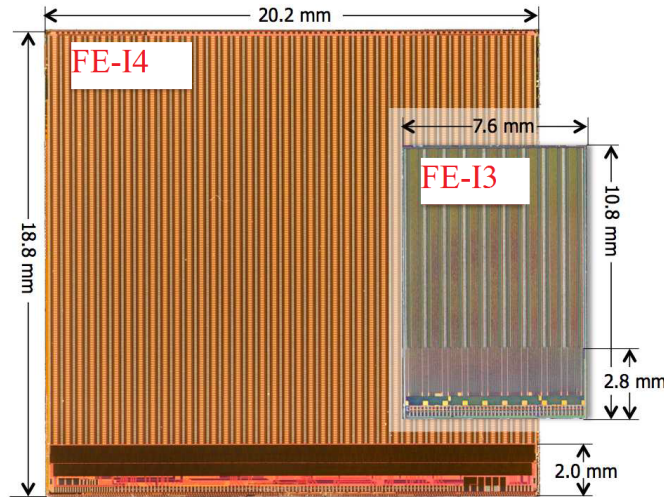


Fig. 3.3 Comparison between the $20.2 \times 18.8 \text{ mm}^2$ FE-I4 and the $7.6 \times 10.8 \text{ mm}^2$ FE-I3 used in the Pixel Detector.

The FE-I4 is designed in a 130 nm feature size bulk CMOS process. The new Front-End is also connected to reduced-area pixel cell sensors and can thus handle a much higher

particle flux. The major innovation of the FE-I4 is the pixel matrix architecture that is radically different from the existing pixel column drain readout followed by peripheral data storage and trigger logic. The data storage is now made locally at the pixel level until triggering and subsequent propagation of the trigger inside the pixel array. The FE-I4 Integrated Circuit consists of an array of 80×336 pixels (for a total of 26880) with a size of $50 \times 250 \mu\text{m}^2$ organized in double-columns.

Each pixel readout channel consists of an independent analog section with continuous reset, amplifying the collected charge from the bump-bonded sensor. In the analog section, hits are discriminated at the level of a tunable comparator with an adjustable threshold, and charge is translated to Time over Threshold (ToT) with a proportionality factor that the user can tune by changing the return to baseline behaviour of the pixel. The analog pixel (Fig. 3.4) is based instead on a two stage architecture, consisting of a preamplifier with leakage current compensation circuitry AC-coupled to a second stage of amplification. Each analog pixel hosts 13 configuration bits, to locally adjust the pre-amplifier feedback current (4 bits), the discriminator threshold (5 bits), and to allow test charge injection (2 bits). The last remaining bit is used for the masking of the pixel in case problems are detected.

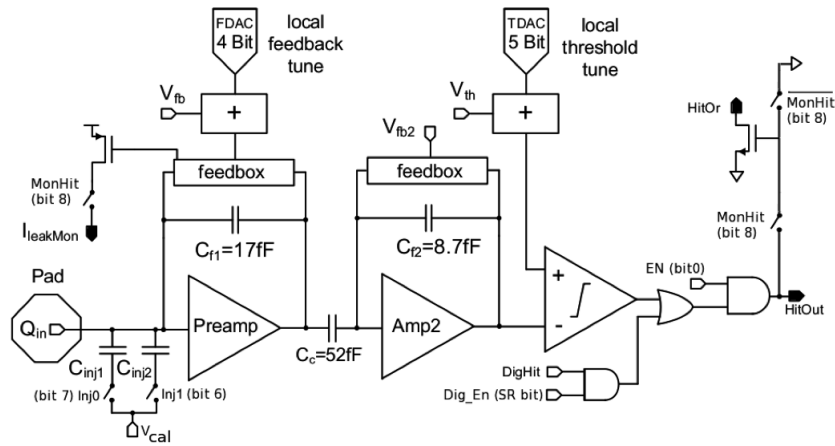


Fig. 3.4 Analog section of a single pixel inside the FE-I4 readout chip.

Inside the double-column, 4 analog pixel channels communicate to a single *4-Pixel Digital Region* (4-PDR, Fig. 3.5). In this structure, 4 independently working analog pixel channels share a common digital block. The outputs of the 4 discriminators are fed to 4 separate hit processing units in which Time-Stamping and Time over Threshold (ToT, the pixel analog information) is processed (Fig. 3.6). An extra level of digital discrimination can also be programmed, to distinguish large recorded charges from small ones. When

one (or more) of the four hit processing unit detects a hit, the unit books one of the central latency counter.

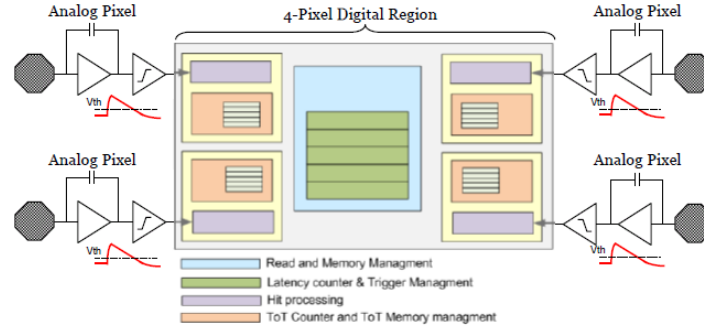


Fig. 3.5 Organization of the 4-pixel region, focusing on a schematic of the digital region.

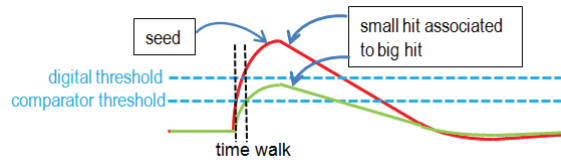


Fig. 3.6 Digital threshold mechanism

Hits smaller than a certain ToT (programmable between 1 and 3 clock periods or between 25 and 75 ns) are classified as small hits and those larger as large hits. This feature is controlled by the 2-bit *HitDiscCnfg* register. The next available time counter in a given region starts whenever there is at least one large hit. Small hits do not start a counter. Once a counter starts, the ToT value of all 4 pixels is always recorded (which is 0 for a comparator that did not fire). This automatically stores small hits in the same time bin as the large hit(s) belonging to the same charge deposition cluster. Thus small hits, for which timing information is degraded due to time-walk, are associated to the correct time slice by physical proximity to large hits, rather than by their own discriminator firing time. This technique exploits prior knowledge about the physical detection process, which can be qualitatively summarized as: large hits are in time, small hits are next to large hits, and isolated small hits are noise. This architectural implementation offers the following advantages:

1. Resource sharing between the pixels of a 4-PDR,
2. The Resource sharing helps in reducing power consumption together with the fact that un-triggered hits are not transferred to the chip periphery,

3. It is efficient in terms of time-walk compensation
4. It improves the active fraction of the FE-I4 since the memory is located at pixel level and not in the chip periphery.

The FE-I4 architecture exploits the fact that 99.75% of the hits will not be triggered at LVL-1 and therefore will not be transmitted off-chip. With the higher integration density the new technology offers, it is now possible to store all hits in local pixel buffers inside the double-column bus and to synchronize them by local logic to the trigger. As a consequence the double-column bus is now used only for the transmission of triggered hits and data traffic is drastically reduced. This has the side effect that power is saved because unnecessary digital activity is avoided.

The periphery of FE-I4 consists in an *End of Chip Logic block* which organizes trigger propagation and where the readout is initiated, pixel hit formatting and does temporary hit storage, a *Phase Locked Loop (PLL) Clock Generator block* which takes the 40 MHz LHC machine clock and generates the 160 MHz clock that is necessary for 160 Mbits data transfer, a Data Output block which does 8b10b data encoding and 160 Mbits serialization, a *Command Decode block* decodes Level-1 Trigger commands as well as the *Global Configuration block* that holds in Configuration Registers and the *Pixel Local Configuration block* that holds in memories at pixel level. Some DACs in the bias generator section convert the stored configuration values to the voltages and currents needed to tune the various sections of the chip. In Tab. 3.2 are summarized the main specifications of the FE-I4 readout chip versus FE-I3.

Table 3.2 Comparison between FE-I4 and FE-I3.

Parameter	Value FE-I4	Value FE-I3	Unit
Number of pixel	26880 (80×336)	2880 (16×160)	<i>column × rows</i>
Pixel unit size	50 × 250	50 × 400	μm^2
Nominal analog supply voltage	1.4	1.6	V
Nominal digital supply voltage	1.2	2.0	V
Nominal analog current per pixel	12	16	μA
Nominal digital current per pixel	6	10	μA
In-time threshold within 20 ns (400 fF)	≤ 4000	~ 5000	e^-
Radiation tolerance	250	50	Mrad
Nominal clock input frequency	40	40	MHz
Nominal data output rate	160	40	Mb/s

3.1.3.1 FE-I4 Low Voltages

The FE-I4 operates giving common power supply to analog signal amplifiers and digital signal-process circuits, referred to as the low voltage (LV) power supply and the clock input. The transistors used in FE-I4 have a 2.2 nm gate oxide and the chip voltage specifications are derived from this one. The only exceptions are the EFUSE³ programming circuitry, and the power circuit inputs. For EFUSE programming the thickest gate oxide for this process (5.2 nm) was used in order to handle the programming voltage. The input to the voltage regulators and voltage reference circuit does not go directly to any gate and is designed to tolerate 2.5 V. In FE-I4 the regulators outputs are not internally hard-wired to the internal power nets, in order to preserve testing and debugging flexibility, thus the FE-I4 can be operated in two modes:

1. with a direct connection to the internal nets
2. through the voltage regulators

The latter is the configuration for the IBL as installed, allowing the use of a single external supply voltage and also providing margin with the use of resistive cables. The FE-I4 provides two options for each analog and digital references, denominated *current reference* and *voltage reference* options. The current reference option uses replica outputs from the master current reference and suitable internal resistors to produce two identical voltages that will result in 1.65 V regulated outputs under high resistance process corner and 2.0 μ A reference current. However, each reference has a *trim down* configuration 8-bit register (*VrefAnTune* and *VrefDigTune*) allowing the user to independently set them to any desired value below 1.65 V after start up. The voltage reference option uses a bandgap circuit designed to accept up to 2.5 V input and so is powered from the analog regulator input (not the output). This produces an analog reference resulting in 1.5 V analog regulator output (VDDA) and a digital reference resulting in 1.2 V digital regulator output (VDDD). In IBL the *current reference* option is used. In Fig. 3.7 the tunable reference voltage for the analog and digital (VDDA and VDDD) in function of the tune DAC (*VrefAnTune* and *VrefDigTune*) is shown. They have a good dynamic range and linearity. In Fig. 3.8 the VDDA and VDDD distributions for the corresponding maximum and minimum *VrefAnTune* and *VrefDigTune* DAC registers values of the modules accepted and sent to the stave assembly site for loading are instead shown.

³The EFUSE block consists of a bank of triple redundant RAM, with an additional parallel write bus connected to a bank of non-volatile ROM based on E-fuses. EFUSE is a technology invented by IBM. This technology enables dynamic real-time reprogramming of computer chips.

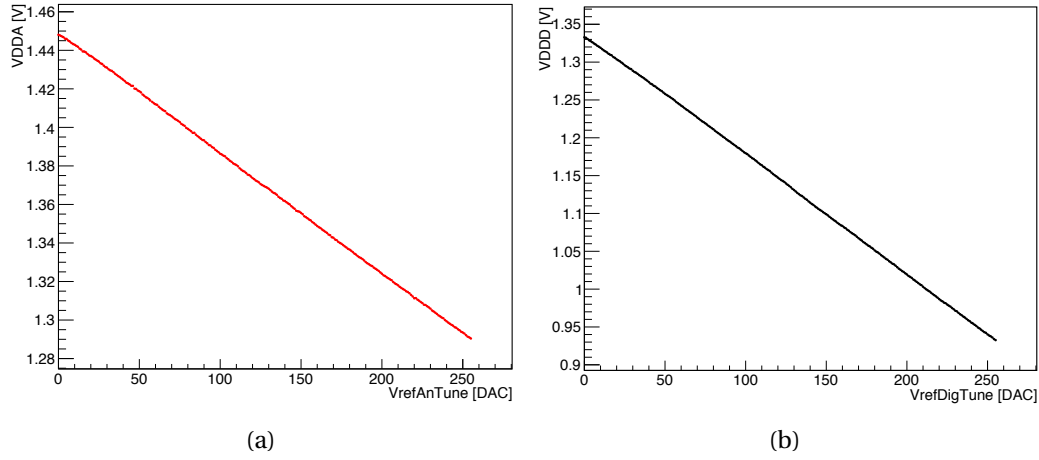


Fig. 3.7 The regulator output voltages for analog and digital supply voltages as a function of the tune DAC ($V_{refAnTune}$ and $V_{refDigTune}$) for an IBL module is shown.

3.1.4 Sensors

Two different detector technologies have been selected: standard $n^+ - in - n$ planar (double chip) and $n - in - p$ 3D (single chip). They satisfy the main requirements for the IBL sensors [25]:

1. In order to reduce the material budget the sensor thickness must be between 150 and 250 μm . This will also allow charge collection in planar sensors to be more efficient at very large radiation fluences [10].
2. The power dissipation has been required to be lower than 200 mW/cm^2 at end of life.
3. The maximum leakage current the FE-I4 can compensate is 100 nA/pixel. The sensors had been designed in order not to overcome this value at the maximum expected fluence.
4. The sensor operating temperature is -15°C or higher at 200 mW/cm^2 .
5. The in-time hit efficiency is requested to be $>97\%$ at a benchmark fluence of $5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ and bias voltage lower than 1000 V (for Planars). The specification does not include geometric inefficiencies. This specification is chosen to limit the degraded performance after irradiation.

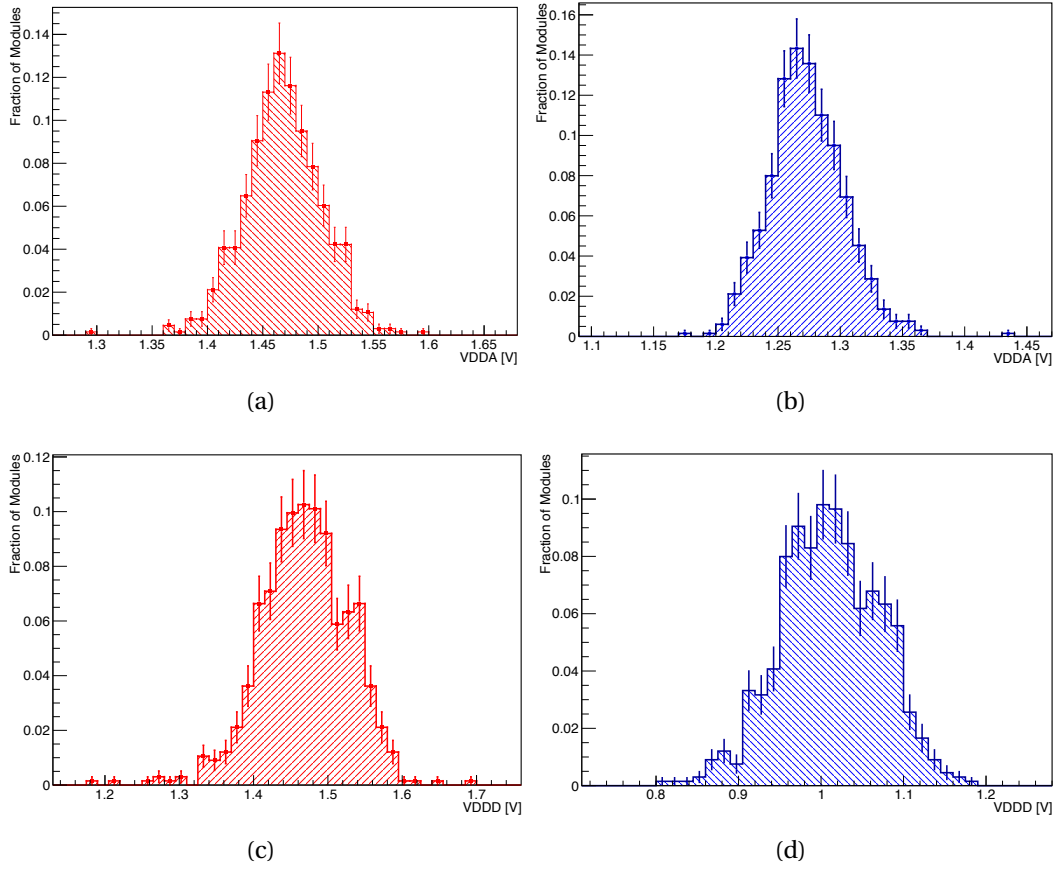


Fig. 3.8 Figures a) and b) show the analog Regulator output (VDDA) distribution for maximum (255) and minimum (0) *VrefAnTune* register value for IBL module production. The maximum and minimum VDDA values correspond to 1.46 and 1.27 (RMS 0.03) V. Figures c) and d) show the digital Regulator output (VDDD) distribution for maximum (255) and minimum (0) *VrefDigTune* register value for the modules accepted and sent to the stave assembly site for loading. The maximum and minimum VDDD values correspond to 1.47 and 1.01 (RMS 0.03) V.

3.1.4.1 Planar Sensors

The devices are produced on n-type, Float Zone (FZ) silicon sensors with $\langle 111 \rangle$ crystal orientation and a bulk resistivity of 2-5 k Ω cm thinned to a thickness of 200 μm . They are fabricated at CiS, Erfurt, Germany. This specific thickness has been chosen because of limitations imposed by the bump-bonding vendor in order to properly perform the Under-Bump Metallisation (UBM). Particular care was taken in the design of the edge termination aiming to minimize dead area without affecting the efficiency of the edge pixels. In the "old" ATLAS three layer Pixel Detector, the sensor design edge consisted in 16 guard rings covering a width of about 600 μm with a safety margin region of 500

μm , adding up to an overall inactive edge of $1100\ \mu\text{m}$ between the edge pixels and the cutting edge. For the IBL design edge the number of guard rings is decreased to 13 and the safety margin width is reduced to $\sim 90\ \mu\text{m}$. Moreover the edge pixels are extended to $500\ \mu\text{m}$ length so that one half of their surface is placed opposite to the guard rings. With these improvements, the active area defined by the 50% hit efficiency, is measured to be approximately $200\ \mu\text{m}$ from the cutting edge [10, 64] (Fig. 3.9).

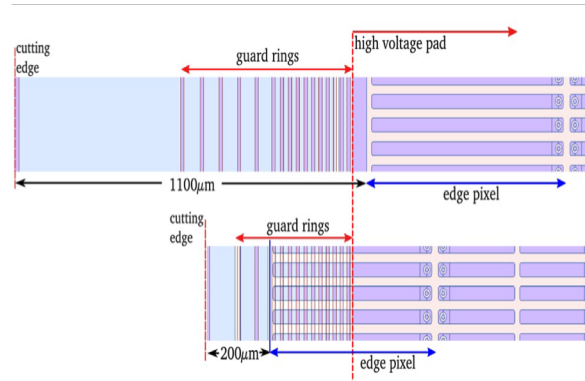


Fig. 3.9 Comparison of the edge region of the current ATLAS Pixel design (upper) and the IBL planar sensor design (lower) [10].

3.1.4.2 3D Sensors

The 3D production used 4" FZ p-type high resistivity wafers. These type of wafers, because of their specifications, are normally adopted for fabrication of high resistivity p-type silicon sensors. In the IBL, the 3D-DDTC (Double-sided Double Type Column) technology with $200\ \mu\text{m}$ slim edges has been used. The junction columns are etched from the front side of the wafer and ohmic columns from the back side. The active-edge is not doable, but a fence of ohmic columns was proven to be effective in reducing the dead area at the edges, in order to meet IBL specifications. 3D wafers have been produced by two vendors: CNM-CSIC (Centro Nacional de Microelectronica, Campus Universidad Autonoma de Barcelona, Spain) and FBK (Fondazione Bruno Kessler, Povo di Trento, Italy) on $230\ \mu\text{m}$ thick wafers having a resistivity of $10\text{-}30\ \text{k}\Omega\text{cm}$.

In CNM sensors (Fig. 3.10) the columns do not traverse completely the substrate, but stop at a short distance from the surface of the opposite side. The isolation implantation between the n^+ columns at the surface is made with p-stops on the front size. The slim edge guard ring design is made using the combination of a n^+ 3D guard ring that is grounded and fences that are at the bias voltage from the ohmic side [64, 65].

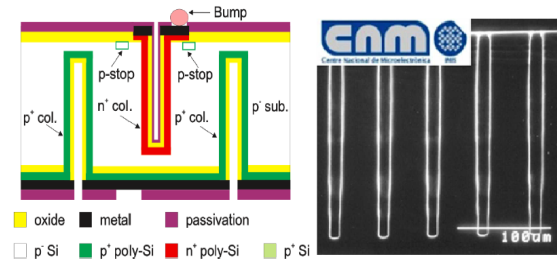


Fig. 3.10 Sketch and SEM micrographs of 3D etched columns of the CNM pixel sensor design [10].

In FBK sensors (Fig. 3.11) the column electrodes traverse the full bulk thickness, requiring p-spray isolation on both sides. The bias- and read-out electrodes are left unfilled after doping [64, 65].

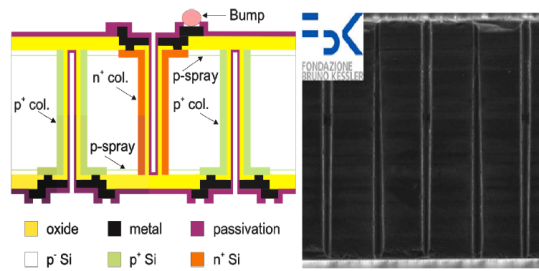


Fig. 3.11 Sketch and SEM micrographs of 3D etched columns of the FBK pixel sensor design [10].

At the wafer level I-V measurements are done to select good sensor tiles. These are made on each sensor using probe stations. FBK exploits a removable temporary metal allowing a measurement of I-V at the column level. The aluminium layer is deposited at the end of the fabrication process, it connects all the 336 pixels in one column transforming the pixel sensor into a strip detector and is removed after the test. The I-V of each of the 80 strips is measured by a dedicated probe card. Each I-V is representative of all the 336 pixels shorted together; the total sensor I-V is obtained by summing up the 80 curves. CNM measures the guard ring current only since the temporary metal is not compatible with their process.

Tiles with a breakdown voltage (V_{bd}) greater than 25 V and leakage current (I_{leak}) at 20 V lower than $0.2 \mu A$ for CNM guard ring and $2 \mu A$ for the whole FBK tile are selected for assembly into *baremodule* (bump-bonded to FE-I4).

3.1.5 IBL Modules Production and Integration

The selected sensor and electronics wafers are sent by the foundries to Fraunhofer IZM Institut (Berlin) to be diced and flip-chipped with SnAg solder bump-bonding. The final assembly is done at two module production centers (Genova and Bonn): a flex hybrid with passive components is glued on the back of the sensors and wire-bonds are done to create a connection with the services. Then modules are qualified and shipped to the stave assembly site where the final stave assembly is performed.

ATLAS IBL modules will need to operate for several years at the LHC, in a very harsh radiation environment, with no opportunity to repair channels developing a failure. Sufficient information must be collected for each module in the qualification procedure, in order to select the modules which are more likely to operate in ATLAS with acceptable efficiency and optimal performance. The qualification of modules consists mainly of four types of tests, that are executed step by step [64]:

- **INIT:** It is a very preliminary electrical test done after assembly to test if all the wire-bonds and connection work properly.
- **ASSY:** It is an electrical test at room temperature, in which the proper basic functioning of the module (e.g. I-V curve, bumps connectivity) is checked. At this step the Tuning at working point of 3 ke^- in threshold and 9 Bunch Crossing at 20 ke^- (corresponding to the signal of a Minimum Ionizing Particle) is also done.
- **BURN:** After the ASSY the power off module is thermally cycled from -40 to $+40\text{ }^\circ\text{C}$ (in about 2 hours) for 2-3 days and retested at room temperature with the same tests of ASSY, except tuning.
- **FLEX:** It is a complete calibration of a module in which a fine tuning is done. All tests are executed at $\sim -10\text{ }^\circ\text{C}$.

A ranking procedure and module selection has been established based on the sensor and FE-I4 performance. The IBL requirement is less than 1% of pixel defects per Front-End chip. Fig. 3.13 shows the yield of IBL module production for sensor types. A high failure rate of IBL modules is present in the first batches due to huge areas or single bump defects distributed over the module. The problem was addressed adopting an alternative bump-bonding technique with the flux-free flip chip. Beyond the bump-bonding issue, about 15% of the modules presented problems on the FE-I4 chips, which can't be checked before the assembly. These problems were mainly due to faulty voltage regulators for analog and digital voltage, that were not tested at wafer level. Moreover, since the very first

tests of assembled modules, a much better agreement between the breakdown voltage at the wafer and module level for FBK than for CNM has been put in evidence (Fig. 3.12). This suggested that the measurement limited to the guard ring used by CNM could not be properly extrapolated at the full device level. To avoid flip-chipping and assembly of poor quality sensors, a remeasurement campaign of CNM sensors not yet used has been put in place. Having the sensors the under bump metallisation, all the pixels could be contacted at once. At this stage the measurement confirmed a yield of 62% when considering the full sensor and not the guard ring only, thus making the overall yield for the two producers rather comparable.

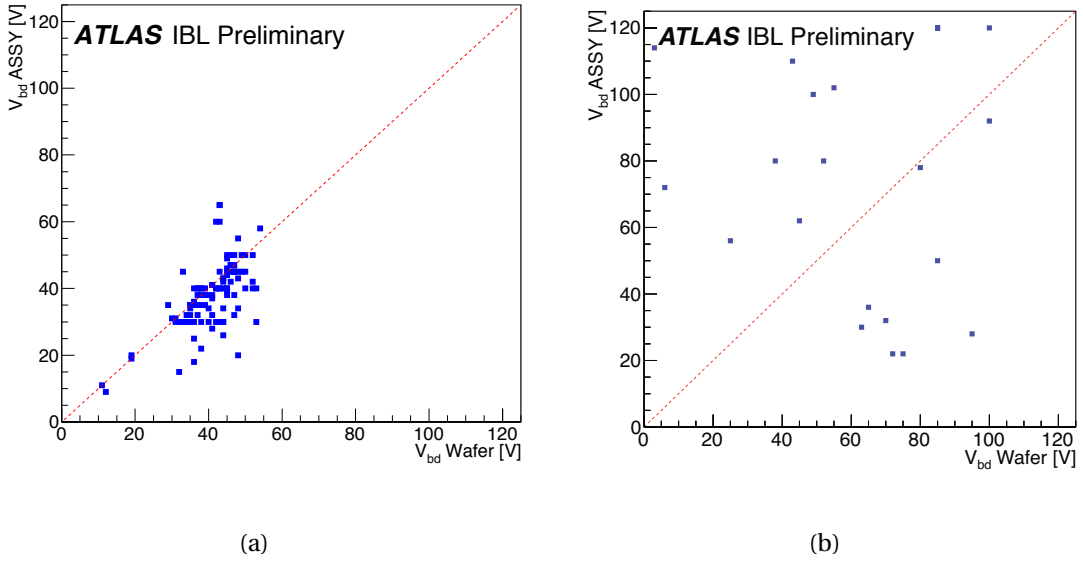


Fig. 3.12 V_{bd} measured on assembly level (ASSY), versus V_{bd} measured on the 3D guard ring at wafer level (before dicing) for a subset of CNM production. Measurements at assembly level were done with a current compliance of $100\ \mu\text{A}$. A better agreement between the breakdown voltage at the wafer and module level for FBK a) than for CNM b) is shown.

After the qualification procedure, the good IBL modules were sent to the stave assembly site where a test upon reception was done. This consists in a fast functionality test that cross-checks the results of the production sites to verify that the modules were not damaged during the shipping. The test is done before cutting the modules from the flex frame that is required before loading them on the stave. Once all the modules are loaded, the wings of the *stave flex* are bent, glued and finally the wire bond connection to the module is made. So testing of the modules is only possible after the entire stave loading process is finished. A single stave is served by two *stave flexes*, one from each side and symmetric to the stave centre. Each flex, has four LV supply lines, each serving four

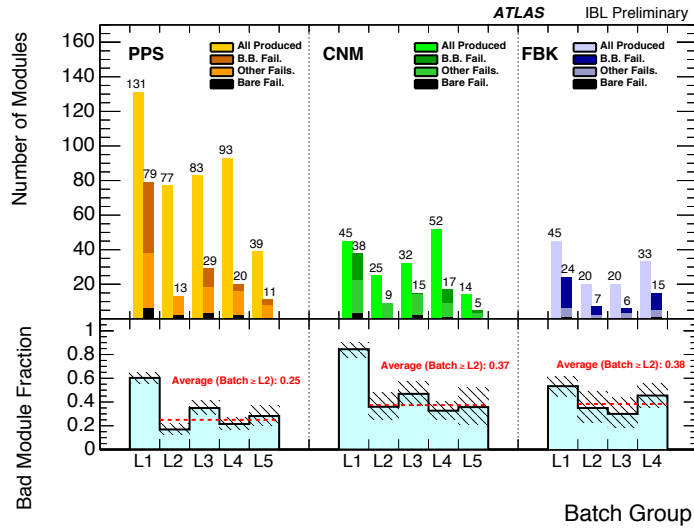
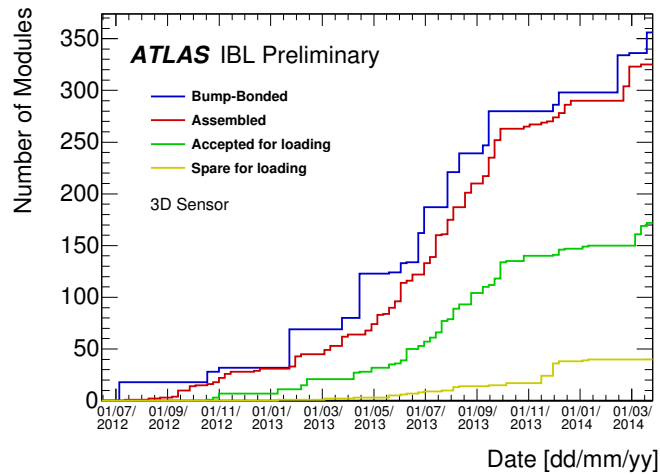
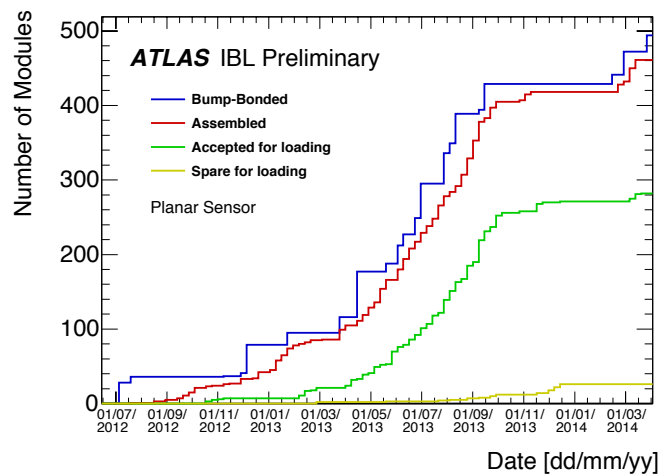


Fig. 3.13 Yield of IBL module production for sensor types of Planar (PPS) and 3D per production batch group. In the top panel for failure modules, “B.B. Fail.” stands for large bump-bonding failure, “Bare Fail.” stands for the module not assembled due to mainly mechanical damages, and “Other Fails.” stands for both electrical and sensor failures discovered after assembly. Within the same batch group, similar configuration of the laser condition and the bump bonding was applied. In the bottom panel, the first batch group was excluded from the average yield in the plot because they were largely affected by bumpbonding problems that were fixed in the following batches. The total average bad module fraction for PPS, CNM, FBK is 0.36, 0.50, 0.44, respectively. If the first batch is excluded, the fraction are 0.27, 0.37 and 0.38 respectively.

FE-chips in parallel; eight Negative Temperature Coefficient sensors (NTC) lines to read out four NTCs located on the modules; 16 data output LVDS pair lines, eight data in and eight clock LVDS pair lines, each serving two FE-chips in parallel; finally four High-Voltage (HV) supply lines, each serving either two double Chip (DC) planar or four single Chip (SC) 3D modules. Figure 3.14 shows the IBL production for 3D Single Chip modules (up to laser batch 13) and Planar Double Chip modules (up to laser batch 12). The blue line represents the sensors that have been bump-bonded to the FE-I4 and almost all of them have been assembled (red line). Excluding the first batch with large bump-bonding failures, 62% of 3Ds and 75% of Planars satisfied the IBL requirements and have been sent to the stave assembly site to be integrated on the stave (green line).



(a)



(b)

Fig. 3.14 Production Trend - The Green line shows the number of modules accepted or lower quality sent to the stave assembly site for loading. a) 62% of 3Ds satisfied the IBL requirements. b) 75% of Planars satisfied the IBL requirements. These percentages are calculated adding those modules accepted for loading and spare modules divided by all the assembled (excluding the first batch).

3.1.6 IBL Performance during LHC Run 2

The combined Inner Detector (ID) performances during LHC Run 2 are mainly latched to the changing of the impact parameter resolutions improvements due to IBL installation. Due to the IBL insertion a change of the material composition of the Inner Detector occurred. The material within the innermost barrel regions of the Inner Detector was studied using reconstructed hadronic interactions and photon conversion vertices from samples of minimum bias events collected at $\sqrt{s} = 13$ TeV in 2015 [11]. This reconstruction is sensitive to the barrel region of the ID, as Fig. 3.15 shows. As seen IBL staves are placed between the IPT and IST. The IPT and IST are made from carbon fibre and resin. In Fig. 3.16 the structure of tubes of the beam pipe at $r = 24$ mm, IPT and IST are clearly visible and consistent between data and simulation. The structure between IPT and IST at $30 < r < 40$ mm is the IBL detector.

IBL is set in proximity of the interaction point so it improves the quality of the impact parameter for the reconstruction of tracks and thereby the vertexing and b -tagging performance. The improvement in impact parameter resolution thanks to the IBL is clearly visible in Fig. 3.17.

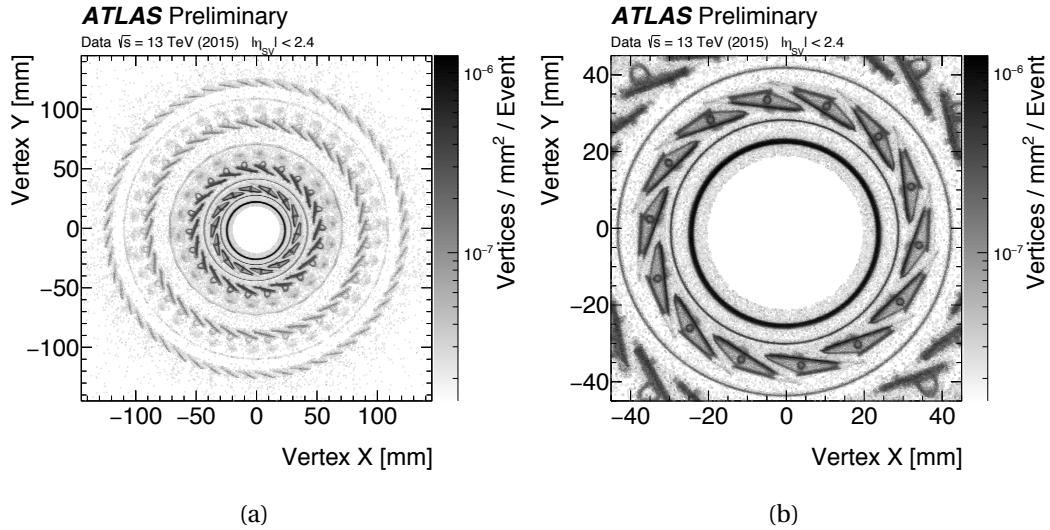


Fig. 3.15 x y -view of the Pixel Detector from the distribution of hadronic interaction vertex candidates in data (a). In (b) it is possible to distinguish the innermost part the beam pipe, IPT, IBL staves and IST [11].

ATLAS uses three distinct basic b -tagging algorithms which provide complementary information: an impact parameter based algorithm (IP2D, IP3D), an inclusive secondary vertex reconstruction algorithm (SV) and a decay chain multi-vertex reconstruction al-

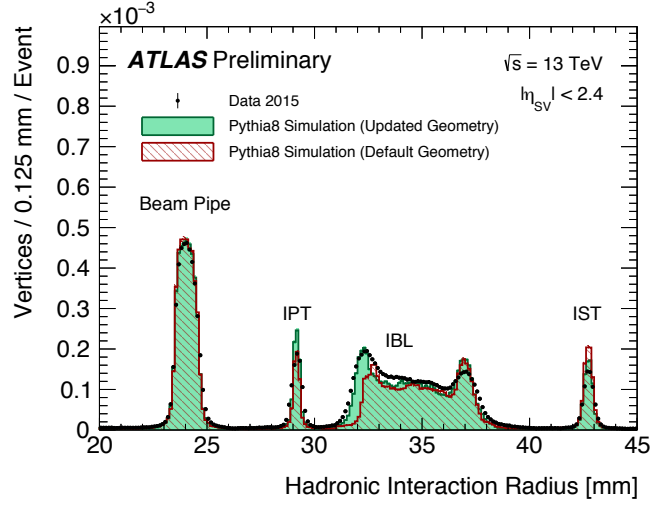


Fig. 3.16 Comparison of the radial distribution of hadronic interaction candidates between data and simulation in $20 < r < 45$ mm region [11].

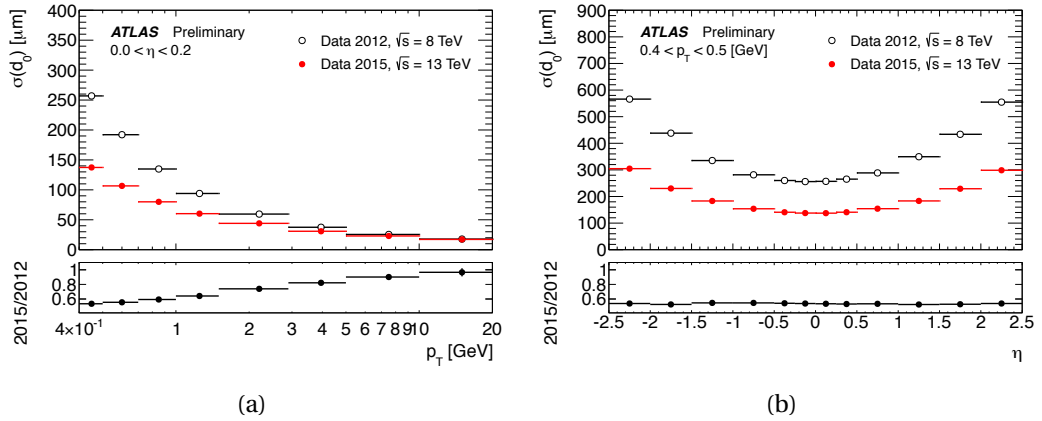
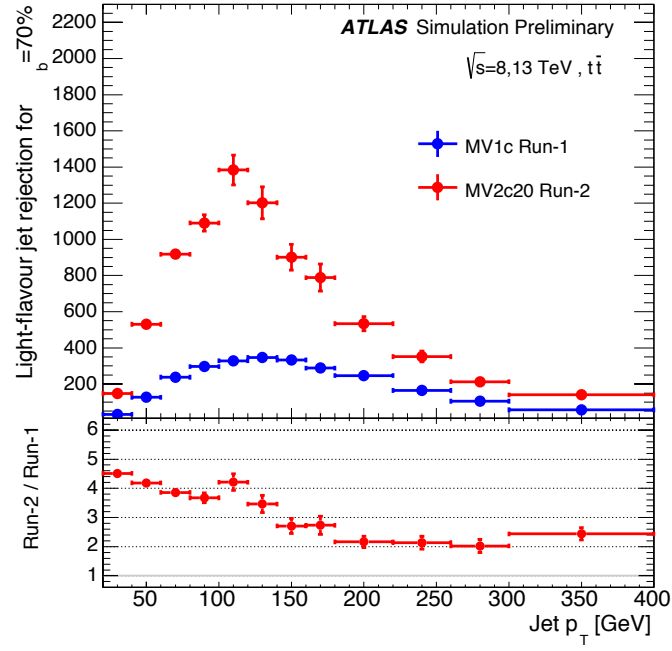
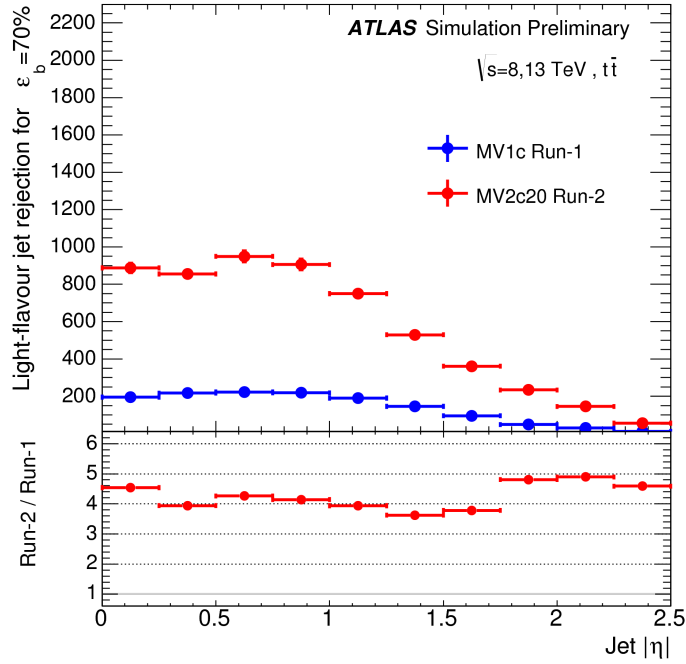


Fig. 3.17 Unfolded transverse impact parameter resolution measured from data in 2015, $\sqrt{s} = 13$ TeV, with the Inner Detector including the IBL, as a function of p_T , for values of $0.0 < \eta < 0.2$, (a) and η and for values of $0.4 < p_T < 0.5$, (b) compared to that measured from data in 2012, $\sqrt{s} = 8$ TeV. The data in 2015 is collected with a minimum bias trigger. The data in 2012 is derived from a mixture of jet, tau and missing E_T triggers.

gorithm (JetFitter) [12]. In Run-2 b -tagging algorithms were improved. As example Fig. 3.18 shows the effect of these algorithmic improvements, together with better tracking performance due to IBL, on the light-flavour jet rejection as a function of b -jet efficiency and jet p_T .



(a)



(b)

Fig. 3.18 The light-flavour jet rejection in bins of jet p_T (a) and $|\eta|$ (b) for the MV1c b -tagging algorithm using the Run-1 detector and reconstruction software (blue) compared to the MV2c20 b -tagging algorithm using the Run-2 setup (red). In each p_T or $|\eta|$ bin the b -tagging cut value has been chosen in such a way to yield a constant b -jet efficiency of 70% [12].

3.2 Pixel Off-Detector Readout Upgrade in LHC Run 2

In Chapter 1 an overview of the ATLAS Pixel Detector was given. In this section the Pixel off-detector electronics will be discussed. The off-detector electronics makes possible the configuration and the control of about 100 million of readout channels of the Pixel Detector, providing also trigger distribution, event-fragment assembly and data storage. The Pixel Detector data acquisition system has several hardware levels and software layers. The back-end electronics is placed in the *Underground Service Area-15* (USA-15) in a radiation safe environment inside 10 VME64x crates. It consists of 146 Readout Driver (ROD) and Back Of Crate (BOC) pair boards and 12 Read Out System (ROS) units. The hardware system is detailed in 3.2.1, 3.2.2 and 3.2.3 subsections. The data-acquisition and calibration software is based on a common ATLAS Trigger and Data Acquisition (TDAQ) software and on a Pixel Detector specific DAQ software called *PixelDAQ*. A brief description is given in section 3.2.4. Finally, in the last subsection (3.2.5), the attention of the reader will be focused on tests that I have performed for the upgrade of Layer-1 and Layer-2 off-detector readout electronics during 2015-2016 LHC Winter Shutdown.

The Large Hadron Collider is working beyond expectations in terms of delivered instantaneous luminosity (see Sec. 1.1). The *in time pile-up* produced by the multiple collisions in the same bunch crossing is problematic for the Pixel readout electronics, in particular in terms of bandwidth saturation. Besides that at the end of LHC Run-1, the number of disabled modules had increased from 2% (beginning of Run-1) to 5%. The modules failures were mainly due to LV or HV powering faults or data transmission faults. For the reasons described, during LHC LS1 the Pixel Detector was brought on surface and the pixel data transmission system was completely renewed. New data cables, new electrical-to-optical converter boards (so-called *opto-boards*), and new data fibres were installed. The installation of the new Service Quarter Panels (nSQP) provided a relocation of the opto-boards and cooling connections between the detector active volume and the outside pixel connectors at $|z| \approx 3.5$ m, for an easier maintenance. Four nSQP are used to serve each side of the Pixel Detector. The new services allowed to fix modules faults related to cables, obtaining 98% of the channels recovered at the beginning of LHC Run-2 in 2014.

Thanks to the increasing of the number of data links and off-detector electronics the bandwidth of Layer-1 can be increased from 80 to 160 Mbit/s and for Layer-2 from 40 to 80 Mbit/s⁴, raising the expected bandwidth saturation limitation at $3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. In Tab.

⁴To have an idea 1 hit in the Pixel System (IBL excluded) has a size of 54 bit. Since one ROD link collected 6 or 7 modules (with 16 FEs each one), assuming 2 hits per module a 40 Mbit/s link will saturate at a trigger rate of ~ 70 kHz.

3.3 the link usage before the upgrade is extrapolated for different data-taking scenarios of bunch spacing (25 ns or 50 ns) and number of pile up events.

Table 3.3 Extrapolated link occupancy for Pixel Readout at different number of pile up events and trigger rate of 75 (100) kHz.

Bunch Spacing	$\langle \mu \rangle$	B-layer [%]	Layer-1 [%]	Layer-2 [%]	Disks [%]
50	37	39 (51)	34 (45)	52 (69)	30 (40)
25	25	35 (47)	31 (42)	48 (65)	27 (37)
25	51	53 (71)	59 (67)	66 (88)	39 (52)
25	76	71 (95)	73 (97)	111 (148)	64 (75)

To fully exploit the data transmission bandwidth an upgrade has been arranged to move all the Pixel crates to the new IBL ROD and BOC cards. The IBL ROD and BOC boards are based on modern FPGAs and can provide more computing power rather than the old ROD system [13].

For time and costs reasons the upgrades have been performed following a staged approach. During 2015-2016 LHC Winter Shutdown Layer-2 and a portion of Layer-1 crates moved to the new off-detector readout, instead 2016-2017 LHC Winter Shutdown is devoted to upgrade the remaining system. B-layer and Disks will not have benefits in terms of higher bandwidth, but in terms of computing power and system uniformity.

3.2.1 Interlude: The Module Controller Chip (MCC)

As seen in Chapter 1 a Pixel module consists of a planar sensor and front-end (FE). The readout part is made up of 16 Front End-I3 (FE-I3) chips [66], one of each controlling 46,080 pixels. The signals of all 16 FE-I3 chips are fed into the Module Control Chip (MCC) [67] which transmits them to the off-detector side. A picture of a Pixel Module is shown in Fig. 3.19. The MCC is connected to the PIN Diode/ DORIC chip, which converts the opto-signal from the down-link fibre into separate clock and data lines, and to the VDC chip/VCSEL, which converts the MCC output data to an optical signal for the up-link fibre. The optical fibres go to the off-detector BOC and ROD, which has the functions to transmit trigger and command signals to the MCC, and to read events back and convert them to the ATLAS event format.

The interconnection between the MCC and the 16 FE chips in a module is a star topology using unidirectional serial links, chosen to improve the tolerance of the system to failure of some components.

A serial protocol has been chosen in order to minimize the number of interconnection lines between FE chips and MCC and between MCC and ROD.

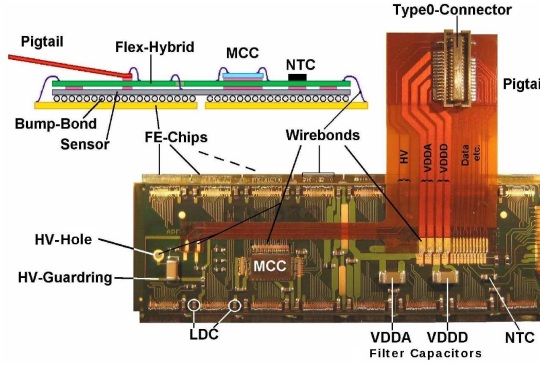


Fig. 3.19 The ATLAS Pixel Module.

The FE-I3 chip encodes and transmits hits from the corresponding event using fixed length packets of 26 bit. Each hit contains a 1-bit header, followed by a 4-bit LV1, an 8-bit row number, a 5-bit column number, and an 8-bit ToT value. Once an event is finished an End-of-Event (EoE) word is sent to the MCC. This EoE word has to be sent to the MCC even if there are no hits associated with the event. All possible errors, warnings and EoE messages from the FEs are coded in the unused 8-bit row number (row numbers from 224 to 255). A row number above 224 is always interpreted as an End-of-Event (EoE). In Fig. 3.20 the data format and timing for event transmission from FE to MCC is shown.

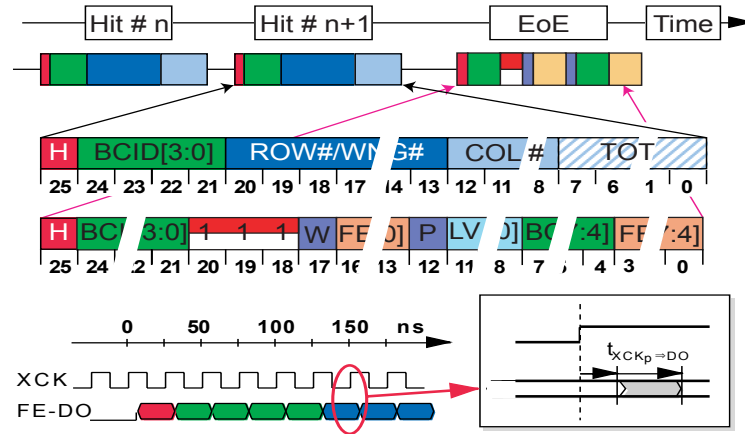


Fig. 3.20 Data format and timing for event transmission from FE to MCC. (a) Hit frame is 26-bit long, (b) EoE frame is also 26-bit long.

The data stream generated by the MCC to the ROD is different since the information is organized on an event format.

The format of MCC event is shown in Fig. 3.21 and defined with the following scheme:

- The events are ordered by LV1 arrival time. The event building is done by grouping all hits belonging to the same LV1 number. The first event which has been triggered is the first to be sent out.
- The pixel hits are sorted by FE chip order.
- Event length is not known until the whole event is transmitted. The event starts with an header ("11101" in binary) and finishes with a trailer ("100 0000 0000 0000"). This trailer is an unique pattern if the data stream is interleaved by synchronization bits ("1").
- Each event is defined by an 8 bit LV1 number, which labels the event, an 8 bit FE number followed by all hits belonging to this FE organized in an 8 bit row number, 5 bit column number and possibly by an optional 8 bit ToT. After the first non empty FE data has been transmitted a second 8 bit FE number followed by row, column, ToT is serialized. Possible error or warning flags produced by the MCC are coded in the data stream.

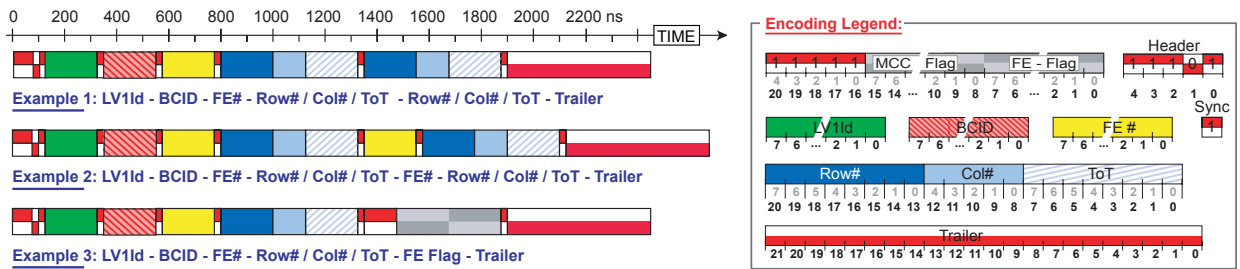


Fig. 3.21 Event Data format at the MCC output. Some Examples of data stream are reported.

In Fig. 3.22 an example of real data coming from one MCC during the ATLAS datataking at ROD level is shown.

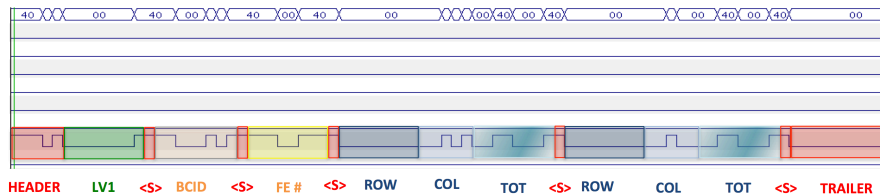


Fig. 3.22 MCC protocol - Real data coming from one MCC during ATLAS datataking at ROD level.

3.2.2 A VME system: SBC, TIM, ROD and BOC

The Pixel Detector is composed by 1456 Pixel modules in three Barrel layers and 144 modules in each of two Endcaps. Each Pixel module has 16 Front-end ICs (FE), with 2880 channels per IC for a total of 46080 channels. A single Module Controller Chip (MCC) [67] per module collects and multiplexes data from the 16 FE chips and translates commands into chip signals. Groups of six or seven modules are connected to a single optoboard, enabling the transmission and reception of optical signals. The IBL is instead composed by 14 staves with each stave playing host to 32 FEs, for a total of 224 double chip modules. The IBL opto-board handles data in both directions and provides 8 receiver channels and 16 transmitter channels, it serves an half stave: six double-chip planar modules and four single chip 3D modules (16 FE-I4). The fibers coming from the optoboards are plugged into the Back Of Crate (BOC) card that is the VME opto-electrical conversion board of the crate. The BOC is paired with a Read Out Driver (ROD) card which is plugged into the same slot, but from the front of the crate. The ROD is the VME data processor board responsible for front-end event-building and detector calibration. In each of 10 crates (9 for Pixels + 1 for IBL) up to 16 of these card pairs can be installed. In Fig. 3.23 a scheme of Pixel Crate in USA15 is shown and in Tab. 3.4 a list of Pixel and IBL readout components is also reported.

Table 3.4 Pixel Detector and IBL readout components.

Part	Stave/Sectors [#]	ROD/BOC Pairs [#]	Optoboards [#]	Original Data Rate [Mbits]	Upgraded Data Rate [Mbits]
IBL	14	14	28	160 (2×80)	160 (2×80)
B-Layer	22	44	44	160 (2×80)	160 (2×80)
Layer-1	38	38	76	80	160 (2×80)
Layer-2	52	26	104	40	80
Disks	48	24	48	80	80

Each crate is also equipped with one Single Board Computer (SBC) and one Timing, Trigger and Control (TTC) board for Level-1 triggers TDAQ distribution. When an event is built on the ROD is sent to Read Out Buffers Input Devices (ROBIN) via S-LINK⁵ protocol from the BOC. The ROBINS are the hardware interface of the Readout Subsystem (ROS), which is the computing farm that buffers event data generated by RODs until High Level Trigger decision is not taken. In Fig. 3.24 an illustration of the readout chain is shown.

In the following a brief description of the main components of the crate is reported.

⁵A Simple LINK (S-Link) is a link that can be thought of as a virtual ribbon cable, moving data or control words from one point to another. The specification describes the interface between the Front-end Mother-board (FEMB) and the Link Source Card (LSC) and the interface between the Link Destination Card (LDC)

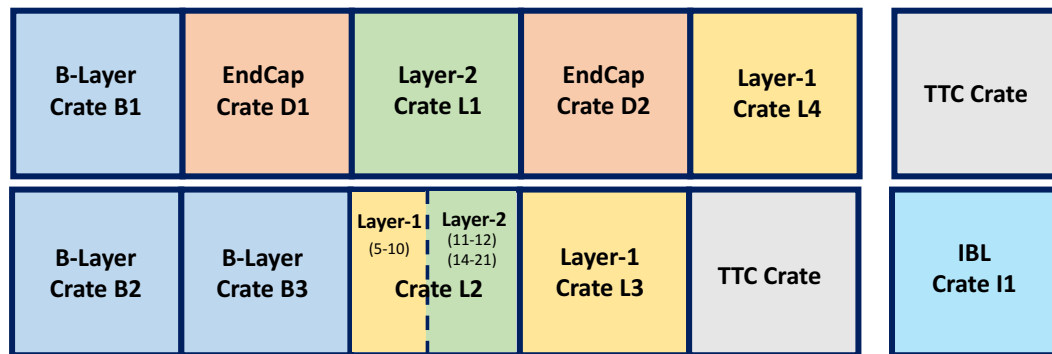


Fig. 3.23 Pixel DAQ Crates in USA15. A crate can contain 16 boards (enumerated from 5 to 21). In slot 13 is always located the TTC Interface Module (TIM) to propagate the timing properly on its left and right crate side.

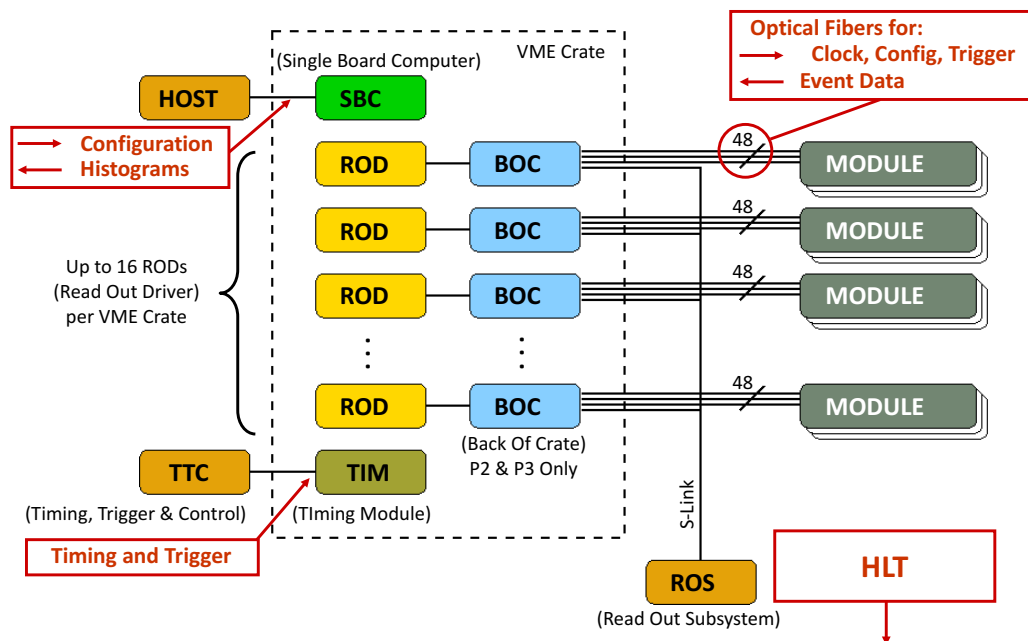


Fig. 3.24 Overview of the VME crate structure for the data readout of the ATLAS Pixel Detector.

SBC Single Board Computer (SBC) is a computer mounted on a 6U board with a VME interface chip. It is used to control all the VME operations on the RODs, to program some of its components and to monitor the temperature on some components of the RODs.

and the Read-out Motherboard (ROMB). It does not describe the physical link itself. More details can be found in [68].

TIM The TTC Interface Module (TIM) card is connected to the TTC system of the ATLAS Detector, it receives the Level-1 trigger and distributes it to the ROD cards in the crate. The TIM, if necessary can send a busy-signal to the Central Trigger Processor (CTP) to stop the sending of further trigger signals. An example is if one of the ROD is busy (masked OR of all ROD busy-signals in the crate). The TIM passes to RODs fast commands and event IDs received from the TTC. The TIM distributes a global, 40 MHz clock to the BOCs to synchronize both on-detector and off-detector readout electronics. In Tab. 3.5 a list of TTC signals is reported. These signals can be generated by the TIM also in stand-alone mode.

Table 3.5 List of TTC signals.

Signal Type	Description/Function
Clock	BC - 40 MHz Bunch Crossing
Fast commands	L1A - Level-1 Accept (Trigger) ECR - Event Counter Reset BCR - Bunch Counter Reset CAL - Calibrate signal
Event ID	L1ID - Level-1 trigger Number BCID - Bunch Crossing Number TTID - Trigger Type

ROD The Readout Driver (ROD) is the central part in the readout chain of the Pixel Detector. It can work in two modalities: data-taking and calibration mode. In data-taking mode, it builds the event fragments from the data of the front-end modules and passes them the TTC signals. In calibration mode the ROD initializes detector modules and it is able to generate trigger, data gathering and histogramming. Two different models of RODs were used in the Pixel Detector during 2016 data-taking: *IBL-ROD* and Silicon Read-Out Driver (*SiROD*). The *SiROD* architecture is based on a Field-Programmable Gate Arrays (FPGA) and Digital Signal Processors (DSP) chosen for maximum stability and versatility during data-taking and calibration. The board has a single Master DSP and four Slave DSPs used for control and coordination of on-ROD operations. Resetting the ROD and the VME interface is handled by the Program Reset Manager (PRM) FPGA. When the ROD is powered up, the PRM activates the host-to-ROD VME interface and resets the Master DSP (MDSP). Once the MDSP has booted, initialization information is transmitted to the ROD Controller FPGA (RCF) as well as the data-path FPGAs: the Formatter (FMT), the Event Fragment Builder (EFB) and the Router (RTR). The farm of Slave DSPs (SDSPs) are

booted with binary firmware images obtained from the host via the MDSP [13]. In Fig. 3.25 a scheme of the old *SiROD* is reported.

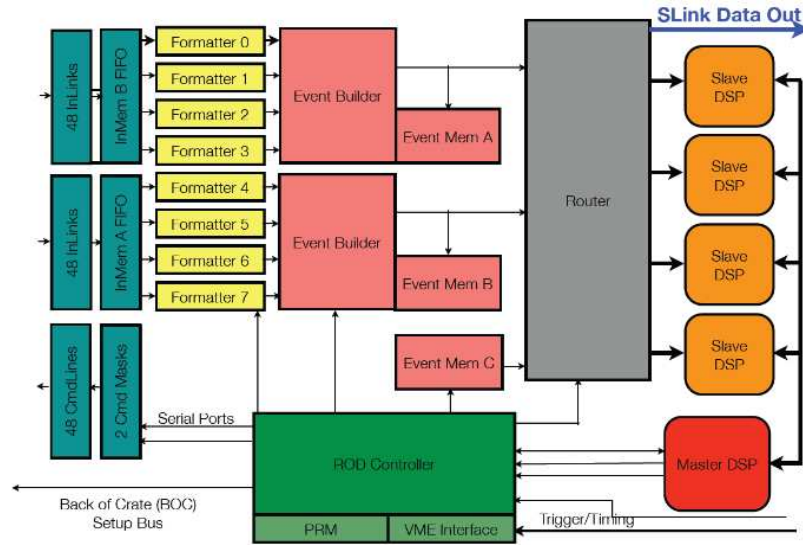


Fig. 3.25 A scheme of the functional blocks of *SiROD* is shown [13].

The *IBL-ROD* is an upgrade of the *SiROD*, developed for the Insertable B-layer. In tab. 3.6 a comparison between the old *SiROD* and the new *IBL-ROD* is reported. In Fig. 3.26 a comparison between the behaviour of *SiROD* and *IBL-ROD* is shown. The *IBL-ROD* has less trigger limitations than the old *SiROD*, thanks to the higher bandwidth available. In this way, just by replacing the ROD, the same Layer-2 modules may be used to 80 Mbits, rather than 40, thus reducing data pressure with FE electronics.

The new readout electronics will be detailed in section 3.2.3.

Table 3.6 Comparison between *SiROD* and *IBL-ROD*

	SiROD	IBL-ROD
Number of FPGAs	12	4
Operating FPGA Type	Spartan-II	Spartan-6
Maximum Bandwidth	Mbits/s	Mbits/s
Layer 1	80	160
Layer 2	40	80
Software Control Interface	VME	Ethernet

BOC The Back Of Crate (BOC) provides the interface between the front-end electronics and the off-detector readout components. It receives the optical data signals from the Optoboards and converts them into electrical data streams which are then passed to the

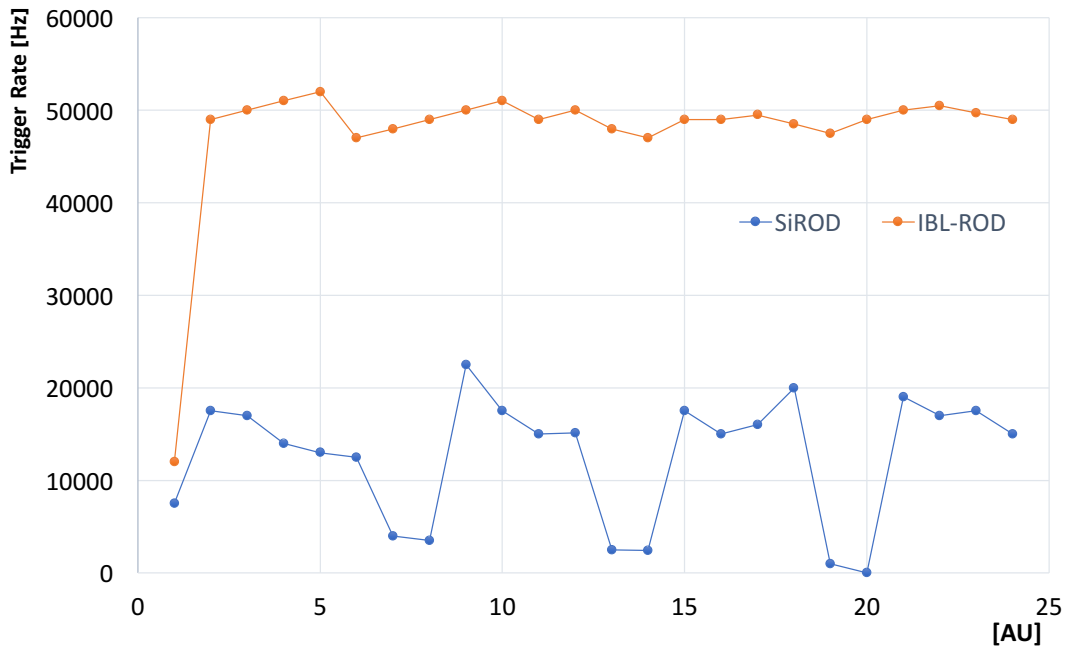


Fig. 3.26 Comparison between the old *SiROD* and *IBL-ROD*. The data are emulated at BOC level, setting 20 hits per channel. Since the old *SiROD* has a lower bandwidth available, it saturates with higher frequency than the *IBL-ROD*. The data-taking of *SiROD* shows also more drops in trigger rate due to the Busy creating to compensate the bandwidth saturation.

ROD. For the IBL a new version of the BOC based on three Xilinx Spartan 6 FPGAs was developed. The first FPGA is called BOC Control FPGA (BCF) and it is responsible for the ethernet and setup bus communication with other devices. The two others called BOC Main FPGAs (BMF) receive data, encoded in 8b/10b or MCC data format encoded, at 80 or 160 Mbits (if two links are used) from the front-end (FE-I4 or MCC). After decoding, they send them out to the ROD via bus. The BMF also manage the output to 4 optical S-Links transceivers that send the data the ROBINS of the ROS.

3.2.3 The IBL Readout Driver (*IBL-ROD*)

The *IBL-ROD* is a 14-layer 9U x 400 mm VME64x board. It has been developed as an improvement of *SiROD*. The board contains 4 FPGA and a Phase-Lock-Loop (PLL), as described in the following:

- **1 Program Reset Manager (PRM)** (Xilinx Spartan6 XC6SLX45-FGG484). It interfaces with the VME bus, the ROD Controller FPGA, the slave FPGAs and the Phase-Locked

Loop (PLL). The PRM has a fundamental role in the VME FPGA's programming and resetting.

- **1 Master FPGA** (Xilinx Virtex5 XC5VFX70T-FF1136). It is the ROD Master. It interfaces with the front-end chips and all the trigger information that comes from TTC (Event ID, Trigger Type and Bunch Crossing ID). In this FPGA there is implemented a microprocessor Power PC (PPC) architecture.
- **2 Slave FPGAs** (Xilinx Spartan6 XC6SLX150-FGG900). The goal of these two FPGAs is passing data during the data taking process, collect histogram data inside an SSRAM and send them to an histogram server if required. To cope with all these tasks a MicroBlaze processor was implemented on each Spartans. Since the main firmware changes for Pixel Upgrade are related with the slaves, their architecture will be discussed with more detailed in 3.2.3.1.
- **1 Phase-Locked Loop PLL** (Lattice ispClock 5620). It is a control system that generates an output signal whose phase is related to the phase of an input signal. The function of the PLL is to compare the distributed clock to the incoming reference clock, and vary the phase and frequency of its output until the reference and feedback clocks are phase and frequency matched.

The connection between the ROD and the off-detector system is schematically shown in Fig. 3.27.

3.2.3.1 ROD Architecture and Data path

As seen in section 3.2.3 the ROD has been designed to process data coming from the BOC, to manage the calibration of the modules sending configuration and commands and to organize the data in histograms. The data from calibration and data-taking are processed in several logical blocks as Fig. 3.28 shows. The most important logical blocks are the Formatters, the Event Fragment Builders (EFBs), the Routers, the Histogrammers and the Merger. The last block was explicitly designed for Pixel Readout Upgrade and it is not present in the IBL firmware. This extension was necessary since for design of the Pixel off-detector electronics the Pixel BOC has two S-links in comparison of four of IBL-BOC (2 for each FPGA of the ROD). For this reason in the IBL the Merger block was not required. Two Formatters, one EFB and one router are grouped in the so called *half slave* block, that is duplicated for each Slave FPGA. A single Formatter block collects the incoming BOC data from four links and performs the data de-serialization in one 2048×32 FIFO per link. The Formatters are different in IBL and Pixel Upgrade implementation,

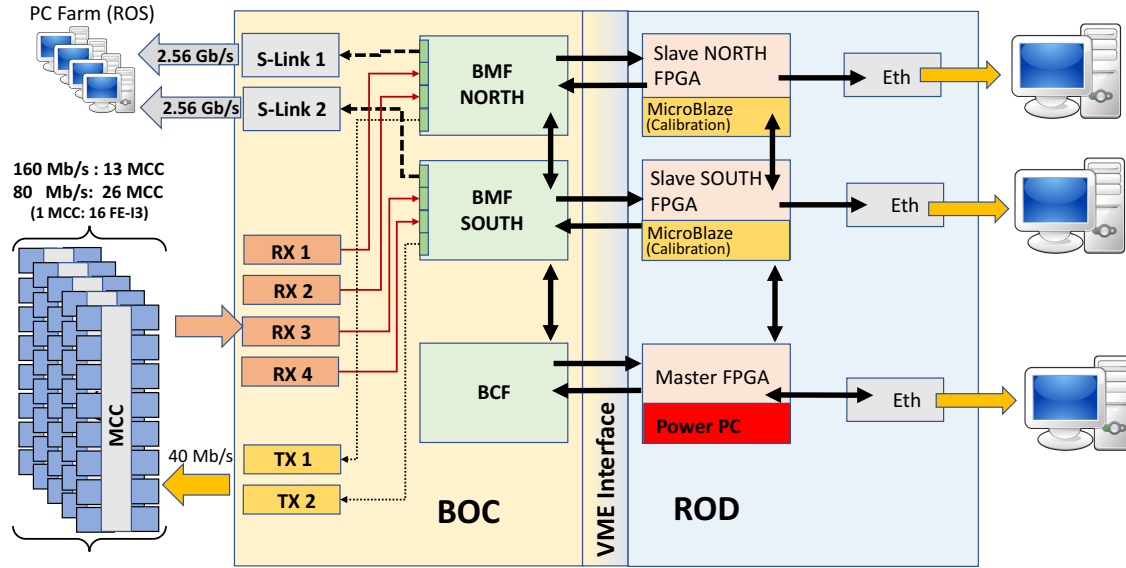


Fig. 3.27 Overview of the main components of the ATLAS Pixel Read-out chain using the new *IBL-ROD*.

since FE-I4 and MCC have a different data transmission format. Two Formatters are then connected to a single EFB that adds header and trailer infos such as: trigger type, event ID, bunch counter ID. The EFB compares the ATLAS Level-1 Trigger and the Bunch Counter ID (BCID) coming from the Pixel Modules with the data information received by the TIM. If there is a mismatch an error flag is added in the output data stream. The Router sends appropriate informations to the Merger block in data-taking mode and to Histogrammer in calibration mode. The main task of the Merger is the creation of an unique data-stream with the data coming from the two routers in one *half slave*. This stream is sent to the BOC, that sends the data via two 1.28 Gbits/s S-Links to the ROSes. In calibration mode the data are instead sent to the histogrammer. This block collects the information about pixels (e.g. the Time Over Threshold) creating a map of pixel response. The data-stream is driven by the MicroBlaze and sent to a PC via Gigabit Ethernet ports.

3.2.4 The TDAQ and PixelDAQ framework

The *PixelDAQ* software is a part of the ATLAS TDAQ⁶ framework, which combines all ATLAS subdetectors. The TDAQ software manages the configuration and data-taking of the ATLAS detector for LHC collision runs. The TDAQ environment contains also

⁶Trigger and Data Acquisition system

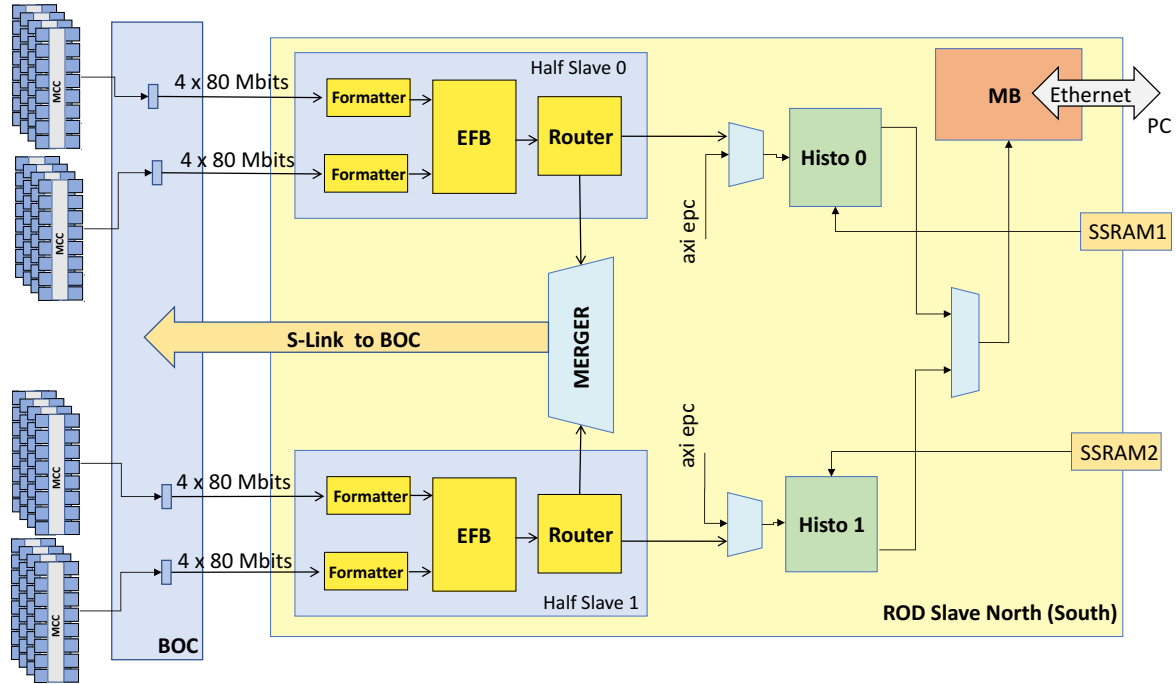


Fig. 3.28 Block scheme of the Firmware of Layer 2 ROD Slave. Only one slave is shown.

the configuration and condition database, an information service which allows software applications to exchange user-defined information and a process manager which performs the basic job control and creates, controls and monitors the status of all processes in the TDAQ system. The organization of the ATLAS detector readout is done in terms of partitions. A partition is the capability of providing the functionality of the complete TDAQ to a sub-set of the ATLAS detector, for example, it is possible to read out all or part of a specific detector with a dedicated local trigger in one partition, while the other detectors are taking data in one or more independent partitions. The Pixel system is split in four partitions: IBL, B-layer, Layer-(1 + 2) and Disks. The *PixelDAQ* is the interface between the common TDAQ software and the Pixel Detector hardware. It implements all the functions needed to configure and control the detector. The main functional blocks are shown in Fig. 3.29.

The different applications can be started and controlled via a Graphical User Interface (GUI). The TDAQ GUI allows to boot a detector partition which starts the Run Controller. Here there are connections to several servers like the Database (DB) server, Histogram Server, Message Server (MRS) and the Information Server (IS). These are the interfaces to the configuration database, store and load histograms, handle messages and information requests respectively. Since the communication between the different blocks is very complex several threads have to be processed at the same time. This is done via Inter

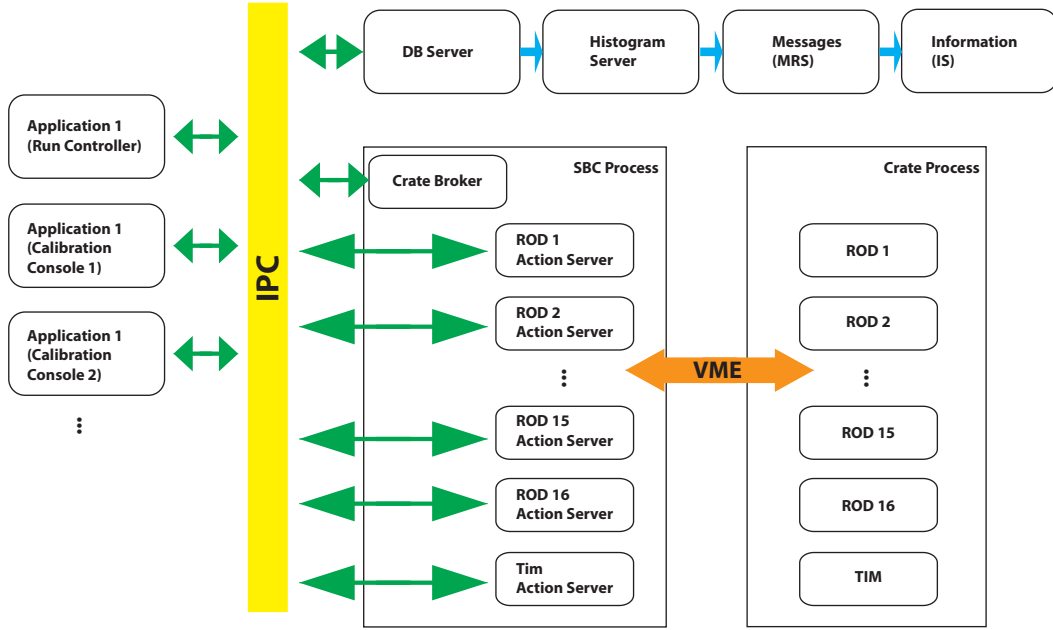


Fig. 3.29 The functional blocks of the TDAQ and PixelDAQ data acquisition software.

Process Communication (IPC). To tune the detector, an application called *Calibration Console* can be used: it configures modules, runs scans and checks their results. The Run Controller and Calibration Console are executed on host PC, instead the so called Action Servers (the Actions are single or groups of tasks) run on the SBC. The coordination of the commands and request sent via the VME interface are handled by the Crate Broker. Different C++ classes are used as virtual interfaces to the hardware such as the *ROD-PixController* that contains all basic functions needed to control the detector, or the *RodModule* class that implement hardware details of the ROD-BOC system, for example memory mapping.

3.2.5 Qualification Procedures for New Pixel Readout

In this section it is described the qualification procedure that I have contributed to develop to check and validate the Pixel data acquisition chain with the new hardware and firmware. The performed tests had two different but common goals: to check if the data frames coming from the new ROD firmware blocks such as the Formatter and the Merger were corrupted and to find possible critical situations in the complete readout chain:

$$\text{Modules} \rightarrow \text{BOC} \rightarrow \text{ROD} \rightarrow \text{S-LINK} \rightarrow \text{ROBIN/ROS} \quad (3.1)$$

To test the firmware two different sources of data were used: the BOC Emulator and the Detector. A brief description is given in the following:

- **Emulator:** In the BOC a FE-I4 or MCC emulator is implemented. It was developed in the BMF to have some kind of detector interface always available, even if no real detector is connected to the card. The BOC emulator consists of two parts: in the first part the FE-I4 or MCC commands are decoded, in the second part they are transferred to a data generator. For qualification purpose is very useful since the generated data-pattern could be known adding also hit information.
- **Detector in Standby Mode:** in this modality the sensors are unbiased. An undepleted sensor can lead to a large number of noise hits per module which can block the data acquisition system. For this reason, the preamplifiers for each pixel are also switched off, therefore detector events are almost empty. This modality is very useful to test the firmware with empty real frames coming from the modules, thus testing data integrity versus trigger rate.
- **Detector in Run Mode:** in this case the sensors are biased and the the preamplifiers for each pixel are also switched on. This test is performed when there is no beam in the LHC. Test the firmware in this condition is useful, since some random hits from noise can be generated even if there is no beam in the collider.

The firmware testing procedure that I have contributed to develop is well-structured in different consecutive step. The first step took place in the clean room of the SR1 building at CERN, here some module staves and a replica of the Pixel Detector readout electronics (*system-test*) is located. The tests in SR1 use the BOC emulator and then the system-test up to a trigger rate of ~ 50 kHz for different readout speeds (40, 80 and 160 Mbits) and with different number of frames and hits patterns in the emulator test. In Tab. 3.7 a summary of tests performed in SR1 is reported. In the Pixel Detector the problematic modules are masked in physics mode that would otherwise cause a busy in the detector. If many modules of the same data link are masked or the number of modules connected to the same link is different by construction, the data volume processed by the ROD Slaves can be unbalanced. This situation could be critical if the ROD firmware is bugged, in fact a data-taking stop can occur. For the reason described, the tests were repeated using different masks for disabled modules and links.

Data sent across the links are checked for transmission errors by the ROS, this means that of an XON-XOFF flow protocol data transmission is halted when the ROS cannot receive additional data. Checking of ROS statistics published in IS is a key step in the

Table 3.7 Test performed in SR1 to validate the ROD firmware. The tests are repeated using different masks for disabled modules.

Data Source	Number of Frames	Number of Hits per Frame	Readout Speed Tested
BOC Emulator	1	0, 10, 20	40/80
BOC Emulator	5	0, 4, 10	40/80
Detector	1, 5, 10	0	40/80
Detector	1, 5, 10	Hits from Noisy Pixels	40/80

qualification procedure, in particular it is required to have no "NotDeleted", "MayCome", "Lost", "Corrupted" or "Truncated" fragments in ROS buffers coming from the *BOC/ROD* system.

In the following a brief description is reported:

Not Deleted Fragments: A request to clear a fragment is failed. This may be due to: fragment was never sent to the Robin or the deletion was requested before the fragment arrived

MayCome: A request to a ROS for a fragment may occur before the fragment has arrived via S-LINK and this is flagged as a MayCome fragment. This is not an error condition but indicates a 'slow' ROD. A high gradient could indicate congestion in the MCC or the RODs.

Lost fragments: Histograms showing the number of lost fragments versus ROS, per (sub) detector and for the whole Readout.

Truncated Fragments: Histograms showing the number of truncated fragments versus ROS, per (sub) detector and for the whole Readout.

The described parameters are critical to have good data-taking quality, since the fragments produced by the ROD are kept in ROS memory until a release request from the HLT is not received. To take under control these parameters, I have developed a tool with a GUI interface (Fig. 3.30) that allows to follow the time evolution of IS variables and one in comparison the other.

If a fragment arrives at the ROBIN/ROS after the release request, it is not deleted from the ROS memory. Since the ROS has finite number of memory allocations, back-pressure can be sent to the ROD. In the case where the internal FIFOs fill beyond a critical limit, a ROD busy signal is raised on the TIM to stop triggers, incrementing the busy time of the Pixel Detector or arriving to the complete stop of the data-taking.

In Fig. 3.31 a comparison between a problematic firmware version during a data-taking test and a good one is reported.

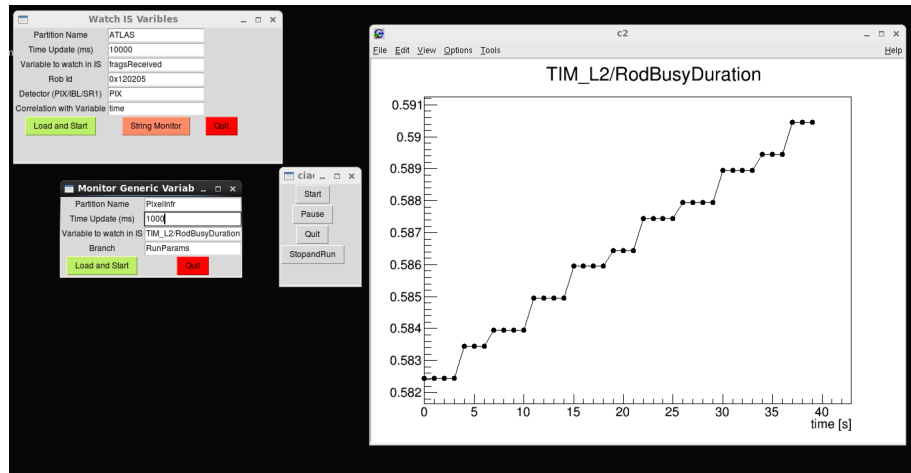


Fig. 3.30 Tool to monitor IS variables.

0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	US2[12]	newreadcorruptions	# fragments detected to be corrupted on transfer to host (and then re-requested)
2980821, 0, 0, 2980821, 2980821, 0, 0, 2980821, 2980821, 2980821, 0	US4[12]	fragsReceived	# of received fragments
2980821, 0, 0, 2980821, 2980821, 0, 0, 2980821, 2980821, 2980821, 0	US4[12]	fragsIndexed	# of fragments added to index
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	US4[12]	fragsTruncated	# of truncated fragments
0, 0, 0, 0, 0, 0, 0, 338608, 233724, 168832, 152072, 0	US4[12]	fragsCorrupted	# of corrupted fragments
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	US4[12]	fragsReplaced	# of replaced (duplicate) fragments
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	US4[12]	fragsOutOfSync	# of fragments with non-consecutive L1 IDs
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	US4[12]	fragsIncompleteOnDMA	# of fragments found incomplete in index upon DMA request
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	US4[12]	fragsDiscarded	# fragments requested while channel in discard mode

a)

0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	# fragments detected to be corrupted on transfer to host (s
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	# of truncated fragments
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	# of corrupted fragments
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	# of replaced (duplicate) fragments
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	# of fragments with non-consecutive L1 IDs
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	# of fragments found incomplete in index upon DMA request
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	# fragments requested while channel in discard mode

b)

Fig. 3.31 ROS parameters as are shown in IS. A comparison between problematic a) and a good b) firmware version is shown.

Another important test performed was the ROD byte-stream check to find protocol violation errors in the header (BCID/LVID/Preamble) field. These tests were performed using Chipscope, that is a set of tools made by Xilinx that allows to easily probe the internal signals of FPGA. The out-coming data from the ROD has to follow a specific data format [69] (as reported in the following) and Tab. 3.8 a summarized the data ROS data format.

- *Start of header marker.* This marker indicates the start of a fragment header.
- *Format version number.* This element gives the format version of the fragment. For example it is a sub-detector fragment.
- *Source identifier.* This element identifies the origin of the fragment. It consists of a sub- detector ID, Module Type and Module ID.

- *Run Number.* It is the LHC Run Number.
- *Extended Level 1 ID.* The extended L1ID formed by the 24-bit L1ID generated in the TTCrx and the 8-bit ECRID implemented in the ROD
- *Bunch Crossing ID.* The 12-bit bunch crossing identifier generated in the TTCrx.
- *Level 1 Trigger Type.* The 8-bit word generated by the Central Trigger Processor and transmitted by the TTC system
- *Detector event type.* This element allows additional information to be supplied on the type of event, particularly in the case of calibration events.
- *ROD Event.* This is firmware dependent.
- *Number of status elements.* The value of this element is the number of status elements in the Header.
- *Number of data elements.* This element reports the number of elements in the ROD Event.
- *Status block position.* This element defines the relative order of the Data and Status elements.

Table 3.8 The ROD data format for ROS.

Start of header marker	0xee1234ee
Header size	0x00000009
Format version number	0xMMMMmmmm M(Major VerNum) m(Minor VerNum)
Source identifier	0x00DDMMMM D(SubDetectorID) M(ModuledID)
Run Number	0xRRSSSSSS R(Run Type) S(Sequence In Run)
Extended Level 1 ID	0xEELLLLLL E(ECR ID) L1 (L1 ID)
Bunch crossing ID	0x00000BBB B(BCID)
ATLAS Level 1 trigger type	0x000000AA A(AtlasEventType)
Detector event type	0x000R000T R(ROD Event Type) T(Tim Event Type)
ROD Event	Header, Hits, Trailer
Err flags 0	0xSSSSGGGG S(Specific Error Flags) G(Generic Error Flags)
Err flags 1	0xUUUUCCCC U(Uncoded Error Flags) C(Err Flags Count)
Number of status elements	0x00000002
Number of data elements	0x0000NNNN
Status block position	0x00000001

An example of ROD violation protocol taken with Chipscope is shown in Fig. 3.32.

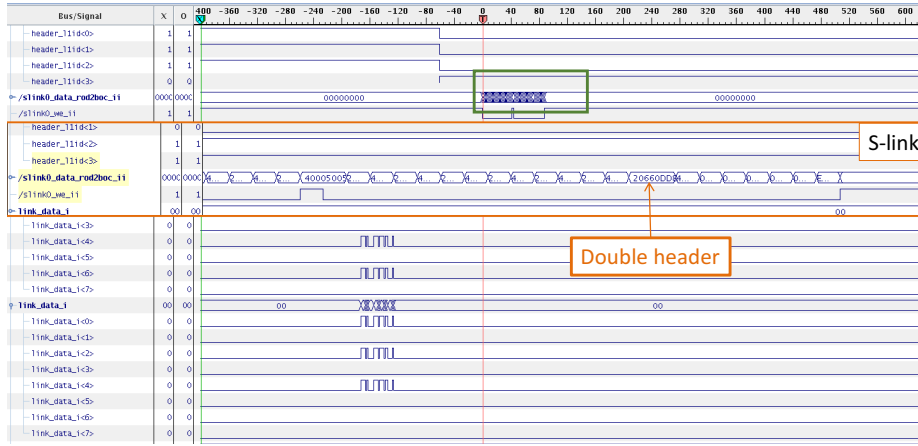


Fig. 3.32 An example of ROD violation protocol.

In Fig. 3.33 an example of two problematic firmwares showing a high rate of Not-Deleted fragments, that increasing linearly with the trigger rate on the ROS is reported.

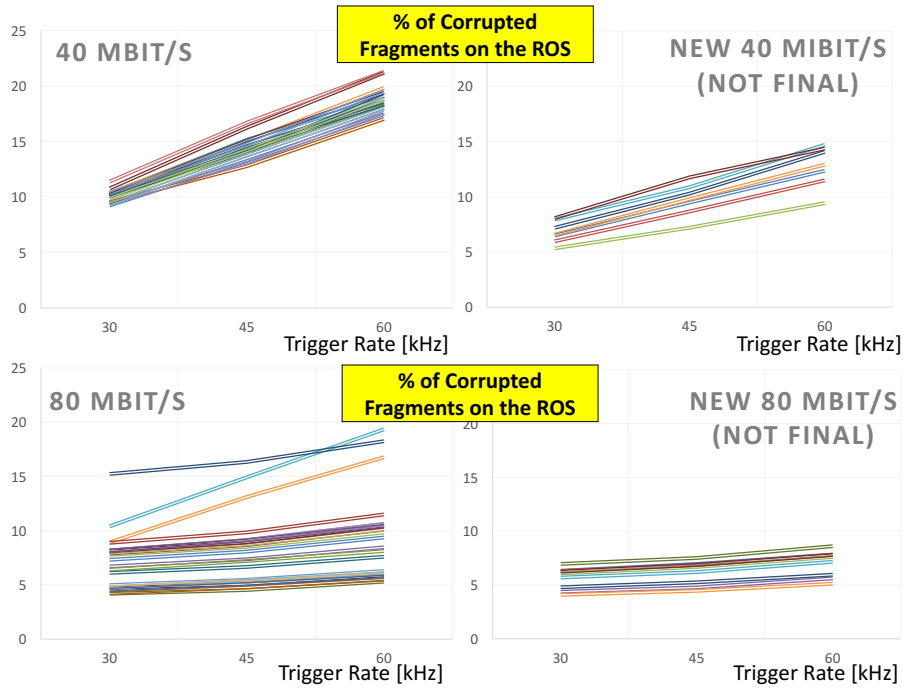


Fig. 3.33 An example of two problematic firmware versions. On the left it is shown one of the first version running at 40 (top) and 80 (bottom) Mbit/s. On the right an intermediate firmware version running at 40 (top) and 80 (bottom) Mbit/s. The fraction of NotDeleted fragments of the ROS links grows with different slopes when increasing the trigger rate at different readout speeds. This problem was due to a bug in the firmware. In the final version used for ATLAS data-taking the fraction of bad fragments was close to 0.

If the firmware passes these checks, the further step is its deployment to a minimal sub-sample (1-2) of Pixel Detector IBL-RODs in which tests are performed again up to a trigger rate of 90 kHz. If the validation is fine, the final qualification of sub-sample is LHC pp collisions before deploying the firmware to the full pixel system. In the final version used for ATLAS data-taking the fraction of bad fragments was lower than 10^{-6} .

A 4-layers Pixel detector: Charge collection, Cluster properties and Track Pixel dE/dx

The ATLAS Pixel Detector is able to measure the charge deposited by each particle crossing it. It is used to detect massive, highly ionizing particles and to reconstruct their mass based on a parametrization of the most probable value of the specific rate of energy loss. In the following sections, the new track dE/dx algorithm developed after the IBL insertion and used in 2015 and 2016 analyses and the calibration of the mass parametrization function will be detailed. The new algorithm takes advantage of the new pixel layer, but is equivalent to the LHC Run-1 algorithm if the IBL layer is not considered. This chapter describes the algorithm and the studies performed on dE/dx after the IBL insertion. The main reference is [70] where the ATLAS pixel algorithm before IBL insertion and its use for particle identification is well detailed. This information can be used to identify non relativistic particles like long-lived particles (LLPs) are. The Pixel dE/dx is the key signal discriminant in the analysis described in Chapter 5 and in [16].

4.1 Charge Measurement in Pixels

As described in Chapter 3, in 2014 the Pixel Detector has been upgraded to a 4-layer detector with the addition of the IBL detector. When a minimum ionizing particle (MIP) crosses a silicon pixel sensor approximately 80 electron-hole pairs per micrometer of thickness are generated. In Chapter 2 we discussed that the electric signal from the current induced by the traversing particle is first shaped by a preamplifier and then amplified and formed in a digital signal. The signal will spend a certain time over the digital threshold; it is stored as Time over Threshold (ToT, measured in bunch crossings (BC) units, $1\ BC = 25$

ns) with an accuracy of 4 bits in the new IBL readout electronics (FE-I4) and 8 bits in the old pixel layers (FE-I3). To calibrate the FEs a predefined charge can be injected.

According to the set threshold, the calibration of the FE-I3 is such that when a MIP crosses $250\ \mu\text{m}$ of the sensor thickness, the Landau peak is set at 18 BC for the B -layer and 30 BC for Layer 1 and 2. In IBL two types of sensors (planars and 3Ds) with different thickness ($200\ \mu\text{m}$ and $230\ \mu\text{m}$ respectively) are present, and they are both calibrated to give a ToT Landau peak of 8 BC. Furthermore in IBL electronics the ToT overflow information can be recorded, while in the rare case (since the maximum the ToT DAC scale corresponds to a released ~ 8 times MIP) when this happens in FE-I3 the hit is lost and this could help to discriminate between very large or MIP energy releases. In Fig. 4.4 the ToT average versus the injected charge for each pixel of a module with a FE-I4 read-out chip is shown.

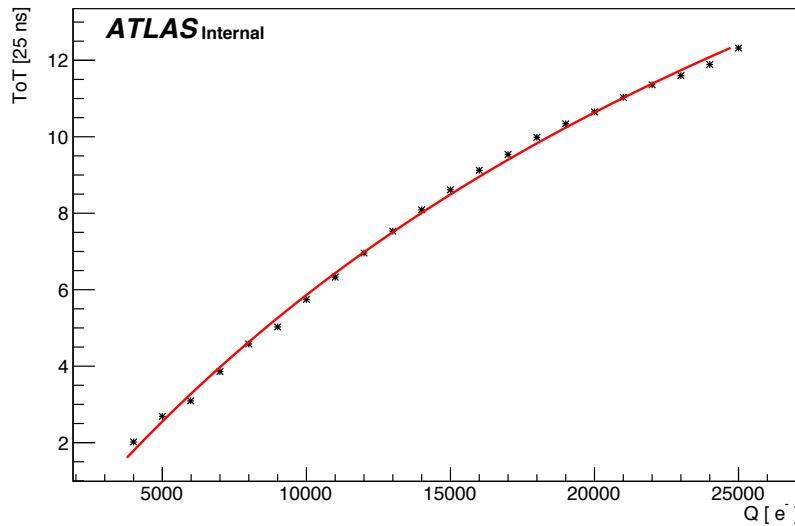


Fig. 4.1 Time over threshold (TOT) mean values vs injected charge for a FE-I4 module

The relationship between charge and ToT is parametrized by eq. 4.1:

$$ToT = a_0 \times \frac{(a_1 + Q)}{(a_2 + Q)} \quad (4.1)$$

where a_0 , a_1 , and a_2 are the parameters of the fit, Q is the deposited charged, and ToT is the average ToT over all the pixels in a front-end. In the ATLAS Pixel Detector this relationship is measured in dedicated calibration scans. The Pixel Detector has a dispersion between pixels between 3% and 5%¹.

¹Depending from the tuning quality.

When a charged particle traverses a pixels sensor, usually the charge is deposited in more than one pixel. This is due to the incident angle of the particle, to the diffusion of electrons and holes in the sensor and to drift of the charge generated by the particle track owing to magnetic field. Different scenarios of charged particles traversing a silicon sensor with incident angle ϕ are shown in Fig. 4.2.

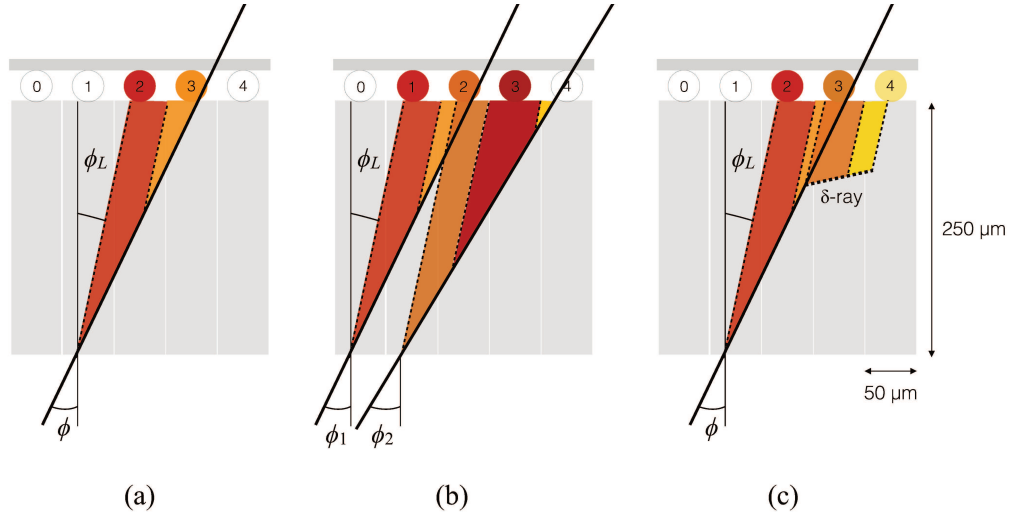


Fig. 4.2 Different scenarios of charged particles traversing a silicon sensor [14]: (a) a single charged particle traversing the silicon sensor producing a cluster with a width of two pixels. (b) a merged cluster produced by two close-by particles that both deposit charge in the second pixel. The fourth pixel is not read-out as the charge is below the read-out threshold. (c) a large cluster created from a single charged particle due to a δ -ray produced in the silicon.

If two pixels have in common one corner are considered neighbouring, so a single pixel can be surrounded by, at most, eight cells. A group of connected pixels is defined *cluster*. The information of all the pixels that composes the cluster is used to estimate the position using a linear approximation. The cluster measurements are refined during the fitting of the tracks by using the incident angle and predicted position of incidence on the pixel module of the track associated with the cluster. It also considered the not perfect planarity of the silicon modules for this reason a correction for module distortions is applied. An interpolation technique is used to estimate where the particle intersects the module, improving the purely geometrical limit determined by the pixel size. The geometrical coordinates of the cluster (x_c, y_c) are defined in the local reference of the sensor surface. The interpolation is performed using the charge measurements in the first

and last rows and columns of the cluster as equations 4.2 and 4.3 show:

$$x_{cluster} = x_c + \Delta_x(\phi, N_{row}) \cdot [\Omega_x - \frac{1}{2}] \quad (4.2)$$

$$y_{cluster} = y_c + \Delta_y(\theta, N_{col}) \cdot [\Omega_y - \frac{1}{2}] \quad (4.3)$$

where $\Omega_{x(y)}$ is defined as:

$$\Omega_{x(y)} = \frac{q_{Last row(col)}}{q_{First row(col)} + q_{Last row(col)}} \quad (4.4)$$

and q is the charge collected in a given pixel. The parameters of $\Delta_{x(y)}$ are extracted from MonteCarlo or data and where ϕ, θ represent the projected incident angles with respect to the sensor surface and $N_{row(col)}$ the number of pixels within the clusters in the $x(y)$ direction. In dense environments different particles crossing the pixel could be merged together if the spatial separation between the particles on the sensor plane approaches the pixel size. To avoid this problem neural network algorithm has been developed to determine a more precise position and improve the two-particle separation. If the p_T of the primary charged particle is greater than 400 MeV, the cluster size can variate from 1.4 to 3 pixels in the transverse direction and between 1 and ~ 3.5 pixels in the longitudinal one [14]. The cluster ToT and in particular the cluster charge is the base for the Pixel dE/dx Calculation Algorithm (Sec. 4.2.1). Another possible approach to determine the cluster position is to use artificial neural networks (NN). The NN is a powerful tool for solving complex pattern recognition problems characterised by significant non-linearities. Thanks to the increased CPU power for event reconstruction a novel approach for clustering can be also used. In ATLAS from 2014 a single NN is used to estimate the probability that a cluster was created by one or many particles and to split the cluster when possible. Two sets of NNs are instead used to estimate cluster positions and uncertainties. This new approach allows to improve the cluster position estimation and hence the resolution of the track parameters. A detailed description can be found in [14].

4.2 The Pixel Track dE/dx

A cluster produced, for a given track, in a layer of the ATLAS Pixel Detector gives an energy loss measurement. The specific cluster energy loss dE/dx [70] (expressed in units: MeV $g^{-1}cm^2$) is derived from the cluster charge taking into account the average energy needed

to create an electron-hole pair, $W = 3.68 \pm 0.02$ eV/pair, the path in silicon $x = d / \cos \alpha^2$ (where d is the sensor thickness: 200, 230, 250 μm for IBL planars, 3Ds and Pixel planars respectively) and the silicon density ρ :

$$\frac{\Delta E}{\Delta x} = \frac{Q}{e} \frac{W \cos \alpha}{\rho d} \quad (4.5)$$

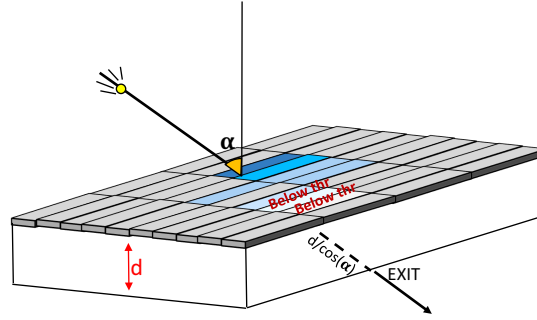


Fig. 4.3 In the cartoon a particle that is crossing more pixels generating the specific cluster energy loss is shown.

The ionization energy loss has a typical Landau distribution. IBL is tuned so that 1 ToT unit corresponds to 2 ke^- , for this reason the MPV of charge deposition of a MIP is expected to be at 16 ke^- ³. The rest of the Pixel Detector is tuned so that 1 ToT unit corresponds to $\sim 1.1 \text{ ke}^-$ for B-layer and $\sim 670 \text{ e}^-$ for Layer 1 and 2 respectively. The MPV of charge deposition for a MIP is expected at 20 ke^- . In reality the passage of a MIP is usually distributed among several neighboring pixels. If the threshold is too high, some of these hits will be lost and the clusters can be split or mis-measured (also degrading the position resolution). For this reason, depending on the threshold set for the module, the Landau peak could be shifted, this is due to picking up pixels collecting charge which were previously cut by the threshold. The comparator threshold is set to 2.5 ke^- for IBL and 3.5 ke^- for the rest of Pixel Detector. In June 2016 B-layer threshold moved to 4 ke^- , as discussed in Sec. 4.2.2. For the reasons described, the Landau fit of the cluster charge distribution results in a MPV for IBL modules $\sim 14 \text{ ke}^-$ and $\sim 18 \text{ ke}^-$ for the rest of Pixel Detector as Fig. 4.4 shown.

The main purpose of a dE/dx estimator is to combine the individual cluster $\Delta E / \Delta x$ measurements (charge collected in the cluster, corrected for the track length) distributed

² α is the spatial incident angle calculated versus the normal to module surfaces. It is defined as $\arctan \sqrt{\tan^2(\phi_{loc}) + \tan^2(\theta_{loc})}$ where ϕ_{loc} and θ_{loc} are the local incident angles.

³ 3D sensors are $30 \mu\text{m}$ thicker than planar ones. Due to the different operation point, a shift and a larger spread for both threshold and ToT scale is expected.

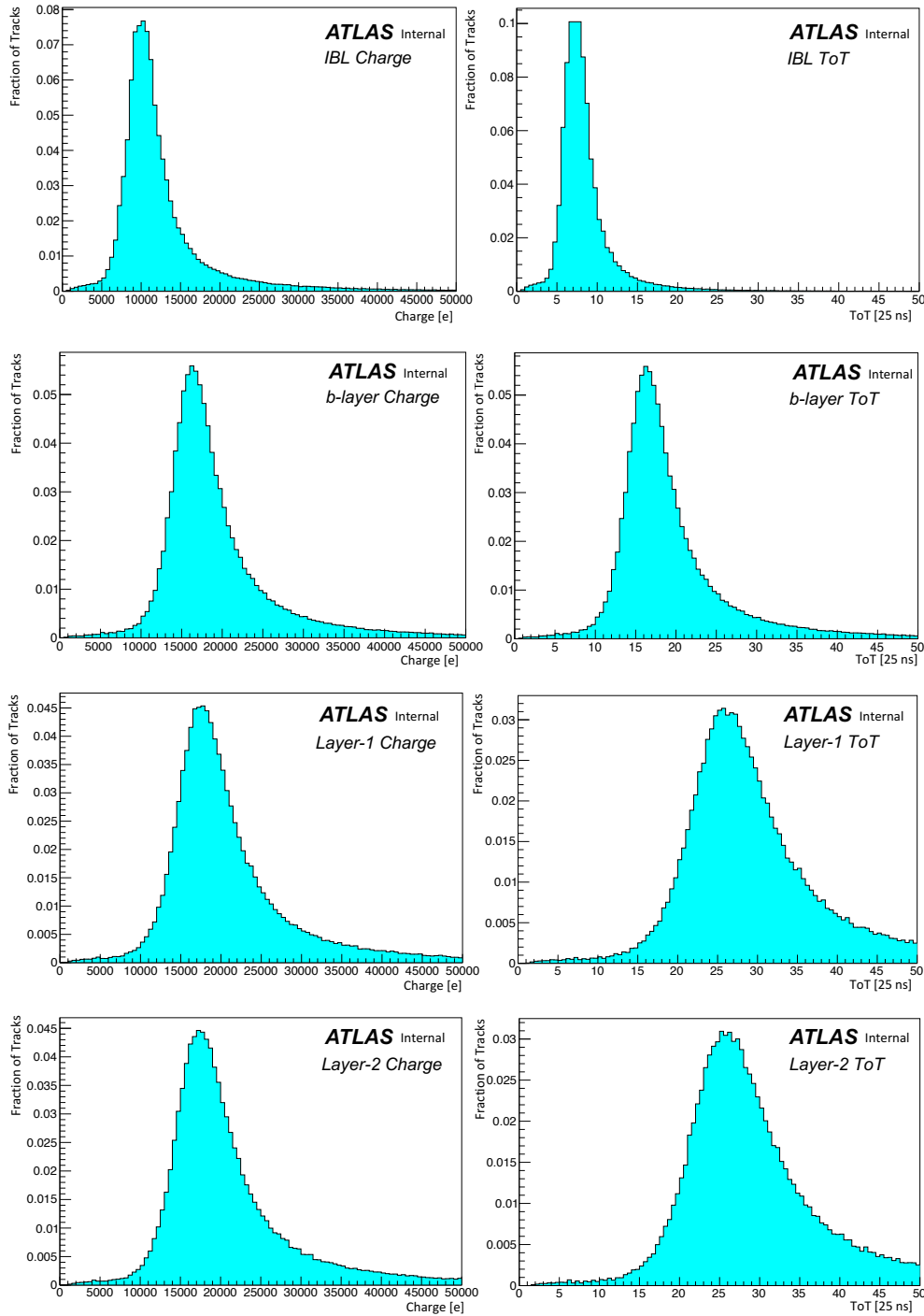


Fig. 4.4 The cluster ToT and Charge in IBL and in the three layers of the "old" pixel detector for pp collisions in 2016 is reported. IBL is tuned to have the MIP peak of 16 ke^- at 8 BC, instead the b-Layer and Layer-1(2) are tuned at 20 ke^- with a ToT peak at 18 and 30 respectively.

along the particle trajectory into a unique value, that is basically an estimator of the energy loss of the track. There are several methods for the estimation of the differential energy loss of a charged particle. As seen in Chapter 2, Landau distribution has a long tail at high energy losses due to resonance and Coulomb excitations. Estimators have to reduce the influence on of high energy deposits in the tail of the energy deposit. After reducing the Landau tails, it is possible to fit the charge distribution with a Gaussian.

The resolution of the Gaussian is given by:

$$Resolution = \frac{Sigma}{Mean} \quad (4.6)$$

Different estimators as the *geometric mean*, the *harmonic mean* or the *truncated mean* can be used. The *geometric mean*, $\overline{x_g}$ of a sample with n values is given by the expression:

$$\overline{x_g} = \sqrt[n]{\prod_{i=1}^n x_i} \quad (4.7)$$

The geometric mean reduces the bias to large values, this means that the saturated hits have less effect.

The *harmonic mean* $\overline{x_h}$ of n samples is instead given by:

$$\overline{x_h} = \frac{n}{\sum_{i=1}^n 1/x_i} \quad (4.8)$$

As described for the geometric mean, the harmonic one gives less bias to high value and a low average value for the dE/dx . Its distribution shape is similar to the geometric mean. The *truncated mean* is currently used for ATLAS Pixel dE/dx computation⁴ since it is a robust and simple estimator that is traditionally used in gas filled detector chambers [71]. This method reduces the influence of high energy deposits in the Landau tail discarding the highest 30% of the cluster measurements on the track and averaging with equal weights the remaining measurements. The algorithm will be described with more accuracy in Sec. 4.2.1. In Fig. 4.5 the comparison between the three different mean algorithms is shown. Here is possible to observe that the *truncated mean* distribution is more gaussian than the others, reducing more low ionization tail. The resolution has been evaluated with a Gaussian fit for the three mean. The truncated improves the resolution value of $\sim 5\%$ with respect to the harmonic and the geometric mean as shown in Tab. 4.1.

⁴The algorithm will be illustred in Sec. 4.2.1.

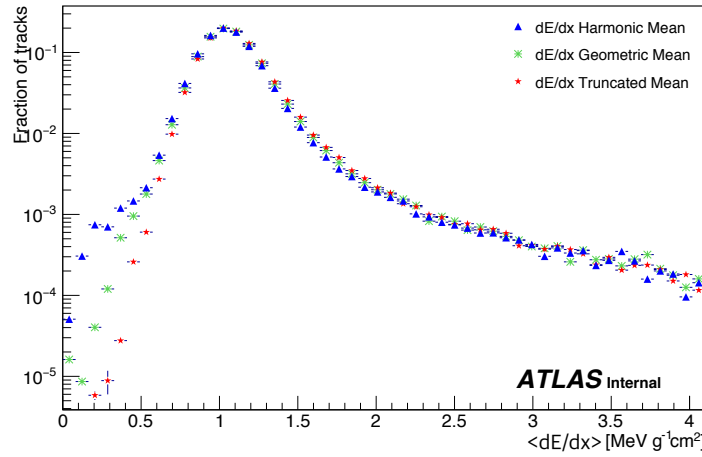


Fig. 4.5 A comparison between harmonic, geometric and truncated mean is reported for pp collision data at $\sqrt{s} = 13$ TeV.

Table 4.1 Comparison between Geometric, Harmonic and Truncated Mean $\langle dE/dx \rangle$. The Truncated mean has a better resolution, and lower fraction of tracks at low ($dE/dx < 0.5$ MeV g⁻¹cm²) and high ionization ($dE/dx > 2$ MeV g⁻¹cm²) tails than the other means.

Mean	$MPV_{dE/dx}$ [MeV g ⁻¹ cm ²]	σ [MeV g ⁻¹ cm ²]	Resolution [%]	$dE/dx < 0.5$ [%]	$dE/dx > 2$ [%]
Geometric	1.001	0.134	13.4	0.4	1.9
Harmonic	0.996	0.133	13.3	0.7	1.8
Truncated	1.010	0.128	12.6	0.1	1.6

4.2.1 The ATLAS Pixel dE/dx Calculation Algorithm

In 2014 the Pixel Detector has been upgraded to a 4-layer detector with the addition of the Insertable B-Layer (IBL). As already discussed IBL uses different sensors and readout electronics than the old 3-layer detector, and thus an extension of the existing calculation of the pixel ionization was necessary. In previous subsection, it was discussed that the track dE/dx is defined as an average of the individual cluster dE/dx measurements, in this section the algorithm operation is better detailed. In the Pixel Detector the modules can have, by construction, different orientations into the magnetic field and it is also necessary to take into account the Lorentz angle [72] effect⁵. For the calculation are used only the well defined clusters associated to the track. This means that the clusters are

⁵Trackers work in presence of a magnetic field, that influences electrons and holes drift in silicon, making them move at an angle with respect to electric field direction: called Lorentz Angle (Θ_l). Θ_l impacts mainly on pixel cluster size and spatial resolution shifting the cluster coordinate in the direction perpendicular to electric and magnetic field.

constrained not to be at the edge of the module or in the ganged region. The cuts are different if clusters are located in the IBL (3D and Planars modules), Pixel Barrel or in the EndCap, Tab. 4.2 reports the selection applied in the ATLAS Pixel dE/dx track algorithm. Shallow cluster with $\cos \alpha < 0.16$ are always discarded as relation 4.5 no longer holds.

Table 4.2 x_{loc} and y_{loc} are the local coordinates of the cluster barycentre with respect to the geometrical centre of the module. d_L denotes a shift to take into account the Lorentz angle and is set to 50/0 μm in the Barrel/EndCap

IBL 3D Modules	IBL Planar Modules	Pixel Barrel and EndCap
$x_{loc} \in [-8.33, 8.3]$	$x_{loc} \in [-8.33, 8.3]$	$0.55 < x_{loc} + d_L < 8.15 \text{ mm}$
$ y_{loc} < 10 \text{ mm}$	$ y_{loc} < 20 \text{ mm}$	$ y_{loc} < 30 \text{ mm}$

Fig. 4.6 shows the effect of the cluster selection cuts on the distribution of the cluster dE/dx .

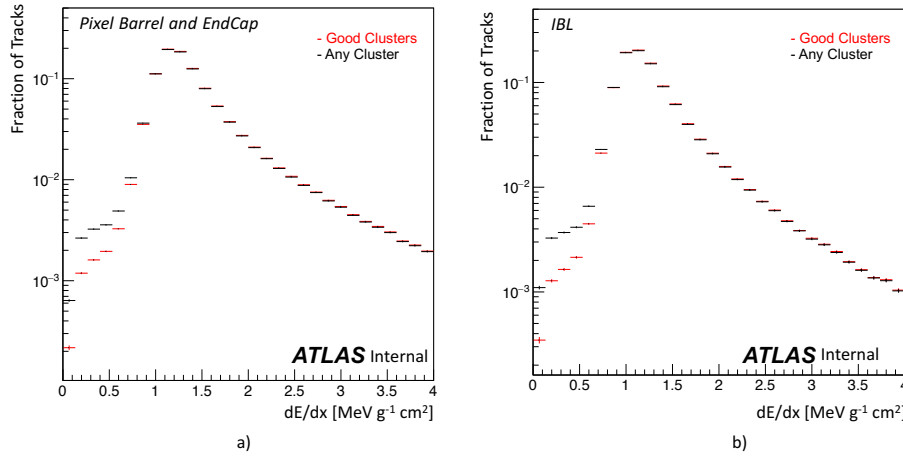


Fig. 4.6 The cluster dE/dx distribution in logarithmic scale is shown before and after having applied the Good Cluster cuts for Pixel Barrel and EndCap (a) and IBL (b).

To reduce the Landau tails, the average is evaluated after having removed the cluster(s) with the highest charge. To calculate the truncated mean the following computing rules have been adopted:

- One cluster is removed for tracks with 2,3,4 good clusters.
- Two clusters are removed for tracks with 5 or more good clusters.
- If one or more IBL clusters are in overflow, the charge value can not be evaluated properly and these clusters are not considered in the mean calculation (See Tab. 4.3).

The number of good cluster effectively used for the dE/dx calculation, once removed the clusters as explained, is referred to as *numberOfUsedHitsdEdx* (or *nUsedHitsdEdx*).

A track is considered to have a good ionization measurement only if *nUsedHitsdEdx* > 0.

Table 4.3 Removed Cluster(s) in the mean computing in presence of IBL Overflow dE/dx Clusters for some different good clusters values. The Pixel and IBL cluster(s), that are not in overflow, are labeled sorting them in descending order of dE/dx ($C_i > C_{i+1}$, where $i=0,1,\dots$). C_{IBL} is the dE/dx value associated to the overflow IBL cluster. To underline that the IBL overflow cluster is always removed by the truncated mean, while in the case of a number of good cluster = 3,4 the greatest cluster (C_0) is removed only if its value is greater than the C_{IBL} value.

Track dE/dx with IBL Overflow Case		
# Good Clusters	Removed Clusters	Truncated dE/dx
1	-	IBL Overflow Value
2	C_{IBL}	C_0
3,4	if $C_0 > C_{IBL} \rightarrow C_{IBL}$ and C_0 if $C_0 < C_{IBL} \rightarrow C_{IBL}$	Average of remaining Average of remaining
≥ 5	C_0 and C_{IBL}	Average of remaining

The comparison between track dE/dx based on three pixel layers algorithm used during LHC Run 1 and the new algorithm that uses also IBL is shown in Fig. 4.7.

In Fig. 4.8 the number of good pixel clusters associated to the selected tracks for the old and new dE/dx algorithm is also shown. As expected, the new algorithm has on average one good cluster more due to IBL.

In Tab. 4.4 the resolutions that are obtained for a given set of averaged clusters is reported, showing similar performance with the two algorithms. However the important thing to underline is that including the IBL charge information reduces the tails of the dE/dx distribution and increases the fraction of tracks for which the ionization measurement is valid from 77% to 91%.

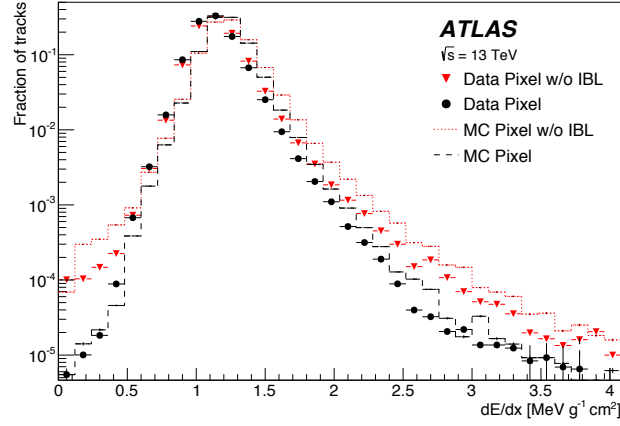


Fig. 4.7 Distribution of the dE/dx computed with the Pixel algorithm in data (black dots) and Pixel without IBL (red triangles) for minimum bias event tracks selected as in Ref. [15], with the additional requirements of a momentum $p > 3$ and at least two associated pixel clusters. The corresponding dE/dx distributions for simulation with and without the IBL are also plotted, respectively, as dashed and dotted lines. The simulation overestimates the dE/dx , which is taken into account in the systematic uncertainty evaluation. The addition of IBL clusters reduces the tails at both low and high dE/dx . The fraction of tracks with $dE/dx < 0.5$ (> 1.8) g $^{-1}$ cm 2 decreases with the use of the IBL charge information from 0.065% to 0.018% (from 0.89% to 0.44%) [16].

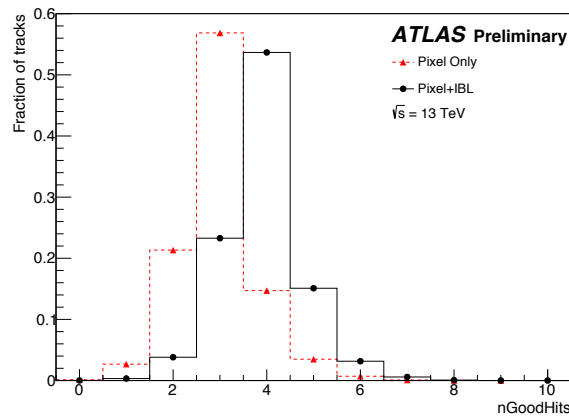


Fig. 4.8 Number of pixel good cluster associated to the selected tracks. The red distribution corresponds to the Pixel only algorithm, while the dots are the Pixel+IBL good clusters. As observed in the plot, the new algorithm has on average one good cluster more.

Table 4.4 Resolution of the truncated mean ($\text{MeV g}^{-1} \text{ cm}^2$) for the new and old algorithm. The resolution is computed as the RMS of a Gaussian fit to the distribution of the dE/dx for tracks with momentum larger than 3 GeV and have ≥ 6 SCT clusters.

nUsedHitsdEdx	New Definition			nGoodClusters	Old Definition		
	Mean	Resolution (%)	% Tracks		Mean	Resolution (%)	% Tracks
1	1.187 ± 0.002	15.9	8.72	1	1.253 ± 0.004	16.2	5.42
2	1.209 ± 0.001	13.3	19.35	2	1.169 ± 0.001	13.9	17.36
3	1.211 ± 0.001	11.6	60.45	3	1.202 ± 0.001	10.9	41.67
4	1.200 ± 0.002	9.9	8.81	4	1.230 ± 0.001	10.1	23.62
≥ 5	1.213 ± 0.002	9.5	2.67	≥ 5	1.256 ± 0.001	9.5	11.93

4.2.2 Stability of Track dE/dx during LHC Run 2

The Track dE/dx changes in time due to several factors described below. In 2015 the calibration of the IBL detector showed significantly more sensitivity to the low rates of radiation than it was expected. After tuning the ToT to 10 bunch crossings (BC) for an injected charge of 16 ke^- , it was observed that the measured target ToT of FE-I4 drifted downward as a function of integrated luminosity. In addition a 0.2 A rising up of the LV regulators current of the FE-I4 chip was observed (for a four-chip unit the nominal current is $\sim 1.6 - 1.7\text{ A}$). The FE-I4 tuning parameters drifting and the increasing of LV regulators current focused the attention to a generation of a leakage current in NMOS transistors. The radiation induces the creation of positive charges that are trapped in the oxide at the edge of the transistor, opening a source-drain channel where the leakage current flows [73]. In 2016 LHC run, to mitigate the problems described, the operation temperature was increased from $-10\text{ }^\circ\text{C}$ to $15\text{ }^\circ\text{C}$ and the digital supply voltage was lowered from 1.2 V to 1 V to decrease the LV current. In addition, the ToT working point for IBL has been moved from 10 for 16 ke^- to 8 ToT for 16 ke^- .

To cope with the high instantaneous luminosity the latency of the front-end electronics in the B-layer has been reduced from 255 to 150, this implies that hits with $\text{ToT} > 150$ are lost. To save the recording of hits with high charge, the ToT tuning has been changed so that the MIP peak corresponds to a ToT of 18 for 20 ke^- rather than the 2015 ToT of 30 for 20 ke^- . Moreover to mitigate also the high fraction of desynchronization of the B-layer modules, the threshold of the B-layer has been increased from 3500 to 5000 electrons during the first LHC technical stop (TS1) on July 2016.

A track dE/dx MPV drop has been observed, due to FE decalibration and possible trapping due to radiation damage in the sensors in all LHC periods of data-taking used in the analysis as Fig. 4.9 shows. The track dE/dx MPV has a drop maximum variation of $\sim 16\%$ (referred to the starting value in 2016 run). In this instance a variation of the percentage of tracks with IBL overflow up to $\sim 1.2\%$ is also observed.

Fig. 4.10 shows the trend of the cluster MPV dE/dx associated to a track. Here is possible to observe that $\sim 8\%$ drop of the MPV track dE/dx between the starting of 2016 data-taking and the change of B-layer threshold during TS1 looks associate to B-layer inefficiencies. The B-layer drop is currently under investigation with pixel online and offline groups. To reduce the effect, a scale factor has been applied to the track dE/dx measurement. The scale factor has been computed from the ratio of the track MPV dE/dx in each run to the value of a reference run in which the Bethe-Bloch calibration (Sec. 4.2.2.2) is performed.

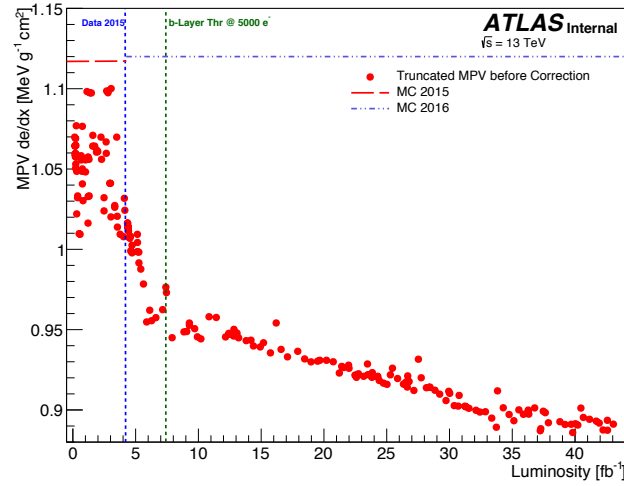


Fig. 4.9 The track dE/dx MPV over luminosity is reported for all the data-taking runs used in the analysis of 2015 and 2016. In dark green dashed line is reported the B-layer new threshold set at 5000 electrons. The points at the left of the dashed blue line represents the datasets used in 2015 analysis where a variation of the dE/dx MPV due to the ToT drift of the IBL electronics was present. The other points show a drop of dE/dx MPV over luminosity for 2016 data. The MPV of simulation for 2015 and 2016 are reported with red dashed and blue dash-dot lines respectively.

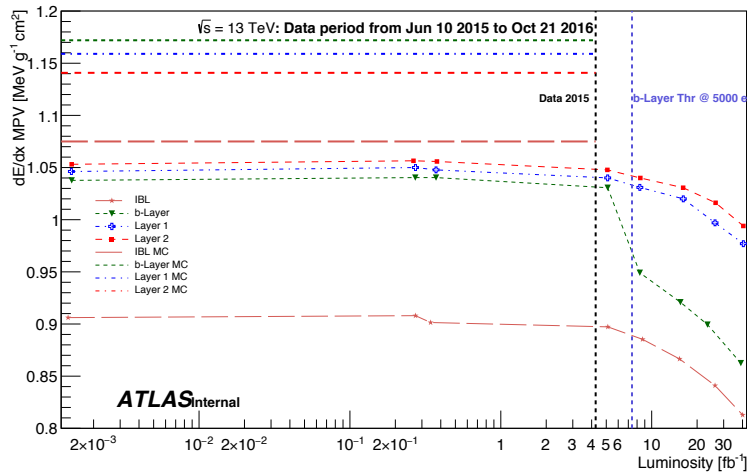


Fig. 4.10 The plot shows the dE/dx MPV over luminosity for the clusters associated to a track for the different pixel layers. The dashed lines without points represent the dE/dx MPV for 2015 simulation. A strong drop of B-layer dE/dx MPV between the start of 2016 data-taking and its threshold change, in accordance to Fig. 4.9 are shown. A drop is also visible for the other layers, this is currently under investigation by the pixel online and offline groups.

4.2.2.1 dE/dx path correction and η dependence

In Eq. 4.5 the assumption that the charge released in the active region of the sensor had only a linear dependence by the path length was done. In reality the energy loss produced by a charged particles depends both on the thickness of the traversed material t and the velocity of the particle expressed by the relativistic factor β :

$$\beta = \sqrt{\frac{p^2}{p^2 + m^2}} \quad (4.9)$$

where p and m are respectively the particle momentum and mass.

We can express with good approximation, the MPV energy loss (Δ_p) as [71]:

$$\Delta_p = \xi \left[\ln\left(\frac{2mc^2\beta^2\gamma^2\xi}{I^2}\right) - \beta^2 \right] \quad (4.10)$$

where:

$$\xi = \frac{K}{2} z^2 \frac{Z}{A} \rho \frac{t}{\beta^2} \quad (4.11)$$

$K = 4\pi N A r_e^2 m_e c^2 = 0.3070 \text{ MeVcm}^2/\text{mol}$, z is the charge of the particle in electron charge units; Z , A and ρ are the mass number, atomic number and the density of the material, respectively [71]. If we consider the distribution of energy loss $dE/dx_{(MPV)} = \Delta_p/t$ its width ($\Gamma(dE/dx_{(MPV)}) = 4.018\xi/t = 4.018\frac{K}{2}z^2\frac{Z}{A}\rho\frac{1}{\beta^2}$) is independent of t , while the most probable value scales with t as:

$$dE/dx_{(MPV)}(t) = dE/dx_{(MPV)}(d) + \frac{K}{2} z^2 \frac{Z}{A} \frac{\rho}{\beta^2} \ln\left(\frac{t}{d}\right) \quad (4.12)$$

where d is the reference sensor thickness as described in Sec. 4.2, since $t = d/\cos\alpha$, Eq. 4.12 can be rewritten as:

$$dE/dx_{(MPV)}(t) = dE/dx_{(MPV)}(d) - \frac{K}{2} z^2 \frac{Z}{A} \frac{\rho}{\beta^2} \ln(\cos\alpha) \quad (4.13)$$

In Sec. 4.2 we have seen ATLAS Pixel dE/dx algorithm uses definition in Eq. 4.5 to estimate the energy loss of the particle using the charge of the cluster associated to the track. It does not take into account the logarithmic correction and therefore analysing ATLAS data and simulation a dependence of the Pixel track dE/dx by pseudorapidity of $\sim 10\%$ (for both) has been observed. The variation is shown in Fig. 4.11 for the data case.

Eq. 4.14 can be used to compute the cluster dE/dx as:

$$\frac{\Delta E}{\Delta x} = \frac{Q}{e} \frac{W \cos\alpha}{\rho d} + \frac{K}{2} z^2 \frac{Z}{A} \frac{\rho}{\beta^2} \ln(\cos\alpha) \quad (4.14)$$

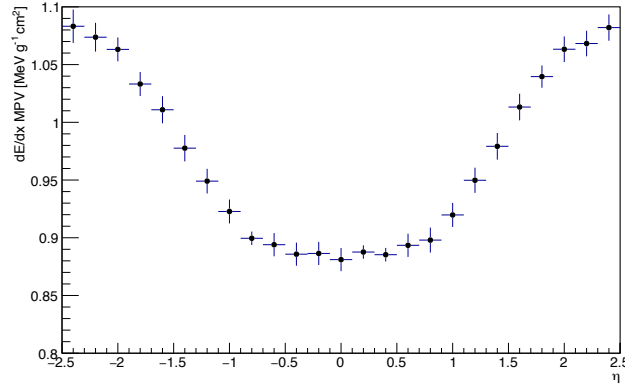


Fig. 4.11 Variation in the truncated track dE/dx due to geometrical effects.

The β term can be considered ~ 1 in case that the particle passing through the silicon sensor are MIPs ($p \gg m$), as the most part of LHC particles are. Using 4.14 in the algorithm the effect shown in Fig. 4.11 is strongly reduced, as it is reported in Fig. 4.12. In Fig. 4.13 the effect of the logarithmic correction is shown for dE/dx clusters in the different ATLAS Pixel Detector layers.

Finally in Fig. 4.14 the track *Truncated* dE/dx before and after the cluster path correction described in Eq. 4.14 is shown. The shift of MPV is expected, as also shown in Fig. 2.2.

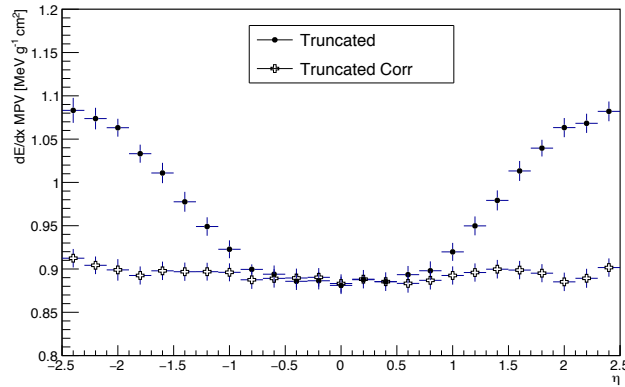


Fig. 4.12 Variation of the truncated track dE/dx due to geometrical effects (*Truncated*). Using the logarithmic term in the cluster dE/dx computation the effect is strongly reduced (*Truncated Corr*).

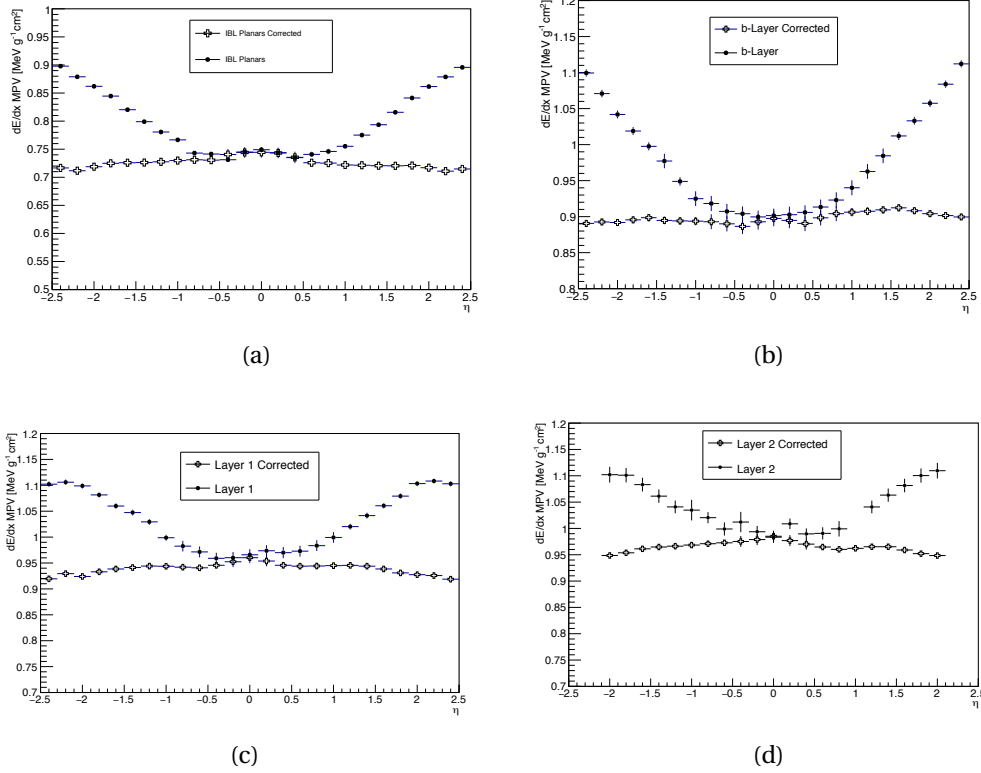


Fig. 4.13 Variation of the cluster dE/dx in the different ATLAS Pixel Detector layers due to geometrical effects (*Truncated*). Using the logarithmic term in the cluster dE/dx computation the effect is strongly reduced (*Truncated Corr*).

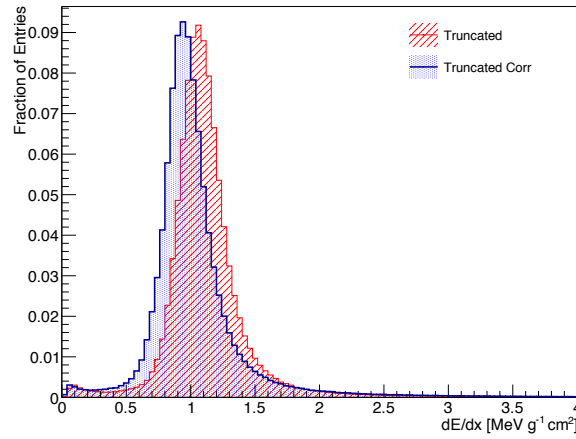


Fig. 4.14 Truncated track dE/dx (*Truncated*) in comparison with the truncated after the cluster path correction described in Eq. 4.14 (*Truncated Corr*). The distribution width is independent of the path correction, instead the most probable value scales with path length as shown in Fig. 2.2.

4.2.2.2 Bethe-Bloch Fit

In a tracker, thanks to the magnetic field the particle momentum p can be measured evaluating the curvature of the track produced. Correlating this information with a measurement of ionization, it is possible to determine the particle mass m , thus identifying the particle. The identification process consists in parametrizing the expected behaviour of the specific energy loss as a function of the particle $\beta\gamma = p/m$. An empirical 5-parameters (Eq. 4.15) function describes how the Most Probable Value of the specific energy loss ($\text{MPV}_{dE/dx}$) depends on $\beta\gamma$. It has been defined considering a functional form which adequately follows the simulated data.

$$\text{MPV}_{\frac{dE}{dx}}(\beta\gamma) = \frac{p_1}{(f(\beta\gamma))^{p_3}} \ln(1 + (p_2\beta\gamma)^{p_5}) - p_4 \quad (4.15)$$

$$f(\beta\gamma) = \frac{(\beta\gamma)^2}{1 + (\beta\gamma)^2} \quad (4.16)$$

where $\beta = v/c$, $\gamma^2 = 1/(1 - \beta^2)$ and p_i are free parameters.

A Crystal Ball function⁶ with three free parameters is used to model the MPV dE/dx at fixed $\beta\gamma$. For the fit of Eq. 4.15 a large data sample with tracks with a reconstructed momentum down to 0.2 GeV has been used. The values of the 8 fit free parameters (p_i, σ, α, n)⁷ are obtained under the hypothesis that the sample used in the momentum range $p \in [0.2, 1]$ GeV contains mainly three different charged particle species: pions, kaons and protons (π , K and p). To perform the fit the sample is first divided in 16

⁶ The Crystal Ball function [74], named after the Crystal Ball Collaboration is a probability density function commonly used to model various lossy processes in high-energy physics. It consists of a Gaussian core portion and a power-law low-end tail, above a certain threshold.

$$f(x, x_0; \sigma, \alpha, n) = \frac{1}{N(\alpha, n)} \begin{cases} e^{-\frac{1}{2}(\frac{x-x_0}{\sigma})^2}, & \text{if } x < x_0 + \alpha\sigma \\ A(\alpha, n)(B(\alpha, n) + \frac{x-x_0}{\sigma})^{-n}, & \text{if } x \geq x_0 + \alpha\sigma \end{cases}$$

(4.17)

where:

$$A(\alpha, n) = \left(\frac{n}{\alpha}\right)^n e^{-\frac{1}{2}\alpha^2} \quad (4.18)$$

$$B(\alpha, n) = \frac{n}{\alpha} - \alpha \quad (4.19)$$

$$N(\alpha, n) \text{ is a normalization factor} \quad (4.20)$$

α, σ, n, x_0 are parameters which are fitted with the data.

⁷cf. footnote 6 for their definition.

(logarithmic) momentum slices (Fig. 4.15), then the observed dE/dx distribution is fitted in each momentum interval using the sum of three Crystal Ball functions for π , K and protons. The MPV of the peaks are required to follow eq. 4.15 function.

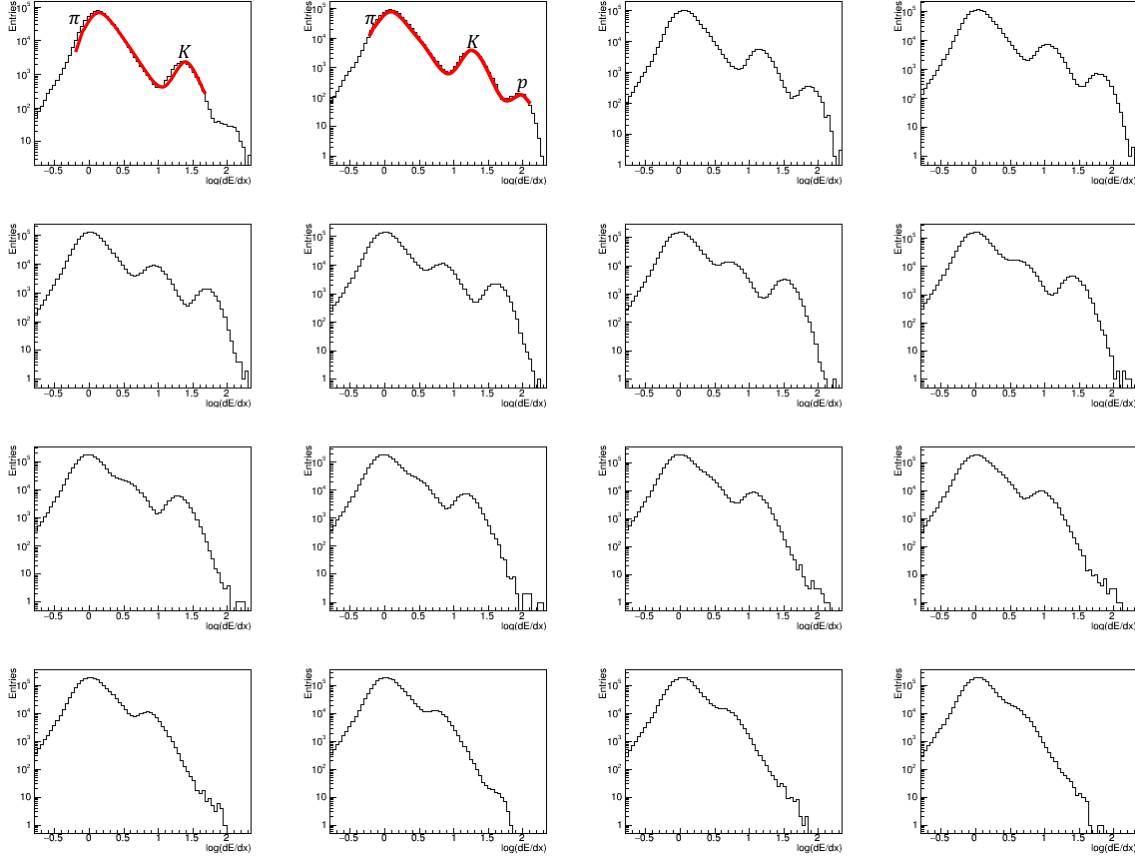


Fig. 4.15 dE/dx distribution in 16 slices of momentum $p \in [0.2, 1]$ GeV in which the three peaks of pions, kaons and protons (π , K and p) are clearly visible for positive charged particles. In red is reported an example of the fit performed with the Crystal Ball function.

As the usual ATLAS track reconstruction is done with tracks with $p \geq 400$ MeV, a special sample to perform the fit lower reconstructed momenta tracks were necessary. The best option available was the special LHC and ATLAS minimum bias run at low $\langle \mu \rangle$ done in June 2015. Here L1 decision is taken by the minimum bias trigger scintillators (MBTS) mounted at a pseudorapidity (η) region of $2.07 < |\eta| < 2.76$ and $2.76 < |\eta| < 3.86$. This trigger selects random events by requiring at least one reconstructed track with $p_T > 200$ MeV [75].

The fit, independently for data and simulation, is done without any a priori knowledge of the particle ID for 6 cases:

- numberOfUsedHitsdEdx equal to 2, 3 and greater than 3

- Positively and negatively charged tracks

In Fig. 4.16 the most probable value for the fitted probability density functions of pions, kaons and protons, with two hits used for dE/dx , are superimposed to the corresponding Minimum Bias distribution of the dE/dx with respect to the signed momentum.

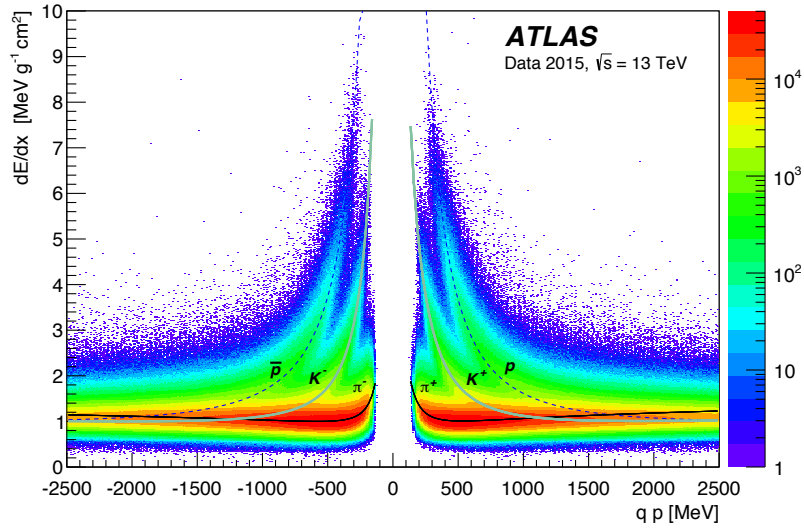


Fig. 4.16 Two-dimensional distribution of dE/dx versus charge signed momentum (qp) for minimum-bias event tracks compatible with a primary vertex, which has the same data selection as in Ref. [15]. The distributions of the most probable value for the fitted probability density functions of pions, kaons and protons are superimposed [16].

Fig. 4.17 shows the agreement between the 5-parameter function and the $MPV_{dE/dx}$ for pion, kaon, proton in ATLAS minimum bias 2015 data.

In Tab. 4.5 the fitted peak mass for kaons and protons, obtained on 10^8 pp collision and simulations with minimum bias trigger requirements (so-called MinBias Events) for all 6 independent categories is reported. The fitted peak masses agree with the nominal K and proton masses respectively within a ~ 10 MeV. Finally, the kaon and proton mass are shown for data in Fig. 4.18, as a function of *numberOfUsedHitsEdx* categories.

A slight trend can be observed; we consider it negligible with respect to the intrinsic resolution of the high mass range.

A cross-check of the calibration has been done evaluating the Deuteron peak mass (Fig. 4.19) in simulation (a) and data (b) for the particles with unsigned impact parameter $|d_0|$ ranging between 10 and 100 mm (and therefore likely to come from secondary hadronic interactions), here the agreement with the nominal value (1876 MeV) is within ~ 20 MeV.

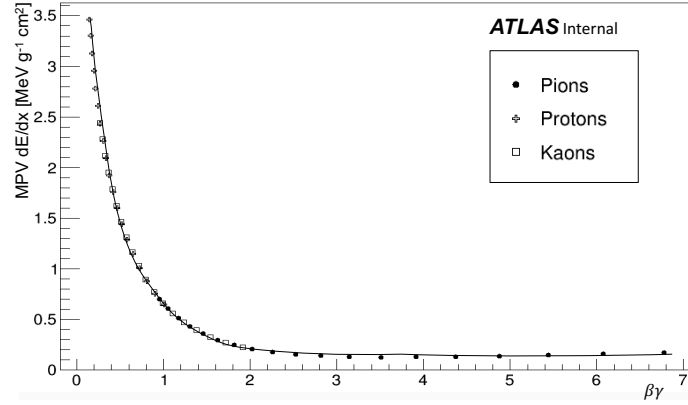


Fig. 4.17 Distribution of the Most Probable Value of the dE/dx distribution for pions, kaons and protons fitted with function 4.15 for 2015 ATLAS minimum bias data.

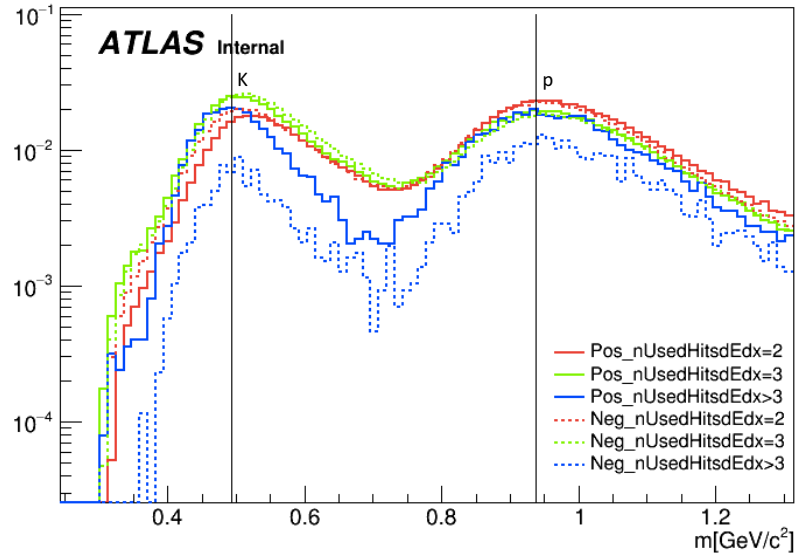


Fig. 4.18 Distribution of the the mass estimate m obtained from 2015 Minimum Bias data having a measured specific energy loss $dE/dx > 1.9 \text{ MeV g}^{-1} \text{ cm}^2$. The solid lines: shows positive tracks instead dashed lines the negative ones. $numberOfUsedHitsdEdx = 2$ (red), $= 3$ (green), >3 (blue).

The performed empirical 5-parameters (Eq. 4.15) function calibration gives satisfy results in terms of mass determination for SM particles. The obtained calibration parameters have been used for ATLAS analysis such as the search described in Chapter 5 for long-lived particles (LLPs).

Table 4.5 Fitted peak mass m_i (where $i = K, p$) for the K and proton peaks, obtained on a 10^8 minimum bias simulation and data events . The quoted error on m_i is the one obtained from the fit and does not include any systematic contribution. For each fit category ($q = \pm e$, $nUsedHitsdEdx = 2, 3, 4+$) the residual Δm_i ($i = K, p$) of the fitted peak mass w.r.t. the nominal one is also shown.

MC					
nUsedHitsdEdx	q	m_K [GeV]	Δm_K [GeV]	m_p [GeV]	Δm_p [GeV]
2	+	0.493 ± 0.001	-0.001	0.936 ± 0.001	-0.003
3	+	0.494 ± 0.003	0.001	0.935 ± 0.001	-0.006
≥ 4	+	0.490 ± 0.002	-0.004	0.929 ± 0.003	-0.01
2	-	0.494 ± 0.002	-0.001	0.935 ± 0.001	-0.004
3	-	0.500 ± 0.001	0.006	0.941 ± 0.002	0.003
≥ 4	-	0.486 ± 0.002	-0.007	0.940 ± 0.002	0.002
Data					
nUsedHitsdEdx	q	m_K [GeV]	Δm_K [GeV]	m_p [GeV]	Δm_p [GeV]
2	+	0.511 ± 0.002	0.02	0.942 ± 0.002	0.00
3	+	0.496 ± 0.003	0.001	0.941 ± 0.003	0.003
≥ 4	+	0.486 ± 0.007	-0.004	0.943 ± 0.002	0.005
2	-	0.503 ± 0.002	-0.01	0.942 ± 0.004	0.004
3	-	0.503 ± 0.003	0.01	0.946 ± 0.003	0.008
≥ 4	-	0.489 ± 0.001	-0.004	0.947 ± 0.002	0.009

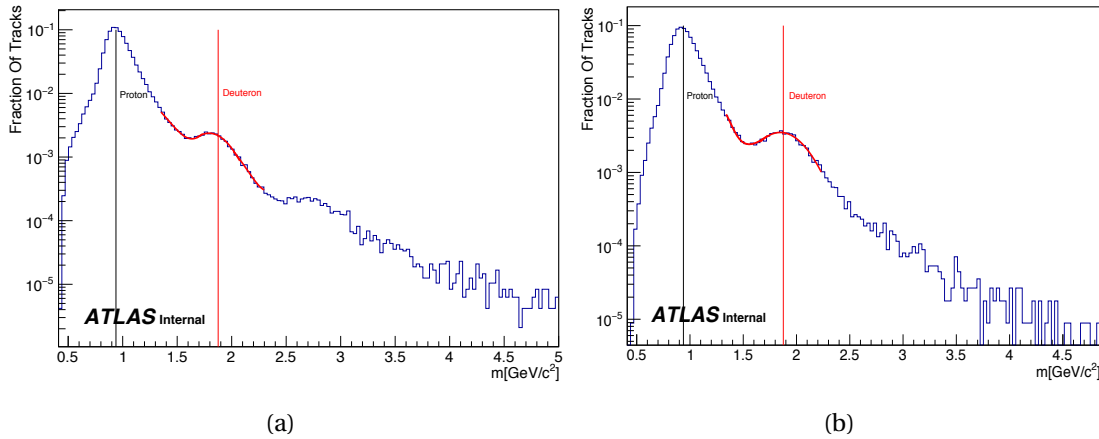


Fig. 4.19 Fitted peak mass for Deuteron using positive tracks and all $nUsedHitsdEdx$ categories, from (a) minimum bias simulation and (b) data 2015. The mass value of the deuteron in simulation is 1884 ± 7 MeV, while in data 1847 ± 8 MeV, compatible with the expected value (1876 MeV) within ~ 20 MeV.

Search of massive charged particles using the *Track* dE/dx

The *Track* dE/dx may be used as a discriminant variable to identify low $\beta\gamma$ charged particles. It has been used in a search for massive, long-lived particles (LLPs) such as R -hadron candidates. I have contributed to this analysis, mainly as the expert of the dE/dx by optimising the definition of *Track* dE/dx , giving a calibration of empirical 5-parameters Bethe-Bloch, measuring its stability and evaluating its systematics. LLPs are predicted in many extensions of the Standard Model (SM) and they appear, for example, in both R -parity conserving and violating supersymmetry (SUSY) and in universal extra dimensions theories. R -hadrons can be stable or metastable, in the second category we include all those decaying in the detector volume. With a lifetime-range coverage from a fraction of a nanosecond to several tens of nanoseconds. If produced at the LHC, such heavy particles are expected to be slow ($\beta \ll 1$) and, if charged, to have a specific ionization higher than any SM particles of unit charge at large momenta. In particular the ATLAS Pixel Detector provides a measurement of the charge deposited by charged particles crossing it and the usually high specific rate of energy loss (dE/dx , as described in Chapter 4) may be used to identify massive, highly ionizing particles, if their lifetime is adequately long to create a track in the detector. As no trigger is available based on large momentum or highly ionizing particles, events are selected requiring missing transverse energy (MET), calculated from energy deposits in the calorimeter. For events with R -hadrons which decay before or inside the calorimeter, undetected neutralinos of the R -hadron decays contribute to the measured transverse energy imbalance. Events with R -hadrons decaying beyond the calorimeters or stable are selected by the missing transverse energy trigger only in case the QCD initial-state radiation (ISR) unbalances the momentum of the R -hadron pair.

5.1 Theoretical Overview

In this section the theoretical models in which heavy stable (metastable) particles interacting directly with matter and their decays are described. The main references for this section are [17] and [76]. A stable massive charged particle (SMP) is a particle which does not decay during its passage through a detector, instead a metastable massive charged particle (MMCP) can decay in the detector volume, since the lifetime-range coverage goes from a fraction of a nanosecond to several tens of nanoseconds. Before moving to Beyond Standard Model theories, it is instructive to have a look at different types of long-lived particles. Here we can find stable elementary particles such as the electron, the metastable elementary particles as e.g. the muon, and long-lived (composite) particles such as neutrons and protons. The electron can't decay since in SM a lighter electrically charged state is not possible. Proton is the perfect example of particle with very long lifetime, so long that it can be classified as stable. This is because decays such as $p \rightarrow \pi^0 e^+$ are kinematically possible, but not possible from conservation of lepton- and baryon-number laws. However, certain theories inside Grand Unification Theory (GUT) requires that protons have a finite lifetime of $\sim 10^{36}$ years, even if for the moment there are no experimental observations. An example of long lived particle is the neutron with a mean lifetime of 881.5 s, decaying as $n \rightarrow p^+ e^- \bar{\nu}_e$.

In high energy physics particles that moves at relativistic speed and can travel enough to be classified as long-lived thanks to the relativistic effect of time dilatation¹ (or length contraction). An example is the muon μ with a mean lifetime of 2.197 μ s. In the SM we can find also several examples of meta-stable particles with lifetimes of the order of nano-seconds such as the Kaons and charged pions ($\sim 10^{-11} - 10^{-8}$ s).

Massive, long-lived particles (LLPs) are predicted by a wide range of physics models that extend the Standard Model (SM). LLPs arise in proposed solutions or the gauge hierarchy problem, including supersymmetric (SUSY) models that either violate and conserve R -parity. The lifetime of these particles depends on the mass difference between the particle and the lightest stable supersymmetric particle, and on the size of any R -parity violating coupling. A long-lived particle possessing color charge is expected to hadronize to form a color singlet hadron. A stable massive particle with colour charge can have long-lived hadronic states called R -hadrons in the SUSY framework.

¹The formula for determining time dilatation in special relativity is:

$$\Delta t' = \gamma \Delta t \tag{5.1}$$

where $\gamma = 1/(\sqrt{1 - \frac{v^2}{c^2}})$ is the Lorentz factor and where Δt is the time interval between two co-local events.

The electric charge of the resulting hadron will depend on the quark contents. A stable color octet, C_8 , such as the gluino ($\tilde{g}$), can form meson states with a quark-antiquark pair, $C_8 q \bar{q}$ and (anti) baryon states together with three quarks, $(C_8 \bar{q} \bar{q} \bar{q}) C_8 q q q$. In similar way, a color triplet, C_3 , i.e. a stop quark, $\tilde{t}$ could form mesons ($C_3 \bar{q}$) and baryons ($C_3 q q$) [77].

A massive long-lived particle having an electric charge $|q| \gg e$ (e is the elementary charge), could represent an evidence for physics beyond the Standard Model. An example of particles with high electric charge could be Q – *balls* [78] or stable micro black-holes [79].

5.1.1 Production and Decay

SMPs and MMCP could be pair-produced at a collider² [17]:

$$ab \rightarrow X_c X_d \quad (5.4)$$

where a and b are the constituents of the incoming beams, and X_i are the new particles produced. These processes can have large production cross-section, while the decay of X_c and X_d can be suppressed by the existence of a new quantum number, possibly resulting in long-lived particles which could interact in the detector. At LHC the centre of mass energy should assume sufficient for the process to be detected.

If the production of a particle X is allowed singly:

$$ab \rightarrow X \quad (5.5)$$

consequently also the inverse process $X \rightarrow ab$ can occur. The production cross-section is directly proportional to the decay width:

$$\sigma(ab \rightarrow X) \propto \Gamma(X \rightarrow ab) \quad (5.6)$$

²The general expression for decay rate $X \rightarrow ab$ (total width Γ) is given by:

$$\Gamma = \frac{|p|}{32\pi^2 m_i} \int |M_{fi}|^2 d\Omega \quad (5.2)$$

where $|p|$ is the magnitude of the momentum of the final state, M_{fi} is the amplitude of the process that includes spins and couplings (Usually it is calculated by perturbative approximation) and $d\Omega = d(\cos\theta)d\phi$ is the solid angle. The lifetime of the particle instead is given by:

$$\tau = \frac{1}{\Gamma} \quad (5.3)$$

where the constant of proportionality involves mass, spin and colour factors³. The process described in 5.5 has a production rate which is negligible at the LHC, this because the larger is the lifetime, the smaller is the production rate⁴. Therefore the pair production described in 5.4 is the only production mechanism considered. If the state is a colour octet, there is a factor eight to be added, or considering a spin one particle, another factor three must be added. However the production rates will still be negligible [17].

In a pair production we have coloured particles in both the incoming and outgoing states, for this reason Initial State Radiation (ISR) and Final State Radiation (FSR) can occur. The radiation is due to soft gluons that, in first approximation, are collinear with the emitting particles. The probability of the final state radiation scales inversely with the mass of the secondaries. SMP and MMCP are expected to be very heavy, hence low level of FSR is expected.

Initial State Radiation is instead possible also with significant rates. This because the jets in other regions of the detector can be associated with the production of SMP. The rate of ISR emission is latch to the amount of colour charge in the initial state, e.g. gluon-gluon (gg) production will lead to more jets than fermion-antifermion ($f\bar{f}$) production.

The precise phenomenology of decay is dependent on the nature of the SMP. Luckily a search is possible since the detector interaction are independent from the choosen model, as described in 5.1.2.

5.1.2 Interaction of Massive Charged Particles

The dominant interactions for massive charged particles are electromagnetic and strong interactions. The theory of electromagnetic energy loss was already described in Chapter 2 and it is expected that these particles follow it (Eq. 2.1), with a velocity β significantly lower than 1 and that they deposit large amounts of energy through ionization in a narrow region along their trajectory without producing extended showers. Hence the main observable for SMP and MMCP is the measurement of the energy loss dE/dx . Concerning strong interactions, when heavy charged hadrons pass through a medium, scattering from the nuclei of material is possible. The interaction cross-sections for R -hadrons ($\sigma(RN)$) are

³ The differential cross-section for a process $ab \rightarrow cd$ is:

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} \frac{|p_f|}{|p_i|} |M_{fi}|^2 \quad (5.7)$$

where $|p_i|$ and $|p_f|$ are respectively the magnitudes of initial- and final-state momenta in the centre of mass frame.

⁴As example considering a singlet scalar state with a mass of 200 GeV. A lifetime of $c\tau = 1$ mm will translate into a small production rate of 0.0002 events per year, assuming full LHC luminosity, 100 fb^{-1} [17].

expected to be of the order of those for pion scattering ($\sigma(\pi N)$). This model is based on *Regge theory* [80] where R -baryons or conversion from mesons into baryons are not taken in proper account [17]⁵. Considering a gluino R -hadron process $RN \rightarrow R'X$, where R is the initial R -hadron state, N a single nucleon (e.g. a proton or neutron), R' is the R -hadron after the scattering and X a generic system produced in the scattering. The cross-section ratio is expressed as:

$$\frac{\sigma(\pi N)}{\sigma(RN)} = \left(\frac{C_F}{C_A}\right) \frac{\langle r_\pi^2 \rangle}{\langle r_R^2 \rangle} \quad (5.8)$$

where $C_F = 4/3$ and $C_A = 3$ are the colour factors due to the low-mass colour-octet constituent of the R -hadron. $\langle r_\pi^2 \rangle$ and $\langle r_R^2 \rangle$ are the squared transverse size of the particle. For R -hadrons and pions $\langle r_R^2 \rangle \propto 1/m_g^2$ and $\langle r_\pi^2 \rangle \propto 1/m_q^2$ where m_g and m_q are the constituent masses of gluons and light quarks respectively. The cross-section is expected to be sufficiently small to allow to penetrate through the calorimeters and reach outer muon chamber and be reconstructed as a slow moving exotic particle. With the model described, taking in account the uncertainties in the constituent masses of the partons, a collision in length in iron for R -mesons is ~ 40 cm (in comparison with ~ 19 cm without considering uncertainties). In some Split Supersymmetry (SSUSY) models feature a long-lived gluino due to the fact that it must decay to the lightest supersymmetric particle through a highly virtual squark. In SSUSY context gluino can have very long lifetime arriving at $c\tau \sim 10$ m. Instead R -hadrons could be stopped inside the detector material, because they come to the end of their ranges due to electromagnetic and hadronic energy losses, with lifetime τ in ns-range.

A parton C_i of colour state i^6 can interact perturbatively with the quarks in the target nucleon with a small probability, since such interactions are suppressed by the squared inverse mass of the parton [17]. The mass of a parton is meant as the constituent mass. The heavy hadron can be seen consequently as consisting of non-interacting heavy state C_i , accompanied by a coloured hadronic cloud of light constituents, responsible for the interaction. The interaction energy of the hadron is small, e.g. considering a $C_8 q \bar{q}$ state with a total energy $E = 450$ GeV, if the mass m of C_8 is 300 GeV the Lorentz factor γ will be 1.5. The kinetic energy of interacting $q \bar{q}$ system is only $(\gamma - 1)m_{q\bar{q}} \approx 0.3$ GeV (if the quark system consists of up and down quarks) in comparison with the kinetic energy of the hadron of 150 GeV. This shows that the energy scale for heavy hadron scattering processes off nucleons is low. R -hadron can scatter elastically or inelastically as Fig. 5.1 shows, but the inelastic collisions are expected to be largely responsible for the energy

⁵ Other models have been proposed e.g. Kraan model [81]

⁶ Exotic colour triplet will be denoted as e.g. C_3 , the antitriplet as $C_{\bar{3}}$

loss. The energy loss of R -hadron scattering on nucleon N in the process $RN \rightarrow R'X$ is expected to be:

$$\Delta E = \frac{m_X^2 - m_N^2 + |t|}{2m_N} \quad (5.9)$$

where t is the four-momentum transferred from R to R' , and m_X is the mass of the remaining system of final state particles produced.

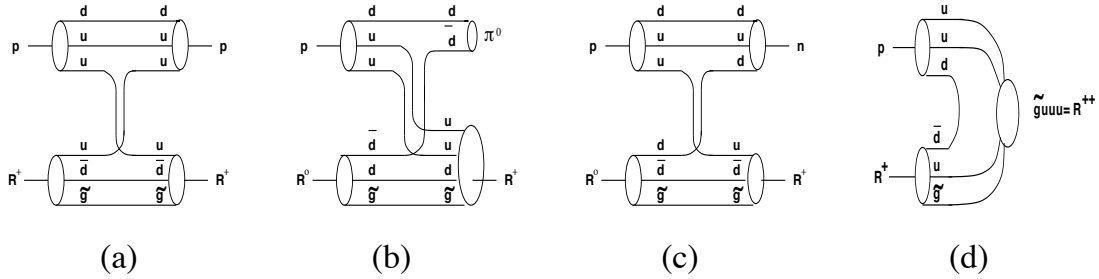


Fig. 5.1 R -hadron scattering of a proton. (a) Elastic scattering, (b) Inelastic scattering leading to baryon and charge exchange, (c) Inelastic scattering leading to charge exchange, (d) Resonance formation [17].

5.1.2.1 Mass spectrum

The mass of the lowest hadronic states (with no radial excitation or orbital angular momentum) can be approximated by [82]:

$$m_{hadron} = \sum_i m_i - k \sum_{i \neq j} \frac{(\mathbf{F}_i \cdot \mathbf{F}_j)(\mathbf{S}_i \cdot \mathbf{S}_j)}{m_i m_j} \quad (5.10)$$

where the sum is over all partons i contained in the hadron, m_i is the mass of the parton constituent, $\mathbf{F}_i$ is the SU(3) colour matrix for parton i , $\mathbf{S}_i$ the SU(2) spin matrix for parton i and k is a constant related to the wave function with the dimension of a mass. The mass splittings are of critical importance for a search strategy. For example if one state is significantly lighter than another, one would expect this state to be dominantly present in the detector.

The hadron mass for colour triplet C_3 can be obtained from standard quark and diquark⁷ constituent masses. For C_3 mesons a significant mass splitting is not expected,

⁷It is an hypothetical state of two quarks grouped inside a baryon. The forces between the two quarks in a diquark is attractive when both the colors and spins are antisymmetric. When both quarks are correlated in this way they tend to form a very low energy configuration. This low energy configuration has become known as a diquark.

since the second term of Eq. 5.10 is negligible (smaller than that of the BB^* system, which is only 46 MeV) instead for C_3 baryons i.e. $C_3 qq$ states the mass spectrum expected is (in GeV):

$$M_{C_3 qq} \approx M_{C_3} + 0.3 + 0.3 - 0.026 \times \frac{(-\frac{2}{3} \times -\frac{3}{4})}{0.3 \times 0.3} \approx M_{C_3} + 0.46 \quad s_{qq} = 0 \quad (5.11)$$

$$M_{C_3 qq} \approx M_{C_3} + 0.3 + 0.3 - 0.026 \times \frac{(-\frac{2}{3} \times +\frac{1}{4})}{0.3 \times 0.3} \approx M_{C_3} + 0.65 \quad s_{qq} = 1 \quad (5.12)$$

where s_{qq} denotes the total spin of the qq system and for simplicity, we take into account only states containing u and d quarks, with constituent masses assumed to be $m_q = 0.3$ GeV.

In the case of a $C_8 q \bar{q}$ state the mass spectrum is given by:

$$M_{C_8 q \bar{q}} \approx M_{C_8} + 0.3 + 0.3 - 0.043 \times \frac{(\frac{1}{6} \times -\frac{3}{4})}{0.3 \times 0.3} \approx M_{C_8} + 0.66 \quad s_{q \bar{q}} = 0 \quad (5.13)$$

$$M_{C_8 q \bar{q}} \approx M_{C_8} + 0.3 + 0.3 - 0.043 \times \frac{(\frac{1}{6} \times \frac{1}{4})}{0.3 \times 0.3} \approx M_{C_8} + 0.58 \quad s_{q \bar{q}} = 1 \quad (5.14)$$

As seen if unstable over nanosecond time scales, R -hadrons could decay inside the detector. These decays could violate baryon or lepton number, via such processes as $\tilde{g} \rightarrow uds$.

5.2 Search for metastable heavy charged particles with large ionisation energy loss in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment

The described analysis has been performed to search massive charged long-lived particles (with lifetimes of $O(\text{ns})$ or longer) produced in pp collisions at $\sqrt{s} = 13$ TeV at the LHC using the ATLAS experiment. The used dataset corresponds to an integrated luminosity of 3.2 fb^{-1} . This analysis extends the studies performed on data collected at $\sqrt{s} = 8$ TeV [18]. The next subsections are based⁸ on [16]. The increase in probability for high-energy parton-parton collisions significantly enhances the production cross-section of LLPs via the strong interaction. The Pixel dE/dx is the key signal discriminant in this analysis, it is used to detect massive, highly ionizing particles and to reconstruct their mass based on a parametrization of the most probable value of the specific rate of energy loss. For

⁸In agreement with CC-BY-4.0 license

the described reason, my developments on Pixel dE/dx calculation algorithm and the new the calibration of empirical 5-parameters Bethe-Bloch function have been used. In Chapter 3 and 4 the decalibration of IBL Front-End was shown. It produced a track dE/dx MPV drop, causing also a variation of the percentage of tracks with IBL overflow (Sec. 5.2.3). To mitigate this effect, I have evaluated a method to apply a correction factor to the track dE/dx , taking in proper account the variation in the analysis systematics.

5.2.1 Analysis Strategy

This search is based on the signature of R -hadron events containing at least one reconstructed track with large measured dE/dx and high transverse momentum (p_T). This signature optimizes the search for metastable R -hadrons with lifetimes of $O(ns)$, as the selection requires that the R -hadron only live long enough to traverse the seven layers of the silicon detectors, corresponding to a distance from the beam axis of 37 cm. The search is also sensitive to R -hadrons with longer lifetimes, with a small dependence on the modelling of the interaction of R -hadrons in the calorimeter and muon systems.

In the models studied in this search and described in Section 5.2.2, pair-produced gluinos hadronize into two colorless R -hadrons with the following charge states: approximately 33% events with two neutral R -hadrons, 47% events with one neutral and one charged R -hadron, and 20% events with two charged R -hadrons. The fragmentation is extremely hard and the R -hadrons are therefore isolated. As massive particles with $\beta < 1$, the charged R -hadrons are expected to deposit more ionization energy in the detector than typical particles of the same momentum. This deposited charge is used both to select signal events, as described in Section 5.2.4, and to calculate the mass of selected candidates. The estimated candidate mass is used as the final search discriminant.

If the R -hadrons decay before or in the calorimeter, the decay products of R -hadrons in models studied here include quarks, which are identified as jets in the calorimeters (see Section 5.2.4), and a 100 GeV neutralino, which carries away significant momentum undetected. If R -hadrons traverse the calorimeter without decaying, they are expected to deposit significantly less energy in the calorimeters than SM hadrons of the same momentum, as the heavy parton carries almost all the momentum of the composite particle and limited kinetic energy is available for interactions between the light SM partons and the detector. In the models studied here, over 90% of stable R -hadrons, independent of mass, deposit less than 20 GeV of energy in the calorimeters. However, the electric charge of the R -hadron can change due to the hadronic interactions, even if little energy is lost, and the charge of the R -hadron leaving the calorimeter is expected to be decoupled from the charge at production [83]. As hadronic interactions are rare in the

tracking detectors, the probability for an R -hadron to change its electric charge before the calorimeters is only around 3%.

Events are selected by a trigger requiring missing transverse momentum (p_T^{miss}), calculated from energy deposits in the calorimeter. For events with R -hadrons that decay before or inside the calorimeter, undetected neutralinos contribute to the measured transverse momentum imbalance. As stable R -hadrons deposit little energy in the calorimeters, most stable R -hadron events are selected by the trigger only when QCD initial-state radiation (ISR) boosts the R -hadron pair system. Details of the event selection are given in Section 5.2.4.

5.2.2 Simulation: Montecarlo Samples

A number of samples of simulated signal events are used in this analysis to determine the expected LLP signal efficiencies and to estimate uncertainties in the efficiency. For stable R -hadrons, pair production of gluinos with masses between 800 GeV and 1800 GeV is simulated in PYTHIA 6.4.27 [84] with the AUET2B set of tuned parameters for the underlying event and the CTEQ6L1 [85] parton distribution function (PDF) set, incorporating dedicated hadronization routines [81] to produce final states containing R -hadrons. The cross-sections are calculated at next-to-leading order in the strong coupling constant (NLO), including the resummation of soft-gluon emission at next-to-leading-logarithmic accuracy (NLO+NLL) [86, 87, 88, 89, 90]. The nominal cross-section predictions and the uncertainty are taken from an envelope of cross-section predictions using different PDF sets and factorization and renormalization scales, as described in Ref. [91].

Selected events containing R -hadrons undergo a full detector simulation, where interactions of R -hadrons with matter are handled by dedicated GEANT4 [92] routines based on the physics model described in Refs. [81, 93]. This model assumes, for each light valence quark, a cross-section of 12 mb per nucleon and neglects the heavy parton, other than as a reservoir of kinetic energy. This hadronic scattering is described through a purely phase-space-driven approach. The probability for a gluino to form a gluon–gluino bound state is assumed to be 10% [17]. The simulation of samples of metastable gluino-based R -hadrons is performed similarly to the stable R -hadrons. The gluinos within R -hadrons are then required to decay via the process $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$, using PYTHIA 6. Gluino masses (m) between 400 GeV and 3000 GeV are simulated, with the neutralino mass fixed to 100 GeV. This benchmark decay mode is chosen as it has the highest sensitivity among those studied in Ref. [18]. Heavier neutralino masses would give lower signal efficiencies, mainly because of the smaller missing transverse momentum available to trigger. The gluino lifetime (τ) is varied from 0.4 ns to 50 ns. All simulated samples include a modeling of pileup,

adding the expected number of minimum bias proton–proton interactions from the same (in-time pileup) and nearby (out-of-time pileup) bunch crossings. Simulated events are reconstructed using the software used for the collision data. Additional samples of gluinos are generated for all mass points using MG5_aMC@NLO [94], to get a more accurate description of radiative effects than PYTHIA 6 provides. The distribution of the transverse momentum of the gluino–gluino system simulated with PYTHIA 6 is then reweighted in such a way as to match that obtained in samples simulated with MG5_aMC@NLO. This is especially important for stable R -hadrons as detailed in Section 5.2.4.

Table 5.1 Simulated stable gluino R -hadron signal samples. For each gluino mass, dataset ID number, and number of generated events are specified. The used production tag is quoted: The samples from 800 to 1800 use the same tag; the other samples have been produced at a later stage.

$m(\tilde{g})$ [GeV]	DSID	events
400	402154	9800
600	402155	9600
800	402000	100004
1000	402001	9900
1200	402002	9600
1400	402003	9600
1600	402004	9700
1800	402005	4600
2000	402006	4600
2200	402007	10000
2400	402008	10000
2600	402009	10000
2800	402010	10000
3000	402011	10000

Table 5.2 Simulated metastable gluino R -hadron signal samples with different lifetimes. For each gluino mass, the decay $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ with a neutralino mass of 100 is intended, while gluino lifetime, dataset ID number, and number of generated events are specified.

$m(\tilde{g})$ [GeV]	$\tau(\tilde{g})$ [ns]	DSID	events	$m(\tilde{g})$ [GeV]	$\tau(\tilde{g})$ [ns]	DSID	events
400	0.4	402034	10000	1000	10	402055	9800
500	0.4	402035	10000	1100	10	402070	9600
600	0.4	402036	9600	1200	10	402076	9800
700	0.4	402041	9600	1300	10	402091	9600
800	0.4	402043	10000	1400	10	402097	9600
900	0.4	402049	9600	1500	10	402111	9000
1000	0.4	402052	9600	1600	10	402116	9800
				1700	10	402129	10000
				1800	10	402133	10000
600	1.0	402037	9800	1000	30	402056	9600
700	1.0	402042	9600	1100	30	402071	9600
800	1.0	402044	10000	1200	30	402077	9600
900	1.0	402050	9600	1300	30	402092	9400
1000	1.0	402053	9800	1400	30	402098	9800
1100	1.0	402068	10000	1500	30	402112	10000
1200	1.0	402074	10000	1600	30	402117	10000
				1700	30	402130	10000
				1800	30	402134	10000
800	3.0	402045	9600	1000	50	402057	9600
900	3.0	402051	9600	1100	50	402072	9600
1000	3.0	402054	9800	1200	50	402078	9800
1100	3.0	402069	9400	1300	50	402093	10000
1200	3.0	402075	9800	1400	50	402099	9200
1300	3.0	402090	9800	1500	50	402113	10000
1400	3.0	402096	10000	1600	50	402118	10000
1500	3.0	402110	9000				
1600	3.0	402115	5000	1800	50	402135	10000
1700	3.0	402128	5000				

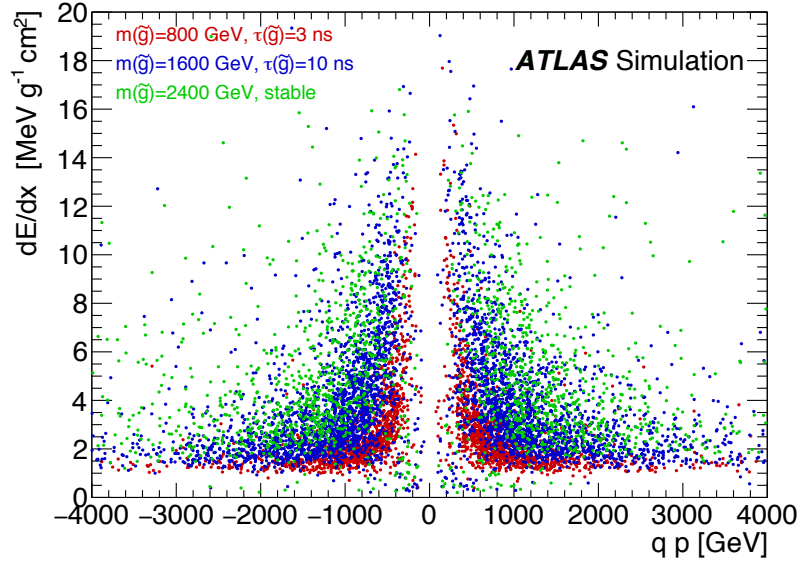


Fig. 5.2 Two-dimensional distribution of dE/dx versus signed momentum for 800 GeV and 1600 gluino R -hadron with a lifetime of 3 ns and 10 ns respectively, decaying to $q\bar{q}$ plus a light neutralino of mass $m(\tilde{\chi}_0)=100$ GeV (red and blue dots), and for 2400 GeV stable gluino R -hadrons. Good events are selected with at least one high- p_T track matched to a true R -hadron particle.

5.2.3 dE/dx MPV drift due to IBL Front-End decalibration

In Chapter 3 and 4 the decalibration of IBL Front-End due to radiation has been described. A track dE/dx MPV drop has been observed, due to the IBL ToT drift over runs, in all LHC periods of data-taking used in the analysis as Figure 5.3 shows. The track dE/dx MPV has a drop variation of $\sim 1.7\%$ to a maximum of $\sim 7\%$ (referred to the starting value after the IBL retuning), this causes also a variation of the percentage of tracks with IBL overflow, of up to $\sim 3\%$. The variation of dE/dx MPV causes a change in the proton mass measurement, as Figure 5.4 shows. To reduce the effect, a scale factor has been applied to the track dE/dx measurement. The scale factor has been computed from the ratio of the track MPV dE/dx in each run to the value of a reference run in which IBL was known to be stable with respect to this effect. For the rescaling the tracks with IBL in overflow have been excluded, since in this case the IBL doesn't affect the dE/dx computation (see Table 4.3). The correction applied gives satisfactory results for the proton mass computation stability, as shown in Figure 5.4. Still the measurement of the proton mass exceeds the reference proton mass computed in low $\langle\mu\rangle$ runs by $\sim 2\%$, most probably due to the different LHC bunch structure.

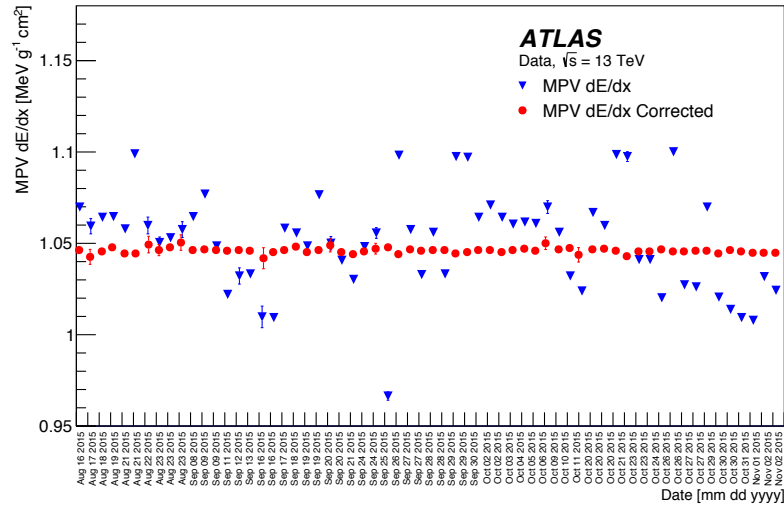


Fig. 5.3 The track dE/dx MPV over time is reported for all the runs of 2015 data-taking used in the analysis (blue dots). They show a variation of the dE/dx MPV due to the ToT drift of the IBL electronics. The red dots show the dE/dx MPV after the run-by-run rescaling.

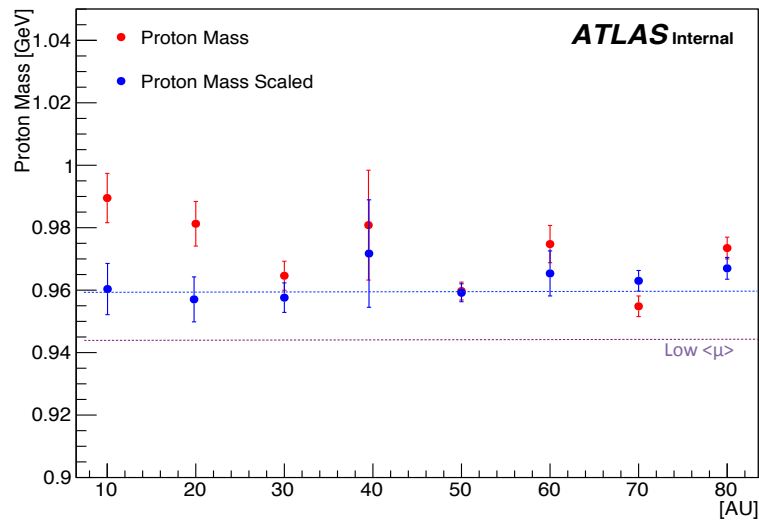


Fig. 5.4 The proton mass versus grouped continuous run numbers (arbitrary units, from data periods D and E) before (red dots) and after (blue dots) the track dE/dx rescaling is shown. The runs with a dE/dx MPV difference $< 0.01\%$ have been merged in a single dot. In violet the proton mass from low $\langle \mu \rangle$ runs is also reported.

5.2.4 Data Sample and Event Selection

The data sample used for this search was collected while tracking detectors, calorimeters, muon chambers, and magnets were operating normally and corresponds to an integrated luminosity of 3.2 fb^{-1} in 2015. The luminosity measurement was calibrated during dedicated beam-separation scans, using the same methodology as that described in Ref. [95]. The uncertainty in the luminosity measurement is 5%.

Candidate events are selected by a E_T^{miss} trigger, formed from energy deposits in the calorimeter [96], with a threshold of 70 GeV.

The event selection, described in detail below, was optimized relative to the $\sqrt{s} = 8 \text{ TeV}$ search [18] to improve the sensitivity to events with R -hadrons relative to background events from SM processes. Major improvements include the addition of selections designed to reject tracks from hadrons and electrons, as well as changes to the isolation requirements, which now reject background events from overlapping tracks by identifying clusters in the Pixel or SCT detectors which are consistent with energy deposition from multiple particles. Two signal regions are defined: one targets metastable R -hadrons with shorter lifetimes, and the other is optimized for metastable or stable R -hadrons that are expected to pass through the muon spectrometer before decaying.

A primary vertex reconstructed from at least two well-reconstructed charged-particle tracks, each with $p_T > 400$, is required in order to remove non collision background events. If there is more than one such vertex in an event, the primary vertex is defined as the vertex with the largest scalar sum of associated track momentum. To reduce backgrounds from SM processes, events must have $E_T^{miss} > 130 \text{ GeV}$, where E_T^{miss} is the offline missing transverse momentum. Jets are reconstructed with the anti- k_t algorithm with radius parameter $R = 0.4$ using clusters of energy depositions in the calorimeter as inputs. Events are rejected if they contain a jet with $E_T > 20 \text{ GeV}$ that is consistent with noise contributions as determined based on timing and shower shape information. The offline E_T^{miss} is estimated from reconstructed electrons with $|\eta| < 2.47$, reconstructed muons with $|\eta| < 2.5$, calibrated jets with $p_T > 20 \text{ GeV}$ within $|\eta| < 4.5$, and reconstructed tracks which are not associated with other objects and that pass kinematic requirements designed to reject poorly reconstructed tracks.

For signal events, the trigger efficiency varies significantly depending on the model considered. For metastable R -hadrons with a mass of 1000 GeV, decaying into a 100 GeV neutralino and quarks, the trigger efficiency increases from 65% for R -hadrons with a lifetime of 50 ns to 95% for R -hadrons with a lifetime of 0.4 ns. For an R -hadron with a lifetime of 10 ns, the trigger efficiency increases slightly with the R -hadron mass, from 91% for a mass of 1000 GeV to 96% for a mass of 1600 GeV. For stable R -hadrons, the

trigger efficiency is approximately 40% for all masses studied. All efficiencies quoted in this section include both the acceptance and 150 efficiency effects.

The offline E_T^{miss} calculation includes the momentum of identified muons, which is important to reject background events from SM processes with muons, such as $Z \rightarrow \mu\mu$, that pass the calorimetric E_T^{miss} trigger. For events with metastable R -hadrons, the offline E_T^{miss} requirement is very efficient (around 95%) due to the neutralinos in the event.

For stable R -hadrons that pass the trigger requirement, the offline E_T^{miss} cut is also efficient (around 90%), as the R -hadrons do not deposit significant energy in the calorimeter and in most events the R -hadron pair is boosted from initial-state radiation. Many R -hadrons fail to be identified as muons because they are in a neutral charge state going through either the inner detector or the muon spectrometer. Even if a charged R -hadron with $\beta \ll 1$ traverses the muon spectrometer, it can fail to be identified by the standard muon reconstruction algorithm as a prompt muon due to its late time of arrival. In a typical R -hadron model considered in this search, only 30% of stable R -hadrons with a reconstructed track in the inner detector are identified as prompt muons entering into the E_T^{miss} calculation.

Selected events must contain at least one candidate R -hadron track. For a track to be identified as a candidate, it must have $p_T > 50$ GeV and meet the following selection criteria. The track must contain at least seven clusters from silicon detector layers in order to make a good measurement of the track's momentum, must have a cluster in the innermost Pixel layer if expected, and must be associated with the primary vertex. In order to ensure a good ionization measurement, the track must have at least two clusters in the Pixel Detector used to measure dE/dx . These selection requirements on associated clusters are summarized as cluster requirements.

To reject background events with overlapping tracks that could produce clusters with significant measured ionization, the candidate track must not contain any cluster that is compatible with contributions from two or more tracks. This requirement is over 90% efficient for signal events with lifetimes of 3 ns or greater. For background tracks, it lessens the high ionization tail of the distribution from photon conversions and collimated particles, reducing the size of the background and leaving the remaining tracks with a dE/dx distribution largely independent of background source. In order to reduce backgrounds from particles inside hadronic jets, the scalar sum of the p_T ($\sum p_T$) of other tracks, with $p_T > 1$ GeV and consistent with the primary vertex, in a cone of size $\Delta R < 0.25$, where $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, around the candidate track, must be less than 20 GeV.

The background from SM processes is further reduced by requiring that the candidate track momentum exceeds 150 GeV and that the relative uncertainty on the momentum

measurement be less than 50%. The contribution from leptons from W boson decays is reduced by imposing a condition that the transverse mass, m_T , built with the candidate track and the E_T^{miss} , be greater than 130 GeV, where:

$$m_T = \sqrt{2p_T E_T^{miss}(1 - \cos(\Delta\phi(E_T^{miss}, \text{track})))} \quad (5.15)$$

and $\Delta\phi(E_T^{miss}, \text{track})$ is the azimuthal separation between the track and the E_T^{miss} . This selection has an efficiency between 78% and 89% for R -hadrons with lifetimes of 3 ns or greater, and reduces the background by roughly a factor of three.

Background events due to tracks from electrons and hadrons are reduced by requiring that the energy of any jet associated with the candidate track must be less than the candidate track's measured momentum. Jets are associated with tracks if they are within $\Delta R < 0.05$ of the candidate track and have $p_T > 20$ GeV. Background events containing electrons are further reduced by rejecting candidate tracks associated with a jet with 95% or more of its energy deposited in the electromagnetic calorimeter. These selections are found to be 95% efficient for all signal models studied.

Tracks identified as well-reconstructed muons with $p_T > 25$ GeV are rejected in the search for metastable R -hadrons with lifetimes of 30 ns or less. R -hadrons with a lifetime equal to or greater than 50 ns typically reach the muon spectrometer, and therefore no such veto is applied in the long-lived R -hadron search. To further reject hadronic background in the search for stable R -hadrons, the isolation requirement on the $\sum p_T$ of nearby tracks is tightened from 20 GeV to 5 GeV for candidate R -hadron tracks, eliminating 30% of the remaining expected background.

The specific ionization of the candidate track, as measured by the Pixel Detector, must be larger than $1.80 - 0.11|\eta| + 0.17\eta^2 - 0.05|\eta|^3 \text{ MeV g}^{-1} \text{ cm}^{-2}$. This requirement corrects the slight (5%) $|\eta|$ dependence of the dE/dx measurement [97] while maximizing the expected sensitivity to signal events. This selection is approximately 70–90% efficient for signal events with lifetimes of 3 ns or greater, depending on the R -hadron mass, and retains less than 1% of background events. Additionally, a time-dependent correction is applied to the ionization measurement in data to account for an observed variation in the charge measurement by the IBL electronics due to effects of radiation. The size of this correction is around 5%.

The observed numbers of events in data and the predicted numbers of simulated signal events, for a 1600 GeV R -hadron with a lifetime of 10 ns, are shown in Table 5.3 after each stage of the event selection. The total selection efficiency relative to generated events, which includes both the acceptance and efficiency effects, is also shown for the signal.

Table 5.3 Expected number of events at different steps of the selection for metastable 1600 GeV gluino R -hadrons decaying with a 10 ns lifetime, along with the number of events observed in data, for fb^{-1} . The simulated yields are shown with statistical uncertainties only. The total efficiency $\times$ acceptance is also shown in parentheses for the signal.

Selection level	Exp. signal events	Observed events in fb^{-1}
Generated	26.0 ± 0.3	
E_T^{miss} trigger & preselection	24.8 ± 0.3 (95%)	
> 130 GeV	23.9 ± 0.3 (92%)	
Track $p_T > 50$ and cluster requirements	10.7 ± 0.2 (41%)	368324
Isolation requirement	9.0 ± 0.2 (35%)	108079
Track $p > 150$ GeV	6.6 ± 0.2 (25%)	47463
$m_T > 130$ GeV	5.8 ± 0.2 (22%)	18746
Electron & hadron veto	5.5 ± 0.2 (21%)	3612
Muon veto	5.5 ± 0.2 (21%)	1668
Ionization requirement	5.0 ± 0.1 (19%)	11

5.2.5 Signal Selection Efficiency

The overall signal selection efficiency depends on the mass and lifetime of the signal, ranging from about 19% for a 1600 GeV R -hadron with a lifetime of 10 ns to less than 1% for R -hadrons with a lifetime of 0.4 ns. The trigger and offline E_T^{miss} requirements are more efficient for R -hadrons that decay before or inside the calorimeters. However, as the R -hadron lifetime decreases, the probability of reconstructing the track from the original R -hadron in the silicon detectors decreases. For these two reasons, R -hadrons with lifetimes in the 10–30 ns range have the highest selection efficiency.

The inefficiency for selecting R -hadrons with short lifetimes can be better understood by calculating the selection efficiency relative to a simple fiducial region that separates out acceptance effects due to basic kinematic properties of the R -hadrons. An event is considered to be within the fiducial acceptance if it contains at least one R -hadron that passes the following requirements at MC generator level: charged at production, $p_T > 50$ GeV, $p > 150$ GeV, $|\eta| < 2.5$, and transverse decay distance ≥ 37 cm from the origin. With this definition, the acceptance for R -hadron events with a lifetime of 1 ns ranges from 7% for a mass of 600 GeV to 4% for a mass of 1600 GeV. The selection efficiency for R -hadron events in the fiducial region has only a mild dependence on the mass; in the R -hadron mass range from 600 to 1600 GeV, the selection efficiencies are 20% to 25% ($\tau = 1$ ns), 35% to 39% ($\tau = 3$ ns), 39% to 45% ($\tau = 10$ ns), and 31% to 35% ($\tau = 30$ ns), respectively.

Table 5.4 summarizes the systematic uncertainties in the predicted signal yields. The systematic uncertainties are calculated and used independently for each mass bin and signal lifetime. In the table, only the maximum uncertainty is quoted.

The trigger and offline E_T^{miss} selections are sensitive to the modeling of ISR in the event, in particular for signal events that do not decay inside the detector volume. Half of the difference between the selection efficiency of the PYTHIA 6 samples and those reweighted with MG5_aMC@NLO is taken as an uncertainty due to radiative effects.

The E_T^{miss} trigger modeling is studied in a sample of $Z \rightarrow \mu\mu$ events and an uncertainty is assigned based on differences between efficiencies measured in data and in simulation. The uncertainty in the E_T^{miss} calibration comes primarily from uncertainties on the jet energy scale. A systematic uncertainty in the measurement of the Pixel ionization is evaluated by comparing the ionization of an inclusive sample of simulated and observed low-momentum tracks. An asymmetric uncertainty is assigned due to the selection efficiency difference observed after the most probable value of the signal distribution is reweighted based on the comparison of low-momentum tracks between data and simulation. The uncertainty in the signal acceptance is asymmetric since the ionization in simulation is systematically larger than that observed in data. An uncertainty in the efficiency of the muon veto is estimated by studying the modeling of the muon spectrometer's timing measurement.

The signal selection efficiency is found to be largely independent of the number of pileup events in simulation. However, to cover any remaining difference, efficiency differences from variations in the pileup distributions are accounted for as an additional source of uncertainty. The uncertainty on the momentum scale and resolution of the tracks results in a small uncertainty in the selection efficiency. Variations of the requirements to reject tracks from electrons and hadrons are found to have a negligible effect on the signal efficiency. The theoretical uncertainty in the signal cross-section is described in Section 5.2.2.

5.2.6 Background Estimation

The expected shape and normalization of the mass distribution of background events from SM processes is derived from data. The distributions of key variables are extracted in two control regions in data and these templates are used to generate the expected background distribution in the signal region. The choice of control samples takes into account the measured correlations between the key variables p , dE/dx and η , and the control region selections minimize the possible signal contamination. The same regions are used in the searches for stable and metastable particles, except for the rejection of

Table 5.4 Systematic uncertainties on the predicted signal yields. The uncertainty depends on the mass and on the lifetime; only the maximum negative and positive values across all signal models (see Section 5.2.2) are reported here.

Source of uncertainty	-[%]	+[%]
ISR modeling (R -hadron stable)	14	14
ISR modeling (R -hadron metastable)	1.5	1.5
Trigger turn-on	0.9	0.9
E_T^{miss} scale	1.1	2.2
Pileup	1.1	1.1
Ionization parameterization	7.1	0
Momentum parameterization	0.3	0.3
μ identification (metastable only)	4.3	4.3
Total systematic uncertainty in acceptance $\times$ efficiency		
<i>Stable R-hadron</i>	16	14
<i>Metastable R-hadron</i>	9	5
Luminosity	5	5
Signal cross-section	28	28

track candidates identified as muons in the latter case and for the tighter track isolation requirement in the former case.

The first control region (hereafter called CR1) is selected by applying all the selections described in Section 5.2.4, except for the requirement on high ionization, which is inverted. The tracks in this control region are kinematically similar to those in the signal region for SM processes, and the expected p and $\eta(p)$ distributions of tracks from background processes are extracted from this region. The second sample (CR2 hereafter) is selected by inverting the E_T^{miss} requirement ($E_T^{miss} < 130$ GeV), while keeping all other selections unchanged. As more than 90% of R -hadron events that pass the trigger have $E_T^{miss} > 130$ GeV, while the E_T^{miss} distribution from SM background processes falls steeply in the range 70–130 GeV, CR2 is background-dominated. Tracks from this region are used to derive dE/dx templates in bins of η , as E_T^{miss} and dE/dx are uncorrelated for tracks from SM processes. The signal contamination is less than 1% in both control regions for all R -hadron masses and lifetimes considered in this search.

The shape of the background in the signal region is estimated from the control region templates with the following procedure: 1 million $(p, \eta, dE/dx)$ triplets are generated, where the momentum is randomly sampled according to the template from CR1 tracks, the pseudorapidity is generated according to the $\eta(p)$ -binned templates based on CR1 tracks, and the ionization is sampled according to $dE/dx(\eta)$ -binned templates from CR2 tracks. This procedure maintains the measured correlations between p , η , and dE/dx for

tracks from SM sources. The particle mass M is calculated given the predicted dE/dx and p values, using the technique explained in Chapter 4.

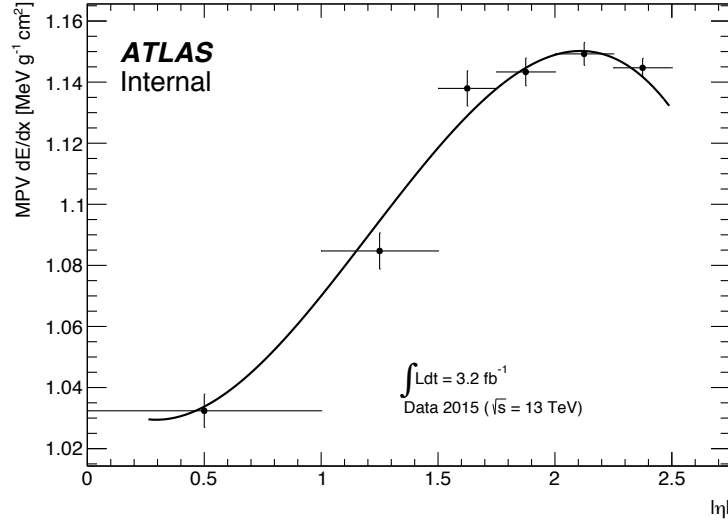


Fig. 5.5 Ionization MPVs as a function of $|\eta|$, obtained from *CR2* tracks for each η interval. The distribution is overlapped with a third order polynomial function.

The normalization of the generated background is obtained by scaling the background to the data in the shoulder region of the mass distribution (i.e. $M < 160$ GeV), where a possible signal has already been excluded [18]. The normalization is performed on the samples before the ionization requirement. The expected mass distributions of the background and the observed data, before the ionization requirement, are shown in Figure 5.6 for the metastable R -hadrons selection.

Systematic uncertainties in the background estimate are evaluated by varying the relative fraction of muons in the control regions, using an analytical description to vary the shape of the high ionization tail in the dE/dx template, and by changing the IBL ionization correction by $\pm 1\sigma$. The statistical uncertainty in the template shape, which is estimated by Poisson fluctuations of the templates, dominates. There is also a small statistical uncertainty from the size of the normalization region. The breakdown of uncertainties in the background estimate is shown in Table 5.5.

The complete procedure is tested on signal-depleted validation regions. The validation regions are selected with the same requirements as for the nominal signal and control regions, but requiring the track momentum to be in the range $50 < p < 150$ GeV. Applied to these validation samples, the procedure described above yields a calculated background

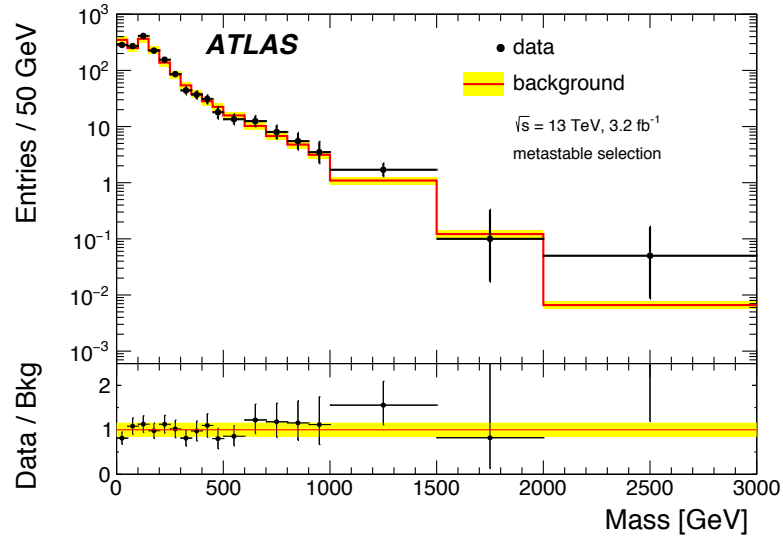


Fig. 5.6 Expected mass distribution from background events in the signal region for the metastable R -hadrons, before the ionization requirement is imposed. Data are superimposed. The ratio of data to expected background is shown in the lower panel with statistical uncertainties only.

Table 5.5 Summary table of the uncertainties in the background estimate.

Source of uncertainty	[%]
Statistical uncertainty from control region templates	15
Statistical uncertainty from normalization region	3
Analytical description of dE/dx	4
Particle species composition of CR2	3
IBL ionization correction	4

of 20.0 ± 3.0 (stat.) ± 1.2 (syst.) events in the validation region for metastable R -hadrons, while 14 events are observed in the data. For the validation region for stable R -hadrons, 28.1 ± 4.2 (stat.) ± 1.9 (syst.) events are estimated from this procedure and 20 are observed. While the observed numbers of events in the validation regions are lower than predicted, they are consistent with statistical fluctuations at the level of 1.7σ .

5.2.7 Results

In data, 16 events are observed for the stable R -hadron selection and 11 are observed for the metastable selection. Table 5.6 summarizes the background estimates with total statistical and systematic uncertainty as well as the observed events for the metastable and stable R -hadron selection. The observed mass distribution in data is shown in Figure 5.7 for both selection regions, along with the background expectation.

Table 5.6 Estimated number of background events and the number of observed events in data in the final selection regions. The background predictions show both the statistical and systematic uncertainties.

Selection region	Background exp.	Data
Metastable R -hadron	$11.1 \pm 1.7 \pm 0.7$	11
Stable R -hadron	$17.2 \pm 2.6 \pm 1.2$	16

No evidence of a signal above the background is observed. Expected and observed upper limits on R -hadron production cross-sections are evaluated at 95% CL for a discrete set of R -hadron mass values by counting simulated signal, background and observed data events that survive the selection in a $\pm 1.4\sigma$ wide mass window around the position of each simulated signal mass peak for the corresponding mass hypothesis being probed. The peak position and width are estimated by a Gaussian fit to each individual signal mass distribution ($\sigma \approx 280$ [≈ 500] GeV at an R -hadron mass of 1200 [1600] GeV). When the lifetime of the R -hadron is long enough to reach the muon spectrometer, the stable selection becomes more efficient than the metastable one and improves the expected sensitivity. This transition happens around 50 ns. The choice of whether to apply the metastable or stable R -hadron selection to each lifetime is based on the best expected limit. Based on this procedure, the stable selection is applied to both the 50 ns and stable lifetimes.

The cross-section upper limits are extracted, separately for the stable and the metastable searches (in the latter case, for each lifetime value), with the CL_S method [98], using the profile likelihood ratio as a test statistic. In the procedure, the systematic uncertainties

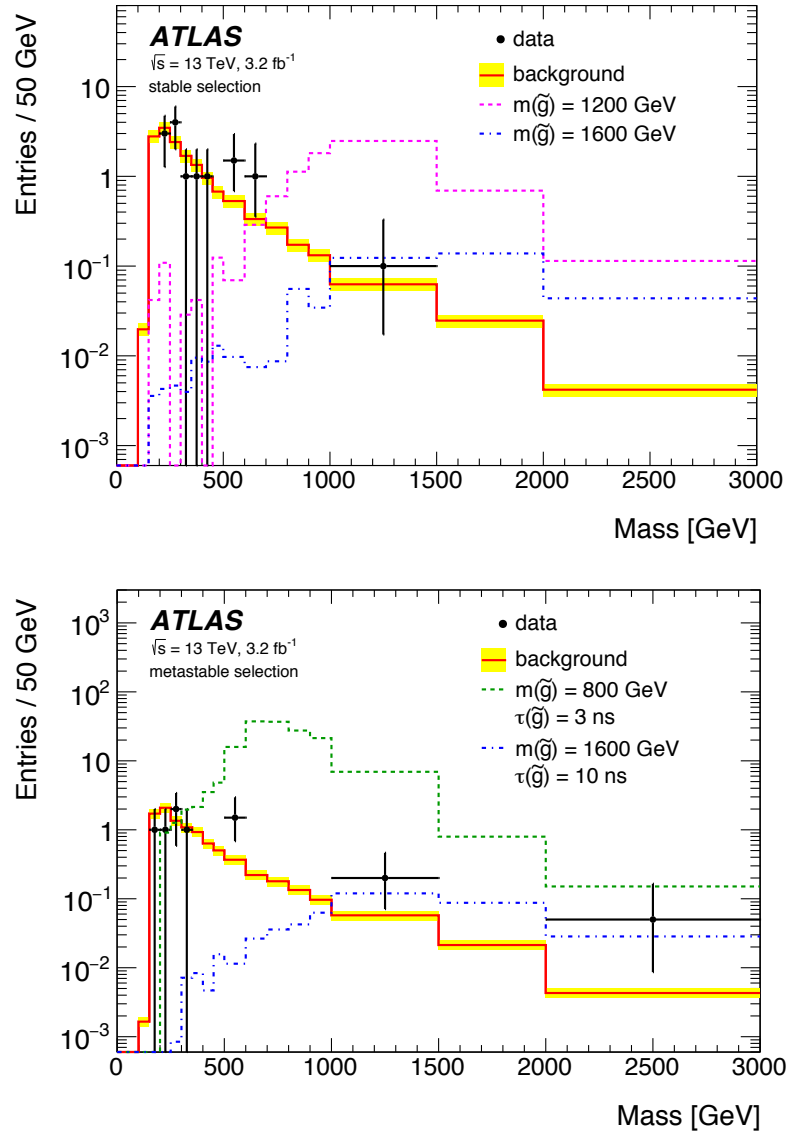


Fig. 5.7 Mass distribution for data and background for stable (top) and metastable (bottom) particle searches. The yellow band around the background estimation includes both the statistical and systematic uncertainties. Also shown are two examples for signals as expected for gluino R -hadrons in the explored mass range.

in the signal and background yields, as evaluated in Section 5.2.5 and Section 5.2.6, are treated as Gaussian-distributed nuisance parameters. The statistical uncertainty in the background distribution also takes into account the uncertainty due to the normalization. Lower limits on the R -hadron mass are then derived, for each lifetime, by comparing the measured cross-section upper limits to the theoretically predicted production cross-section. The resulting lower limits set on the mass of the stable and metastable particles are summarized in Table 5.7.

Table 5.7 Observed and expected 95% CL lower limit on mass is listed for gluino R -hadrons that are either stable or decaying to $q\bar{q}$ plus a light neutralino of mass $m(\tilde{\chi}_0) = 100$ GeV. The stable selection is more efficient for lifetimes of 50 ns or more.

Selection	τ [ns]	$M_{\text{obs}} > [\text{GeV}]$	$M_{\text{exp}} > [\text{GeV}]$
Metastable	0.4	740	730
"	1.0	1110	1150
"	3.0	1430	1470
"	10	1570	1600
"	30	1580	1620
"	50	1540	1590
Stable	50	1590	1590
"	stable	1570	1580

The strongest mass limits are obtained for lifetimes of 10 ns or more. The cross-section upper limits for 10 ns lifetime R -hadrons decaying to $q\bar{q}$ plus a light neutralino of mass $m(\tilde{\chi}_0)=100$ GeV are shown in Figure 5.8. For this signal, the expected and observed lower mass limits are 1600 GeV and 1570 GeV, respectively. The 8 TeV result excluded R -hadrons with a 10 ns lifetime and masses up to 1185 GeV, using the lower edge of the $\pm 1\sigma$ band around the theoretical cross-section.

The excluded regions on the lifetime–mass plane for R -hadrons decaying to $q\bar{q}$ plus a light neutralino of mass $m(\tilde{\chi}_0)=100$ GeV are shown in Figure 5.9.

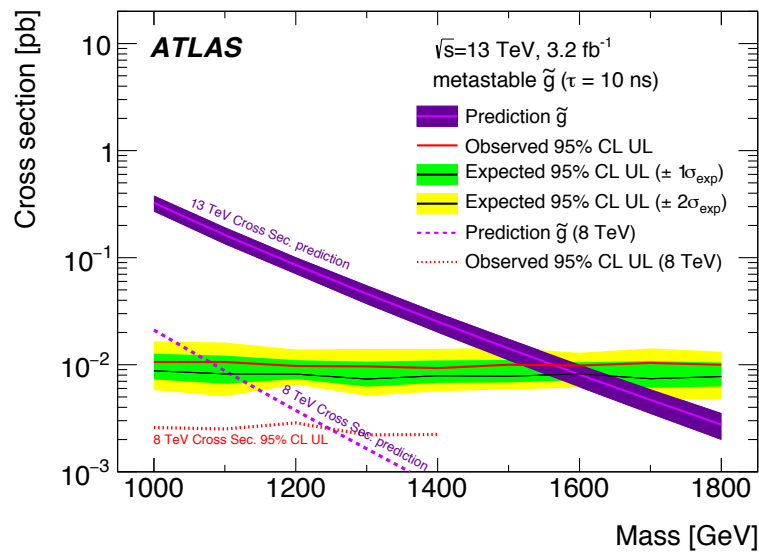


Fig. 5.8 cross-section as a function of mass for gluino R -hadrons with lifetime $\tau=10$ ns, decaying to $q\bar{q}$ plus a light neutralino of mass $m(\tilde{\chi}_0) = 100$ GeV. Theoretical values for the cross-section are shown with their error. The expected upper limits (UL) in the case of background only is shown by the solid black line, with its $\pm 1\sigma$ and $\pm 2\sigma$ bands, green and yellow respectively. The observed 95% UL is shown as a solid red line. The cross-section for the same process and the corresponding 95% UL measured at $\sqrt{s} = 8$ TeV [18] are shown as dashed lines.

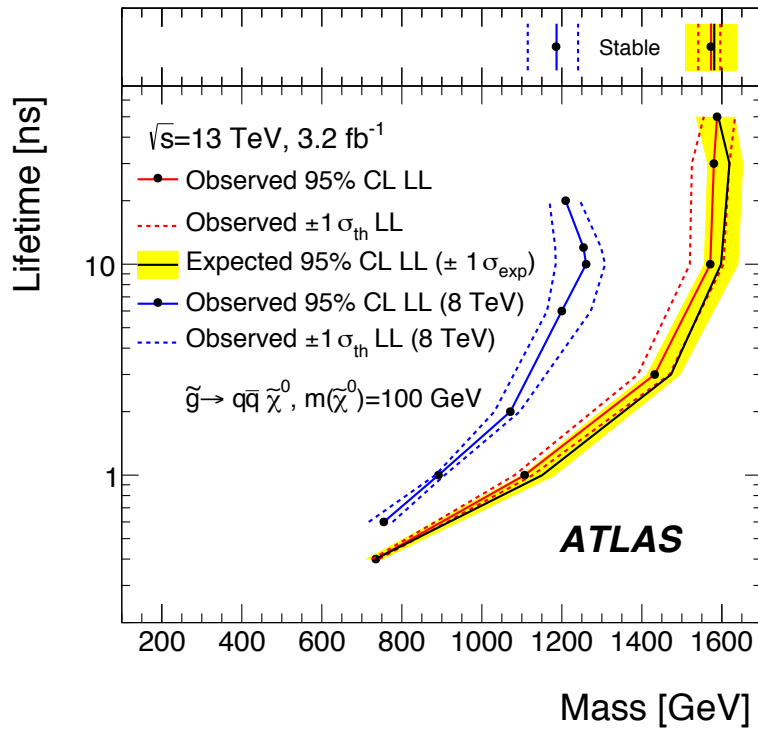


Fig. 5.9 Excluded range of lifetimes as a function of gluino R -hadron mass. The expected lower limit (LL), with its experimental $\pm 1\sigma$ band, is given with respect to the nominal theoretical cross-section. The observed 95% LL obtained at $\sqrt{s} = 8 \text{ TeV}$ [18] is also shown for comparison.

5.3 Analysis Improvements and Discovery perspectives with LHC 2016 Data

The analysis described in previous subsections is currently ongoing with LHC $\sqrt{s} = 13$ TeV 2016 data, where ATLAS detector has recorded more than 40 fb^{-1} . Having an integrated luminosity greater than about one order of magnitude than 2015, this analysis should improve the mass limit by $\approx 20\%$ or find a signal. In 2016 analysis some improvements and studies have been performed. In the following the main changes are reported:

- As seen in Chapter 4 the dE/dx has a slightly dependence on the pseudorapidity η of the track. To mitigate the effect a data-driven correction factor to the track dE/dx in order to make it flat in η has been applied. In this way the Bethe-Bloch calibration will take into account the track η and thus the mass will not have a slight η dependence. Unfortunately for 2016, since data was already partially processed the correction shown in Section 4.2.2.1 has not been applied yet at ATLAS reconstruction framework level.
- As already discussed in 2015 analysis the calibration of the dE/dx was done through a global fit of the three dE/dx curves for low momentum protons, kaons and pions. The reconstructed momentum p is underestimated for $p < 500$ MeV due to the assumption that all tracks are pions (this is the more reasonable hypothesis applicable to treat multiple scattering). This is reflected on the analysis giving a bias in the R -hadron mass measurement at low β . To avoid this problem the calibration has now been changed to include the momentum correction. In this framework also the Bethe-Bloch fit formula has been approximated by a simpler parametrization for non-relativistic particles: $MPV_{dE/dx}(\beta\gamma) = A/(\beta\gamma)^C + B$. This function has been already used by CMS Experiment [99] with good results. In [100] is possible to find a complete dissertation of this approximation.
- As reported in 4.2.2 the charge collected by the Pixel Detector seems to have a decrease during the 2016 period as consequence of the accumulated dose. As done in 2015 (sec. 5.2.3) some corrections on dE/dx MPV are necessary to efficiently cope with the rate increase. In comparison with 2015 as Fig. 4.9 shows the change in dE/dx is larger than before and dominated by the radiation damage of the pixel B-layer (Fig. 4.10).

- The insertion of the IBL in the ATLAS Pixel Detector makes possible to reconstruct short tracks ("Tracklets") using only the pixel hits. Using the tracklets the sensitivity in the low lifetime region (1 ns or below) should be increased.

Towards the HL-LHC: Pixel detector technologies for the Inner tracker (ITk)

The technologies developed for IBL are the starting point for the LHC upgrades projects (HL-LHC) when the instantaneous luminosity should reach $\sim 5\text{--}7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, up to 200 interactions per crossing (pile-up) and a total integrated luminosity of 3000 fb^{-1} . In particular, the current trackers will be completely replaced. In HL-LHC the trackers should operate under high fluencies (up to $1.4 \times 10^{16} \text{ n}_{eq} \text{ cm}^{-2}$), with a correlated high radiation damage. The pixel detectors, the innermost part of the trackers, will need a completely new design in the readout electronics, sensors and interconnections. A new 65 nm front-end (FE) electronics is being developed by the *RD53* collaboration. It will be compatible with smaller pixel sizes than the actual ones to cope with the high track densities. Consequently the bump density will increase up to $4 \cdot 10^4 \text{ bumps/cm}^2$. The possibility to develop bump-bonding at high density and find new hybridization forms will be crucial for HL-LHC experiments upgrades and above all for the planned ATLAS Pixel detector upgrade of 2025. In this Chapter I have reported my work on resistive chains using high density bump bonding on 6" and 12" wafers (Sec. 6.2.1.1) and some results on the ongoing R&D on capacitive coupling for HV-CMOS detectors (Sec. 6.2.1.2). In the upgrade framework I have studied new 3D sensors with smaller pixel sizes fabricated by Fondazione Bruno Kessler (Sec. 6.2.2.1) and the first CMOS sensor realized in the BCD8 technology by STMicroelectronics (Sec. 6.2.2.3). In Sec. 6.3 a laser system that I have developed and tested is described. The system has been built in order to evaluate parameters such as the efficiency and the time walk of the new sensors.

6.1 The High-Luminosity LHC Upgrade and Deficiencies of the existing *ATLAS* Inner Detector

The discovery of the Higgs boson by *ATLAS* and *CMS* on July 2012 has been a great triumph for Particle Physics, but many unanswered questions are still open. The LHC should conclude its first life phase (*Phase I*) at the end of 2023 with an integrated luminosity for proton-proton collisions of of $\sim 300 \text{ fb}^{-1}$. High-Luminosity LHC (HL-LHC), with its expected integrated luminosity of $\sim 3000 \text{ fb}^{-1}$ will be able to maximize our understanding on SM and maybe it will open new physics scenarios beyond the SM. The ultimate luminosity reachable with HL-LHC upgrade will be $L \sim 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and the expected average pile-up μ will be ~ 200 [101]. Some improvements are necessary to achieve accelerator performance, in particular during Long Shutdown 3 (LS3) starting at the end of 2023 will include major performance upgrades of the accelerator for the high-luminosity phase. Here a new tracking detector will be required for the *ATLAS* detector during HL-LHC: the Inner Tracker (ITk) [102]. To sustain the increasing of the trigger rate due to higher luminosity, changes to the trigger architecture are also planned. The Level-0 trigger will be moved to 1 MHz with a minimum latency of $6 \mu\text{s}$ and the second hardware trigger (Level-1) at a maximum sustained rate of 400 kHz with minimum latencies of $30 \mu\text{s}$.

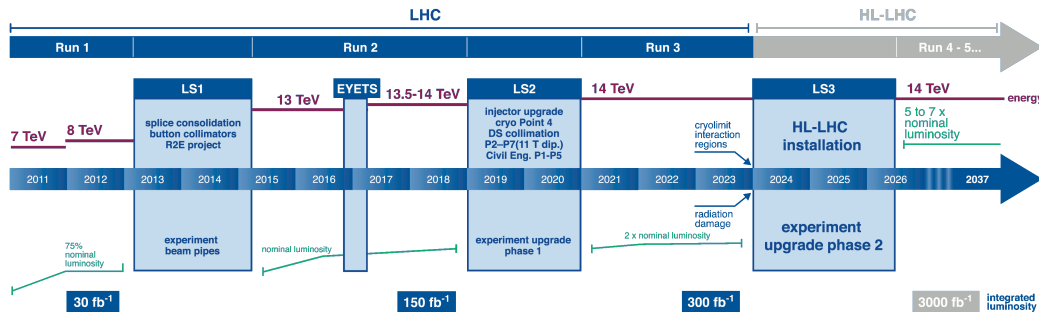


Fig. 6.1 Status of the LHC baseline programme including the HL-LHC run.

The current *ATLAS* Inner Detector (ID) was designed for 10 years of operation, at a peak instantaneous luminosity of $1.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, 14 TeV centre-of-mass energy, 25 ns between beam crossings and ~ 23 inelastic proton-proton collisions per beam-crossing. The front-end was designed around a single (hardware) Level-1 trigger signal running up to 100 kHz. The current pixel detector was designed using radiation hard sensors and electronics to sustain an equivalent radiation damage corresponding to integrated luminosity of 400 fb^{-1} . The Semi-Conductor Tracker (SCT) was designed and constructed to operate up to integrated luminosity of 700 fb^{-1} . This was before the insertion of the Insertable B-Layer. The Insertable B-Layer (IBL) was instead designed

for a fluences equivalent to 850 fb^{-1} . By inserting the IBL, the additional material in the services will increase the fluence in the SCT end-caps by nearly a factor of 2 thus reducing the expected original design lifetime. Therefore, the specifications for radiation tolerance of the detectors in the current ID are significantly below to the 3000 fb^{-1} that will be collected at the end of the lifetime of the High Luminosity LHC.

Further problems are present in the bandwidth saturation and the occupancy. The front-end electronics of both the pixel and SCT can accommodate events with about 50 proton-proton interactions per crossing and sustained instantaneous luminosity of about $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Beyond this value limitations in the buffering and the links between the on-module electronics and the read-out driver card (ROD) will lead to inefficiencies [101].

Concerning the occupancy, with the expected pile-up at the HL-LHC the SCT would be unable to resolve close-by particles, and the TRT straws will approach 100 % occupancy. Some degradation in the TRT performance has already been observed in the most central heavy-ion collisions.

6.1.1 Inner Tracker (ITk) Layout

Due to the motivations outlined in the previous section, at the end of Phase I the whole of the inner tracker (TRT and silicon) will be removed, and it will be replaced with an all-silicon tracker which fills the existing tracking volume. An all-silicon-detector tracker is proposed, with pixel sensors within a radius of 362 mm around the beamline, surrounded by microstrip sensors outside of this radius. The current *ATLAS* Inner Detector has a pseudorapidity η coverage of $|\eta| < 2.5$. The ITk will have η -coverage at least of $|\eta| < 3.2$ and at the moment the scenario up to $|\eta| < 4$ is suggested. The design and sensor layout of the ITk are not yet finalised. Four possible layouts are being considered, as shown in Fig. 6.2:

- *STEP 1 Layout concept: Extended 3.2* with an η -coverage up to 3.2. The layout consists of pixel barrel stave designs with all sensors parallel to the beam-line. In this layout high- η particles will pass at shallow angles, creating elongated charge clusters. The cluster length information can be used to determine the incident angle of incident particle.
- *STEP 1 Layout concept: Extended 4.0* with an η -coverage up to 4. This layout has the same concepts of *Extended 3.2* but with higher extension in η .

- *STEP 1 Layout concept: Fully inclined 4.0* with an η -coverage up to 4. The aim of this layout is to have sensors more perpendicular to incoming particles. In this way the material and cluster size can be reduced, but the number of hits is increased.
- *STEP 1 Layout concept: Inclined 4.0* with an η -coverage up to 4. This layout is an hybrid between *Extended 4.0* and *Fully inclined 4.0*

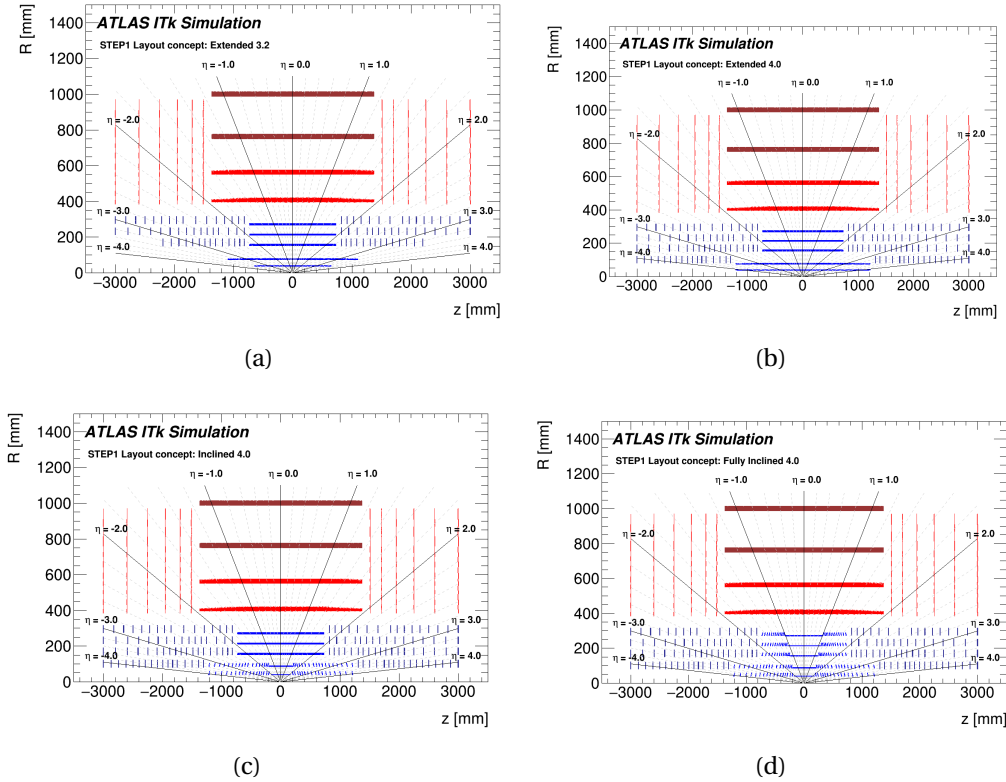


Fig. 6.2 Simulated hit positions on the R-z plane for a simulated *ATLAS* Inner Tracker layout with extended inner barrel layers, optimized for measuring at least 9 space points on tracks up to $|\eta| < 3.2$ or $|\eta| < 3.4$ for $|z_0| < 150$ mm. Pixels (blue), short strips (light red) and long strips (dark red) are shown.

Depending from the layout chosen the Inner Tracker is expected to have a total area up to 14 m^2 of pixel silicon modules.

6.2 Pixel Technologies for the HL-LHC

To cope with the high instantaneous luminosities expected in HL-LHC a new 65 nm front-end (FE) electronics is being developed by the RD53 collaboration. The new front-end chip

will be compatible with $50 \times 50 \mu\text{m}^2$ or $25 \times 100 \mu\text{m}^2$ pixel size sensors. Different sensor pixel technologies are currently being developed such as hybrid sensor and active hybrid pixel sensor. In the first case sensor pixels are connected to the readout chip through metallic bumps (see Sec. 2.2.3.2). The smaller pixel sizes imply up to 5 times the bump density used in the current *ATLAS* Insertable B-Layer ($4 \cdot 10^4$ bumps/ cm^2 in comparison of $8 \cdot 10^3$ bumps/ cm^2 of an IBL module) and consequently an order of $1.2 \cdot 10^5$ pixels per FE-I4 size chip¹ ($1.92 \times 2.08 \text{ cm}^2$). In the second case the so-called semi-monolithic detectors (e.g. HR/HV-CMOS), having amplifier stages implemented in the sensor part, allow interconnections using a capacitive medium like a glue layer between FE and the sensor rather than resistive coupling. The pixel electronics of HV-CMOS detectors is based on nMOS and pMOS transistors (CMOS-electronics), embedded inside a single deep n-well that acts as a charge-collection electrode. Thanks to n-well process, the low-voltage devices is separated from the p-type substrate. The HV-CMOS technology was implemented for the first time in 2006 [45] and allows to apply up to 100 V for biasing the diode. Studies performed on hybridization technologies are reported in Sec. 6.2.1, instead some results on new FBK 3D sensors production and CMOS sensors based on BCD8sP process by STMicroelectronics are shown in Sec. 6.2.2.

6.2.1 Hybridization Technologies

During 2016 dummy 6" wafers with resistive and capacitive chains have been designed by INFN and produced by FBK² to test high density indium (*In*) bump-bonding (see Sec. 2.3.1.2) and capacitive coupling (see Sec. 2.3.2), respectively. Moreover a *In* bumps deposition has been also performed on blank 12" wafers without resistive chains. The layout of resistive chains tiles on 6" wafers was chosen to have a final bump density close to the one expected for the front-end chip of HL-LHC Detector upgrades. In the following subsections a summary of first results is reported.

6.2.1.1 High Density Bump Bonding

Dummy resistive chains have been used to check the capability of Leonardo-Finmeccanica to deposit and flip-chip $\sim 4 \text{ cm}^2$ devices with high bump density, since the availability of a small pitch readout (first RD53 full scale prototype) is expected in mid-2017. The resistive chain layout on $640 \mu\text{m}$ thick 6" silicon wafers have been produced by FBK. Each wafer contains 30 FE-I4 size dummy tiles, with two dimensions of diameter for the

¹An IBL module consists of 26880 bumps per readout front-end

²Fondazione Bruno Kessler, Trento (IT)

passivation opening (10 and 12 μm) and a bump density of $4 \cdot 10^4$ bumps/ cm^2 . FE-I4 size was chosen since the new readout chip for HL-LHC upgrades has not a defined size yet, but its dimension is expected to be close to the actual generation of front-end chip. The layout includes metallic lines between pads that form a chain once the flip-chip of the two tiles is performed. The dummy tiles have probing pads at the end of the chains on both sides in order to detect missing or merged bumps. Thanks to this design a single missing bump generates an interruption of the chain, while merged bumps produce shorts between the chain. Both situations are detectable by the measurement of the resistance between the two probing pads. Due to a limited amount of space for pads in the tile periphery only $2.13 \cdot 10^4$ (124 chains of 172 bumps) over $1.2 \cdot 10^5$ bumps may be effectively probed. The bump deposition and the flip-chip was performed by Leonardo-Finmeccanica using two different bump sizes (see Fig. 6.3) of 12 (16) μm for a passivation opening diameter of 10 (12) μm respectively.

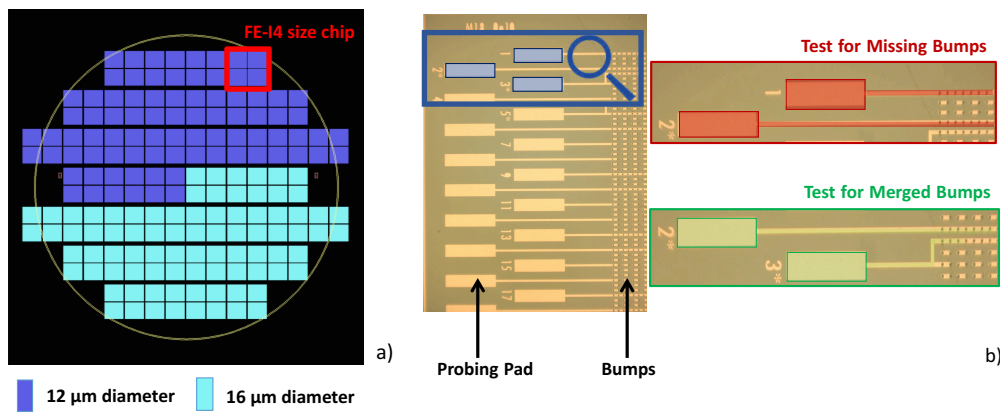


Fig. 6.3 a) The bump deposition and the flip-chip has been performed using two different bump sizes: 12 and 16 μm bumps. b) A picture of the bump deposition before flip-chip. Some probing pads to test the resistive chains are also shown. As example pads numbered as 1 and 2 can be used to check missing bumps (dark red pads), instead 2 and 3 for merged ones (green pads).

Some tiles with bump deposition only were analysed with a mechanical profilometer (KLA-Tencor P7) showing a bump height of 10 ± 1 μm and a diameter compatible with what was expected for both bump types, as shown in Fig. 6.4.

These values are also compatible with what was measured during *ATLAS* pixel production modules. The flipped chips have been scanned with X-ray at 120 keV (Fig. 6.5) to check the indium distribution on the entire surface and the uniformity of the pressure applied on the chip area during the assembly. The results obtained together with uniform electrical resistance values all over the assembly of 11 ± 2 Ω per bump (compatible with the

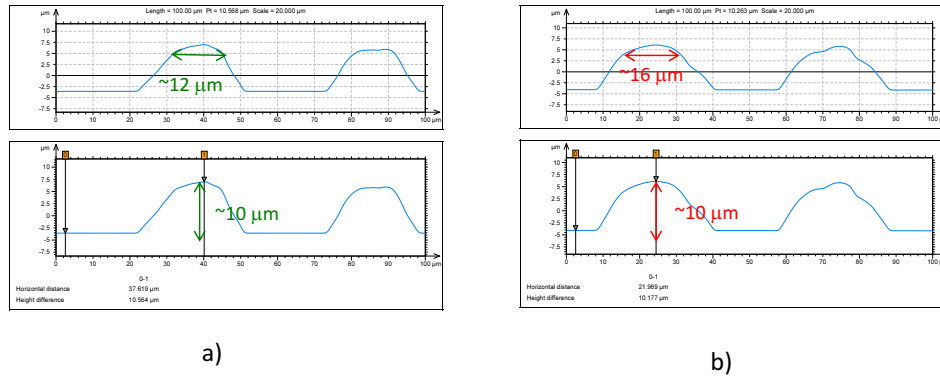


Fig. 6.4 Measurements of bumps dimension before the flip-chip, done in Genova using KLA-Tencor P7 mechanical profilometer. Picture a) and b) shows 12 and 16 μm bumps size.

10 Ω per bump obtained for the *ATLAS* pixel production), show that a uniform pressure was applied. In Fig. 6.6 the initial distribution of the resistance of single bump after the breaking of the indium oxide is reported for 12 and 16 μm bumps respectively. In the same figure the trend of single bump resistance after several HV cycles is also shown.

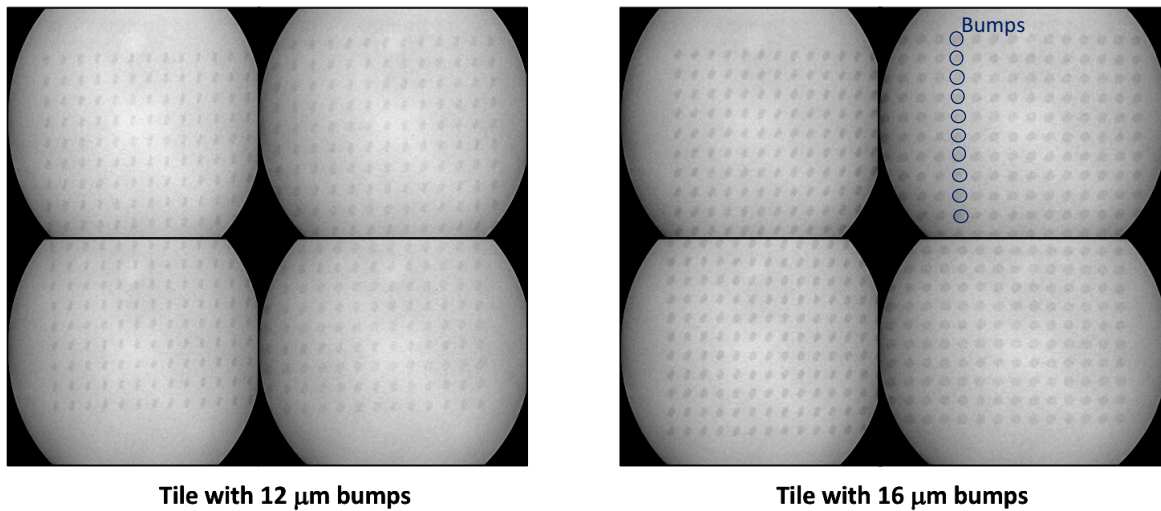


Fig. 6.5 Four corner X-ray images of a silicon dummy assembly showing the good level of planarity reached by the flip-chip process for both bump size chosen, confirmed also by the uniformity of the resistance measurements.

Concerning 12" wafers size, only the deposition of bumps without resistive chains was performed on one wafer. It was visually analysed and bumps height were measured using the KLA-Tencor P7 mechanical profilometer. Preliminary results show a uniform bump

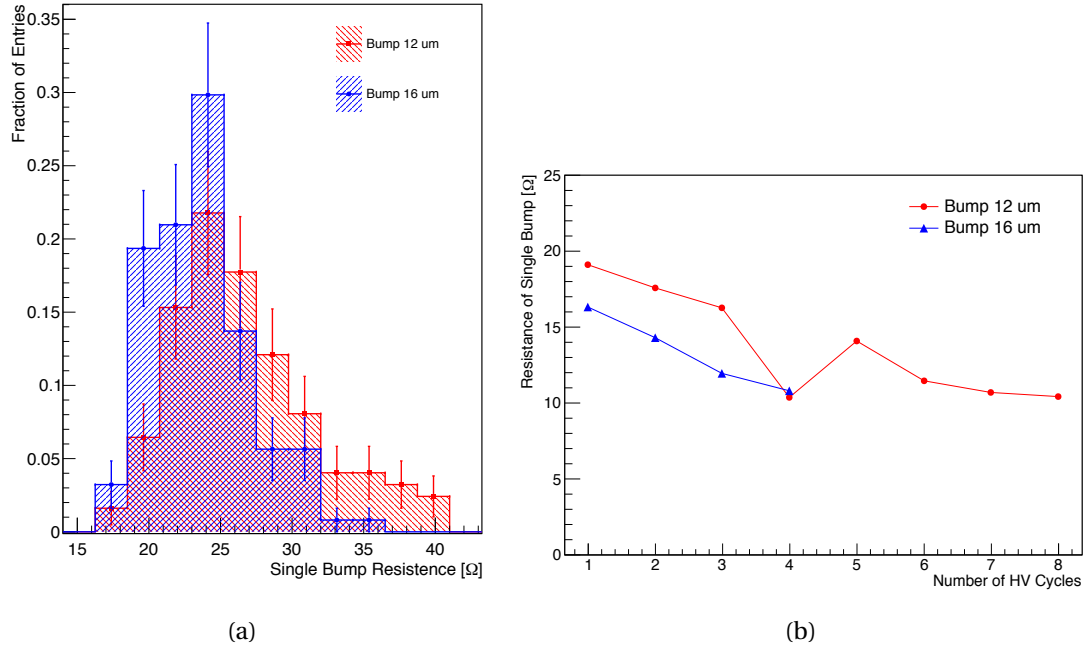


Fig. 6.6 a) Distribution of the resistance of single bump after the breaking of the indium oxide. The mean values obtained with a gaussian fit are compatible: 24.8 ± 0.5 and 24.4 ± 0.7 Ω for 12 and 16 μm bumps respectively. b) Trend of single bump after resistance for 12 and 16 μm bumps after several HV cycles.

height (10 ± 2 μm). By the beginning of 2017 more tests will be also performed on thin 12" wafers with resistive chains, the layout in production is shown in Fig. 6.7.

6.2.1.2 Capacitive Coupling

We started capacitive studies in 2014, with first preliminary tests and assemblies on glasses. In 2015, this technology was extended to CCPD (Capacitively Coupled Pixel Detector) with a successful capacitive coupling between a front-end (FE-I4) and a small High Voltage CMOS (HV-CMOS) sensor. The capacitive coupling can be done through metal pads (typical values for passivation opening are about 18 μm), present on the facing HV-CMOS and on the FE chip.

During 2016 a batch of 6" dummy silicon wafers was produced at Fondazione Bruno Kessler (FBK) with capacitive structures to test uniformity of glue thickness layer. Each wafer contains 30 FE-I4 size tiles with a different number of capacitors per tile (24, 32 and 48). The single capacitor area is different for tile with 24 capacitors is 1.5×1.5 mm^2 ,

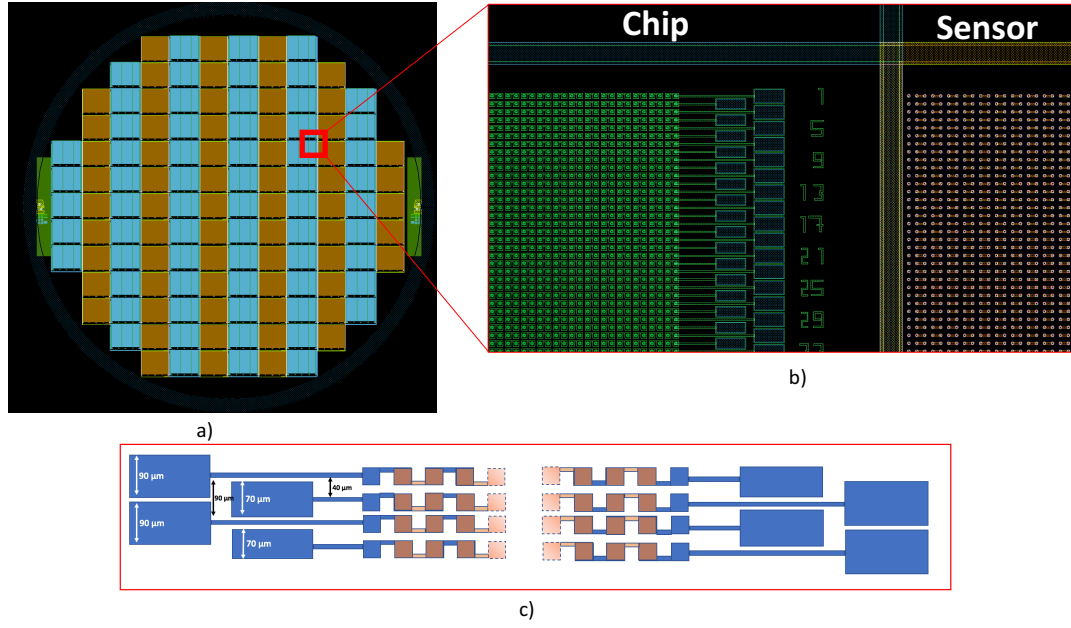


Fig. 6.7 Dummy chains on 12-inch wafer. a) On the wafer are present 62 dummy chip and sensor tiles with a dimension of $\sim 1.92 \times 2.08 \text{ cm}^2$ respectively. On each tile is present a pixel matrix of 400×336 , close to the final RD53 FE chip. b) Zoom of a portion of tile and sensor, this layout was chosen to avoid electric arc between 2 adjacent bumps between two contiguous rows. c) Sketch of chain after the flip chip between the dummy chip and sensor.

instead for 32 and 48 ones is $0.5 \times 1.5 \text{ mm}^2$. In Fig. 6.8 a picture with the corresponding project file from GDSII³ is shown.

Considering the plate areas (S) mentioned, a relative dielectric constant (ϵ_r) of the coupling medium of $\epsilon_r = 3.2$ (typical values for epoxy glues), and a separation (d) between plates of $3 \text{ } \mu\text{m}$ the corresponding capacitance value is:

$$C = \epsilon_0 \epsilon_r \frac{S}{d} \quad (6.1)$$

$C \approx 10 \text{ pF}$ for $1.5 \times 1.5 \text{ mm}^2$ and $C \approx 3.5 \text{ pF}$ for $0.5 \times 1.5 \text{ mm}^2$ cases respectively. The measurement is performed on two capacitors in parallel and an equivalent capacitance $C_{meas} = C/2$ can be therefore estimated. However the first wafer production showed a non negligible contribution of the expected parasitic capacitance between the pad and the silicon oxide used for the passivation. In Fig. 6.9 the equivalent electric circuit is shown. The parasitic model has to be considered as at least composed by three different parasitic

³The GDS (Graphic Database System) is a database file format which is the de facto industry standard for data exchange of integrated circuit or IC layout.

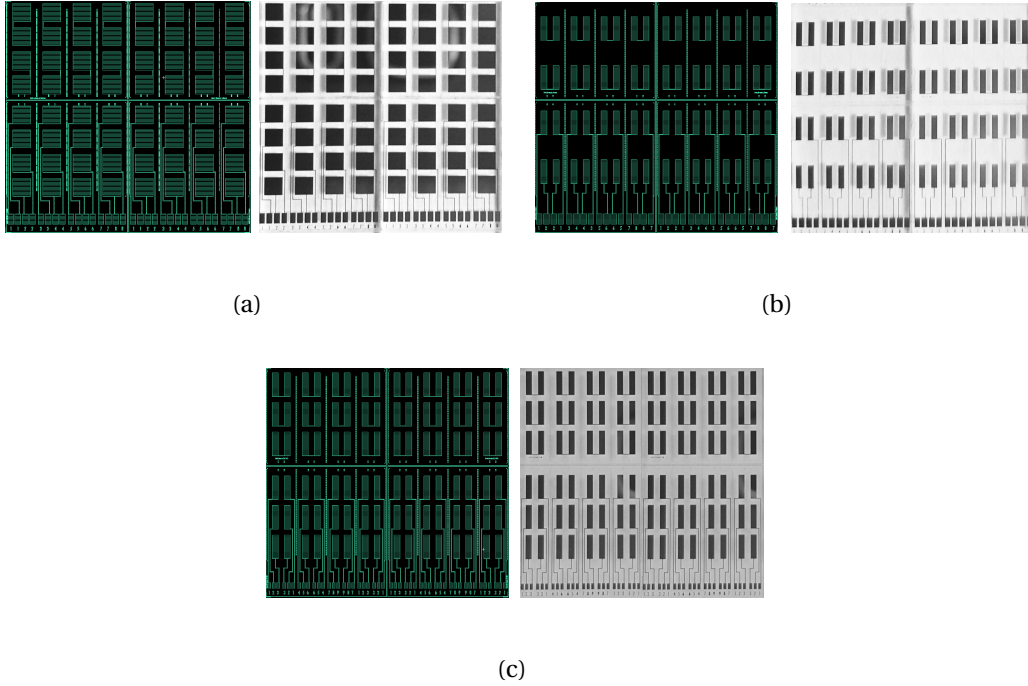


Fig. 6.8 GDSII project and a picture of the corresponding tile on quartz. a) 24 capacitors with a single plate surface of $1.5 \times 1.5 \text{ mm}^2$ b) 32 capacitors with a single plate surface of $0.5 \times 1.5 \text{ mm}^2$ c) 48 capacitors with a single plate surface of $0.5 \times 1.5 \text{ mm}^2$

capacitances: the once between the two plates in the silicon bulk and the oxide (C_{Bulk} and C_{Oxide}) and the once from the plates to the substrate (C_{sub}). The measured capacitance in silicon tiles corresponds to the value expected in the model, with a value of $\sim 45 \text{ pF}$.

The observed problem can be simulated with tools such as HyperLynx 3D EM Design and COMSOL Multiphysics⁴. The results for C_{meas} for different substrate resistivity, using HyperLynx 3D EM Design, are shown in Fig. 6.10. Here is possible to observe that C_{meas} tends towards the expected value for high resistivity substrate values. Since silicon with such resistivity was not available on the market at the moment of survey, a fused quartz support with an electrical resistivity of $> 10^{18} \Omega \cdot m$ has been chosen for a new production.

The new batch has been produced by MicroFab Solutions⁵. The first wafer received (without pillars) allowed to perform the first assemblies using the tiles with 24 capacitors (cut in 1/4 FE-I4 size). In first assemblies two different type of glues (Araldite 2011 and 2020) and a tape (ARclad 5913) have been chosen. In this way the gluing uniformity of the process has been evaluated, extrapolating from Eq. 6.1 the height between the capacitor

⁴A cross-check with a different simulation tool has been performed at Université de Genève, Genève, CH.

⁵Povo di Trento, Trento (Italy)

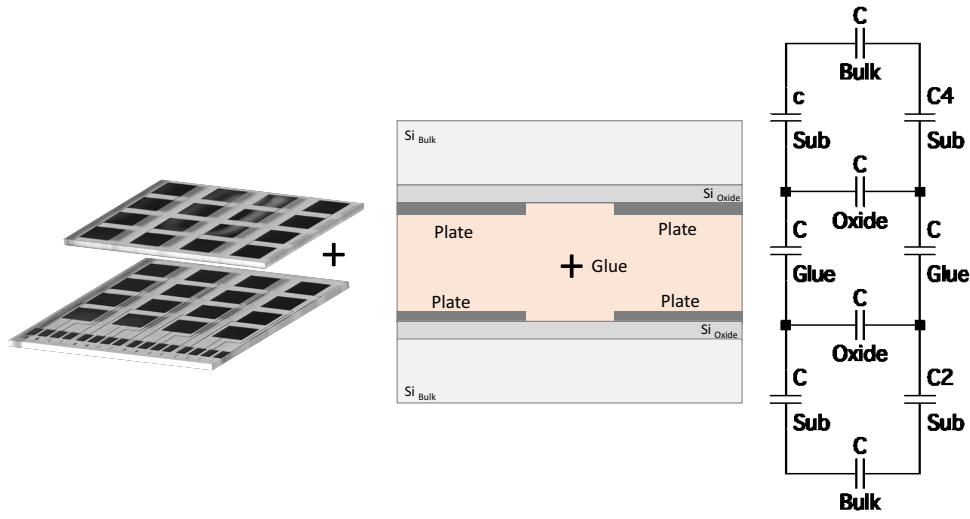


Fig. 6.9 The equivalent electric circuit of the one tile after the assembly is reported. C_{glue} is the goal capacitance to measure. The other three capacitances are parasitic and should be made as small as possible. C_{Ox} and C_{Si} are the capacitance between two plates in the oxide and the silicon respectively. C_{Sub} is the capacitance from one plate to the biased substrate.

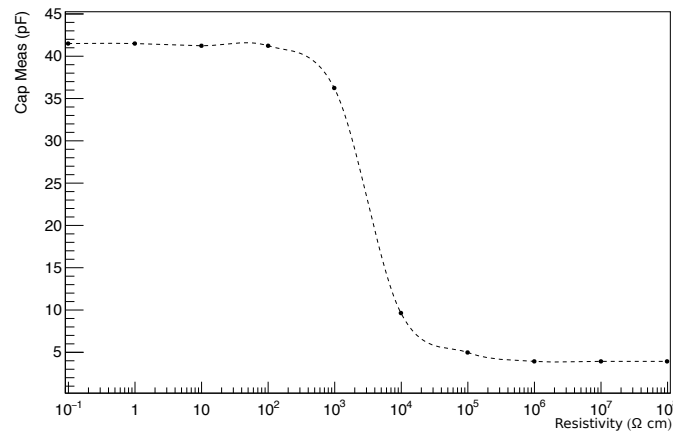


Fig. 6.10 Value of C_{meas} for different substrate resistivity using HyperLynx 3D EM Design is shown.

plates in different positions of the tile:

$$h_{eq} = d = \epsilon_0 \epsilon_r \frac{S}{2C_{meas}} \quad (6.2)$$

The measurements have been performed with an HP 4280A capacitometer at a frequency of 1 MHz. It is important to take care of the frequency, since a decrease in the dielectric constant with increasing frequency is expected due to the dielectric relaxation, as the speed of dipole rotation at high frequency is insufficient to match the shift in the applied AC bias [103]. In Fig. 6.11 an example of C-V measurement for frequencies from 1 kHz to 5 MHz taken with a B1500A Semiconductor Device Analyser of Keysight for a tile assembled with Araldite 2020 is shown.

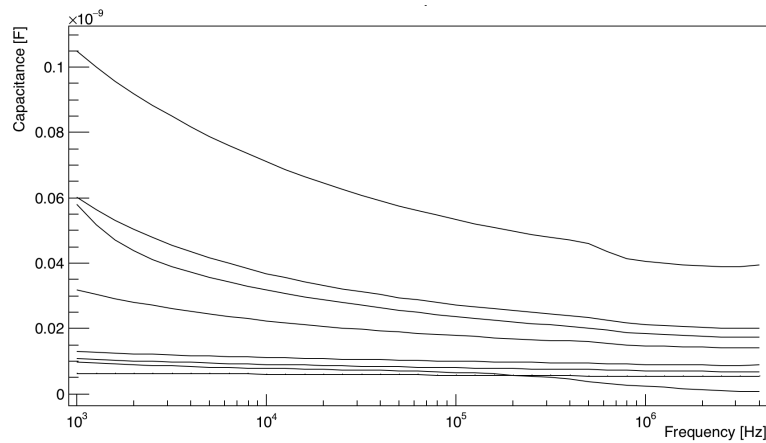


Fig. 6.11 C-V measurement for frequencies from 1kHz to 5MHz taken with a B1500A Semiconductor Device Analyser of Keysight performed on a tile assembled with Araldite 2020 at 25 °C.

In Fig. 6.12 an example is reported for ARclad 5913 and Araldite 2020 cases. The tile assembled with ARclad 5913 shows a good uniformity the capacitor heights with a difference of $\sim 1 \mu\text{m}$ between the upper and the lower part of the tile. ARclad has a declared height of $25 \mu\text{m}$, before the assembly. The tile assembled with Araldite 2020 shows instead a lower uniformity of the capacitor heights with a maximum variation of $\sim 4 \mu\text{m}$. The alignment between the plates on XY plane has been cross-check with a microscope finding a maximum variation of $5 \pm 1 \mu\text{m}$. Considering a misalignment of $5 \mu\text{m}$ on XY directions, this impact on the extrapolated equivalent heights for only 1%. Some assemblies with a different flip-chip machine⁶ have been also performed at Université de Genève with 48 capacitors FE-I4 size tiles to cross-check the used flip-chip pressure (50 kPa) and the correct alignment of the flip-chip head of Genoa. In Fig. 6.13 a picture of FE-I4 size tile with 48 capacitors and assembled with Araldite 2011 is shown. The estimated equivalent height are also shown. The result shows a maximum variation

⁶Accura 100 semi-automatic flip-chip machine of Smart Equipment Technology (SET).

of $\sim 9 \mu\text{m}$. The obtained results suggest a worse control of the glue assemblies probably dominated by the wafer bow⁷ that is guaranteed to be $< 20 \mu\text{m}$.

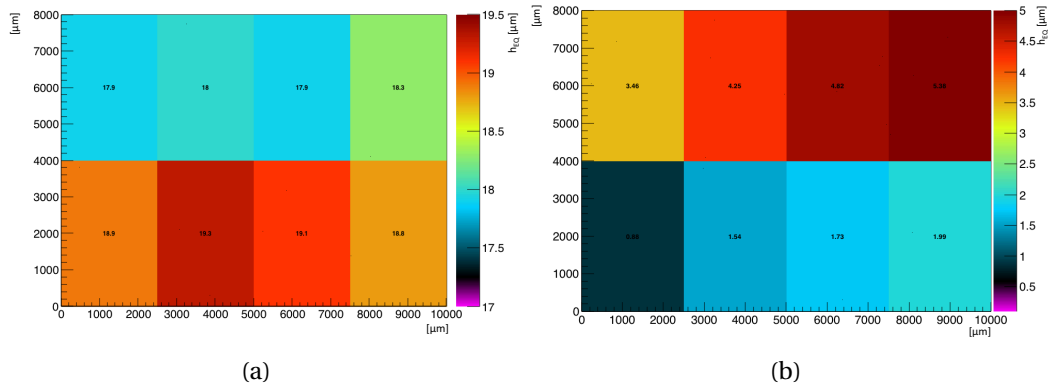


Fig. 6.12 a) The tile assembled with ARclad 5913 shows a good uniformity the capacitor heights with a difference of $\sim 1 \mu\text{m}$ between the upper and the lower part of the tile. ARclad has a declared height of $25 \mu\text{m}$, before the assembly. b) The tile assembled with Araldite 2020 shows a worse uniformity the capacitor heights with a maximum variation of $\sim 4 \mu\text{m}$. This is due to a lower control of the glue during the flip-chip process in comparison with the tape. The quoted error is 2 % of the height value shown.

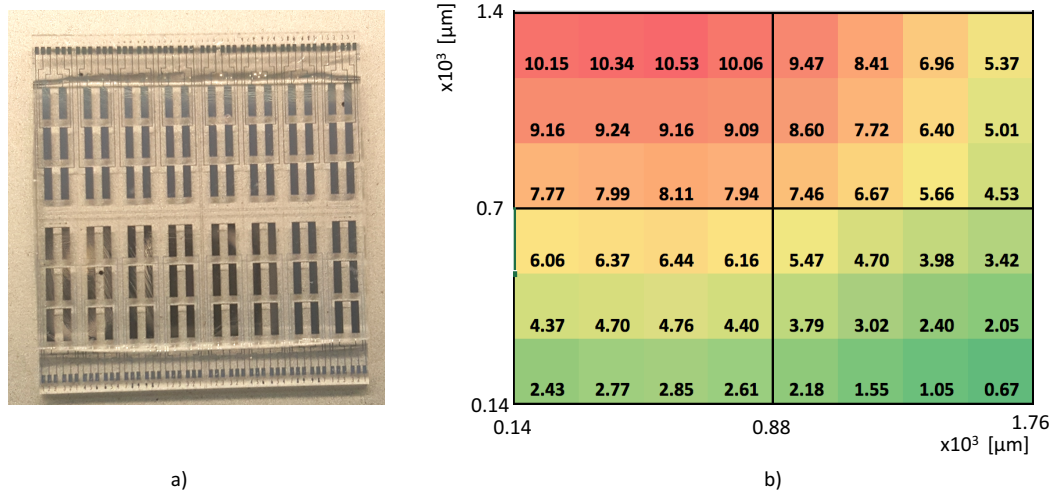


Fig. 6.13 a) Picture of a 48 capacitors FE-I4 size tiles assembled with Araldite 2011. b) Estimated equivalent height in μm . The quoted error is 2 % of the height value shown.

The stability of the capacitance value versus temperature (Fig. 6.14) for different coupling medium (Araldite 2020 and 2011) has also been tested.

⁷The wafer bow is defined as the deviation of the centre point of the median surface of a wafer from the median surface to the reference plane.

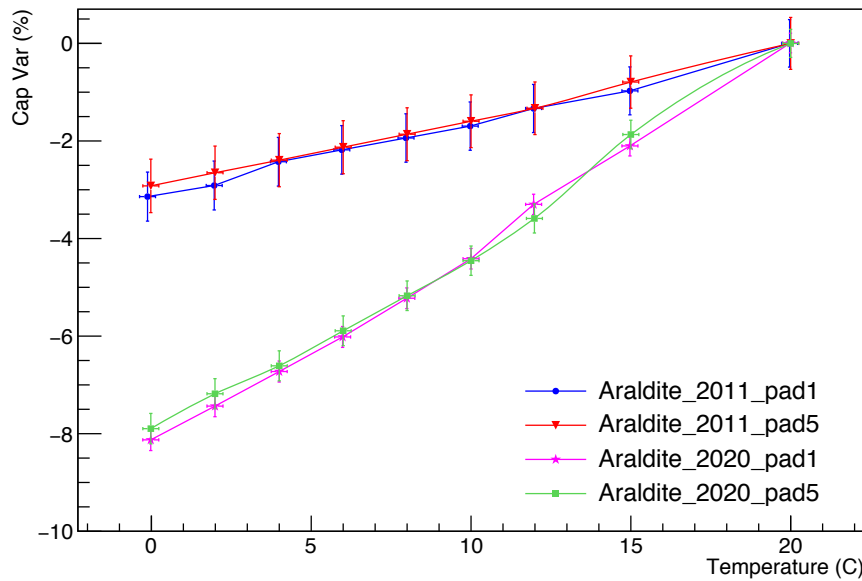


Fig. 6.14 Stability of the capacitance value versus temperature for different glues (Araldite 2020 and 2011) for various capacitor positions in the tile. The quoted error includes the negative thermal expansion of the aluminium plates.

Some assemblies have also performed using MasterBond UV15DC80LV. It is a special dual cure epoxy based system which offers a primary cure utilizing UV light (365 nm) along with a secondary heat curing mechanism (from 80 °C to 125 °C). This system addresses the problem of curing areas on parts that do not allow UV light curing because of “shadowing” issues. The UV curing mechanism, with tested times < 4 min (faster cures can be achieved at higher energy outputs.) can be very useful in future capacitive CMOS production line reducing the flip-chip machine time-consumption.

A deposition on silicon tiles with 3, 6 μm thick pillars respectively was performed. The measurements, performed with KLA-Tencor P7 mechanical profilometer, show a good planarity and uniform distribution of the pillars as it is shown in Fig. 6.15 for the 3 μm case.

In February 2017 tiles with 3, 5 and 7 μm thick pillars, made by Microchem KPMR⁸ produced by MicroFab should be received and first gluing tests performed.

At the moment, the available CMOS prototypes need a capacitance of at least of ~ 3 fF to properly propagate the signal. This means that considering a passivation opening of ~ 15 μm , the equivalent height can be roughly estimated close to ~ 1 μm . Since usually the

⁸It is a high contrast, epoxy based photoresist

metallization of the pads are $\sim 1 \mu\text{m}$, the $3 \mu\text{m}$ pillars could be a good choice to control the thickness of the glue between the readout chip and CMOS sensor.

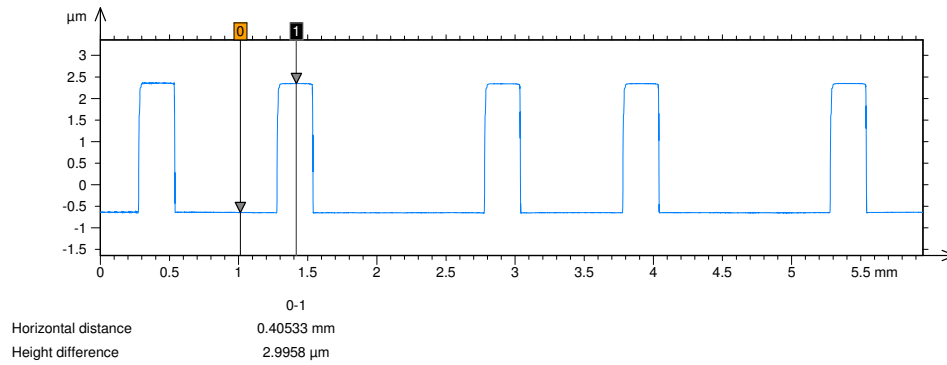


Fig. 6.15 In the plot a pillar measurement for the $3 \mu\text{m}$ case is shown. The height measurement was performed using the KLA-Tencor P7 mechanical profilometer.

6.2.2 Sensors

In this section a brief description and results for two sensor technologies currently in development, in the INFN Phase-2 program framework, are given. Firstly in Sec. 6.2.2.1 some results from new generation of 3D sensors is given, instead in Sec. 6.2.2.3 preliminary results on HV-CMOS technology based on BCD8 (Bipolar - CMOS - DMOS, version 8) at 160 nm are shown.

6.2.2.1 New FBK 3D Sensors

3D technology has been proven to be reliable with the IBL detector, and more recently in AFP [104] and PPS [105] detectors. It is the baseline for the innermost layers of *ATLAS* ITk upgrade, thanks to excellent radiation hardness (with HL-LHC fluence of $1 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$ the efficiency is tested to be 97% at $\sim 180 \text{ V}$) at low operational voltages and moderate temperatures with low power dissipation ($12\text{-}15 \text{ mW}/\text{cm}^2$ power consumption at -25°C). A new generation of 3D sensors has been developed in the framework of the INFN Phase-2 program and fabricated by FBK on 6" wafers for High Luminosity LHC *ATLAS* and CMS inner trackers R&D programs. As seen, to reduce the material budget, sensors should have thinner active layers. Different options are currently available for the fabrication of thin pixels such as *Silicon On Insulator* (SOI)⁹ or *Epitaxial*¹⁰. For 3D sensor fabrication Si-Si Direct Wafer Bonded (DWB) wafers has been chosen. DWB is obtained bonding together two different wafers: a high-resistivity (HR) Float Zone sensor wafer and a low-resistivity (LR) Czochralski handle wafer. The wafer is thinned to the desired thickness value, so as to obtain a wafer with a thin active layer plus a relatively thick mechanical support layer. P-type wafers of two different active depths (100 and 130 μm) with 500- μm thick handle wafer were purchased from *IceMOS Technology Ltd* [106]. A schematic cross-section of the technological approach used for 3D sensors on DWB substrate is shown in Fig. 6.16. The column of 3D sensors are performed using the Deep Reactive Ion Etching (DRIE) technique from the front-side of the wafer. Two different depths have been used: slightly shorter $\sim 15 \mu\text{m}$ than the active layer for junction n^+ columns to obtain a high breakdown voltage, and slightly deeper than the active layer for ohmic columns, so that a good ohmic

⁹This technology refers to the use of a layered silicon-insulator-silicon substrate in place of conventional silicon substrates. SOI-based devices differ from conventional silicon-built devices in that the silicon junction is above an electrical insulator, typically silicon dioxide or sapphire.

¹⁰The word *epitaxy* comes from the Greek roots *epi*, meaning "above", and *taxis*, meaning to arrange. Thus, the epitaxial silicon deposition requires the ability to add and arrange silicon atoms upon a single crystal surface. Epitaxial silicon layers can be created with different techniques such as evaporation, sputtering, molecular beams and regrowth concepts.

contact is obtained by the highly doped handle wafer, making sensor bias possible from the back side [106].

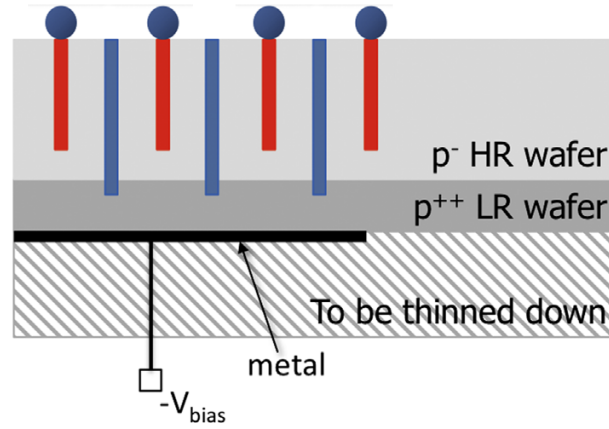


Fig. 6.16 Schematic cross-section of 3D sensors on on SiSi DWB substrate.

On the wafer several variants of pixel sensors FE-I4 compatible are available: sensors with small pixel dimensions ($50 \times 50 \mu\text{m}^2$, $25 \times 100 \mu\text{m}^2$) and some sensors with *ATLASIBL* pixel size ($50 \times 250 \mu\text{m}^2$) as shown in Fig 6.17. In Fig. 6.18 a summary of different pixel dimensions distribution on the wafer is reported. Here also the V_{BD} values measured for the first wafer produced after the deposition of the temporary metal layer as seen in 3.1.4.2 are shown.

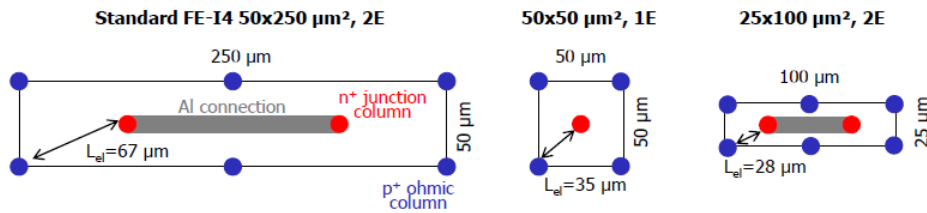


Fig. 6.17 On the wafer are present different pixels dimensions: $50 \times 50 \mu\text{m}^2$, $25 \times 100 \mu\text{m}^2$ and some sensors with *ATLASIBL* pixel size $50 \times 250 \mu\text{m}^2$.

6.2.2.2 Results

The sensors of FBK-W76 wafer, after the indium deposition and the flip-chip with FE-I4 readout chips performed at Leonardo-Finmeccannica, have been assembled and tested in Genova. In Fig. 6.19 an assembled module is shown as example.

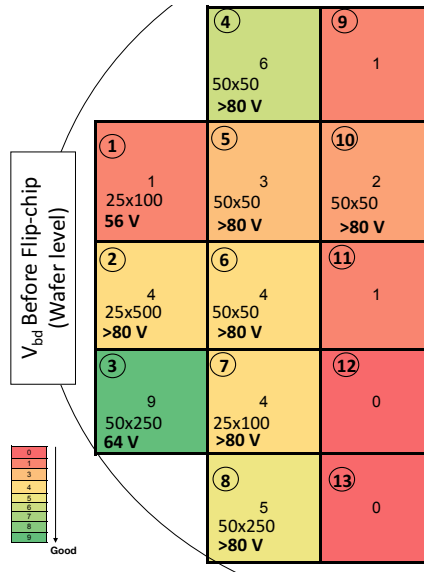


Fig. 6.18 In the new FBK production several wafer have been produced. In the sketch the yield of first FBK 3D wafer is reported (FBK - W76). The colour scale defines the quality of the sensor (9 - good to 0-very bad). The pixel dimensions and the V_{BD} values are also reported. Sensors number 9,11,12 and 13 have been rejected for either early breakdown or too-large leakage current.

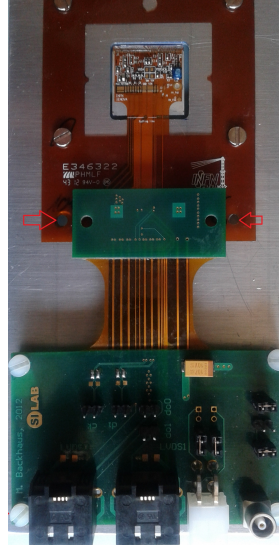


Fig. 6.19 An example of assembled module.

In Tab. 6.1 a summary of the measured voltage breakdown (V_{bd}) at wafer level and before and after the assembly are reported. In that table is possible to observe a mismatch between the measurements performed at wafer level and the ones before and after the module assembly. The reason of this variation is currently under investigation.

Device ID	Pixel size [μm^2]	Wafer V_{bd} [V]	Before Assembly V_{bd} [V]	After Assembly V_{bd} [V]
W76-1	25×100	56	24	24
W76-2	25×100	> 80	15	15
W76-3	50×250	64	25	25
W76-4	50×50	> 80	15	15
W76-5	50×50	> 80	2	2
W76-6	50×50	> 80	12	12
W76-7	25×100	> 80	> 80	> 80
W76-8	50×250	> 80	38	12
W76-10	25×100	> 80	> 80	> 80

Table 6.1 Summary of the measured voltage breakdown at wafer and before and after the assembly. They have been measured with a current limitation of $10 \mu\text{A}$.

Despite the observed mismatch between the measured V_{bd} , the devices show good performance in terms of noise (the discriminator threshold has been tuned at $e^- 3000$), with a difference of $\sim 10 e^-$ between the sensors with $50 \times 50 \mu\text{m}^2$ ($90 e^-$) and the ones with 25×100 and $50 \times 250 \mu\text{m}^2$ ($100 e^-$) due to a lower pixel capacitance. In Fig. 6.20 an example of noise plot for a $50 \times 50 \mu\text{m}^2$ pixel size device and a $50 \times 250 \mu\text{m}^2$ one is shown.

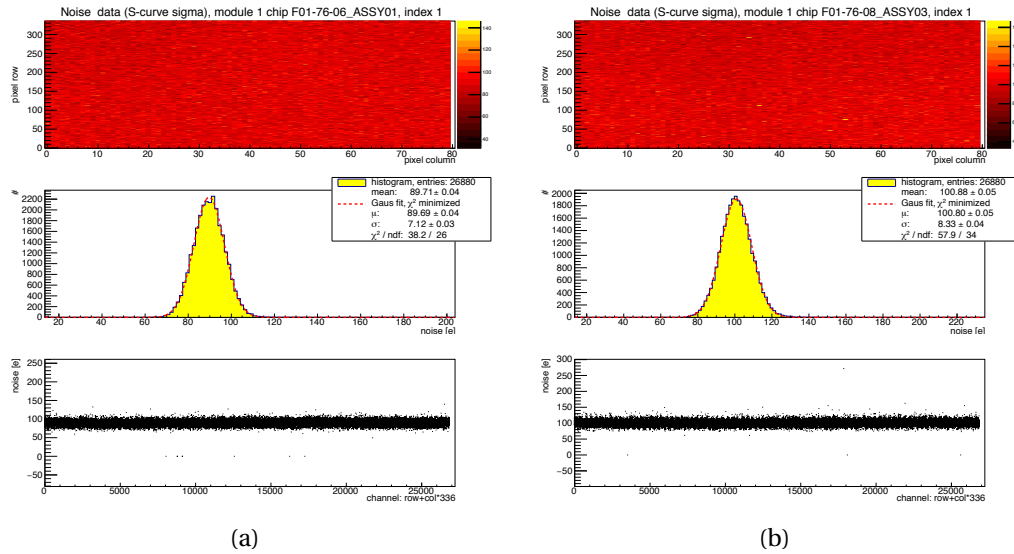


Fig. 6.20 Example of two device with different pixel size. a) A device assembled with W76-6 ($50 \times 50 \mu\text{m}^2$ pixel size) sensor shows a noise mean of $89.7 \pm 0.04 e^-$ b) A device assembled with W76-8 ($50 \times 250 \mu\text{m}^2$ pixel size) sensor shows a noise mean of $100.9 \pm 0.05 e^-$.

A scan using a ^{241}Am radioactive source has been also performed. It is needed to identify pixels that are not answering to ionization because of either bumps defects (disconnected, merged) or read-out defects (badly tuned). The scan also provides data for

eventual recalibration of the charge calibration, if needed. The whole module should be exposed to the source until the number of events (hits) exceeds the target event number of 2 million hits in order to have an average occupancy of ~ 75 hits per pixel. In Fig. 6.21 an example of source scan for a module is shown. The tested modules showed good performance in terms bump of connectivity with an average of $\sim 0.03\%$ of unconnected bumps per module.

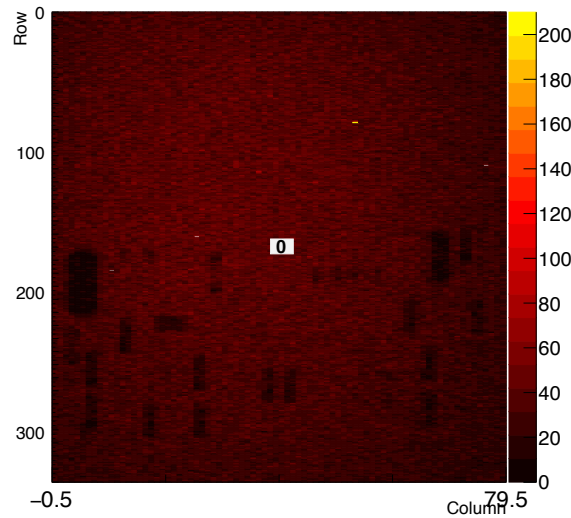


Fig. 6.21 An example of Source Scan in false colour for a 3D module (W76-8). In white are represented the disconnected bumps. The shadows (in black) are the SMDs components of the module.

An irradiation campaign has been performed during summer 2016, with three different pixel size devices (W76-6, W76-7 and W76-8). The test beam was performed using Aconite EUDET [107] telescope at SPS H6A beam line¹¹. In Fig. 6.22 is shown the test beam setup.

Preliminary results of test beam data show good results in terms of pixel efficiency. For $50 \times 250 \mu\text{m}^2$ pixel size is $>99\%$ above ~ 10 V, instead 50×50 and $50 \times 100 \mu\text{m}^2$ pixel size modules have similar values, with an efficiency of $\sim 98\%$ in the high voltage range 2-15 V.

6.2.2.3 HV-CMOS detectors in BCD8 technology

BCD8 (Bipolar - CMOS - DMOS, version 8) is a 160 nm HV-CMOS technology provided by STMicroelectronics¹² [108]. It consists of a combination of bipolar, CMOS and DMOS

¹¹The H6 beam is a secondary particle beam that provides hadrons, electrons or muons of energies between 10 and 205 GeV/c, depending on the conditions. This beam is a part of the SPS North Area at CERN, Geneva.

¹²Agrate Brianza, Italy

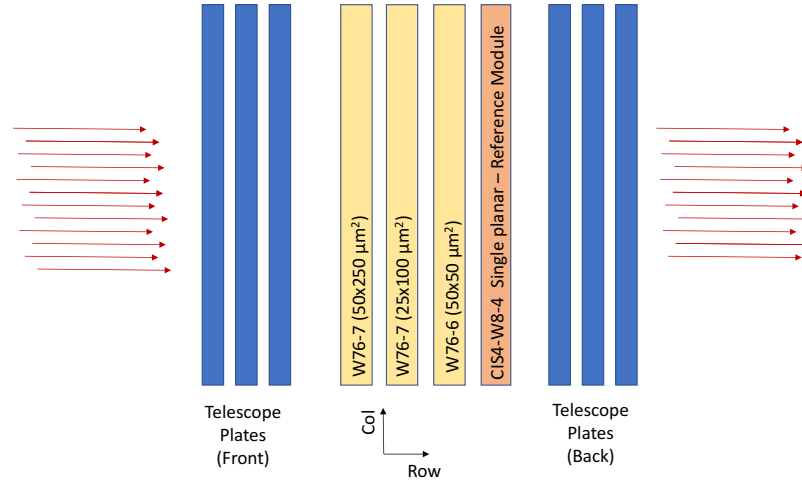


Fig. 6.22 The test beam setup used SPS H6A beam line.

devices based on a p -epitaxial growth on a p^- or p^+ substrates with the introduction of an n -type buried layer. The process shares with standard CMOS platform the main technology modules, as columnar poly-silicon, Shallow Trench Isolation (STI), cobalt salicide and borderless contacts. This technology mainly targets for automotive application. In 2015 BCD8 process has been used to produce HV-CMOS detectors prototype (called KC53A) done on a substrate with resistivity $\rho = 120 \Omega \cdot \text{m}$: a pixel sensor prototype with an array of 8 active pixels (containing a charge sensitive amplifier, a buffer and a current injection circuit) and 4 passive diodes have been designed and tested. The pixel sensor diode has a dimension of $250 \times 50 \mu\text{m}^2$. It can be supplied with a voltage up to 70 V. The analog signal processing circuitry and the digital operation of the circuit is designed with the supply voltage of 1.8 V. The KC53A chip has 22 pads for an available area of $1 \times 2 \text{ mm}^2$. Each pixel can be tested through an input provided by a current injection circuitry. For this reason each pixel has two pads: one for the current injection input and one for the measurement response at an output pad. On the chip three pads have been used for the supply voltage (VDD), the Substrate (called -50 V pad) and the ground ($GND \text{ pad}$) pads respectively, as Fig. 6.23 shows.

The tests performed on the passive pixels showed that design used in KC53A has satisfied performance in particle detection. The depletion depth can be estimated using a C-V measurement [109]. The measured capacitance is latched to the applied V_{Bias} , as shown in Eq. 6.3.

$$C(V_{Bias}) = C_P + \frac{1}{\sqrt{k(-V_{Bias} + V_{bi})}} \quad (6.3)$$

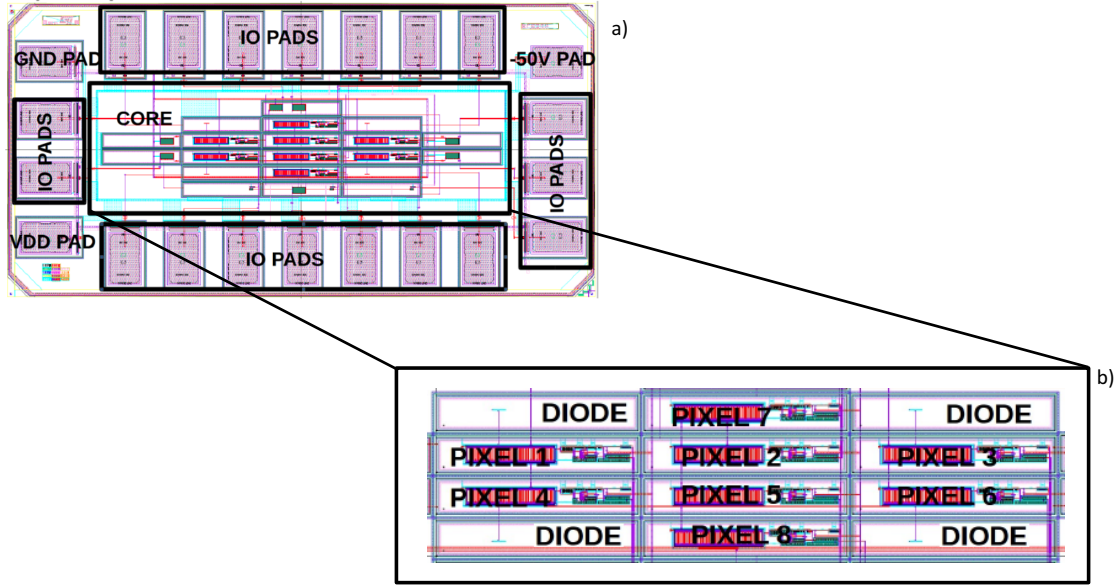


Fig. 6.23 The layout of a) the complete chip b) the active and passive diodes. In b) is possible to observe the four passive diodes in the corners and the the 8 active pixels in the centre and on the edges.

where $k = \frac{\mu\rho}{2\epsilon_0\epsilon_r A^2}$, C_P is a parasitic capacitance inside the chip, considered independent of the voltage, V_{bi} is the built-in voltage of the diode, μ is the holes (electrons) mobility, ρ is the substrate resistivity, ϵ is the silicon dielectric constant and A is the area of a pixel¹³.

As discussed in Chapter 2 the depletion depth d can be estimated by the Parallel Plate Capacitor relation:

$$d = \epsilon \frac{A}{C(V_{Bias}) - C_P} \approx 0.3 \sqrt{V_{bias} \cdot \rho} \approx 23 \mu m \quad (6.4)$$

using a reasonable working point of $V_{Bias} = -50$ V.

Fig. 6.24 shows an example of the I-V and C-V curve for one diode that is in good agreement with expectations. The I-V shows a uniform breakdown at 70 V between the tested diodes.

Measurements with radioactive sources of ^{241}Am have been performed. The dominant decay for ^{241}Am is:



¹³A complete derivation of Eq. 6.3 can be found in Appendix A

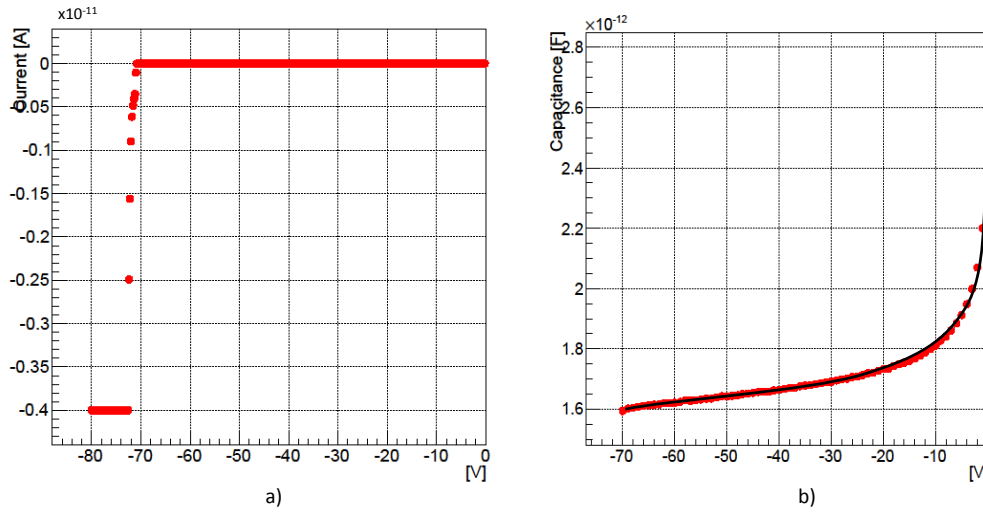


Fig. 6.24 An example of a) I-V curve b) C-V curve for one passive diode, fitted with Eq. 6.3.

The excited state of ^{237}Np can emit 59.5 keV or 26.3 keV γ -rays producing two peaks in the photon energy spectrum. The 59.5 keV γ -peak is shown in Fig. 6.25.

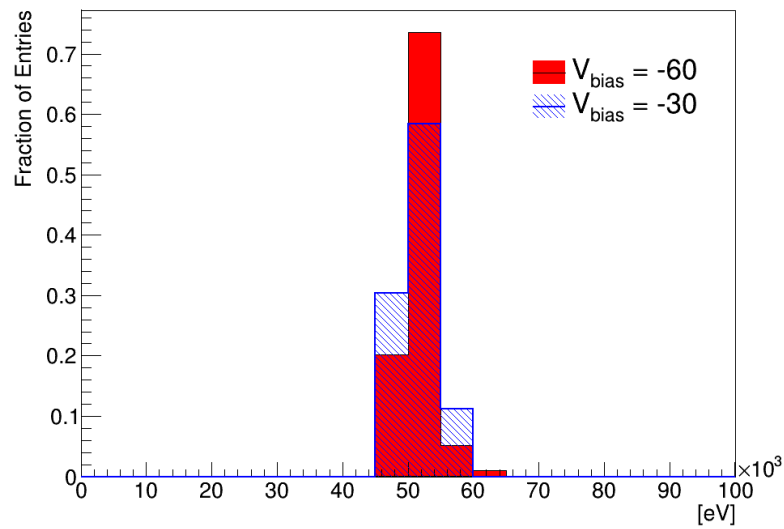


Fig. 6.25 Peak of from γ -rays at 59.5 keV of ^{241}Am at different V_{Bias} for a passive diode. The spectrum measurement has been performed using two different bias voltages of -30 and 50 V. The shaping time of the amplifier has been set to 5 μs .

Unfortunately the tests performed on the active pixels have demonstrated that their electronic chain is not suitable to detect an ionizing particle signal because the noise is too high (the RMS of the noise corresponds to a energy loss of 30 - 36 keV) [109]. However, the

tests performed on a single active pixel have shown that the amplifier gain was low with an high spread between the different pixels. The reason of the low gain is probably related to non-optimized simulation of the sensor capacitance, in the design phase. In 2016 an extended version (called KE15A) of the design with 282 pixels with complete analog processing chain has been delivered for the fabrication. The new chip FE-I4 compatible (using input-output (IO) pads, available at the bottom of the chip) has a dimension of $3\text{ mm} \times 4\text{ mm}$. In Fig. 6.26 the new chip layout is reported. The CMOS implementation of the pixels operates at 1.8 V. The routing of the supply rail and ground potential for such a large area is a challenging part. The supply voltage pads VDD, GND and -50V are kept in all four corners of the chip so that all the pixels can get the supply voltage with equal IR drop¹⁴ and equal RC loss. The IO pads of the top, the right and the left positions have been kept for testing the chip when the chip is not connected to FE-I4. Some dummy pixels of $50 \times 250\text{ }\mu\text{m}^2$ and $50 \times 50\text{ }\mu\text{m}^2$ have been kept to test the capacitance contribution from each of the pixels.

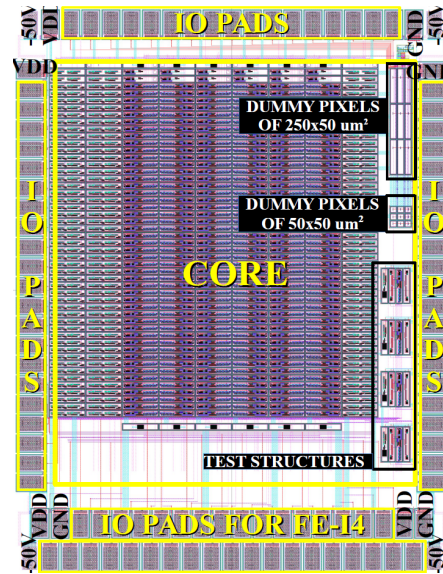


Fig. 6.26 The complete chip layout of KE15AA.

As in previous chip the particle signal, detected at the NWELL terminal of the DNWSUB, is amplified using folded cascode single ended amplifier. The amplifier has been completely redesigned for the KE15A chip, with better transistor sizing and more robust bias circuitry (Fig. 6.27).

¹⁴Due to the resistance of the interconnects constituting the network, there is a voltage drop across the network, commonly referred to as the IR-drop

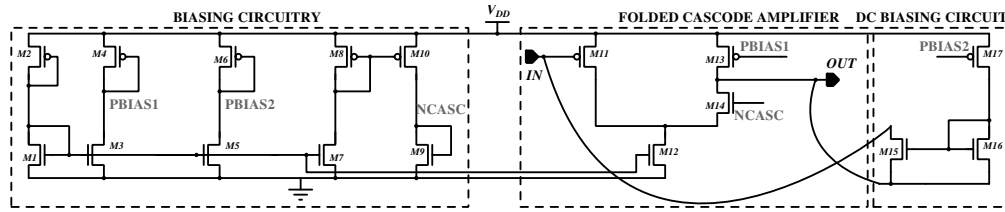


Fig. 6.27 Preamplifier scheme of a KE15A active pixel.

KE15A chips have been received from STMicroelectronics in November 2016. Preliminary C-V tests have been performed on passive diodes showing depletion depth values compatible with previous chip version (Fig. 6.28), showing a depletion depth of $24 \pm 1 \mu\text{m}$.

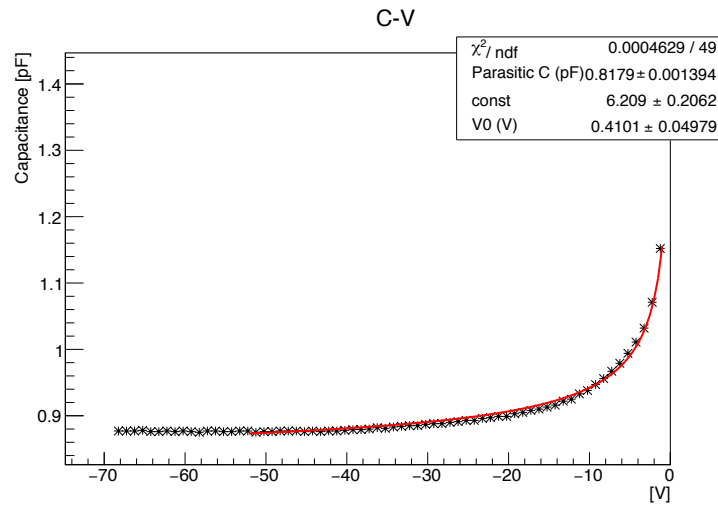


Fig. 6.28 C-V curve for one $50 \times 250 \mu\text{m}^2$ passive diode of KE15A fitted with Eq. 6.3. The depletion depth extrapolated from the fit corresponds to $24 \pm 1 \mu\text{m}$.

6.3 A Laser Setup to Measure the Hit Efficiency

Several sensor concepts (some prototypes already discussed in Sec. 6.2.2) for a new pixel detector generation needed for HL-LHC challenge are under currently investigation. In order to evaluate in the new sensor different parameters such as the efficiency and the time walk, a laser system was set-up and tested.

6.3.1 Laser System

The main components of the setup are the laser system and the Newport Motion Control unit that provided micro-metric movements: the device under test (DUT) can be moved on $XYZ\theta$ direction giving an accurate positioning of the sensor and the beam-spot. A USBPix system [110] (Sec. 6.3.1.1) is used as interface board to digitally communicate with the read-out chip. *STcontrol* (Sec. 6.3.1.1), a C++ and ROOT based software application, based on the *ATLAS PixLib* package (Sec. 3.2.4) is used to perform scans. For this purpose a custom efficiency scan has been developed for the laser system, the axis are also controlled in order to make efficiency scans at predefined positions. The core of the system is a stand-alone laser driver (PDL 800-B from PicoQuant) that can use picosecond pulsed laser diode heads from 375 to 1990 nm. The laser provides a peak power up to 1 Watt. Pulses as short as 50 ps (FWHM) at repetition rates from single shot up to 80 MHz can be emitted, depending on the diode laser head in use. The internal clock generator produces a master frequency of 40 MHz that can be divided by a factor of 1, 2, 4, 8 or 16 to produce user-selectable frequencies of 40, 20, 10, 5 or 2.5 MHz. Alternatively, the laser pulses can be triggered by an external trigger input. This feature was used for the system described, since the trigger is provided by USBPix. The control unit is connected to a laser head (LDH-P-1060) with a wave length in the range 1051-1067 nm and minimum pulse width 44 ps. This laser head is connected via optical fibres to an attenuator (BB-200-3A3A-1060-S), followed by a splitter and finally a focuser pigtailed with a predicted spot size about 9 μm (at a working distance of 12 mm). In Fig. 6.29 a scheme the system is shown.

In Fig. 6.30 the most important signals in the setup are shown. The laser system is triggered via the strobe signal generated within the Multi-IO board (laser-trigger), an infrared pulse is generated causing the release of charge carriers which are collected in the sensor and generate a signal in the pre-amplifier of the front-end. In the front-end the ToT information is stored and tagged with a time-stamp corresponding to the leading edge (LE) of the signal. After a predefined time (trigger delay) controlled by *STControl*, a read-out trigger piloted by USBPix is sent. The trigger delay mimics the time to generate a trigger signal in the real detector. The hit is read out if a trigger pulse arrives within the

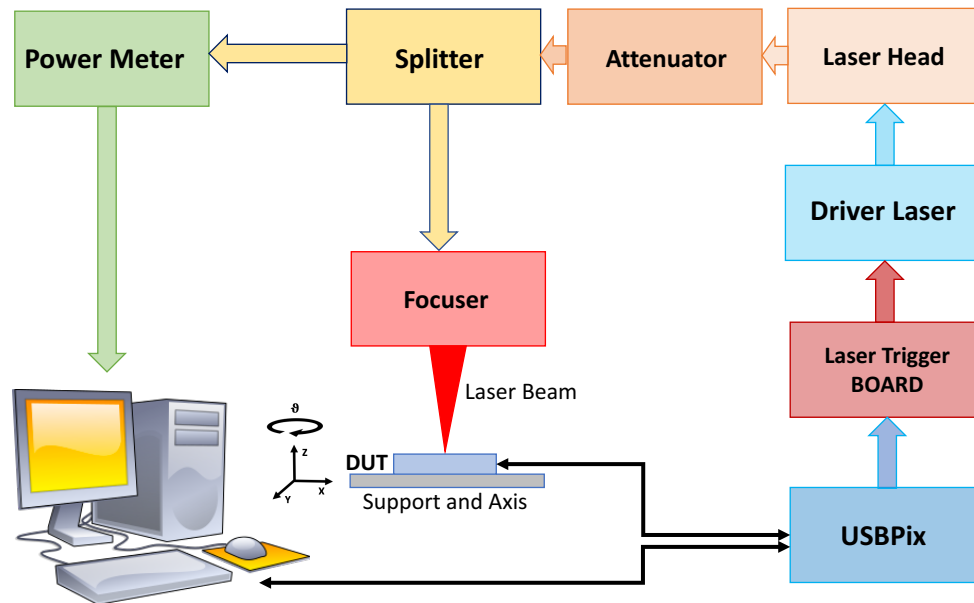


Fig. 6.29 The sketch shows the main communication chains in the lab setup.

read-out window after the FE L1 latency has elapsed with respect to the LE time-stamp. Otherwise, it is discarded.

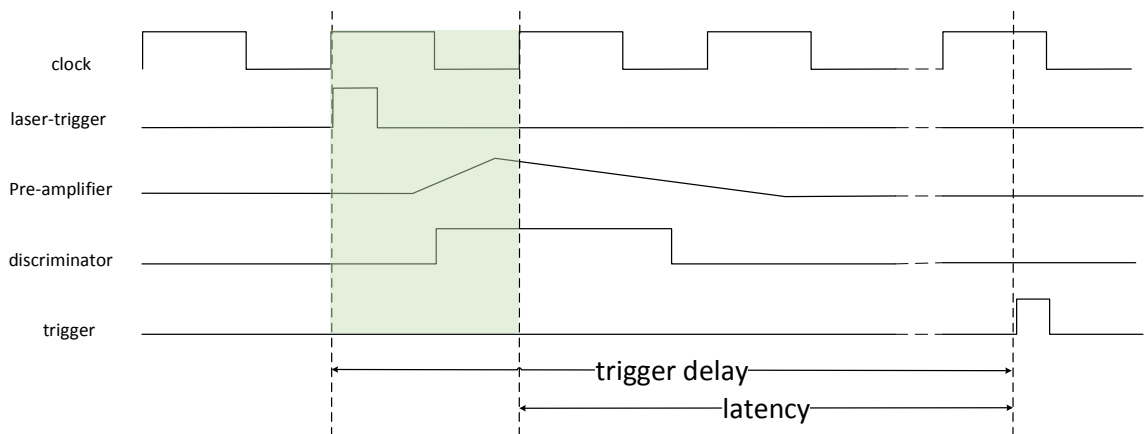


Fig. 6.30 Signals in the laser test system. A measurement starts with the laser-trigger which causes a laser-pulse. The deposited charge is amplified by the preamplifier and digitised by the discriminator of the front-end. Finally, the read-out trigger requests data within the time window (green).

6.3.1.1 USBPix and read-out

The Module electrical characterization is performed using a custom test system built by the *ATLAS* Pixel Collaboration during the qualification of the IBL modules. It is referred as USBpix [110] setup. For completeness a layout of the system is given in order to easily refer to specific equipment in the test description. The USBpix test system (Fig. 6.32) is a modular test system in terms of hardware and software. The hardware consists of a Multi-IO board developed at SiLab in Bonn University. The Multi-IO board provides a USB interface with a micro controller and is connected to an adapter card dedicated to the specific flavour of the readout chip. The Multi-IO board holds a FPGA, 2 MB on board memory and also a RJ45 connector (for the EUEDET telescope [107] trigger interface). The Multi-IO board is connected to the FE-flavour specific adapter card and has a physical size of 10 cm × 10 cm. Additional to the boards and a PC, only one low voltage (2.5 V, 1 A) and one high voltage power supply (1000 V, 10 μ A) is needed to power the module electronics and sensor.

All digital functionality is implemented in the FPGA, and the USB micro controller controls the standard scan routines using a custom firmware. Together with histogramming and data storage in the on board memory by the FPGA, this enables processing a large amount of standard test routines without communication to the PC, thus saving processing time. All connections for the front-end chip are routed to the adapter card, which provides the signals via LVDS transmitters or CMOS level shifters on a 50 pin connector.

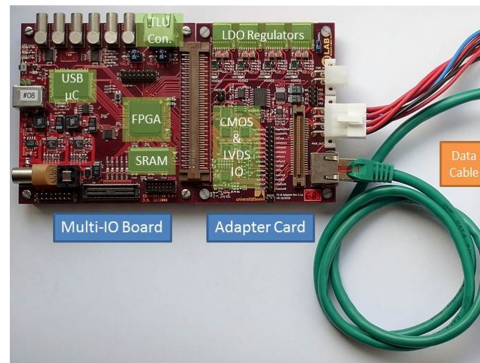


Fig. 6.31 The USBpix Readout system (left) with the Adapter card (Right) to analyse one module per time.

The software structure consists of two layers. The high level functionality like data analysis and multi dimensional scan control is implemented in the GUI layer. The two GUIs are composed by the USBpixTest and STcontrol software (Fig. 6.32). They communicate to the interface library *USBpix.dll*, which takes over the USBpix hardware and the related communication to the Multi-IO board.

The chip configuration and first data formatting is also handled in *USBpix.dll*. This modular structure decouples high level software development from the FPGA firmware development, which enables working on the two major tasks simultaneously while updating the system to the needs of future readout chip generations. One USBpix setup supports data acquisition of a single FE or SC module only due to resources limitation of the FPGA.

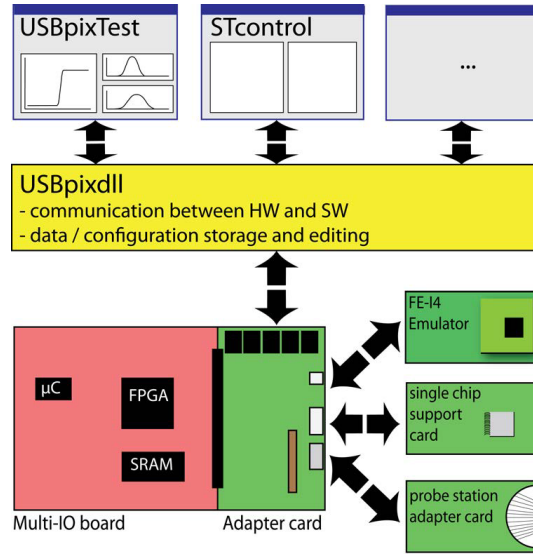


Fig. 6.32 Schematic of USBpix test system.

6.3.1.2 Charge Injection

The aim of the laser injection is to simulate a minimal ionising particle (MIP). A MIP release is about $80 \text{ e}^- / \mu\text{m}$. In case of $250 \mu\text{m}$ thick sensor corresponds to $20\,000 \text{ e}^-$ with an energy $E_{MIP} = 20000 \cdot W_{silicon} \approx 72 \text{ keV}$ where $W_{silicon} = 3.65 \text{ eV}$ is the pair production energy in silicon. The described laser system (Sec. 6.3.1) uses an infrared wavelength of $\lambda = 1060 \text{ nm}$. At this wavelength electron hole (eh) pairs are generated along the whole sensor depth and both electrons and holes contribute to the induced current. The single photon energy is:

$$E_{photon} = \frac{ch}{\lambda} \approx 1.16 \text{ eV} \quad (6.6)$$

which is less than the average energy (considering the phonon excitation) needed to produce an eh pair in silicon. The maximal deposited energy (E_{pulse}) of the laser can be estimated as:

$$E_{pulse} = P_{peak} \cdot t_{pulse} \quad (6.7)$$

where P_{peak} is the laser peak power and t_{pulse} the duration of laser pulse (for the setup described in 6.3.1 is 44 ps).

P_{peak} can not be estimated directly, but the average power P_{Ave} is usually measured. P_{Ave} is the rate of energy flow averaged over one full period T in which the train of optical pulses is reaped, defined as:

$$P_{Ave} = \frac{E_{pulse}}{T} \quad (6.8)$$

In Fig. 6.33 the laser average power measured at different intensities for several trigger frequencies f is shown.

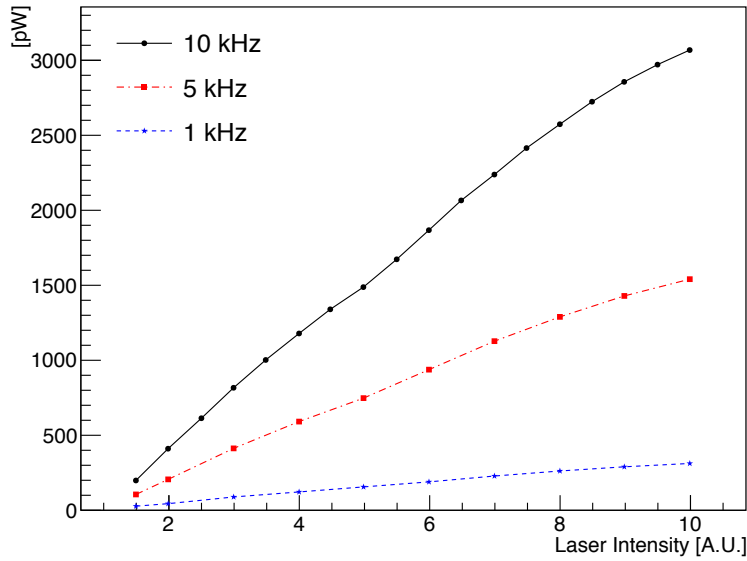


Fig. 6.33 The power of the laser measured at different intensities for several trigger frequencies.

Solve both Eq. 6.7 and Eq. 6.8 for E and equate, we can define a new quantity called *Duty Cycle* (D_c), that is the fractional amount of time in which the laser is firing during any given period, defined by Eq. 6.9.

$$D_c \equiv \frac{t_{pulse}}{T} = \frac{P_{Ave}}{P_{peak}} \quad (6.9)$$

Therefore the peak power of a pulse can easily be calculated if P_{Ave} and D_c are known:

$$P_{peak} = \frac{P_{Ave}}{D_c} \quad (6.10)$$

From previous equation described, knowing P_{Ave} and the trigger frequency ($f = 1/T = 10$ kHz, for the setup in Sec. 6.3.1) it is possible to estimate the deposited energy in the silicon by the laser. Anyway some beam attenuation factors have to be considered for a realistic discussion, such as the transmission coefficient in silicon for infrared wavelength at $\lambda = 1060$ nm, the transmission coefficient due to silicon passivation and the attenuation of the beam in air. Combined both attenuation factors, the estimated energy is reduced of a factor ~ 0.7 from the calculated E_{pulse} .

The injection depth in silicon can be instead obtained using Lambert-Beer law:

$$I(x) = I_0 \cdot e^{-\mu x} \quad (6.11)$$

where $I(x)$ is the intensity of the beam at a depth x with a starting intensity I_0 . μ is called absorption coefficient and is function of the wavelength. The absorption coefficient in silicon for $\lambda = 1060$ nm at 300 K is 11.1 cm^{-1} . As seen for *ATLAS* Pixel sensors the maximum active region is $250 \text{ }\mu\text{m}$, in that case the starting beam is reduced of:

$$\frac{I(250)}{I_0} = 1 - e^{-\mu x} = 25\% \quad (6.12)$$

In Fig. 6.34 a laser MIP-like energy release for a module with a sensor thickness of $200 \text{ }\mu\text{m}$ tuned at $1 \text{ ToT} = 2000 \text{ e}^-$ and a threshold of 3000 e^- is shown. The results are compatible with the expectations.

6.3.2 Results

The small spot of the laser allows to investigate disuniformity in the charge collection inside the pixel cell. In order to properly evaluate the pixel efficiency is necessary to cover the entire pixel area with the laser, using a small step sampling ($2 \text{ }\mu\text{m}$) over the surface of the sensor. At each position the charge generated in the sensor by the laser pulse is injected several times (10^4) in the sensor. STControl software has been properly modified, implementing a new scan called *Laser Scan*. In this way a ROOT file with a ToT histogram for each step can be produced and analysed off-line with a dedicated macro. The obtained result is an hit efficiency map, that is extrapolated from the mean of ToT distribution in each step using a gaussian fit. Basically the mean ToT value is a measurement on how the effective charge collection works in the sensor. In Fig. 6.35 a 2D scan performed on several

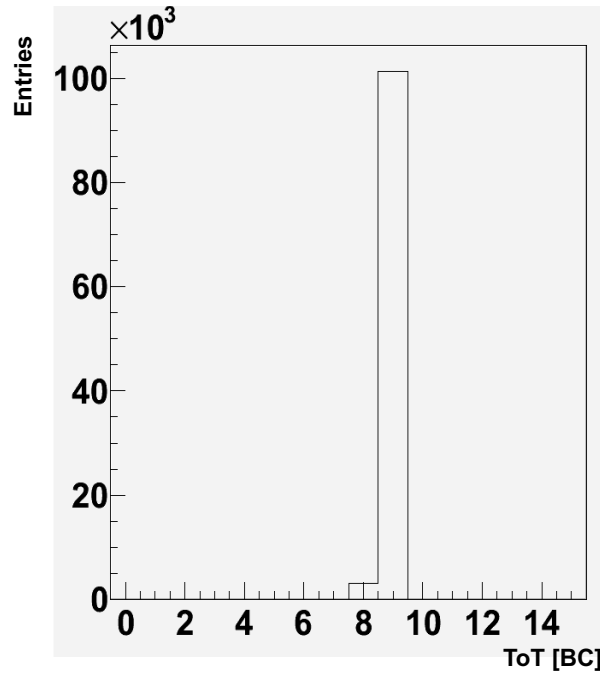


Fig. 6.34 A laser MIP-like energy release example for a module with a sensor thickness of $200\ \mu\text{m}$ tuned at $1\ \text{ToT}=2000\ \text{e}^-$ and a threshold of $3000\ \text{e}^-$.

pixels of a planar sensor with a depletion region of $100\ \mu\text{m}$ and a pixel size of $50 \times 250\ \mu\text{m}^2$ is shown. In the plot is possible to observe the ineffective areas between the pixels and that the maximum ToT value is reached in the centre of each pixel and falls to the edges (this is due to charge sharing with adjacent pixels). The plot shows also that the pixel size extrapolated from the 2D scan is in good agreement with the resolution given by used step.

The collected charge for different V_{bias} values has been also evaluated for a non-irradiated planar sensor with a depletion region of $100\ \mu\text{m}$ and a substrate resistivity $\rho > 10000\ \Omega\cdot\text{cm}$. The comparator threshold was tuned at $2500\ \text{e}^-$ and tuning point set to $1\ \text{ToT} = 1000\ \text{e}^-$. In Fig. 6.36 it is possible to observe that the pixel efficiency reaches its maximum above $9\ \text{V}$ as expected from the second term of Eq. 6.4.

In Fig. 6.37 a 2D scan has been also performed on a 3D sensor with $50 \times 250\ \mu\text{m}^2$ pixel size. The obtained result, in terms of collected charge regions, are in agreement with the geometry of the sensor.

The showed results have exploited the test potentiality of the laser system to study the pixel efficiencies, anyway some improvement on software side has to be performed to reduce the scan time. At the moment a full scan in $2\ \mu\text{m}$ step of pixel with a size of $50 \times 250\ \mu\text{m}^2$ takes at least $\sim 14\ \text{h}$.

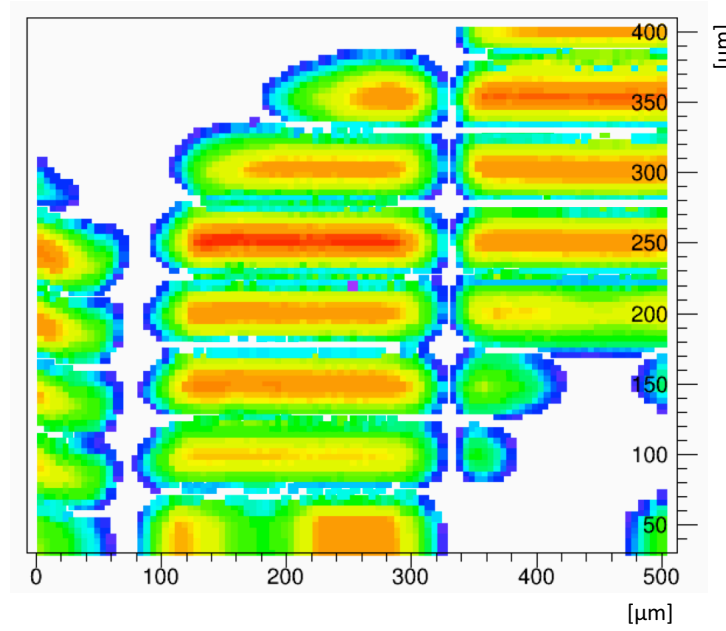


Fig. 6.35 Laser Scan 2D of a planar sensor.

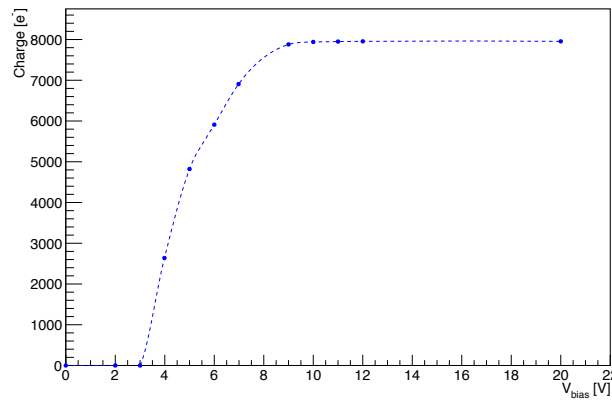
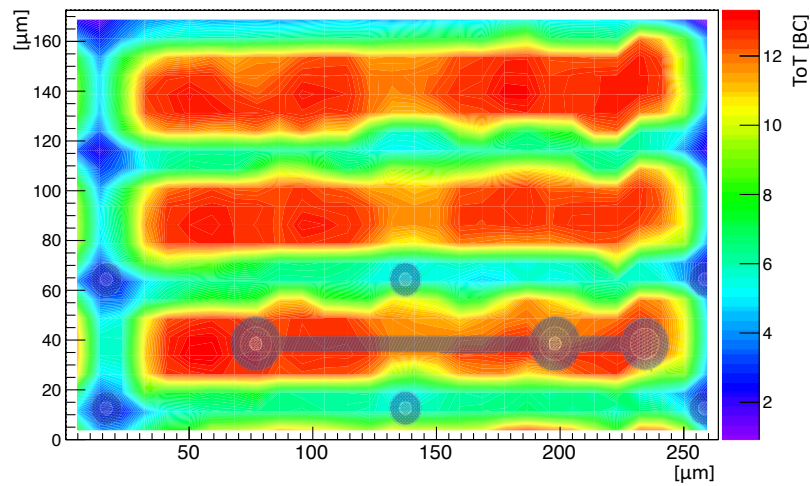
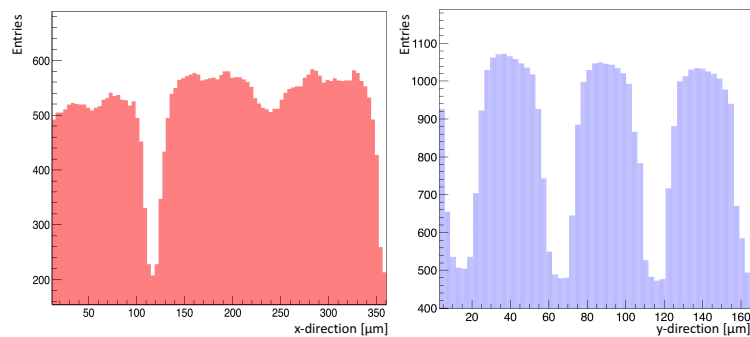


Fig. 6.36 The collected charge for a planar sensor with a depletion region of $100 \mu\text{m}$. The comparator threshold was tuned at $2500 e^-$ and the tuning point set to $1 \text{ ToT} = 1000 e^-$.



(a)



(b)

Fig. 6.37 a) 2D Laser Scan 2D of a 3D sensor with $50 \times 250 \mu\text{m}^2$ pixel size. The scan is in agreement with expected pixel geometry (superimposed). b) Projection along x and y direction. The dimension of the pixel is in agreement with expectations.

Conclusions

In the next decades the properties of the recently discovered Higgs boson will be thoroughly investigated. Several open questions in the Standard Model (SM) of particle physics (such as e.g. the strong CP problem or the dark matter and dark energy) indicate that the theory, despite its success, is not yet complete. In last three decades numerous theories have been proposed to extend it and many have been refuted. LHC and its experiments have the exciting goal to try to provide answers to the SM open questions. To increase the discovery potential, the LHC luminosity has been boosted constantly and the detectors have been improved to cope with the new luminosity conditions. The improvement of the LHC performance sets important challenges: higher radiation doses, particle rates and pile-up that endanger the performance of the tracking systems.

The presented thesis focuses on the work that I have done on two correlated topics. The first aspect is the ATLAS pixel detector, its current operation and the upgrades that it has recently undergone and will face in next years. The second is its use to identify particle using the specific ionization energy loss (*track dE/dx*).

The first major upgrade underwent by the ATLAS detector was the insertion of the Insertable B-layer in the ATLAS Pixel detector in April 2014. In that contest I followed the production of IBL modules, that had a yield of 75% for planars and 62% for 3D modules. From a technological point of view the IBL is the first large scale application of 3D silicon sensors and it exploits the new FE-I4 Front End chip, the largest FE that has ever been used in High Energy Physics. The insertion of the IBL was crucial to maintain excellent performance of the ATLAS tracking detector and compensate possible inefficiencies of the old three layer Pixel Detector. Furthermore after repairs done in surface during the Long Shutdown, several failures in the Pixel Detector have been recovered, having 98% of the channels operational at the beginning of LHC Run 2.

During 2015-2016 LHC Winter Shutdown, thanks to the increased number of data links the bandwidth of Pixel Layer-1 was increased from 80 to 160 Mbit/s and for Layer-2 from

40 to 80 Mbit/s supported by a new off-detector electronics (ROD). In that framework I have followed and developed the tests and some tools to qualify the new ROD firmware blocks implemented for Pixel off-detector electronics upgrade. Thanks to the feedback received the final version used for ATLAS data-taking showed a negligible error rate.

The ATLAS Pixel Detector provides at least three precision measurements for each track in the region $|\eta| < 2.5$ at radial distances from the LHC beam line $R < 13$ cm. It is able to measure the charge deposited by each particle crossing it. The detector can be used to detect massive, highly ionizing particles and to reconstruct their mass based on a parametrization of the most probable value of the specific rate of energy loss. In this contest, I have developed a new algorithm that uses IBL information. It reduces both Landau tails of the dE/dx distribution with $dE/dx < 0.5$ (> 1.8) $\text{MeV g}^{-1} \text{cm}^2$ from 0.065% to 0.018% (from 0.89% to 0.44%) and increases the fraction of tracks for which the ionization measurement is solid from 77% to 91%. I worked also to increase the performance of the *track* dE/dx observable, developing a *track* dE/dx path correction thus correcting its dependence on the track pseudorapidity η . The Pixel *track* dE/dx is the key discriminant signal to identify non relativistic massive charged particles as long-lived particles (LLPs) are. One postulated type of LLP is the R -hadron, a supersymmetric particle with colour-charge combined with Standard Model quarks and gluons. I have contributed to this analysis, mainly as the expert of the dE/dx by optimising the definition of *track* dE/dx , providing a calibration of empirical 5-parameters Bethe-Bloch, measuring its stability and evaluating its systematics. The search shows no excess of events observed over the background estimate. Gluino R -hadrons with lifetimes above 0.4 ns and decaying to $q\bar{q}$ plus a 100 GeV neutralino are excluded at the 95% confidence level with lower mass limit range between 740 GeV and 1590 GeV depending on their lifetime. In the case of stable R -hadrons the lower mass limit at the 95% confidence level is 1570 GeV.

The technologies developed for IBL are important milestones and they are the starting point for the new LHC upgrades (HL-LHC) projects, when the instantaneous luminosity should reach $\sim 5\text{-}7 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$, up to 200 interactions per crossing (pile-up) and a total integrated luminosity of 3000fb^{-1} . HL-LHC data should drive new theories, if proposed theoretical models will not work at that time. I am highly involved in this R&D developing bump-bonding at high density and finding new hybridization techniques. This will be crucial for HL-LHC experiments upgrades and above all for the planned ATLAS Pixel detector upgrade of 2025. In this thesis some results from the first tests on resistive chains using high density bump bonding on 6" and 12" wafers have been shown with very promising results. The deposition on 6" wafers shows an uniform electrical resistance value all over the assembly of $11 \pm 2 \Omega$ per bump, but we need to extend the results to 12"

wafers that will be used for HL-LHC upgrades. The rising capacitive coupling technique has given good results, but a lot of work is necessary to come to a mature industrial process. First R&D results on $2 \times 2 \text{ cm}^2$ dummy tiles coupled capacitively without pillars have been assembled showing a lower uniformity of the capacitor heights for glue in comparison with the tape. In the upgrade framework I have also studied the first CMOS sensor realized in the BCD8 technology by STMicroelectronics. The tests performed on the passive pixels have demonstrated that the used design has good performance in particle detection, even if the active pixels region have too high noise in their electronic chain to detect an ionizing particle signal. Promising results come from new 3D sensors FE-I4 compatible fabricated by Fondazione Bruno Kessler and bump-bonded at Leonardo Finmeccanica, with smaller pixel dimensions than IBL ones ($50 \times 50 \text{ }\mu\text{m}^2$, $25 \times 100 \text{ }\mu\text{m}^2$). A radiation campaign has been performed during summer 2016, giving good results in terms of pixel efficiency ($\sim 99\%$). Finally, in order to evaluate parameters such as the efficiency and the time walk of the new sensors, I have developed and tested a laser system in Genova. The aim of the laser injection is to test the charge collection inside the pixel cell, similarly to what is done during the test with a beam of particles. Different sensors have been tested showing good performance of the setup to built pixel efficiency maps.

Appendix A

The depletion region is charged positively on one side and negatively on the other, it resembles a parallel-plate capacitor, but we have to consider that the charge is distributed over a volume rather than being on plates.

The charge stored on each side is given by the *neutrality equation*:

$$|Q| = eN_Dx_nA = eN_Ax_pA \quad (6.13)$$

where x_n and x_p are the depletion widths on the n -side and the p -side respectively and N_A and N_D the donor and acceptor concentrations, e is the elementary charge (negative define for electrons) and A the detector area.

Q is related to the applied voltage through the equation for the depletion width:

$$W = x_n + x_p = \frac{Q}{eA} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) = \sqrt{\frac{2\epsilon_0\epsilon_{Si}}{e} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) (V_{bias} + V_{bi})} \quad (6.14)$$

where W is the total width of the depletion zone, x_n and x_p its part on the n - and p -side respectively, and V_{bias} the externally applied voltage.

From Eq. 6.14, Q can be expressed as:

$$Q = eA \left(\frac{N_A N_D}{N_A + N_D} \right) \sqrt{\frac{2\epsilon_0\epsilon_{Si}}{e} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) (V_{bias} + V_{bi})} \quad (6.15)$$

$C = dQ/dV$, so differentiating the equation gives the capacitance:

$$C = \frac{dQ}{dV} = \sqrt{\frac{e\epsilon_0\epsilon_{Si}A^2}{2(V_{bias} + V_{bi})} \frac{N_A N_D}{(N_A + N_D)}} \quad (6.16)$$

It is possible to define the conductivity (σ) and resistivity (ρ) of doped semiconductors as:

$$\sigma = (e\mu_n n + e\mu_p p) = \frac{1}{\rho} \quad (6.17)$$

where μ_n and μ_p are the mobilities of electrons and holes and p, n are the concentrations of holes and electrons respectively.

Assuming n -type detector, $N_A \gg N_D$ and using the mass action law $np = n_i^2$ (where n_i is the intrinsic concentration of the silicon), one find $x_p \ll x_n$. The resistivity can be also expressed as:

$$\frac{1}{\rho} = eN_D\mu_n \rightarrow \frac{1}{eN_D} = \mu_n\rho \quad (6.18)$$

In the same approximation ($N_A \gg N_D$) and substituting Eq. 6.18, Eq. 6.16 can be written as:

$$C = \sqrt{\frac{e\epsilon_0\epsilon_{Si}A^2}{2(V_{bias} + V_{bi})}}N_D \rightarrow C = \sqrt{\frac{\epsilon_0\epsilon_{Si}A^2}{2\mu_n\rho(V_{bias} + V_{bi})}} \quad (6.19)$$

Defining $k = \frac{\mu_n\rho}{2\epsilon_0\epsilon_{Si}A^2}$, Eq. 6.3 is then obtained:

$$C(V_{Bias}) = \frac{1}{\sqrt{k(V_{bias} + V_{bi})}} \quad (6.20)$$

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