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A silicon pixel detector for LHCb

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στον παππού μου και στην γιαγιά μου.*

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Introduction

The goal of particle physics is to understand the structure of matter and the fundamental forces. The theory that so far successfully describes interactions between the subatomic particles is the Standard Model (SM) [1]. The validity of the SM has been confirmed with the prediction and discovery of particles like the spin-1 W and Z force carriers and the spin-0 Higgs boson [2]. So far the SM predictions are in agreement with observations in particle physics experiments. However, there remain unanswered fundamental questions such as for example the mystery of missing antimatter [3] and the nature of dark matter [4]. Theories beyond the SM attempt to solve these problems.

Particle physics experiments are conducted to verify predicted SM quantities and to look for phenomena beyond it. To discover new particles or examine new theories particles are collided at increasingly high energies. At the Large Hadron Collider (LHC) at CERN particles can be accelerated and collided with a center of mass energy of 13 TeV. The LHC hosts a number of experiments. An example of such an experiment, optimised for the study of b -mesons, is LHCb.

The LHCb experiment has recorded $> 3 \text{ fb}^{-1}$ of data during Run 1. A particle originates from an interaction point known as *vertex*. One of the characteristics of b -particles such as the B_s meson, is the occurrence of a secondary displaced vertex with respect to the primary vertex. To identify a b -meson, the lifetime and subsequent decay length are powerful handles. In addition, to study fast particle-antiparticle oscillations that occur for these mesons, a good decay time resolution is required. A detector with superior tracking capabilities is needed to measure these properties.

A higher data rate requires the upgrade of the current LHCb detector. The LHC shutdown, during which the LHCb detector is scheduled to be upgraded, is planned from 2019 to 2020. In the five year period after 2020, referred to as Run 3, the experiment will run at a 5 times higher luminosity. Because of the improved trigger performance, it is expected to acquire 10 times more statistics for signal events.

All tracking detectors of LHCb will be upgraded to cope with the higher luminosity and to be able to read the data from each collision. The current Vertex Locator (VELO), which is a silicon strip detector, will be substituted in the upgrade with a silicon pixel detector allowing for improved particle reconstruction and pattern recognition.

An important element of the VELO upgrade is the silicon sensor. The sensors that will be used are 200 μm thick and feature square pixels with a 55 μm pitch. At the end of Run 3 the LHCb detector will have accumulated a maximum fluence of $8 \times 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$. The silicon sensors must therefore be radiation hard and maintain a high charge collection and hit efficiency after operation at these levels of radiation.

This thesis focuses on the performance of prototype silicon sensors obtained from testbeams at the SPS at CERN. These prototype sensors are designed according to the requirements for the detectors that will be installed in the upgrade of the LHCb VELO detector.

In Chapter 1 the LHCb experiment is described. The main subsystems of the LHCb detector and the motivation for the upgrade are presented.

The main requirements and features of the VELO upgrade are discussed in Chapter 2. Simulation studies on the impact parameter resolution in the VELO upgrade are the topic of discussion of Chapter 3.

Since the upgraded VELO consists of a silicon pixel detector, the principles of operation of such a detector are presented in Chapter 4.

A number of prototype silicon sensors were tested in testbeams. Measurements on the prototype sensors were performed using a high precision telescope. The Timepix3 telescope is described in Chapter 5.

In view of the upgrade, the resolution and efficiency of active-edge silicon sensors were evaluated as described in Chapter 6. Additional results on the performance of non-irradiated and irradiated sensors obtained with the Timepix3 telescope are presented in Chapter 7.

Finally a number of recommendations for additional studies are given in Chapter 8.

Chapter 1

The LHCb experiment at CERN

The European Organization for Nuclear Research, commonly known as CERN, is the largest particle physics research center in the world. The CERN accelerator complex is depicted in Figure 1.1.

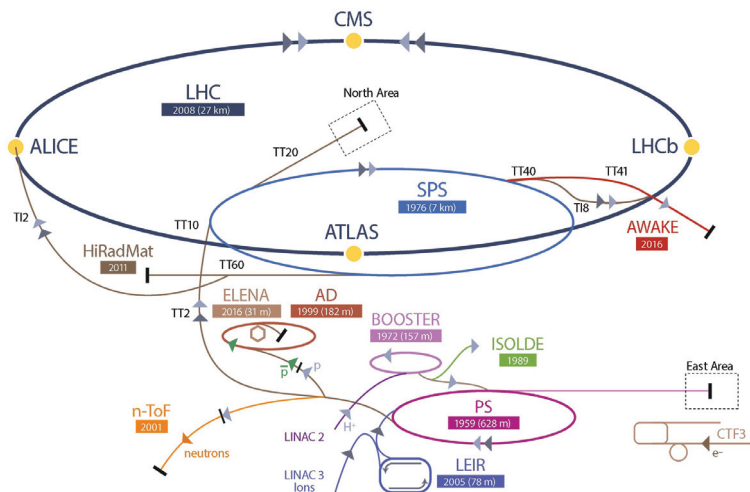


Figure 1.1: The CERN accelerator complex.

The accelerator complex houses experiments of relatively low energy and experiments at the highest energy provided by the Large Hadron Collider (LHC). Protons are provided to the LHC through a network of accelerators before being brought into collision.

The protons, originating from a hydrogen gas source, first enter a linear accelerator (LINAC2) after which they are accelerated to 50 MeV. Next they enter the proton synchrotron Booster reaching an energy of 1.4 GeV. Afterwards the protons enter the Proton Synchrotron (PS) which accelerates them to 26 GeV. The bunches are then injected to the Super Proton Synchrotron (SPS) where they are accelerated up to 450 GeV. A tangent delivers proton beams

from SPS to the testbeam areas located at the North Area (close to the center of the LHC). After the SPS, the proton bunches are finally injected in the LHC. In the LHC, the proton beams are accelerated and collide up to a maximum center of mass energy of $\sqrt{s} = 13$ TeV with a maximum instantaneous luminosity of $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The protons from each beam collide at 25 ns intervals that are referred to as bunch crossings. Four large scale experiments take place at the LHC. One of these experiments is the LHCb experiment.

1.1 Highlights from Run 1

The LHCb experiment is searching for physics beyond the SM by studying decays of beauty and charm hadrons [5]. Any deviations from the SM predictions in the measurements performed may be a hint of new physics. An example of such a measurement is that of the $B_s^0 - \bar{B}_s^0$ oscillation frequency. Neutral b -mesons undergo particle-antiparticle mixing due to second-order weak interactions involving box diagrams [6]. The $B_s^0 - \bar{B}_s^0$ oscillation frequency Δm_s is governed by the mass difference of the B_s^0 mass eigenstates [7]. The frequency of the particle-antiparticle oscillations observed in the $B_s^0 - \bar{B}_s^0$ system is extremely high ($\sim 10^{13}$ Hz). In the distance between production and decay of a b hadron, which is typically in the order of 1 cm, a B_s^0 changes flavour nine times on average. In order to resolve the fast $B_s^0 - \bar{B}_s^0$ oscillation a high decay time resolution is therefore necessary. The average decay time resolution provided by the VELO is $\sigma_t = 44$ fs making it possible to observe the $B_s^0 - \bar{B}_s^0$ oscillations as shown in Figure 1.2. The measured oscillation frequency is found to be $\Delta m_s = 17.768 \pm 0.023$ (stat) ± 0.006 (syst) ps^{-1} [8], which is the most precise measurement to date, and is in good agreement with the current world average $17.69 \pm 0.08 \text{ ps}^{-1}$. The Δm_s is one of the quantities that influence the dilution of the observed oscillation. The dilution factor D according to [9] is:

$$D = e^{-\left(\frac{1}{2}\Delta m_s^2 \sigma_t^2\right)} \quad (1.1)$$

where σ_t is the decay time resolution and t the decay time.

In addition, the complex CP-violating phase ϕ_s [10] of the $B_s^0 - \bar{B}_s^0$ mixing amplitude is measured by LHCb. This parameter quantifies CP-violation effects arising from the interference between two quantum amplitudes. These amplitudes are B_s^0 directly decaying to a final state of $J/\psi(\rightarrow \mu^+\mu^-)\phi(\rightarrow K^+K^-)$ and B_s^0 first oscillating to $\bar{B}_s^0$ and then decaying to $J/\psi(\rightarrow \mu^+\mu^-)\phi(\rightarrow K^+K^-)$. The error σ_{ϕ_s} on the ϕ_s measurement depends on decay time resolution in the same manner as in the case of the Δm_s measurement, particularly $\sigma_{\phi_s} \propto 1/D$.

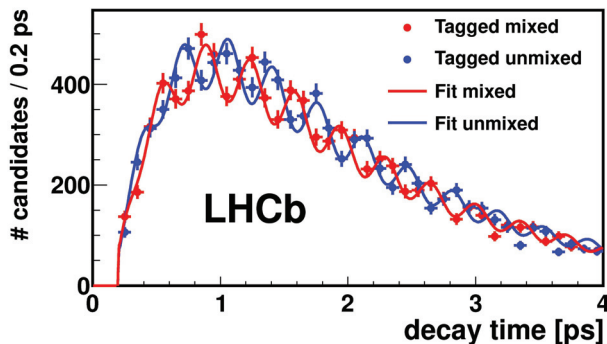


Figure 1.2: Decay time distribution for candidates tagged as mixed (different flavour at decay and production drawn with a red line) or unmixed (same flavour at decay and production drawn with a blue line). A poor proper time resolution would smear neighbouring points influencing the oscillations.

The measured CP violating phase in $B_s^0 \rightarrow J/\psi K^+ K^-$ decays combined with $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ decays is $\phi_s = -0.010 \pm 0.039$ rad [11], which is in good agreement with the predicted value from the SM [81].

1.2 The LHCb experiment

During the first years of operations known as Run 1, LHCb accumulated 3 fb^{-1} of data. Following a two year long shutdown, the LHCb experiment is currently going through Run 2. LHCb is operating at an instantaneous luminosity of $L = 4 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. At this luminosity the average number of visible proton-proton (pp) collisions per bunch crossing is $\nu = 1.62$.

The LHCb detector (Figure 1.3) is a single-arm spectrometer covering a pseudorapidity range of $2 \leq \eta \leq 5$. Due to the fact that $b\bar{b}$ pairs are mainly produced at small angles with respect to the interacting beams (see Figure 1.4), the LHCb detector is built to detect b -hadrons produced in the so-called forward direction¹. A dipole magnet with a bending power of 4 Tm bends charged particles to allow measurement of their momentum. The detector setup consists of a tracking system and a particle identification system. The particle identification (PID) system includes two Ring Imaging Cherenkov detectors (RICH) to identify charged hadrons, an electromagnetic (ECAL) and a hadronic (HCAL) calorimeter for hadron, electron and photon separation

¹Since the $b\bar{b}$ production is symmetric, the definition of forward direction is a matter of choice.

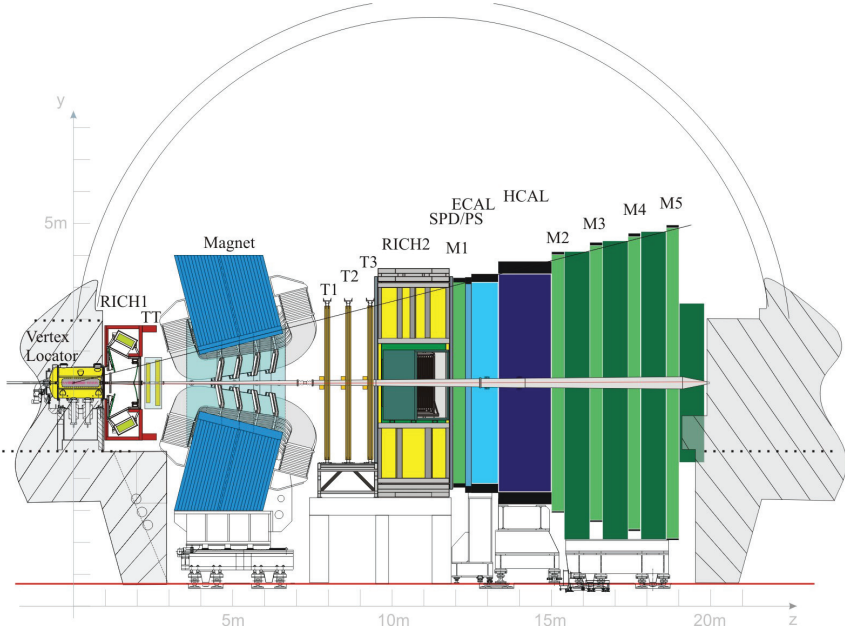


Figure 1.3: The LHCb spectrometer. The tracking system includes the Velo, TT and T-stations. The PID system includes RICH 1 and 2, ECAL, HCAL and M1–M5.

and a set of muon chambers (M1–M5) to identify muons. In the LHCb reference system, *upstream* refers to the negative and *downstream* to the positive z direction. Upstream of the LHCb magnet, the tracking system consists of a silicon strip detector for vertexing known as the Vertex Locator (VELO) and a large area silicon strip detector, the Tracker Turicensis (TT). Downstream of the magnet are the three T-stations. Each T-station consists of an Inner Tracker (IT), a silicon strip detector, surrounded by the Outer Tracker (OT), a straw drift tube detector. The track reconstruction is explained in more detail in Section 1.2.2.

Since the amount of data produced at all pp -collisions is too high to be stored, a selection of this data is being made using a trigger. During Run 2, the trigger [13] consists of two levels, the first level trigger (L0) and the High Level Trigger (HLT). L0, which is a hardware trigger, selects mainly b and c events at a maximum rate of 1.1 MHz. Subsequently the HLT reduces the rate of accepted events to 12.5 kHz, at which point the data can be stored.

A secondary, “displaced” vertex in addition to the pp collision vertex is a characteristic of a b -hadron. An example of such a displaced vertex is visualised in Figure 1.5 in the case of a B^+ decaying to a J/ψ and a K^+ . The distance in the XY plane between production and decay of the b -meson here is $\sim 300 \mu\text{m}$. Two important quantities contributing to a good proper time

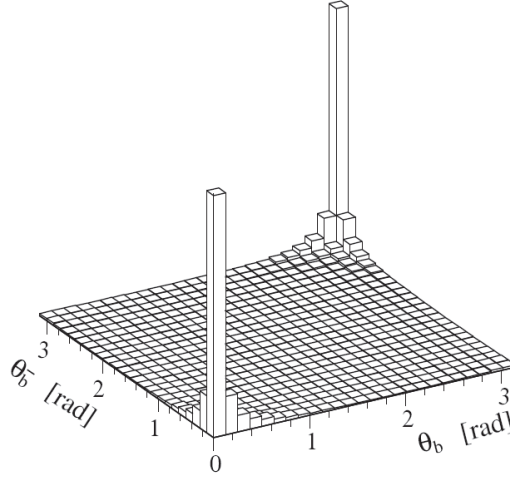


Figure 1.4: Production rate of b and $\bar{b}$ -mesons in the lab reference frame, using PYTHIA [12].

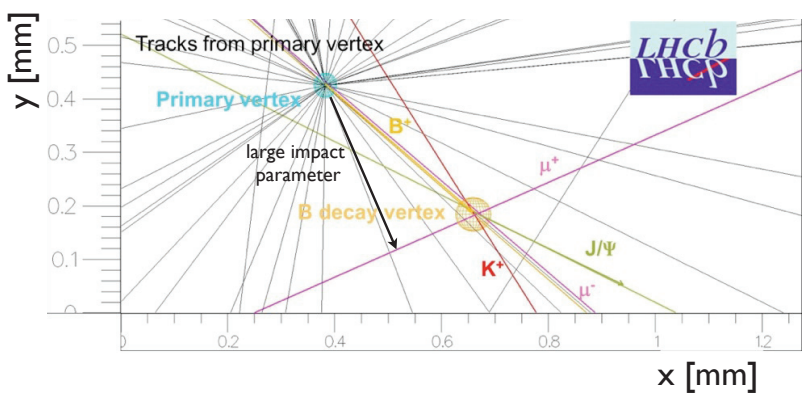
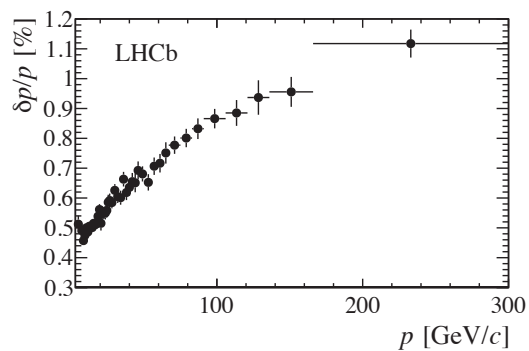
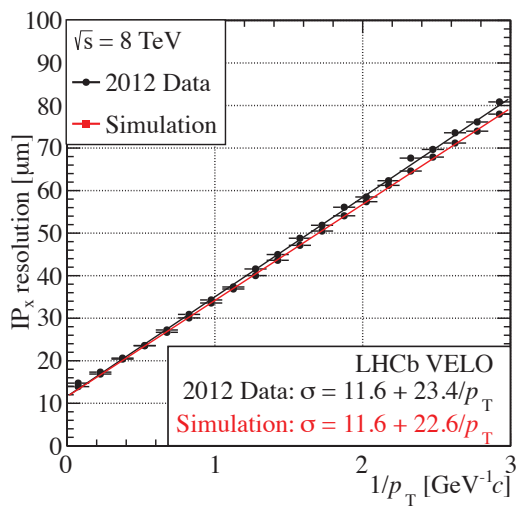


Figure 1.5: B decay products from a $B^+ \rightarrow J/\psi K^+$ candidate event from the LHCb data.



(a) Momentum resolution.



(b) Impact parameter resolution.

Figure 1.6: Two quantities demonstrating the performance of the LHCb detector are the momentum resolution (a) and the impact parameter resolution (b).

resolution, necessary to study the fast oscillating b -mesons, are the impact parameter resolution and the momentum resolution [14]. The momentum resolution for tracks, tested with J/ψ decays, is $\delta p/p \sim 0.45 - 1.1\%$ in the momentum range from 10–250 GeV/ c (Figure 1.6(a)). The impact parameter (IP) is the distance of closest approach between a track and the primary vertex. According to Figure 1.6(b), the IP resolution in the XZ plane is approximately inversely proportional to the transverse momentum of the track. The IP resolution will be studied in more detail in Chapter 3.

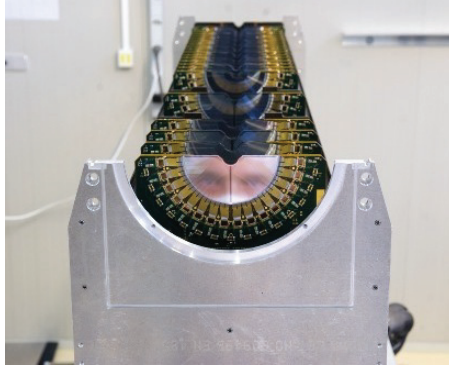
1.2.1 The Vertex Locator

The VELO is a silicon strip detector surrounding the interaction point of the LHCb detector. The VELO plays a significant role in the track reconstruction and also in the trigger by contributing to the event selection. The detector is installed closely surrounding the interaction region where there is a negligible magnetic field. It covers the full angular range of LHCb and its primary objective is to reconstruct primary and secondary vertices.

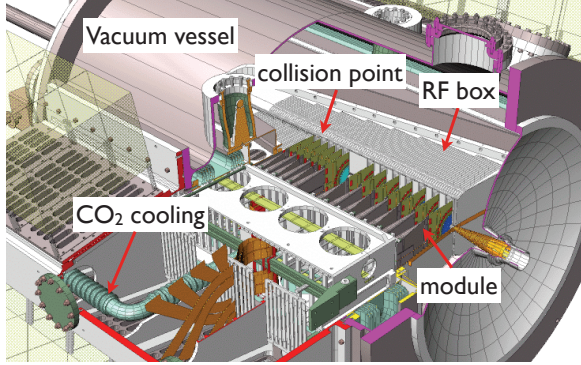
The VELO consists of two halves each containing 21 modules each (see Figure 1.7(a)). To achieve a good IP resolution the first strips of the VELO sensors are placed 8.2 mm away from the beam. This distance is smaller than the beam aperture required by the LHC machine during injection, therefore the two VELO halves are retractable. To measure the radial (R -sensor) and the azimuthal (ϕ -sensor) coordinates, two 300 μm thick semicircular silicon sensors with different strip orientation are mounted back to back on a module [15]. The total number of strips is $\sim 180,000$ with a pitch ranging from 38 μm in the inner to 102 μm in the outer edge of an R -sensor and from 38 μm to 97 μm for a ϕ -sensor. In an inelastic pp -collision the average number of observed clusters is ~ 2500 with on average ~ 2 strips per cluster.

The detector is operated in a secondary vacuum separated from the beam vacuum by a thin aluminium shield known as the RF-box (Figure 1.7(b)). The modules are cooled with an evaporative system using CO_2 as coolant [16]. The heat dissipation is about 17 W per module. The operational temperatures on the silicon sensors range from -10°C to 0°C [5] to minimize radiation induced effects.

Due to the high particle fluence that the modules are exposed to, the performance due to irradiation is a concern. One of the silicon properties affected by the amount of radiation is the leakage current as will be discussed in Section 4.5. According to Affolder et al. [17] the average rate of increase of the sensor current is 18 μA per fb^{-1} at a sensor temperature of -7°C . To compensate for a reduced depletion depth due to irradiation the bias voltage of the sensors needs to be increased. However, to avoid breakdown in the sensors a hardware limit of 500 V has been set.



(a) Photograph of one of the VELO retractable halves rotated by 90°.



(b) 3D model of the LHCb VELO vacuum tank.

Figure 1.7: (a) Photograph of one of the VELO retractable halves. (b) 3D model of the LHCb VELO vacuum tank. The cut-away view allows the CO₂ cooling system, the RF-box and the module support on the left-hand side to be seen.

1.2.2 Track Reconstruction

Track reconstruction in LHCb is performed by combining hits in the VELO with the TT and the downstream T-stations (T1 – T3). The reconstruction of a track starts with grouping hits known as *segments*. There are two type of track reconstruction sequences depending on where the segments are located, the forward and the backward tracking sequence. Both tracking sequences start from the VELO. Since the collision point of the pp -beams is located near the center of the VELO, segments using VELO hits are reconstructed assuming they originate from the z -axis. These segments are then extrapolated towards the T-stations. An algorithm searches for hits in the T-stations and if any are found they are added to the track. The forward track finding algorithm

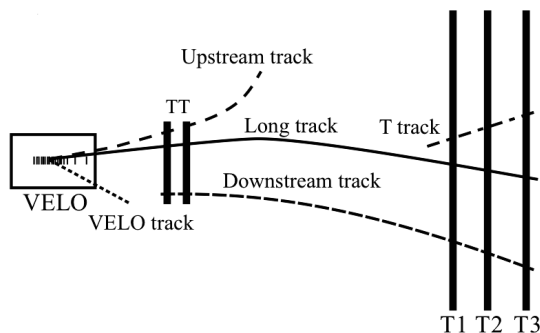


Figure 1.8: Track types (see text).

searches for a match to the track in the TT. In the backward sequence, segments from the T-stations, assuming they originate from the collision point, are extrapolated to the VELO in order to find a match with a VELO segment.

Tracks are labelled according to the subdetector hit information used as shown in Figure 1.8. A track that has hits in all subdetectors is tagged as *Long*. Tracks with segments only in the VELO and the TT are tagged as *upstream*. Tracks with segments only in the T-stations and the TT are tagged as *downstream*. Tracks with segments only in the VELO or the T-stations are tagged as *VELO* and *T-tracks* respectively. In the Impact Parameter studies that will be described in Chapter 3 only VELO and Long tracks are considered.

1.3 The LHCb upgrade

Despite its excellent performance, the LHCb detector has an integrated luminosity limit of about 2 fb^{-1} data per year [18]. Most of the studies in LHCb are statistics limited. Therefore more data is needed. Operating the LHCb detector at a higher luminosity in order to collect more data will however lead to the saturation of the current L0 trigger yield for hadronic channels, as illustrated in Figure 1.9. This saturation is due to the hardware limit imposed by the maximum readout rate. As a result L0 must reduce the rate below this limit which cannot be done efficiently at larger luminosities. The L0 trigger reconstructs one or two muons with the highest p_T and the hadron/electron/photon with the highest E_T distinguishing between electron and photon candidates using information from the ECAL. To increase the data rate without influencing the trigger efficiency, a new trigger scheme needs to be adopted, which drives the upgrade of the LHCb detector.

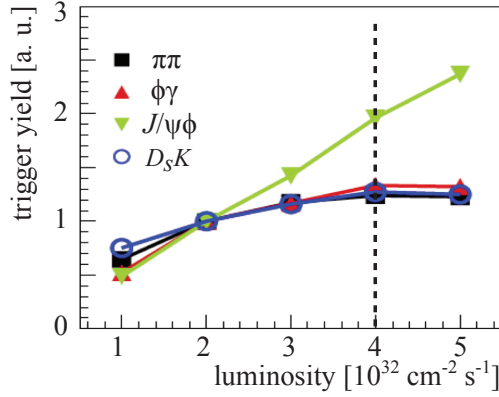


Figure 1.9: Low-level trigger efficiency as a function of luminosity for various hadronic decays [19]. Several modes saturate beyond the operation point of the LHCb detector at the end of Run 1 indicated by the dashed line. The decay $J/\psi(\rightarrow \mu^+\mu^-)\phi(\rightarrow K^+K^-)$ profits from two muons in the final state.

The LHCb detector is scheduled to be upgraded in the second long shutdown in 2019–2020. The upgraded detector will run at a 5 times higher luminosity and collect 50 fb^{-1} of data in Run 3. The expected number of visible pp interactions per bunch crossing at the upgrade luminosity is ~ 7.6 .

In the upgrade the L0 trigger will be removed and LHCb will adopt a full software trigger. The adaptation to the new readout scheme requires upgrade of all the tracking detectors described in Section 1.2.2. This thesis focuses on the upgrade of the VELO detector.

Chapter 2

The VELO upgrade

The LHCb detector will be upgraded in the second long LHC shutdown to profit from the high luminosity delivered by the LHC. To cope with the expected beam conditions and comply with the new data acquisition scheme the VELO detector needs to be replaced. Two options were considered, a silicon strip detector analogous to the current VELO and a silicon pixel detector. After reviewing both options [20] the LHCb collaboration selected the pixel design.

In this chapter several general aspects and challenges of the upgrade detector are listed, while in the subsequent chapters specific performance studies are presented in detail.

2.1 Resolution requirements

A number of requirements are given for the design of the VELO upgrade. The new detector must cover the pseudorapidity region of $2 < \eta < 5$. To reconstruct a charged particle, each track should have a minimum of three spatial measurements in the VELO. The hit resolution and the ability to separate tracks are important performance parameters. For a good hit resolution, the channel pitch needs to be in the same order of magnitude as in the current VELO.

In the analysis, tracks are extrapolated to the z -axis. The IP resolution of the VELO upgrade needs to be better than or equal to the performance of the current VELO. To achieve this, the distance from the first sensor element to the beam will be reduced from 8 to 5 mm. In addition, the material between the interaction point and the first hit needs to be minimised. The effect of extrapolating the distance from the first hit to the beam and of the material budget on the IP resolution of the VELO upgrade is studied in detail in Chapter 3. The resulting performance of these studies were used for the technology choice, eventually resulting in a validation of the pixel detector.

2.2 Constraints

Operating the VELO upgrade in a higher luminosity environment will lead to an increased particle flux. This high rate combined with the smaller distance from the detector to the beam increases the amount of radiation that the detector will be exposed to.

2.2.1 Data rates

During Run 1 the average number of hits per inelastic pp -collision was around 5,000. In the upgrade conditions of Run 3 at the instantaneous luminosity of $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, the number of hits per bunch crossing will be about $5.2 \text{ cm}^{-2} \times R^{-2}$ where R is defined as the radial distance from the beam to the outermost module edge in cm. Assuming an average of 32 tracks per module in an event [21] and an average of 2.2 pixels per cluster, the total number of hits per event is 7,300. The data acquisition and front end electronics of the VELO upgrade must be able to cope with these data rates.

2.2.2 Radiation damage

By moving the modules closer to the beam, the estimated integrated radiation dose per fb^{-1} increases by a factor of 2.5. Moreover, since the particle fluence is proportional to R^{-2} the resulting radiation profile along the module is not homogeneous.

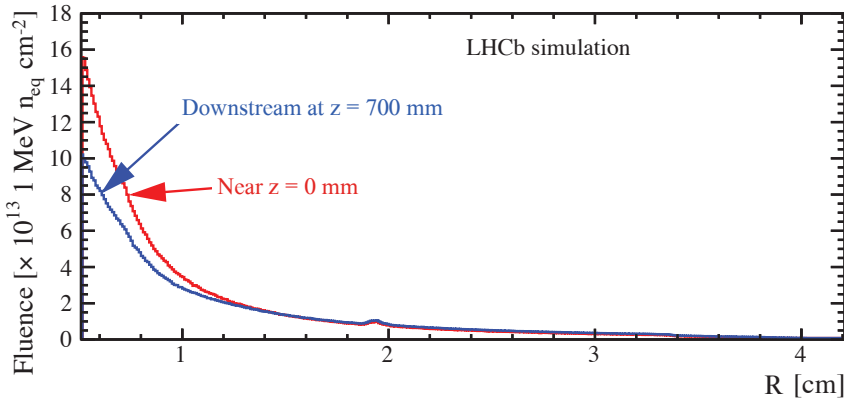


Figure 2.1: Fluence as a function of the radius R per delivered fb^{-1} for two sensors at different z positions. Plot taken from [21].

A simulation of the expected fluence¹ [$1 \text{ MeV } n_{\text{eq}}/\text{cm}^2$] as a function of the distance from the beamline R for modules at different z positions is shown in Figure 2.1. For both modules the fluence is maximum at the edge and decreases $\propto R^{-2}$. Close to the center of the interaction region ($z = 0$) the fluence at the edge of a module is a factor of 1.5 higher than the fluence at the edge of a downstream module at $z = 700 \text{ mm}$.

The integrated luminosity at the end of Run 3 is expected to be 50 fb^{-1} with a corresponding fluence of $8 \times 10^{15} \text{ } 1 \text{ MeV } n_{\text{eq}}/\text{cm}^2$. The exposure of silicon sensors to these high fluences reduces the amount of charge collected as will be explained in Section 4.5.1.

2.3 Layout in the upgrade

The design of the VELO upgrade is based on the requirements and constraints imposed in Section 2.2. The layout of the VELO upgrade detector is similar to the current VELO covering the same acceptance. The modules will be mounted on two halves that can move away from the beam line whilst the LHC beam is injected. This retraction mechanism ensures a reduced exposure of the modules during these conditions. When stable beams are declared the detector will be closed. The layout of the detector within the LHCb coordinate system is shown in Figure 2.2.

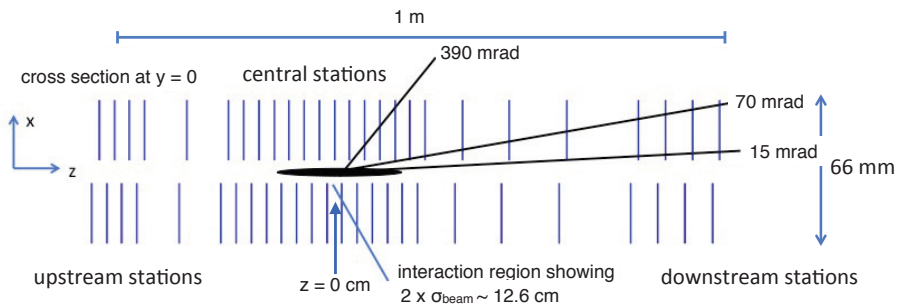


Figure 2.2: Schematic layout of the VELO upgrade [21].

2.3.1 Module description

The upgraded VELO is a silicon pixel detector. The silicon sensors have pixels of $55 \mu\text{m} \times 55 \mu\text{m}$ and cover an area of $15 \text{ mm} \times 43 \text{ mm}$. The detector consists of 26 stations where one station refers to a pair of modules, one on each half.

¹This is the neutron equivalent flux that will be explained in detail in Section 4.5.1.

Each module will host 4 sensor tiles, 2 at each side of the module as depicted in Figure 2.3(a). The modules are separated from the primary beam vacuum by a thin aluminium foil known as RF foil. Next to the tiles lie the so called hybrids, which are printed circuit boards. The dimensions of one sensor tile match the surface of the 3 adjacent ASICs² as shown in a prototype assembly in Figure 2.4.

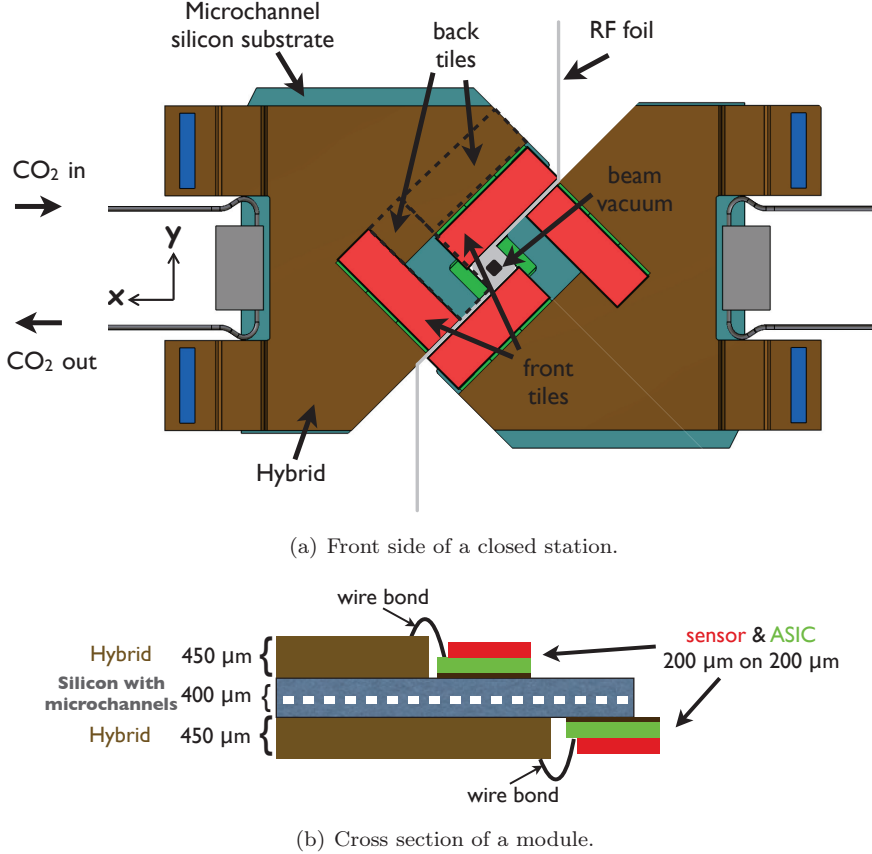


Figure 2.3: Schematic of the upgrade module: (a) front side of a closed station and (b) cross section of a module.

Between the two hybrids is an innovative type of cooling that will be discussed in Section 2.4.2. This microchannel cooling substrate is visible in the cross section view of Figure 2.3(b). The cooling substrate is made of silicon to minimise any mismatch in the thermal expansion coefficient that could lead to deformation of the module. No cooling substrate is placed under the first

²The acronym ASIC stands for Application Specific Integrated Circuit.

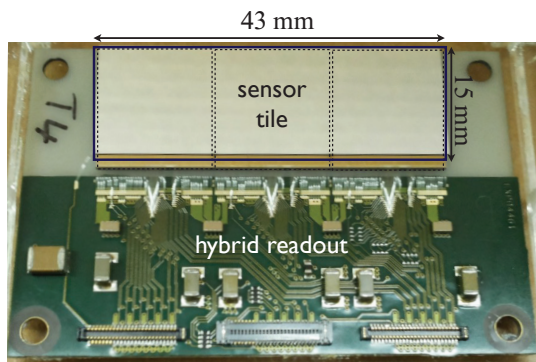


Figure 2.4: Three ASICs (dotted squares) share a common 3×1 sensor tile on a hybrid board.

5 mm of the sensor at the edge of the module in order to reduce the amount of material close to the beam. The amount of material is related to multiple scattering that is one of the quantities contributing to the IP resolution as will be discussed in Chapter 3.

2.4 Technical challenges

The construction of the VELO upgrade brings a number of technical challenges that need to be dealt with.

2.4.1 RF-foil

The RF-foil, separating the secondary vacuum from the beam vacuum, shields the modules from beam induced electromagnetic interference and guides the mirror currents of the beam. Although the foil is required to have a maximum thickness of about 250 μm , it is still the main contributor to the material budget as can be seen in the material description of the current VELO (Figure 2.5).

The foil contributes significantly to the material budget since due to its corrugated shape particles can traverse it multiple times. As shown in the prototype RF foil extending to 10 stations in Figure 2.6, a track with high η (track B) will traverse the foil at more points than a track with low η (track A).

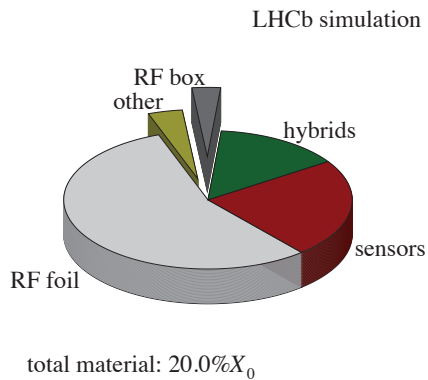


Figure 2.5: Radiation length of the current VELO. The main contribution comes from the RF foil [21].

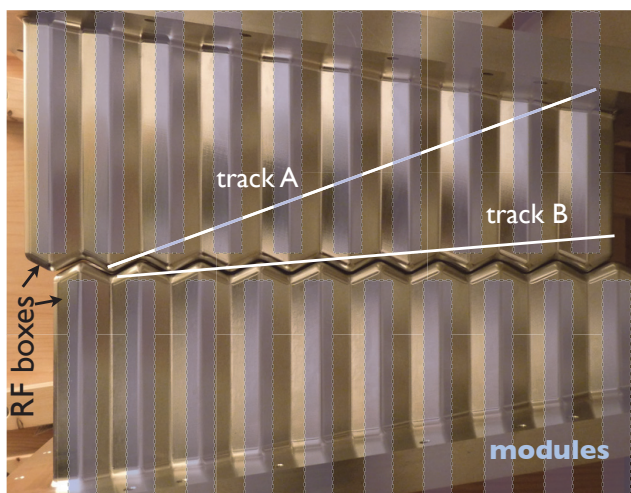


Figure 2.6: Prototype RF box with both half boxes extending to 10 stations. The modules are also illustrated (dotted rectangles). A track can cross the edge of the box at a few (track A) or multiple (track B) points [22].



Figure 2.7: Photograph of the “snake” design on a prototype sample with dimensions 4 cm $\times$ 6 cm.

2.4.2 Microchannel cooling

The cooling substrate of each module needs to remove 43 W. The main power dissipation comes from the ASICs and the sensors that are thermally coupled. The heat dissipation is expected to be 3 W per ASIC. Since the ASICs are between the cooling substrate and the sensors, the sensors can only be cooled via the ASICs. If not sufficiently cooled, the expected dissipated power may lead to thermal runaway. To prevent thermal runaway, the sensors need to be kept below -20°C [23].

Two-phase CO_2 cooling using microchannels in a 400 μm thick silicon substrate has been developed at Nikhef and at CERN. These channels of dimensions 200 μm $\times$ 120 μm will be etched in a silicon wafer which is subsequently sealed with another wafer. The expected CO_2 pressure at room temperature is about 65 bar but the system will be qualified up to 170 bar for safety reasons.

Measurements on a prototype Si-pyrex plate with a size of a quarter of one upgrade module demonstrated that 12.9 W of power could be removed [24]. A photograph from the pyrex side of a prototype sample is shown in Figure 2.7. The microchannels follow a “snake” design that serpentine along the sample.

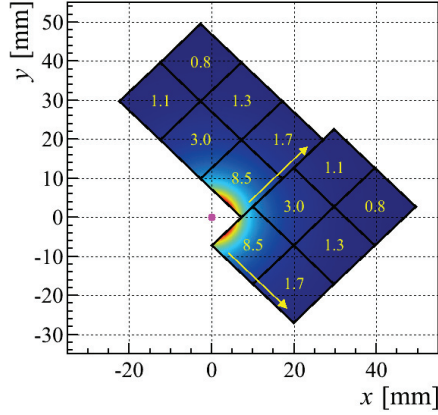


Figure 2.8: Average number of tracks per ASIC per bunch crossing in a VELO upgrade module.

2.4.3 The VeloPix ASIC

A new front end chip derived from the Medipix [25] family has been designed, VeloPix [26]. The VeloPix is built in a 130 nm CMOS technology and consists of a pixel matrix of 256×256 square pixels with a $55 \mu\text{m}$ pitch. The ASIC will provide a zero suppressed data driven readout. When charge generated by a traversing particle surpasses a certain threshold, the Time of Arrival (ToA) is measured and stored with the pixel location. The ToA has a timing resolution of 25 ns. Subsequently this information, together with the state of its neighbours in a 2×4 group of pixels, known as “superpixel”, is immediately sent off the chip.

In one bunch crossing the average number of tracks crossing the ASIC receiving the maximum number of hits is 8.5 per bunch crossing and <1 for the outermost ASIC (Figure 2.8). The peak hit rate is expected to be 900 MHits/s per ASIC. Because of the high particle flux, the VeloPix ASIC has to be radiation hard up to 400 MRad. To reduce the amount of material in a module, the new chip will be thinned down to $200 \mu\text{m}$.

2.4.4 Sensors

The baseline option for the VELO upgrade sensors are $200 \mu\text{m}$ thick, n -on- p type diodes with a conservative guard ring design with a total width of $450 \mu\text{m}$. However, other design variants in terms of thickness, sensor type and implant width are also considered. Prototype sensors based on these design variants were produced by two vendors, Hamamatsu and Micron. Although

Table 2.1: Properties of the prototype sensors for the VELO upgrade.

type	n -on- p , n -on- n
thickness [μm]	150, 200
size [$\text{mm} \times \text{mm}$]	15×15 , 15×43
vendor	Hamamatsu, Micron
implant width [μm]	35 – 39
guard ring [μm]	450

the dimensions of one sensor tile are $15 \text{ mm} \times 43 \text{ mm}$ and cover the surface of the 3 adjacent VeloPix ASICs, smaller sensors that cover one ASIC were also produced. The properties of the prototype sensors are summarised in Table 2.1.

The temperature of the silicon sensors must be kept $< -20^\circ\text{C}$ in order to avoid thermal runaway [21]. At -20°C the expected leakage currents are in the order of $200 \mu\text{A}/\text{cm}^2$ at the benchmark voltage of 1000 V. The estimated noise threshold of the VeloPix ASIC is $1000 e^-$. In order to collect sufficient signal in a pixel after charge sharing, a minimum signal yield of $6000 e^-$ is required.

2.5 Testbeam programme and Timepix3

Since the LHCb detector will be operated at a 5 times higher luminosity during Run 3, the silicon sensors must be radiation hard up to $8 \times 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$. The performance of the sensor tiles needs to be evaluated before proceeding to mass production.

A number of prototype silicon sensors with the sensor characteristics described in Table 2.1 have been developed by Hamamatsu and Micron. Ideally, the sensors would have been tested in combination with the VeloPix readout. However, VeloPix was not available at the time the prototype sensors were tested. Another member of the Medipix family, the Timepix3 ASIC, was used to test the prototype sensors. Timepix3 will be discussed in more detail in Section 4.3.

Contrary to VeloPix, Timepix3 provides also information on the amount of charge collected. When compared to VeloPix the main limitations of Timepix3 is that its data rate is lower by an order of magnitude and that it is not protected against radiation induced single event upsets.

The testbeam programme involved beam tests at SPS at CERN. In the testbeams, a telescope based on multiple Timepix3 ASICs was used. First,

the principles of operation of a silicon sensor are discussed in Chapter 4. The telescope is described in Chapter 5. The results of the testbeam programme are given in Chapters 6 and 7.

Chapter 3

Impact Parameter Studies for the VELO upgrade

A typical signature of a particle track originating from the decay of a b -meson is a large impact parameter with respect to the primary vertex of the particle. The impact parameter (IP) is the distance of closest approach between a reconstructed track and the true origin of the particle. In the VELO upgrade, the IP resolution is required to be at least as good as that of the current VELO. The upgraded VELO introduces some new features. The major differences between the current and the upgraded VELO that have an impact on the IP resolution are:

- the geometry of the RF foil, shape and corrugations and distance from the LHC beam,
- the shorter distance from the beam to the first active sensor element: 8.2 mm $\rightarrow$ 5.1 mm,
- the larger thickness: 200 μm thick sensor on top of a 200 μm ASIC, bonded using 20 μm thick spherical Tin-Lead (SnPb) bumps, plus 400 μm thick silicon substrate with microchannels used for cooling, compared to the current: 300 μm thick R and 300 μm ϕ sensor on a single current VELO module increasing the radiation length by a factor of 1.3,
- the coarser pitch of the channels close to the beamline: square pixels of 55 μm pitch compared to the 40 μm strips of current VELO.

The studies presented in this chapter were used to validate the resolution performance of the pixel detector. The final design of the detector that will be used in the upgrade was still under development at the time this study was performed. As a consequence, the geometry of the pixel detector simulated in these studies here differs slightly from the detector described in Chapter 2. In the simulated VELO upgrade layout the modules are rotated by 45° and the RF foil has a thickness of 300 μm . Schematic views of the simulated VELO upgrade layout are shown in Figure 3.1.

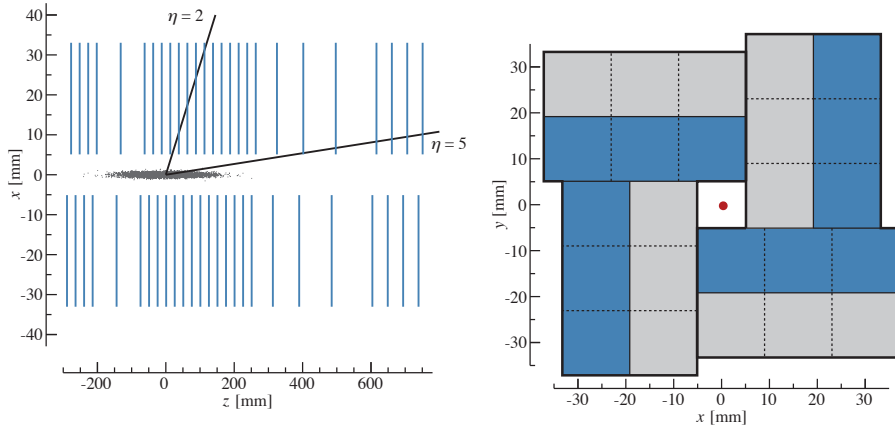


Figure 3.1: Simulated VELO upgrade layout. Schematic cross section at $y = 0$ with illustrations of the nominal LHCb acceptance (left). Schematic layout of the xy plane of two closed modules (right). The sensor elements in blue are in the back side of the modules, the ones in grey are in the front side. The red circle in the center represent the beam spot (not in scale).

The resolution of the VELO with the VeloPix detector was simulated in order to compare the resolution performance with the current VELO. The pp -interactions, the decay of the produced particles and their interaction with the detector materials are simulated using the GAUSS package, which is based on GEANT4. The digitization and the detector response is done using the BOOLE package. Finally, the track reconstruction is made using the BRUNEL package. The GAUSS, BOOLE and BRUNEL packages are based on the GAUDI framework [27]. Using the BRUNEL reconstruction package the impact parameter resolution of the pixel detector is studied.

3.1 Definition of Impact Parameter

Neglecting multiple scattering and energy loss the local trajectory of a charged particle around a reference point z_0 is described by a vector, called a *state*, consisting of 5 parameters. In LHCb the 5 parameters are chosen to be $(x_0, y_0, t_x, t_y, q/p)$ where x_0 and y_0 are the coordinates at the reference position z_0 , t_x and t_y are the slopes in the xz and yz planes respectively and q/p is the ratio of the charge to the momentum, also called curvature. An interaction vertex is described as a point (x_v, y_v, z_v) in the 3-dimensional space. The 3-dimensional IP between a reconstructed track and a vertex can be expressed as:

$$\text{IP}_{3D} = \frac{\sqrt{\Delta x^2 + \Delta y^2}}{\sqrt{1 + t_x^2 + t_y^2}} \quad , \quad (3.1)$$

where Δx and Δy are:

$$\begin{aligned} \Delta x &= x_0 + (z_v - z_0)t_x - x_v \equiv \text{IP}_x \\ \Delta y &= y_0 + (z_v - z_0)t_y - y_v \equiv \text{IP}_y, \end{aligned} \quad (3.2)$$

the IP components in the yz and xz planes, respectively. In Eq. (3.2) it is assumed that the reference position z_0 is close to the vertex position z_v such that a linear extrapolation can be used. The IP_x or IP_y will be referred to as the 2-dimensional IP. In order to study the IP resolution, the distances δIP_{3D} , δIP_x , δIP_y of a reconstructed track with *its own* production vertex can be determined.

The calculated δIP is generally non-zero due to the finite hit¹ resolution of the VELO and due to multiple scattering in the detector material and the RF foil. To illustrate this, consider a track measured at two points A and B (Figure 3.2) with position (z_1, x_1) and (z_2, x_2) respectively and its production vertex located at (z_v, x_v) . The 2-dimensional δIP_x in the xz -plane (Eq. 3.2) is expressed as a function of the measured points as

$$\Delta x = x_1 + (z_v - z_1) \frac{x_2 - x_1}{z_2 - z_1} - x_v \quad . \quad (3.3)$$

Since x_1 and x_2 are uncorrelated measurements, propagating their errors to Δx gives:

$$\sigma_{\Delta x}^2 = \sigma_{x_1}^2 \left(\frac{\partial \Delta x}{\partial x_1} \right)^2 + \sigma_{x_2}^2 \left(\frac{\partial \Delta x}{\partial x_2} \right)^2 \quad (3.4)$$

where the first derivatives are:

$$\frac{\partial \Delta x}{\partial x_1} = \frac{z_2 - z_v}{z_2 - z_1} \quad (3.5)$$

$$\frac{\partial \Delta x}{\partial x_2} = -\frac{z_1 - z_v}{z_2 - z_1} \quad . \quad (3.6)$$

¹In this chapter the term *hit* refers to the center of gravity of a cluster while in Chapter 2 the same term refers to a pixel.

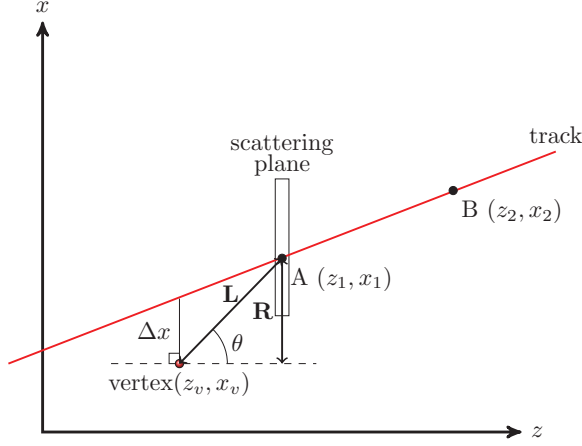


Figure 3.2: Impact parameter component in the xz plane.

Assuming that the errors on x_1 and x_2 are equal we set $\sigma_{x_1} = \sigma_{x_2} = \sigma_0$. Substituting (3.5) and (3.6) in (3.4) we get:

$$\sigma_{\Delta x}^2 = \frac{\sigma_0^2}{(z_2 - z_1)^2} [(z_2 - z_v)^2 + (z_1 - z_v)^2] \equiv \delta \text{IP}_x^2, \quad (3.7)$$

which is the error on the IP due to extrapolation. The next step is to include multiple scattering in our simplified model. The width of the Coulomb scattering distribution is given by [28] :

$$\theta_0 = \frac{13.6 \text{ MeV}}{p \beta c} q \sqrt{x/X_0} [1 + 0.038 \ln(x/X_0)] \quad (3.8)$$

where x/X_0 the number of radiation lengths of the material traversed by the particle, p the momentum, βc the velocity and q the charge of the incident particle. Since the charged particle of Figure 3.2 is first measured at point A and subsequently at point B, multiple Coulomb scattering (MCS) would change the track angle at point A. The scattering at point A leads to a kink at $z = z_1$ so the IP resolution (3.4) becomes:

$$\sigma_{\Delta x}^2 = \underbrace{\frac{\sigma_0^2}{(z_2 - z_1)^2} [(z_2 - z_v)^2 + (z_1 - z_v)^2]}_{\text{resolution term}} + \underbrace{\theta_0^2 (z_1 - z_v)^2}_{\text{MCS term}}. \quad (3.9)$$

The IP resolution thus consists of two terms, the resolution and the MCS term. The resolution term depends on the measurement error and the “lever-arm”, i.e. the relative positions of the measurement points with respect to the primary vertex. The MCS term depends on the momentum of the particle, the amount of material that the particle traverses and the distance from the first scattering point to the primary vertex.

Defining L (L_x, L_y, L_z) as the distance between the first hit and the vertex (see Figure 3.2), the MCS term can be expressed as a function of the transverse momentum p_T and the radial distance $R = \sqrt{L_x^2 + L_y^2}$. The following relation holds between the momenta and the distance from the first hit to the vertex:

$$\sin(\theta) = \frac{R}{L} = \frac{p_T}{p} \quad (3.10)$$

so the MCS term can be written using Eq. (3.10) and the fact that $\theta_0 \propto 1/p$ from Eq. (3.8):

$$\theta_0^2(z_1 - z_v)^2 \propto \frac{(z_1 - z_v)^2}{p^2} \quad (3.11)$$

$$= \frac{L^2 - R^2}{p^2} \approx \frac{R^2}{p_T^2} \quad , \quad (3.12)$$

since for forward tracks at the pseudorapidity region of LHCb $\sin(\theta) \approx \theta \ll 1$. Combining (3.11) with Eq. (3.8) and Eq. (3.9) the IP resolution can be written as:

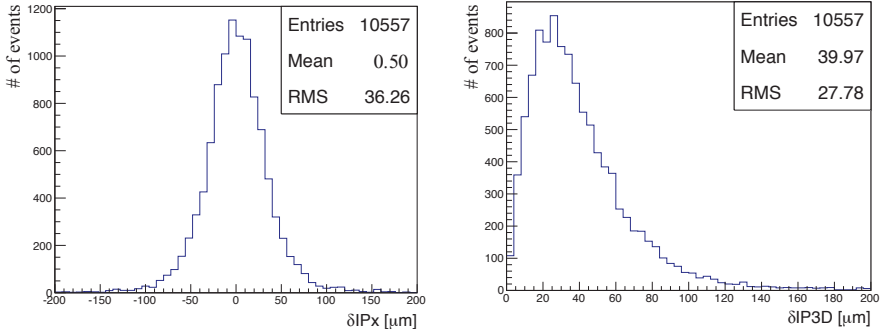
$$\begin{aligned} \sigma_{\Delta x}^2 = & \frac{\sigma_0^2}{(z_2 - z_1)^2} [(z_1 - z_v)^2 + (z_2 - z_v)^2] \\ & + \frac{R^2}{p_T^2} \left(\frac{13.6 \text{ MeV}}{\beta c} q \sqrt{x/X_0} [1 + 0.038 \ln(x/X_0)] \right)^2 . \end{aligned} \quad (3.13)$$

For tracks with high p_T the resolution term will be dominant while for low p_T tracks both MCS and the resolution term are important. Looking at the differences between the current and the VELO upgrade scenario, a prediction of how the IP resolution will evolve is not straightforward. A thinner RF foil will reduce the MCS before the first measurement. The thicker silicon modules will contribute more to the MCS with each additional measurement. The shorter distance from the vertex to the point of the first measurement (as well as to the RF foil) shall decrease the extrapolation error in contrast to

the coarser channel pitch, which will increase the error. All these factors are studied in detail in Section 3.3.

3.2 Extracting the Impact Parameter resolution

Before looking at the factors that have an effect on the IP the statistical method with which the IP resolution is obtained is presented. All studies for calculating the IP are made using the offline reconstruction package BRUNEL. In all studies, samples of the decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$ were used. The truth information of the MC particle properties (trajectory, energy, momentum, E_{dep} in the sensor etc.) is used to extract the resolution on the IP measurement. Only forward tracks with at least 3 hits in the VELO at a pseudorapidity range of $2 < \eta < 5$ are considered.



(a) Distribution of the 2-dimensional impact parameter δIP_x on the xz plane. (b) Distribution of the 3-dimensional impact parameter δIP_{3D} .

Figure 3.3: Impact parameter distributions for $0.9 < 1/p_T < 1.1$ [$\text{GeV}^{-1}c$]. Samples of the decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$ were used.

Due to the non-Gaussian shape and the long “tails” of the IP distribution, the resolution of the IP is calculated using a truncated RMS method. At each inverse transverse momentum bin the RMS of the IP distribution like in Figure 3.3(a) is calculated as:

$$\text{RMS} = \sqrt{\frac{\sum_{i=1}^N w_i (x_i - \bar{x})^2}{\sum_{i=1}^N w_i}} \quad (3.14)$$

where N is the number of bins of the distribution, $\bar{x}$ the mean IP, x_i the value of the IP and w_i the number of entries corresponding to bin i . The IP distribution is then iteratively truncated at $N = 3$ times the RMS. The 3-dimensional δIP_{3D} distribution is by its definition in Eq. (3.1) a positive non-symmetric distribution as can be seen in Figure 3.3(b). If δIP_x and δIP_y are Gaussian distributed with their mean close to zero then the mean of the δIP_{3D} is equal to $\sqrt{\frac{\pi}{2}}\sigma_{\text{IP}_X}$ with $\sigma_{\text{IP}_X} = \sigma_{\text{IP}_Y}$ [29].

3.3 Decomposition of Impact Parameter terms

In this section it is studied how factors related to the detector (detector resolution, material), factors related to the distance between first hit and vertex and factors related to the particle (momentum, pseudorapidity, vertex type) have an effect on the IP resolution.

3.3.1 Detector resolution

In a non-irradiated detector, a particle traversing the sensor activates more than one pixel and the resolution is optimised by weighing the amount of charge liberated by the incident particle that is shared over the hit pixels. The lower resolution limit of a pixel detector is determined by the resolution of 1-pixel clusters known also as binary resolution. Binary resolution depends on the pixel pitch and is expected to be smaller than or equal to $\text{pitch}/\sqrt{12}$. The resolution of the detector becomes binary after the sensor is heavily irradiated since the effective sensor thickness is reduced and the field strength in the sensor is so high that there will hardly be any diffusion and subsequent charge sharing.

The simulated detector resolution for the binary as well as the charge sharing case for a non-irradiated sensor with a 55 μm pitch are superimposed in Figure 3.4. The residual is defined as the true x position of the track minus the x position reconstructed from the detector. For the binary resolution, the reconstructed x position is defined as the center of the pixel that is hit. The binary resolution follows a uniform distribution. For the charge sharing resolution obtained for multi-pixel clusters, the reconstructed x position is calculated using the center of gravity method. In the center of gravity method the hit position x_{cog} of N pixels is calculated after weighing the position of the pixels using their respective charge with the formula

$$x_{cog} = \frac{\sum_{i=0}^N x_i q_i}{\sum_{i=0}^N q_i} . \quad (3.15)$$

The two peaks in the charge sharing distribution come from 2-pixel clusters where the residual of the center of gravity and true position in X depends on the track slope t_x . The charge sharing resolution can be improved by applying a correcting parametrisation [30] which is not applied in the studies presented here.

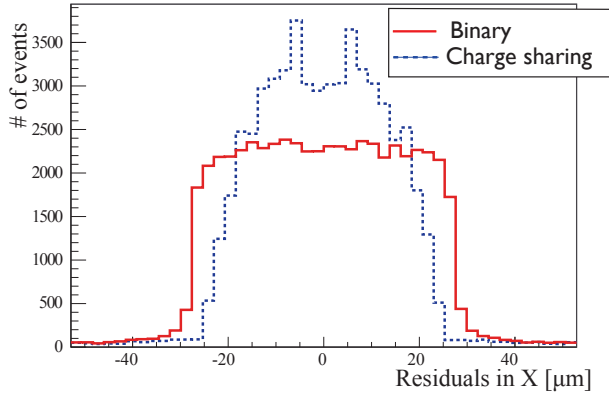


Figure 3.4: Simulated detector resolution: binary (red), with charge sharing (dashed blue).

To estimate the effect of the binary resolution on the IP resolution, the detector response is simulated without charge sharing. The IP resolution as a function of $1/p_T$ for three different detector resolution scenarios is depicted in Figure 3.5. The blue dotted line represents the IP resolution including the charge sharing information for multi-pixel clusters, the red line with the triangles the IP resolution when the detector has a binary resolution and the black line with the crosses the IP resolution of the current VELO. Both the charge sharing and binary scenarios have a better IP resolution than the current VELO. This means that in the VELO upgrade low p_T tracks will have a better IP resolution. The IP resolution when the detector response is binary is almost identical with the IP resolution with multi-pixel clusters included showing that charge sharing has a negligible effect on the IP resolution.

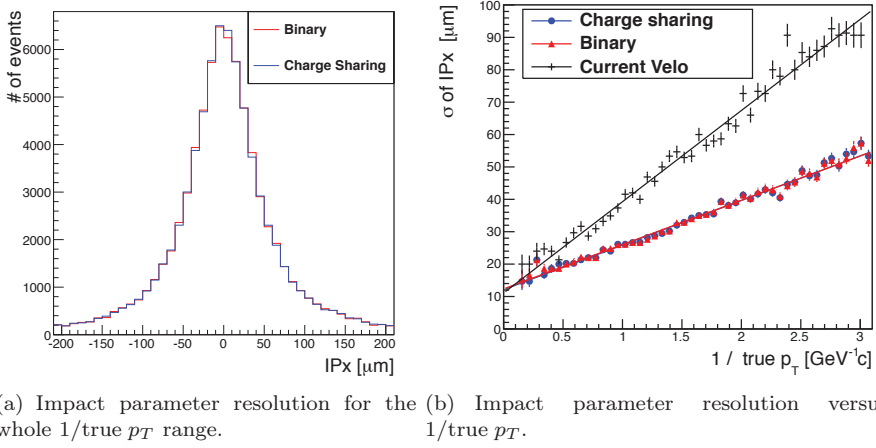


Figure 3.5: Impact parameter for different detector resolution: binary (red), with charge sharing (blue).

3.3.2 Geometrical decomposition

According to Eq. (3.13) the impact parameter consists of a MCS and an resolution term. A further decomposition of the impact parameter into these terms is illustrated in Figure 3.6. The total IP resolution contains contributions from scattering as well as the detector resolution. Figure 3.6(a) illustrates the scattering contribution in the case of a perfect detector resolution measurement. This contribution includes:

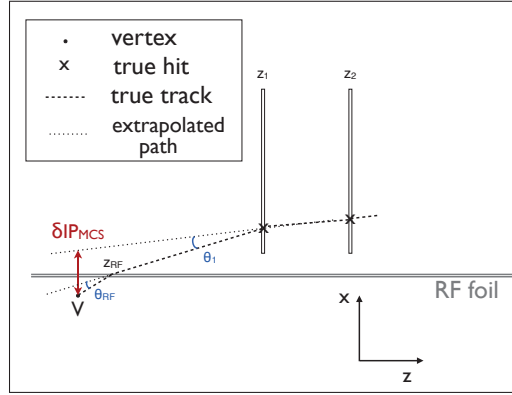
$$\delta\text{IP}_{MCS} \approx \theta_1(z_v - z_1) + \theta_{RF}(z_v - z_{RF}) \quad (3.16)$$

where θ_1 and θ_{RF} are the scattering angles in the first detector measurement and RF foil respectively. Figure 3.6(b) shows the contribution of the track slope measurement to the IP calculated as:

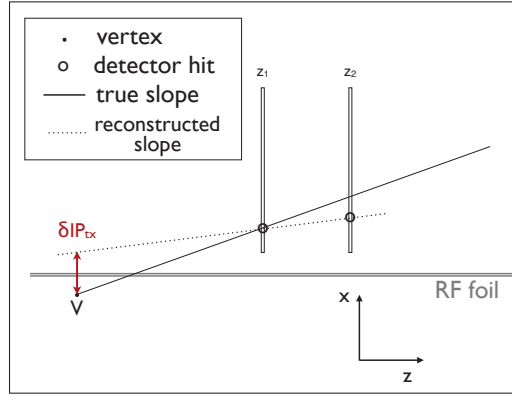
$$\delta\text{IP}_{tx} = (t_{x,rec} - t_{x,true})(z_v - z_1) \quad (3.17)$$

where $t_{x,rec}$ is the slope of the reconstructed track at the first measurement and $t_{x,true}$ the corresponding slope according to the truth information. Finally Figure 3.6(c) shows the contribution of the position offset due to the track measurement and it is obtained as:

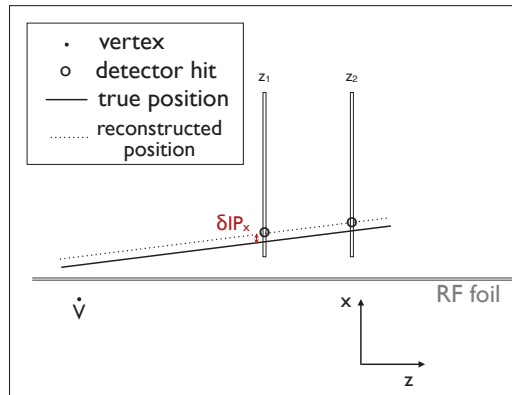
$$\delta\text{IP}_x = x_{rec} - x_{true} \quad (3.18)$$



(a) Scattering error contribution to the IP.



(b) Slope measurement contribution.



(c) Position measurement contribution.

Figure 3.6: Geometrical decomposition of the impact parameter terms. The total IP can be described by the scattering error (a) and the resolution error. The terms contributing to the resolution error are the slope measurement (b) and the position measurement of the first hit (c).

where x_{rec} and x_{true} are the positions of the reconstructed and true tracks at the z position of the first measurement.

As suggested by Eq. (3.13) the IP resolution is well described by a linear dependence on the inverse transverse momentum ($1/p_T$) plus a constant offset [29]. In Figure 3.7, the IP resolution as a function of $1/p_T$ is plotted for VELO tracks and Long tracks. The track finding and track fitting procedure is different for the two track types. VELO tracks are created in the HLT where no momentum information is available. Long tracks have hits on all tracking detectors of LHCb and have a momentum requirement $p > 2$ GeV/c. Moreover, Long tracks are fitted with a Kalman-filter [31] and consist of a collection of 5-dimensional states, one for each hit. The advantage of using the Kalman filter is that the positions, slopes and their respective errors at each measurement take the MCS into account, which is approximated by a gaussian “noise”.

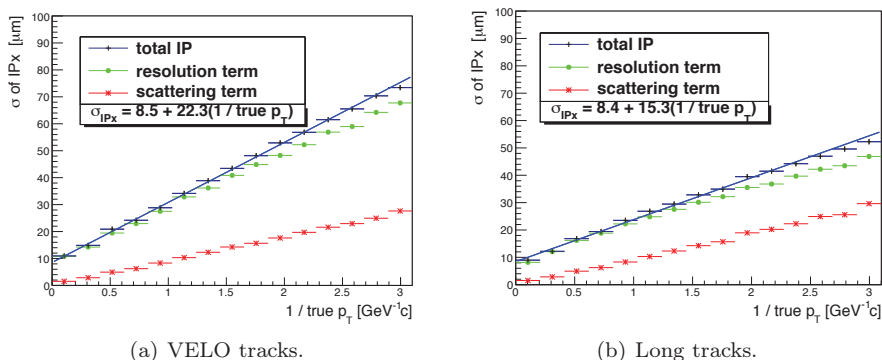


Figure 3.7: Decomposition of impact parameter terms.

The use of the Kalman-filter results in the error on the slope of the Long track’s state closest to the vertex being smaller than the error on the slope from the straight line fit. For very high p_T tracks the amount of scattering is negligible hence the main contribution to the IP error comes from the uncertainty in the resolution term. Lower p_T particles are expected to scatter more, adding up to a steeper slope of the IP resolution versus $1/p_T$ plot. The scattering error per inverse transverse momentum bin is the same for both track types. The error on the resolution term is smaller in the case of the Long tracks (Figure 3.7(b)) due to the fact that they are fitted with the Kalman-filter leading to a more precise measurement of the track slope at the first point. The smaller error on the resolution term makes the total IP error of Long tracks smaller than the IP error of the VELO tracks (Figure 3.7(a)).

The contribution of the fitted track slope and position error on the first hit to the resolution term of the IP resolution is further decomposed in Figure 3.8. The position error at the first hit increases with a small rate for the

VELO tracks (Figure 3.8(a)) while it is almost constant for Long tracks (Figure 3.8(b)). The difference in the position error at first hit between VELO and Long tracks originates from the track fitting method.

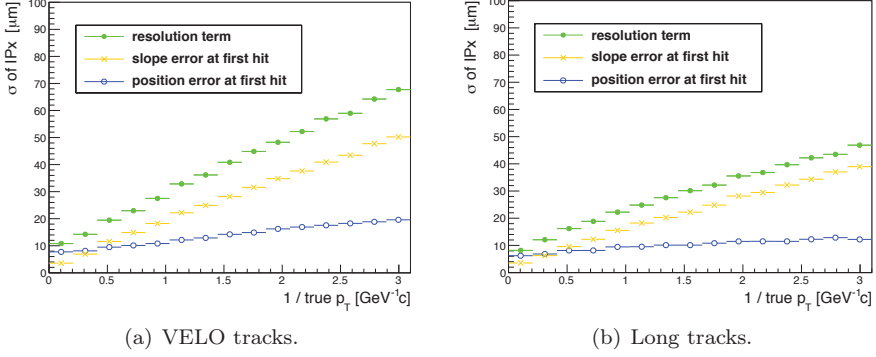


Figure 3.8: Decomposition of the resolution term components.

In general a trajectory is better estimated in the case of Long tracks, which are fitted with the Kalman-filter, compared to the straight line fitted VELO tracks since the former includes MCS. This can be seen in the pull distributions of the IP at the first hit in Figure 3.9.

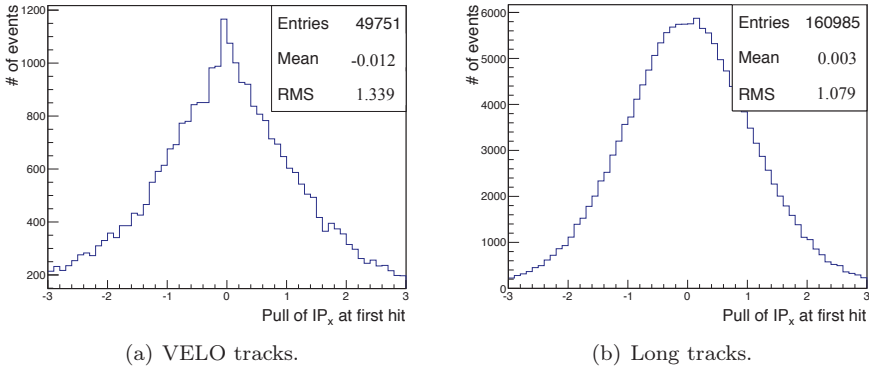


Figure 3.9: Pull distributions at first hit.

For Long tracks the RMS of the pull distribution (Figure 3.9(b)) is about one, indicating that the errors from the track fit are well estimated. The fact that the RMS of the pull distribution for VELO tracks (Figure 3.9(a)) is larger than one indicates that the errors assigned from the track fit are underestimated. The slope error at the first hit is the main source of uncertainty in the extrapolation error term for both track types. The smaller slope error at the first hit in the case of Long tracks compared to the respective error of VELO

tracks is responsible for the smaller extrapolation error of the Long tracks.

3.3.3 First hit contribution

According to Eq. (3.13) minimizing the radial distance² R between the particle production point and the first measurement point will decrease the extrapolation error. The IP resolution as a function of the mean R is depicted in Figure 3.10. The grey lined histogram in the background represents qualitatively the R distribution. The majority of the tracks are beyond $R = 5$ mm which is the distance between the edge of the sensor and the beam. Tracks with $R < 5$ mm do not come from a primary vertex but from secondary vertices. The IP resolution for both VELO and Long tracks increases as R becomes larger with Long tracks having a better resolution.

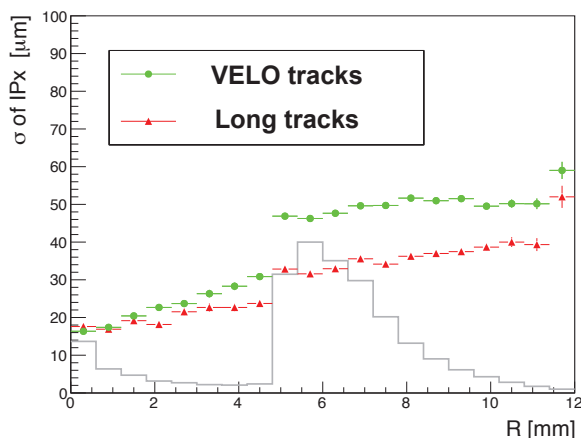


Figure 3.10: Impact parameter resolution versus radial distance at the first hit. The distribution of the radial distance between first hit and particle production point is represented qualitatively by the grey solid histogram in the background.

The mean R as a function of pseudorapidity (η) and the azimuthal angle (ϕ) is presented in Figure 3.11. The mean R is 6-8 mm over the whole η coverage of LHCb (Figure 3.11(a)). The shape of the mean R versus ϕ in Figure 3.11(b) is related to the module geometry. When the two retractable arms are closed the upgraded modules form a square around the beam with the beam spot at the center of the square (Figure 3.1(right)). The maximum distance between the beam and the edge of the sensors in the xy plane is between the beam spot and the corners of the square. Hence the peaks of R in Figure 3.11(b) appear at values of ϕ equal to $\pi/4$, $3\pi/4$, $-\pi/4$, and $-3\pi/4$ marked with the vertical dashed lines.

²The radial distance was defined in Section 3.1 as $R = \sqrt{L_x^2 + L_y^2}$.

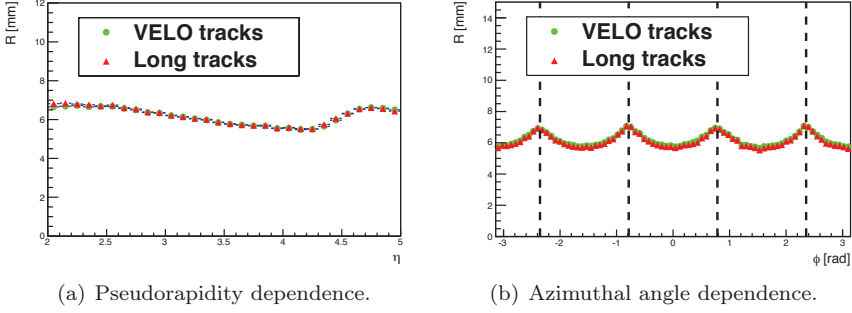


Figure 3.11: Distance between vertex and first hit versus pseudorapidity η (a) and azimuthal angle ϕ (b).

3.3.4 Momentum and η dependence

So far the effects of the detector characteristics (resolution, MCS and first hit contribution), the track type (VELO, Long) as well as the components of the track fit (slope, error) on the IP resolution have been examined. Subsequently the effects of the particle's kinematics on the IP error are investigated.

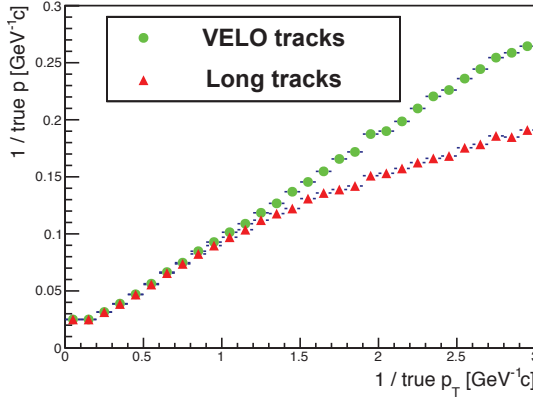


Figure 3.12: Mean inverse momentum versus inverse transverse momentum for different track types.

Plotting the IP resolution as a function of $1/p_T$ has the advantage that the IP resolution can be described to first order by a straight line. The angular acceptance and the momenta of VELO and Long tracks are, however, different. In Figure 3.12, the inverse momentum versus the inverse transverse momentum is plotted for VELO (green circles) and Long tracks (red triangles). On average Long tracks with low p_T values ($1/p_T > 1.5 \text{ GeV}^{-1}c$) have higher momentum than VELO tracks with the same p_T . This is expected since a particle must

have a momentum >1.5 GeV/c in order to cross the magnet and be detected in the T stations.

The track momenta are also correlated with their production angle. Figure 3.13 shows the total IP resolution for three different η regions. As η decreases the IP resolution becomes better.

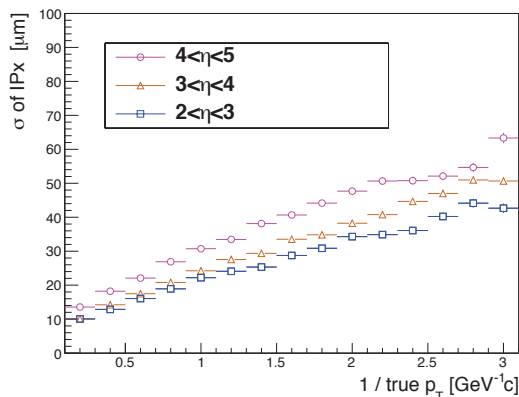
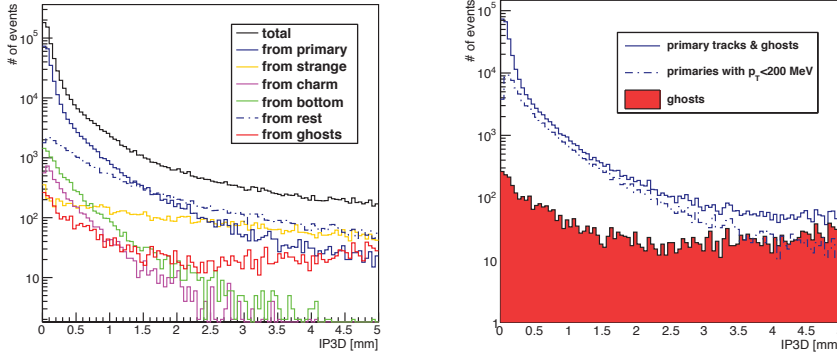


Figure 3.13: Total IP resolution of Long tracks for different η ranges.

3.3.5 Impact Parameter distributions of b and ghost tracks

The track selection in HLT during Run I is based on a lower cut of 100 μ m on the IP3D of the VELO segment of the tracks. The distributions of the IP3D with respect to the type of reconstructed vertex are presented in Figure 3.14(a) with the LHCb detector simulated in the upgrade conditions. Using the Monte-Carlo truth tracks coming from a primary vertex (blue solid line), tracks coming from a b -quark (green line) and ghost tracks (red line) can be distinguished. For the LHCb physics analyses it is important to select b tracks. The IP3D is used as an input for this selection. Almost 50% of tracks coming from a b -quark have an IP >100 μ m while tracks from a primary vertex are dominating for values of IP3D lower than 3.5 mm.

In the VELO upgrade the improved IP resolution in the low p_T region will allow to make an even tighter requirement. Note that a dangerous background for the trigger are incorrectly reconstructed tracks, the so-called ghost tracks. Even though the total amount of ghost tracks in the VELO upgrade is much lower than in the current VELO [21], Figure 3.14(b) shows that ghosts remain an important background component in the trigger.



(a) Reconstructed IP3D distribution of different vertices. (b) Reconstructed IP3D distribution of primaries and ghosts.

Figure 3.14: Reconstructed IP3D distributions with the detector simulated in the upgrade conditions.

3.4 Conclusions

The IP resolution is described in (3.13) as a function of the amount of material, detector resolution, momentum and extrapolation from the first measurement. The total material of the upgraded VELO detector averaged over the nominal η range of LHCb will be a factor 1.3 larger than the current detector. This fact alone would contribute more to the MCS increasing the slope of the IP resolution. As shown in Figure 3.5(b), this is not the case for the VELO upgrade. This is due to the fact that the IP resolution depends strongly on the extrapolation lever arm. Reducing the radial distance of the first hit by placing the edge of the sensors 3.1 mm closer to the beam will minimise the extrapolation error. That results in a smaller IP error for the upgrade compared to the current VELO. According to Eq. (3.9) the coarser pitch of the pixels will result in a worse detector resolution σ_0 influencing the resolution term of the IP. Looking at the IP resolution of tracks with the highest p_T , the difference between the current VELO and the upgrade scenarios is negligible.

Two different track types are considered: reconstructed VELO tracks with an unknown value for p and Long tracks where p is known. Long tracks compared to VELO tracks have smaller extrapolation errors from the first hit to the position of the vertex (Figure 3.8) due to the fact they are fitted with a Kalman-filter. The extrapolation error depends strongly on scattering. The reason Long tracks have a better impact parameter resolution at the first hit is due to the fact that the Kalman-filter accounts for the scattering at that measurement. Since the error due to scattering is equal for the two track types (Figure 3.7), the smaller extrapolation error leads to a better IP resolution in

the case of Long tracks. In addition to that, tracks reconstructed as Long on average have higher momentum as shown in Figure 3.12, which can be translated to less MCS in the modules.

The improved IP resolution in the VELO upgrade of tracks with low p_T will affect the majority of tracks coming from a primary vertex as illustrated in Figure 3.14(b).

For LHCb it is of great importance to measure the IP with high precision. The upgrade detector is designed to have an IP resolution equal to or better than the current VELO. Based on the studies presented in this chapter the upgraded VELO detector is expected to perform better than the current VELO in terms of IP resolution.

Chapter 4

Silicon sensors

Silicon sensors for high energy physics experiments were first developed by Heijne et al. [32]. They have been used in a variety of applications where a large occupancy, fast charge collection time and a high signal to noise ratio are required. To explain the principles of operation of a silicon sensor the interaction mechanisms of charged particles with matter are first introduced. Next, the basic characteristics of a silicon sensor are described along with how they affect the signal formation. Subsequently the signal acquisition using a readout chip, in particular Timepix3, is described. Since the VELO upgrade will be exposed to a high amount of radiation, finally the effect of radiation on the sensor performance is discussed.

4.1 Interaction of particles with matter

4.1.1 Mean energy loss

The average energy loss per unit thickness or stopping power $\langle dE/dx \rangle$ of charged particles is described by the Bethe-Bloch equation [28] in units of MeV g⁻¹cm²:

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi N_A r_e^2 m_e c^2 z^2}{\beta^2} \frac{Z}{A} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad (4.1)$$

where N_A is Avogadro's number, r_e the classical electron radius, A and Z the atomic mass and atomic number of the absorber, z the charge of the incident particle, β the ratio of the velocity to the speed of light, γ the Lorentz factor, $m_e c^2$ the rest mass of the electron, T_{max} the maximum kinetic energy that can be transferred to a free electron in a single collision, I the mean excitation energy in eV and $\delta(\beta\gamma)$ the density effect correction to the ionization energy loss added by Bichsel. With increasing energy the stopping power of

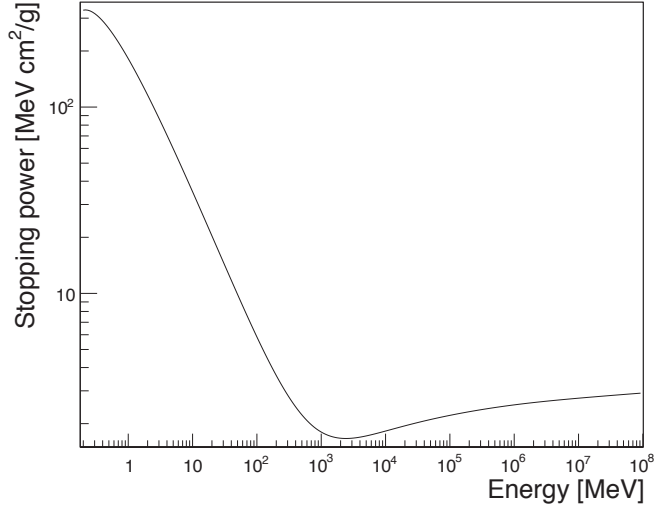


Figure 4.1: Stopping power versus kinetic energy of protons in silicon. The stopping power reaches a minimum which marks the minimum ionizing regime.

an ionizing particle drops until it reaches a minimum (Figure 4.1). When the momentum of the particle is at that minimum (10^3 – 10^4 MeV) the particle is called minimum ionizing. Beyond that minimum there is a small logarithmic rise of the stopping power which finally flattens due to the so-called density effect.

As described by Nakamura et al. [28], the Bethe-Bloch formula does not fully describe the energy deposited in a material. The mean energy loss given by Eq. (4.1) is not fully absorbed in the detector due to δ -rays escaping and carrying part of that energy as described in Section 4.1.2.

4.1.2 Most probable energy loss

The energy loss Eq. (4.1) shows statistical fluctuations. To calculate the energy loss distribution, also known as energy straggling function, of a particle through a material one has to solve the transport equation. Landau solved the transport equation using Laplace transformations [33] for thin absorbers i.e. absorbers satisfying the condition $\frac{\xi}{T_{max}} \ll 1$ [34] with ξ defined as:

$$\xi = \frac{K}{2} \left\langle \frac{Z}{A} \right\rangle \frac{x}{\beta^2} \quad (4.2)$$

where x is the absorber thickness in g cm^{-2} and K expresses the terms

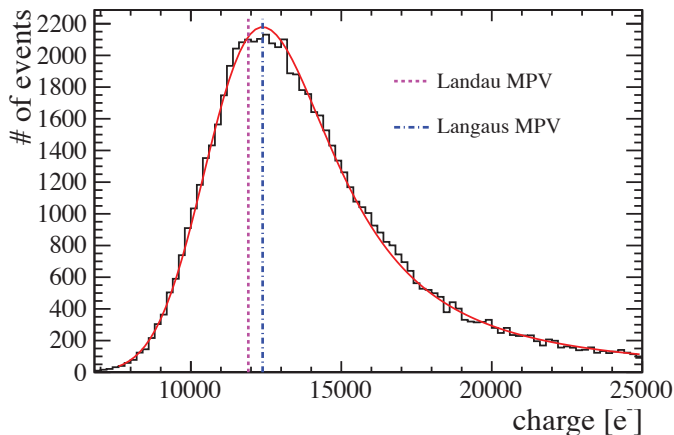


Figure 4.2: Charge collected from a 180 GeV proton and pion beam traversing a 150 μm thick sensor fitted with a Landau convoluted with a Gaussian. The most probable value of the Landau component does not match the MPV of the Langaus. The plot is from testbeam data with the Timepix3 telescope.

$4\pi N_A r_e^2 m_e c^2$. The derived energy loss distribution is right-skewed with a long tail as the energy loss increases. For a thin absorber the most probable value (MPV) is given by:

$$\text{MPV} = \xi \left[\ln \frac{2m_e c^2 \beta^2 \gamma^2}{I} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right] \quad (4.3)$$

where the constant $j=0.200$ and the density effect correction have been added by Bichsel [35]. For thick absorbers i.e. absorbers for which $\frac{\xi}{T_{max}} \gg 1$ the energy loss turns from a skewed distribution into a Gaussian. In his solution of the transport equation Landau assumed a charged particle scattering in a gas of electrons and neglected the electron binding energies to the nucleus. By using a modified cross section that takes into account the electron binding energy [36] the energy loss distribution can be written as a convolution of a Landau distribution with a Gaussian distribution also known as *Langaus*. The convolution with a Gaussian distribution results in broadening the width of the peak. The energy loss distribution, acquired from testbeam data, of a minimum ionizing proton and pion beam traversing a 150 μm thick sensor is shown in Figure 4.2. Fitting the energy loss distribution with a Langaus one acquires the MPV of the Landau component which actually differs by 4% from the MPV of the convoluted function. The most probable energy loss in this case is 11,900 e^- , which is the Landau component, while the MPV of the distribution is 12,400 e^- . The most probable energy loss given by Eq. (4.3) is well suited to describe the energy deposited in thin materials like the silicon

sensors used in particle detectors.

4.1.3 Non-ionizing Energy loss

The energy loss of a charged particle traversing a thin ($\xi \ll T_{max}$) material described in Section 4.1.2 is due to collisions with atomic electrons which is normally referred to as ionization. In non-ionizing energy-loss (NIEL) processes, nuclear interactions may result in collisions where the knock-on atom is dislocated from the lattice and the energy is dissipated in lattice vibrations [34]. Although the average energy deposition by non-ionizing processes is much lower than that by ionization, NIEL is important for radiation damage in silicon as will be discussed in Section 4.5.

4.2 Principles of a silicon sensor

To detect a charged particle interacting with the sensor, the charge liberated has to be collected and converted to measurable signal. The principles behind the design and operation of a silicon sensor that creates the signal are explained in this section.

4.2.1 Semiconductors

The energy gap between the valence and the conduction band of a solid state material is called the bandgap. The bandgap in semiconductors is larger than in conductors and smaller than in insulators. This can be translated as less energy is required to ionize the atoms of a semiconductor than the atoms of an insulator. Although in silicon the bandgap is only $E_g = 1.12$ eV the ionization energy is $E_i = 3.6$ eV. The band structure of silicon has an offset between the minimum of the conduction band and the maximum of the valence band and a non-zero wavevector (momentum) that is known as an indirect bandgap. In order to excite an electron to the conduction band simultaneous transfer of both energy and momentum is required. The presence of this offset results in 70 % of the ionization energy being transformed to phonon excitation [37].

Silicon and Germanium, two of the most commonly used semiconductors, have four valence electrons per atom. These four electrons combine with the electrons from the neighbouring atoms and form covalent bonds. When a semiconductor is at room temperature, electrons can move from the valence to the conduction band thereby creating electron-hole pairs. In an intrinsic semiconductor the number of free electrons is equal to the number of holes. The intrinsic carrier concentration of silicon at 300 K is in the order of 10^{10} cm^{-3} .

Two common methods of producing and cleaning the silicon crystal from impurities are the *float zone* (FZ) and the *Czochralski* (CZ) process. The CZ grown silicon is generally characterised by low resistivity ($\leq 100 \, \Omega \, \text{cm}$ typically), making it less suitable as a radiation detector material [38]. For detectors requiring a higher resistivity, the FZ silicon is used. The prototype sensors studied in Section 7 are developed with diffusion oxygenated FZ silicon (DOFZ). Enriching the silicon substrate with oxygen in the order of $10^{17} \, \text{cm}^{-3}$ at the end of the FZ process increases the radiation tolerance of the sensor [39].

Intrinsic semiconductors are rarely used. To have a better control over the conductivity of the semiconductor, atoms from other elements are added to the silicon. This addition of impurities is known as doping. A typical doping level is in the order of $10^{12} \, \text{cm}^{-3}$. Replacing a silicon atom with an atom with five valence electrons is called *n*-type doping. Since one electron of the *n*-type material will not form a bond with an electron from a neighbouring silicon atom, this excess electron is called donor. Similarly, replacing a silicon atom with an atom with three valence electrons is called *p*-type doping. The incomplete covalent bond creates a hole, also known as acceptor, that may be filled with an electron from a neighbouring atom.

4.2.2 The pn-junction

By joining a *n*-type doped with a *p*-type doped semiconductor a *pn*-junction is created. Electrons diffuse to the *p* region while holes diffuse to the *n* region and recombine [40]. The formation of two space charge regions creates an electric field which counteracts the diffusion. The presence of this “built-in” electric field results in a region which is free of mobile charge carriers commonly known as *depletion region*. From a radiation detector perspective, this depletion region is the most important feature of the *pn*-junction as will be seen in this section. To determine the width of the depletion region x as a function of the potential V one has to solve Poisson’s equation:

$$\frac{d^2V}{dx^2} + \frac{Ne}{\epsilon_0\epsilon_{Si}} = 0 \quad (4.4)$$

with N being the dopant concentration, e the unit of electric charge in Coulomb and ϵ_0 and ϵ_{Si} the permittivity of free space and the dielectric constant of the silicon (relative permittivity), respectively. Integrating Eq. (4.4), the electrostatic potential is obtained:

$$V(x) = \begin{cases} V_n(x) = V_n - e \frac{N_d}{2\epsilon_0\epsilon_{Si}}(x - x_n)^2 & \text{for } 0 \leq x \leq x_n \\ V_p(x) = V_p + e \frac{N_a}{2\epsilon_0\epsilon_{Si}}(x + x_p)^2 & \text{for } -x_p \leq x \leq 0 \end{cases} \quad (4.5)$$

where V_n and V_p the electrostatic potentials and x_n and x_p the depletion lengths on the n -side and p -side, respectively. The potential difference or built-in potential between the unbiased n and p regions is equal to [37]:

$$\begin{aligned} V_{bi} &= V_n - V_p \\ &= \frac{kT}{e} \ln \left(\frac{N_a N_d}{n_i^2} \right) \end{aligned} \quad (4.6)$$

where k the Boltzmann constant, T the temperature in Kelvin, n_i the intrinsic carrier concentration and N_d and N_a the concentrations of donors and acceptors respectively. Since there is no free charge in the depletion region

$$N_d x_n = N_a x_p \quad . \quad (4.7)$$

The total depletion width combining Eq. (4.5) and Eq. (4.6) and using Eq. (4.7) is:

$$\begin{aligned} X &= x_n + x_p \\ &= \sqrt{\frac{2\epsilon_0\epsilon_{Si}V_{bi}}{e} \left(\frac{1}{N_a} + \frac{1}{N_d} \right)} \quad . \end{aligned} \quad (4.8)$$

The depleted region extending across X is a volume empty of mobile charge carriers due to the presence of the electric field. If a charged particle traverses the depletion region, the liberated electrons (holes) will drift towards the n (p) side. The drift of the charge carriers is responsible for inducing the signal in the electrodes. The amount of charge needed to detect a signal can be reached by collecting all the charge liberated in a thin sensor. In order to achieve this, the pn -junction needs to be extended across the whole thickness of the sensor.

Applying bias voltage across the pn -junction

The pn -junction becomes reverse biased by applying a potential V_b between the two sides of the pn -junction. The potential V_b adds to the built-in voltage and Eq. (4.8) becomes

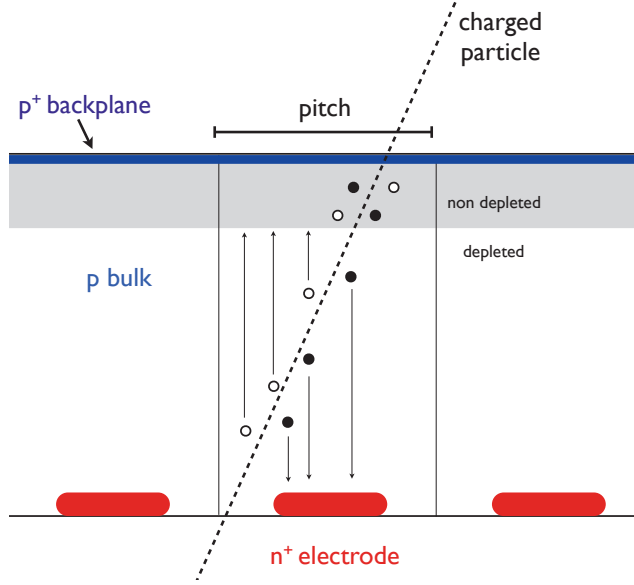


Figure 4.3: Cross section of a partially under depleted sensor. A charged particle (dashed line) traverses the sensor. The electrons (full circles) and holes (open circles) liberated in the depleted region (white background) will drift towards the n^+ and p^+ electrodes respectively, contributing to the signal formation in contrast to the charge carriers liberated in the non-depleted region (grey background).

$$X = \sqrt{\frac{2\epsilon_0\epsilon_{Si}(V_b + V_{bi})}{e} \left(\frac{1}{N_a} + \frac{1}{N_d} \right)} \quad , \quad (4.9)$$

which shows that the depletion width increases with the square root of the applied bias voltage. The depletion region starts growing from the pn -junction. In the silicon sensors that will be installed in the VELO upgrade the pn -junction is asymmetrically built with a highly doped n^+ implant in a lowly doped p bulk material ($N_a \ll N_d$). In this n -on- p sensor type the depletion width starts from the n^+ implant. The depletion width for an asymmetric pn -junction is

$$X \approx \sqrt{\frac{2\epsilon_0\epsilon_{Si}}{eN_a}(V_b + V_{bi})} \quad (4.10)$$

The fact that a charged particle liberates charge locally when traversing a sensor can be used to acquire position information. Assume a charged particle traversing a sensor with dimensions $l \times w \times t$ where l is the length in the x -

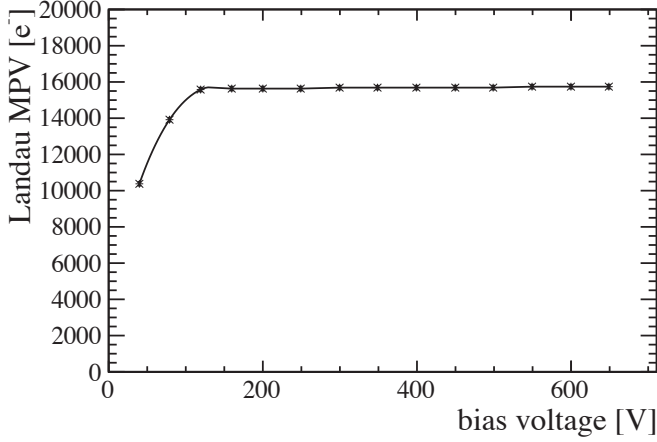


Figure 4.4: Landau MPV as a function of the applied bias for a 200 μm thick n -on- p sensor from Hamamatsu exposed to a 180 GeV proton and pion beam.

coordinate, w the width in the y -coordinate and t the thickness of the sensor in the z -coordinate. By segmenting the sensor in multiple electrodes along x , the position of the charged particle traversing the sensor along one dimension can be evaluated. By segmenting the sensor also in y then the two dimensional position of the charged particle can be evaluated. Each two dimensional segmented electrode is called *pixel* and the whole structure is known as a *pixel sensor*.

When a charged particle traverses a partially depleted pixel sensor the charge carriers liberated in the non-depleted region will not drift to the electrodes. Therefore not all of the charge liberated by the particle will contribute to the signal formation. This is visualised in Figure 4.3 where a charged particle (dashed line) traverses the sensor and thereby liberates charge carriers. The electrons (full circles) and holes (open circles) liberated in the depleted region (white background) will drift towards the n^+ and p^+ electrodes respectively. The n^+ segmented electrode will be referred to as pixel electrode. The charge carriers liberated in the non-depleted region (grey background) will not drift due to the absence of an electric field and consequently not induce any signal. Collecting only a fraction of the charge liberated leads to a smaller measured signal. In order to measure the whole charge liberated by the particle the sensor needs to be fully depleted. If w is the sensor thickness, the full depletion voltage V_{fd} can be calculated by setting $X = w$ and solving Eq. 4.10 in terms of V_b :

$$V_{fd} = \frac{w^2 e N_a}{2 \epsilon_0 \epsilon_{Si}} - V_{bi} \quad (4.11)$$

Since the built in voltage is very small compared to the full depletion voltage the second term of Eq. (4.11) can be neglected. The full depletion voltage can be extracted by looking at the charge collection as a function of the applied voltage. In Figure 4.4 the Landau MPV of the collected charge is plotted as a function of the applied bias voltage for a 200 μm thick *n-on-p* sensor from Hamamatsu exposed to a 180 GeV proton and pion beam. The MPV increases until it reaches a plateau after about 100 V where the sensor is fully depleted and does not collect more charge. The bias voltage at the beginning of the plateau region is the full depletion voltage. Knowing the silicon sensor thickness and measuring the full depletion voltage one can use Eq. (4.11) to calculate N_a or vice versa.

Leakage current

A flow of the charge carriers occurs when the sensor is reverse biased. This *leakage* or *dark* current is due to thermal generation at recombination centers in the depleted region. The leakage current [34]:

$$I \propto T^2 \exp\left(-\frac{E_g}{2kT}\right) \quad (4.12)$$

depends strongly on the temperature T in Kelvin and on the sensor geometry [37]:

$$I = I_0 w p^2 \quad (4.13)$$

where I_0 the leakage current per unit volume, p the pixel pitch and w the sensor thickness. Applying a bias voltage of $V_b = 100$ V across a 200 μm thick sensor leads to the formation of an average electric field of 5 kV/cm. Operating the sensor at bias voltages $\gg V_b$ will lead to the formation of a high electric field in the sensor. This high field may cause an avalanche breakdown that can destroy the sensor if the current is not limited. For a prototype 200 μm *n-on-p* sensor from Micron the abrupt increase of the leakage current above 300 V is shown in Figure 4.5 . To avoid breakdown, sensors are operated with bias voltages below the breakdown voltage.

Charge Motion

When a charged particle traverses the depleted sensor charge will be liberated. The current densities of the charge carriers [34] are:

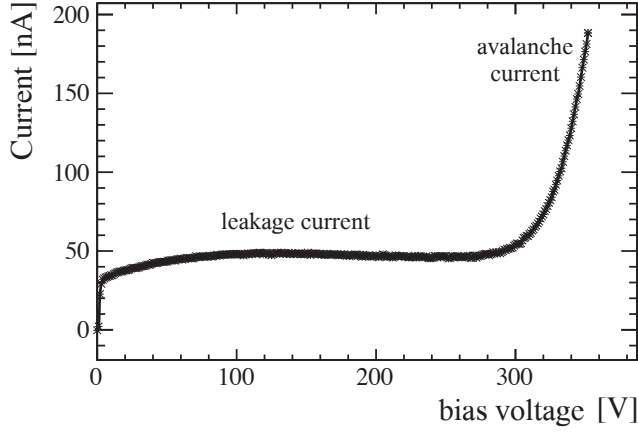


Figure 4.5: Measured leakage current as a function of applied bias voltage for a prototype 200 μm n -on- p sensor from Micron.

$$\begin{aligned}\vec{J}_n &= qn\mu_e\vec{E} + \mu_e k T \nabla n \\ \vec{J}_p &= qp\mu_h\vec{E} + \mu_h k T \nabla p\end{aligned}\tag{4.14}$$

where μ the mobility of the charge carriers ($c = e, h$), $\vec{E}$ the electric field and n (p) the electron (hole) concentration. The mobility of the charge carriers is related to the diffusion constants D_c using Einstein's relation

$$D_c = \frac{kT}{e} \mu_c \quad .\tag{4.15}$$

The liberated charge carriers are affected by the concentration gradient ∇n or ∇p and tend to move from a high concentration region to a region where the concentration is lower. This effect known as diffusion is described by:

$$\begin{aligned}\vec{J}_{n,\text{diff}} &= D_e \nabla n \\ \vec{J}_{p,\text{diff}} &= -D_h \nabla p \quad .\end{aligned}\tag{4.16}$$

In the case of the n -on- p type sensor, the presence of the electric field will force the holes to move towards the electrode at the backplane of the sensor and the electrons to the n^+ pixel electrode. This motion of the charge carriers can be described by an average drift velocity as a function of the mobility and the electric field:

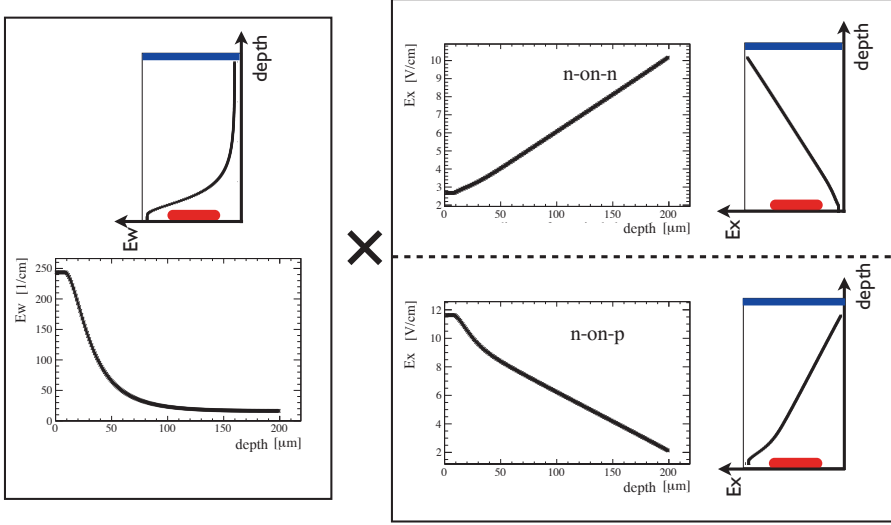


Figure 4.6: Weighting field and electric field for two sensors of same geometry (thickness, pixel pitch) but different type (*n-on-n* and *n-on-p*).

$$\begin{aligned}\vec{v}_e &= \mu_e \vec{E} \\ \vec{v}_h &= -\mu_h \vec{E} .\end{aligned}\tag{4.17}$$

The mobility of electrons is about 3 times higher than the mobility of holes in silicon ($\mu_e = 1350 \text{ cm}^2/\text{Vs}$ and $\mu_h = 470 \text{ cm}^2/\text{Vs}$). This proportionality of the drift velocity as a function of the electric field is valid up to electric field values of 10^4 V/cm . For higher electric fields the drift velocity saturates [41].

Signal Formation

The charge carriers liberated in bulk of the sensor will drift due to the electric field. According to Ramo's theorem [42] the displacement of charge carriers in the presence of an electric field induces a current on the electrodes:

$$i_c = e \vec{E}_w \cdot \vec{v}_c\tag{4.18}$$

where c is the type of charge carrier (electron or hole) and E_w the weighting field. The weighting field, which should not be confused with the electric field, can be obtained by applying unit potential to an electrode while grounding the neighbouring electrodes. The weighting field depends on the distance from

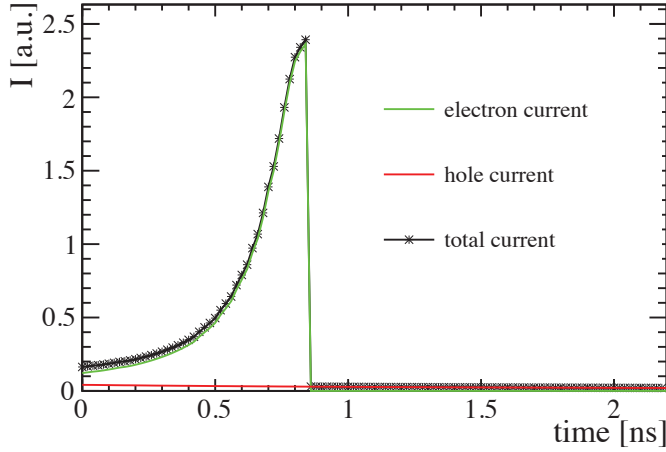


Figure 4.7: Simulated signal formed by $4000\text{ e}^-/\text{hole}$ pairs drifting from the middle of a $200\text{ }\mu\text{m}$ $n\text{-on-}p$ sensor biased at 120 V and assuming a full depletion voltage at 80 V . The current induced by the electrons provides the major contribution to the total induced current.

the pixel electrode to the backplane electrode, the pixel implant width and the distance to the neighbouring electrodes.

The electric field profile E_x depends on the sensor type as shown in Figure 4.6. For the $n\text{-on-}n$ sensor (n^+ -type pixel electrode in a n -type bulk) the electric field is minimum close to the pixel electrode and increases linearly as the depth, which is the distance from the pixel electrode, increases. The electric field profile is different for the $n\text{-on-}p$ sensor. It is maximum close to the pixel electrode and drops linearly as a function of depth. As a consequence of the two different electric field profiles the product of the electric field and the weighting field will be different for the two $n\text{-on-}x$ designs (with x being p or n). The mobility of the charge carriers is constant, hence the product of the electric and the weighting field determines the induced current. The total induced current i_t is the sum of the electron and hole induced currents. A charged particle traversing $55\text{ }\mu\text{m}$ of silicon, which is the pixel pitch of the silicon sensors studied in this manuscript, will liberate about $4000\text{ e}^-/\text{h}$ pairs. A calculation of the currents induced by $4000\text{ e}^-/\text{h}$ pairs drifting from the middle of a $200\text{ }\mu\text{m}$ $n\text{-on-}p$ sensor is shown in Figure 4.7. The sensor is biased at 120 V assuming a full depletion voltage at 80 V . The main contribution to the total induced current comes from the drifting electrons. Electrons in the $n\text{-on-}p$ sensor type will drift towards the pixel electrode where the product of the weighting and the electric field is maximum. In the case of two sensors with the same thickness and pixel electrode geometry but of different bulk type the induced currents will have a different profile due to the different electric

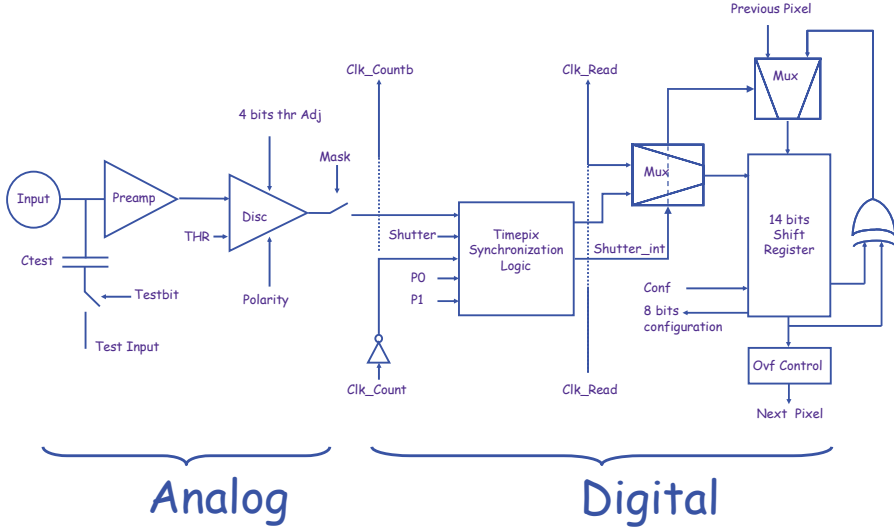


Figure 4.8: Diagram of a Timepix pixel logic [43] (see text for explanation). On the left side the analog part including the preamplifier and the discriminator is shown. On the right side the digital part including the TSL and the 14-bit Shift Register is shown.

fields. By integrating i_t over time, the same total amount of collected charge is obtained:

$$Q = \int_{t_0}^t i_t dt \quad (4.19)$$

which is equal to the charge initially liberated by the charged particle in the sensor assuming no charge is lost due to trapping or charge recombination. After the signal is formed the next step involves its readout and measurement.

4.3 Signal acquisition

The readout of the signal is done by an application specific integrated circuit (ASIC). The two ASICs used in the results presented in this manuscript, Timepix and Timepix3, derive from the Medipix family of chips [82].

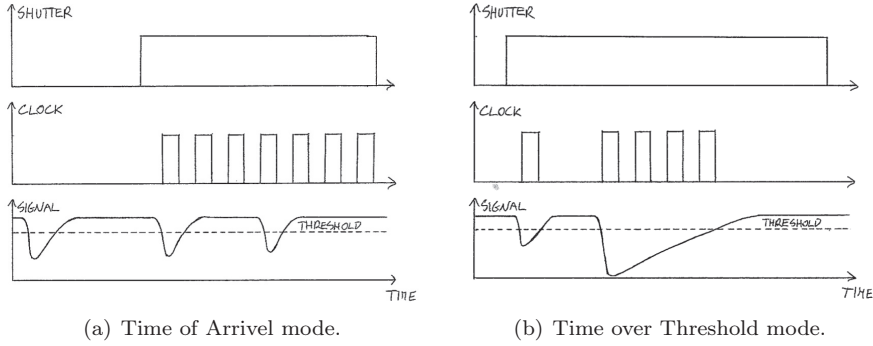


Figure 4.9: Operation modes of TimePix involving time measurement. Plots taken from [45].

4.3.1 Timepix ASIC

The Timepix ASIC [44], designed in a 250 nm technology, consists of a matrix of 256×256 square pixels each with a pitch of 55 μm . In Figure 4.8 the diagram of the Timepix pixel logic is visualised. The signal induced current is integrated and slowly discharged by the preamplifier. The time the preamplifier needs to fully discharge the integrated signal can be adjusted by setting the Ikum current¹. The output of the preamplifier is then compared to a threshold value. This threshold is the sum of a value commonly distributed to all pixels (THL) and a 4-bit trim set per pixel.

Timepix can be operated in one of the three modes: 1) counting, 2) time of arrival and 3) time over threshold. The operation mode can be set in the Timepix Synchronization Logic (TSL). In the event counting mode the digital counter of a pixel is incremented by one unit each time the measured signal is above threshold. The time of arrival (ToA) and time over threshold (ToT) mode make use of an external clock distributed globally to the pixel matrix. By operating the clock at maximum speed (100 MHz) the corresponding timing resolution is 10 ns. In ToA mode the 14-bit Shift Register starts counting when the signal crosses the threshold until the end of the shutter. Once the shutter is closed the information from all pixels is shifted out sequentially. During this time (about 8 ms) the chip does not record signals. In ToT mode the Shift Register starts counting when the signal crosses the threshold until the signal falls below threshold. The ToA and ToT modes are explained in more detail in Section 4.3.3. The need for faster data acquisition, higher timing resolution and extracting more information from the sensor led to the development of Timepix3.

¹The Ikum current is in the preamplifier circuit.

4.3.2 Timepix3 ASIC

As successor to the Timepix chip, Timepix3 [46] introduces a number of new features and improvements. Timepix3 is designed in a 130 nm CMOS technology. In order to minimize the time needed to read the data it features a zero-suppression scheme in which only pixels that are hit are read out. Moreover, when operated in the so-called data driven mode, the transmission of a hit is instantaneous and is not postponed until the shutter is closed. In addition, Timepix3 measures simultaneously ToA and ToT in each pixel. The ToA information normally measured with a 14-bit register can be extended with additional 4 bits reaching a timing resolution of 1.56 ns. Timepix3 has the same square pixel matrix and pixel pitch as Timepix. The maximum hit rate of Timepix3 is 80 Mhits/s.

4.3.3 Time of Arrival and Time over Threshold

The ToA mode in Timepix uses a shutter for the measurement of the charge drift time. Since the shutter time is known, the ToA expresses the difference between the time the integrated current induced by the drifting charge crossed the threshold and the end of the shutter (Figure 4.9(a)). In Timepix3 instead, the arrival of a the hit expresses the current time obtained from a continuously counting of clock cycles. The time synchronisation between different Timepix3 ASICs is obtained from an external reference pulse (t_0).

In ToT mode, the time the signal was above threshold is measured (Figure 4.9(b)). The ToT is an indication of the total energy deposited. A typical ToT value for a minimum ionizing charged particle traversing a 150 μm thick sensor is 150 counts². To translate the ToT in equivalent units of charge a calibration of the ASIC is necessary.

4.3.4 Calibration

In Timepix and Timepix3 the measured ToT value is an indication of the charge liberated by a charged particle in a pixel. In order to translate the ToT to equivalent units of charge, the ASIC must be calibrated. The calibration is performed by injecting a known amount of charge via test pulses and measuring the detector response [47]. The data can be described by a so-called surrogate function [48]:

$$\text{ToT}(q) = g \cdot q + \text{ToT}_0 - \frac{c}{q - t} + o \quad (4.20)$$

²One count or clock cycle in the ToT mode corresponds to 25 ns.

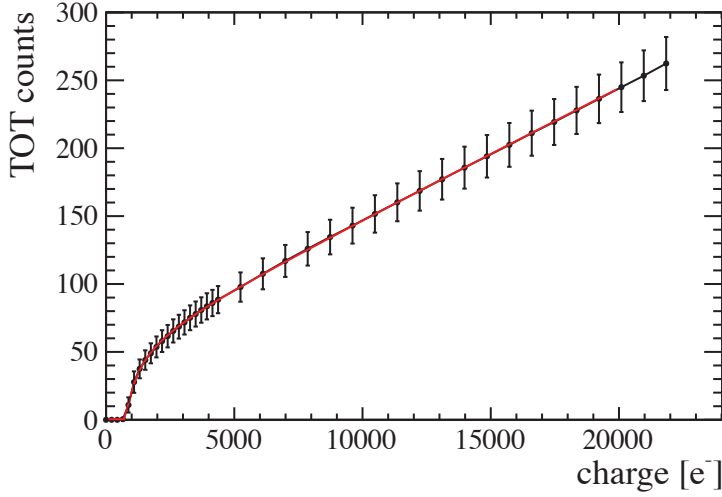
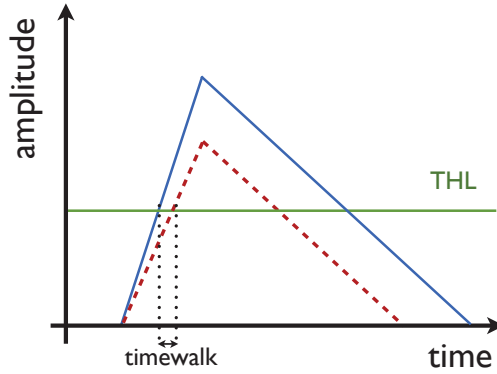


Figure 4.10: Typical calibration curve of a Timepix obtained with testpulses.

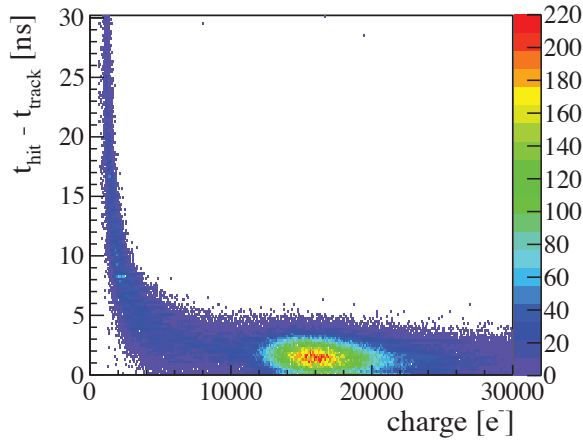
where q the amount of charge injected, g is the gain, o the offset, c, t and ToT_0 other fit parameters. An example of a calibration curve for a Timepix ASIC is shown in Figure 4.10. The surrogate function consists of a linear part $>2000 \text{ e}^-$ and a non-linear part when the charge of the injected test pulses is close to the detector threshold. Per pixel calibrations for all the prototype assemblies studied in this manuscript were performed.

4.3.5 Timewalk

The signal measurement is influenced by the response time of the discriminator along and the value of the threshold. This means that two signals of different amplitude arriving simultaneously will not be detected at the same time (Figure 4.11(a)). This effect is called *timewalk*. Since Timepix3 can measure both the ToA and the ToT of the signal in each pixel it is an ideal candidate to quantify the timewalk effect. To do so, a Timepix3 ASIC bump-bonded to a silicon sensor was placed perpendicular to a 180 GeV proton and pion beam. The time t_{track} at which a charged particle intercepts the detector is known by using the averaged time of the 8 planes in the Timepix3 telescope (see Section 5.2.2). The effect of timewalk is shown in Figure 4.11(b) where the time difference between the hit t_{hit} and t_{track} is plotted as a function of the charge collected in each pixel hit. The majority of the hits deposit enough charge such that the distribution of the difference between t_{hit} and t_{track} projected on the y -axis follows a Gaussian distribution around zero. However, hits with a charge $<6000 \text{ e}^-$ will be subject to non negligible timewalk having a response time $>5 \text{ ns}$.



(a) Illustration of the timewalk effect.



(b) Measured timewalk on a 200 μm thick $n\text{-on-p}$ sensor from Hamamatsu operated at 200 V and bump-bonded on a Timepix3 chip. The sensor was placed perpendicular to the beam. Hits with charge $< 6000\text{ e}^-$ have a response time $> 5\text{ ns}$.

Figure 4.11: The timewalk effect.

4.3.6 Noise

In case of the Timepix ASIC, the noise per pixel is about 100 e^- RMS and a threshold variation of 35 e^- RMS [47]. The Timepix3 ASIC has a noise level of about 60 e^- RMS [49] with the threshold variation being typically 30 e^- RMS. Setting the THL at 6σ above the total noise level, defined as the square root of the quadratic sum of the noise level and the threshold variation, would be sufficient to reduce hits due to noise. However, in order to avoid noise hits Timepix and Timepix3 are operated at a threshold value of 1000 e^- .

4.4 Overview of sensor configurations

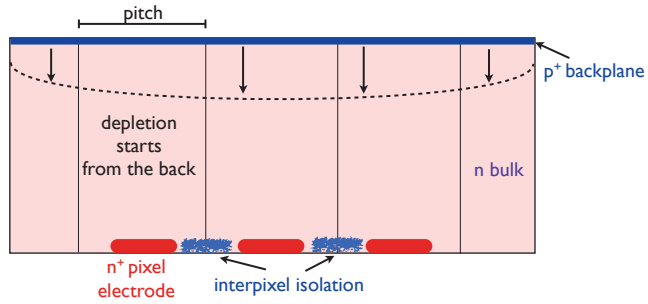
4.4.1 Sensor types

In a silicon sensor of any type (x -on- x), the concentration of donors N_D or acceptors N_A in the implants is several orders of magnitude larger than the doping concentration of the bulk. The concentration of acceptors in the bulk is in the order of 10^{12} cm^{-3} and the ratio of donors in the implants over acceptors in the bulk is $N_d/N_a \approx 10^7$.

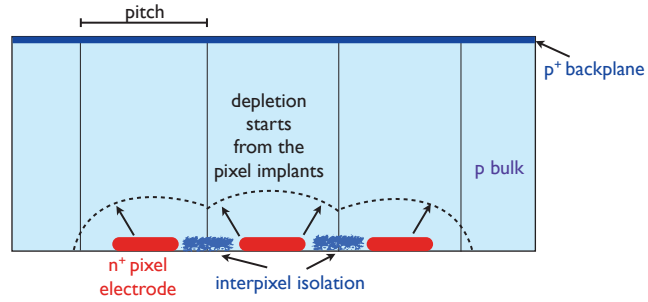
The formation of the pn -junction in a silicon sensor depends on the types of the pixel electrode, bulk and backplane electrode. The most commonly used sensor is the p -on- n type. In a p -on- n type of sensor the depletion region starts from the p^+ pixel electrode and grows towards the backplane as a function of the applied reverse bias voltage. Holes are collected in the p^+ pixel electrodes while electrons drift to the backplane. One of the main drawbacks of the p -on- n design is its performance after heavy irradiation. At about a fluence of $10^{13}\text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$ the bulk undergoes type inversion³ after which the depletion region grows from the backplane. For a p -type bulk, the introduction of acceptor like states due to irradiation will not cause type inversion as in the case of the n -type bulk but will increase the p -type effective doping concentration. This behaviour of the p -bulk makes the n -on- p design radiation hard. Eventually to deplete the sensor it needs to be operated at high bias voltages [38] due to the difference in its effective doping concentration. Increasing the bias voltage is limited due to the formation of high leakage currents that can destroy the sensor. In case of the p -on- n design, long after type inversion full depletion cannot be reached so the drifting charge carriers will induce signal to multiple pixel electrodes degrading the spatial resolution of the detector.

For the LHCb VELO upgrade two sensor designs were considered, the n -on- n and n -on- p type. In the n -on- n design, the n^+ pixel electrodes collect electrons

³Type inversion will be discussed in Section 4.5 .



(a) n -on- n



(b) n -on- p

Figure 4.12: Cross section of a sensor with n^+ type pixel electrodes in (a) n -type or (b) p -type bulk. Note that depletion starts from the backplane in the n -on- n sensor in contrast to the n -on- p sensor type where depletion starts from the pixel electrodes.

and depletion starts from the backplane (Figure 4.12(a)). When the n -type bulk undergoes type inversion, the sensor turns to n -on- p type where depletion starts from the pixel electrodes. Drifting charge carriers will not induce signal to multiple electrodes in contrast to the case of the type inverted p -on- n design. This behaviour under irradiation makes the n -on- n sensor radiation harder than p -on- n . However, extra steps are needed during the sensor production to isolate the n^+ implants and avoid short circuit between the pixels as will be discussed in Section 4.4.2. Although the n -on- n design requires a more expensive double sided processing it is preferred in many experiments where the sensor is exposed to high levels of radiation.

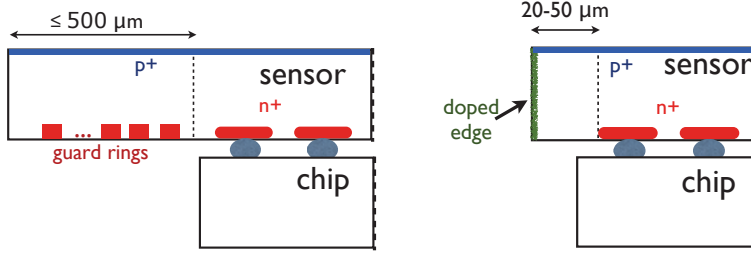
The second design for the VELO upgrade, the n -on- p design, is easier to realise since only single sided processing is required. The n^+ pixel electrodes collect electrons and need to be isolated as in the n -on- n design. Depletion starts from the side of the pixel electrodes as shown in Figure 4.12(b) in contrast to the n -on- n design. The fact that the n -on- p design is also radiation hard and its manufacturing is cheaper than n -on- n makes it an ideal candidate for applications where the radiation levels are high.

4.4.2 Interpixel isolation

In p -on- n sensors, the adjacent p^+ -implants are isolated by the electron accumulation layer which is formed below the oxide due to radiation. However, in the case of n -type implants, this electron layer needs to be interrupted as this would short circuit neighbouring pixels. This can be achieved by the p -stop or the p -spray isolation technique as depicted in Figure 4.12. The advantages of the p -spray technique is the absence of one photolithographic step and better high voltage performance due to the reduction of the electric field with increasing oxide damage [50]. An advantage of the p -stop technique is that a high dose of a p^+ dopant can achieve a good isolation. Both techniques of interpixel isolation have been used for the prototype sensors studied in this manuscript.

4.4.3 Guard Rings

If the depletion region reaches the edge of a silicon sensor a large increase in the leakage current may occur. Another hazardous scenario involves the accumulation of electrons at the edge surface leading to a high electric field at the edge which can cause breakdown. Multiple rings known as *guard rings* are used to slowly drop and terminate the potential at the edges of the sensor. The guard rings are placed at the sensor perimeter as depicted in Figure 4.13(a) and extend the physical edge of the sensor up to 500 μm from the edge pixels. Extending the sensors beyond the edge pixel results in introducing an inactive



(a) Conventional sensor with guard rings. (b) Active edge sensor with doped edge.

Figure 4.13: Different designs to reduce the electric field at the edge: (a) conventional sensor using guard rings and (b) active-edge sensor with doped edge.

area that will contribute to the multiple coulomb scattering. Moreover, it prevents from placing the sensors closer to the beam. Both effects are unwanted, hence a small guard ring design is desired.

4.4.4 Edgeless sensors

An innovative concept of reducing the inactive area at the edge introduced by the guard rings has been developed with the edgeless sensors. Edgeless sensors can have a slim-edge or an active-edge. Slim-edge sensors are diced and passivated closer to the pixel matrix [51] while active-edge [52] sensors are etched and doped. Although the extra doping at the sides of the active-edge sensor (Figure 4.13(b)) suppresses the surface current between electrodes, the electric field lines at the edge are distorted. The effect of the distortion of the electric field streamlines on the detector efficiency and resolution is reported in Chapter 6.

4.5 Radiation Damage

With the term radiation damage we are referring to the defects in our detector caused by exposure to a flux of particles. These defects can be divided into bulk damage and surface damage.

4.5.1 Bulk damage

The NIEL described in Section 4.1.3 is responsible for bulk damage effects. The damage effect due to initial and cascading-displacements induced by neutrons, charged particles and photons is expressed by the damage function $D(E)$ in

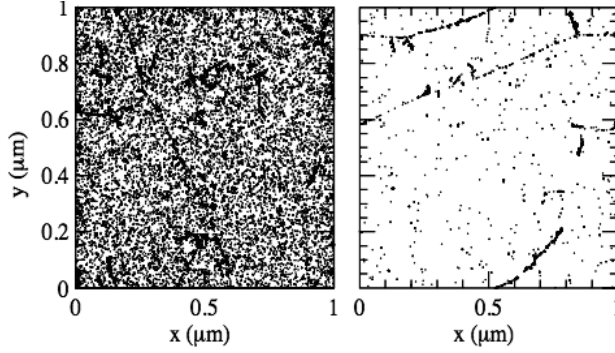


Figure 4.14: Simulated distributions of vacancies from 10 MeV (left) and 24 GeV protons projected over 1 μm of depth in silicon (plots taken from [54]).

units of MeV cm^2 , whose value at 1 MeV is the American Society for Testing and Materials (ASTM) standard $D(1 \text{ MeV}) = 95 \text{ MeV mb}$. The proportionality between NIEL and the resulting damage effects is referred to as the NIEL-scaling hypothesis [53]. Using the NIEL scaling as a basis, the damage caused by a particle p with a certain kinetic energy is described by a hardness factor κ and the total fluence Φ_p . It can be expressed in terms of 1 MeV neutron equivalent fluence as

$$\Phi_{eq} = \kappa \cdot \Phi_p \quad . \quad (4.21)$$

Bulk damage is caused when a high energetic particle displaces a Primary Knock on Atom (PKA) out of its lattice position. Such a process will lead to a point defect. A collection of point like defects will form a region of cluster defects [53]. Point defects are caused by photons, cluster defects by neutrons while electrons and charged hadrons can cause both type of defects. In case of protons the type of defect depends on the energy. In Figure 4.14 the vacancies in the silicon lattice made by 10 MeV and 24 GeV protons at a fluence of 10^{14} cm^{-2} is simulated. Low energy protons produce mainly point defects and only a few cluster defects. High energy protons produce both types of defects. Radiation damage in the bulk leads to an increase of the leakage current, a change of the effective doping concentration and an increase of charge trapping.

Leakage current

Defects in the bulk can act as generation-recombination centers leading to an increase of the current proportional to the 1 MeV neutron equivalent fluence Φ_{eq} :

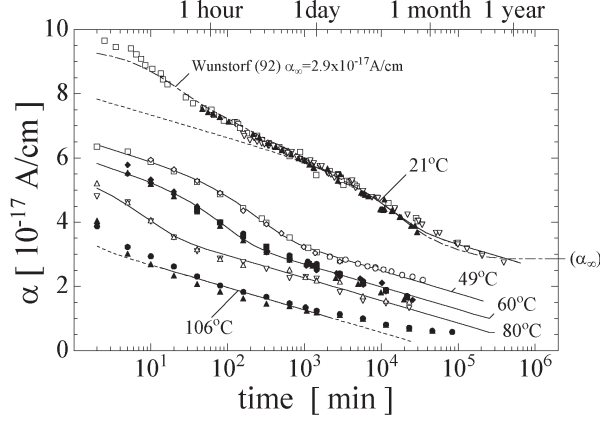


Figure 4.15: Current related damage rate versus annealing time (plot taken from [57]).

$$I = \alpha \Phi_{eq} V \quad (4.22)$$

where α is the current related damage rate and V the active volume. The damage rate α is independent of the material type, process technology and the irradiating particle⁴ [55]. The relation between α and time-temperature can be found in [56]. As shown in Eq. (4.12), the leakage current scales with T^2 . For an irradiated sensor, the leakage current anneals with time and the annealing effects depend on T as shown in Figure 4.15.

The expected leakage current due to irradiation for the current VELO is plotted in Figure 4.16. Uncertainties on the leakage current prediction coming from the annealing factor and the damaging fluence prediction are represented by the shaded region. The predicted leakage current is on average within 7% of the measured one, with a 15% spread from all the individual sensor measurements [58].

An increase in the leakage current will increase the power dissipation of the sensor, which can be seen as excess heat. If this excess heat is not removed, it will increase the temperature resulting in a further increase of the leakage current. As a result the sensor may become thermally unstable. This mechanism is known as *thermal runaway* [23]. To avoid thermal runaway the sensors are cooled to keep the leakage current low.

⁴Here the type of particle is implied (μ, p, n) and not the particle's energy.

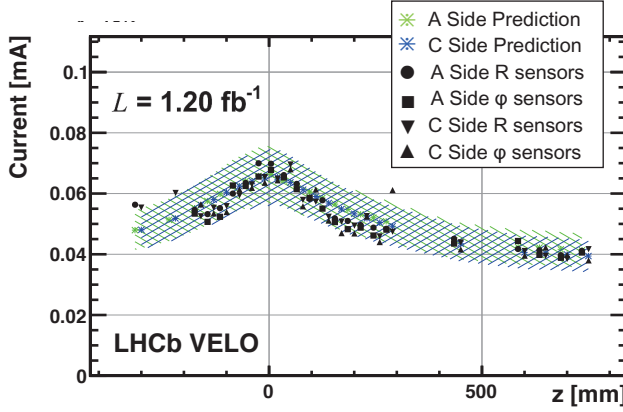


Figure 4.16: Leakage current for different detector planes in the current VELO after 1.2 fb^{-1} . The predictions (shaded region) include the data from the A and C sides of the VELO [58]. The two sensors at $z = -400 \text{ mm}$ are the n^+ -on- p type sensors.

Effective doping

The defects described in Section 4.5.1 lead to donor removal and generation of acceptor like states in the bulk. Defining the difference between all donor-like states and acceptor-like states as effective doping N_{eff} , the relation of the depletion voltage V_{dep} with this quantity can be written using Eq. (4.11) as

$$V_{\text{dep}} = \frac{e}{2\epsilon_0\epsilon_{Si}} |N_{\text{eff}}| w^2 \quad (4.23)$$

where w is the thickness of the depleted layer of the detector. The dependence of the effective doping and full depletion voltage on the fluence is shown in Figure 4.17. The doping concentration changes such that the initially n -type silicon bulk becomes intrinsic and after more fluence turns to p -type with the acceptor concentration growing as the fluence increases. This space charge sign inversion is most commonly known as type-inversion.

All but two of the current VELO sensors are n^+ -on- n type consisting of a highly doped n -implant in a n -type bulk with a highly doped p -implant in the backplane. As a test for the upgrade two n^+ -on- p sensors are installed at the upstream end of the VELO. When comparing the depletion voltages after irradiation between the two different sensor designs, the n^+ -on- p type sensors reach the hardware limit of 500 V at $35 \times 10^{12} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$ less fluence than the n^+ -on- n type sensors⁵ [17]. This fluence corresponds to 9%

⁵The n -on- n sensors are expected to reach the 500V limit at a fluence of about $380 \times 10^{12} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$.

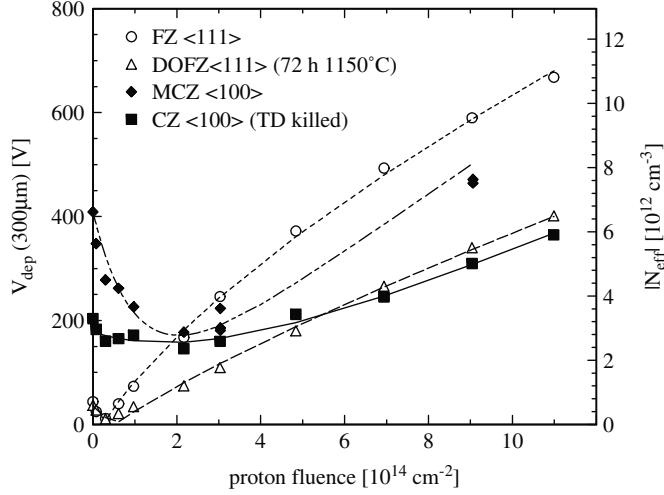


Figure 4.17: Effective doping concentration (N_{eff}) as a function of fluence after irradiation with 23 GeV protons [59]. Type inversion for the diffusion oxygenated FZ silicon (DOFZ) occurs at about $2 \times 10^{13} \text{ cm}^{-2}$. On the left hand axis is the resulting depletion voltage for a 300 μm thick sensor. The indexes $\langle 1xx \rangle$ indicate the crystal structure (Miller indexes).

of the total fluence needed for the n^+ -on- n type sensors to reach the hardware limit.

The effective doping concentration after irradiation is described as a function of the fluence, time and the doping concentration before irradiation using the expression:

$$N_{\text{eff}} = N_{\text{eff}, \Phi=0} - [N_a(\Phi, T_a, t) + N_C(\Phi) + N_Y(\Phi, T_a, t)] \quad (4.24)$$

known as the Hamburg model [60]. This model is a parametrization with the term N_a expressing the short term annealing component, N_C the stable damage and N_Y the reverse annealing. Each term influences differently the effective doping concentration as depicted in Figure 4.18 where the change in N_{eff} of a sample irradiated to a fluence of $1.4 \cdot 10^{14} \text{ cm}^{-2}$ and kept at 60°C is plotted as a function of annealing time [57]. The short term annealing N_a is observed in the order of hours after irradiation by a decrease in the depletion voltage. This beneficial annealing is caused by a change in the effective doping concentration that for a n - to p -type inverted bulk (as shown in Figure 4.17) means positive space charge is removed. The ΔN_{eff} reaches a minimum at the end of the short term annealing period. This minimum is representative of the stable damage. The stable damage term N_c is independent of temperature and time. According to the Hamburg model it can be parametrised as

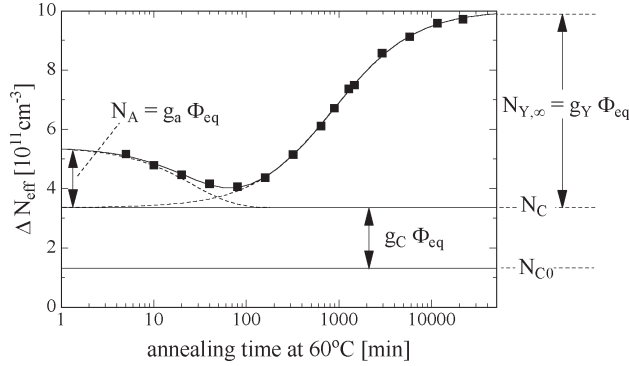


Figure 4.18: Annealing of a sample at 60°C after being irradiated to a fluence of $1.4 \cdot 10^{14} \text{ cm}^{-2}$ [57].

a function of fluence and expresses the donor removal rate. The end of the short term annealing is followed by the reverse annealing N_Y that describes an effect opposite to the short term annealing. During the reverse annealing the space charge of the type inverted sensor becomes more negative, leading to an increase of the full depletion voltage.

The reverse annealing is a serious threat for the current and upgrade VELO sensors since the LHCb detector is planned to run several years. Keeping the sensors at room temperature for weeks will lead to an increase of the full depletion voltage. Therefore the VELO sensors are cooled down in order to be kept at the phase of beneficial annealing. The effective depletion voltage⁶ as a function of fluence is plotted in Figure 4.19 for the current VELO sensors. The solid green lines are the predictions from the Hamburg model where all three annealing components have been taken into account. The Hamburg model predictions have been plotted over the different sensor categories and are in good agreement for low and high fluences.

Charge trapping

Another effect induced by radiation is the trapping of the signal charge resulting in a reduced charge collection efficiency. The density of the trapping defects depends on the fluence and can be described by a parameter called effective trapping rate $1/\tau$ [ns⁻¹] that can be written as:

$$\frac{1}{\tau_c} = \beta_c \Phi \quad (4.25)$$

⁶The effective depletion voltage is defined as the voltage at which the MPV is equal to 80% of the plateau ADC value for that sensor.

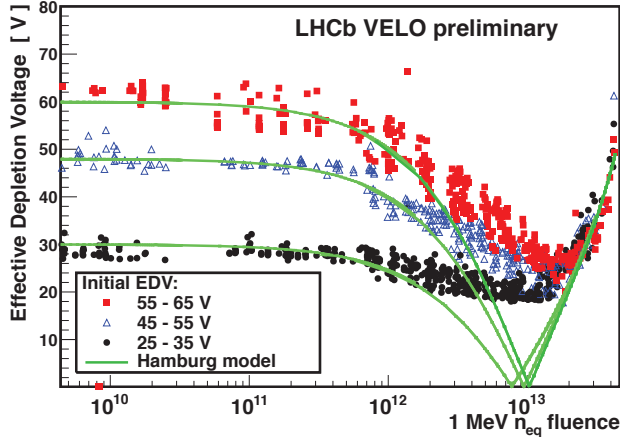


Figure 4.19: Fluence dependence of the full depletion voltage in current VELO sensors [17].

where c the type of charge carrier, Φ the fluence in cm^{-2} , β_c a fit parameter in cm^2/ns . For a neutron irradiated sensor the values of the fit parameter for electrons and holes are $\beta_e = 4.1 \cdot 10^{-16} \text{ cm}^2/\text{ns}$ and $\beta_h = 6.0 \cdot 10^{-16} \text{ cm}^2/\text{ns}$ respectively [61]. Operating an irradiated sensor at high bias voltages will result in a shorter collection time of the charge. By keeping the collection time shorter than the trapping time enough charge will be collected.

4.5.2 Surface damage

The second type of radiation damage affects the oxide (such as SiO_2) and the silicon-oxide interface. Since the crystal structure of the SiO_2 -Si surface is irregular, the displacement of single atoms does not cause the effects that occur in the bulk. Ionization on the other hand can cause permanent defects [62]. The mobility of electrons is several orders of magnitude higher than the hole mobility in the oxide. Due to this difference in mobility holes can be captured in the interface region between silicon and oxide (Figure 4.20).

The immobilised holes result in an increase of positive charge causing a shift in the flat band voltage [40]. Ionization can also introduce new energy levels in the large bandgap (8.8 eV for SiO_2) of the silicon-oxide surface. Electrons or holes can occupy one of these levels thereby increasing or decreasing the oxide charge.

Positive surface oxide charge density caused by surface damage may short circuit the n^+ pixel electrodes in a n -on- p type of sensor and create a conduction channel. As a result, the charge liberated by a charged particle may spread over multiple pixels and degrade the spatial resolution. The p -stop or

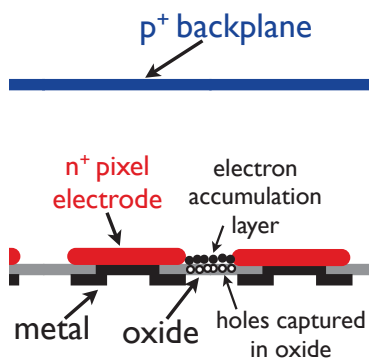


Figure 4.20: Surface damage in the oxide. Holes (open circles) are captured in the interface region between silicon and oxide. An electron accumulation layer (full circles) is formed between the n -type implants. This layer needs to be interrupted to avoid short circuit between neighbouring pixels.

p -spray technique described in Section 4.4.2 can provide enough insulation between the pixels. According to [63] the n^+ pixel electrodes are insulated up to a proton fluence of $7 \cdot 10^{14} \text{ cm}^{-2}$ even in the absence of an interpixel isolation structure. Moreover, Dalal et al. [64] found by studying the combined effect of bulk and surface damage that the increasing surface oxide charge density is compensated by the increasing concentration of defects in the sensor bulk.

Chapter 5

Testbeam set-up

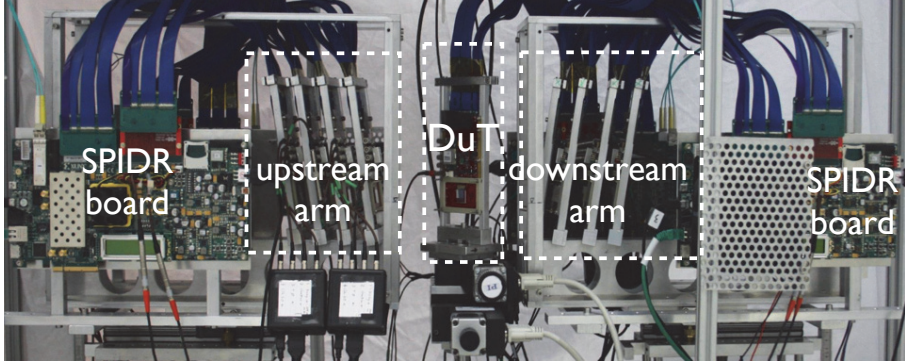
Prototype silicon sensors for the LHCb VELO upgrade need to be characterised before proceeding to mass production. These prototype sensors were placed in a beam of 180 GeV protons and pions at the SPS at CERN. To understand the behaviour of the sensors on a pixel level, a large amount of data is required. For this reason the prototype silicon sensors were bump-bonded to Timepix3 ASICs. The Timepix3 ASIC [46] has been designed for a maximum hit rate of 80 MHits/s. To allow dedicated studies of the performance of the sensors, a telescope of Timepix3 ASICs has been assembled. This telescope, operated in the period of 2014–2015, has evolved from the Timepix telescope. Both telescopes allow detailed studies of the prototype silicon sensors. The main principles of operation of the Timepix3 telescope are explained in this chapter.

5.1 The Timepix and Timepix3 telescopes

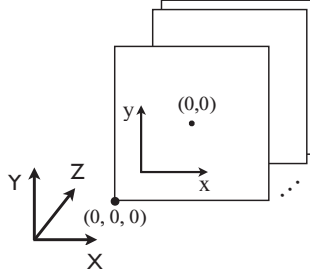
The Timepix telescope [65], which was operated until 2012, consists of 8 Timepix detectors with 300 μm thick silicon sensors equally divided in two arms. The Device-under-Test (DuT) is placed between the two telescope arms where the track-pointing resolution is better than 2 μm . The frame based readout of Timepix allowed a maximum frame rate of 60 Hz. With the Timepix ASIC clock frequency set at 10 MHz, a maximum of 125 tracks per frame were acquired.

The Timepix3 telescope has a similar configuration as the Timepix telescope as shown in Figure 5.1(a). It consists of 8 Timepix3 detectors with 300 μm thick silicon sensors with the DuT placed between the two telescope arms. The Timepix3 telescope features also the same track-pointing resolution as the Timepix telescope. The main differences with respect to the Timepix telescope are:

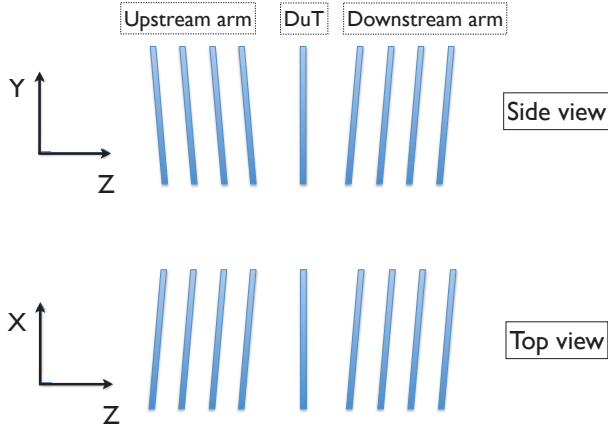
- use of the Timepix3 ASIC instead of the Timepix ASIC



(a) The Timepix3 telescope (picture taken from [66]). The 8 telescope planes are divided over two arms with the Device under Test (DuT) placed in the middle. The SPIDR boards needed to read out the Timepix3 ASICs are also visible.



(b) Local and global reference frames. The global frame is defined with the $(0,0,0)$ set at the bottom left corner of the first telescope plane. The local frame (x, y) is defined with the $(0,0)$ set at the center of a pixel matrix.



(c) Telescope orientation. The telescope planes are rotated by 9° around the global Y and global X axis to achieve optimum spatial resolution.

Figure 5.1: The Timepix3 telescope: (a) picture of the telescope, (b) local and global reference frames, (c) orientation of the telescope in the global reference frame.

- use of the SPIDR system [67] needed to readout the Timepix3 ASICs instead of the RELAXD system needed to readout the Timepix ASICs
- no PCB at the back of the Timepix3 assemblies reducing the radiation length by a factor of 2,
- the track reconstruction algorithm of the Timepix3 telescope is based on timestamps compared to the space residual based algorithm of the Timepix telescope.

A global reference frame (X,Y, Z) is defined with the (0, 0, 0) placed at the bottom left corner of the first telescope plane (Figure 5.1(b)). The Z direction is defined as the beam axis with the XY plane perpendicular to Z. A local coordinate system (x,y) is defined with the (0,0) set at the center of the pixel matrix. The column number of the pixel matrix corresponds to the x coordinate and the row number to the y coordinate. The telescope planes are placed at fixed positions along the Z axis. In addition, the telescope planes are rotated by 9° around the global Y and global X axis as shown in Figure 5.1(c) to achieve the optimal spatial resolution [47].

The pointing resolution of the telescope is smaller than the DuT pixel pitch by a factor of 27 giving the possibility to study the DuTs with sub-pixel precision. The DuT is mounted on a computer controlled translation and rotation stage which allows translations in directions transverse to the beam in steps of 1 μm as well as rotations with 0.01° accuracy. In Chapter 6 the results on DuTs with specific edge characteristics acquired with the Timepix telescope will be presented. In Chapter 7 the performance of irradiated sensors mounted as DuTs in the Timepix3 telescope will be discussed.

In the following sections the main principles of operation of the Timepix3 telescope are explained. The quality of the data is monitored with an online tool. Track reconstruction and data analysis is performed with dedicated offline software.

5.1.1 Data taking

The beam in the SPS has a *spill* structure. One spill comes typically every 33 s and lasts for 4.5 s containing on average 10^6 particles. A typical run lasts for two spills. The Timepix3 telescope allows the collection of up to 10^7 tracks/s due to the high pixel hit rate of the Timepix3 chip.

5.1.2 Online monitoring

A dedicated software has been developed in Qt [83] and C++ for the online monitoring of the telescope. A number of variables from each telescope plane,

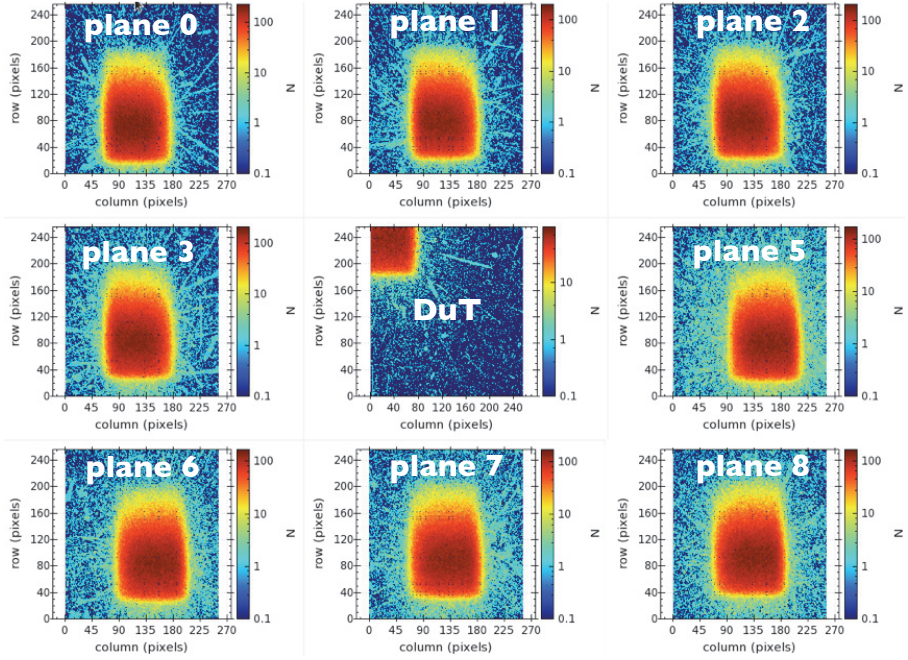


Figure 5.2: Pixel hit maps from the online display. The beam spot is roughly in the center of the telescope planes (planes 0–3 and 5–8). For this particular study the device under test (DuT) is set such that the beam is at its corner.

such as ToT distributions and pixel hit maps, are plotted during data acquisition. The online monitoring tool is regularly used to verify the position of the beam with respect to the telescope during data taking. An example of a monitoring plot using a sample of about 10^6 tracks from the data is shown in Figure 5.2. The number of hits per pixel on each plane mark the beam spot with the color axis expressing the number of hits. For this particular run the DuT is set such that the beam is positioned at its corner.

5.2 Telescope track fit

In this section the track fit procedure in the telescope will be discussed. A dedicated software framework KEPLER, based on the GAUDI framework, is developed for the offline analysis of the testbeam data. The steps of the track reconstruction sequence along with the most important features of each step are described.

5.2.1 Hit collection and clustering

The collected hits are ordered in time using their timestamp information¹. For each pixel hit, a clustering algorithm loops over the adjacent pixels. If an adjacent pixel is hit within a time window of 250 ns the hit is added to the cluster. The ToT value of each pixel hit is converted to charge using a per pixel surrogate function as described in Section 4.3.4. The cluster charge is the sum of the charges from all hits while the time of the cluster is taken as the time of the earliest hit. The position of the cluster is calculated using the center of gravity method. The cluster size distribution of all clusters for one of the telescope planes (plane 2) is shown in Figure 5.3. For every telescope plane, the most probable value is 3 pixels per cluster.

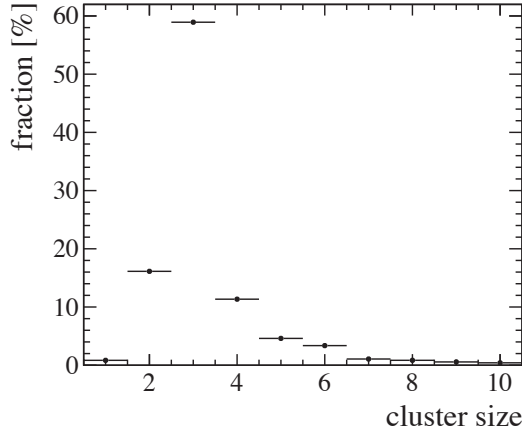


Figure 5.3: Cluster size distribution of all clusters in a telescope plane.

A drawback of looping over adjacent pixels is that if a pixel is dead or masked it may interrupt the clustering sequence. The clustering can be adjusted to group non-adjacent pixels. The requirements are that the pixel hits are separated by ≤ 3 columns and rows and all are inside the 250 ns time window. The concept of this algorithm is illustrated in Figure 5.4. This feature of the clustering algorithm is used in the study of large clusters as in the grazing angle analysis in Section 7.7.

5.2.2 Time based tracking

The track reconstruction sequence is based on the timestamp information of each cluster. Starting from a cluster in plane 0 the algorithm searches for

¹The timestamp of each hit pixel, in units of ns, is the time difference between the time the pixel was hit and the start of the run.

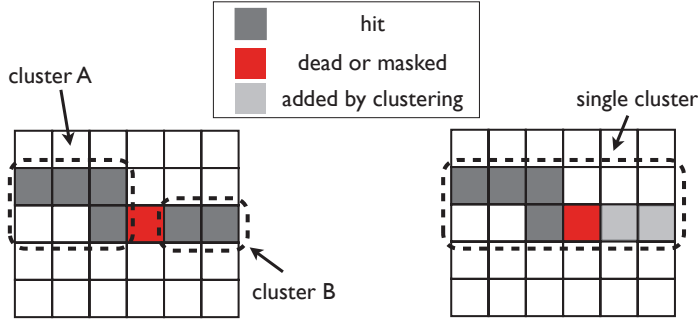


Figure 5.4: Illustration of the clustering algorithm feature that looks for hits beyond adjacent pixels: two clusters (A and B) appearing to be separate are adjacent to a dead or masked pixel (left), are joined together by the clustering algorithm to a single cluster (right).

clusters on plane 1 within a time window of 10 ns. If a cluster is found on plane 1, the clusters from the two planes form a *track seed*. This track seed is extrapolated to the next plane searching for a cluster within a time and a spatial window. The cluster closest in time within a 10 ns time window and within a spatial window defined as $0.01 \text{ rad} \times dz$ where dz the distance between the two planes, typically about 5 cm, is added to the seed. Since tracks are required to consist of clusters from all 8 telescope planes, the tracking sequence is repeated until the last plane. Clusters formed on the DuT are not included in the sequence in order to avoid biasing of the DuT results.

The cluster association efficiency in a telescope plane is defined as the ratio of clusters associated to a track over the total number of clusters. A number of effects may introduce additional hits not associated to tracks resulting in a decrease of the efficiency. If the noise in a pixel exceeds the threshold value then the pixel will appear as hit. Another effect that may decrease the efficiency are pixel hits associated to scattered tracks that are created from nuclear interactions.

To avoid these hits, a cluster occupancy cut is applied in the tracking sequence. By applying this cut, the tracking algorithm starts with a fixed number N_s of seed clusters. Next, it searches for a maximum of N_s clusters per each plane within the 10 ns time window. The resulting cluster associating efficiency per plane is shown in Figure 5.5 with all planes having an efficiency $>99.9\%$.

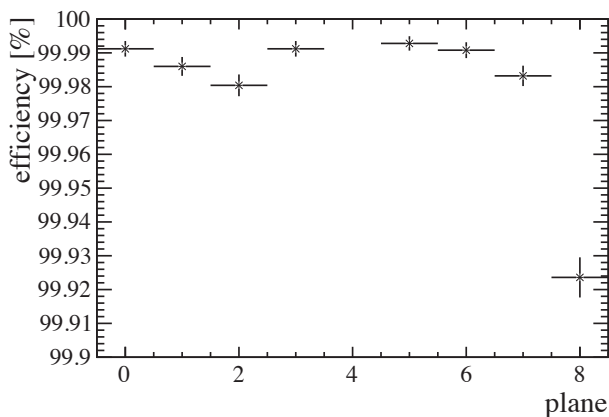


Figure 5.5: Cluster association efficiency of the telescope planes. The DuT (plane 4) is not included in the track reconstruction.

5.2.3 Alignment

The alignment of the DuT with respect to the telescope reference system is of key importance in order to take advantage of the pointing resolution of the telescope. To achieve this, the telescope planes need to be aligned first. To check the quality of the alignment, tracks are reconstructed and fitted with a straight line. In the alignment and tracking processes only clusters with a size of ≤ 4 pixels are used. A fixed error of $4 \mu\text{m}$ is assigned to the local x and local y position of each cluster that is transformed to the global frame.

To align the Timepix3 telescope a sample in the order of 10^4 tracks is needed. The alignment of the telescope is based on the Millipede algorithm [84] [68]. To improve the quality of the alignment, a sequence of alignment algorithms including Millipede and the Minuit [85] package is used, as described below.

For the alignment of the telescope planes the free parameters $(X, Y, Z, \theta_X, \theta_Y, \theta_Z)$ need to be determined where θ are the rotations around the X, Y, Z axes. The DuT is excluded from the telescope alignment. The telescope planes are positioned at fixed Z positions, rotated around the X and Y axes by 9° so the initial conditions for a plane i are $(0, 0, Z_i, 9^\circ, 9^\circ, 0^\circ)$. The first telescope plane is selected as a reference plane. Initially the algorithm aligns the planes by minimising the X and Y cluster residuals on a plane with respect to the reference plane allowing only X, Y and θ_Z to vary. Next, straight line tracks are fitted to the clusters on the telescope planes. The track χ^2 is minimised using Minuit. Next, this process is performed a second time in order to minimise θ_X, θ_Y and a third time in order to minimise θ_Z and Z .

Having determined the free parameters $(X, Y, Z, \theta_X, \theta_Y, \theta_Z)$ one can trans-

form from the local to the global reference frame and vice versa. The residuals in the local reference frame, defined as x (y) predicted by the telescope minus the x (y) of the cluster calculated using the center of gravity method, have a σ of 3-5 μm for the telescope planes. The track selection is a lower cut in the χ^2 probability of 0.5%. The tracks that pass the selection are used to subsequently align the DuT.

5.3 DuT tracks

The relative Z position of the DuT to the two telescope arms is measured each time a DuT is placed in the telescope. Tracks that pass the probability cut are extrapolated to the Z position of the DuT. The DuT is not included in the track fit allowing an unbiased calculation of the residuals. These residual distributions are used to check the quality of the DuT alignment. The x (y) residuals of one-pixel clusters are expected to follow a uniform distribution with the mean centered at 0. A non-zero mean value of the residual distribution smaller than the maximum pointing resolution of the telescope ($|\mu_{\text{residual}}| < 2 \mu\text{m}$) is an indication of a good alignment.

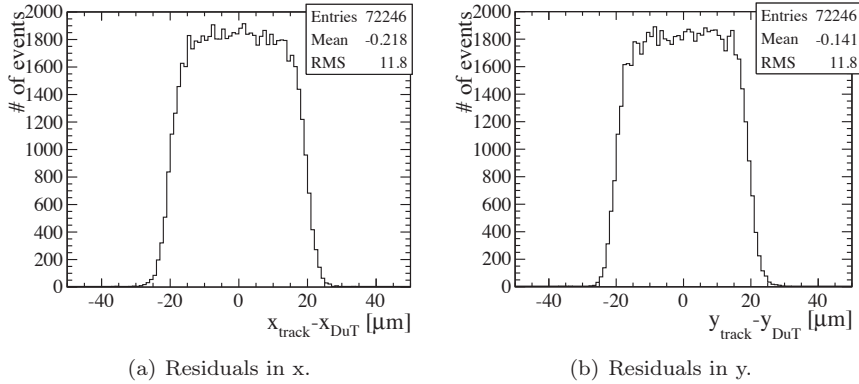


Figure 5.6: Unbiased residuals in x (a) and y (b) for one-pixel clusters of a 150 μm thick n -on- n sensor operated at -20 V (the full depletion voltage of the sensor is -10 V).

The unbiased x and y residuals in the local reference frame of one-pixel clusters in case of a 150 μm thick n -on- n sensor operated² at -20 V are plotted in Figure 5.6. The RMS of each residual distribution is 11.8 μm , which is smaller than the binary resolution equal to $\text{pitch}/\sqrt{12}$. This 3 μm discrepancy comes from the fact that at the regions close to the pixel edge charge carriers

²The full depletion voltage of this sensor is around -10 V.

have a high probability to form two-pixel clusters, such that the effective cross section for one-pixel clusters is reduced.

The DuT residuals are 9-12 μm depending on the bias voltage and the thickness of the sensor. The DuT residuals are larger than the residuals in the telescope planes by roughly a factor 2 because the telescope planes are rotated by 9° around the X and Y axis, in contrast to the DuT that is perpendicular to the beam.

5.3.1 Spatial association of DuT clusters

To predict the intercept point of the track on the DuT, the fitted track from the telescope is extrapolated to the Z position of the DuT. If a pixel is hit in a square window of 220 μm (equal to 4 pixels wide) around the track intercept on the DuT, then the cluster this pixel belongs to is associated to the track. A visualisation of the acceptance cut that associates DuT hits to telescope tracks is shown in Figure 5.7.

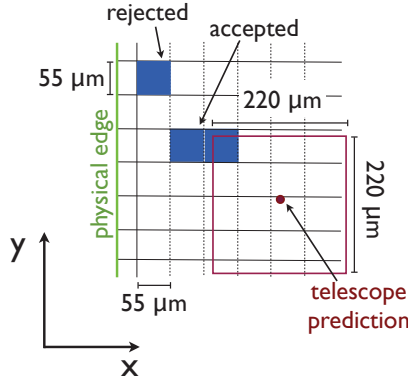


Figure 5.7: Association of DuT clusters (blue filled squares) to a telescope track.

For a minimum ionizing particle (MIP) traversing the sensor perpendicularly, the cluster size depends on the intercept of the MIP on the pixel. Normalising the telescope prediction to the pixel pitch, the track intercept position for one, two, three and four pixel clusters within the pixel is visualised in Figure 5.8. Looking at each cluster type in more detail a number of conclusions can be drawn:

- one-pixel cluster will be formed when all the charge carriers liberated in the silicon induce signal in one pixel while the signal induced in the neighbouring pixels is below threshold. This is most likely to occur in the center of the pixel as shown in Figure 5.8(a).

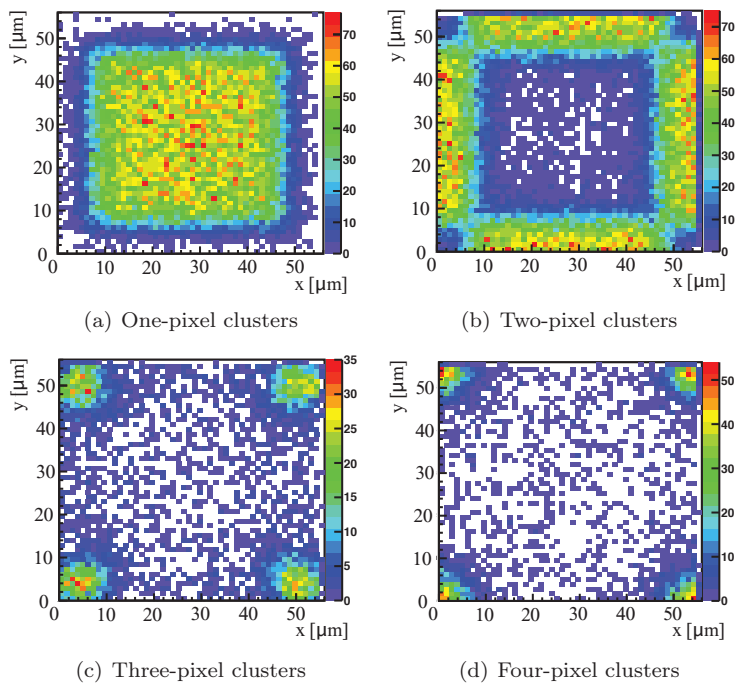


Figure 5.8: Track intercept position for one, two, three and four pixel clusters in a pixel of a $150\ \mu\text{m}$ thick n -on- n sensor operated at $-20\ \text{V}$ (the full depletion voltage of the sensor is $-10\ \text{V}$).

- When the charged particle traverses the sensor close to the pixel's edge, collecting charge in the neighbouring pixel is probable due to the diffusion of the charge carriers which leads to the formation of two-pixel clusters (Figure 5.8(b)).
- At the corners of the pixel the charge carriers may diffuse to all adjacent pixels leading to the formation of three or four-pixel clusters as depicted in Figure 5.8(c) and 5.8(d).

In case of the Timepix telescope a track could only be associated to a DuT cluster using the spatial method depicted in Figure 5.7. However, in the studies performed with the Timepix3 telescope a DuT cluster is associated to a track using the timestamp information.

5.3.2 Timing association of DuT clusters

In case of the Timepix3 telescope, a cluster on the DuT is associated to a track by selecting the cluster closest in time around the track but not larger than 50 ns. The track time t_{track} is defined as the mean time of all clusters that the track consists of.

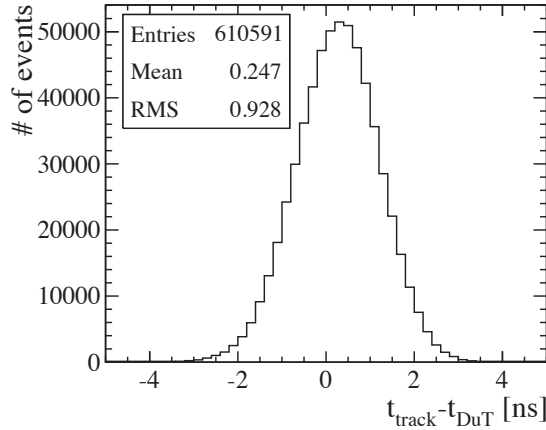


Figure 5.9: Time residuals of a 200 μm thick sensor operated at 200 V set perpendicularly to the beam.

The time residuals, defined as $t_{track} - t_{DuT}$ where t_{DuT} the time of the earliest hit from the associated DuT cluster, for a sensor set perpendicularly to the beam are shown in Figure 5.9. The RMS of the distribution is about 1 ns while the 0.25 ns offset of the mean from zero is due to timing offsets introduced by the readout (like differences in cable length).

In all studied performed with the Timepix3 telescope the DuT clusters were associated to tracks using both the space and time window selection. Associating clusters from the DuT is the last step of the offline analysis sequence. The data of one spill are processed with a rate of about 15×10^3 tracks/s. Therefore the time needed for the offline analysis software to process the data of one Run is comparable to the typical Run duration.

5.4 Summary

The Timepix and Timepix3 telescopes are excellent tools to study silicon sensors. The 2 μm spatial resolution of both the Timepix and Timepix3 telescopes allows the study of pixel sensors with sub-pixel precision. The two prime advantages of the Timepix3 telescope are the much higher track rate, which is larger by a factor 100 with respect to the Timepix telescope, as well as the simultaneous measurement of ToA and ToT. By recording these quantities simultaneously charge collection measurements with a timing resolution in the order of 1 ns can be performed.

In the studies performed with the Timepix telescope the DuT to track association was done based on a spatial window. In case of the Timepix3 telescope, the simultaneous measurement of ToA allows the association of DuT clusters to a track using an additional time selection.

Chapter 6

Results with active-edge sensors

A number of prototype sensors from VTT [86] with active-edge were studied with the Timepix telescope [65]. The sub-pixel pointing resolution of the telescope was used to study the efficiency and the streamlines of the electric field at the edge of these prototype sensors. The results of the measurements were published in Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. This publication [69] is reprinted in this chapter with permission of Elsevier Publishers.



Probing active-edge silicon sensors using a high precision telescope

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ABSTRACT

The performance of prototype active-edge VTT sensors bump-bonded to the Timepix ASIC is presented. Non-irradiated sensors of thicknesses 100–200 μm and pixel-to-edge distances of 50 μm and 100 μm were probed with a beam of charged hadrons with sub-pixel precision using the Timepix telescope assembled at the SPS at CERN. The sensors are shown to be highly efficient up to a few micrometers from the physical edge of the sensor. The distortion of the electric field lines at the edge of the sensors is studied by reconstructing the streamlines of the electric field using two-pixel clusters. These results are supported by TCAD simulations. The reconstructed streamlines are used to study the field distortion as a function of the bias voltage and to apply corrections to the cluster positions at the edge.

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1. Introduction

Silicon pixel detectors are chosen in experiments where radiation hardness and high precision tracking are demanded. In order to cover a large detection area, the tiling of many sensors is necessary. Conventional sensors use guard ring electrodes to gradually reduce the electric field towards the edge and in this way isolate the pixel matrix from edge effects. However, this results in an area with reduced sensitivity at the edge of the sensor up to a few hundred microns. In recent years, novel types of sensors with a smaller inactive area at the edge have been developed. These so-called edgeless sensors are divided into two sub-categories, slim-edge and active-edge. In the case of slim-edge sensors the sensor is diced and passivated closer to the pixel matrix [1] while in the case of the

active-edge [2] the sensor is etched and doped¹ [3]. The presence of this doping layer suppresses the surface current between electrodes but also distorts the electric field at the edge of the sensor. In this paper the performance at the edge of a series of non-irradiated active-edge sensors manufactured by VTT² is studied.

2. Experimental setup

As part of the LHCb VELO upgrade programme, a high efficiency telescope had been assembled in the SPS North Area at CERN. The telescope [4] consisted of eight Timepix [5] detectors with 300 μm

¹ The implant type at the edge depends on the sensor type: n^+ edge for a p-on-n sensor and p^+ edge for a n-on-x where x is either n or p.

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Table 1

A list of the VTT sensors tested.

Timepix chip	Sensor type	Thickness (μm)	PTE (μm)	Full depletion voltage (V)	Guard ring	Interpixel isolation ^a	Bias voltage (V)
D07-W0160	n-on-n	150	50	7–10	No	p-Stop	–40, –20
J08-W0171	n-on-p	100	50	10–13	No	p-Spray	–60
F08-W0171	n-on-n	200	50	14–17	No	p-Spray	–60
C07-W0171	n-on-p	100	100	10–13	No	p-Spray	–80
H08-W0171	n-on-n	200	100	14–17	Floating ^b	p-spray	–80, –40

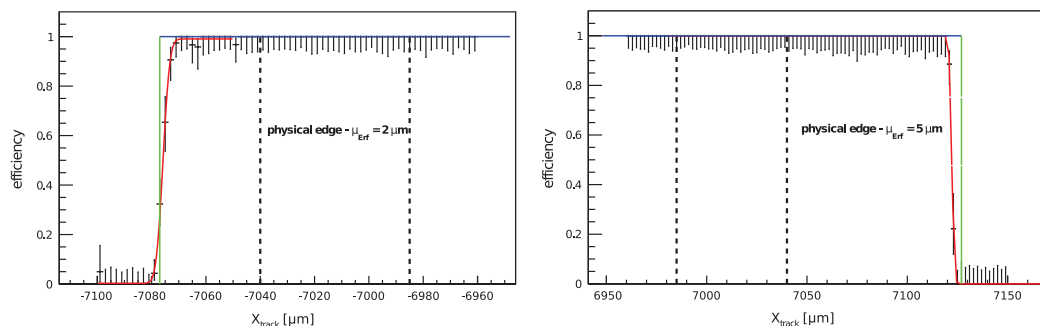
^a A p-type implant is needed between the pixels of an n-on-x sensor to interrupt the electron layer formed below the oxide.^b A floating guard ring is a guard ring that is not grounded.

Fig. 1. Efficiency at the side edge of the 150 μm thick n-on-n sensor D07-W0160 with 50 μm PTE (left) and at the side edge of the 100 μm thick n-on-p sensor C07-W0171 with 100 μm PTE (right). The dashed lines represent the boundaries of the last pixel, the (green) vertical line represents the physical edge and the (blue) horizontal line indicates the maximum efficiency. The legend states the distance between the mean of the error function and the physical edge. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

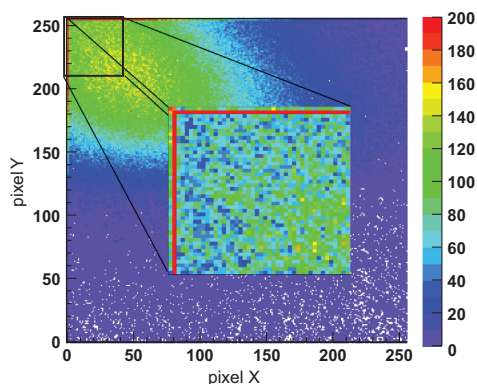


Fig. 2. Hit map of the 150 μm thick n-on-n sensor D07-W0160 with 50 μm PTE. A “hot” column and row (shown in the zoomed picture) second to the last ones are the results of the distortion of the electric field pattern at the edge.

thick sensors equally divided into two arms with an additional ninth plane providing timing information. The device under test (DUT) was mounted on a computer controlled translation and rotation stage which allowed translations in transverse directions to the beam in steps of 1 μm , as well as 0.01 of a degree accurate rotations. The stage was placed between the two telescope arms where the track pointing resolution is less than 2 μm . A series of prototype active-edge sensors from VTT of thicknesses 100–200 μm , pixel-to-edge (PTE) distances of 50 μm and 100 μm and different sensor types (n-on-n and n-on-p) were bump-bonded on Timepix chips and installed as DUTs in the Timepix telescope. The PTE is defined as the distance from the edge of the last pixel implant to the cut edge. All sensors have a pixel pitch of 55 μm . The pixel implants are

circular with a diameter of 28 μm . The sensor of one of the DUTs (H08-W0171) has one guard ring with a width of 11 μm . Metrology results indicate that the sensor size and alignment with respect to the readout ASIC are in agreement with the values from the design. A list of the five sensors and their properties is presented in Table 1.

The center of the beam spot was aligned with the edge of the sensors in order to acquire higher statistics for this sensor region. The beam consisted of charged hadrons with a momentum of 180 GeV/c. All data shown in this paper were taken with the DUT orientated perpendicular to the beam axis. Runs at different bias voltages were taken for a selection of these sensors.

3. Determination of hit position

The tracks are reconstructed and fitted using only hits on the telescope planes in order to avoid biasing of the results. The fitted track from the telescope is extrapolated to the position of the DUT to predict the intercept point of the track on the DUT. The track selection cut is an upper cut in the χ^2 probability of 0.5%. The surviving tracks are used to align the telescope planes and subsequently the DUT. The telescope planes are tilted to 9° to achieve the optimum spatial resolution [6]. The residuals (defined as the X (Y) predicted by the telescope minus the X (Y) of the cluster) have a σ of 3–5 μm for the telescope planes and 9–12 μm for the DUTs depending on the bias voltage supplied and the thickness of the sensor. The smaller residuals are a result of setting the telescope planes in their optimum angle in contrast to the DUT which is set perpendicular to the beam. The telescope and the DUT planes are lying on the XY plane where the column number of the pixel matrix corresponds to the X -axis and the row number to the Y -axis. A local coordinate system (X, Y) is defined with the (0,0) set at the center of the pixel matrix.

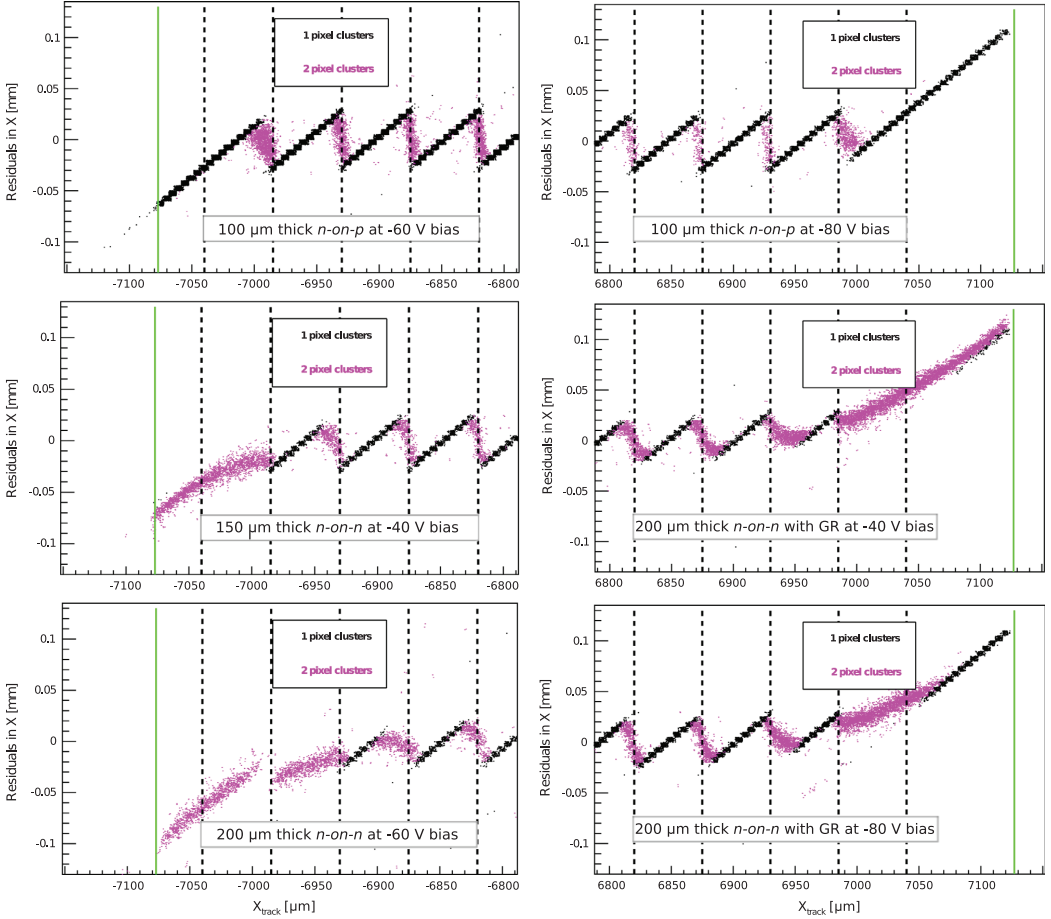


Fig. 3. Residuals in X as a function of the X coordinate predicted by the telescope for the sensors with 50 μm PTE (left column) and 100 μm PTE (right column): 100 μm thick $n\text{-on-p}$ J08-W0171 at -60 V bias (top left), 150 μm thick $n\text{-on-n}$ D07-W0160 at -40 V bias (middle left), 200 μm thick $n\text{-on-n}$ F08-W0171 at -60 V bias (bottom left), 100 μm thick $n\text{-on-p}$ C07-W0171 at -80 V bias (top right), 200 μm thick $n\text{-on-n}$ H08-W0171 at -40 V bias (middle right) and at -80 V bias (bottom right). The dotted lines represent the pixel boundaries and the green line the physical edge. The absence of hits in the boundary between the last two pixels of the 200 μm thick $n\text{-on-n}$ sensor F08-W0171 (bottom left) is due to the appearance of three-pixel clusters and is discussed in Section 6. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

All the DUTs were operated in Time-over-Threshold (ToT) mode. In ToT mode, for each pixel hit a counter is incremented for as long as the preamplifier output is above threshold, thereby giving a measurement of the energy deposited in this pixel. The counting clock had a frequency of 40 MHz. For a minimum ionizing particle (MIP) traversing the 150 μm thick $n\text{-on-n}$ sensor (D07-W0160), the most probable value is 150 ToT counts when collecting electrons. The most probable ToT value depends on the thickness, type and polarity of the sensor. The ToT counts provided by the pixels are then converted into charge by applying a surrogate function [6] with different fit parameters for each device obtained from testpulse data. The center position of the cluster is calculated by using the center of gravity (CoG) method.³ For

clusters containing edge pixels, the CoG method does not provide accurate information about the track position causing a divergence from zero in the residual distributions as will be described in Section 5.

4. Efficiency towards the physical edge

To measure the efficiency (defined as the ratio of number of tracks with a matching cluster on the DUT over the number of tracks predicted by the telescope) the following procedure is used:

(footnote continued)

charge calibration correction with the formula

$$x_{\text{CoG}} = x_0 + \frac{\sum_{i=0}^N x_i q_i}{\sum_{i=0}^N q_i}$$

³ In the center of gravity method the position of the hit on N pixels is calculated after weighting the position of the pixels using their respective charge after the

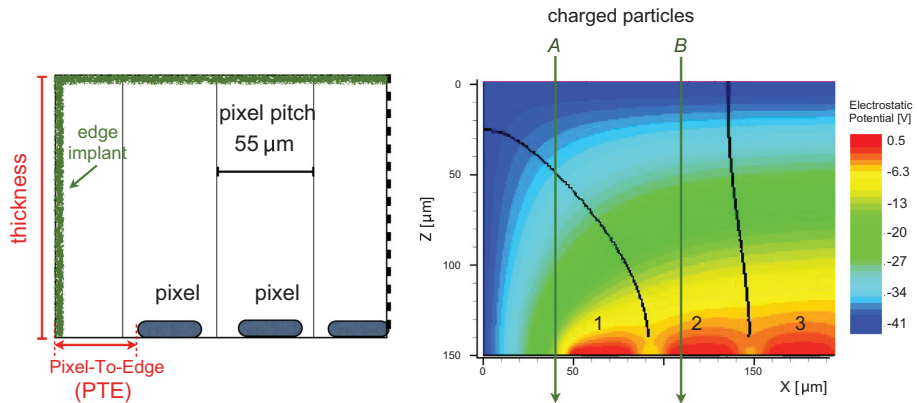


Fig. 4. Left: Anatomy of an active-edge sensor. Figure not to scale. Right: TCAD simulation of the electrostatic potential of a 150 μm thick n-on-n sensor with 50 μm PTE, *p*-stop interpixel isolation operating at −40 V. The streamlines of the electric field at the edge are not perpendicular to the sensor.

a track is declared as *found* when a pixel is hit in a square window of 110 μm (two pixel pitch wide) around the telescope's prediction on the DUT. Since the pointing resolution is below 2 μm, it is possible to probe the efficiency at the edge in detail. The results are shown in Fig. 1 for the 150 μm thick n-on-n sensor (left) and the 100 μm thick n-on-p sensor (right). The efficiency distributions of all sensors with 50 μm PTE are identical to Fig. 1 (left) and the distributions for all sensors with 100 μm PTE are identical to Fig. 1 (right). The (green) vertical line represents the physical edge and the dashed lines represent the boundaries of the last pixel. The dashed lines are fixed by aligning to the pattern of one-pixel clusters within the main body of the pixel array. The position of the physical edge is defined by the PTE and verified by metrology in the case of the 150 μm thick sensor (D07-W0160). Metrology was performed at CERN using the optical measuring system MAHR Wegu OMS 600 with an uncertainty of ± 1 μm. The distance between the physical edge and the boundary of the last pixel is 37 μm for the 50 μm PTE sensors and 87 μm for the 100 μm PTE sensors. The DUTs are $\sim 100\%$ efficient through all the pixel matrix. At the edge of the sensor, the efficiency is $> 99\%$ up to 10 μm from the physical edge. The efficiency distribution is fitted with an error function. The mean of the fitted error function is 2–7 μm away from the physical edge.

5. Residuals at the physical edge

Looking at the raw data and the integrated hit map in Fig. 2, the pixels of the second but last row (column) of some of the sensors of Table 1 show an excess of hits compared to their neighboring pixels. In those sensors it is never the case that a pixel hit is seen in the last row (column) which does not share charge with the neighboring row (column). To understand this effect the residuals at the edge were studied.

Clusters with a size larger than one are formed due to charge sharing if tracks intercept close to the boundaries of the pixel cell. In Fig. 3 the one-pixel and two-pixel cluster residuals are plotted as a function of the *X* coordinate of the track intercept as predicted by the telescope. The dotted vertical lines represent the pixel boundaries and the solid (green) vertical line represents the physical edge of the sensor. The requirement for all two-pixel clusters used in this analysis is that both pixels belong to the same row. The first and last five rows are excluded to avoid influences from the corners of the sensors. The increased rate of two-pixel clusters with respect to the center of the pixel matrix and the

absence of one-pixel clusters from the last pixel up to the physical edge are indications of the distorted pattern of the electric field. This electric field distortion at the edge depends on the thickness of the sensor, the PTE and the bias voltage applied. The dependence on the thickness and the PTE is studied in Section 6 and the dependence on the bias voltage in Section 7.

A previous paper [7] reports a distorted pattern of the electric field lines at the last columns (rows) of active-edge sensors.⁴ Looking at the cross-section of such an active-edge sensor in TCAD simulations [8] we can visualize this distortion of the electric field pattern. The PTE distance and the edge implant are depicted in Fig. 4 (left). In Fig. 4 (right) the electrostatic potential of a 150 μm thick active-edge sensor with a 50 μm PTE, *p*-stop interpixel isolation operating at −40 V is simulated. In a homogeneous electric field the field lines are perpendicular between the top and bottom contact of the sensor. However, the field line at the boundary of the two edge pixels, which will be referred to as streamline, is shaped in such a way that it reduces the volume of the sensor where free charge carriers will be collected by the last pixel. Simultaneously, this effective volume⁵ is increased for the one but last pixel.

For a charged particle, free charge carriers will be liberated along the whole path of the particle through the sensor (Fig. 4 right). In the case of particle B, all electric field lines originating from a point along the particle's trajectory end on pixel 2. However, when a particle traverses the sensor close to the edge (particle A) where the streamlines are curved, both the last and one but last pixel (pixels 1 and 2) collect charge. Reconstructing the edge streamline and estimating the effective volume of the edge pixels are the main topics of Section 6.

6. Charge fraction of the edge pixels

The ratio of the charge of a pixel over the total charge of the cluster can be used to estimate the effective volume of each pixel. In Fig. 5 the CoG of the two-pixel clusters as a function of the prediction from the telescope for the *X* coordinate are plotted.⁶ The empty space between the charge ratio curves represents areas where the liberated charge is not shared between pixels. A particle

⁴ In [7] the sensors are placed at large angles with respect to the beam. No telescope is used to define the intercept of a particle on the sensor.

⁵ The term effective volume refers to the volume formed by the streamlines.

⁶ In Figs. 5 and 6 the charge fraction is defined as the charge of the pixel closest to the edge (outer pixel) over the total charge of the two-pixel cluster it belongs to.

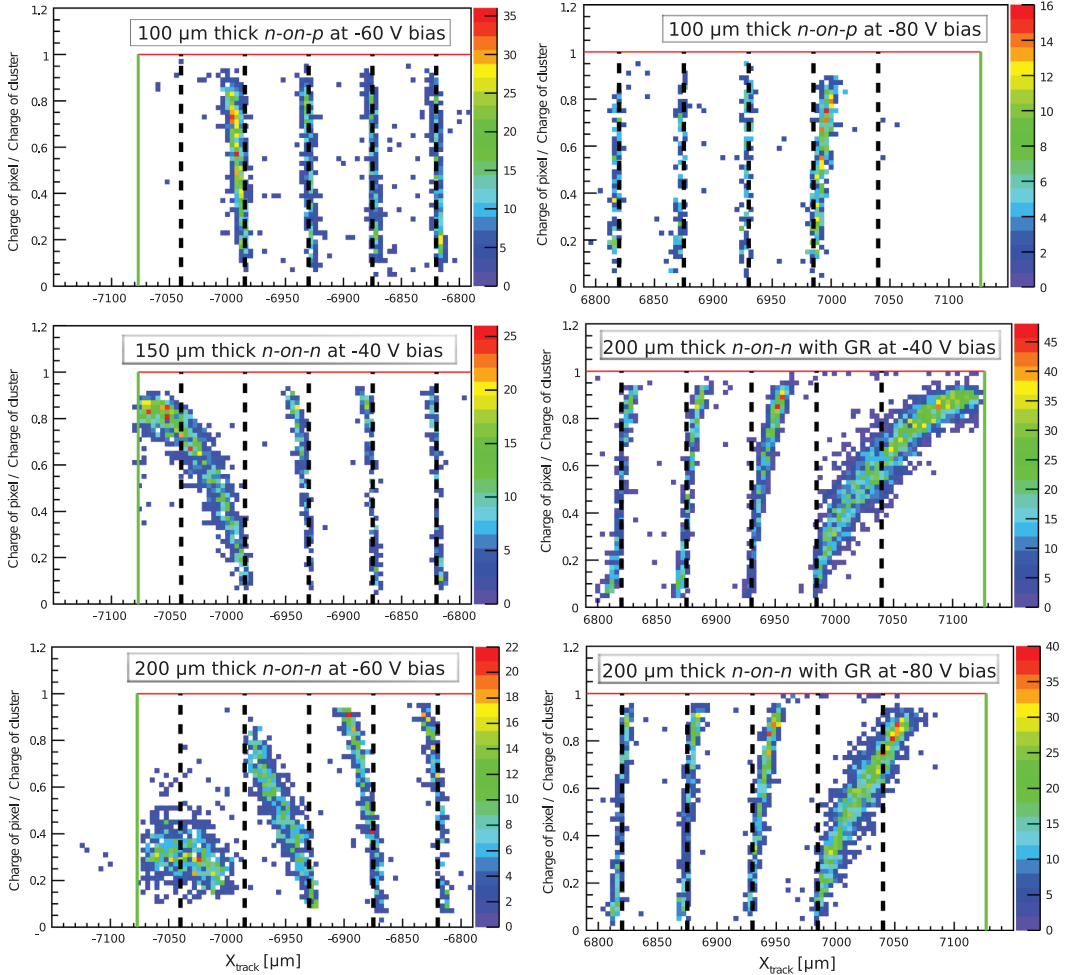


Fig. 5. Charge fractions of pixels forming two-pixel clusters at the edge of the sensors with 50 μm PTE (left column) and 100 μm PTE (right column): 100 μm thick n-on-p J08-W0171 at -60 V bias (top left), 150 μm thick n-on-n D07-W0160 at -40 V bias (middle left), 200 μm thick n-on-n F08-W0171 at -60 V bias (bottom left), 100 μm thick n-on-p C07-W0171 at -80 V bias (top right), 200 μm thick n-on-n H08-W0171 at -40 V bias (middle right) and at -80 V bias (bottom right). The dotted lines represent the pixel boundaries and the green line the physical edge. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

traversing the sensor at a region corresponding to such an empty space will form a one-pixel cluster. For the 150 μm thick sensor with 50 μm PTE (D07-W0160) at -40 V bias the effective volume of the second to last pixel is ~ 1.7 times larger⁷ compared to the volume of a more central pixel while the effective volume of the last pixel (extending up to the physical edge of the sensor) is approximately the same as the volume of a more central pixel. Note that all sensors were operated at a voltage larger than the full depletion voltage, as listed in Table 1. The cluster-charge distribution (Landau) of each sensor has been compared to that expected for a fully depleted sensor and found to be in accordance to expectation. This provides an independent cross-check that the sensors were fully depleted.

The effect of the curved streamlines at the edge is also present in the case of the 200 μm thick sensor with the same PTE (F08-W0171)

at -60 V bias as shown in Fig. 6. In the region located at the boundary of the last and one but last pixel marked with the (red) dotted ellipse, three-pixel clusters with all three pixels in the same row are formed. The additional appearance of three-pixel clusters at the rows close to the edge of the 200 μm thick sensor is evidence of an even more distorted electric field than in the case of the 150 μm thick one.

The electric field pattern at the edge is less distorted in the case of J08-W0171 and C07-W0171. Fig. 5 (top left) and (top right) shows that the field lines at the pixel boundaries are uniform up to the edge of J08-W0171 and C07-W0171 respectively. Both J08-W0171 and C07-W0171 are 100 μm thick and were operated at -60 V and -80 V respectively.

The amount of distortion depends on the thickness and the PTE. For the sensors of Table 1 without guard ring we observe a reduction of the distortion as the dimensionless ratio of thickness over PTE decreases. The distortion becomes negligible when the ratio approaches one. This dependence of the electric field on the geometrical features of the sensor is expected since for a small thickness over PTE ratio the sensor

⁷ This value is calculated from the testbeam data.

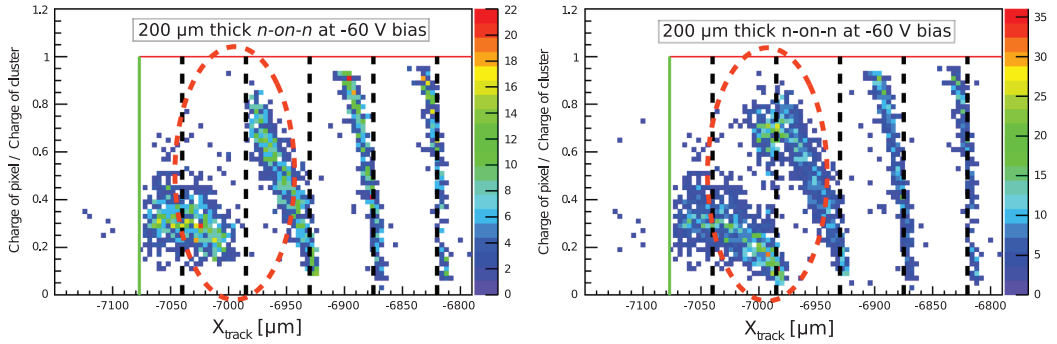


Fig. 6. Charge fractions of pixels forming two-pixel clusters (left) and two and three-pixel clusters (right) at the side edge of the 200 μm n-on-n sensor F08-W0171 with 50 μm PTE showing a greater distortion than Fig. 5. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

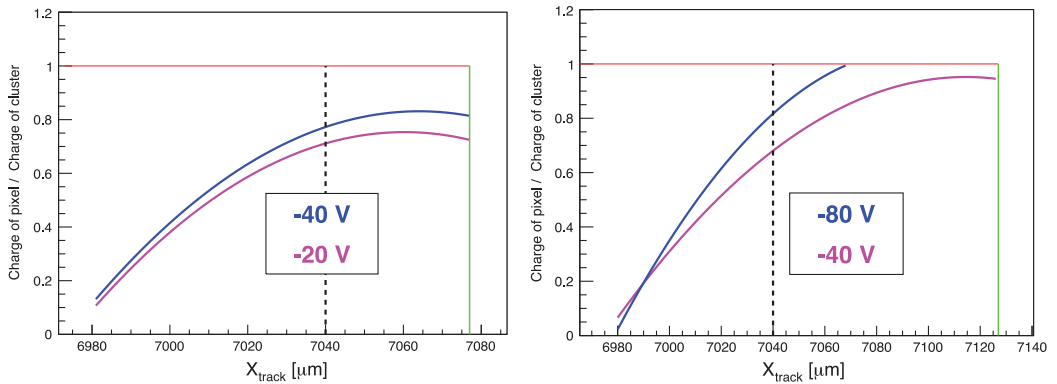


Fig. 7. Measured stream lines at the edge of the 150 μm thick n-on-n sensor D07-W0160 with 50 μm PTE (left) and the 200 μm thick n-on-n H08-W0171 with 100 μm PTE and floating GR (right) at different bias voltages. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

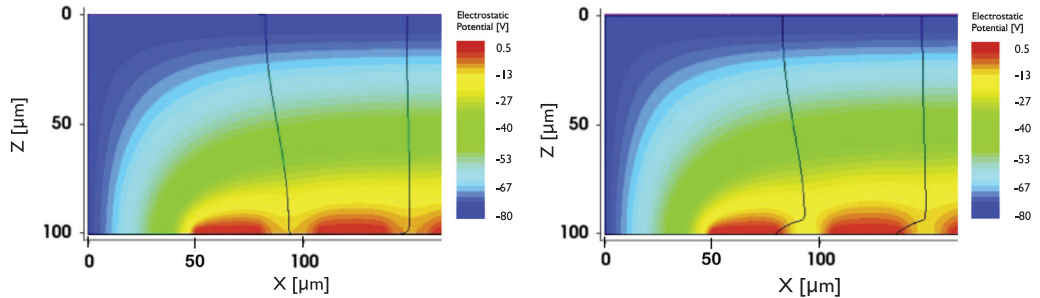


Fig. 8. TCAD simulations of the electrostatic potential of a 100 μm thick n-on-p (left) and n-on-n (right) sensor, both with a 50 μm PTE and operating at -80 V. For both sensor types, the streamlines at the edge are closer to perpendicular than the ones in Fig. 4 (right).

resembles a parallel plate configuration where the edge is relatively far away from the one but last pixel.⁸

⁸ The comparison to a parallel plate configuration is of limited use when the sensor is mildly overdepleted since in that case the electric field is not constant as a function of Z .

7. Bias dependence on the electric field lines at the edge

The electric field at the edge as a function of the supplied bias voltage was studied for D07-W0160 and H08-W0171. The shape of the edge streamline was determined by the following procedure: (i) each bin of the track coordinate in the charge fraction plots was fitted with a Gaussian, (ii) the mean of each Gaussian was plotted as a function of the X or Y coordinate predicted by the telescope and (iii) the plot was fitted with a second order polynomial.

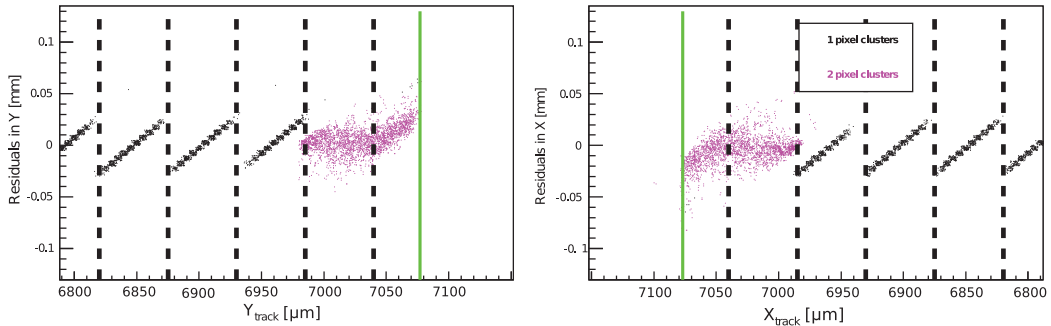


Fig. 9. Residuals in Y as a function of the Y coordinate predicted by the telescope (left) and residuals in X as predicted for the X coordinate (right) for the $150\ \mu\text{m}$ thick n-on-n sensor D07-W0160 with $50\ \mu\text{m}$ PTE after applying the correction in the CoG method. The residuals of the edge two-pixel clusters are not larger than the one-pixel cluster residuals.

For different bias voltages the shape of the streamlines of the electric field at the edge of the $150\ \mu\text{m}$ thick sensor (D07-W0160) does not change significantly as shown in Fig. 7 (left). For the $200\ \mu\text{m}$ thick sensor with the floating GR (H08-W0171) in Fig. 7 (right), the shape of electric field streamlines shows a strong dependence on the applied bias voltage. At $-40\ \text{V}$ bias, perpendicular tracks beyond $7.04\ \text{mm}$ will form two-pixel clusters since the electric field streamlines (purple line) have the usual distorted pattern extending from the boundary of the last two electrodes up to the physical edge. Increasing the bias voltage results in a significant change of the electric field pattern. The edge streamlines become steeper and extend up to the bias side of the sensor (blue line) leading to the formation of one-pixel clusters beyond the boundary of the last pixel.

8. Simulations

Simulations in TCAD provide us with an internal view of the electric field pattern in the sensor. The simulated pattern of the electric field lines at the edge of the $150\ \mu\text{m}$ n-on-n sensor in Fig. 4 (right) is in good agreement with the streamlines obtained from the charge ratio of the edge pixels shown in Fig. 5 (middle left). Additional simulations of a $100\ \mu\text{m}$ thick sensor with a $50\ \mu\text{m}$ PTE sensor were made to investigate the behaviour at the edge. As depicted in Fig. 8 (left), the streamlines at the edge are expected to be closer to perpendicular compared to the case of the $150\ \mu\text{m}$ thick sensor with the $50\ \mu\text{m}$ PTE due to the fact that in this last case the physical edge is further away. This is confirmed by the charge ratio measurement of the J08-W0171 sensor shown in Fig. 5 (top left).

From the sensors of Table 1, both sensors with the minimum distorted edge streamlines (J08-W0171 and C07-W0171) are of sensor type n-on-p. To exclude that the reduction of this distortion is due to the sensor type, sensors with geometries same as J08-W0171 and C07-W0171 but of opposite bulk type were simulated. In Fig. 8 simulations of a sensor with the same geometry as J08-W0171 in n-on-p (left) and in n-on-n configuration (right) show that the distortion of the edge streamlines is independent of the sensor type for highly overdepleted sensors.

9. Corrections on the cluster position at the edge

Using the information from the charge ratios, a better estimate of the cluster position at the edge can be achieved. The spatial

resolution of a pixel or strip detector for one-pixel clusters is $\text{pitch}/\sqrt{12}$.⁹ This so-called binary resolution can be improved in the case of multi-hit clusters by applying the CoG method mentioned in Section 3 or by applying other corrections such as the eta-function [9]. A similar correction in the CoG of the last two columns (rows) is applied in order to improve the spatial resolution at the edge.

By plotting the cluster coordinates predicted by the telescope as a function of the CoG information from the DUT a correlation function between the two quantities is derived. This correlation function (a second order polynomial) is used to correct the cluster positions beyond $6.98\ \text{mm}$. In Fig. 9 the residuals using the corrected cluster position are plotted for the $150\ \mu\text{m}$ thick sensor (D07-W0160). The distribution of the two-pixel cluster residuals up to the end of the pixel matrix is similar to that of one-pixel clusters. The charge ratio of the two-pixel clusters is uniform beyond the boundary of the last pixel up to the physical edge therefore no correction in the COG position can be applied. The corrections on the cluster position in Fig. 9 are made for perpendicular tracks. The correction function at the edge (similar to the eta function) depends on the angle of the track. One could also apply a correction to the cluster position for angled tracks if an indication of the track angle is given.

10. Conclusions and outlook

The performance at the edge of a novel type of active-edge sensors from VTT using a high precision telescope with a pointing resolution below $2\ \mu\text{m}$ is reported. All sensors are $\sim 100\%$ efficient through all the pixel matrix and $> 99\%$ efficient up to $10\ \mu\text{m}$ from the physical edge. A known feature of these active-edge sensors is the distorted pattern of the electric field at the edge. By studying the charge fractions of the edge two-pixel clusters a reconstruction of the streamlines is possible. These reconstructed streamlines are in good agreement with TCAD simulations. The formation of two-pixel clusters at the edge can be used to improve the spatial resolution at the edge of the sensor after applying a correction function. The studies presented should also be made with irradiated sensors. This was however not possible with the Timepix as this ASIC is not radiation hard. Recently the Timepix3 ASIC has become available allowing us to repeat these studies as a function of radiation dose.

⁹ The measured σ of the resolution is smaller than $\text{pitch}/\sqrt{12}$ due to the fact that one-pixel clusters are formed in the center of the pixel.

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References

- [1] V. Fadeyev, et al., Nuclear Instruments and Methods in Physics Research Section A 731 (2013) 260.
- [2] C.J. Kenney, et al., Nuclear Instruments and Methods in Physics Research Section A 565 (2006) 272.
- [3] X. Wu, et al., JINST 7 (2012) C02001.
- [4] K. Akiba, et al., The Timepix Telescope for High Performance Particle Tracking, [arXiv:1304.5175v1](https://arxiv.org/abs/1304.5175v1) [physics.ins-det].
- [5] X. Llopart, Design and Characterization of 64 K Pixels Chips Working in Single Photon Processing Mode, CERN-THESIS-2007-062, 2007.
- [6] K. Akiba, et al., Nuclear Instruments and Methods in Physics Research Section A 661 (2012) 31.
- [7] M.J. Bosma, Active-Edge planar silicon sensors for large-area pixel detectors, in: IEEE Nuclear Science Symposium Conference Record, 2011, pp. 1329–1333.
- [8] Synopsys TCAD, (<http://www.synopsys.com/tools/tcad/>).
- [9] E. Belau, et al., Nuclear Instruments and Methods in Physics Research 214 (1983) 253.
- [10] J. Jakubek, et al., Nuclear Instruments and Methods in Physics Research Section A 563 (2006) 254.

Chapter 7

Results with prototype sensors for the upgrade

As part of the VELO upgrade a testbeam programme has been carried out to compare the performance of the sensors before and after irradiation. A number of prototype sensors from Hamamatsu and Micron have been examined as DuTs (Devices under Test) in the Timepix3 telescope. Different measurements, depending on the DuT configuration with respect to the beam, were performed on the irradiated and non-irradiated sensors. With the sensors being placed perpendicular with respect to the beam, measurements on the charge collection efficiency and diffusion were performed. In addition, measurements of the collected charge versus depletion depth profile, time to threshold versus depletion depth profile and of various radiation induced effects (like charge trapping and the effective doping concentration) were performed with the sensors rotated by large (grazing) angles with respect to the beam.

7.1 Assemblies tested

Each assembly consists of a Timepix3 ASIC bump-bonded to either a Hamamatsu or a Micron sensor. The sensors from Hamamatsu are produced from one single wafer, are 200 μm thick *n-on-p* type and feature 35 or 39 μm implant widths that are isolated using the *p*-stop technique described in Section 4.4.2. The sensors from Micron come from two different wafers. The sensors from the 200 μm thick wafer are *n-on-p* type while the ones from the 150 μm thick wafer are *n-on-n* type. All Micron sensors feature 36 μm wide implants isolated using the *p*-spray technique. The non-irradiated assemblies tested are presented in Table 7.1.

A subset of the assemblies were irradiated with neutrons at the JSI institute in Ljubljana [87] up to fluences of $8 \times 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$. This fluence corresponds to the expected NIEL¹ fluence that the sensors will have been

¹The NIEL is defined in Section 4.1.3.

Table 7.1: Non-irradiated sensors tested.

Assembly ID	Thickness [μm]	Sensor Type	Vendor	Implant width [μm]	Full depletion [Volts]	Doping level [cm^{-3}]
S6	200	<i>n-on-p</i>	Hamamatsu	39	140	4.5×10^{12}
S20	200	<i>n-on-p</i>	Hamamatsu	35	140	4.5×10^{12}
S23	200	<i>n-on-p</i>	Micron	36	<40	$<1.2 \times 10^{12}$
S33	150	<i>n-on-n</i>	Micron	36	<25	$<1.4 \times 10^{12}$

Table 7.2: Irradiated sensors tested.

Assembly ID	Thickness [μm]	Sensor Type	Vendor	Implant width [μm]	Fluence 1 MeV $n_{\text{eq}}/\text{cm}^2$
S15	200	<i>n-on-p</i>	Hamamatsu	35	4×10^{15}
S17	200	<i>n-on-p</i>	Hamamatsu	39	8×10^{15}
S22	200	<i>n-on-p</i>	Hamamatsu	35	8×10^{15}
S27	150	<i>n-on-n</i>	Micron	36	8×10^{15}

exposed to at the end of LHC Run 3. The irradiated sensors that were tested are presented in Table 7.2.

7.2 Equalisation & Calibration

The threshold settings for all pixels of an assembly need to be adjusted in order to achieve an equal threshold. This process is known as *equalisation*. If the threshold level of a pixel cannot be adjusted to the same level as the rest of the pixels then that pixel is deactivated. The number of deactivated pixels for the devices in Tables 7.1 and 7.2 are in the range of 300–500 corresponding to $< 1\%$ of the total number of pixels.

The amount of charge collected by a pixel is measured in ToT counts. To convert the ToT counts to charge, a calibration function is used that is obtained from testpulses as described in Section 4.3.4. Subsequently the measured charge is converted to electron units thus the detectors are calibrated. The most probable electron/hole pair generation in a 200 μm thick sensor is about 15,000 e^- , which (for a Timepix3 ASIC) corresponds to about 200 ToT counts².

²The number of ToT counts depends on the time the preamplifier needs to fully discharge the integrated signal, which is adjusted by the *lkrum* setting.

The charge distribution of the collected charge is fitted with a Landaus and the most probable value (MPV) errors from the fit are $<10\text{ e}^-$. In a perfectly calibrated, non-irradiated detector and assuming a uniform thickness and depletion width throughout the sensor, the Landau MPVs of all pixels should be equal. In reality the MPVs of all pixels differ. Assuming that the thickness is uniform, the calibration error is defined as the standard deviation of the MPVs per pixel. The calibration error, which is about 100 e^- , is the main contributor to the error on the amount of charge collected. The individual error bars are not shown in figures showing charge distributions.

7.3 Leakage current

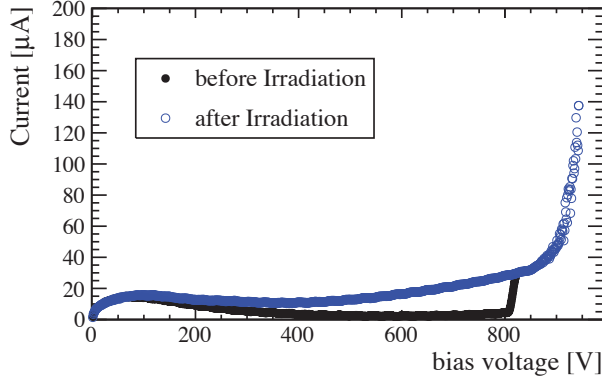
The leakage current as a function of bias voltage was measured for each assembly of Tables 7.1 and 7.2. Operating a sensor at bias voltages beyond the breakdown voltage leads to high currents as shown in Figure 4.5. These currents are a signature of the avalanche breakdown that may destroy the sensor. The leakage current as a function of the bias voltage for a $200\text{ }\mu\text{m}$ thick sensor from Hamamatsu (S22) before and after irradiation is plotted in Figure 7.1(a). The measurements before irradiation were taken with the sensor kept at a temperature of 15°C while after irradiation the sensor was at -24°C . Before irradiation the breakdown voltage of the sensor is about 800 V while after irradiation the sensor reaches breakdown at voltages in excess of 900 V .

According to Eq. (4.12) the leakage current depends on temperature. Operating the sensor at low temperatures is required in order to avoid thermal runaway. The leakage current of the irradiated sensor was measured with the sensor cooled with a Peltier cooling module at -24°C and with dry air at $+17^\circ\text{C}$ (Figure 7.1(b)). If the sensor is operated at $+17^\circ\text{C}$ breakdown occurs at about 800 V while when the sensor is kept at -24°C the breakdown shifts to a higher bias voltage.

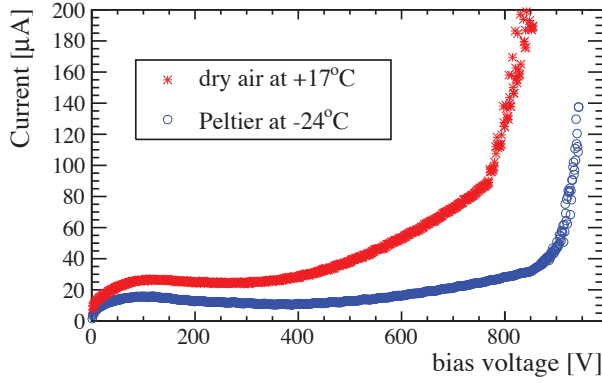
7.4 Testbeam data

The data presented in the rest of the chapter are acquired by placing the prototype assemblies as DuTs in the Timepix3 telescope described in Chapter 5. The telescope was placed in a beam of 180 GeV protons and pions at SPS. The duration of a typical Run is one or two SPS spills corresponding to about 10^6 particles per spill.

A number of selection criteria are applied to the data (see Section 5.2.2). The cluster on the DuT closest in time to a track, but within a time window of 50 ns , is associated to the track. Tracks traversing the detector at the edges of



(a) Leakage current before and after irradiation.



(b) Leakage current after irradiation at two different temperatures.

Figure 7.1: Leakage current plot of a Hamamatsu sensor (S22): (a) before and after being irradiated to $8 \times 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$ and (b) operated at two different temperatures after irradiation.

the sensor (3 first and last rows and columns) and tracks close to deactivated or dead pixels are excluded from the measurements since part of the charge liberated may not have been collected. In general, around 600,000 tracks per Run qualify for further study.

All sensors were operated at negative bias voltages. However, the voltage values in all plots are positive to ease the interpretation of the magnitude of the bias voltages applied.

In Sections 7.5 and 7.6 measurements of the charge collection efficiency and charge diffusion of the non-irradiated and irradiated assemblies are presented, respectively. In both measurements the DuTs are placed perpendicular to the beam.

7.5 Charge collection efficiency

If the sensor is partially or fully depleted and assuming there are no inactive areas close to the electrodes, the energy deposited in each pixel's volume follows a Landaus distribution. The charge collection efficiency is shown by plotting the Landau MPV component as a function of the bias voltage. The charge collection efficiency for the non-irradiated devices is illustrated in Figure 7.2.

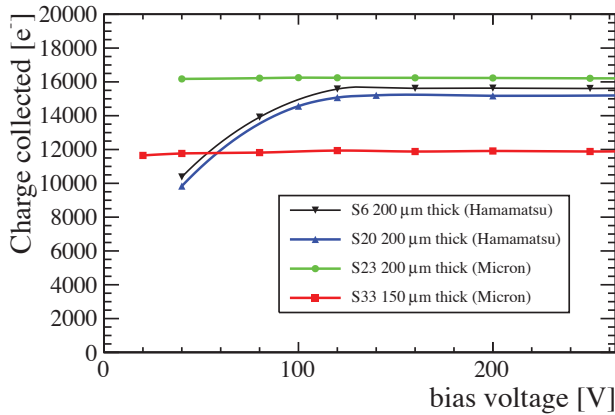


Figure 7.2: Charge collection efficiency for the non-irradiated devices.

The charge collected from the depleted region of the Hamamatsu sensors (blue and black lines with triangles) increases with bias voltage until a plateau is reached at about 140 V. The beginning of the plateau region marks the full depletion voltage. In case of the Micron sensors (red and green lines with squares and circles) the charge collection efficiency has a different pattern. The amount of charge collected is constant as a function of the applied bias voltage

indicating that the full depletion voltage is already reached below a few tens of Volts.

The difference in charge collection efficiency between two assemblies irradiated to different fluences can be seen in Figure 7.3. Two Hamamatsu sensors, S15 and S22, were irradiated to 4 and $8 \times 10^{15} \text{ 1 MeV } n_{\text{eq}}/\text{cm}^2$, respectively. The amount of charge collected increases linearly as a function of the applied bias voltage. At the maximum voltage, the amount of charge collected is less than half of the charge collected when the sensor is non-irradiated, as can be seen in comparison to Figure 7.2. The assembly irradiated to the lower fluence (S15) was not protected against sparking and therefore could not be operated up to 1000 V .

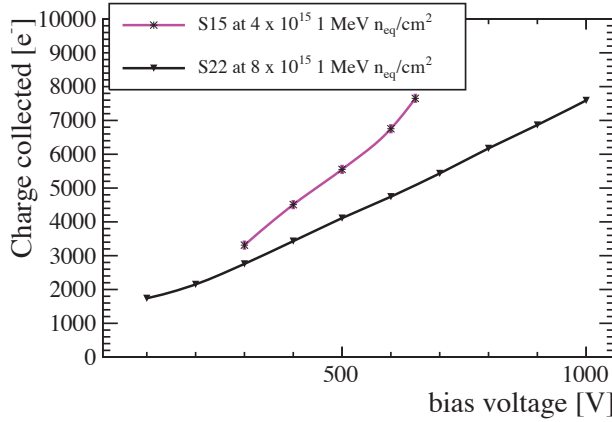


Figure 7.3: Charge collection efficiency for Hamamatsu sensors irradiated at different fluences. The lines are drawn to guide the eye.

Comparing the amount of charge collected from each sensor at a certain bias voltage, the assembly exposed to the lower fluence (S15) collects more charge. The value of the effective doping concentration N_{eff} for S15 is lower than that of S22, implying that for the same bias voltage the depleted region extends deeper into the bulk resulting in more charge being collected. Another factor contributing to the higher charge collection efficiency of S15 is the smaller charge trapping rate. According to Eq. (4.25), the trapping rate of the charge carriers increases with fluence. The width of the depleted region as well as the effect of charge trapping are studied and evaluated in Section 7.7.

In total three of the prototype sensors from Table 7.2 (sensors S17 and S22 from Hamamatsu and the Micron sensor S27) were exposed to a fluence of $8 \times 10^{15} \text{ 1 MeV } n_{\text{eq}}/\text{cm}^2$. The charge collection efficiency for these sensors is plotted in Figure 7.4. The amount of collected charge for the irradiated Micron sensor is almost equal to that of the $50 \mu\text{m}$ thicker irradiated Hamamatsu sensors. The amount of charge collected grows almost linearly as a function of

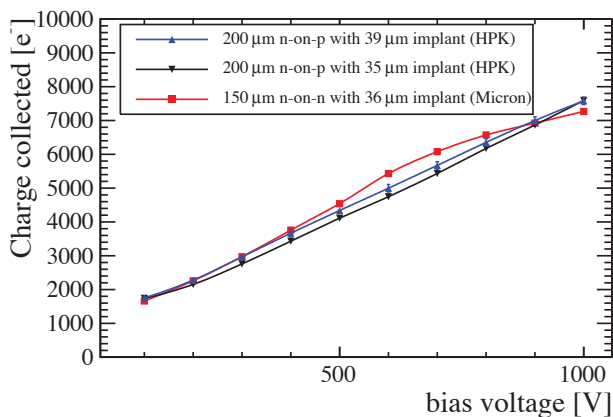


Figure 7.4: Charge collection efficiency for the devices irradiated to the highest fluence.

the applied bias voltage. This linear dependence implies that the square root dependence of the depletion width on the bias voltage ($w \propto \sqrt{V_{dep}}$), as in the case of a non-depleted non-irradiated sensor, fails to describe the data because other radiation induced effects (like charge trapping) are not taken into account in the simple model of Eq. (4.23). The effect of charge trapping is similar in the Micron and the Hamamatsu sensors due to the fact they are exposed to the same fluence. Since the initial doping concentrations are small with respect to the radiation induced doping, the effective doping concentration N_{eff} is about the same for all sensors. Thus the depleted depth is equal for the same bias voltage, hence the same amount of charge is collected for the 200 μm and 150 μm thick sensors.

7.6 Diffusion measurement

Assuming that charge carriers drifting towards the electrodes form a *cloud*, charge diffusion in the sensor can be studied by measuring the width of this charge cloud. The DuTs for this study are placed perpendicular to the beam. The telescope information is used to predict the point at which a track traverses the DuT.

The number of one-pixel clusters is compared with the prediction of the impact point. The telescope prediction of the intercept point of a track on the DuT is scaled to the pixel pitch as shown in Figure 7.5. Since the DuTs are placed perpendicular to the beam, tracks forming one-pixel clusters follow a flat distribution in the center of the pixel. The distribution decreases towards the edges of the pixel. This is due to the fact that the charge liberated along the

track intercepting the sensor close to a pixel boundary has a high probability to be shared between several pixels, as shown in Figure 5.8.

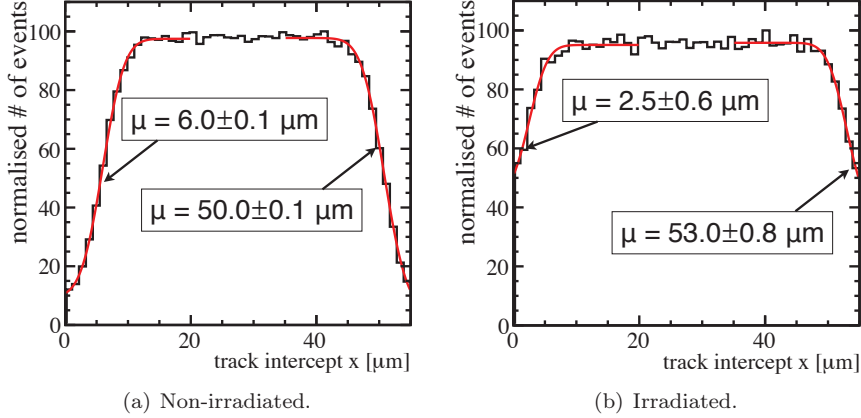


Figure 7.5: Formation of one-pixel clusters normalised in the pixel pitch for a non-irradiated (a) and an irradiated (b) sensor. Both sensors are 200 µm thick. In the case of the irradiated sensor, one-pixel clusters are formed in a larger fraction of the pixel. The solid (red) curves represent the fits from 7.1.

The widths of the flat regions are now used to compare the amount of charge diffusion between the non-irradiated and irradiated sensor. Each edge of the distribution is fitted with the cumulative distribution function of the normal distribution:

$$f(x) = c + s \cdot \frac{1}{2} \left(1 + \text{Erf} \left(\frac{x - \mu}{\sigma \sqrt{2}} \right) \right) \quad (7.1)$$

where c is an offset, s is a scaling factor, $\text{Erf}()$ the error function with μ the mean and σ the standard deviation of the normal distribution. The mean μ is used as a measure for the width of the flat region. For the non-irradiated sensor (Figure 7.5(a)) the width of the flat region is 44 µm while for the irradiated sensor (Figure 7.5(b)), the width of the flat region is 50.5 µm. The larger width of the flat region in the distribution indicates that the width of the charge cloud is smaller for the irradiated sensor.

The difference in the formation of one-pixel clusters between the irradiated and non-irradiated sensor is mainly due to the amount of charge collected with respect to the threshold value, which is depicted qualitatively in Figure 7.6. According to Figure 7.2, the measured Landau MPV of the non-irradiated 200 µm thick sensors is about 15,000 e^- . Assuming that at a certain position x_s the majority of that charge is collected by pixel B (Figure 7.6(a)), then only 7 % of the total amount of charge needs to be collected by the neighbouring pixel A

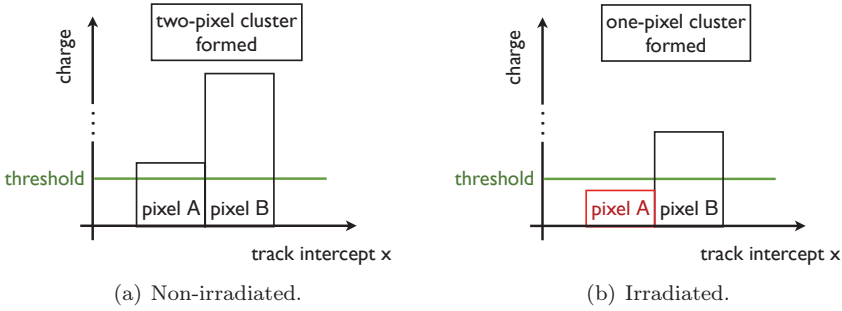


Figure 7.6: Dependence of cluster formation on the amount of charge collected at a given position. For a non-irradiated sensor (a) the formation of two-pixel clusters is more probable and Hamamatsu (b) sensor .

in order to cross the threshold of 1000 e^- and form a two-pixel cluster. For an irradiated sensor operated at 1000 V , the Landau MPV is 7500 e^- according to Figure 7.4. Since at the same position x_s charge sharing is the same for the two sensors, for a charge deposition of 7500 e^- the amount of charge collected by pixel B will not be larger than the threshold ($7\% \text{ of } 7500 \text{ e}^- < 1000 \text{ e}^-$). As a result only pixel B will register a hit therefore an one-pixel cluster is formed. The low signal yield and the effect of the threshold need to be taken into account when studying the cluster size distribution and cluster formation in an irradiated sensor.

An additional factor that contributes to the formation of one-pixel clusters is the effect of the drift time. According to [37], the profile of the diffusion follows a gaussian distribution where its variance σ_d grows with the square root of the drift time t_{drift} of a single electron. In the depleted region of the sensor, t_{drift} is influenced by the electric field. The non-irradiated and irradiated DuT sensors have average electric fields of $8,000 \text{ V/cm}$ and $50,000 \text{ V/cm}$, respectively. For a non-irradiated fully depleted $200 \mu\text{m}$ thick sensor operated at 160 V , the time needed for a single electron to drift from the backplane to the pixel electrode is about 3.2 ns . For an irradiated sensor operated at 1000 V , the drift time of a single electron is about 2 ns . Since $\sigma_d \propto \sqrt{t_{\text{drift}}}$, in the non-irradiated sensor diffusion is larger than in the irradiated sensor by a factor of 1.3 . The combined effects of lower signal yield and shorter drift time lead to the formation of one-pixel clusters in a larger fraction of the pixel for an irradiated sensor.

7.7 Grazing angle measurements

Studying the depletion depth profile of irradiated sensors helps to understand the details of the charge collection process. This profile can be studied by

generating a known amount of charge at a certain depth in the sensor while measuring the detector response. A commonly used technique makes use of infra-red light with the sensor illuminated from the side [70]. The drawback of this technique is that one cannot probe the center pixels of a large pixel matrix (like for the sensors on the Timepix3 chips) due to the small mean free path of the infra-red light³. In addition, the point where the photons interact and liberate the charge carriers is not precisely known. The method used in this manuscript instead makes use of minimum ionizing particles and is known as the grazing angle technique [71].

7.7.1 Grazing angle setup

In this technique the sensor is rotated with respect to the beam as depicted in Figure 7.7. The incoming particle traverses multiple adjacent pixels and forms long tracks. The path length in each pixel is the same except for the first and last pixel on the track. Knowing the angle of incidence (θ), the pixel pitch (p) and the number of hit pixels (N), the information from a pixel $N(i)$ is assigned to a certain depth $d(i)$ using the formula:

$$d(i) = \frac{p \times N(i)}{\tan(\theta)} \quad . \quad (7.2)$$

A particle traversing a sensor with a thickness $t = 200 \mu\text{m}$ and a pixel pitch of $p = 55 \mu\text{m}$ at $\theta = 85^\circ$ with respect to the beam yields a value of $N \approx 42$. According to Eq. (7.2) the depth of the interaction can be determined with a step size of $4.8 \mu\text{m}$. In reality, the number of pixels hit varies due to a number of factors as will be discussed in Section 7.7.3.

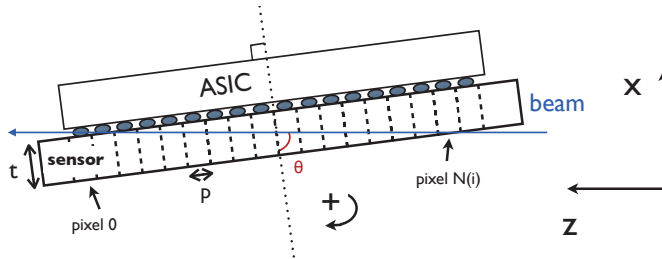


Figure 7.7: Illustration of the grazing angle technique in the XZ plane (top view of the sensor).

³Although different wave lengths can be used to probe deeper in the sensor bulk, focusing the laser in a pixel is difficult.

7.7.2 Thickness calculation

The accuracy of the grazing angle technique can be extracted by calculating the sensor thickness⁴ defined as t . Solving Eq. (7.2) for N gives:

$$N(\theta) = \frac{\tan(\theta) \times t}{p} \quad . \quad (7.3)$$

The most probable cluster length is measured at different grazing angles and plotted in Figure 7.8 for one of the 200 μm thick Hamamatsu sensors, S6. The systematic offset from the rotation is 0.2° and the cluster size error is 1 pixel⁵. The nominal thickness of the sensor and the angle offset can be extracted from a fit to the data using Eq. (7.3). The calculated thickness ($193 \pm 14 \mu\text{m}$) is in good agreement with the nominal thickness of the sensor.

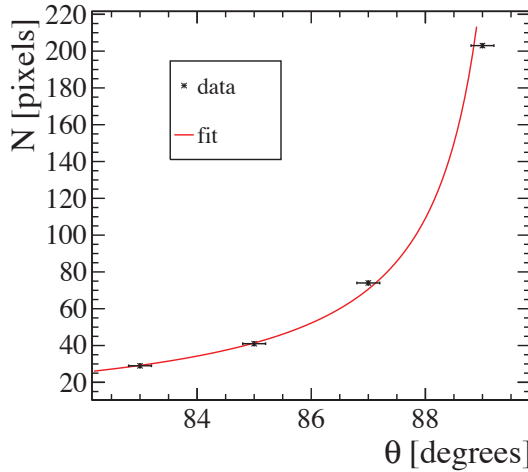


Figure 7.8: Calculating the sensor thickness and the angle offset using the grazing angle technique in the case of a 200 μm thick sensor from Hamamatsu.

For all non-irradiated sensors, the thickness calculation using the grazing angle technique showed no deviation from the nominal thickness as presented in Table 7.3 illustrating that the sensors are indeed fully depleted. Taking into account the fit errors, the largest error (15 μm) is chosen as the thickness error.

⁴A precise measurement of the sensor thickness with metrology was not performed.

⁵In the measurement of the number of hit pixels N in Eq. (7.3), 1 pixel was subtracted.

Table 7.3: Calculated thickness of non-irradiated sensors tested.

Assembly	S6	S20	S23	S33
nominal thickness [μm]	200	200	200	150
thickness from fit [μm]	193 ± 14	197 ± 15	209 ± 15	157 ± 10

7.7.3 Data selection

For all grazing angle data, the sensors were rotated at a large angle around the y-axis (see Figure 7.7) and at a small angle around the x-axis estimated to be 1.36° . The path length of a track in the sensor is expressed in units of adjacent columns. Similarly, the width of the track is expressed in units of adjacent rows. For the grazing angle set up, the projected cross section of the sensor is smaller compared to the perpendicular set up. The time duration of each Run was adjusted to ensure that the number of tracks in the DuT is of the same order of magnitude as in the charge collection and diffusion studies.

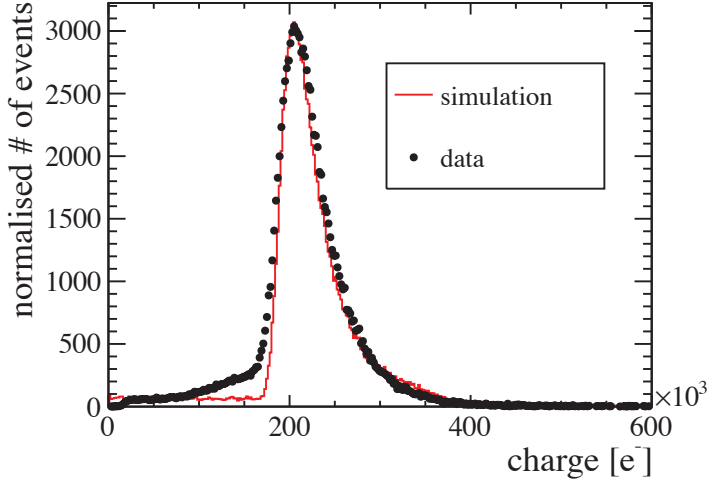
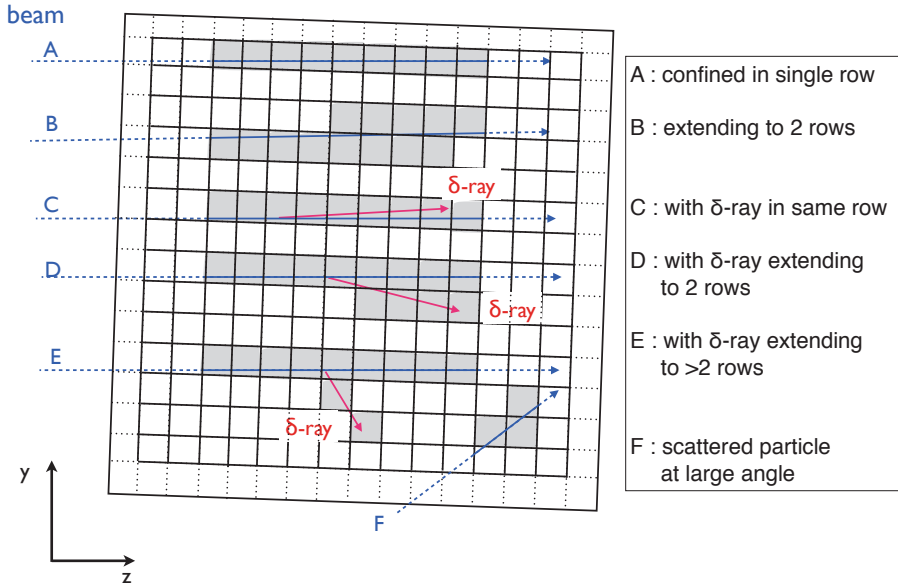
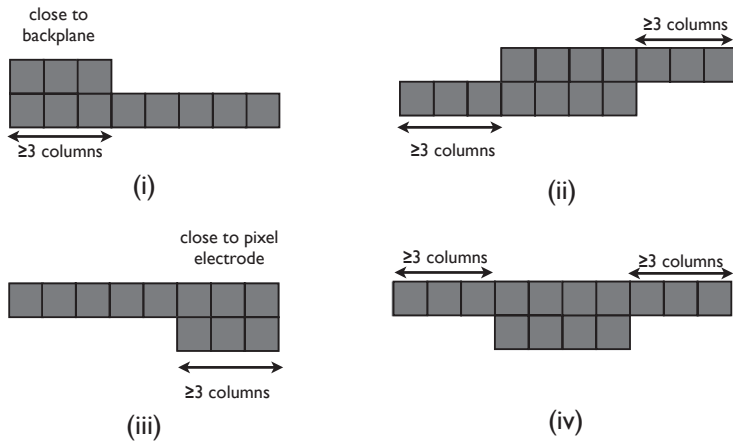


Figure 7.9: Charge distribution in a 200 μm thick sensor (S6) set at 85° . The peak positions and width of the simulated charge distribution from GEANT4 (red solid line) are in fair agreement with the peak positions and width of the data (black circles).

Before looking at the different types of tracks in the sensor, the charge collected in a non-irradiated sensor at the grazing angle configuration is examined. The charge distribution of all clusters formed in a 200 μm thick sensor set at 85° is plotted in Figure 7.9. For comparison the same configuration is simulated in GEANT v4.9.5 and superimposed to the data. The peak positions and the widths of the two distributions are in fair agreement. Any difference is



(a) Track types at grazing angles, viewed from the YZ plane (side view of the sensor). The pixels hit by the beam (blue) or a δ -ray (red) are marked as grey.



(b) Tracks extending to two rows with the row crossing occurring: (i) close to the backplane, (ii) in the middle of the sensor, (iii) close to the pixel electrode and (iv) in the middle of the track. The most common tracks are these of type (ii).

Figure 7.10: Different tracks types at grazing angles.

due to the fact that various chip and sensor mechanisms, like the effect of the threshold and charge sharing, were not taken into account in the simulation.

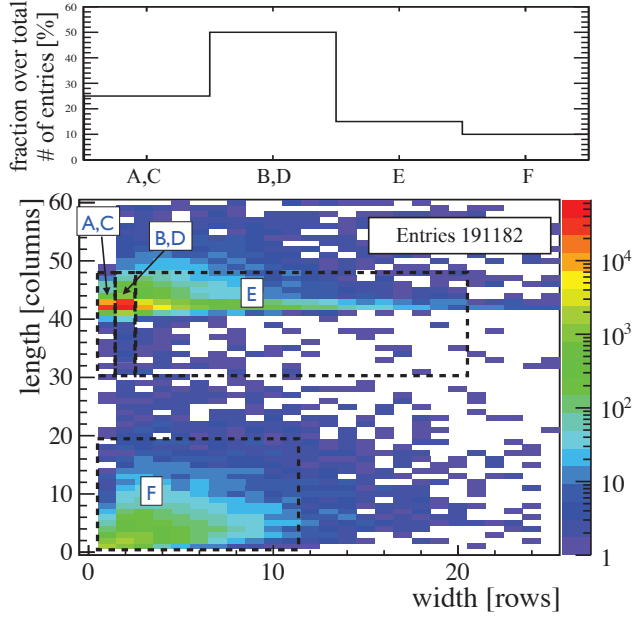
A couple of effects influence the track length. One of these effects is charge sharing which is more likely to occur at the boundaries of a pixel or when electrons⁶ drift from deeper in the bulk. Another frequent phenomenon that will increase the number of pixels hit is the creation of δ -rays. The most common types of tracks formed by taking into account the previous effects are depicted in Figure 7.10(a). These are tracks:

- confined in one row (particle A)
- extending to two rows (particle B)
- releasing a δ -ray in the same row (particle C)
- releasing a δ -ray that extends to two rows (particle D)
- releasing a δ -ray that extends to more than two rows (particle E)
- formed from scattered particles intercepting the sensor at an angle smaller than the grazing angle (particle F)

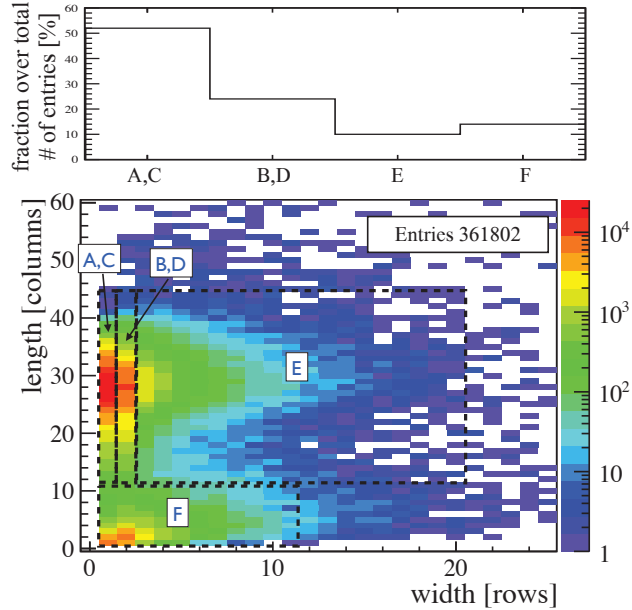
The distribution of length versus width for tracks formed in a non-irradiated sensor operated at 160 V and set at a grazing angle of 85° is shown in Figure 7.11(a). The majority of tracks have a length equal to 42 and a width ≤ 2 . These tracks are of type A, B, C and D. Tracks of type A and C have a width equal to 1 while tracks of type B and D have a width equal to 2. Tracks of type E have a length about 42 but extend to more rows. Tracks of type F appear as a separate smaller distribution having a smaller length and width than tracks of the other types. An indication of a δ -ray is a larger energy deposition per track segment compared to the theoretical MPV in that track segment. A cut in the energy deposition per track segment to distinguish between tracks containing δ -rays and tracks with no δ -rays (track type A from C and track type B from D) was not applied to avoid biasing the energy loss distribution of the tracks.

Tracks with a width of 2 (types B and D) can be further categorised. The most common tracks extending to two rows are depicted in Figure 7.10(b). If the double row group of pixels is within 3 columns from the first (last) pixel then the row crossing occurs close to the pixel electrode (backplane) that is defined as *type i* (*type iii*). If the double row group of pixels is more than 3 columns away from the first and the last pixel, the row crossing occurs in the middle of the sensor and the track is defined as *type ii*. A last category includes tracks in which the double row group of pixels is more than 3 columns away from the first and the last pixel but the majority of the pixels are in one

⁶For all assemblies tested, electrons give the major contribution to the induced currents in the pixel electrodes. This is not true for depths close to the pixel electrodes where electrons cannot induce large currents due to their short drift distance.



(a) Non-irradiated S23 operated at 160 V.



(b) Irradiated S22 operated at 1000 V.

Figure 7.11: Distribution of the number of columns versus the numbers of rows for tracks in non-irradiated S6 operated at 160 V (a) and irradiated S22 operated at 1000 V (b) set at a grazing angle of 85° . The areas in the dashed lines correspond to the track types defined in Figure 7.10.

row. This track is defined as *type iv* and it is an evident case of a δ -ray. More than 85 % of the tracks with a width of 2 are of type (ii) .

The distribution of length versus width for tracks formed in an irradiated sensor at the same grazing angle is shown in Figure 7.11(b). The most probable length is about 10 columns smaller than the length of tracks in the non-irradiated sensor indicating that not all of the charge liberated deeper in the bulk of the irradiated sensor is collected. The irradiated sensor in this case is operated at a bias voltage of 1000 V. Due to the high electric field in the sensor (> 60 kV/cm), the velocity of the charge carriers is higher compared to the velocity of the charge carriers in the non-irradiated sensor. The higher velocity corresponds to a shorter collection time. Hence, charge carriers diffuse less and as a result the majority of tracks are contained in a single row (track type A or C). The fraction of track type F is larger for the irradiated sensor. These additional tracks are formed from particles produced from the decay of radioactive elements in the irradiated assembly.

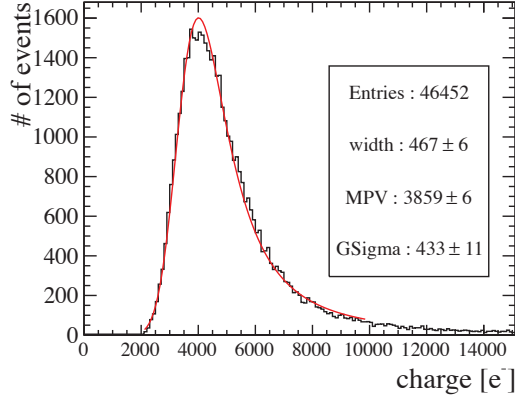
Opposed to the charge sharing and δ -ray creation that increase the number of pixels hit, N becomes smaller if the amount of charge deposited in a pixel is below threshold. The feature of the clustering algorithm described in Section 5.2 that searches for hits beyond adjacent pixels is used to bind segmented tracks and include them in the data selection.

All tracks except tracks of type F are considered for the analyses. The track selection is based on a lower cut in length. For the non-irradiated sensors tracks with length >30 are considered while for the irradiated sensors tracks with length >11 are selected. An additional selection is applied in case of tracks extending to two rows (track types B and D). For these tracks, only the ones for which the row crossing occurs in the middle (type ii) are considered.

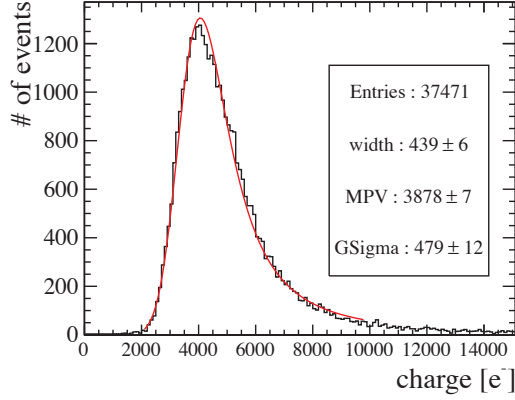
7.7.4 Collected charge profile of the sensor

Since the Timepix3 ASIC measures the ToT and ToA, a simultaneous measurement of the charge deposition and the charge drift time on each pixel is made. Using this feature of Timepix3, the collected charge and time to threshold as function of depth of the sensor can be measured.

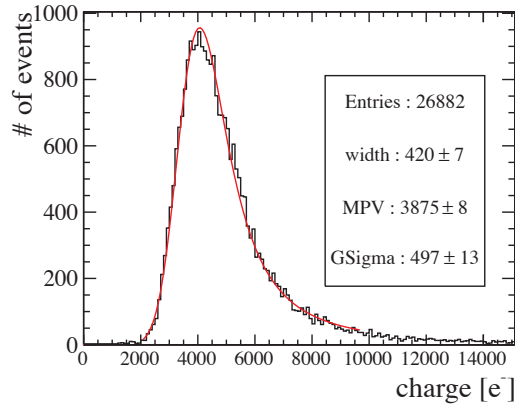
To measure the collected charge profile, each pixel hit from a track formed in the sensor is assigned to a certain depth using Eq. (7.2). The distribution of the charge collected at a certain depth bin is fitted with a Langaus. Only distributions with >1000 entries are taken into account in order to make a reliable fit.



(a) Close to the pixel electrode (20 μm depth).



(b) At the middle of the sensor (100 μm depth).



(c) Close to the backplane (180 μm depth).

Figure 7.12: Charge distribution fitted with a Langaus at (a) 20 μm, (b) 100 μm and (c) 180 μm depth of the non-irradiated 200 μm thick sensor (S6) operated at 160 V.

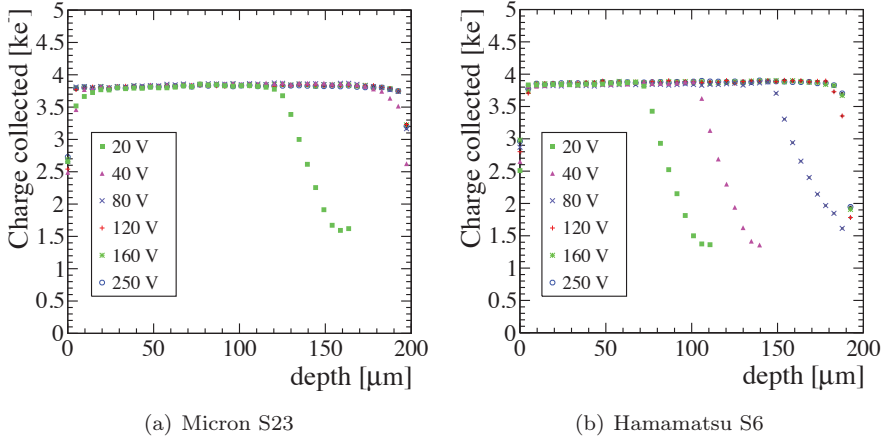


Figure 7.13: Collected charge profile of the 200 μm thick non-irradiated Micron (a) and Hamamatsu (b) sensor .

Non-irradiated sensors

The charge distributions close to the pixel electrode, at the middle of the sensor and close to the backplane are presented in Figure 7.12. The most probable value as a function of depth for the 200 μm thick Hamamatsu and Micron sensors at different bias voltages is plotted in Figure 7.13. The pixel electrode is at 0 and the backplane at 200 μm . The depletion in an n -on- p sensor starts from the pixel electrode as described in Section 4.4.1. When a non-irradiated sensor is operated at voltages above the full depletion voltage, all the deposited charge will be collected. This explains the constant amount of charge collected when the sensors are fully depleted ($V_{bias} > 40$ V for S23 and $V_{bias} > 140$ V for S6) in Figure 7.13. The path traversed by the particle in each pixel when the sensor is tilted at 85° with respect to the beam is 55.2 μm , which is almost equal to the pixel pitch. A minimum ionizing particle is expected to create about $72\text{ e}^-/\text{h pairs per } \mu\text{m}$ [37], therefore the most probable charge deposited in each pixel is 3960 e^- . The amount of liberated charge is measured to be $3850 \pm 100\text{ e}^-$ where the error is from the calibration as explained in Section 7.2. The amount of charge collected from the first and the last pixel is lower because the path traversed by the particle in those edge pixels is on average smaller than in a center pixel.

In case of the Micron sensor (Figure 7.13(a)) the amount of charge collected at 20 V bias is constant up to about 120 μm . Beyond that depth the amount of charge collected drops almost linearly. The same behaviour occurs for the Hamamatsu sensor (Figure 7.13(b)), but at a higher voltage. The depth region in which the amount of charge collected is lower corresponds to the non-

depleted region of the sensor. The amount of charge collected from this region decreases up to a point where it is equal to about 1500 e^- and the detector no longer registers a hit. Although the threshold is set at 1000 e^- , the collected charge does not go down to that value. The reason that no charge is collected between 1000 e^- and 1500 e^- is due to the time limit in the integration of the signal. If the time required to integrate a signal is too long, then it will not be registered as a hit. The time needed for charge liberated deep in the non-depleted region to diffuse and then drift towards the pixel electrodes is larger than that of charge liberated in the depleted region.

For bias voltages below the full depletion voltage ($V_{bias} < 40\text{ V}$ for S23 and $V_{bias} < 140\text{ V}$ for S6) the minimum amount of charge collected flattens for about $10\text{ }\mu\text{m}$. As can be seen in the number of hits per depth bin plot of S6 at 20 V in Figure 7.14, for depths beyond $100\text{ }\mu\text{m}$ (where the saturation occurs) the number of entries is less than half compared to the maximum number of entries. This will result in enhancing the tails of the Landau distributions influencing the MPV. Because of these low number of entries the fits are biased and reach an equilibrium value around 1500 e^- .

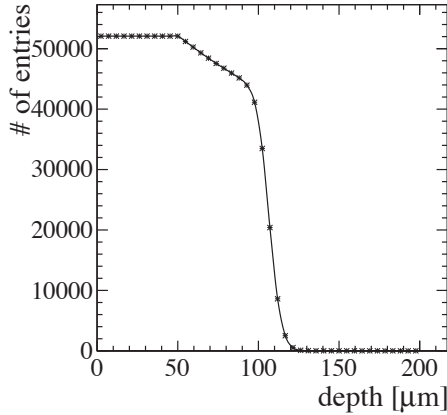


Figure 7.14: Number of entries in the profile histogram of S6 at 20 V .

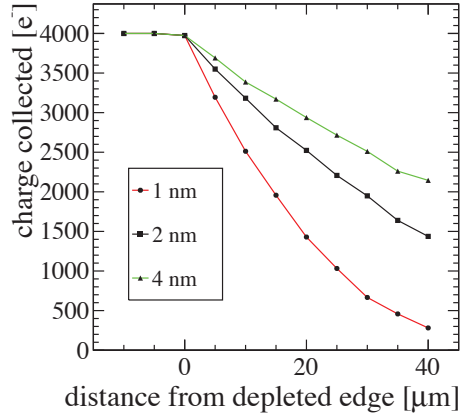


Figure 7.15: Simulation of charge collected in the non-depleted region of a $200\text{ }\mu\text{m}$ thick sensor for values of the mean free path of electrons λ_e in Si equal to 1, 2 and 4 nm.

In principle, charge liberated in the non-depleted region will not drift towards the electrodes due to the absence of the electric field and will hence not be collected. However, charge carriers diffuse independently of the drift field presence. According to [72] electrons and holes liberated in the non-depleted region close to the boundaries of the depleted region, may diffuse towards the depleted region and subsequently drift to the electrodes. This effect is

known as charge migration. The collection of the charge carriers liberated in the non-depleted region is simulated in a dedicated Monte-Carlo. A charge cloud (consisting of the most probable number of charge carriers liberated in 55 μm of Si) is liberated at different distances from the edge of the depleted region. In Figure 7.15, the collected charge is plotted as a function of the distance from the depleted edge assuming a maximum charge collection time of 100 ns. The amount of collected charge drops linearly as a function of the distance from the edge of the depletion region. Different values of the mean free path of electrons λ_e in silicon, corresponding to the electron energy range of 50-2000 eV [88], are plotted in order to study which value describes the data best. For a value of $\lambda_e = 2$ nm the slope, which represents the amount of charge collected per distance, agrees well with the slope of S23 and S6 in Figure 7.13.

Irradiated sensors

The effects that reduce the amount of charge collected in an irradiated sensor are charge trapping and the fact that the sensor is only partially depleted. The grazing angle measurements provide us additional information about how these effects contribute to the collected charge.

The charge distributions at three different depths in the irradiated Hamamatsu sensor (S22), operated at 1000 V, are presented in Figure 7.16. The charge distribution at 150 μm has an order of magnitude less hits therefore a larger statistical uncertainty compared to the other two histograms. Looking at the number of entries per depth bin of S22 at 1000 V in Figure 7.17(a), the number of entries decreases significantly beyond 100 μm . This is due to the fact that charge drifting from deep in the sensor has a high probability to be trapped as will be discussed later in this section. For depths >130 μm the number of entries is less than half of the maximum entries therefore the corresponding charge distributions are biased.

The collected charge profile for S22 is plotted in Figure 7.17(b) for different bias voltages. For the irradiated S22 the depleted region does not reach the backplane even when the sensor is operated at 1000 V. The shape of the collected charge is similar at each applied bias voltage. The amount of charge collected slightly increases as a function of depth until it reaches a maximum. Beyond this point, the amount of charge collected decreases. At 1000 V and for depths >130 μm the amount of charge collected flattens. As explained using Figure 7.17(a), this flattening is related to the low number of entries per depth bin similar to the case of the non-irradiated sensor.

To understand the charge profile in the irradiated sensor the effect of charge trapping needs to be taken into account. As discussed in Section 4.5.1 the trapping rate of electrons and holes is not the same. Holes drifting to the

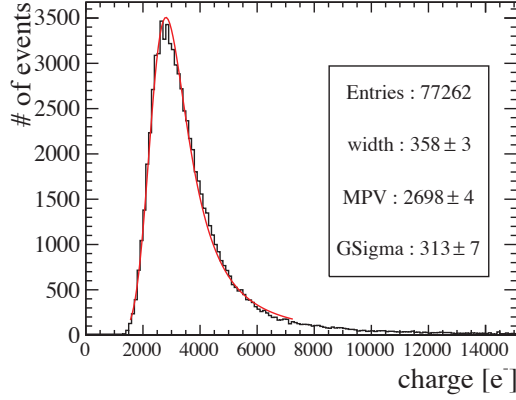
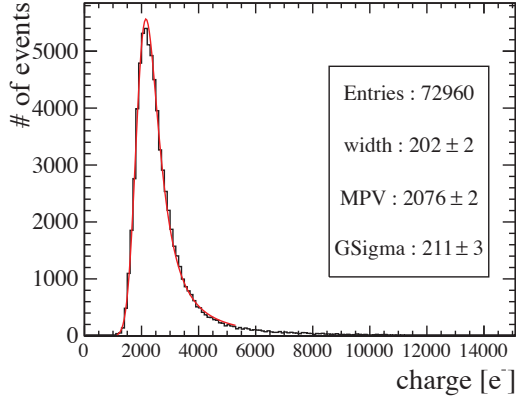
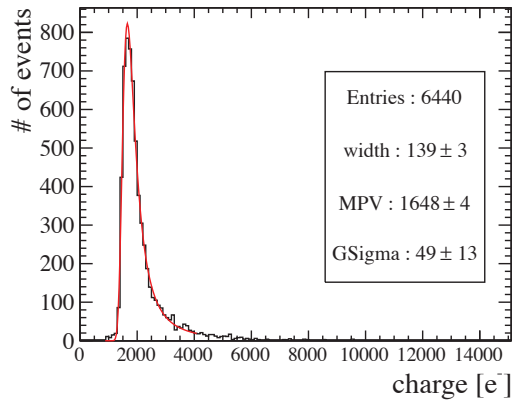
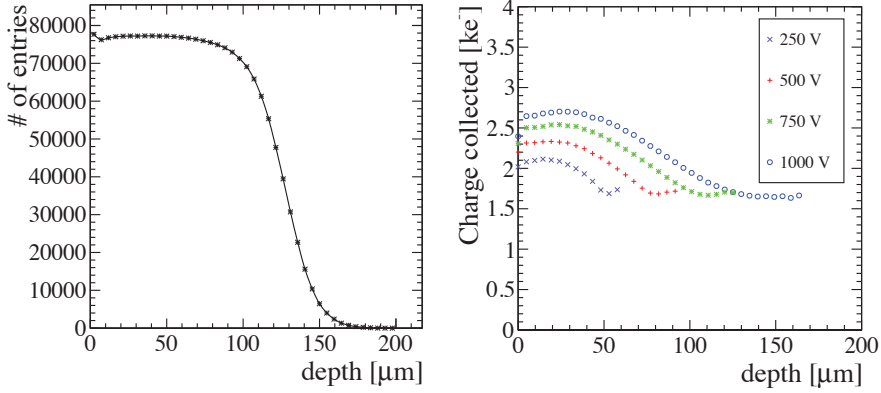

 (a) Charge distribution at 35 μm depth.

 (b) Charge distribution at 90 μm depth.

 (c) Charge distribution at 150 μm depth.

Figure 7.16: Charge distribution fitted with a Langaus at (a) 35 μm , (b) 90 μm and (c) 150 μm depth of an irradiated 200 μm thick sensor (S22) operated at 1000 V.



(a) Number of entries of S22 profile at 1000 V. (b) Collected charge profile at different bias voltages.

Figure 7.17: Collected charge profile of a 200 μm thick irradiated sensor from Hamamatsu (S22).

backplane have a higher probability to be captured than electrons drifting towards the pixel electrode. According to [73], the effective trapping rate can be described by the formula:

$$q(d) = q(0)e^{-d/(v_{\text{sat}} \cdot \tau_{\text{eff}})} \quad (7.4)$$

where $q(d)$ the amount of charge drifting at depth d , $q(0)$ the amount of charge initially deposited, v_{sat} the saturated velocity⁷ and $1/\tau_{\text{eff}}$ the effective trapping rate in ns^{-1} defined in Eq. (4.25). At the depleted region close to the backplane (between 70 and 155 μm) electrons contribute more to the collected charge since holes drift for a short distance. Fitting Eq. (7.4) to the collected charge profile of the irradiated S22 operated at 1000 V (Figure 7.18) and excluding the depth range with the low number of entries, the calculated effective trapping rate for electrons is found to be $1/\tau_{\text{eff},e} = 0.65 \pm 0.12 \text{ ns}^{-1}$.

The same procedure is repeated for the other irradiated Hamamatsu sensors, S15 and S17 and the results are summarised in Table 7.4. The results of the S15 sensor are compatible with reports at similar fluences [74]. Measurements of the effective trapping rate in neutron irradiated sensors at fluences beyond $4 \times 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$ have not been reported in literature. Extrapolating the effective trapping rate from lower fluences as reported in [73] does not agree well with the data giving a trapping rate larger than the measured rate. A more elaborate model than that of Eq. (7.4), which takes also the hole

⁷As a consequence of the high electric field in the sensor the charge drift velocity is constant (velocity saturation).

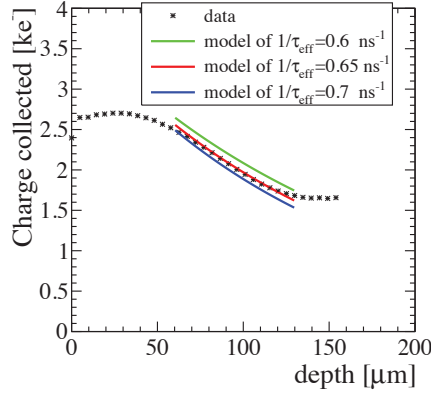


Figure 7.18: Collected charge profile of S22 at 1000 V fitted with Eq. (7.4). The depth region with the low number of entries ($>130 \mu\text{m}$) is not included in the fit.

contribution into account, needs to be implemented to describe the collected charge profile of the irradiated sensor.

Table 7.4: Effective trapping rates of the irradiated Hamamatsu sensors.

Assembly	S15	S17	S22
Fluence [$10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$]	4	8	8
Measured $1/\tau_{\text{eff}} [n\text{s}^{-1}]$	0.51 ± 0.14	0.61 ± 0.12	0.65 ± 0.12

For the $150 \mu\text{m}$ thick irradiated Micron sensor, the grazing angle measurements were taken with the preamplifier discharging faster (high Ikrom value). As a result the entire ToT distributions⁸ have <5 counts. The resulting small dynamic range of the measured ToT values provides only a very coarse measurement of the collected charge therefore the charge profile of the irradiated Micron sensor is not studied in detail.

Track type dependence

As described in the end of Section 7.7.3, the selection criteria for the non-irradiated sensors include tracks with length >30 and for the irradiated sensors tracks with length >11 . However, according to the distributions in Figure 7.11 the width of the selected tracks varies. In a track with a width >1 , the charge liberated at the boundaries of two rows is shared between the pixels in these adjacent rows. In order to study how charge sharing influences the collected charge profile, these profiles are measured separately for tracks extending to

⁸A typical calibration curve was presented in Section 4.3.4.

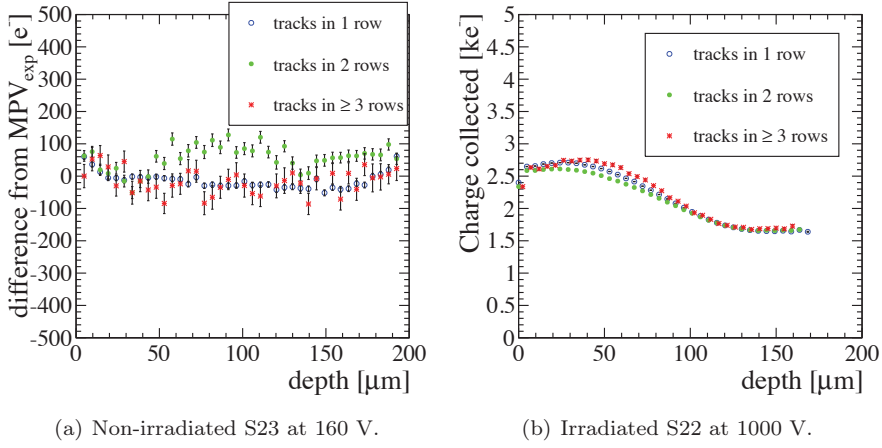


Figure 7.19: Collected charge profile for different track types for a non-irradiated (a) and an irradiated (b) sensor.

one, two and ≥ 3 rows for a non-irradiated and an irradiated sensor (Figure 7.19).

For the non-irradiated sensor (Figure 7.19(a)), the difference from the expected most probable charge deposition is not significant in the order of a $100 e^-$. The error bars represent the uncertainty from the fits. For tracks extending to two rows the difference is less than $100 e^-$ in the depth range of 50–140 μm . This depth range corresponds to the region where the charge liberated from the track registers hits in adjacent rows. The $100 e^-$ difference is within the measurement error calculated by adding the calibration errors of the two pixels in quadrature.

For the 200 μm thick irradiated sensor (S22), the collected charge profiles for the three categories are almost identical except for the depth range of 20–100 μm (Figure 7.19(b)). The average charge collected in the case of tracks extending to two rows is about $150 e^-$ smaller than the average charge collected in the case of tracks confined in one row.

Studying tracks that extend to two rows in more detail provides additional information. The majority of these ($>85\%$) consist of tracks where the row crossing occurs roughly in the middle of the track⁹. The charge distribution of individual, which will be referred to as *single*, pixels from these tracks is plotted in Figure 7.20. The distribution has a minimum of about $1300 e^-$ that indicates an offset compared to the expected threshold value of $1000 e^-$. Additional information on this threshold offset can be found in Appendix A.

⁹These tracks are defined as type (ii) in Figure 7.10(b).

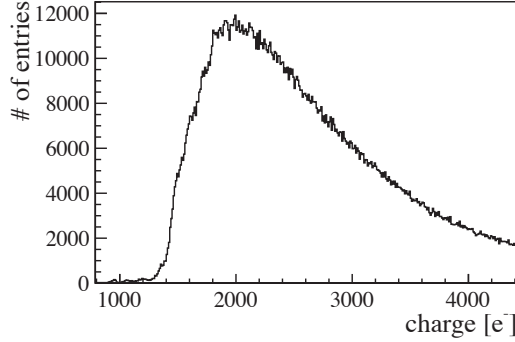


Figure 7.20: Charge distribution of single pixels in track type (ii) in case of the irradiated sensor (S22) set at 85° . The charge distribution has a threshold of 1300 e^- .

The effect of the higher threshold on the pattern of the collected charge profile can be understood by looking at the charge distribution of single row and double row pixels. For every track extending to two rows, pixels in the same row are studied separately from pixels in double rows (Figure 7.21). Most of the hits confined in a single row collect $<2600\text{ e}^-$ as shown in Figure 7.22(a). Adjacent pixels extending to two rows (Figure 7.22(b)) have two characteristics. Firstly, they are located in the depth range of $20\text{--}100\text{ }\mu\text{m}$ due to the cuts imposed in Section 7.7.3. Secondly, the total amount of charge collected is $>2600\text{ e}^-$.

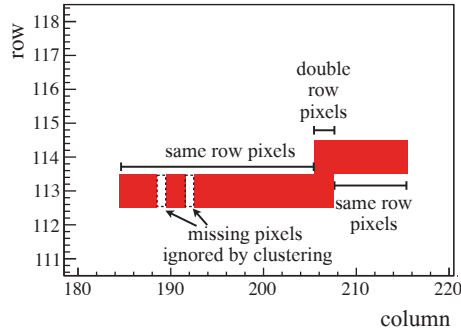


Figure 7.21: Example of a track (type ii) extending to two rows in the $200\text{ }\mu\text{m}$ thick irradiated sensor (S22) set at 85° . The intermediate missing pixels are added from the clustering algorithm.

The fact that the amount of charge collected in adjacent pixels extending to two rows is larger than the charge collected in pixels confined in a single row is due to the threshold. Pixels collecting charge $<1,300\text{ e}^-$ will not be

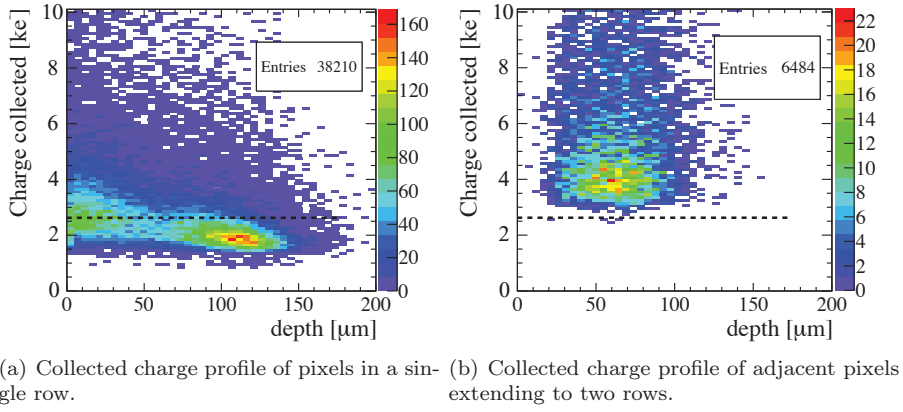


Figure 7.22: Collected charge profile for pixels in a single (a) and adjacent pixels extending to two rows (b) for the irradiated sensor S22 at 1000 V.

activated due to the higher threshold. Hence, the amount of charge collected by adjacent pixels extending to two rows will be at least two times larger than the threshold.

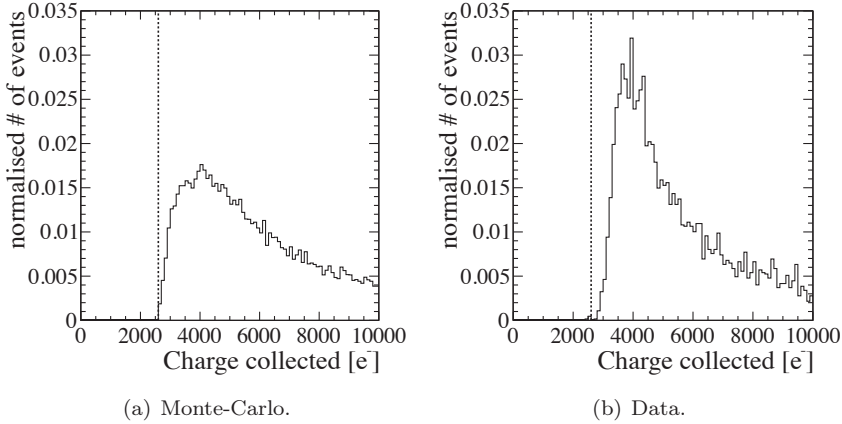


Figure 7.23: Normalised charge distributions of hits in adjacent rows for the irradiated sensor (S22) simulated in a dedicated Monte Carlo (a) and plotted from data (b). The majority of the charge collected is $> 2600 \text{ e}^-$ (dashed vertical line).

The effect of the threshold is reproduced using a dedicated Monte Carlo. Random charge values are generated from Landau distributions with MPVs in the range of 1600–2800 e^- and widths of 100–300 e^- based on the distributions of Figure 7.16. According to the number of entries of each profile in Figure 7.22, this charge is assigned to one-pixel clusters with a probability of

0.85 and to two-pixel clusters with a probability of 0.15. Next, the charge assigned to two-pixel clusters is shared between the two pixels assuming a probability drawn from a uniform distribution. If the charge of each pixel is larger than the threshold value of 1300 e^- , the summed charge is plotted in the distribution of Figure 7.23(a). For comparison, the same distribution from the data (projected from Figure 7.22(b)) is plotted in Figure 7.23(b). Both distributions of Figure 7.23, where each is normalised to the integral of the histogram, peak at about 4000 e^- . The difference in the widths of the distributions is probably due to the assumption that the charge assigned to two-pixel clusters is shared between the two pixels following a uniformly distributed probability. This distribution was used since a theory that describes the charge sharing ratio is not reported in literature. A more detailed model of how charge is shared in a two-pixel cluster is not studied.

7.7.5 Time to threshold profile of the sensor

Besides the charge distribution, the charge collection time has also been investigated. Each pixel hit on the DuT gets a timestamp (t_{hit}) as described in Section 5.2.1. This timestamp indicates the time the hit is registered with respect to the beginning of a Run. A track intercepting the telescope will liberate charge almost instantaneously in both the telescope and the DuT sensors. Since the DuT shares the same clock with the telescope planes, the time needed from the moment the charge is liberated to drift and cross the threshold in the DuT can be calculated by subtracting the time the track intercepted the telescope¹⁰ t_{track} from t_{hit} . The time difference $t_{\text{hit}} - t_{\text{track}}$ will be referred to as *time to threshold*.

The time to threshold of a pixel hit (t_{hit}) is a combination of two factors: the drift time due to the presence of the electric field (t_{drift}) and the time needed for the integrated charge to cross the threshold (t_{int}). In addition, a number of small factors may contribute to t_{hit} . If the charge is liberated in the non-depleted region of the sensor, the extra time needed for the charge to diffuse to the depleted region will add to t_{drift} . If the amount of charge is small, additional time will be introduced due to timewalk (t_{walk}) as described in Section 4.3.5. In this section the effect on time to threshold from t_{drift} , t_{int} and t_{walk} is studied for the non-irradiated and irradiated sensors.

The timewalk effect can be visualised by plotting $t_{\text{hit}} - t_{\text{track}}$ as a function of the charge collected per pixel hit. This is shown in Figure 7.24 for the non-irradiated Micron S23, Hamamatsu S6 sensors and the irradiated Hamamatsu S22 sensor¹¹. The time to threshold is different for the three sensors beyond 2500 e^- due to the different electric fields in the sensors. Although

¹⁰The calculation of t_{track} is described in Section 5.3.2.

¹¹The data is from the grazing angle measurements in contrast to Figure 4.11 in which the data is taken with the DuT perpendicular to the beam.

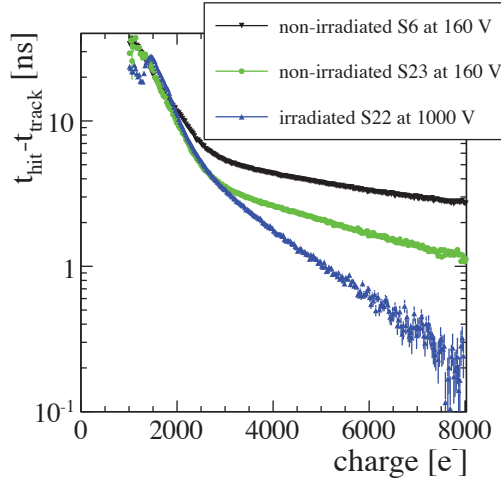


Figure 7.24: Time to threshold for irradiated and non-irradiated sensors set at grazing angles. For charges $>3000 e^-$ the average timewalk of all assemblies is <5 ns.

the two non-irradiated sensors are operated at the same bias voltage, the different doping level (as shown in Table 7.1) influences the shape of the electric field according to Eq. (4.5). For the irradiated sensor the time to threshold is shorter compared to the non-irradiated sensors due to the higher electric field. For charges $>3000 e^-$ the average timewalk of all assemblies is <5 ns. Therefore, for these amounts of charge collected timewalk will not contribute significantly to the time to threshold.

Non-irradiated sensors

Similar to Section 7.7.4 where the depth dependence of the collected charge was studied, the time to threshold is studied as a function of depth. In Figure 7.25 the time to threshold profiles of the non-irradiated 200 μm Micron S23 and Hamamatsu S6 sensors are plotted. When the sensors are fully depleted the time to threshold is <10 ns along the whole sensor depth. The average time to threshold in the depleted region is about 5 ns.

The depth regions with the strong increase of the charge collection time (>20 ns for S23 at 20 V and S6 at 20 V) correspond to the non-depleted regions of the sensors. The increase of the time to threshold is due to the fact that charge liberated beyond this depths needs additional time to diffuse towards the depleted region (before it drifts towards the electrodes and induces a signal high enough to cross the threshold).

In a fully depleted non-irradiated sensor, $t_{\text{hit}} - t_{\text{track}}$ is influenced by both the collection time t_{int} and timewalk t_{walk} . At depths close to the pixel electrodes,

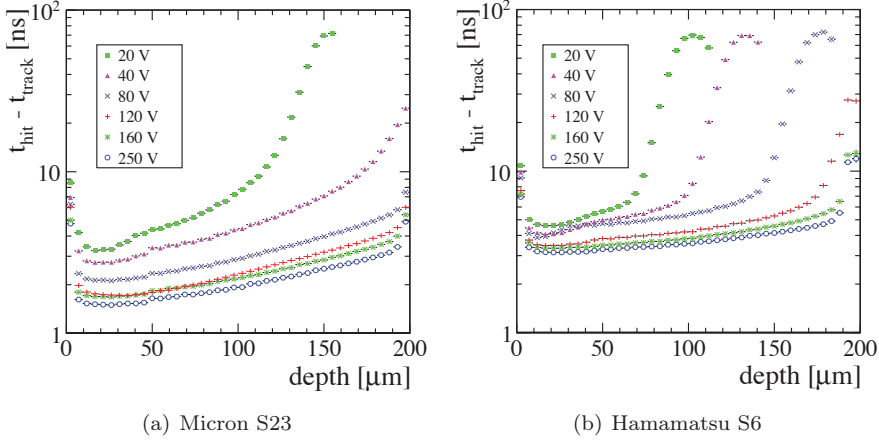


Figure 7.25: Time to threshold versus depth for the 200 μm thick non-irradiated Micron (a) and Hamamatsu (b) sensor.

electrons will drift for a short distance until being collected and therefore barely contribute to the induced charge. Hence the induced current is mainly due to the motion of the slower holes. In a similar way, at depths close to the backplane holes will drift for a short distance so the induced current is largely due to the drift of electrons. This information is crucial to understand the shape of the measured profile.

The time to threshold profile is simulated for the sensors of the same geometry, type and doping as S23 and S6 operated at 120 V and 160 V respectively. The electric and weighting fields are simulated numerically using WEIGHT-FIELD [89]. The fields are then used to simulate the current induced by the drift of electrons and holes liberated at a certain depth. Subsequently, the time needed for the integrated current to cross the threshold of 1000 e^- at each depth is calculated and superimposed to the data as shown in Figure 7.26. The error in the calculated time, which is due to the assumed uncertainty on the full depletion voltage, is marked by the grey area. A constant offset, which is related to the response time of the discriminator, of 1.6 ns for S23 and 2.3 ns for S6 has been added to the simulations. Overall, the simulation agrees well with the data. Beyond about 100 μm the measured time to threshold becomes larger than the simulated time. This can be due to the fact that the behaviour of the discriminator is not well described by simply adding a constant offset in the simulation curves.

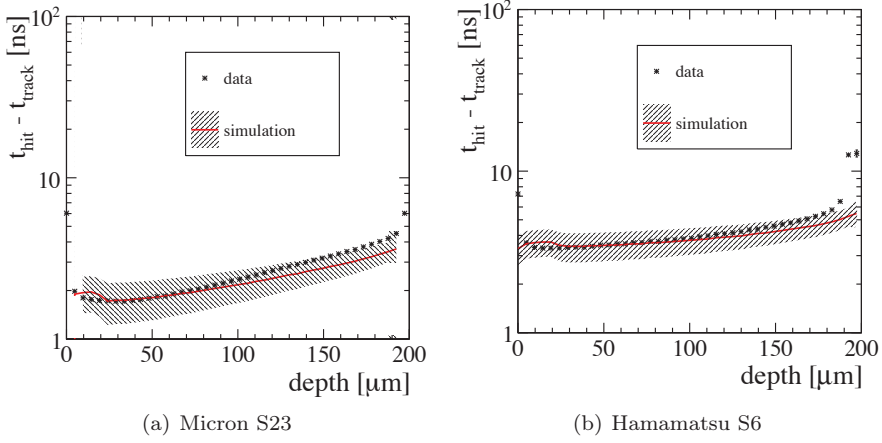


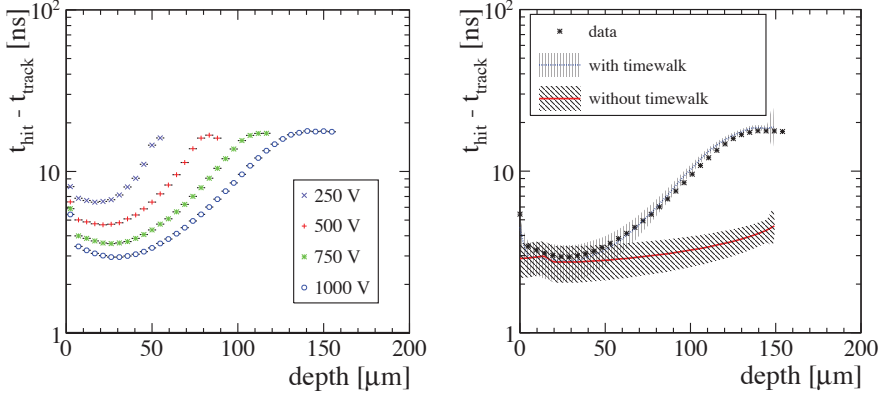
Figure 7.26: Simulation and measured time-to-threshold profile of the non-irradiated 200 μm thick n -on- p sensors: (a) Micron S23 operated at 120 V, (b) Hamamatsu S6 operated at 160 V. The grey area represents the error in the calculated time due to the assumed uncertainty on the full depletion voltage. A constant offset, which is related to the response time of the discriminator, has been added to each simulation curve.

Irradiated sensors

For the operational voltage of the sensor used in the grazing angle measurements, the drift time t_{drift} of the irradiated sensors is shorter than the non-irradiated ones. The depletion width of S22 at 1000 V is about 160 μm (as seen in Figure 7.17(b)) and the depletion width at 250 V is about 55 μm resulting in average electric fields of 66,000 V/cm and 45,000 V/cm, respectively. At these high fields, the t_{drift} of a single electron from the edge of the depleted region is <0.5 ns assuming that the velocity is saturated and no charge trapping takes place.

The time to threshold profile of the irradiated Hamamatsu sensor S22 is presented in Figure 7.27(a). The time to cross the threshold is <20 ns independent of the applied bias voltage. Due to the effect of charge trapping, no charge is collected from the non-depleted region of the irradiated sensor (in contrast to the non-irradiated sensor where charge is collected also from the non-depleted region). The smaller time to threshold range compared to the non-irradiated sensors is a result of the shorter charge collection time in the irradiated sensor and the fact that charge is not collected from the non-depleted region.

To understand the pattern of the time to threshold profile, the time to threshold is simulated and superimposed on the data of the irradiated S22 op-



(a) Time to threshold profile for the 200 μm thick irradiated Hamamatsu sensor S22. (b) Simulation of the time to threshold profile for a 200 μm thick n -on- p sensor operated at 1000 V superimposed on data from Hamamatsu S22 operated at the same bias voltage. The grey area represents the error in the calculated time due to the assumed uncertainty on the full depletion voltage.

Figure 7.27: Time to threshold profile of a 200 μm thick n -on- p sensor.

erated at 1000 V (Figure 7.27(b)). The error in the calculated time (due to the assumed uncertainty on the full depletion voltage) is marked by the grey area. A simulation of the time to threshold based on Ramo's theorem (red line) [42], as done in the case of the non-irradiated sensor, fails to describe the data. According to the collected charge profile of S22 in Figure 7.17(b) the charge collected at each depth is $<2800 e^-$. For these amounts of charge timewalk should not be neglected according to Figure 7.24. The time to threshold is well described by the simulation including the average timewalk as function of charge as shown in Figure 7.27(b).

7.7.6 Effective doping concentration

Based on the width of the depleted region as a function of the bias voltage, a simple model is used to extract the effective doping concentration N_{eff} for an irradiated sensor. More elaborate models, e.g. involving the formation of a double junction in the sensor [75], are not studied in this manuscript.

The data for S22 is plotted in Figure 7.28. The errors represent the uncertainty in depth for the non-irradiated sensors calculated in Section 7.7.2. Fitting Eq. (4.23) to the data, the N_{eff} for the irradiated sensors of Table 7.2 can be calculated. Since measurements of the effective doping concentration in neutron irradiated sensors at these fluences have not been reported,

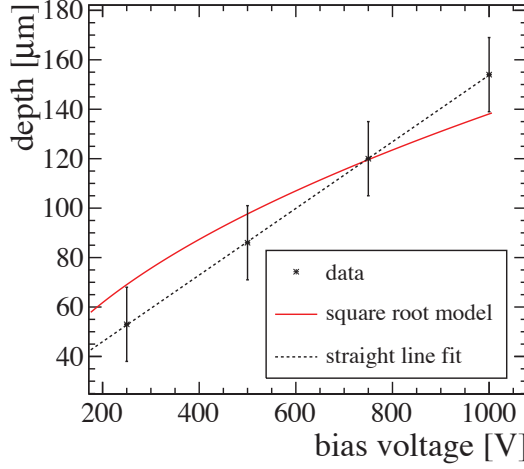


Figure 7.28: Depth as a function of depletion voltage of the irradiated Hamamatsu sensor S22. Data fitted with Eq. (4.23) and with a straight line for comparison.

the expected N_{eff} is predicted by extrapolating the curve in Figure 4.17 for oxygenated float zone silicon (DOFZ). The measured and expected values of N_{eff} for the irradiated sensors are summarised in Table 7.5. Although the poor ToT resolution of the irradiated Micron sensor (S29) did not allow a detailed study of the charge profile of the sensor, it is not an obstacle in calculating its N_{eff} . This is due to the fact that the depth at each bias voltage is based on measuring the track length and not the amount of charge collected.

Table 7.5: Effective doping concentration of the irradiated sensors.

Assembly	S15	S17	S22	S29
Fluence [10^{15} 1 MeV $n_{\text{eq}}/\text{cm}^2$]	4	8	8	8
Measured N_{eff} [10^{13} cm^{-3}]	3.2 ± 0.3	6.9 ± 1.0	6.8 ± 0.9	6.7 ± 0.9
Expected N_{eff} [10^{13} cm^{-3}]	3.1	6.3	6.3	6.3

The measured N_{eff} for all sensors is in fair agreement with the expected value. However, the square root model of Eq. (4.23) fails to describe the data accurately. The depletion depth appears to depend linearly on the bias voltage suggesting that the sensor has a resistor-like behaviour.

7.8 Conclusions

Prototype sensors from Hamamatsu and Micron irradiated to the maximum required fluence of 8×10^{15} 1 MeV $n_{\text{eq}}/\text{cm}^2$ have been studied. The maxi-

imum operational voltage is determined by the breakdown region as shown in Figure 7.1(b).

The irradiated sensors can deliver 7000 e^- when operated at 1000 V , as shown in Figure 7.4, hence satisfying the minimum amount of charge collected that is required for the VELO upgrade. The $150\text{ }\mu\text{m}$ thick sensor from Micron collects the same amount of charge as the $50\text{ }\mu\text{m}$ thicker Hamamatsu sensors. This shows that by using a thinner sensor the material budget can be minimised without a loss in the signal yield.

The collected charge and time to threshold profile of the sensors are obtained by performing measurements at grazing angles. Using the grazing angle technique, the maximum thickness error is found to be $15\text{ }\mu\text{m}$. In addition, the depth in the sensor can be measured in bins of $5\text{ }\mu\text{m}$.

The collected charge profile in a fully depleted non-irradiated sensor is uniform (Figure 7.13) in contrast to the collected charge profile in an irradiated sensor (Figure 7.17(b)). In an irradiated sensor, charge collection is influenced by charge trapping and the fact that the sensor is not fully depleted even at the maximum operational bias voltage (1000 V). The measured effective trapping rates $1/\tau_{eff}$ for electrons, the charge carriers that give the major contribution to the signal of the tested irradiated sensors, agree with other results reported in literature [74].

The time to threshold profile in a depleted non-irradiated sensor can be described by using Ramo's theorem of induced currents (Figure 7.26). However, for an irradiated sensor set at grazing angles the measured time to threshold contains a contribution from timewalk. After a long wait, the time to threshold profile of an irradiated sensor can be described by taking into account the timewalk effect as shown in Figure 7.27(b).

The effective doping concentration N_{eff} is calculated using a simple model based on the information of the depleted depth. Although the model does not describe the data accurately, the measured values of N_{eff} (Table 7.5) are in fair agreement with the expected values.

The measurements performed in this chapter show that the tested prototype irradiated sensors from Micron and Hamamatsu qualify for the VELO upgrade in terms of charge collection and time of arrival.

7.9 Recommended R&D sensor studies

Based on the testbeam results, a number of effects presented in this work can be further studied. Although these studies strictly speaking are not required for the VELO upgrade, they are interesting from an R&D perspective.

Bias voltage & threshold

Two parameters that influence the charge collection and charge drift time are the bias voltage and the threshold. Measurements of the collected charge and time to threshold profiles should be performed with the sensors operated at different bias voltages to investigate the effect of the electric field on the ToT and ToA of the charge. Additional studies with the assemblies operated at lower threshold values will provide a higher signal yield. The minimum threshold value at which the noise becomes significant and the maximum threshold value at which the hit efficiency is about 100 % can be used as input for the future operation of the silicon sensors.

Diffusion

Another effect that can be studied in further detail is diffusion. Diffusion has been discussed briefly in Section 7.6 where the sensor was placed perpendicularly to the beam. Placing the sensor at grazing angles allows to measure the effect of charge sharing between adjacent pixels in different rows in more detail. As a result, the magnitude of the charge cloud can be described as a function of depth. Similar measurements have been reported with Timepix [76] [45]. However, performing these measurements with the Timepix3 assemblies gives the possibility to study the time to threshold profile of the charge cloud. This is particularly interesting for irradiated sensors where, compared to the non-irradiated ones, the lower amount of charge collected influences cluster formation.

Radiation induced effects

The effects of radiation in the silicon sensor studied in this manuscript, i.e. effective trapping rate and effective doping concentration, can be studied in more detail. The effective trapping rate of electrons has been calculated in Section 7.7.4. However, the effective trapping rate of holes needs to be determined to provide a better understanding of how trapping between the different charge carriers behaves. Regarding the effective doping concentration N_{eff} of the irradiated sensors a more elaborate model, compared to the simple model presented in Section 7.7.6, such as the Hamburg model needs to be studied in order to acquire a more accurate value of N_{eff} . Another effect that needs to be taken into account is the formation of a doubly peaked electric field in a n -on- x type heavily irradiated sensor. The trapping of the mobile charge carriers will produce a net positive (negative) space charge near the p^+ back-plane (n^+ implant). As a result, pn -junctions will be formed in both sides of the sensor (Figure 7.29). This effect, which is described by the so-called double junction model [75], can be studied using the grazing angle measurements.

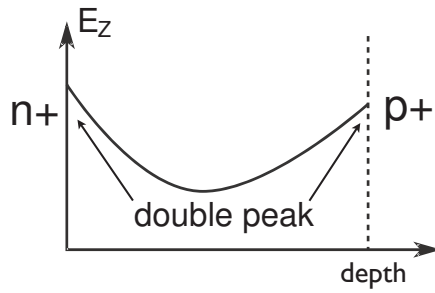


Figure 7.29: Illustration of the double peak of the electric field [75].

The results from this thesis support the decision to start procurement of the sensors for the upgrade. To arrive at an even more detailed understanding of the future behaviour of the sensors, a number of additional tests should be performed.

Chapter 8

Outlook

The pixel detector for the VELO upgrade should be installed before the next long shutdown of the LHC accelerator that is planned from 2019 to 2020. In this thesis we have demonstrated that the design of pixel sensors that will meet the requirements and withstand the harsh conditions expected in Run 3 is possible. Nevertheless, a number of additional studies are required to examine whether the sensors qualify fully for the VELO upgrade .

8.1 Sensor design

The prototype irradiated sensors have a signal yield about 1000 e^- higher than the minimum required signal yield when operated at the benchmark voltage of 1000 V, as discussed in Chapter 7.5. However, the sensors need to meet the requirements imposed in Section 2.1 in the high luminosity environment described in Section 2.2.2.

Resolution & efficiency

The sensors need to have high hit efficiency ($> 99.9\%$) along the whole pixel matrix and close to the physical edge of the sensor. A high hit efficiency at the edge of the sensor is required because, as demonstrated in Chapter 3, the distance from the first active sensor element to the beam contributes significantly to the IP resolution. A small inefficient region effectively leads to short extrapolation distances and therefore good spatial resolution.

In Chapter 6 the efficiency of prototype active edge sensors is reported. Although these sensors have a high hit efficiency at the edge, they cannot be operated at high bias voltages therefore do not fully qualify for the the VELO upgrade. The sensors that will be used in the upgrade feature a guard ring design as described in Section 2.4.4. However, between the edge of the pixel matrix and the sensor edge part of the sensor may be inactive due to the

presence of the guard rings. The hit efficiency at the sensor edge should be evaluated and the inactive sensor area quantified.

Non-homogeneous irradiation

The exponential decrease of the fluence as a function of the radial distance from the beam will result in a non-homogeneous irradiation along a sensor tile. The fluence at the most irradiated part of the sensor tile is larger by a factor 40 than the least irradiated part. The effective trapping rate and the effective doping concentration in a sensor change as a function of fluence. As a result, the charge collection efficiency is influenced. Therefore, studying this effect is of importance for the VELO upgrade.

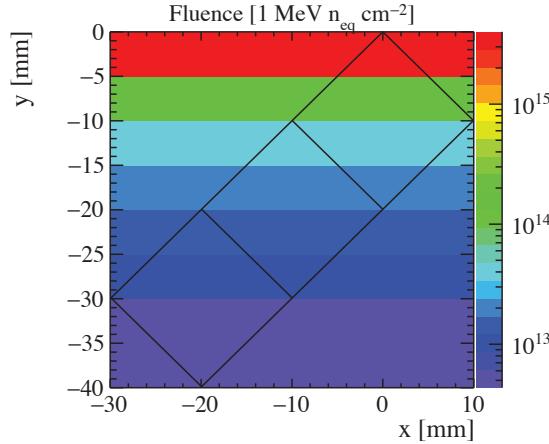


Figure 8.1: The fluence profile at KIT. The outline of a sensor tile is superimposed.

To mimic the irradiation profile of a sensor tile after accumulating the maximum fluence, prototype sensor tiles have been irradiated with non-uniform beam profiles at KIT in Karlsruhe [90] with 25 MeV protons and at the IRRAD facility at CERN [91] with 24 GeV protons. An example of such a fluence profile that was used in KIT is depicted in Figure 8.1. The outline of a sensor tile is superimposed.

Vendor comparison

Based on the results presented in Chapter 7, the irradiated prototype silicon sensors provided by the two vendors (namely Hamamatsu and Micron) qualify for the VELO upgrade. The fact that the 50 μm thinner Micron sensor collects the same amount of charge as the Hamamatsu sensors gives an advantage to

the Micron design since with smaller radiation length the same signal yield is acquired. However, in order to select which vendor sensors are more suitable, at least one sample with each of the sensor properties listed in Table 2.1 needs to be tested. To come to a conclusion, the performance of the sensors after non-homogeneous irradiation needs to be taken into account as this is a key requirement for the VELO upgrade.

In this thesis the sensors are characterised using the Timepix3 ASIC, which allows simultaneous ToA and ToT measurements. Timepix3 is the predecessor of the ASIC that will be used in the VELO upgrade, VeloPix. With the availability of the VeloPix ASIC, a new testbeam campaign will be commissioned to fully characterise the chip.

8.2 Readout/ASIC design

The VeloPix ASIC is designed to cope with the high particle rate environment of the LHCb upgrade. The performance of VeloPix has to be studied before the VELO upgrade is completed in 2019 to examine whether the ASIC qualifies for the upgrade. High rate tests need to be performed in order to measure the hit rate of the VeloPix ASIC. These tests must take place in a facility, such as Fermilab (USA), that can deliver a high particles flux with a frequency equal to the bunch crossing of LHC. The successful operation of the Timepix3 telescope has proved that using the same ASIC both in the telescope planes and the DuT, a variety of measurements can be performed in order to characterise a detector. A VeloPix telescope would be the ideal set-up to perform the final measurements needed for the LHCb VELO upgrade.

Appendix A

Threshold offset in the irradiated sensors

The threshold offset for one of the irradiated sensors (S22) is studied by plotting the charge distributions of the lowest ToT count for all pixels (single). The charge distribution of single pixel clusters with $\text{ToT} = 1$ counts is presented in Figure A.1 with the sensor set at a grazing angle of 85° .

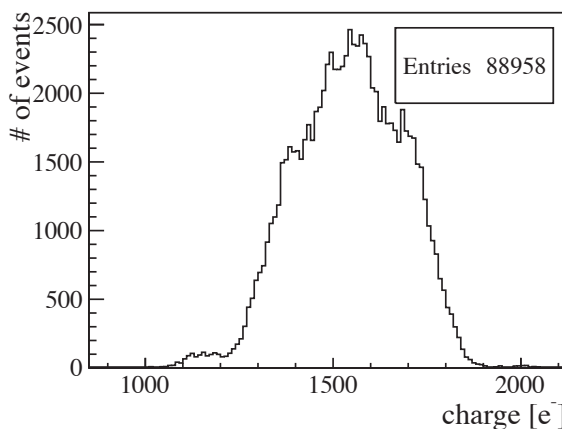


Figure A.1: Charge distribution of single pixels with $\text{ToT} = 1$ counts from the irradiated sensor (S22) set at a grazing angle of 85° .

Most of the entries have a charge >1200 e⁻. This threshold offset may originate from the equalisation.

Bibliography

- [1] I. Aitchison and A. Hey, *Gauge theories in Particle Physics*. IoP publishing, 2004.
- [2] ATLAS, CMS Collaboration, G. Aad *et al.*, “Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments”, *Phys. Rev. Lett.* **114** (2015) 191803.
- [3] A. Sakharov, “Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe”, *Soviet Physics Uspekhi* **34** (1991) 392.
- [4] M. Klasen, M. Pohl, and G. Sigl, “Indirect and direct search for dark matter”, *Progress in Particle and Nuclear Physics* **85** (2015) 1 – 32.
- [5] LHCb Collaboration, R. Aaij *et al.*, “The LHCb Detector at the LHC”, *JINST* **3** no. 08, (2008) S08005.
- [6] J. Boucrot, “Oscillations of neutral B mesons systems”, *Nuclear Physics B - Proceedings Supplements* **75** no. 3, (1999) 261 – 266.
- [7] A. Lenz and U. Nierste, “Theoretical update of the $B_s - \bar{B}_s$ mixing”, *JHEP* **2007** no. 06, (2007) 072.
- [8] LHCb Collaboration, R. Aaij *et al.*, “Precision measurement of the $B_s^0 - \bar{B}_s^0$ oscillation frequency with the decay $B_s^0 \rightarrow D_s^- \pi^+$ ”, *New J. Phys.* **15** (2013) 053021.
- [9] K. Hartkorn and H. G. Moser, “A new method of measuring $\Delta\Gamma/\Gamma$ in the $B_s^0 - \bar{B}_s^0$ system”, *Eur. Phys. J.* **8** no. 3, (1999) 381–383.
- [10] M. Kobayashi and T. Maskawa, “CP Violation in the Renormalizable Theory of Weak Interaction”, *Prog. Theor. Phys.* **49** (1973) 652.
- [11] LHCb Collaboration, R. Aaij *et al.*, “Precision measurement of CP violation in $B_s^0 \rightarrow J/\psi K^+ K^-$ decays”, *Phys. Rev. Lett.* **114** (2015) 041801.
- [12] A. Sarti, “B Physics at LHC”, [arXiv:0809.0450v1](https://arxiv.org/abs/0809.0450v1) [hep-ex].
- [13] LHCb Collaboration, R. Aaij *et al.*, “The LHCb Trigger and its Performance in 2011”, *JINST* **8** no. 04, (2013) P04022.
- [14] LHCb Collaboration, R. Aaij *et al.*, “LHCb Detector Performance”, *International Journal of Modern Physics A* **30** (2015) 1530022.

- [15] LHCb Collaboration, R. Aaij *et al.*, “Performance of the LHCb Vertex Locator”, *JINST* **9** (2014) P09007.
- [16] B. Verlaet *et al.*, “CO₂ Cooling for the LHCb-VELO Experiment at CERN”, *8th IIF/IIR Gustav Lorentzen Conference on Natural Working Fluids, Copenhagen, Denmark* (2008) .
- [17] A. Affolder *et al.*, “Radiation damage in the LHCb vertex locator”, *JINST* **8** no. 08, (2013) P08002.
- [18] LHCb Collaboration, R. Aaij *et al.*, “Letter of Intent for the LHCb Upgrade”, *CERN-LHCC-2011-001* (2011) . Private communication.
- [19] C. Fitzpatrick, “The upgrade of the LHCb trigger system”, [arXiv:1410.5012v1 \[physics.ins-det\]](#).
- [20] LHCb Collaboration, R. Aaij *et al.*, “LHCb VELO Upgrade Technology Review Support Document”, *LHCb-INT-2013-025* (2013) . Private communication.
- [21] LHCb Collaboration, R. Aaij *et al.*, “LHCb VELO Upgrade Technical Design Report”, *CERN/LHCC 2013-021 LHCb TDR 13* (2013) . Private communication.
- [22] D. Hynds, “The LHCb VELO Upgrade”, *Physics Procedia* **37** (2012) 1055 – 1061.
- [23] G. Beck and G. Viehhauser, “Analytic model of thermal runaway in silicon detectors”, *Nucl. Instrum. Meth. A* **618** (2010) 131 – 138.
- [24] A. Nomerotski *et al.*, “Evaporative CO₂ cooling using microchannels etched in silicon for the future LHCb vertex detector”, *JINST* **8** (2013) P04004.
- [25] M. Campbell *et al.*, “A readout chip for a 64×64 pixel matrix with 15-bit single photon counting”, *IEEE Transactions on Nuclear Science* **45** no. 3, (1998) 751–753.
- [26] M. van Beuzekom *et al.*, “VeloPix ASIC development for LHCb VELO upgrade”, *Nucl. Instrum. Meth. A* **731** (2013) 92–96.
- [27] G. Barrand *et al.*, “GAUDI - A Software Architecture and Framework for building HEP Data Processing Applications”, *Computer Physics Communications* **140** no. 1–2, (2001) 45 – 55.
- [28] Particle Data Group Collaboration, K. A. Olive *et al.*, “Review of Particle Physics”, *Chin. Phys.* **C38** (2014) .
- [29] A. Papadelis, *Characterisation and commissioning of the LHCb VELO detector*. PhD thesis, VU University, Amsterdam, 2009.

- [30] E. Belau *et al.*, “Charge Collection in Silicon Strip Detectors”, *Nucl. Instrum. Meth.* **214** (1983) 253–260.
- [31] R. Frühwirth, “Application of Kalman Filtering to track and vertex fitting”, *Nucl. Instrum. Meth. A* **262** (1987) 444–450.
- [32] E.H.M. Heijne *et al.*, “A silicon surface barrier microstrip detector designed for high energy physics”, *Nucl. Instrum. Meth.* **178** (1980) 331 – 343.
- [33] L. Landau, “On the Energy loss of fast particles by ionization”, *J. Exp. Phys (USSR)* **8** (1944) 201.
- [34] C. Leroy and P. Rancoitta, *Principles of Radiation Interaction in Matter and Detection*. World Scientific, 2009.
- [35] H. Bichsel, “Straggling in thin silicon detectors”, *Rev. Mod. Phys.* **60** (1988) 663 – 699.
- [36] S. Hancock *et al.*, “Energy loss and energy straggling of protons and pions in the momentum range 0.7 to 115 GeV/c”, *Phys. Rev. A* **28** (1983) 615–620.
- [37] H. Spieler, *Semiconductor Detector Systems*. Oxford science publications, 2005.
- [38] L. Rossi, P. Fischer, T. Rohe, and N. Wermes, *Pixel detectors: From fundamentals to Applications*. Springer, 2006.
- [39] G. Lindström *et al.*, “Radiation hard silicon detectors—developments by the RD48 (ROSE) collaboration”, *Nucl. Instrum. Meth. A* **466** (2001) 308 – 326.
- [40] G. Lutz, *Semiconductor Radiation Detectors*. Springer, 1999.
- [41] C. Jacobini, C. Canali, G. Ottaviani, and A. Guaranta, “A review of some charge transport properties of silicon”, *Solid-State electronics* **20** (1977) 77–89.
- [42] S. Ramo, “Currents induced by electron motion”, *Proc. Ire* **27** (1939) 584–585.
- [43] X. Llopart, “The Timepix manual”, (2006) .
- [44] X. Llopart, *Design and Characterization of 64K Pixels Chips Working in Single Photon Processing Mode*. PhD thesis, CERN-THESIS-2007-062, 2007.
- [45] E. J. Schioppa, *The color of X-rays*. PhD thesis, UvA, Amsterdam, 2014.

- [46] T. Poikela *et al.*, “Timepix3: a 65K channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout”, *JINST* **9** (2014) C05013.
- [47] K. Akiba *et al.*, “Charged particle tracking with the Timepix ASIC”, *Nucl. Instrum. Meth. A* **661** (2012) 31–49.
- [48] J. Jakubek, “Precise energy calibration of pixel detector working in time-over-threshold mode”, *Nucl. Instrum. Meth. A* **633** (2011) S262 – S266.
- [49] M. De Gaspari *et al.*, “Design of the analog front-end for the Timepix3 and Smallpix hybrid pixel detectors in 130 nm CMOS technology”, *JINST* **9** (2014) C01037.
- [50] R. Richter *et al.*, “Strip detector design for ATLAS and HERA-B using two-dimensional device simulation”, *Nucl. Instrum. Meth. A* **377** (1996) 412–421.
- [51] V. Fadeyev *et al.*, “Scribe-cleave-passivate (SCP) slim edge technology for silicon sensors”, *Nucl. Instrum. Meth. A* **731** (2013) 260–265.
- [52] C. Kenney *et al.*, “Active-edge planar radiation sensors”, *Nucl. Instrum. Meth. A* **565** (2006) 272–277.
- [53] G. Lindström, “Radiation damage in silicon sensors”, *Nucl. Instrum. Meth. A* **512** (2003) 30–43.
- [54] M. Huhtinen, “Simulation of non-ionising energy loss and defect formation in silicon”, *Nucl. Instrum. Meth. A* **491** (2002) 194–215.
- [55] G. Lindström, M. Moll, and E. Fretwurst, “Radiation hardness of silicon detectors – a challenge from high-energy physics”, *Nucl. Instrum. Meth. A* **426** (1999) 1–15.
- [56] M. Moll, E. Fretwurst, and G. Lindström, “Leakage current of hadron irradiated silicon detectors – material dependence”, *Nucl. Instrum. Meth. A* **426** (1999) 87–93.
- [57] M. Moll, *Radiation Damage in Silicon Particle Detectors*. PhD thesis, Hamburg University, 1999.
- [58] A. Hickling *et al.*, “Use of IT (current vs temperature) scans to study radiation damage in the LHCb VELO”, *LHCb-PUB-2011-021*, *CERN-LHCb-PUB-2011-021* (2011) . Private communication.
- [59] M. Moll, “Radiation tolerant semiconductor sensors for tracking detectors”, *Nucl. Instrum. Meth. A* **565** (2006) 202–211.
- [60] M. Moll, E. Fretwurst, and G. Lindström, “Investigation on the improved radiation hardness of silicon detectors with high oxygen concentration”, *Nucl. Instrum. Meth. A* **439** (2000) 282 – 292.

- [61] G. Kramberger *et al.*, “Determination of effective trapping times for electrons and holes in irradiated silicon”, *Nucl. Instrum. Meth. A* **476** (2002) 645 – 651.
- [62] K. Iniewsky, *Radiation Effects in Semiconductors*. CRC Press, 2005.
- [63] Y. Unno *et al.*, “p-Bulk silicon microstrip sensors and irradiation”, *Nucl. Instrum. Meth. A* **579** (2007) 614 – 622.
- [64] R. Dalal *et al.*, “Combined effect of bulk and surface damage on strip insulation properties of proton irradiated n^+ -p silicon strip sensors”, *JINST* **9** (2014) P04007.
- [65] K. Akiba *et al.*, “The Timepix Telescope for High Performance Particle Tracking”, *Nucl. Instrum. Meth. A* **723** (2013) 47–54.
- [66] P. Tsopelas, “The LHCb Vertex Locator upgrade”, *IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)* (2014) 1–4.
- [67] J. Visser *et al.*, “SPIDR: a read-out system for Medipix3 & Timepix3”, *JINST* **10** (2015) C12028.
- [68] V. Blobel, “Software alignment for tracking detectors”, *Nucl. Instrum. Meth. A* **566** (2006) 5 – 13.
- [69] P. Tsopelas *et al.*, “Probing active-edge silicon sensors using a high precision telescope”, *Nucl. Instrum. Meth. A* **777** (2015) 110–117.
- [70] G. Kramberger *et al.*, “Investigation of Irradiated Silicon Detectors by Edge-TCT”, *IEEE transactions on Nuclear Science* **57** (2010) 2294 – 302.
- [71] B. Henrich, “Depth Profile of Signal Charge Collected in Heavily Irradiated Silicon Pixels”, *CMS NOTE 1997/021* (1997) . Private communication.
- [72] N. Croitoru, P. Rancoita, and A. Seidman, “Charge migration contribution to the sensitive layer of a silicon detector”, *Nucl. Instrum. Meth. A* **234** (1985) 443 – 450.
- [73] G. Kramberger *et al.*, “Effective trapping time of electrons and holes in different silicon materials irradiated with neutrons, protons and pions ”, *Nucl. Instrum. Meth. A* **481** (2002) 297 – 305.
- [74] CMS Tracker Group Collaboration, W. Adam *et al.*, “Trapping in proton irradiated p^+ - n - n^+ silicon sensors at fluences anticipated at the HL-LHC outer tracker”, *JINST* **11** (2016) P04023.
- [75] V. Chiochia *et al.*, “A double junction model of irradiated silicon pixel sensors for LHC”, *Nucl. Instrum. Meth. A* **568** (2006) 51 – 55.

- [76] E. J. Schioppa *et al.*, “Study of Charge Diffusion in a Silicon Detector Using an Energy Sensitive Pixel Readout Chip”, *IEEE transactions on Nuclear Science* **62** (2015) 2349–2359.
- [77] LHCb Collaboration, R. Aaij *et al.*, “LHCb Trigger and Online Upgrade Technical Design Report”, *CERN/LHCC 2014-016 LHCb TDR 16* (2014) . Private communication.
- [78] LHCb Collaboration, R. Aaij *et al.*, “Framework TDR for the LHCb Upgrade: Technical Design Report”, *CERN-LHCC-2012-007 LHCb TDR 12* (2012) . Private communication.
- [79] R. Wunstorf, *Systematic Investigation of the Radiation Hardness of Silicon Detectors for Application in High Energy Physics Experiments*. PhD thesis, Hamburg University, 1992.
- [80] C. Leroy *et al.*, “Study of charge collection and noise in non-irradiated and irradiated silicon detectors”, *Nucl. Instrum. Meth. A* **388** (1997) 289 – 296.

Web Sources

- [81] CKM fitter Group Collaboration, J. Charles *et al.*
<http://ckmfitter.in2p3.fr/>.
- [82] Medipix Collaboration, M. Campbell *et al.*
<http://medipix.web.cern.ch/medipix/>.
- [83] The Qt Company, Qt cross-platform application framework.
<http://www.qt.io/>.
- [84] V. Blobel. <http://www.desy.de/~blobel/mptalks.html>.
- [85] F. James *et al.*, Minuit package. www.cern.ch/minuit.
- [86] VTT Technical Research Centre. www.vtt.fi.
- [87] Jožef Stefan institute. <https://www.ijs.si/ijsw/JSI>.
- [88] National Institute of Standards and Technology.
<http://www.nist.gov/>.
- [89] N. Cartiglia, Weightfield 2.0.
personalpages.to.infn.it/~cartiglia/Weightfield2/Main.html.
- [90] KIT Irradiation Center. www.ekp.kit.edu/.
- [91] CERN irradiation facilities.
<https://irradiation.web.cern.ch/irradiation/>.

Summary

As we study matter in detail, we can zoom in from molecules to atoms down to the smallest blocks that make up matter, the subatomic particles. The first challenge in the subatomic realm is to understand how these particles interact with each other. Physicists have been developing theories to explain these interactions and have been performing experiments in order to examine them. The most successful theory so far that describes interactions between the subatomic particles is the Standard Model. Although this theory has been vigorously tested, a number of questions remain unanswered, e.g. why is there no antimatter in the universe and what is the nature of dark matter? A search for physics beyond the Standard Model can be carried out through precision measurements of decays of B -mesons.

B -mesons are produced by colliding bunches of high energy protons. This is achieved at the Large Hadron Collider at CERN where the colliding protons have a center of mass energy of 13 TeV. Among the particles produced by the colliding protons, large amounts of B -mesons are produced at small angles with respect to the interacting beams. These particles travel on average about 1 cm from the point they are produced until the point they decay. These two points are called primary and secondary vertex, respectively. To identify a B -meson, the lifetime of the particle can be used. The lifetime is reconstructed from the distance between the primary and the secondary vertex. In addition, a characteristic aspect of neutral B -mesons is that particle-antiparticle transitions, called oscillations, occur on average nine times during the lifetime of the particle. To study these fast oscillations, that occur between the primary and secondary vertex, a good decay time resolution of the detector is required.

The LHCb experiment at CERN is optimised to study B -mesons. The LHCb detector setup consists of a tracking system and a particle identification system. One of the detectors of the tracking system is the Vertex Locator (VELO), which is a silicon strip detector. The VELO plays a central role in studying B -meson properties like their primary and secondary vertices.

In the coming years LHCb will operate its detectors at a higher luminosity in order to collect more data. To increase the data rate a new trigger scheme will be adopted that requires the upgrade of all tracking detectors. This upgrade brings a number of challenges. The VELO upgrade is required to read out all data from each bunch crossing, have a good decay time resolution and operate

smoothly after accumulating fluences up to 8×10^{15} 1 MeV n_{eq}/cm^2 . To meet these challenges the VELO upgrade will feature a new silicon pixel detector.

The new silicon detector is based on a new pixel front-end chip, the VeloPix ASIC. The ASIC is built in a 130 nm CMOS technology and consists of a pixel matrix of 256×256 square pixels with a 55 μm pitch. To reduce the amount of material, the chip will be thinned down to 200 μm . If the charge liberated by a traversing particle is above a certain threshold, the Time of Arrival (ToA) is measured with a timing resolution of 25 ns and stored with the pixel location.

The signature of a single particle track originating from the decay of a B -meson is a large impact parameter with respect to the primary vertex. Measuring the impact parameter (IP) with a small error is one of the key ingredients leading to a good decay time resolution.

The IP resolution worsens with the amount of material traversed by the particle and depends on the detector resolution, the particle momentum and the extrapolation length from the position of the first measurement plane to the particle vertex. The VELO upgrade will feature channels with coarser pitch and a radiation thickness larger by a factor of 1.3 resulting in a worse detector resolution and larger extrapolation error, respectively. However, the edge of the sensors in the VELO upgrade will be 3 mm closer to the beam thereby reducing the extrapolation error.

The performance of the VELO upgrade has been simulated in order to predict how these factors contribute to the IP resolution. Although the worse detector resolution and the larger radiation length in the VELO upgrade have a small negative effect on the IP, the reduced extrapolation error results in a better IP resolution. The VELO upgrade is expected to perform better than the current VELO in terms of IP resolution.

An important element of the VELO upgrade is the silicon sensor. The baseline option for the VELO upgrade sensors are 200 μm thick, n -on- p type diodes. In addition to the baseline option, other design variants in terms of thickness and sensor type were also considered.

A number of prototype silicon sensors with the above sensor characteristics were produced by the companies VTT, Hamamatsu and Micron. A subset of these sensors were irradiated with neutrons at the JSI institute in Ljubljana up to the highest fluence the VELO upgrade will be exposed to. Ideally, all sensors would have been tested with the VeloPix readout. However, VeloPix was not available at the time the prototype sensors were tested.

Most of the prototype sensors were instead bump-bonded to Timepix3 ASICs and were placed in a beam of 180 GeV protons and pions at the SPS at CERN. To perform dedicated studies on these sensors, a telescope of 8 Timepix3 detectors was assembled. The Timepix3 telescope planes were equally divided

in two arms. Each prototype sensor was placed as Device-under-Test (DuT) between the two telescope arms where the track-pointing resolution is better than $2\text{ }\mu\text{m}$. This resolution allowed the study of pixel sensors with sub-pixel precision.

By placing the sensors perpendicular with respect to the beam, tracking efficiency and charge collection efficiency measurements were performed. Using the sub-pixel point resolution of the telescope, the tracking efficiency at the edge of active-edge sensors from VTT was measured. These sensors are about 100% efficient through all the pixel matrix and $>99\%$ efficient up to $10\text{ }\mu\text{m}$ from the physical edge.

During operation, the VELO upgrade sensors will be irradiated. The charge collection yield in an irradiated sensor decreases due to various radiation induced defects as for example charge trapping. For the VELO upgrade at the benchmark voltage of 1000 V , a minimum signal yield of 6000 e^- is required when the sensors are irradiated at the maximum fluence of $8 \times 10^{15}\text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$. The charge collection efficiency of the irradiated sensors was measured in order to investigate whether enough charge is collected. The irradiated sensors can deliver 7000 e^- when operated at 1000 V satisfying the VELO upgrade requirements.

A set of precision measurements was performed with the sensors at large (grazing) angles with respect to the beam such that the incoming particle traverses multiple adjacent pixels. Knowing the angle of incidence, the path length from the entry point of a track to a pixel is assigned to a certain depth in the sensor. Using this technique the collected charge and time to threshold versus the depth of charge deposition were measured.

According to the charge collection profile of the sensors irradiated to the highest fluence, most of the charge is collected from depths close to the pixel electrode. The depleted region does not reach the backplane even when the sensor is operated at 1000 V . To understand the charge collection profile data, the charge trapping from both electrons and holes needs to be taken into account.

Besides the charge collection profile, the time to threshold profile has also been investigated. The time it takes for the charge to drift and cross the threshold can be calculated by subtracting the time the track intercepted the telescope (t_{track}) by the time a pixel hit is recorded on the DuT (t_{hit}). A simulation of the time to threshold based on Ramo's theorem, which describes well the charge collection time in a non-irradiated sensor, fails to describe the data. Including the average timewalk in the simulation describes well the time to threshold profile of an irradiated sensor because the time is dominated by timewalk.

Both prototype silicon sensors from Hamamatsu and Micron qualify for the VELO upgrade in terms of charge collection and time of arrival. Additional

future measurements will reveal more information on how radiation induced effects influence charge collection.

The road is open for new exciting results with VeloPix prototype sensor assemblies and finally the installation and commissioning of the VELO upgrade.

Samenvatting

Bij het nauwkeurig bestuderen van materie kunnen we inzoomen via moleculen en atomen naar de kleinste bouwstenen van materie, de subatomaire deeltjes. Een eerste uitdaging in deze subatomaire omgeving is het begrijpen van de wisselwerking tussen deze deeltjes. Natuurkundigen hebben theoriën ontwikkeld om deze wisselwerkingen te verklaren en hebben experimenten uitgevoerd om deze te onderzoeken. De tot nog toe meest succesvolle theorie die de wisselwerkingen tussen subatomaire deeltjes beschrijft, is het Standaard Model. Ondanks het feit dat deze theorie uiterst zorgvuldig getest is, blijven er toch een aantal vragen onbeantwoord: Waarom bevat het heelal geen antimaterie? Wat is donkere materie eigenlijk? De zoektocht naar natuurkundige verschijnselen die niet verklaarbaar zijn binnen het Standaard Model gebeurt onder andere door het doen van nauwkeurige metingen aan het verval van B -mesonen.

B -mesonen worden geproduceerd door protonen met hoge energie op elkaar te laten botsen. Dit gebeurt in de Large Hadron Collider op CERN waar de botsende protonen een zwaartepuntsenergie van maar liefst 13 TeV kunnen bereiken. Bij dergelijke botsingen ontstaan, naast andere deeltjes, grote hoeveelheden B -mesonen die van het botsingspunt wegspatten onder een kleine hoek ten opzichte van de inkomende bundels. De B -mesonen leggen gemiddeld 1 cm af vanaf het productiepunt tot aan het punt waar ze vervallen.. Het eerste punt noemt men de primaire vertex en het tweede punt de secundaire vertex. De levensduur van het B -meson wordt bepaald uit de afstand tussen de primaire en secundaire vertices en deze levensduur gebruikt men om het B -meson te identificeren. Een ander belangrijk kenmerk van neutrale B -mesonen is dat ze periodieke wisselingen ondergaan van deeltje naar antideeltje. Deze zogenoemde oscillaties vinden gedurende hun levensduur gemiddeld negen keer plaats. Het onderzoek naar deze snelle oscillaties vereist een scherpe tijd en positieresolutie van de vertex detector.

Het LHCb-experiment op CERN is speciaal gebouwd om B -mesonen te bestuderen. De detectoropstelling van LHCb bestaat uit een systeem voor spoorreconstructie (tracking) en een systeem voor de identificatie van deeltjes. Een van de trackingdetectoren is de Vertex Locator (VELO). De VELO is een silicium stripdetector en speelt een centrale rol bij het bestuderen van de eigenschappen van B -mesonen zoals de afstand tussen hun botsings- en vervalpunt.

Om in de toekomst steeds meer data te verzamelen, zullen de LHCb-detectoren straks bij een hogere intensiteit moeten kunnen werken. Zo zal er een nieuwe procedure worden gebruikt voor het selecteren van de interessante botsingen waarvoor betere detectoren nodig zijn. Deze vernieuwing brengt een aantal uitdagingen met zich mee. De nieuwe vertex detector, VELO, moet alle gegevens van elke botsing uit kunnen lezen, een goede tijdsresolutie hebben en betrouwbaar blijven functioneren zelfs na blootstelling aan straling met een fluentie die op kan lopen tot wel $8 \times 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$. Om aan deze eisen te voldoen wordt de nieuwe VELO detector gemaakt met speciaal ontwikkelde silicium pixeldetectoren.

De nieuwe siliciumdetector maakt gebruik van een nieuw ontwikkelde geïntegreerde schakeling voor pixeldetectoren, de VeloPix ASIC. Deze ASIC bestaat uit een pixelmatrix van 256 pixels bij 256 pixels met een onderlinge afstand van $55 \text{ }\mu\text{m}$ en is geproduceerd in een 130 nm CMOS technologie. Om de hoeveelheid materiaal te minimaliseren, is de ASIC verdund tot een dikte van slechts $200 \text{ }\mu\text{m}$. Als de door een passerend deeltje vrijgemaakte lading groter is dan een bepaalde drempelwaarde wordt de aankomsttijd (Time of Arrival, ToA) ervan gemeten met een tijdsresolutie van 25 ns en samen met de pixelpositie geregistreerd.

Een kenmerk van een spoor van een enkel deeltje dat uit een B -meson verval voortkomt is de waarde van de impact parameter: de kortste afstand naar het botsingspunt. Nauwkeurige bepaling van deze impact parameter (IP) is cruciaal voor een betrouwbare berekening van de vervaltijd.

De bepaling van de impact parameter wordt minder nauwkeurig naarmate een deeltje meer materiaal moet passeren. Ook hangt de nauwkeurigheid af van de positieresolutie van de detector, van de deeltjesimpuls en van de extrapolatie vanuit de gemeten punten op een spoor naar de bundellijn.. In het nieuwe ontwerp zullen de positieresolutie en hoeveelheid materiaal waar de deeltjes doorheen gaan iets ongunstiger uitvallen. Echter, omdat rand van de sensoren van de nieuwe VELO 3 mm dichter bij de deeltjesbundels geplaatst worden, zal de extrapolatiefout in zijn geheel afnemen.

Om te bepalen in hoeverre deze factoren de IP resolutie beïnvloeden zijn er simulaties van de nieuwe VELO uitgevoerd. De slechtere detectorresolutie en de grotere stralingsdikte van de nieuwe VELO blijken slechts een klein negatief effect op de IP resolutie te geven. Daarentegen geeft de verminderde extrapolatiefout een verbetering van de IP resolutie. De verwachting is dat de nieuwe VELO wat betreft de IP resolutie beter zal presteren dan de huidige.

Een belangrijk onderdeel van de nieuwe VELO vormen de siliciumsensoren. De basisuitvoering van de sensor is er een met n -op- p type diodes en heeft een dikte van $200 \text{ }\mu\text{m}$. Naast deze uitvoering zijn er ook alternatieve ontwerpen met verschillende diktes en type diodes getest.

Prototype siliciumsensoren met bovengenoemde kenmerken zijn geproduceerd door VTT, Hamamatsu en Micron. Een aantal van deze sensoren zijn bij JSI in Ljubljana met neutronen bestraald tot de hoogste fluentie die voor de nieuwe VELO wordt verwacht. Idealiter zouden al tijdens de testen alle prototype sensoren met de VeloPix ASIC uitgelezen moeten worden maar de VeloPix was tijdens deze prototypetests nog niet beschikbaar.

In plaats daarvan zijn de meeste prototypesensoren met Timepix3 ASICs verbonden. Vervolgens zijn ze bij de SPS op CERN in een bundel protonen en pionen met een energie van 180 GeV geplaatst. Om gedetailleerde studies van deze sensoren mogelijk te maken is een telescoop met 8 Timepix3 detectoren gebouwd. De Timepix3 meetvlakken zijn gelijk verdeeld over de twee telescooparmen. Elke prototype sensor werd als testobject tussen de twee telescooparmen geplaatst, waar de resolutie van de spoorreconstructie beter is dan 2 μm . Deze resolutie maakt het mogelijk de pixelsensoren te bestuderen met een nauwkeurigheid die veel beter is dan het formaat van een pixel.

Voor het bepalen van de efficiëntie van de spoorreconstructie en van de efficiëntie van de ladingscollectie, werden de sensoren loodrecht ten opzichte van de bundel geplaatst. Dankzij de hoge resolutie van de telescoop kon de detectie-efficiëntie van de rand van de VTT-sensoren met actieve rand nauwkeurig bepaald worden. Deze sensoren zijn ongeveer 100% efficiënt in de gehele pixel matrix en meer dan 99% efficiënt tot op een afstand van 10 μm van de fysieke rand.

De sensoren van de nieuwe VELO zullen tijdens gebruik, blootgesteld zijn aan straling. De ladingscollectie neemt na bestraling af ten gevolge van verschillende effecten zoals bijvoorbeeld ladingstransport in de sensor. Bij de maximale spanning van 1000 V moet een minimale ladingsopbrengst van 6000 e^- gewaarborgd zijn, zelfs na blootstelling aan de maximale fluentie $8 \times 10^{15} \text{ 1 MeV } n_{\text{eq}}/\text{cm}^2$. De ladingsopbrengst van de bestraalde sensoren is gemeten om te bepalen of er aan bovenstaande eis voldaan wordt. De bestraalde sensoren leveren 7000 e^- bij een spanning van 1000 V en voldoen dus aan de eisen van de VELO upgrade.

Een aantal precisiemetingen zijn uitgevoerd waarbij de sensor onder een grote hoek ten opzichte van de bundel geplaatst was, zodanig dat een deeltje door meerdere pixels gaat. Bij een bekende invalshoek kan de in de sensor afgelegde weglengte tot aan een bepaalde pixel omgerekend worden naar een diepte in de sensor. Met behulp van deze techniek is de ladingsopbrengst en de snelheid van de ladingstransport als functie van de diepte van de ladingsdepositie gemeten.

Uit het ladingsprofiel van de zwaarst-bestraalde sensoren volgt dat het merendeel van gemeten lading dicht bij de pixel electrode verzameld wordt. Het gevoelige, verarmde gebied van de sensor reikt niet tot aan achterkant van de sensor, zelfs al wordt de sensor bedreven met een spanning van 1000 V. Om

de vorm van het ladingsopnameprofiel te begrijpen moet er rekening worden gehouden met de ladingstransport van zowel elektronen als gaten.

Naast dit ladingsprofiel is ook de snelheid van het ladingstransport onderzocht. De tijd die lading nodig heeft om naar de sensor elektrodes bewegen en een drempelwaarde te overschrijden kan berekend worden door de tijd zoals gemeten door de sensor (t_{hit}) af te trekken van de tijd gemeten door de telescoop (t_{track}). Een simulatie van deze tijd-tot-drempel, gebaseerd op de stelling van Ramo, geeft een goede beschrijving van de gemeten waarden van niet-bestraalde sensoren, maar geeft een slechte beschrijving van de resultaten voor bestraalde sensoren. Wanneer echter het effect van het zogenaamde "time-walk" effect in de simulatie meegenomen wordt komt het gesimuleerde profiel van de bestraalde sensoren goed overeen met de gemeten waarden.

Beide types sensoren van Hamamatsu en Micron voldoen aan de ontwerp-eisen voor de nieuwe VELO wat betreft de ladingsopbrengst en de snelheid van het ladingstransport. Aanvullende metingen zullen meer informatie verschaffen over de invloed van stralingseffecten op de ladingsopbrengst.

De weg is vrij voor nieuwe, spannende resultaten met VeloPix-prototypes en voor de voltooiing van de VELO detector.

Περίληψη

Καθώς μελετάμε την ύλη σε λεπτομέρεια, μπορούμε να εστιάσουμε από τα μόρια σε άτομα μέχρι και στα μικρότερα μέρη από τα οποία αποτελείται η ύλη, τα υποατομικά σωματίδια. Η πρώτη πρόκληση που αντιμετωπίζουμε στον υποατομικό κόσμο είναι να κατανοήσουμε πως αλληλεπιδρούν τα σωματίδια μεταξύ τους. Οι φυσικοί αναπτύσσουν θεωρίες ώστε να εξηγήσουν αυτές τις αλληλεπιδράσεις και εκτελούν πειράματα με σκοπό να εξετάσουν αυτές τις θεωρίες. Η πιο επιτυχημένη θεωρία ως τώρα είναι το Καθιερωμένο Μοντέλο. Παρόλο που αυτή η θεωρία έχει εξεταστεί επανειλημμένα κάποια ερωτήματα ακόμα παραμένουν αναπάντητα όπως π.χ. γιατί υπάρχει περισσότερη αντιύλη στο σύμπαν και από πού προέρχεται η σκοτεινή ύλη; Έρευνες πάνω σε θεωρίες πέραν του Καθιερωμένου Μοντέλου μπορούν να διεξαχθούν μέσω ακριβή μετρήσεων των B -μεσονίων.

Τα B -μεσόνια παράγονται συγκρούοντας δέσμες πρωτονίων που έχουν επιταχυνθεί σε πολύ υψηλές ενέργειες. Αυτό επιτυγχάνεται στον Μεγάλο Αδρονικό Επιταχυντή στο CERN όπου τα πρωτόνια έχουν ενέργεια 13 TeV στο κέντρο μάζας τους. Ανάμεσα στα σωματίδια που παράγονται από τις συγκρούσεις των πρωτονίων, ένας μεγάλος αριθμός από B -μεσόνια παράγεται σε μικρές γωνίες σε σχέση με τις αλληλεπιδρώντες δέσμες. Αυτά τα σωματίδια ταξιδεύουν κατά μέσο όρο 1 cm από το σημείο που παράγονται μέχρι το σημείο που διασπώνται. Τα δύο αυτά σημεία είναι γνωστά ως πρωτεύων και δευτερεύων κόμβος αντίστοιχα. Για να αναγνωριστεί ένα B -μεσόνιο μπορούμε να χρησιμοποιήσουμε τον χρόνο ζωής του. Ο χρόνος ζωής υπολογίζεται από την απόσταση μεταξύ του πρωτεύων και του δευτερεύων κόμβου. Ένα ακόμα χαρακτηριστικό των ουδέτερα φορτισμένων B -μεσονίων είναι οι μεταστοιχειώσεις από σωματίδιο σε αντι-σωματίδιο, γνωστές ως ταλαντώσεις, που συμβαίνουν κατά μέσο όρο εννιά φορές μέσα στον χρόνο ζωής του σωματιδίου. Για να μελετήσουμε αυτές τις ταλαντώσεις, που λαμβάνουν χώρα μεταξύ του πρωτεύων και του δευτερεύων κόμβου, χρειάζεται ένα ανιχνευτής με καλή χρονική διακριτική ικανότητα.

Το πείραμα LHCb στο CERN είναι ειδικά σχεδιασμένο στο να μελετάει B -μεσόνια. Οι διάφοροι ανιχνευτές που αποτελούν το πείραμα μπορούν να χωριστούν σε αυτούς που αποτελούν το σύστημα ανίχνευσης και σε αυτούς που αποτελούν το σύστημα αναγνώρισης των σωματιδίων. Ένας από τους ανιχνευτές του συστήματος ανίχνευσης είναι ο Vertex Locator (VELO) που θα μπορούσε να μεταφραστεί σαν Ευρετής Κόμβων ο οποίος στην ουσία είναι ανιχνευτής σε γεωμετρία λουρίδων φτιαγμένος από πυρίτιο. Ο VELO παίζει κεντρικό ρόλο στην μελέτη διάφορων ιδ-

ιοτήτων των B -μεσονίων όπως στον προσδιορισμό των πρωτευνόντων και δευτερευόντων κόμβων.

Στα επόμενα χρόνια ο αριθμός των πρωτονίων που συγκρούονται μέσα στον Μεγάλο Αδρνιακό Επιταχυντή θα αυξηθεί. Οι ανιχνευτές του LHCb θα λειτουργούν υπό πιο απαιτητικές συνθήκες ώστε να συλλέξουν περισσότερα δεδομένα. Για να αυξηθεί ο ρυθμός με τον οποίο θα συλλέγονται τα δεδομένα, όλοι οι ανιχνευτές του συστήματος ανίχνευσης θα αναβαθμιστούν. Αυτή η αναβάθμιση φέρνει κάποιες προκλήσεις. Το αναβαθμισμένο VELO θα πρέπει να συλλέγει όλα τα δεδομένα σε κάθε σύγκρουση των δεσμών των πρωτονίων, να έχει καλή χρονική διακριτική ικανότητα και επίσης να μπορεί να λειτουργεί ομαλά αφότου έχει ακτινοβοληθεί με $8 \times 10^{15} \text{ 1 MeV } n_{eq}/\text{cm}^2$. Για να ανταπεξέλθει σε αυτές τις προκλήσεις, το αναβαθμισμένο VELO θα περιέχει έναν καινούργιο ανιχνευτή με εικονοστοιχεία (pixels) φτιαγμένο από πυρίτιο.

Ο νέος ανιχνευτής με εικονοστοιχεία είναι βασισμένος σε ένα νεό ολοκληρωμένο επεξεργαστή, το VeloPix. Ο επεξεργαστής είναι φτιαγμένος με τεχνολογία 130 nm CMOS και αποτελείται από μια μήτρα με 256×256 τετράγωνα εικονοστοιχεία που το καθένα έχει πλευρά 55 μm . Για να μειωθεί το υλικό που θα διαπερνάει ένα σωματίδιο, ο επεξεργαστής θα έχει πάχος 200 μm . Όταν το φορτίο που θα απελευθερωθεί από ένα σωματίδιο ξεπεράσει ένα συγκεκριμένο κατώφλι, ο χρόνος άφιξης μπορεί να μετρηθεί με χρονική διακριτική ικανότητα 25 ns και να αποθηκευτεί μαζί με τις συντεταγμένες του εικονοστοιχείου.

Το χαρακτηριστικό της τροχιάς ενός σωματιδίου που προέρχεται από την διάσπαση ενός B -μεσονίου είναι η μεγάλη ενεργός διατομή σε σχέση με τον πρωτεύων κόμβο. Η μέτρηση της ενεργού διατομής (ΕΔ) με μικρό σφάλμα είναι ένα από τα κύρια συστατικά για μια καλή διακριτική ικανότητα.

Η ΕΔ χειροτερεύει σε συνάρτηση με το πόσο πολύ υλικό πρέπει να διαπεράσει το σωματίδιο και εξαρτάται από την χωρική ανάλυση του ανιχνευτή, την ορμή του σωματιδίου και το μήκος προεκβολής από την πρώτη μέτρηση μέχρι τον πρωτεύων κόμβο. Το κανάλια του αναβαθμισμένου VELO θα είναι μεγαλύτερα στις 2 διαστάσεις και θα αποτελούνται από 1.3 φορές πιο πολύ υλικό με αποτέλεσμα να έχουν χειρότερη χωρική ανάλυση και μεγαλύτερο σφάλμα στο μήκος προεκβολής αντίστοιχα. Παρόλα αυτά, οι άκρες των αισθητήρων θα βρίσκονται 3 mm πιο κοντά στις δέσμες μειώνοντας με αυτόν τον τρόπο το σφάλμα στο μήκος προεκβολής.

Η απόδοση του αναβαθμισμένου VELO έχει προσομοιωθεί ώστε να μπορούμε να προβλέψουμε πως αυτοί οι παράγοντες επηρεάζουν το σφάλμα στην ΕΔ. Παρόλο που η χειρότερη χωρική ανάλυση και το επιπρόσθετο υλικό στο αναβαθμισμένο VELO έχουν αρνητικό αντίκτυπο στην ΕΔ, το μικρότερο σφάλμα στο μήκος προεκβολής οδηγεί σε μικρότερο σφάλμα στην ΕΔ. Το αναβαθμισμένο VELO αναμένεται να έχει καλύτερη απόδοση όσον αφορά το σφάλμα και την διακριτική ικανότητα της ΕΔ.

Ένα σημαντικό στοιχείο του αναβαθμισμένου VELO είναι οι αισθητήρες πυριτίου. Η βασική επιλογή για το αναβαθμισμένο VELO είναι αισθητήρες πάχους 200 μm τύπου *n-on-p*. Επιπρόσθετα στην βασική επιλογή, άλλες τιμές πάχους ή τύπου έχουν ληφθεί υπόψιν.

Ένας αριθμός από πρωτότυπους αισθητήρες με τα παραπάνω χαρακτηριστικά σχεδιάστηκαν από τις εταιρείες VTT, Hamamatsu και Micron. Ένα υποσύνολο αυτών των αισθητήρων ακτινοβολήθηκαν με νετρόνια στο ινστιτούτο JSI της Λουμπλιάνας μέχρι την μέγιστη τιμή της ακτινοβολίας στην οποία θα εκτεθεί το αναβαθμισμένο VELO. Ιδανικά οι αισθητήρες θα εξετάζονταν με τον επεξεργαστή VeloPix. Αυτό δεν ήταν δυνατό καθώς το VeloPix δεν ήταν ακόμα κατασκευασμένο όταν αυτά τα πειράματα διεξάχθηκαν.

Παρόλα αυτά οι περισσότεροι από τους πρωτότυπους αισθητήρες συνδέθηκαν με Timerix3 επεξεργαστές και τοποθετήθηκαν σε δέσμες πρωτονίων και πονίων ενέργειας 180 GeV στον επιταχυντή SPS στο CERN. Ένα τηλεσκόπιο από 8 ανιχνευτές Timerix3 δημιουργήθηκε για να διεξαχθούν συγκεκριμένες μελέτες πάνω τους αισθητήρες. Οι ανιχνευτές του τηλεσκοπίου χωρίστηκαν ίσα σε δύο μεριές. Κάθε πρωτότυπος αισθητήρας τοποθετήθηκε ως Συσκευή-υπό-Μελέτη (ΣυΜ) στο κέντρο του τηλεσκοπίου όπου η χωρική διακριτική ικανότητα του τηλεσκοπίου είναι καλύτερη από 2 μm . Αυτή η χωρική ανάλυση επέτρεψε να μελετηθούν με ακρίβεια τα εικονοστοιχεία των πρωτότυπων αισθητήρων.

Τοποθετώντας τους αισθητήρες κάθετα στην δέσμη διεξάχθηκαν μελέτες πάνω στην απόδοση ανίχνευσης και απόδοση συλλογής φορτίου. Χρησιμοποιώντας την υψηλή διακριτική ικανότητα του τηλεσκοπίου μετρήθηκε η απόδοση ανίχνευσης στις άκρες των αισθητήρων από την VTT. Οι συγκεκριμένοι αισθητήρες έχουν απόδοση σχεδόν 100% σε όλη την μήτρα των εικονοστοιχείων και απόδοση >90% μέχρι περίπου 10 μm από την άκρη του αισθητήρα.

Κατά την διάρκεια της λειτουργίας του αναβαθμισμένου VELO οι αισθητήρες θα ακτινοβολούνται συνεχώς. Σε ένα αισθητήρα που έχει ακτινοβοληθεί η απόδοση συλλογής φορτίου μειώνεται λόγω διαφόρων φαινομένων όπως η παγίδευση φορτίου. Όσον αφορά το αναβαθμισμένο VELO στην προβλεπόμενη τάση λειτουργίας των 1000 V, το ελάχιστο φορτίο που απαιτείται όταν οι αισθητήρες έχουν υποστεί την μέγιστη τιμή ακτινοβολίας των $8 \times 10^{15} \text{ 1 MeV } n_{\text{eq}}/\text{cm}^2$ είναι 6000 e^- . Η απόδοση συλλογής φορτίου των ακτινοβολημένων αισθητήρων μετρήθηκε ούτως ώστε να εξασφαλιστεί αν συλλέγεται το απαιτούμενο φορτίο. Οι ακτινοβολημένοι αισθητήρες μπορούν να συλλέξουν 7000 e^- όταν η τάση λειτουργίας τους είναι 1000 V ικανοποιώντας τις προαπαιτήσεις του αναβαθμισμένου VELO.

Ένα σύνολο από μετρήσεις διεξάχθηκαν με τους αισθητήρες τοποθετημένους σε μεγάλες γωνίες σε σχέση με την δέσμη έτσι ώστε το προσπίπτον σωματίδιο να διαπεράσει πολλαπλά γειτονικά εικονοστοιχεία. Γνωρίζοντας την γωνία πρόσπτωσης, η διαδρομή που διέσχισε ένα σωματίδιο από το σημείο εισόδου του σε ένα εικονοστοιχείο μπορεί να συσχετιστεί με ένα συγκεκριμένο βάθος μέσα

στον αισθητήρα. Χρησιμοποιώντας αυτήν την τεχνική, το φορτίου που συλλέχθηκε καθώς και ο χρόνος που χρειάζεται να ξεπεραστεί το κατώφλι μετρήθηκαν σε συνάρτηση με το βάθος στο οποίο απελευθερώθηκε το φορτίο.

Σύμφωνα με το προφίλ του συλλεγόμενου φορτίου των αισθητήρων που δέχτηκαν την μέγιστη ακτινοβολία, το περισσότερο φορτίο συλλέγεται στο βάθος κοντά στο ηλεκτρόδιο του εικονοστοιχείου. Η απομονωμένη από ηλεκτρικό φορτίο περιοχή δεν εκτείνεται μέχρι την πίσω πλευρά του αισθητήρα ακόμα και όταν η τάση λειτουργίας του φτάνει τα 1000 V. Για να κατανοήσουμε τα δεδομένα από το προφίλ συλλογής φορτίου πρέπει να λάβουμε υπόψη το γεγονός ότι το ηλεκτρικό φορτίο (τόσο τα ηλεκτρόνια και όσο και οι τρύπες) παγιδεύεται.

Πέραν του προφίλ συλλογής φορτίου ερευνήθηκε επίσης το προφίλ του χρόνου που χρειάζεται να ξεπεραστεί το κατώφλι. Ο χρόνος που χρειάζεται το φορτίο μέχρι να παρασυρθεί και να ξεπεράσει το κατώφλι μπορεί να υπολογιστεί αφαιρώντας τον χρόνο που η τροχιά προσπίπτει στο τηλεσκόπιο (t_{track}) από τον χρόνο στον οποίο ένα εικονοστοιχείο ενεργοποιήθηκε στην ΣυΜ (t_{hit}). Η προσομοίωση του χρόνου που χρειάζεται να ξεπεραστεί το κατώφλι βασισμένη στο θεώρημα του Ramo, το οποίο περιγράφει επαρκώς την συλλογή φορτίου σε ένα μη-ακτινοβολημένο αισθητήρα, αποτυγχάνει να περιγράψει τα δεδομένα. Λαμβάνοντας υπόψη στην προσομοίωση το μέσο χρόνο καθυστέρησης των ηλεκτρονικών (timewalk) βοηθάει στο να περιγραφεί σωστά το προφίλ του χρόνου που χρειάζεται να ξεπεραστεί το κατώφλι σε ένα ακτινοβολημένο αισθητήρα.

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