

Simulation of the ATLAS ALFA detector in comparison with testbeam data

Diplomarbeit im Fach Physik
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09. April 2010



Abstract

ALFA (Absolute Luminosity for ATLAS) is a scintillating fiber detector for the determination of the absolute luminosity. ALFA consists of eight Roman Pots, four on each side of ATLAS at a distance of 240 m. Each detector is made of scintillating fibers with quadratic cross section, glued in UV geometry on ten double sided layers.

The detectors are mounted in moveable Roman Pots and can approach the LHC beam up to 1.5 mm, to determine the luminosity from the differential t spectrum of elastically scattered protons using the optical theorem. This is done in special LHC calibration runs with large β^* , special focusing and low instant luminosity. The results of ALFA are needed for the calibration of ATLAS luminosity monitors like LUCID. This diploma thesis deals with the simulation of ALFA and the most recent testbeam campaign. A special focus is put on the comparison of results from simulation and testbeam.

Zusammenfassung

ALFA (Absolute Luminosity for ATLAS) ist ein Spurdetektor aus szintillierenden Fasern zur Bestimmung der absoluten Luminosität. ALFA besteht aus acht Roman Pots, d.h. vier Stationen, symmetrisch links und rechts im Abstand von ca. 240 m zu ATLAS. Jeder Detektor besteht aus szintillierenden Fasern, mit quadratischem Querschnitt, aufgeteilt auf 10 doppelseitige Ebenen in UV Geometrie.

Die Detektoren sind in beweglichen Roman Pots untergebracht und können bis auf 1.5 mm an den LHC Strahl herangefahren werden, um aus der Messung des differentiellen t Spektrums elastisch gestreuter Protonen mit Hilfe des optischen Theorems die Luminosität zu bestimmen. Dies geschieht in speziellen LHC Läufen mit grossem β^* , besonderer Fokussierung und niedriger instantaner Luminosität. Die Ergebnisse von ALFA werden zur Kalibration der ATLAS Luminositätsmonitore wie LUCID gebraucht.

Diese Diplomarbeit befasst sich mit der Simulation von ALFA und dem kürzlich zu Ende gegangenen Teststrahl. Insbesondere sollen die Ergebnisse aus Simulation und Testexperiment miteinander verglichen werden.

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1 Introduction

1.1 Large Hadron Collider

The Large Hadron Collider (LHC) is the latest and biggest particle accelerator in the world. It is located at CERN (Conseil Européen pour la Recherche Nucléaire) in Geneva (Switzerland) and takes advantage of the already existing accelerator complex and LEP tunnel. In 2000 the LEP (Large Electron Positron collider) was shut down after eleven years of successful operation to make room for the LHC in the tunnel. The tunnel complex has a circumference of almost 27 km and lies 100 m below ground. The large hadron collider is built to provide p-p collisions at 14 TeV center of mass energy and a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and Pb-Pb collisions at 5.5 TeV and a luminosity of $10^{27} \text{ cm}^{-2}\text{s}^{-1}$. The current plan is to run the LHC at half of its maximum energy, 7 TeV center of mass, for 18-24 months and to collect 1 fb^{-1} of data in this period. A shutdown will follow to be used for maintenance and magnet upgrades. The LHC will restart afterwards with its full energy of 14 TeV.

The protons and ions traverse several preaccelerators before they are finally injected into the LHC via a delivery line of 2.5 km length. They start out at a linear accelerator (linac2) before they are fed into the 600 m long proton synchrotron (PS). Once this stage is finished at 25 GeV the particles reach the 6.9 km long super proton synchrotron (SPS) where they are further accelerated up to 450 GeV. The last step is the LHC injection.

In order to provide the magnetic fields required to bend the protons on the track, superconducting magnets are used which reach a maximum field strength of 8 T at 7 TeV beam momentum. There will be 2808 proton bunches, each containing up to 10^{11} protons, circulating in the machine at a nominal bunch spacing of 25 ns [1].

At the LHCs four interaction points (IP) four big experiments exist. ALICE (A Large Ion Collider Experiment), CMS (Compact Muon Solenoid), LHCb (Large Hadron Collider beauty) and ATLAS (A Toroidal LHC Apparatus), the latter being subject of this thesis. Additionally there are two smaller experiments, TOTEM (Total Elastic and diffractive cross section Measurement) and LHCf (Large Hadron Collider forward). ATLAS and CMS are both general purpose detectors and are most famous for their potential to discover the Higgs boson while they use a complementary approach to achieve this goal [2]. ATLAS is subject of Sec. 1.2.

LHCb is dedicated to studying the properties of B mesons ($b\bar{b}$) and the answer to the question why there is an unbalance between matter and antimatter in the universe. As LHCb is designed to be a fixed target experiment the reaction products will emerge to forward directions. This is why LHCb does not

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show the forward-backward symmetry the other big LHC experiments have [3]. ALICE is specialized on studying the properties of quark-gluon plasmas which will be created from the collision of heavy ions like lead [4].

While the cavities for ALICE and LHCb were already there from LEP times, the cavities for the largest two experiments, ATLAS and CMS, had to be built from scratch.

TOTEM is a small detector, addressed to the measurement of the total proton-proton cross section with a luminosity independent method [5]. LHCf is a forward detector located on both sides of ATLAS at a distance of 140 m. It will deliver results that will help to understand cosmic rays at very high energies, by measuring neutral particles in the very forward region [6]. An overview of the entire complex is given in Fig. 1.

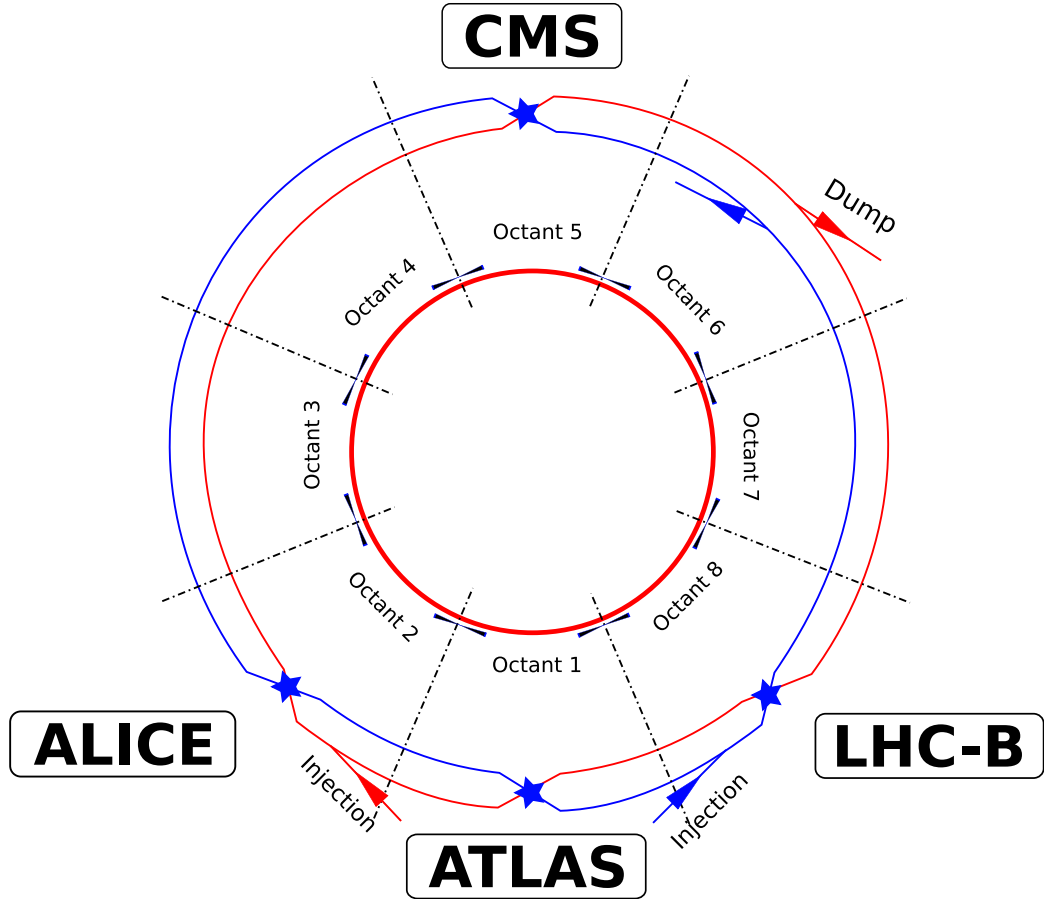


Figure 1: Overview of the entire LHC complex excluding the preaccelerators.

1.2 ATLAS Detector

The ATLAS (A Toroidal LHC ApparatuS) experiment is a general purpose detector for probing p-p collisions. Like most particle physics experiments nowadays it is operated by a huge collaboration consisting of several thousand physicists, technicians and students at 150 universities in 34 countries. With its 44 m in length and 25 m in height at a weight of 7000 tons it is the largest particle physics experiment ever designed. The requirements for ATLAS, defined by a set of processes which cover the new phenomena one expects to observe, have set new standards on detector design. The main purpose is the search for the yet missing particle in the standard model, the Higgs boson. The full ATLAS detector is shown in Fig. 2. In the following it shall shortly be described, while further details can be found in [7].

The azimuthal angle ϕ is measured around z , the beam direction, while the polar angle θ is measured against the z axis. The pseudorapidity η is defined for primary vertex particles by

$$\eta = -\ln \tan (\theta/2) \quad (1)$$

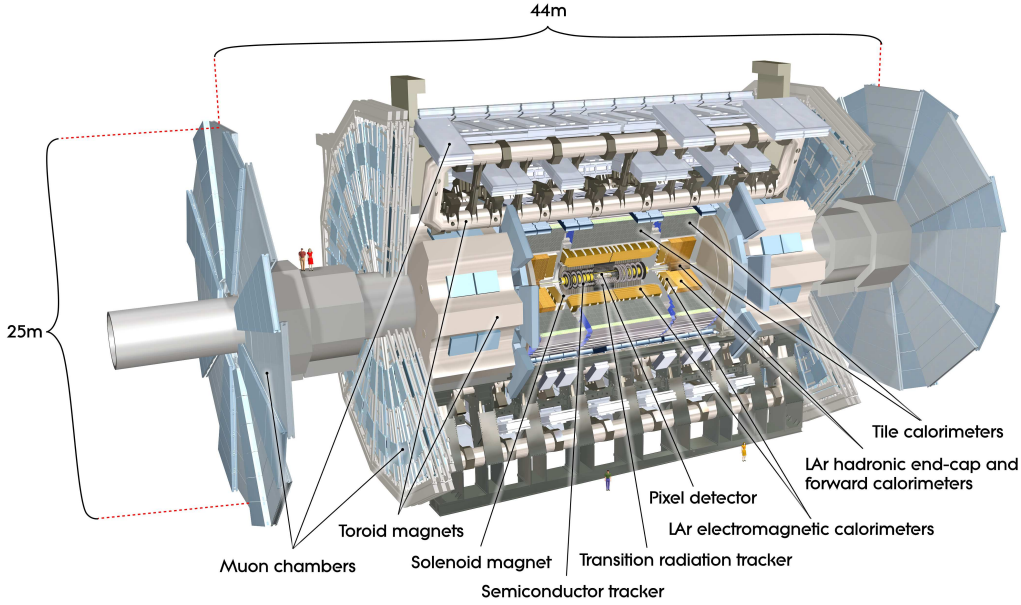


Figure 2: Cut away view of the full ATLAS detector. Its dimensions are 25 m height and 44 m length at a weight of 7000 tons.

1.2.1 Inner detector

Closest to the IP is the inner detector, consisting of pixel detectors, semiconductor and transition radiation trackers. In order to fulfill the requirements imposed by the benchmark physics processes, high resolution momentum and vertex measurements have to be made. Due to the high track density, created about 1000 particles emerging from the IP every 25 ns, detectors with very fine granularity have to be placed closest to the IP since they will provide very valuable information for later pattern recognition, when tracks are calculated from the actual hits. These detectors are the pixel detectors with a granularity of $50 \times 400 \mu\text{m}^2$ and altogether 80.4 million readout channels. While running at design luminosity the pixel detectors will have to be replaced approximately every three years due to radiation damage caused by the high doses deposited.

To bigger radii the pixel detectors are followed by the semiconductor tracker (SCT). The SCT consist of stereo pairs of silicon microstrip layers, at a mean strip pitch of $80 \mu\text{m}$. The pixel detectors and SCT provide primary and secondary vertex measurements in the range of $|\eta| < 2.5$. The utmost part of the inner detector is the transition radiation tracker (TRT), which is made of 4 mm diameter straws. They provide a large number of hits per track which makes them very important for the momentum measurement. The lower resolution is made up for with a longer measured track length. The TRT contributes to the tracking in the range $|\eta| < 2.0$ and provides a total of 351 000 readout channels.

The inner detector is shown in Fig. 3. It is enclosed in a 2 T magnetic field which is generated by a superconducting solenoid and is needed for momentum measurement.

1.2.2 Calorimeters

The next important ATLAS device is the calorimeter. There is an electromagnetic calorimeter and a hadronic calorimeter, to measure the energy of electrons, photons and hadrons respectively.

In order to detect particles that escaped the detector, like e.g. neutrinos, one has to measure the missing transverse energy. For this the calorimeter needs a big η coverage. The ATLAS calorimeter covers the range up to $|\eta| < 4.9$. Furthermore the hadronic calorimeter has to be big enough to limit the punch through of hadrons into the muon spectrometer in order to reduce noise in the latter. However, it is also important to notice that a bigger calorimeter would have an impact on the size of the muonic spectrometer and thus a huge economic impact. The calorimeters are sampling calorimeters, consisting of

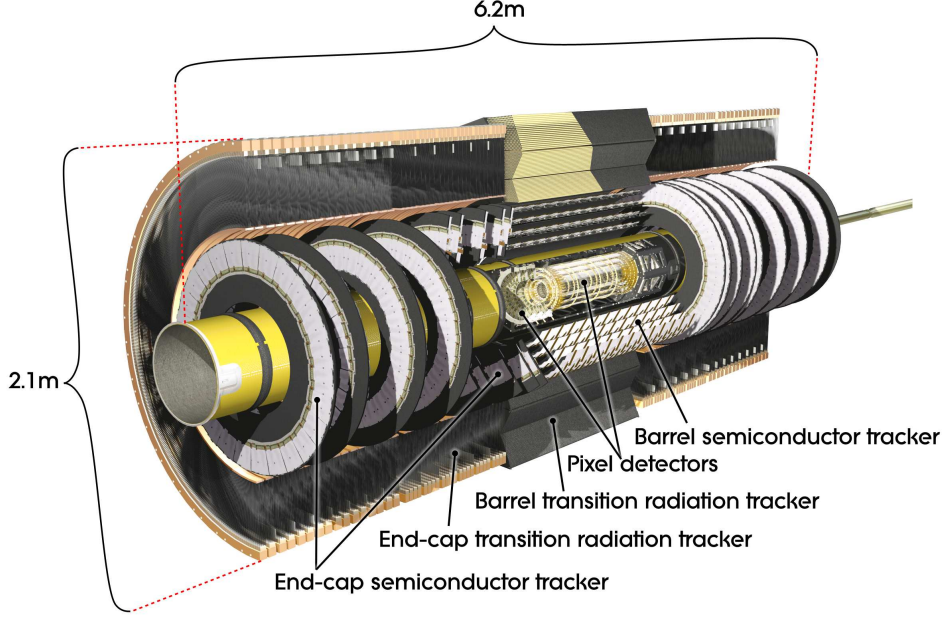


Figure 3: Detailed view of the ATLAS inner detector elements, closest to the IP.

a stopping part and an active sampling part. The required energy resolution of the electromagnetic calorimeter is set by the requirements that energy and momentum resolution of the Higgs decaying to photons and electrons dictate.

The electromagnetic part consist of a barrel and two endcap components, both of which provide full azimuthal coverage. It is made of lead absorber plates, which give the shower development, and liquid argon (LAr) as sampler, both in accordion shape. In the barrel region the calorimeter consists of four sampling layers. A presampler, a first sampling with very fine granularity in η , a second sampling where most of the energy will be deposited due to the size of 16 radiation lengths, and a third sampling with an even coarser η resolution, which is fine due to the big cluster size at that stage of showering.

The electromagnetic calorimeter is followed by the hadronic calorimeter. It consists of several parts. The central barrel, including the extended barrels, cover the region up to $|\eta| < 1.7$ and are made of steel absorbers with scintillating tiles as active sampling part. The hadronic end cap calorimeter is a sampling liquid argon calorimeter as well and covers the region from $|\eta| = 1.5$ to $|\eta| = 3.2$. It is made of copper absorber plates and an electrostatic transformer to collect the ionization signal in the LAr gaps.

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The LAr forward calorimeter (FCal) consists of copper plates for electromagnetic and tungsten plates for hadronic measurements. The FCal is active in the region $0.8 < |\eta| < 1.7$. The calorimetry system is shown in Fig. 4.

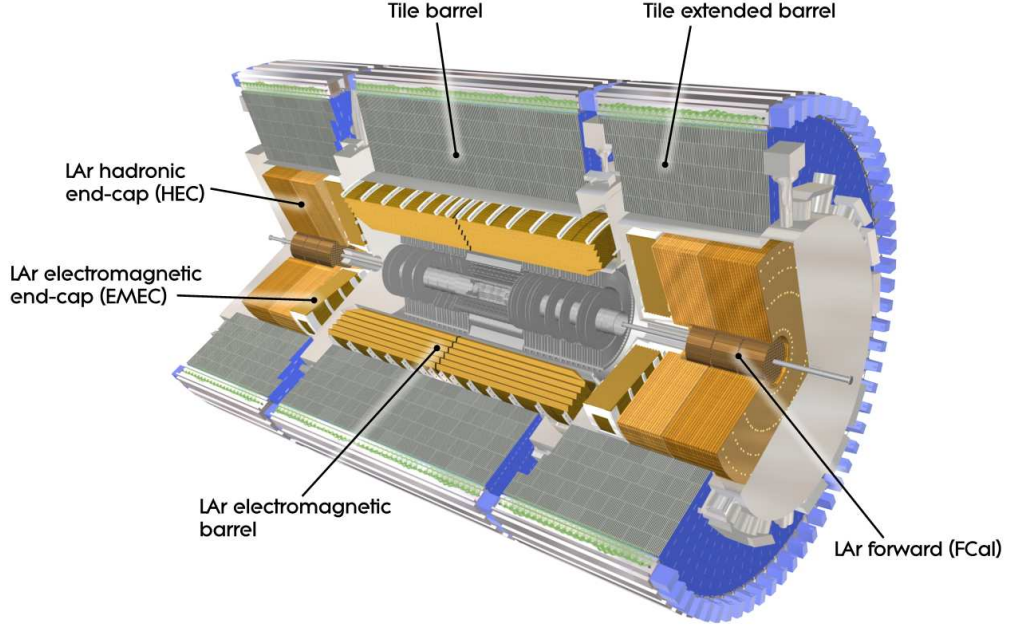


Figure 4: Overview of the ATLAS calorimeter.

1.2.3 Muon spectrometer

The utmost part of the ATLAS detector is the muon spectrometer. It is shown in Fig. 5. It consists of two major parts, barrel and endcap region, and is mainly made of monitored drift tubes (MDT). In the barrel region these are arranged in cylindrical layers, while behind the endcaps they are arranged in planes. In the large $2.0 < |\eta| < 2.7$ regions the MDTs are replaced with cathode strip chambers (CSC) to stand the high interaction rates. The muon spectrometer has its own trigger which covers the range $|\eta| < 2.4$.

1.2.4 Trigger system

The ATLAS trigger system is a very important module of the detector. While most of the events are considered to be “known physics”, the trigger system

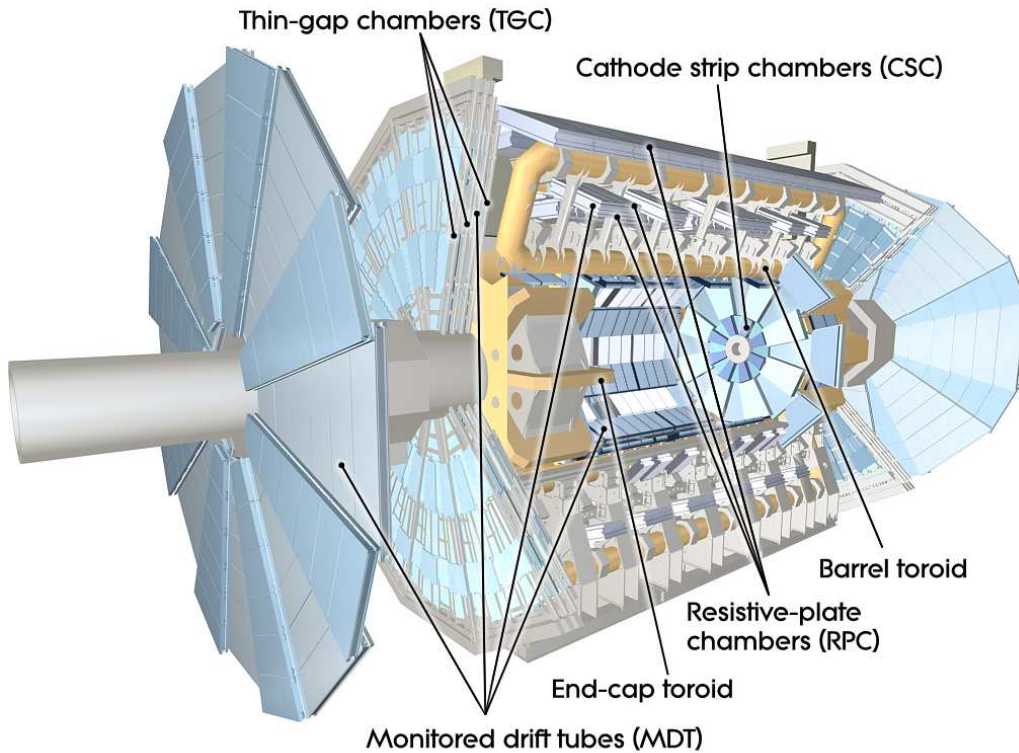


Figure 5: Overview of the ATLAS muon spectrometer.

has the important task of selecting the events which are presumably interesting and could be new physics. Not only this, but also the fact that data can only be written to disk at a rate of 200 Hz, while events will be produced at a much higher rate of tens of MHz. The trigger system consists of three parts: The Level-1 (L1) and Level-2 (L2) trigger, and the event filter. L1 is entirely based on custom made electronics, while the high level trigger (HLT, consisting of L2 and event filter) is based on usual PCs. The L1 trigger will look for events which contain e.g. high p_T muons, or events with large missing transverse energy and define regions of interest for L2. This will reduce the data rate to 75 kHz. The event information is stored in pipelines in the readout electronics and passed to the L2 trigger if it is accepted, which makes it necessary for the L1 to decide within $2.5 \mu\text{s}$. L2 will make decisions using the full detector granularity based on the regions of interest from L1 and pass the accepted events to the event filter, which is basically a full scale physics analysis, within 40 ms. L2 will reduce the rate down to 3.5 kHz. The event filter will do the last cuts and write events at a rate of approximately 100 Hz,

1.3 Mbyte each, on average after four seconds of processing.

1.2.5 Forward detectors

There are three forward detectors belonging to ATLAS. These are LUCID, ZDC and ALFA.

LUCID (Luminosity measurement using Cerenkov Integrating Detector) is a Cerenkov tube based luminosity detector located at ± 17 m from the IP. However, it can only determine the luminosity relative to some calibration. This luminosity calibration will be provided by ALFA, which is described in Sec. 2. For the time without ALFA installed in the tunnel the calibration will come from machine parameters, but with a large error of $\frac{\Delta L}{L} \approx 20\%$.

ZDC, the zero degree calorimeter, is localized at ± 140 m and is made to measure neutrons in the very forward region ($|\eta| > 8.3$) originating from heavy ion collisions.

1.3 Luminosity Determination

The luminosity L depends on properties of the accelerator and is given by machine parameters

$$L = \frac{N_1 N_2 f}{A} \quad (2)$$

where N_i is the number of particles in the bunch i distributed uniformly over the area A , where the bunches collide with frequency f . Since the number dN of events observed in time dt is basically given by

$$\frac{dN}{dt} = \sigma \cdot L \quad (3)$$

and one wishes to have either a high luminosity or a large cross section σ in order to get as many events as possible. Since the cross section is fixed by energy and most of the times to be determined, a large and well known L is desired, as this is what will mainly determine the final error $\frac{\Delta \sigma}{\sigma}$.

1.3.1 Elastic Scattering and optical theorem

To understand the luminosity determination with ALFA, some scattering theory from quantum mechanics is necessary.

For this the following assumptions are made:

- A thin target

- Low projectile density, so interactions between projectiles are negligible
- Each projectile particle has fixed momentum and energy values

With these assumptions the number of particles scattered to the solid angle $d\Omega$ is given by

$$\frac{dN_{\text{scat}}}{dt} = d\Omega J_{\text{in}} N_{\text{target}} \frac{d\sigma}{d\Omega} \quad (4)$$

where J_{in} is the current density of incoming particles, N_{target} is the number of targets and $\frac{d\sigma}{d\Omega}$ is the differential cross section for the interaction.

Under the assumption that the scattering can be described as an incoming plane wave, and after the particle has been scattered it is well described by the plane wave part going straight through and an additional spherical wave, which describes the scattered part, the wave function can be written as

$$\Psi(\vec{r}) = A \left[e^{ikz} + f(\theta) \frac{e^{ikr}}{r} \right] \quad (5)$$

Here $f(\theta)$ is the scattering amplitude, and e^{ikr}/r the outgoing spherical wave. A is just a normalization factor. For these calculations only the stationary solution of Schrödinger's equation is of interest and thus the time dependent factor $e^{-iEt/\hbar}$ is omitted.

Furthermore the particle current density can be calculated from the wave function using

$$\vec{j} = \frac{\hbar}{2mi} \left(\Psi^* \vec{\nabla} \Psi - \Psi \vec{\nabla} \Psi^* \right) \quad (6)$$

where m is the mass. This gives the fundamental relationship between differential cross section and scattering amplitude

$$\frac{d\sigma}{d\Omega} = |f(\theta)|^2 \quad (7)$$

Particle number conservation yields

$$\int_{S \rightarrow \infty} \vec{j} d\vec{F} = 0 \quad (8)$$

with a surface S extending to infinity. Thus Eq. 5 can be plugged into Eq. 6 and after all the integration can be carried out which finally leads to the optical theorem

$$\sigma = 4\pi \text{Im}(f(\theta = 0)) \quad (9)$$

The detailed derivations can be found in literature, e.g. [8].

1.3.2 The ALFA way to determine the luminosity

Having a closer look at Eq. 9 it can be seen that measuring forward scattering will provide information about the luminosity since

$$\frac{dN}{dt} = \sigma \cdot L = 4\pi \text{Im}(f(\theta = 0)) \cdot L \quad (10)$$

ALFA will determine L from the t spectrum of elastically scattered protons, where t is the mandelstam variable given by the four momentum transfer between the protons

$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2 \approx (p \cdot \theta)^2 \quad (11)$$

where the last step is only valid for small scattering angles. The corresponding Feynman diagram is shown in Fig. 6.

For small values of t the differential t spectrum can be written as

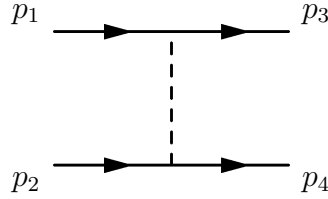


Figure 6: t-channel Feynman diagram.

$$\frac{dN}{dt} = L\pi|f_C + f_N|^2 \approx L\pi \left| -\frac{2\alpha}{|t|} + \frac{\sigma_{\text{tot}}}{4\pi}(i + \rho)e^{-B|t|/2} \right|^2 \quad (12)$$

Here L is the luminosity, t the mandelstam variable t , $\alpha \approx \frac{1}{137}$ the fine structure constant, σ_{tot} the total cross section, ρ the proportion of real to imaginary part in the scattering amplitude, and B the nuclear slope. The scattering amplitude has two contributions, the nuclear scattering amplitude f_N and the coulomb contribution f_C . The theoretical spectra are shown in Fig. 7 with the linear representation in Fig. 7(a) and the more convenient logarithmic representation shown in Fig. 7(b). The latter one nicely showing the coulomb-nuclear interference region as a local minimum.

1.3.3 Alternative ways to determine L

Certainly the determination of L through elastically scattered protons is not the only way. Another way is to use well calculable QED processes. The

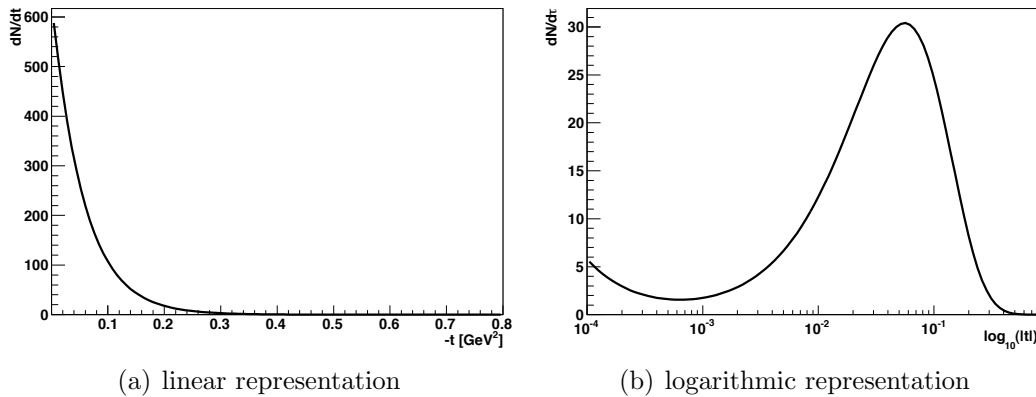


Figure 7: Theoretical distribution in the linear representation and the convenient logarithmic representation with the coulomb-nuclear interference region visible as a local minimum.

most promising among which is the pair production of muons by two photon exchange

$$pp \rightarrow pp + \mu^+ \mu^- \quad (13)$$

Due to the hard trigger constraints for muons on p_T the cross section for this process is very small (1 – 15 pb), which means that it can only be used for offline calibration of a stable high-rate monitor after a certain time of operation [9].

Another method is to determine the luminosity from machine parameters gained from the beam monitors. However, this is difficult since the size of the beam at the IP cannot be measured directly and has to be extrapolated from external measurements. This is used with the Vernier scan (van der Meer scan), where the beams are swept across each other and the interaction rate is measured as function of beam offset using an external device like LUCID. The interaction rate can then be plotted as function of beam offset, which will result in a Gaussian curve. From this the luminosity can be extracted [10]. Like stated before this method will yield large errors in the range of 10%, though these are only estimates.

A better possibility is the measurement of production rates of W and Z gauge bosons for luminosity determination. The cross section for these processes is well known from NNLO QCD calculations and are therefore well suited for luminosity determination with errors in the percent range [11].

1.4 Beam optics with parallel to point focussing

In the following a short overview over the beam transport shall be given. The aim is to calculate the position of a trajectory in a transverse plane away from the interaction point (IP). Using the thin lenses approximation this is a linear transformation and given by

$$\begin{pmatrix} u(s) \\ u'(s) \\ \Delta p/p \end{pmatrix} = M \cdot \begin{pmatrix} u^* \\ u'^* \\ \Delta p^*/p \end{pmatrix} \quad (14)$$

where u is either x or y , and u' the trajectory slope. The values marked with a star are those at the IP to which the transportation matrix M is applied. M is given by

$$M = \begin{pmatrix} \sqrt{\beta/\beta^*}(\cos \Psi + \alpha^* \sin \Psi) & \sqrt{\beta\beta^*} \sin \Psi & D_u \\ \frac{(\alpha^* - \alpha) \cos \Psi - (1 + \alpha\alpha^*) \sin \Psi}{\sqrt{\beta \cdot \beta^*}} & \sqrt{\frac{\beta^*}{\beta}}(\cos \Psi - \alpha \sin \Psi) & D'_u \\ 0 & 0 & 1 \end{pmatrix} \quad (15)$$

Here Ψ is the phase advance, β is the betatron function, D is the dispersion and α is the spatial derivative of β . In the case of elastic scattering, the momentum loss can be neglected. Executing the matrix multiplication yields for the coordinates x, y

$$u = \sqrt{\beta/\beta^*}(\cos \Psi + \alpha^* \sin \Psi)u^* + \sqrt{\beta\beta^*} \sin \Psi \cdot u'^* \quad (16)$$

$$= M_{u,11} \cdot u^* + M_{u,12} \cdot \theta_u^* \quad (17)$$

with usage of $u'^* = \tan(\theta_u^*) \approx \theta_u^*$ for small angles θ_u^* . In order to cancel the vertex contribution, the left-right difference is taken and keeping in mind that the scattering angles are equal in magnitude but opposite in sign. This results in

$$u_L - u_R = 2M_{u,12} \cdot \theta_u^* \quad (18)$$

Solving for the desired θ^* gives

$$\theta_u^* = \frac{u_L - u_R}{2L_{\text{eff},u}} \quad (19)$$

$$L_{\text{eff},u} = \sqrt{\beta\beta^*} \sin \Psi \quad (20)$$

with the effective lever arm $L_{\text{eff},u}$. This is all needed for reconstruction of t from the measured proton positions in ALFA:

$$-t = p^2 (\theta_x^2 + \theta_y^2) \quad (21)$$

Now it is possible to estimate the smallest t values possible to measure. These events will be particles unscattered in the horizontal plane and with minimum scattering in the vertical plane, i.e. $\theta_x^* = 0$. Using Eq. 19 and Eq. 20 gives $y = \sqrt{\beta\beta^*}\theta_y^*$ and thus

$$-t_{min} = \frac{p^2 y_d^2}{\beta\beta^*} \quad (22)$$

with y_d the distance up to which ALFA can approach the beam. Since $t_{min} \sim \frac{1}{\beta\beta^*}$ it can be concluded that β and β^* should be rather big. Using realistic numbers results in the requirements on the optics:

1. $\beta^* > 2600$ m
2. $\beta > 70$ m
3. $\alpha^* \approx 0$
4. negligible dispersion
5. 90° phase advance in the vertical plane

The 90° phase advance ensures that all particles scattered under the same angle will be focused on the same point on the detector, independent of their interaction vertex location, the so-called parallel to point focussing shown in Fig. 8. Now a position in the LHC ring has to be found that fulfills these

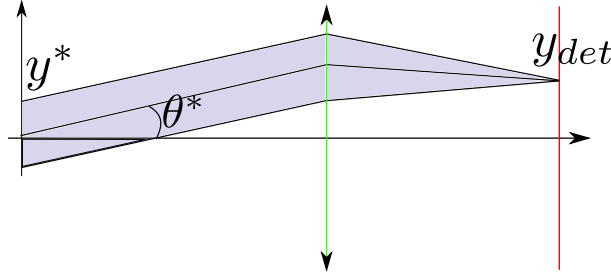


Figure 8: Parallel to point focussing. Protons scattered under the same angle θ^* will be focused on the same y at ALFA.

requirements. The solution found is shown in Fig. 9. It requires that the Roman Pots are placed between quadrupoles Q6 and Q7, 240 m away from the IP. This solution has a $\beta^* = 2625$ m [12].

1 INTRODUCTION

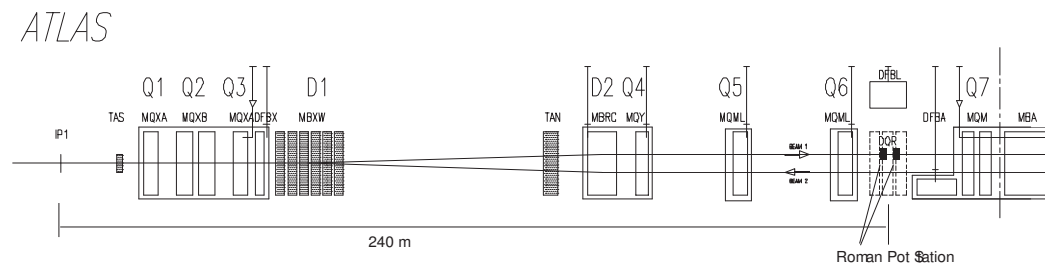


Figure 9: Optics solution found that fulfills all requirements imposed.

2 ALFA Detector

ALFA (Absolute Luminosity For ATLAS) is a detector designed to determine the absolute luminosity from elastic scattering in the coulomb-nuclear interference region. At the nominal LHC energy of 14 TeV this region corresponds to $t = 0.00065 \text{ GeV}$, or scattering angles of the size of 3.5 mrad, $|\eta| \sim 10$. This luminosity will be used as a calibration for LUCID. The small scattering angles make it inevitable for ALFA to be as close as possible to the beamline and use an edgeless detector technology in order to minimize the dead area. Furthermore the

estimated radiation doses are dominated by beam halo contributions which are estimated to about 100 Gy per year. This requires the detector to be modestly radiation hard. Since all this is fulfilled by a scintillating fiber detector, this is the design chosen for ALFA.

The importance of ALFA can be seen from Fig. 10, where the error on the determined cross section of various processes is shown dependent on the error from luminosity determination. ALFA aims at a luminosity determination precision of $\frac{\Delta L}{L} < 3\%$.

ALFA will determine L exploiting the method described in Sec. 1.3.2. Starting from the measured differential t spectrum, a fit of Eq. 12 will be applied and provide the desired values. One should notice however, that only two stations would be necessary in order to determine L using this method. Yet ALFA has four stations, to suppress noise from background events by measuring in coincidence, and to get a better reconstructed t value by taking the average

$$t = \frac{1}{2}(t_1 + t_2) \quad (23)$$

In the following a short overview of the ALFA detector will be given. Details can be found in [12].

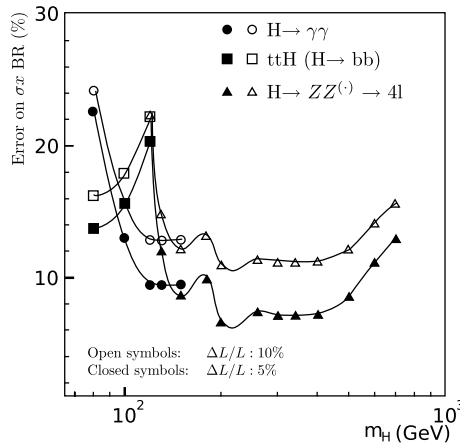


Figure 10: Error on the cross section from luminosity determination [13].

2.1 Roman Pots

The Roman Pot technology has been used successfully at various experiments where the detector had to be moved very close to the actual beamline. At the LHC they are used by TOTEM and at ATLAS with ALFA.

In the case of ALFA the Roman Pots will bring the detectors to a minimum distance of about 10σ , or 1.3 mm, to the beam. This is schematically illustrated in Fig. 11.

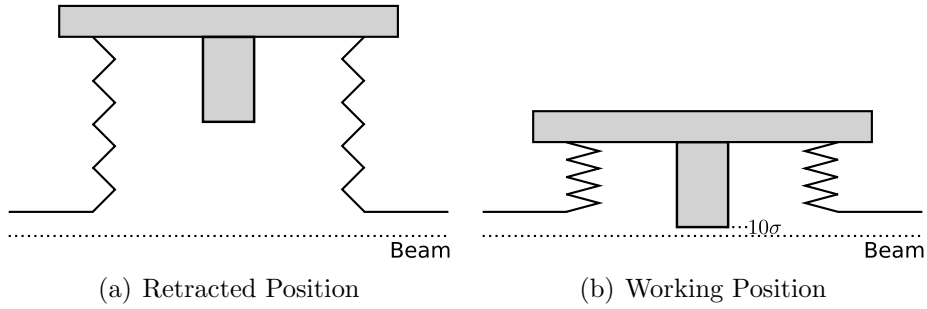


Figure 11: Roman Pot schematically.

A Roman Pot unit is a system of two Roman Pots that allows the independent movement of upper and lower pot, and thereby detector, to the working position. This is done via a high precision roller screw that is moved by a step motor. The maximum extrusion from the beam is 58 mm. For ALFA there will be two Roman Pot units separated by 4 m at a distance of 240 m on both sides of ATLAS. In total ALFA has eight Roman Pots. A full Roman Pot unit is displayed in Fig. 12.

The pot will house the actual detector. Since the detector has to get as close as possible to the beam, the bottom window ought to be especially thin. It has a thickness of only $200\ \mu\text{m}$. The walls perpendicular to the beam are machined down to $500\ \mu\text{m}$, where the other walls have a thickness of 2 mm.

In order to get the pots into the correct working position the coarse positioning is done by reading the beam position from the LHC Beam Positioning Monitors (BPMs). Then the pots are fine positioned by equalizing the count-

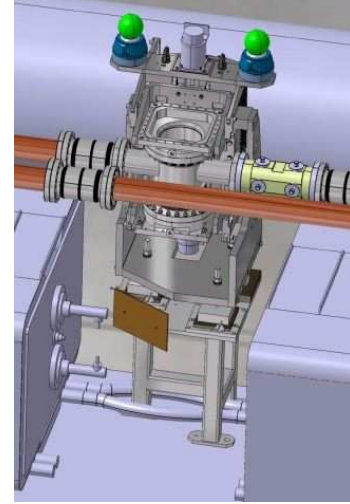


Figure 12: Roman Pot unit.

ing rates in upper and lower pot. The relative position of the pots in each unit can be determined from the overlap detectors, Sec. 2.2.2. The entire ALFA setup can be seen in Fig. 13. The name “Roman” comes from the

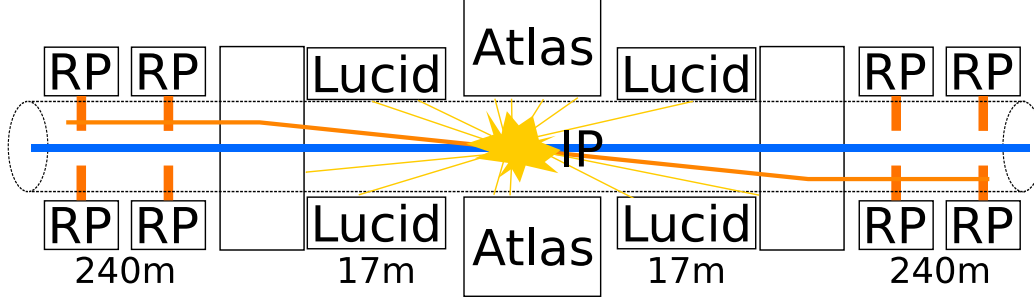


Figure 13: Overview of the entire ALFA setup including all eight Roman Pots. Schematically shown are the positions of LUCID and ATLAS.

fact that the first group using these pots was the CERNRome group in the 1970s to study physics at CERNs ISR (Intersection Storage Ring).

2.2 Scintillating Fiber detector

The fibers used with ALFA, SCSF-87 from Kuraray, are single cladded with squared $0.5 \times 0.5 \text{ mm}^2$ cross section and a cladding thickness of $10 \mu\text{m}$, which gives a sensitive area of $480 \times 480 \mu\text{m}^2$ per fiber. In order to minimize optical crosstalk between adjacent fibers, each fiber is coated with an aluminium film of 100 nm thickness.

A charged particle may now traverse the fibers and excite the atoms therein. These will relax by the emission of scintillation light. For the scintillation light not to be absorbed again, the fibers are doped with a wavelength shifting material, that will absorb and re-emit the light in the visible range, thus making the use of regular photomultiplier tubes (PMT) possible.

Tests have shown that at doses of 1 kGy the light yield will drop noticeably by $\sim 10\%$, which is far away from the doses estimations for ALFA. Therefore these are perfectly suited for the use in ALFA.

2.2.1 Main Detectors

The main detector consist of ten planes in UV geometry. Each plane is made of two layers with 64 fibers each. Both layers have a relative angle of 90° with respect to each other. The planes are staggered by multiples of $500 \mu\text{m}/10 \cdot \sqrt{2}$ which leads to an effective fiber pitch of $50 \mu\text{m}$. Since the

beam spot size at the ALFA position is $\sigma_d = 130 \mu\text{m}$, the spatial detector resolution should be much smaller in order to not be dominated by the latter. The spatial resolution of a perfect detector is given by $50 \mu\text{m}/\sqrt{12} \approx 14.4 \mu\text{m}$. This coming from the fact that the effective fiber overlap of ten fibers is $50 \mu\text{m}$ and that the protons will be distributed uniformly along those $50 \mu\text{m}$. Then σ can be calculated from simple probability calculus to

$$\sigma^2 = \langle x^2 \rangle - \langle x \rangle^2 = \int_0^A x^2 \frac{1}{A} dx - \left(\int_0^A x \frac{1}{A} dx \right)^2 = \frac{A^2}{12} \quad (24)$$

where $A = 50 \mu\text{m}$ is the effective overlap of ten consecutive staggered fibers. However, it is important to notice that this does not take the $10 \mu\text{m}$ of cladding into account. Earlier testbeams and simulations have shown the real resolution to be in the range of $30 \mu\text{m}$, which is considered to be reasonable compared with $\sigma_d = 130 \mu\text{m}$.

At the lower detector edge the fibers are cut at an angle of 45° . The ones on the left and right edge at an angle of 90° . Since half of the light will be directed away from the multianode photomultiplier tubes (MAPMT) used, special care was taken for the optical quality of the cut edges. Reason being that they will serve as a mirror and reflect this light by total reflection to the PMTs. The fiber ends cut under 90° are also coated with an Al film, whereas the 45° cut ends are uncoated, since this was found to result in the highest light yield. The fibers are routed over 25 cm and connected in groups of 64 to a 64 channel MAPMT, a Hamamatsu R7600.

The active area of the detector is defined by the overlap region of the different layers. However, the fibers are also sensitive outside this area, where they are only used as a lightguide and false hits could be generated by beam halo particles. Therefore two plastic scintillator trigger tiles of 3 mm thickness are mounted close to the UV planes, to ensure the number of false hits is minimized. Further reduction from false beam halo hits will be achieved from coincidence measurements between all stations.

2.2.2 Overlap Detectors

It is known that the beam spot position can vary from fill to fill by a few mm. A vertical misalignment of the pots will be evident in the data by asymmetric occupancy distributions. So will be a horizontal misalignment. Both cases can be corrected offline and are therefore no problem. Only a symmetric vertical misalignment of both pots will not show up in the data and cannot be corrected. Thus the relative vertical alignment of both pots has to be known to a precision well below $10 \mu\text{m}$.

This is ensured by so-called overlap detectors which operate in the beam halo

regions. Each pot has two overlaps, one left, one right. Both consist of three layers of 30 fibers, which are of the same type as the main detectors fibers. The planes are staggered by multiples of $500\text{ }\mu\text{m}/3 \approx 167\text{ }\mu\text{m}$, which is also the effective pitch size.

Again the active area is defined by a 3 mm plastic scintillator trigger tile. The final active area is then $6 \times 15\text{ mm}^2$ for each overlap. The overlaps position with respect to the main detector is well known, so once a halo particle traverses the overlap detectors of both upper and lower pot, a y position can be reconstructed. The distance of both pots can then be calculated from

$$d = \frac{1}{N} \sum_i (y_{1,i} - y_{2,i}) \quad (25)$$

The required precision is achieved by acquiring high statistics. Once the pots have a distance of 8.5 mm from the beam axis the overlaps start overlapping and the maximum overlap is 15 mm. The main and overlap detectors are shown in Fig. 14.

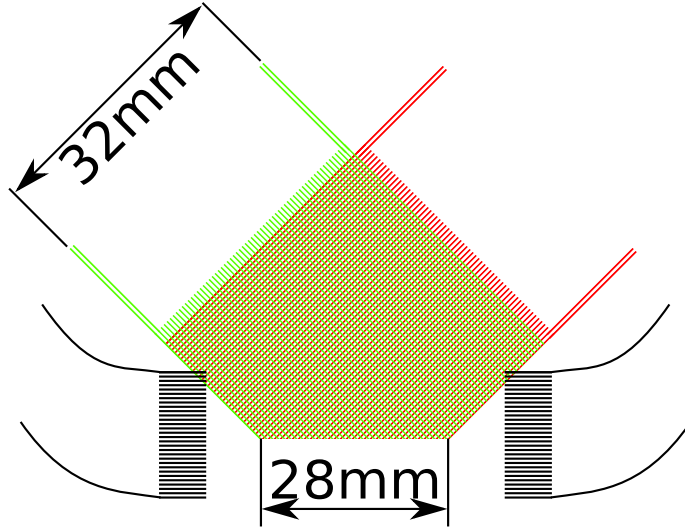


Figure 14: ALFA main detector active area in UV geometry and the overlap detectors on the left and right.

2.2.3 Metrology

Since every fiber is glued by hand it cannot be at its nominal position. There are systematic offsets and thus the fiber positions, described by straight lines,

have to be gained individually for each fiber:

$$y = A \cdot x + b \quad (26)$$

This has been done and metrology files have been created for each plane. For the individual fiber the position is measured along five reference lines, as shown in Fig. 15. A straight line fit is applied to these points as a good approximation of the real fiber shape. The metrology files contain the layer number, fiber number, fiber inclination A and fiber offset b .

Another possibility would have been to measure metrology by shooting particles on the planes using an external reference telescope. From this one can determine the fiber positions from the external information and the fibers that saw light. This has successfully been done at other experiments like e.g. the Hermes recoil detector. It will be later investigated also for ALFA in Sec. 4.5.

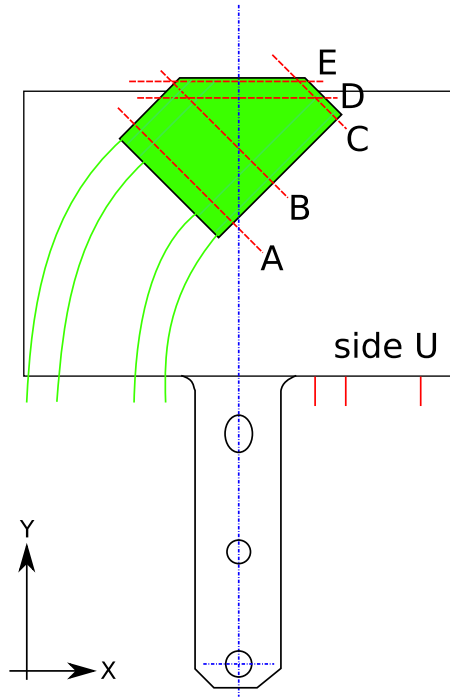


Figure 15: Metrology measurement: The fiber positions are measured along the five reference lines A to E. A straight line fit gives the fiber equation.

3 Simulation

Since ALFA is not yet running in the LHC the only source of information comes from simulation and testbeam. The simulation setup and results shall be described and discussed in this section. Since the simulations are very CPU intensive, most of them were parallelized and ran on the National Analysis Facility (NAF) grid provided by DESY (Deutsches Elektronen Synchrotron).

3.1 Full Chain

The main task of ALFA is the determination of the absolute luminosity calibration for the ATLAS experiment. In the long run the goal is to have the entire simulation running in the ATHENA framework. Since this is not entirely possible yet, the simulation has been divided to several smaller parts. The individual components will be described in detail in further subsections. ALFA will detect elastically scattered protons. These protons are generated at the interaction point (IP) by the Monte Carlo (MC) generator Pythia8. The transport of the protons from the IP to the Roman Pots is done by the beam transport program MadX. Once finished, all proton information is available at the first Roman Pot station on each side of ATLAS. The protons are then injected into the Geant4 simulation, which will provide boolean hitmaps as output. For the 4 m distance between two adjacent RPs no further beam transport program is needed since this region is field free and therefore it is sufficient to let Geant4 do the transport. This is in particular important to see shower effects from the first pot on the second one. The gained hitmaps are used for tracking, and with the overlap algorithm the particle positions are reconstructed. These are used for the t-spectrum reconstruction and the final fit to determine the luminosity. The full chain is summarized in Fig. 16.

3.2 Event Generation with Pythia8

The event generation at the IP is done with Pythia8 [14]. Pythia8 is a MC based event generator written in C++, focused on but not limited to LHC and Tevatron applications.

Based on input parameters Pythia will generate elastically scattered protons at the IP. The used parameters are best guess estimates and may be changed iteratively later, once better values are known. In particular these are the total cross section σ_{tot} , the b-slope B of the nuclear term, the proportion ρ of real to imaginary part of the forward scattering elastic amplitude, the param-

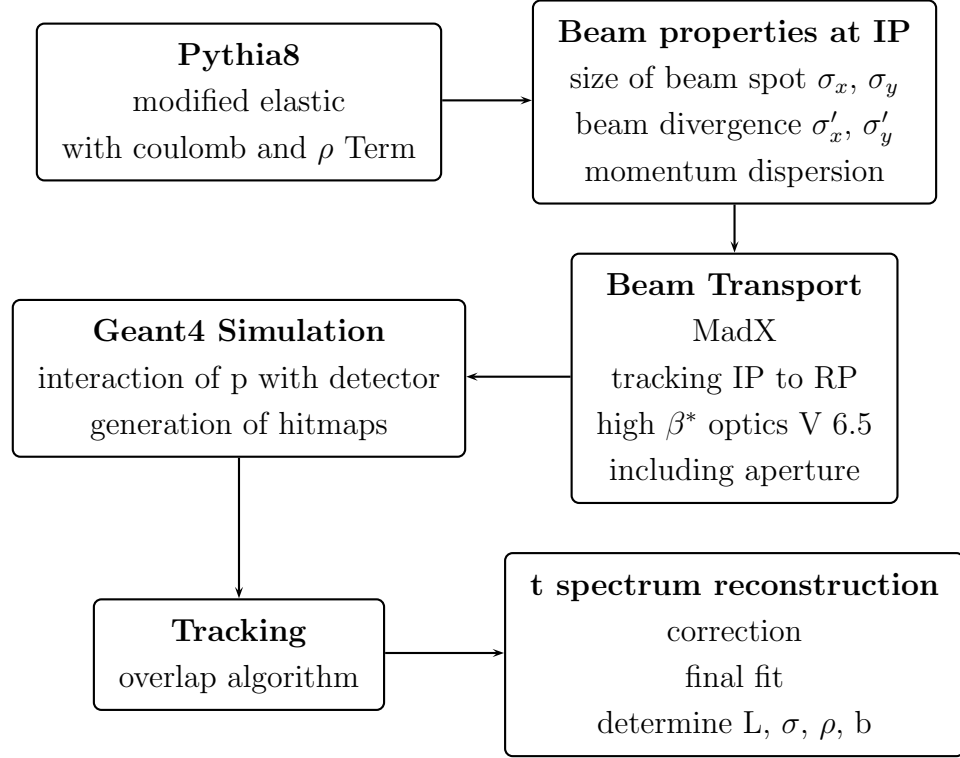


Figure 16: Full simulation flowchart.

eter λ for the proton form factor, the coulomb phase factor γ_E and finally the proton momentum p , which are summarized in Tab. 1. Furthermore beam momentum and vertex smearing are possible and are also applied. The vertex smearing is done in the x-y plane in the shape of a two dimensional Gaussian. The beam transverse momentum is smeared with a two dimensional Gaussian, whereas the longitudinal momentum is set as a triangular shaped function. With these parameters a sample of protons is generated and stored in a format suitable for later usage with MadX.

3.3 Beam Transport with MadX

The beam transport from the IP to the Roman Pots is done with MadX. MadX is developed by the CERN accelerator group and written in C and Fortran, which is unfortunate since it makes it hard to use for integration with ATHENA, the ATLAS computational framework [17].

MadX reads plain text files with input parameters for each proton, i.e. vertex position and momentum, and tracks them to the Roman Pots. This is done

Parameter	Value
σ_{tot} [mb]	111.6
B [GeV ⁻²]	18
ρ	0.1383
λ	0.72
γ_E	0.577
p [GeV]	7000

Table 1: Summary of Pythia input parameters [15][16].

by calculating the required fields and the particle trajectory therein. The description of all LHC elements comes from the LHC optics V6.500.

MadX uses the so called thin lenses approximation, which is basically just matrix multiplications. There is also an extension available, called MadXP, in which thick lenses optics is used and thus nonlinear terms are included. However, this increases computational time tremendously. Detailed studies have shown that the thin lenses approximation is good for this setup and thus used, see Sec. 3.9. The proton distribution at the first station after tracking with MadXP is shown in Fig. 17.

3.3.1 Alternative: FPTracker

There are several disadvantages one has to face when using MadX. The first is that it reads its input from plain-text files. Furthermore, the fact that it is not written in C++ makes it cumbersome for integration with full scale ATLAS simulations in ATHENA. An alternative, without these limitations, is the program FPTracker. It relies on twissfiles from MadXP to do the tracking along the LHC. The advantage is that it is written in modular C++ and therefore is much better suited for the usage in ATHENA. Details can be found in [18].

3.4 Beam Spot determination

The determination of the beam center is a very important task. The beam position monitor (BPM) can provide this information, but just with an accuracy of roughly 100 μm . For ALFA the determination is possible from the measured occupancy distributions in upper and lower pot in one station. One can take the fraction of both as an indication where the beam spot is. If e.g. the beam spot is closer to the upper pot this one will count more protons

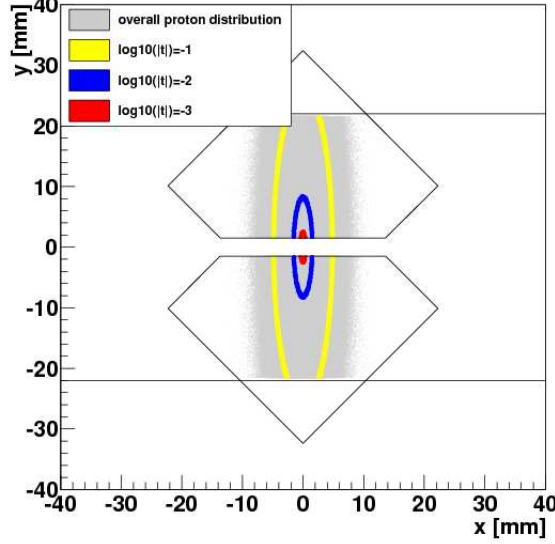


Figure 17: Proton distribution at Roman Pot from MadX. The emphasized regions are the noted value $\pm 5\%$. Also drawn are the beam aperture as horizontal line and the geometrical detector shape.

than the lower one. Therefore it is possible to reconstruct the y position using a calibration curve from Monte Carlo. This has been studied with a calibration curve generated from six million elastics transported with MadX to the Roman Pots. The beam was shifted successively in steps of $12.5\,\mu\text{m}$ and the fraction of upper to lower proton counting rate was calculated. After all, the obtained ratio curve was fitted with a polynomial of degree five. The resulting calibration is shown in Fig. 18.

The next step is to find out how well this method can compete with the BPM. For this a statistically independent run was taken and the beam spot reconstruction evaluated. For a further study of the systematics induced from the calibration curve the physics parameters, nuclear slope B and total cross section σ_{tot} , were changed where the calibration curve values are given in Tab. 1 ($B=18\,\text{GeV}^{-2}$, $\sigma_{\text{tot}} = 111.6\,\text{mb}$). The result is that with this method y can be reconstructed with an accuracy better than $60\,\mu\text{m}$. The results are summarized in Tab. 2 from which it can be clearly seen that the uncertainty on σ_{tot} will induce much bigger systematic errors than the uncertainty on B . Reconstruction of the position in x can simply be achieved from the fact that the proton distribution will look like a simple Gaussian in the Roman Pots. A Gaussian fit will deliver the x position as mean. This can be done

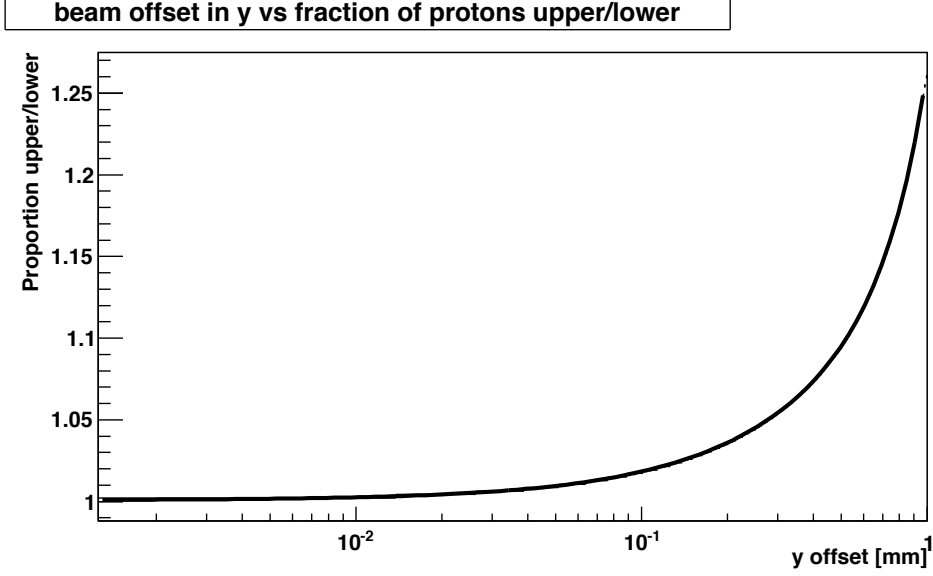


Figure 18: Calibration curve to find the beam spot in y .

with very high accuracy of less than $10\ \mu\text{m}$.

3.5 Detector Simulation with Geant4

3.5.1 The Geant4 Package

In order to achieve progress in the high energy physics field, the experiments needed outgrew the manpower and budget of single groups. Large corporations like e.g. the ATLAS experiment at LHC are required nowadays in order to gain results. Due to budgetary constraints one cannot start from scratch building a detector of that size just to see if it works. A lot of time is

$B\ [\text{GeV}^{-2}]$	$\sigma_{\text{tot}}\ [\text{mb}]$	$ y_{\text{gen}} - y_{\text{rec}} _{\text{max}}\ [\mu\text{m}]$
18	111.6	12
18	100	10
18	125	55
17	111.6	25
19	111.6	15

Table 2: Summary of the systematic beam spot determination studies.

spent beforehand to see if the conceptual design is reasonable. For this the general purpose software framework Geant4 was developed as a successor to the FORTRAN based GEANT3. Initialized by two independent studies at CERN and KEK in 1993, they eventually joined efforts and started the development of a modular, object oriented software package, Geant4 [19]. The Geant4 package is a toolkit for the simulation of particles passing through matter. Though mainly used for high energy physics applications, it is also used e.g. for medical or space technology simulations. Geant4 provides the possibility to describe everything by the concept of predefined volumes. Each volume will be assigned its own physical properties which are essential for the actual simulation. An assembly of volumes will form the detector. Geant4 provides the possibility to test the performance of a detector with a high level of accuracy.

The included physics covers a wide range of electromagnetic, hadronic and optical processes. The main packages important for the ALFA simulation are the hadronic and the standard electromagnetic packages. For the latter package the energy loss is calculated differently for different ranges. Low energy transfers are described continuously, while high energy transfers are described as discrete acts of interaction, which create secondary δ -electrons and photons from bremsstrahlung. The mean of this energy loss is calculated beforehand from

$$\frac{dE}{dx} = - \int_0^{\varepsilon_{lim}} \varepsilon \sigma(E, \varepsilon) d\varepsilon \quad (27)$$

and stored in a table which can be accessed at runtime. Here it is $\varepsilon_{lim} = \min(T_{cut}, T_{max})$, with T_{cut} as production threshold of secondary particles, T_{max} the maximum energy transfer and σ the cross section for each process. The most important processes covered are ionization, bremsstrahlung and gamma conversion for particles in the energy range from 1 keV to hundreds of TeV. For the concrete implementation of models one should consult the physics documentation provided by the Geant4 collaboration [20].

3.5.2 ALFA implementation

The ALFA implementation in Geant4 was mainly done by Prague and Olomouc, who are also responsible for the integration into ATHENA. Adaptations had to be made mainly for parallelization as well as the output format, which is now ROOT trees and therefore much more convenient and flexible. Furthermore the conversion from deposited energy to photoelectrons and hitmaps respectively (see Sec. 5.3) had to be implemented. The setup

contains all important parts and sensitive elements for readout. It covers the main thick elements of the Roman Pot support as well as all fibers, which are necessary in order to get the required hitmaps. The fibers come with cladding and are also mounted on their corresponding support plane. All the thin stainless steel windows are included. Since the fibers are also active in the region where they only act as a lightguide, it is important to mention that the triggers are there as well, as to suppress false positive hits by e.g. secondary particles.

The simulation has been run with two configurations of physics processes to see the differences implied. A less realistic, yet much faster one, with only electromagnetic processes (e.g. Compton scattering, gamma conversion, photoelectric effect, bremsstrahlung) turned on. And a more realistic one with additionally turned on hadronic interactions, especially important for protons (e.g. proton inelastic/elastic scattering, multiple scattering, jets). The configuration used will be quoted throughout the document.

The full setup for luminosity determination is composed of all four stations, consisting of two Roman Pots each. For parallelization however the setup was split to have two independent runs for the left and right side of ATLAS. As an example the zoomed cross section profile of the first ALFA station is shown in Fig. 19. Visible are the overlap and main detector as well as the trigger tiles and the pot support. Drawn are two different events, both with one incident proton traveling from right to left. The first event is a very clean one, with almost no shower generation at all. The second one is a very scruffy event with lots of showering and high hit multiplicities.

3.5.3 Overlap Algorithm

In order to get meaningful results the position where the particle traversed the detector has to be known. However, the detector will ultimately only deliver boolean hitmaps. These have to be joined with the metrology (Sec. 2.2.3) information in order to reconstruct the position.

The actual reconstruction is done using the overlap algorithm. Its application to reconstruction to the overlap detectors is explained - for the main detectors it works pretty much the same, additionally taking the UV geometry into account.

If a particle strikes the overlaps, it will, in the ideal case, leave a signature in exactly one fiber in each of the three overlap layers. From metrology the position of each of these fibers is known. For every fiber that saw light, a $480\text{ }\mu\text{m}$ wide peak is plotted into a histogram which covers the entire range of all fibers. The sum of all the peaks plotted will have a maximum somewhere. The center of this maximum is the best estimate for the position of the

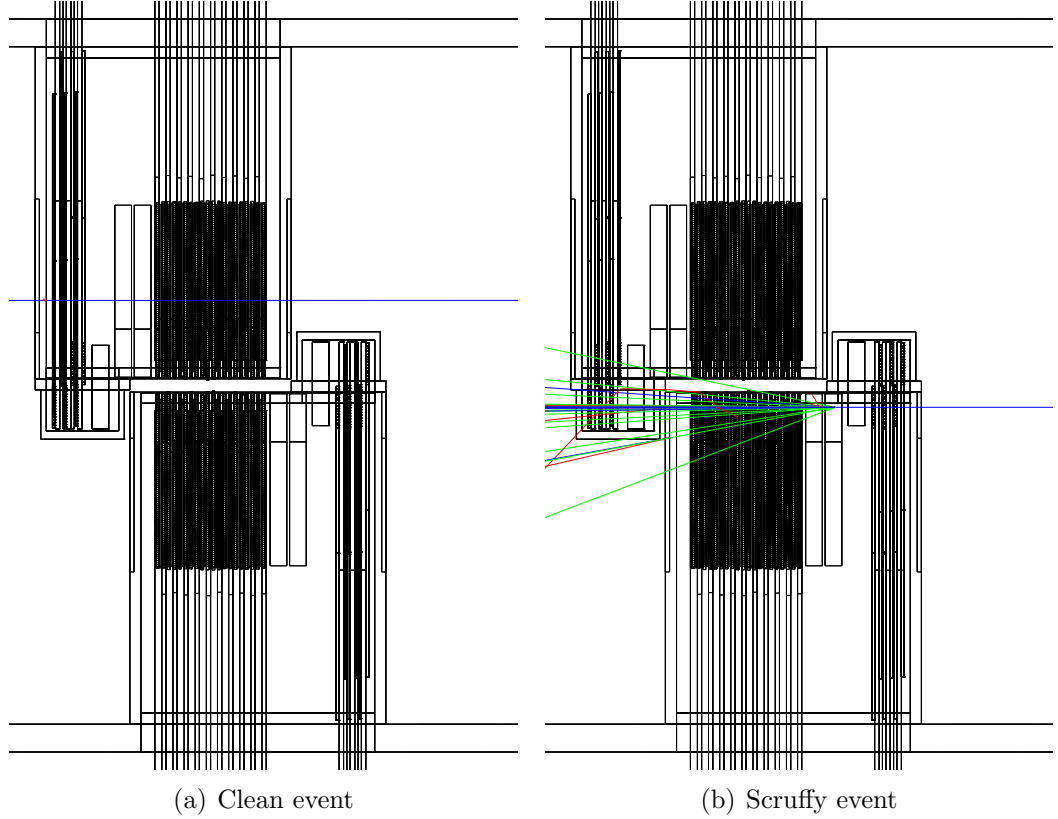


Figure 19: Profile view of the ALFA detector zoomed, in on the sensitive area. Shown is a clean event and one with heavy shower generation.

incident particle. Using this method the staggering is already taken into account, since it is stored in the fiber equations from the metrology files. A schematic sketch of the procedure is shown in Fig. 20. The advantage is that uncorrelated noise will usually not be able to build up a peak comparable to a peak from a real track. This makes the algorithm really stable, error tolerant and easy to implement¹.

For the reconstruction of events generated with the real detector several cuts are available. First there is the overlap width, which is the width of the plotted peak maximum. The default value is 0.5 mm which corresponds to the width of one fiber. Clearly the peak should not be any broader. The second is the UV planes cut. It determines the least number of planes contributing to the peak. For this the default value is five, which means that at least five U and five V planes are required to contribute to the peak. The last cut is the multiplicity cut - each plane with more fibers active than this

¹As an example Fig. 19(b) could be reconstructed.

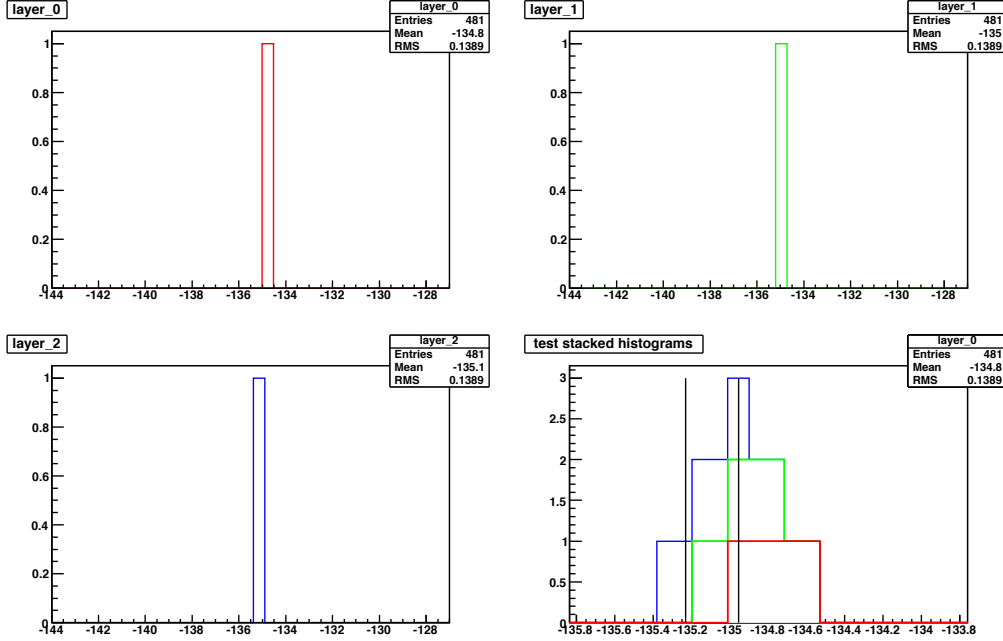


Figure 20: Overlap algorithm for particle coordinate reconstruction. The x axis shows the fiber position in mm. In the bottom right picture the left spike is the actual particle position, the right spike is the reconstructed position.

value will be discarded. Here the default option is five as well.

3.5.4 Overlap Detectors

A very important element of ALFA are the overlap detectors for which various studies have been done. Some of which are related to the pots in “zero position”. This is the nominal working position of the pots, i.e. 1.5 mm vertical detector distance from the beam center.

In the following, whenever the term “real geometry” is used, the testbeam geometry is meant. In particular the geometries for ALFA1 and ALFA2 are used. This will give the possibility to compare results from simulation with actual results from the testbeam. Here it is important to mention that in the testbeam there were only two out of three possible overlap plates included.

What is to be expected as a result from the overlap reconstruction? The staggering of the three overlap plates defines regions of fixed width, which, once traversed by a particle, are reconstructed to the same position, namely the middle of the overlap region. Examples of these are shown in Fig. 21 in

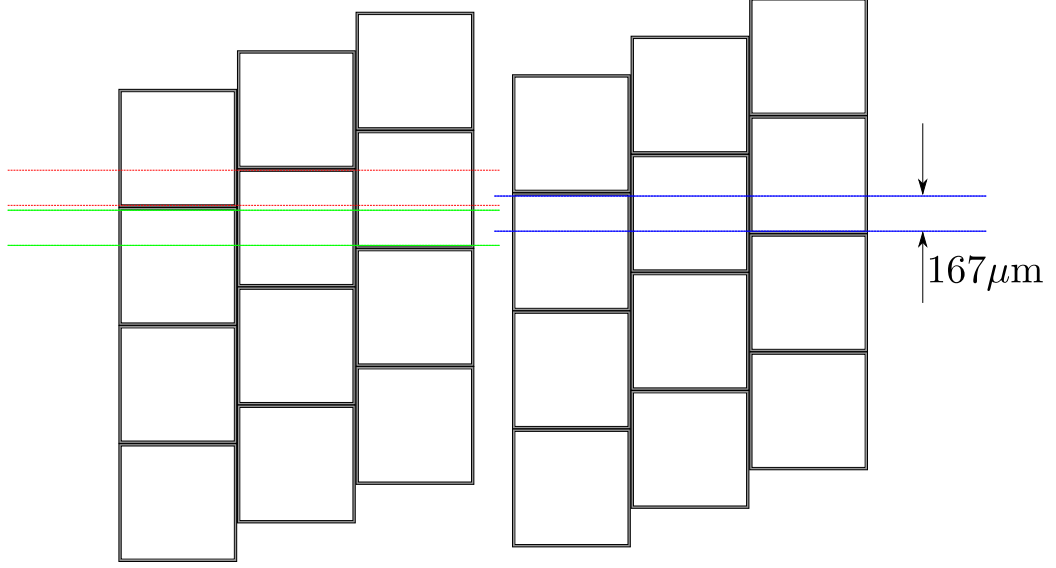


Figure 21: Overlap detectors schematically. Drawn are the fibers with cladding and staggering as well as different reconstructable regions (red, green, blue).

red, green and blue. No matter where the particle actually hits the detector in either of these areas, it will be reconstructed to a position specific to each area. Now if upper and lower overlap detector do perfectly overlap concerning these areas, then upper and lower overlap will always reconstruct exactly the same position, which in the end always gives the same vertical pot distance.

However, usually the overlap will not be perfect. Then the result will be a weighted average over the different possibilities (e.g. the combination red, green and blue in Fig. 21). This will also broaden the distribution $y_{i,\text{upper}} - y_{i,\text{lower}}$, i.e. the RMS. The RMS will be smallest for perfect overlap, and biggest if the overlap is “50%”. This can be seen from Fig. 22, where the

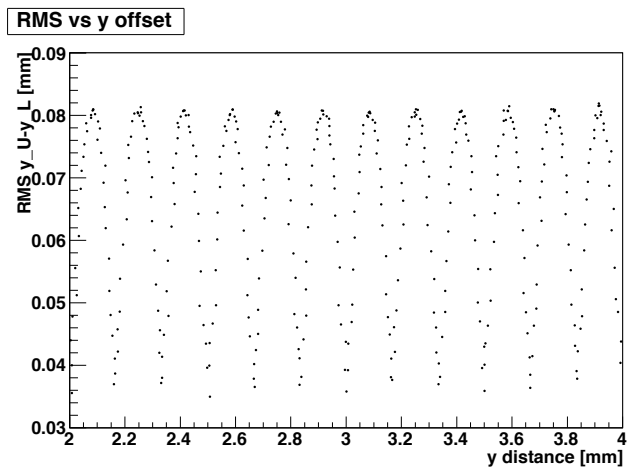


Figure 22: RMS vs. relative Distance.

RMS is plotted versus the relative distance of the pots for ideal geometry.

Each point consists of 60 000 protons shot on the overlaps. One can see that the distribution has a periodicity of $167\ \mu\text{m}$, which is exactly the effective pitch and therefore what was to be expected.

The next step is to look at one individual overlap detector. In particular at the distribution $y_{\text{gen}} - y_{\text{rec}}$, the difference of the generated proton position y_{gen} and the reconstructed position y_{rec} . There are three cases that can happen, which shall shortly be explained. Firstly, the proton can hit exactly one fiber in each of the three layers. This will result in a reconstruction accuracy of, taking the cladding into account, roughly $150\ \mu\text{m}$.

Secondly, the proton can hit the cladding in one layer, and one fiber core in each of the other two layers. Though it is neither known nor used (at least not in the real experiment) that the proton has hit the cladding, clearly the reconstruction accuracy comes out to the cladding width of $20\ \mu\text{m}$.

The last possible case is where the proton only leaves a signature in one fiber, but in only two layers. The resulting reconstruction accuracy is approximately $300\ \mu\text{m}$. These three cases are nicely visible in Fig. 23(a). There the two hit structure in red with the narrow cladding peak, and the three hit structure in green can be seen.

After these preliminary remarks a look at the spectrum resulting from the

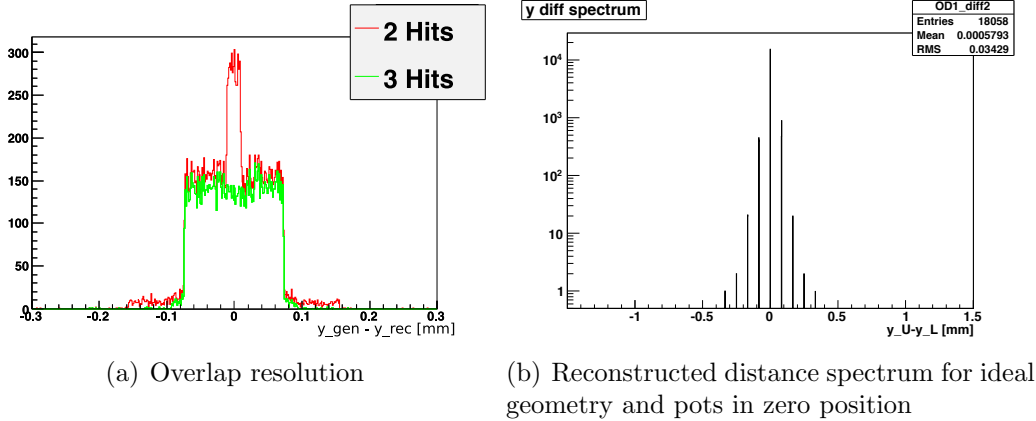


Figure 23: Overlap resolution studies.

pot distance reconstruction for the overlaps with ideal geometry shall be taken. For this purpose Eq. 25 is applied to the reconstructed y values in upper and lower pot. The result is shown in Fig. 23(b). As it can be seen the distance comes out to $d = (6 \pm 3) \times 10^{-1} \mu\text{m}$, where the error on the mean is given by $\Delta d = \frac{\text{RMS}}{\sqrt{N}}$. The real value was exactly $d = 0\ \text{mm}$ since the pots were in zero position.

The spike like structure is easy to explain: Since all the fibers are in their

3 SIMULATION

nominal position, there is only a finite and discrete number of possible pairs (y_U, y_L) that can be reconstructed. Therefore there is also only a finite number of differences which results in the shown structure.

The next question of interest is what pot distance reconstruction resolution can be achieved ultimately. For this purpose the detectors have been shifted apart in steps of $2.5\ \mu\text{m}$. Starting from a distance of 2 mm it went up to 4 mm. This covers the full interesting range since the working position is at a distance of 3 mm. Each event consists of 60 000 protons again. The result is shown in Fig. 24. It can be seen that the difference from the generated to the reconstructed distance comes out nicely with an RMS of $7 \times 10^{-1}\ \mu\text{m}$. The last interesting question is concerning statistics. Up to now not a lot

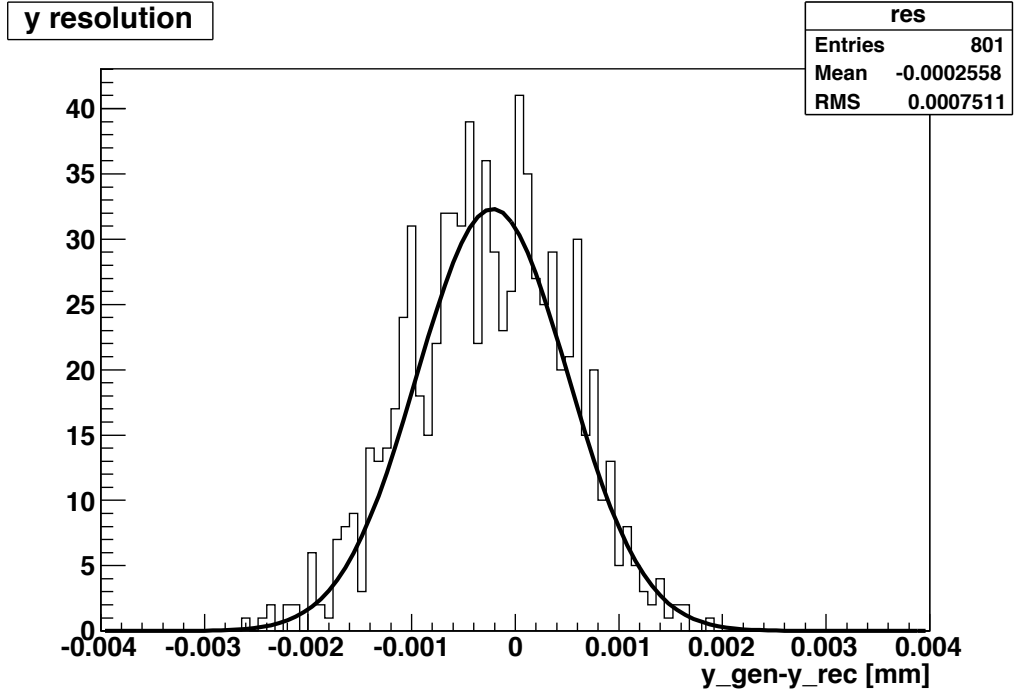


Figure 24: Resolution of the reconstructed position with Ideal geometry.

is known about the beam halo, in which the overlaps operate, it is interesting to know how many events are actually needed in order to achieve the desired resolution of below $10\ \mu\text{m}$. This has been simulated by using the runs with 60 000 events and calculating the mean distance using the first 10, 100, 1000, 10 000 and 60 000 events. The interesting and very calming fact is, that already 100 events are sufficient to come down to an RMS of $10\ \mu\text{m}$ for both ideal and real geometry if all three planes are active. Since in the

Events	10	100	1000	10000	60000
RMS [μm], Ideal, 3 planes	29	9	3	1	1
RMS [μm], Real, 3 planes	34	10	4	1	1
RMS [μm], Ideal, 2 planes	/	19	10	8	8
RMS [μm], Real, 2 planes	/	18	8	6	6

Table 3: Summary of overlap distance reconstruction resolution in dependence on statistics.

testbeam only two planes were available, the simulation has also been run for two planes. Again it is possible to reach the required $10\mu\text{m}$. However, this time at least 1000 events are needed. It is interesting to note that the real geometry comes of slightly better than the ideal geometry.

The results are summarized in Tab. 3. As an example the plot is shown for ideal geometry with all three planes in Fig. 25.

3.6 Hit Multiplicities

A very important property of a detector is the observed hit multiplicity. For the case of ALFA this is the number of fibers per layer that have seen scintillation light. In the ideal case this would be exactly one in each layer and therefore also in the overall mean. However there are effects that may increase, and effects that may decrease the multiplicity. For one there is the insensitive cladding which makes up for $20\mu\text{m}/500\mu\text{m} = 4\%$ of the total sensitive detector area. This will decrease the mean multiplicity since in some layers the proton might hit the cladding and thus there will be no light generation. Furthermore it might happen that the deposited energy will not be sufficient for one photoelectron to be created. Secondly, there is the possibility for the creation of showers. These are generated with a certain probability and will propagate throughout the detector, yielding a higher multiplicity. For the reconstruction the multiplicity cut is set to five as default value. As can be seen from the multiplicity plot for two successive Roman Pots in Fig. 26, this is a reasonable value if only electromagnetic interactions are switched on. Then only very little layers are affected by this at all. The situation changes when hadronic interaction is switched on and a lot more layers are lost by this cut.

These showers might as well worsen the detector resolution, especially of the second station. The showers and multiplicities have been studied using a run with 6×10^7 events. Since here it is only important to have two pots

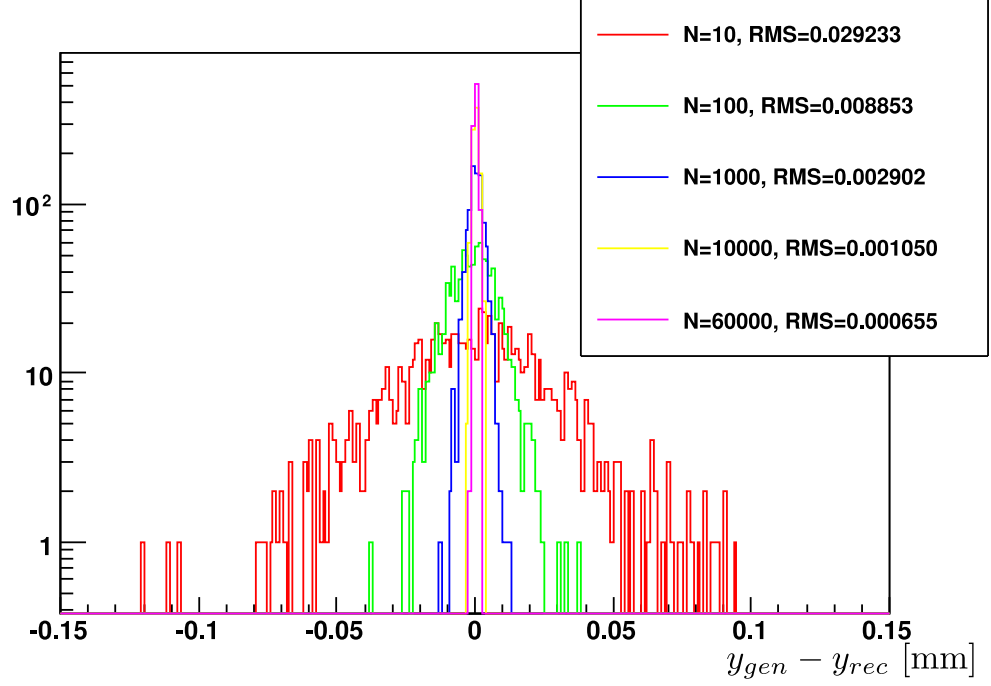


Figure 25: Overlaps distance reconstruction resolution with ideal geometry and all three planes.

separated by 4 m and this run contained both sides of ATLAS, there is a total of 1.2×10^8 events. The mean multiplicity as well as the detector resolution stay practically the same as long as only electromagnetic interactions are present. A fit of a constant function to the fraction of multiplicities in first to multiplicities in the second pot gave (for em interaction only) $(99\,730 \pm 4)10^{-5}$. This means that the fraction is practically constant unity and no impact from showers can be observed. Thus it can be concluded that there is no noticeably impact from first to second Roman Pot arising out of showers from electromagnetic interactions. If hadronic interactions are switched on, the showers from the first pot become clearly visible in the second. Additionally the tails in both pots extend to much higher multiplicity regions. The fraction of multiplicities from second to first pot is shown in Fig. 26(b). Particularly interesting is the rise in the multiplicity distribution from the second pot for multiplicities above 60. The impact on resolution has been studied in Sec. 3.7.

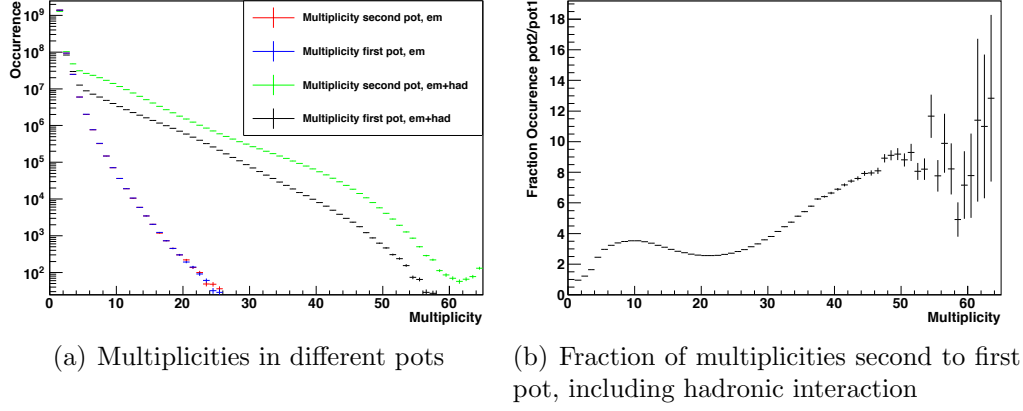


Figure 26: Impact of the first Roman Pot on the second on one side of ATLAS. The high multiplicities are dominated by hadronic showers.

3.7 Detector Resolution

Since the metrology files for a lot of modules are available already, it is very important to determine the resulting spatial detector resolution via simulations. This has been studied for the detectors which have been completed until now. As a remark one has to say that the word detector just refers to ten planes here that have been combined. Later optimization of module combinations with respect to resolution will hopefully result in a better resolution.

For each resolution calculation 500 000 protons with 7 TeV were shot onto the detector. Their initial momentum and position were taken from the tracked position at the Roman Pot calculated with MadX (this also means that only about 2/3 will hit upper or lower detector due to the gap of 3 mm). This ensures that the calculated resolution will match the one expected in real runs in the tunnel later, which is important since the resolution will not be uniform across a detector for real geometry due to different overlaps from geometrical imperfections. For a detector with ideal geometry, the resolution should naturally be uniform. Since in the simulation the protons initial position is known, the difference between reconstructed and initial position, the residual, can be calculated and plotted in a histogram. The result should be a Gaussian with a width σ , the resolution. Of special interest is the effect of the first on the second Roman Pot by showers.

In order to see differences implied from the physics processes, one run was taken with only electromagnetic interactions, and another with both electromagnetic and hadronic interactions. Since for the runs with only electromagnetic processes the multiplicities in the second pot did not change, the

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Series	em		em + hadronic			
	pot 1		pot 1		pot 2	
	$\sigma_x [\mu m]$	$\sigma_y [\mu m]$	$\sigma_x [\mu m]$	$\sigma_y [\mu m]$	$\sigma_x [\mu m]$	$\sigma_y [\mu m]$
C2	22.2	20.8	23.0	22.8	23.6	23.4
C3	27.4	26.8	28.8	28.8	29.8	29.6
A7	26.9	24.0	28.5	28.8	29.3	29.6
A10	29.2	26.6	29.7	27.8	30.8	28.9
A11	27.3	27.1	29.7	29.1	30.5	29.7
A1-2	24.7	24.0	27.6	26.2	28.8	26.9
A2-2	28.5	29.0	32.7	31.1	33.4	31.6
A3-2	24.1	23.0	24.9	25.5	25.6	26.3
A4-2	34.4	40.1	41.7	37.7	44.2	38.8

Table 4: Summary detector resolutions.

resolution also stayed the same. Therefore it is omitted in the summarizing Tab. 4. One should notice that all series are well below or close to the desired $30 \mu m$. Bad results are only achieved for the A4-2 series. Special interest should be paid to A11 and A4-2 since they were used in the testbeam as ALFA1 and ALFA2.

The additional hadronic interaction will not worsen the spatial resolution a lot, on average by about $2 \mu m$. From the table it is evident that even though the showers have a large impact on the second pot, the resolution does not drop drastically. On average by about another $1 \mu m$ from the first to the second Roman Pot. This is a result from the fashion in which the overlap algorithm works. The showers will usually not be able to pile up as much as to disturb the algorithm. As an example, the results, including the Gaussian fit, are shown in Fig. 27 for the x coordinate of A10.

The results for A4-2 are very peculiar and the geometry file should be put under further inspection. It was excluded from the previously calculated averages.

3.7.1 Resolution stability

Another important aspect, particularly for the testbeam, is the stability of the detector resolution with respect to rotations around axis perpendicular to the beamline, i.e. x and y if z is the beamline. While rotations around

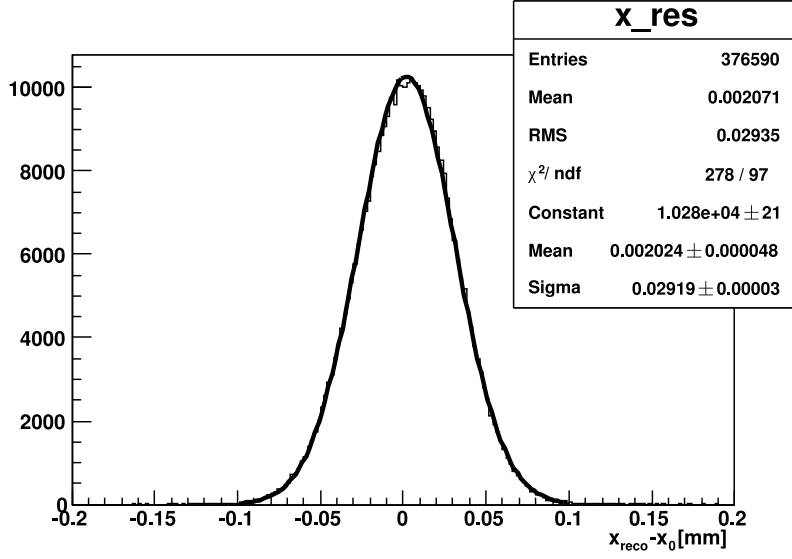


Figure 27: Spatial resolution of the A10 series in x.

the beamline can be corrected offline with software alignment (Sec. 4.2) this will usually not work for the other angles. Thus a simulation has been run in which the detector has been shot with protons which had a certain angle relative to the detector plane. This corresponds to a rotation of the detector around x or y. For both x and y a relative angle in the range of -20 mrad to 20 mrad in steps of 0.2 mrad was covered. The results are shown in Fig. 28. For the mean it can clearly be seen what is expected naturally: If the detector is twisted around the x axis an offset for the mean in y is observed, while the mean residual for x is approximately constant at 0. The same holds for rotations around y with x and y interchanged. More interesting is the resolution change with rotation angle. Over the full range the resolution for x and y changes and clearly it can be seen, that even small rotations of a few mrad have a big impact on the resolution. Furthermore it is interesting to notice that the best resolution is not achieved for a rotation angle of 0° but slightly apart from this. This can be explained from the non uniformity of the fibers over the entire detector, thus that at another angle the overlapping fibers might in total result in a better spatial resolution. One should notice that the error bars have been omitted in order to not overload the graphs. However the statistical error for the mean lies in the range of $1 - 2\%$, whereas the error on σ is even below 4% . The results are in qualitative agreement with previous testbeam measurements [21].

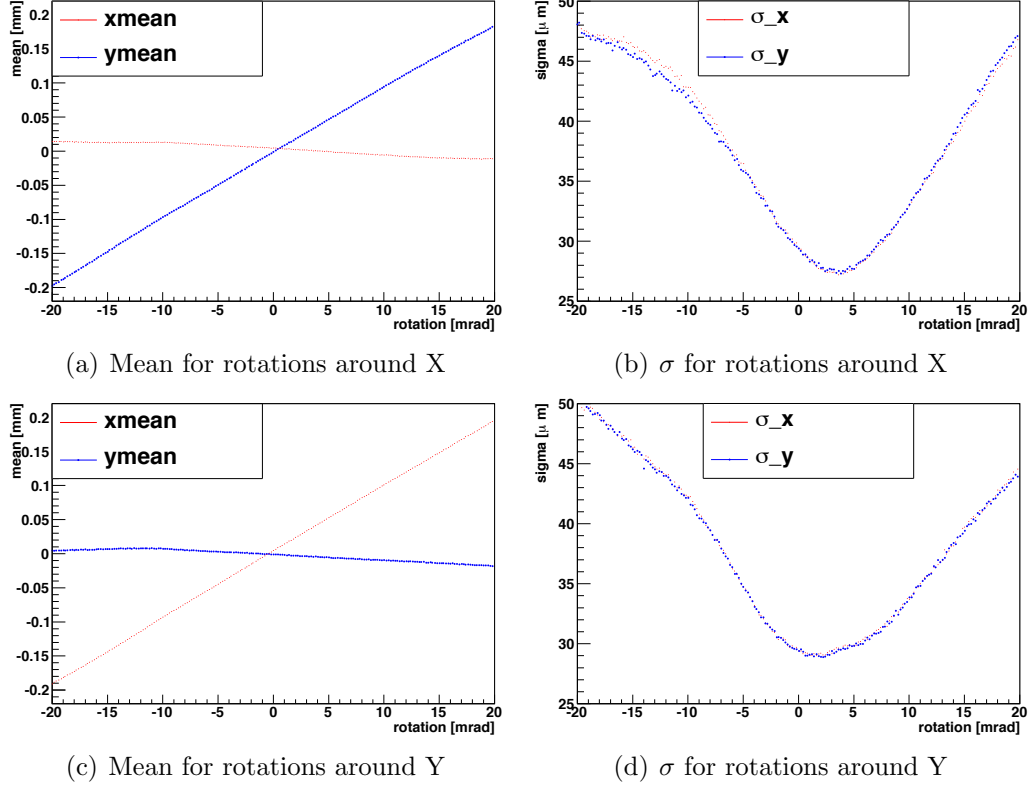


Figure 28: Results of the twist simulations done for ALFA2. Shown are the mean and the width σ of the residual distribution.

3.8 Luminosity determination

The key feature of ALFA is the luminosity determination. Previous studies have not yet had a fully implemented detector simulation available and only relied on simple geometry. This makes the study of the detector impact interesting.

The luminosity L is determined from the measured spectrum of elastically scattered protons. A fit of Eq. 12 is applied from which L can be extracted. In order to do this the entire simulation chain has been run with a setup of eight pots with real geometries. The pots used and their positions are noted in Tab. 5. The values determined from the fit also depend on the fit range. In order to get meaningful results, a range should be used that is defined by a t range in which the ALFA acceptance lies above 50%. The acceptance is shown in Fig. 29, where it is evident that

$$t = 0.000\,55 \dots 0.055 \text{ GeV}^2 \quad (28)$$

Pot	Geometry
A7L1U	C3
A7L1L	A7
B7L1U	A10
B7L1L	A11
A7R1U	A1-2
A7R1L	A2-2
B7R1U	A3-2
B7R1L	C2

Table 5: Geometries used for the individual detectors in the full simulation run.

is a suitable range for the case of electromagnetic interaction only and the linear fit. For the logarithmic fit the range

$$\log_{10}(|t|) = -3.2 \dots -1 \quad (29)$$

is used. Including hadronic interaction the picture changes drastically and a much smaller range would have to be used, to be within 50% acceptance. The ratio of the acceptance with only electromagnetic interactions switched on to the acceptance with hadronic interactions is found to be 1.23 from linear fitting, see Fig. 30(b). The effects of the smaller range will be investigated later. For the acceptance one should notice however, that even though the statistical error is almost 0 over the relevant 50% range, there are still fluctuations. These can be attributed to the detector fiber geometry.

3.8.1 On efficiency errors

In order to calculate the efficiency, one has to calculate

$$\varepsilon = \frac{k_i}{N_i} \quad (30)$$

where k_i is the number of accepted events and N_i are all events in bin i . Since the two variables are correlated one cannot use simple error propagation as this will yield unrealistic errors in the extreme cases, i.e. $\Delta\varepsilon = 0$. For instance the commonly used binomial approximation

$$\Delta\varepsilon = \sqrt{\varepsilon(1 - \varepsilon)N} \quad (31)$$

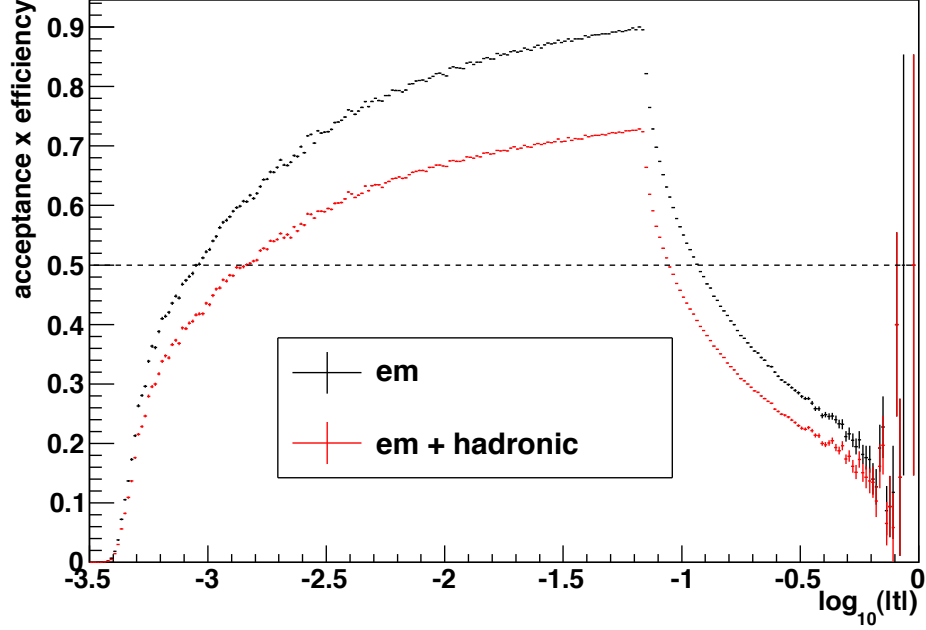


Figure 29: Acceptance as a function of $\tau = \log_{10}(|t|)$. Black for if only electromagnetic interaction is present, red with also hadronic interactions switched on. The 50% acceptance defines the fit range and is drawn as dashed line.

will give $\Delta\varepsilon = 0$ for bins with only one event, no matter if the event was accepted or not.

A better way to do this is to use conditional probabilities. Using the binomial distribution

$$P(k|\varepsilon, N) = \frac{N!}{k!(N-k)!} \varepsilon^k (1-\varepsilon)^{N-k} \quad (32)$$

is found as the probability to get k accepted events, given a binomial distribution with a true acceptance ε and a total of N events. In the experiment or simulation there is only data and the goal is to find $P(\varepsilon|k, N)$, the probability that the efficiency is ε , given k accepted out of N total events. This can be achieved using Bayes theorem. Details can be found in [22], here only the result is stated

$$P(\varepsilon|k, N) = \frac{\Gamma(N+2)}{\Gamma(k+1)\Gamma(N-k+1)} \varepsilon^k (1-\varepsilon)^{N-k} \quad (33)$$

with the gamma function $\Gamma(n) = (n-1)!$. From this distribution the most likely acceptance is found to be $\varepsilon = k/N$, which is in agreement with intu-

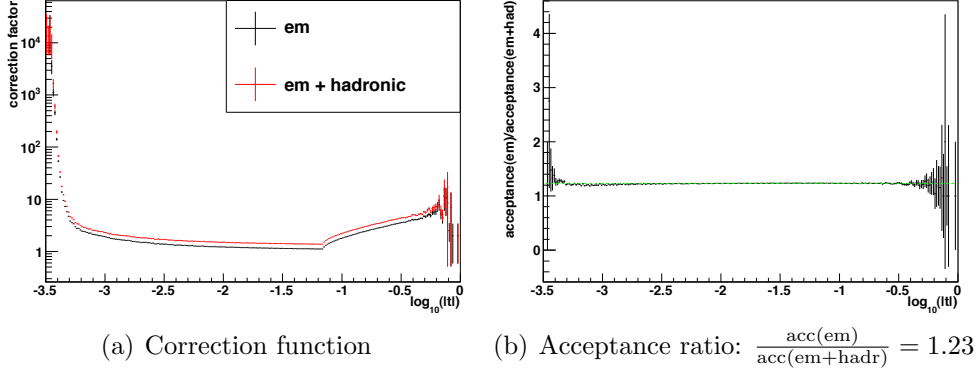


Figure 30: The correction as a function of $\tau = \log_{10}(|t|)$. Black for if only electromagnetic interaction is present, red with also hadronic interactions switched on. On the right side the ratio of ALFA acceptance with only em on to acceptance with hadronics on is shown.

run	int. Acceptance	Error	
		Binomial	Bayesian
em	0.804 576	$\pm 0.000\ 145\ 264$	$\begin{cases} +0.000\ 145\ 33 \\ -0.000\ 145\ 385 \end{cases}$
em + hadronic	0.678 265	$\pm 0.000\ 181\ 656$	$\begin{cases} +0.000\ 181\ 753 \\ -0.000\ 181\ 791 \end{cases}$

Table 6: Comparison of errors on the integral acceptance inside the 50% acceptance cut, calculated with binomial and Bayesian approach.

ition. From this probability distribution meaningful errors, like a one sigma confidence interval, can be calculated. This is already integrated into the software framework ROOT, and used subsequently for the calculation of acceptance and correction function.

As an example of application the integrated acceptance is calculated from Fig. 29 for all bins within the 50% acceptance cut and listed in Tab. 6. Clearly for high statistics there are no noticeable differences as expected. However, for low statistics this becomes important.

3.8.2 Correction function

Before the final fit can be done, corrections to the reconstructed spectrum have to be applied. This correction function has to be calculated from a sta-

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tistically independent run with a different seed. The correction function is calculated simply as a bin-by-bin correction from the ratio of the generated t spectrum at the IP divided by the reconstructed t spectrum after reconstruction from the RPs. Technically this can be broken down into several corrections that are multiplied, namely:

$$C(t) = C^A(t) \cdot C^{\text{div}}(t) \cdot C^{\text{det}}(t) \quad (34)$$

where $C^A(t)$ is the acceptance correction, $C^{\text{div}}(t)$ is the beam divergence correction and $C^{\text{det}}(t)$ is the correction for the detector resolution. This simulation gained correction function will also be applied when L is determined from real ATLAS data. An uncorrected spectrum is shown in Fig. 33 with a corrected one for comparison in both linear and logarithmic representation. The correction function, determined from 6×10^7 events, is shown in Fig. 30(a)². The statistics had to be really high in order for the luminosity fit not to be dominated by uncertainties from the correction function. It should be noticed that the applied correction is only a mean correction. A better way to do this would be a detector dependent correction individually for each detector, which takes into account the systematical errors induced from the non perfect fibers. The effect can nicely be seen from Fig. 31, where for the same input data the fraction of the correction functions gained with ideal detector versus the one gained from real detector geometry is plotted. In Fig. 31(a) it can be seen that over most of the t range the fraction is very close to unity like it is expected. However there is a very strong drop in small t values better visible in Fig. 31(b). It can clearly be seen that a detector dependent

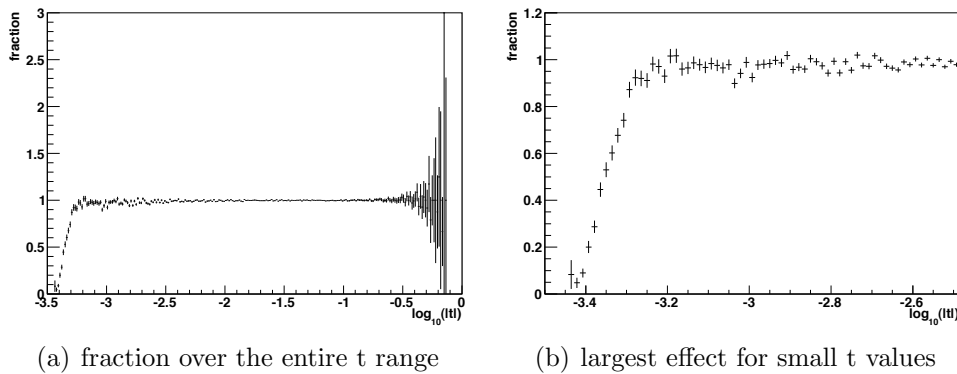


Figure 31: Relation of $\text{corr}_{\text{ideal}}/\text{corr}_{\text{real}}$, the ratio of correction function for ideal setup vs real setup. In principle this represents the ratio of the different C^{det} .

²This was the most CPU intensive task with roughly 83 CPU days

	$ t < 10^{-3.2} \text{ GeV}^2$		$10^{-3.2} \text{ GeV}^2 < t < 10^{-3} \text{ GeV}^2$	
Seed	Ideal effect/ 10^{-3}	Real effect/ 10^{-3}	Ideal effect/ 10^{-3}	Real effect/ 10^{-3}
100	15.29 ± 0.92	38.74 ± 1.12	6.95 ± 0.56	17.99 ± 0.62
101	16.65 ± 0.91	41.41 ± 1.12	8.60 ± 0.56	20.27 ± 0.62

Table 7: Mean of the distribution $\frac{t_{\text{rec}} - t_{\text{generated}}}{|t_{\text{generated}}|}$. For ideal and real geometry the reconstructed t will be bigger than the generated one.

correction function is particularly important for very small values of t . The size of this effect can be estimated from having a look at the distribution

$$\frac{t_{\text{rec}} - t_{\text{generated}}}{|t_{\text{generated}}|} \quad (35)$$

for small values of $t < 10^{-3.2} \text{ GeV}^2$. Here it is evident that the reconstruction, no matter if ideal geometry or real geometry setup, will tend to reconstruct to bigger t values on the order of a few percent - for ideal geometry it is about 1.5%, while for real geometry it is of the order of 4%. In this region the effect is noticeably the strongest. However, this is outside of the used fit range. Thus a look at the region $-3.2 < \log_{10}(|t|) < -3$ has to be taken. Here the effect is of the size of 0.8 and 2.0 percent respectively, see Tab. 7. Considering the errors this is a significant effect, which emphasizes the application of detector specific correction functions. This should be done as a continuation of this thesis.

3.8.3 Reconstruction efficiency

The reconstruction efficiency is defined as the number of protons with reconstructed position divided by the number of protons with an initial y position that is inside the geometrical acceptance. For a full ALFA simulation with all eight pots this has been denoted in Tab. 8. Clearly the effects of the hadronic showers can be seen. Not only will the reconstruction efficiency for the first of two successive pots drop by roughly 4%, but more importantly will it drop for the latter one by almost 10%. Since ALFA will work in coincidence with all four stations this would mean an overall drop to only 70% reconstruction efficiency (if the efficiencies were statistically independent which clearly they are not³ since a shower in the first station might not get reconstructed, but

³The conditional probability that the second pot will not be able to reconstruct given that the first was not is $P(\bar{2}|\bar{1}) = 0.701 \neq 0.006 = P(\bar{1}) \cdot P(\bar{2})$. Which is clearly different from the assumption both are independent.

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		RP1	RP2	RP3	RP4
em	upper	0.983	0.982	0.984	0.983
	lower	0.978	0.979	0.981	0.981
em+hadronic	upper	0.954	0.895	0.955	0.897
	lower	0.935	0.879	0.938	0.881

Table 8: Reconstruction efficiency for different pots and with and without hadronic interactions. In direction of beam RP1 is in front of RP2 on the one side, and RP3 in front of RP4 on the other side of ATLAS.

then there is also a higher chance that it is not reconstructed in the second pot), from 92% with no hadronic showers. The ratio $0.9/0.7 = 1.3$ is in good agreement with the acceptance ratio found earlier from Fig. 30(b). Since the loss is the same for each t range, it is clear that it has to be attributed to the lower reconstruction efficiency from shower noise. The overall values determined from simulation are 94.0% reconstruction efficiency with only electromagnetic interaction, and 76.3% with also hadronic interactions enabled. Now there are several possible solutions for this dilemma. For one the reconstruction cuts should be checked if they can be relaxed. If the overlap algorithm works as desired it should be able to handle more than five fibers per plane, which might increase the reconstruction efficiency. The other possibility would be to loosen the coincidence condition, since clearly the shower received by the second pot decreases the overall efficiency dramatically. Both suggestions should be studied in detail at a later stage.

A remarkable result from Tab. 8 is that for the lower pots the reconstruction efficiency is in general by about 2% lower than for the upper pots. This is caused by the trigger tiles. For the upper pot the trigger tiles sit behind the sensitive planes as seen from the IP, see Fig. 19. Now to make a lower pot out of an upper, the upper pot is rotated by 180° around the beam axis z and then rotated 180° around itself. In the end the trigger tile is sitting in front of the sensitive planes, seen from the IP. Thus for a lower pot there is more shower generating material in front of the layers and thus a slightly higher hit multiplicity. This is nicely illustrated in Fig. 32 where the mean multiplicity is plotted for the different layers, separated according to interaction and pots. The differences between upper and lower pot are evident. A possible solution would be interchanging the sequence of trigger and UV tiles. Doing the math this leads to an overall reconstruction efficiency increase of about 3%.

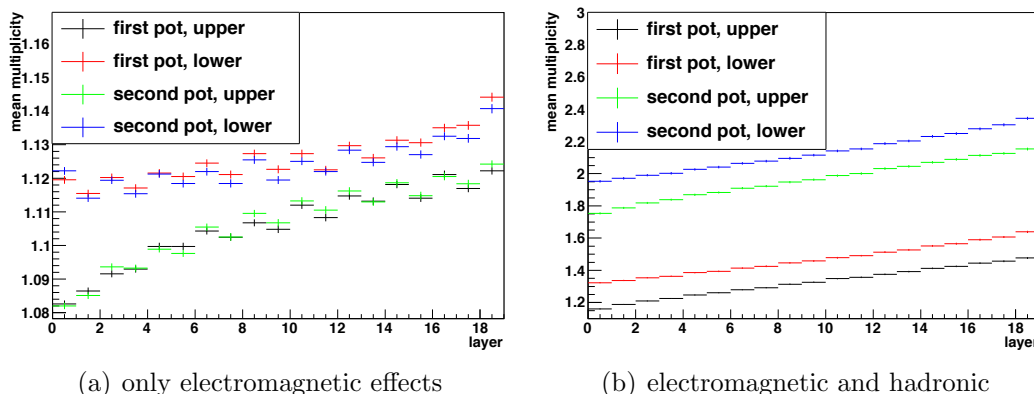


Figure 32: Mean multiplicities for all layers. Counting increasing as seen from IP.

3.8.4 The luminosity fit

The luminosity fit is done in two representations with a sample of 10×10^6 events and a correction function determined from a statistically independent run with 60×10^6 events. In the linear representation this is done with 15 000 bins and in the logarithmic representation with 350 bins. The fit ranges are, like described above, determined by the 50% acceptance cut. The final results are given in Tab. 9. As it turns out all values come out quite nicely, with the statistical error on the luminosity of below 2% like required. Including systematical uncertainties the luminosity precision of below 3% is attainable [23].

In order to study the effects of hadronic showers the entire procedure has to be repeated with these interactions enabled. The result is that this has a major impact on the acceptance. The overall acceptance drops in each bin by about 20%. However, since the geometrical acceptance stays the same, this can only be contributed to the showers generated which will fail the reconstruction cuts. The reconstruction efficiency for all stations of the luminosity determining run is noted in Tab. 8. From the acceptance plot it can be seen that the fit ranges for the run with hadronic interactions would have to be reduced as well to match the required 50%. For now, since the 50% acceptance cut is more or less arbitrary, it will be set to 40% for the luminosity fit, in order to fit the same range like the non hadronic run. Nonetheless this will imply a larger impact from the correction function which is not desired and thus other ways have to be found later.

The impact of insisting on the 50% acceptance for the fit range has been studied. For this the fit procedure was repeated with a reduced fit range of $\log_{10}(|t|) = -2.8.. -1$ for the logarithmic fit and $t = 0.001..0.1 \text{ GeV}^2$ for the linear fit. This corresponds to an acceptance of 50% in the run including

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	Parameter	Unit	Input	Value		stat. Err
linear fit	Luminosity	$[10^{26} \text{ cm}^{-2} \text{ s}^{-1}]$	6.684 29	6.78	± 0.13	1.8%
	Cross section	[mb]	111.6	110.8	± 1.1	1.0%
	B	$[\text{GeV}^{-2}]$	18	18.019	± 0.019	0.1%
	ρ		0.1383	0.1390	± 0.0050	3.6%
	χ^2/Ndof	4852/2977				
log fit	Luminosity	$[10^{26} \text{ cm}^{-2} \text{ s}^{-1}]$	6.684 29	6.73	± 0.12	1.7%
	Cross section	[mb]	111.6	111.20	± 0.98	0.9%
	B	$[\text{GeV}^{-2}]$	18	18.002	± 0.019	0.1%
	ρ		0.1383	0.1375	± 0.0048	3.4%
	χ^2/Ndof	231.7/150				

Table 9: Results of the final luminosity fit from a run with only electromagnetic interaction on.

	Parameter		Input	Value		stat. Err
linear fit	Luminosity	$[10^{26} \text{ cm}^{-2} \text{ s}^{-1}]$	6.684 29	6.63	± 0.12	1.9%
	Cross section	[mb]	111.6	112.1	± 1.0	1.0%
	B	$[\text{GeV}^{-2}]$	18	18.006	± 0.019	0.1%
	ρ		0.1383	0.1354	± 0.0049	3.7%
	χ^2/Ndof	6303/2977				
log fit	Luminosity	$[10^{26} \text{ cm}^{-2} \text{ s}^{-1}]$	6.684 29	6.62	± 0.12	1.8%
	Cross section	[mb]	111.6	112.2	± 1.0	0.9%
	B	$[\text{GeV}^{-2}]$	18	17.984	± 0.019	0.1%
	ρ		0.1383	0.1345	± 0.0049	3.6%
	χ^2/Ndof	328.5/150				

Table 10: Results of the final luminosity fit for a run with hadronic interaction and the extended 40% acceptance fit range.

3.8 Luminosity determination

	Parameter		Input	Value		stat. Err
linear fit	Luminosity	$[10^{26} \text{ cm}^{-2} \text{ s}^{-1}]$	6.684 29	7.00	± 0.37	5.3%
	Cross section	[mb]	111.6	109.1	± 2.9	2.7%
	B	$[\text{GeV}^{-2}]$	18	18.020	± 0.024	0.1%
	ρ		0.1383	0.1422	± 0.0085	6.0%
	χ^2/Ndof	6281/2966				
log fit	Luminosity	$[10^{26} \text{ cm}^{-2} \text{ s}^{-1}]$	6.684 29	1.749	± 0.036	2.1%
	Cross section	[mb]	111.6	218.6	± 2.3	1.1%
	B	$[\text{GeV}^{-2}]$	18	17.872	± 0.018	0.1%
	ρ		0.1383	0.0686	± 0.0092	13.4%
	χ^2/Ndof	302.2/122				

Table 11: Results of the final luminosity fit for a run with hadronic interaction and the 50% acceptance cut for the fitrange.

hadronic interaction. The result is rather depressing. For the logarithmic fit the determined luminosity will be almost a factor of four too small. For the linear fit the luminosity got worse, yet came out to an acceptable value, with an increased error, as was expected. Thus it can be concluded that the logarithmic fit cannot be used with the reduced range. The linear fit might be used, however the results get way worse than before with the 40% acceptance cut. The results are summarized in Tab. 11. It also becomes clear that in case of the logarithmic fit none of the determined parameters come out good, except for the nuclear slope.

3.8.5 t resolution

A very interesting property is the reconstructed t resolution achievable with the previous setup. For this a run of 6×10^7 events was analyzed for both configurations (electromagnetic only and additional hadronic). In particular the analysis will focus on the relative t resolution given by the root mean square (RMS) of

$$\frac{t_{\text{rec}} - t_{\text{gen}}}{t_{\text{gen}}} \quad (36)$$

with t_{rec} the reconstructed and t_{gen} the generated t value. The t -resolution is studied for different ranges of t , indicated by the binning. Visible from Fig. 34 is also the impact from detector resolution and reconstruction, listed as

“only beam divergence”. For this the same sample was analyzed and the t spectrum reconstructed not from the reconstructed particle coordinates, but from the original coordinates from MadX. Yet only particles were kept that actually could be reconstructed. This means that all detector effects but the acceptance are omitted.

One can see that the result is in good agreement with the previous simulations in the TDR, which did not yet contain a full detector simulation but just a detector given by simple geometry with Gaussian smearing for resolution simulation. This is in particular unrealistic since the overlap region defined by the fibers will induce systematic offsets. A noticeable difference is the fact that in the TDR the t dependence on detector resolution and reconstruction was underestimated. This is not a bad approximation since for the small t the resolution is dominated by the beam divergence. Yet for the bigger t 's it becomes apparent that detector effects from hadronic showers are the predominant contribution.

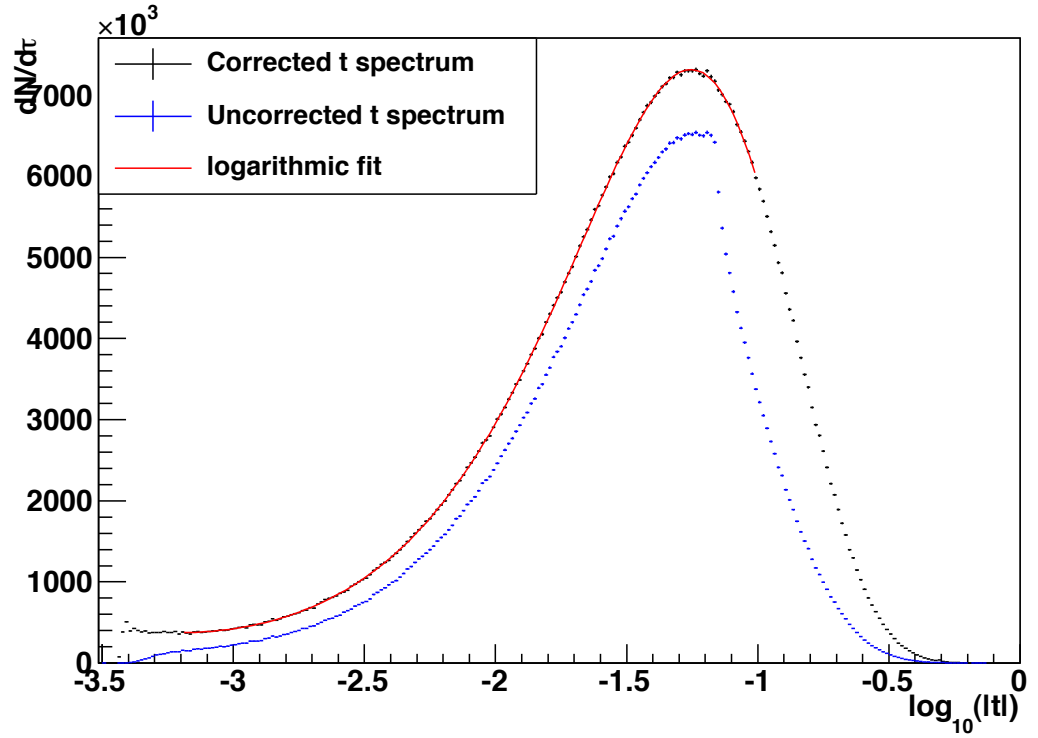
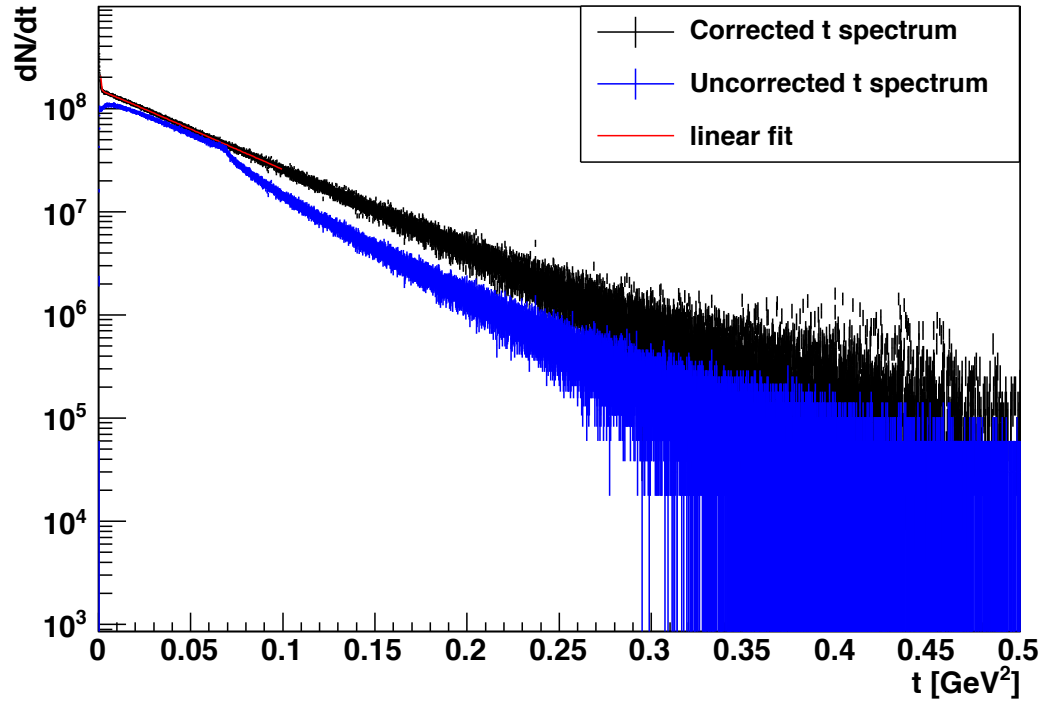
3.9 Comparison thick and thin lenses tracking

The availability of the thick lenses beam transport program MadXP makes it necessary to check the validity of the use of the thin lenses MadX for the purpose of ALFA simulations. Therefore a sample of one million events has been generated with Pythia and used as input for the beam transport with MadX and MadXP respectively. The output at the Roman Pots is compared and differences are studied. It is important to see if the output of both programs is consistent. This can be done by having a look at the different positions both deliver for the protons at the Roman Pots. The result is shown in Fig. 35. However, for ALFA it is more important to have a look specifically at the small t values. This is done in Fig. 36 for $t \leq 0.01 \text{ GeV}^2$. In both figures it is clearly visible that the RMS is much smaller than the detector resolution ($12 \mu\text{m} \ll 30 \mu\text{m}$). The final judgement can only be done after having checked, what the impact of the different correction function is, i.e. the induced systematical error. For this an identical sample of one million events was corrected once with a MadX generated correction function, once with a MadXP generated one. Finally, a luminosity fit gave the results in Tab. 12. It can be seen that within error the reconstructed luminosity corresponds for both cases with the input luminosity. Thus it can be concluded that MadX is sufficient for ALFA simulations, especially since it is computationally much less demanding. A comparison of all three beam transport programs (MadX, MadXP, FPtracker) can be found in [24].

3.9 Comparison thick and thin lenses tracking

Correction	Parameter		Input	Value	Error
MadXP	Luminosity	$[10^{26} \text{ cm}^{-2} \text{ s}^{-1}]$	4.01	4.04	± 0.09
	Cross section	[mb]	111.6	111.2	± 1.3
	B	$[\text{GeV}^{-2}]$	18	18.01	± 0.02
	ρ		0.1383	0.1428	± 0.006
MadX	Luminosity	$[10^{26} \text{ cm}^{-2} \text{ s}^{-1}]$	4.01	3.89	± 0.09
	Cross section	[mb]	111.6	112.8	± 1.4
	B	$[\text{GeV}^{-2}]$	18	17.80	± 0.02
	ρ		0.1383	0.1321	± 0.006

Table 12: Result comparison MadX - MadXP.

(a) Logarithmic t spectrum corrected and uncorrected. Additionally the final fit is drawn.(b) Linear t spectrum corrected and uncorrected. Additionally the final fit is drawn.**Figure 33:** Final luminosity determination step

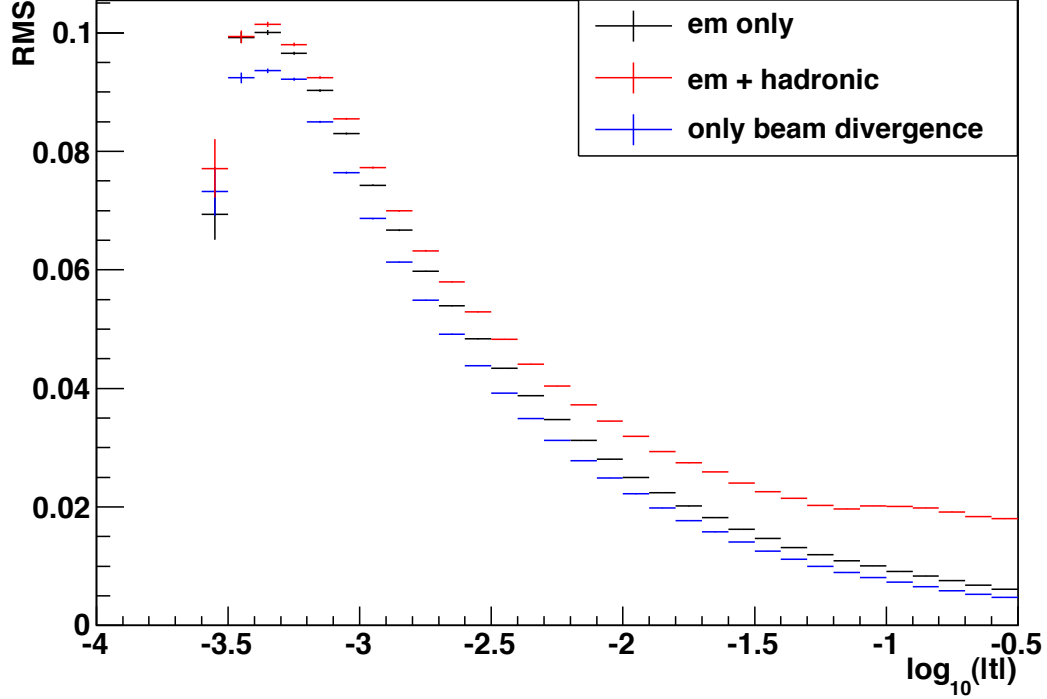


Figure 34: Width of the distribution Eq. 36 for different values of t . Clearly visible is the impact of the detector and reconstruction.

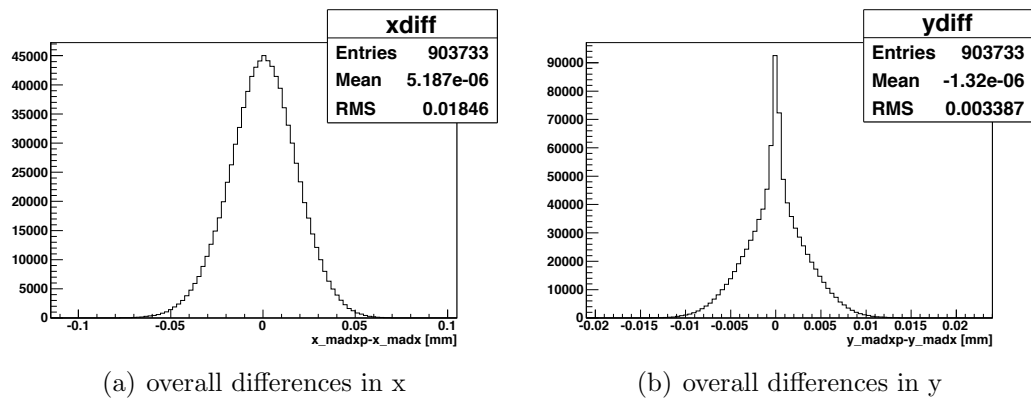


Figure 35: Position differences of protons tracked by MadX and MadXP respectively.

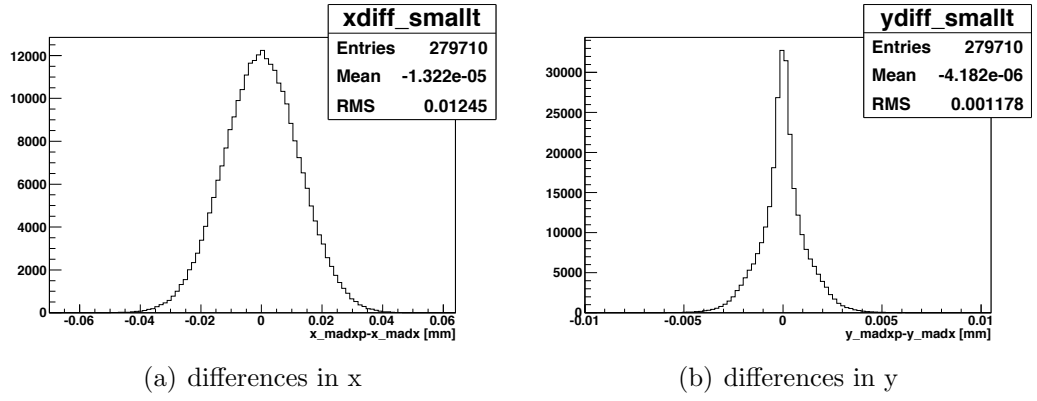


Figure 36: Position differences of protons tracked by MadX and MadXP respectively, where $t \leq 0.01 \text{ GeV}^2$.

4 Testbeam

The latest ALFA testbeam was performed in October 2009 on the Prévessin site of CERN, France. The beam consisted of 120 GeV pions from the SPS test beam line H6. For testing purposes one full station, i.e. one upper and one lower pot, was available. The upper pot contained ALFA1, the lower one ALFA2. To determine the x and y coordinates of the incident particle, the EUDET silicon pixel telescope was used. This allowed the determination of parameters like the spatial resolution et cetera. The entire setup can be seen in Fig. 37. Special attention should be paid to the main detector trigger tiles, which are of special importance later.

Several properties were measured, among these

- high voltage (HV) scans
- threshold scans
- gain scans
- position scans
- angular scans
- edge scans
- overlap detector tests

One major issue was the long integration time of EUDET of $110\mu\text{s}$, which meant that there might be several tracks in EUDET for one ALFA event. In the following all space based listings are meant as seen in beam direction.

4.1 EUDET Telescope

EUDET is a silicon tracker pixel telescope. It consists of two boxes separated by 34 cm, where is space to put the device under test (DUT). Each box contains three 1152×576 pixel planes with an effective pixel pitch of $18.4 \times 18.4\mu\text{m}^2$ and a total active area of $21.2 \times 10.6\text{mm}^2$. Within the boxes the planes are separated by 10 cm. The spatial resolution is given by $\sigma \approx 3\mu\text{m}$ for a DUT placed between the boxes and all six planes active. A summary is given in [25].

There are some peculiarities to notice for the ALFA testbeam. Firstly ALFA is too big to fit between the EUDET boxes. Therefore it was put behind EUDET, looking in beam direction. Secondly, the last silicon plane was dead, which is unfortunate since this is the one delivering the largest lever

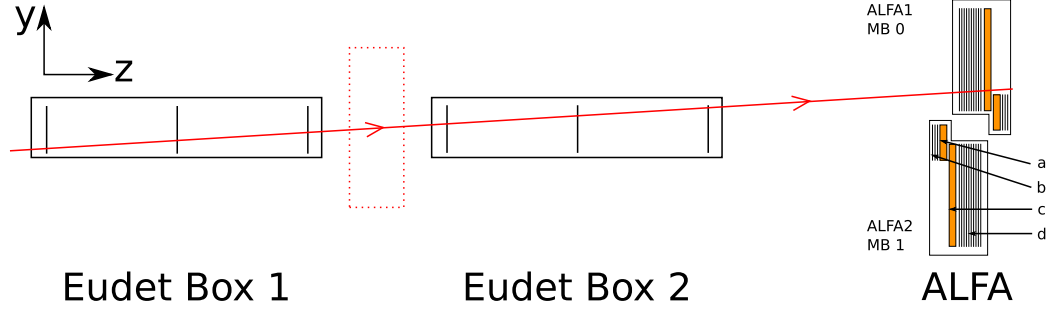


Figure 37: The full testbeam setup including ALFA and the EUDET reference telescope. Usually the device under test would have to be placed in position of the dashed box. a.) overlap trigger, b.) overlap detector, c.) main trigger, d.) main detector.

arm. Thus due to track extrapolation the EUDET resolution is lowered to roughly $10\ \mu\text{m}$, see Sec. 4.3.

4.2 Alignment Procedure

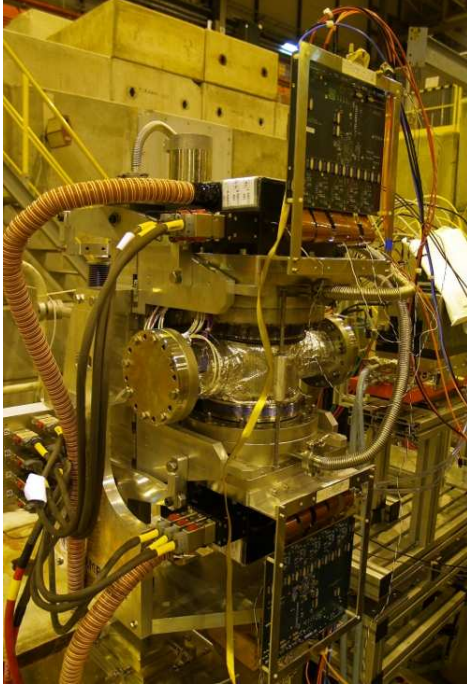
The alignment procedure is divided into three steps. First the track fitting from EUDET information has to be done, then ALFA and EUDET have to be aligned with respect to each other. Finally the EUDET information has to be transformed into the ALFA coordinate system.

The data obtained from the EUDET collaboration is reconstructed clusters in each of the five active planes along with the precise plane z position. The five planes are already aligned with respect to each other. Degrees of freedom (DOF) are shifts in x and y as well as rotations around the beam direction z . Alignment parameters in the range of some hundred μm as well as rotations of a few mrad are achieved compared with the theoretical values. Tests have been carried out to improve the alignment, but the residual from cluster to track fit did not show a significant improvement. Thus the EUDET clusters are taken and for x and y their position is fitted with a straight line as best approximation of the actual track.

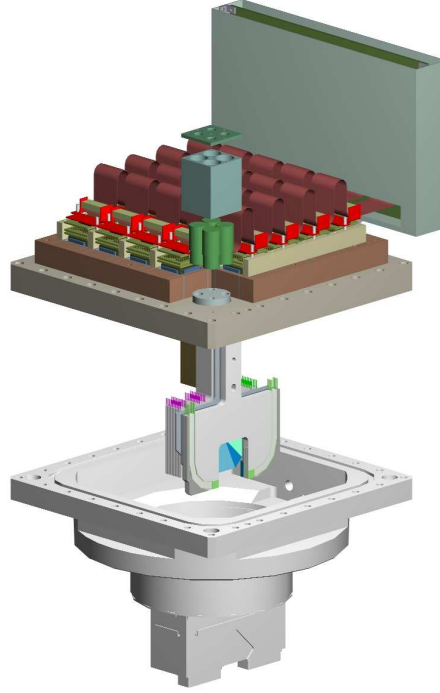
$$\begin{pmatrix} x_i \\ y_i \end{pmatrix} = \begin{pmatrix} A_{x,i} \\ A_{y,i} \end{pmatrix} \cdot z + \begin{pmatrix} b_{x,i} \\ b_{y,i} \end{pmatrix} \quad (37)$$

The residuals in all five planes are between $1\ \mu\text{m}$ and $3\ \mu\text{m}$. This track information is extrapolated to the position of ALFA.

The next step is the alignment of ALFA with respect to EUDET. The DOF are shifts in x (x_0), y (y_0) and z (z_{ALFA}). The z shift had to be introduced



(a) Testbeam setup



(b) ALFA assembly

Figure 38: (a) Picture of the testbeam setup. Visible is the full ALFA station with motherboard and connectors for the beampipe. On the right of ALFA the second EUDET box is partly visible. (b) Insertion of ALFA into the Roman Pot.

since the ALFA position with respect to the first EUDET plane is not exactly known. Furthermore rotations around all three axis x , y and z are allowed. This can be described by simple matrix multiplications with a rotational matrix Λ .

$$\begin{pmatrix} x_{\text{EUDET},i} \\ y_{\text{EUDET},i} \\ \Delta z \end{pmatrix} = \Lambda \cdot \begin{pmatrix} x_{\text{ALFA},i} - x_0 \\ y_{\text{ALFA},i} - y_0 \\ 0 \end{pmatrix} \quad (38)$$

$$\Lambda_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \gamma & \sin \gamma \\ 0 & -\sin \gamma & \cos \gamma \end{pmatrix} \quad \Lambda_y = \begin{pmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{pmatrix} \quad (39)$$

$$\Lambda_z = \begin{pmatrix} \cos \phi & -\sin \phi & 0 \\ \sin \phi & \cos \phi & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \Lambda = \Lambda_x \cdot \Lambda_y \cdot \Lambda_z \quad (40)$$

With $x_{\text{EUDT},i}$ and $y_{\text{EUDT},i}$ as the transformed ALFA coordinates in the EUDT system.

After these preliminaries the aim is the minimization of the χ^2 given by

$$\chi^2 = \sum_i (A_{x,i} \cdot (z_{\text{ALFA}} + \Delta z_i) + b_{x,i} - x_{\text{EUDT},i})^2 / dx_i^2 + (A_{y,i} \cdot (z_{\text{ALFA}} + \Delta z_i) + b_{y,i} - y_{\text{EUDT},i})^2 / dy_i^2 \quad (41)$$

which is the squared residual sum of telescope predicted to measured particle position. Here dx_i and dy_i are the errors, or weight, that are put on each point. For simplicity this was left at one, i.e. same weight for all datapoints. The variables $A_{x,i}$ and $A_{y,i}$, as well as $b_{x,i}$ and $b_{y,i}$ are the parameters of the particle trajectory. The position of ALFA, as determined from the fit, is given by z_{ALFA} . Due to twists around x and y each individual datapoint can be slightly off of z_{ALFA} , which is accounted for by Δz_i . The full procedure is as follows:

At first the points are selected that are used for alignment. This is done in a twofold process. In the beginning the combinations of planes used for the alignment have to be chosen. This is important since certain combinations give a worse extrapolated position than others, which is the case for instance for combinations with only three successive planes. These have a short lever arm and therefore a bad extrapolated position. Naturally, preferred combinations are those with a large lever arm. The advantage of this preselection is that there are less points for alignment and thus it is much faster.

The next step is the selection of a subset of the previous points. This subset is found by looking at the correlation between x_{EUDT} and x_{ALFA} as well as y_{EUDT} and y_{ALFA} . For this purpose the residuals of

$$x_{\text{EUDT}} - x_{\text{ALFA}} \quad (42)$$

$$y_{\text{EUDT}} - y_{\text{ALFA}} \quad (43)$$

are investigated. In each of these distributions there will be a Gaussian as indication of the correlation. This Gaussian is fitted and the tails are cut in a preselected range, which is a multiple of its width σ . Thus only the points within a certain range around the mean (of the Gaussian) are used. This ensures that only well correlated points are involved in the alignment.

This filtered subset is plugged into the minimizer for the χ^2 . The result of the minimization is a set of parameters which will minimize the combined resolution of ALFA and EUDT.

Finally all points, including the previously excluded ones, have to be retransformed from the EUDT frame of reference to the ALFA coordinate system.

This is done by simple inversion of Eq. 38:

$$\begin{pmatrix} x_{\text{ALFA},i} \\ y_{\text{ALFA},i} \\ \tilde{z}_i \end{pmatrix} = \Lambda^{-1} \cdot \begin{pmatrix} x_{\text{EUDET},i} \\ y_{\text{EUDET},i} \\ \Delta z_i \end{pmatrix} + \begin{pmatrix} x_0 \\ y_0 \\ 0 \end{pmatrix} \quad (44)$$

One should notice that due to the longer integration time of EUDET of $110 \mu\text{s}$, it is possible that several tracks are recorded in EUDET for one event in ALFA. However, this is taken care of by the procedure described before. Event selection can therefore be done after alignment, if needed.

For several runs the alignment has been tested and some are used for later analysis. As rotational parameter

$$\varphi_{\text{upper}} = (50.9 \pm 1.9)\text{mrad} \quad (45)$$

$$\varphi_{\text{lower}} = (48.7 \pm 1.3)\text{mrad} \quad (46)$$

is found from the minimization. Like expected both are the same since the two pots are connected and thus can only be turned at once. A rotation of almost 50 mrad might seem big at first, yet it is not. The rotation is only a relative rotation with respect to EUDET. Therefore the order of magnitude is fine. The rotations around x and y , although implemented at first, have been excluded later. Reason being that the errors were orders of magnitudes larger than the actual value, i.e. the value meaningless. Thus, in order to stabilize the alignment, they have been excluded. Other checks concerning

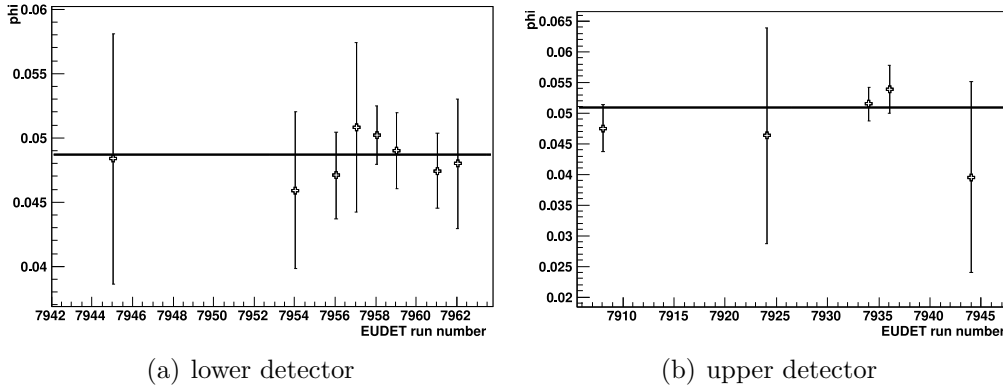


Figure 39: The rotation angle φ as found from software alignment for upper and lower detector.

the consistency of the shift parameters have been performed as well. The ALFA station was moved in two dimensions, x and y . Whenever the station was moved the new position was measured with a ruler, thus that each position is known to $\Delta s = 0.5 \text{ mm}$. The software alignment parameters x_0 and

y_0 should compensate for each movement of the station. Therefore one can have a look at the differences

$$x_0 - x_{\text{ALFA,station}} \quad (47)$$

$$y_0 - y_{\text{ALFA,station}} \quad (48)$$

both of which should be constant along the runs. This check has been performed and indeed the differences are found to be constant.

4.3 EUDET Resolution

The track parameters gained from fitting are also subject to an error. This error will propagate to an error on the extrapolated position prediction and shall be subject of investigation next. At first a proper error for each datapoint used in the fit has to be found. This can be done via the χ^2 of the tracks. There is a certain probability that a given χ^2/ndf will occur. One can obtain this probability for each fitted track and have a look at the resulting distribution. From theory it is known, that, if the errors on the datapoints are correct, the distribution should be flat. If the error is overestimated, the distribution will increase to the right. Should the errors be underestimated it will rise to the left. Variation of the error, subject to the constraint that the resulting χ^2 probabilities are distributed flatly, will give the correct error. Since all EUDET planes are the same, the same error is assumed for each plane. The result is an error of $\sigma = 3.5 \mu\text{m}$ for x and y in each EUDET plane, shown in Fig. 40 among the other two cases. With this σ the errors on the track parameters gained from fitting are meaningful and can be propagated. Since the track parameters are correlated special care has to be taken. The proper error propagation is given by

$$\sigma_x^2 = \left(\frac{\partial x}{\partial A_x} \Delta A_x \right)^2 + \left(\frac{\partial x}{\partial b_x} \Delta b_x \right)^2 + 2 \cdot \frac{\partial x}{\partial A_x} \cdot \frac{\partial x}{\partial b_x} \cdot \text{cov}(A_x, b_x) \quad (49)$$

$$= z^2 \Delta A_x^2 + \Delta b_x^2 + 2 \cdot z \cdot \text{cov}(A_x, b_x) \quad (50)$$

with

$$x = A_x \cdot z + b_x \quad (51)$$

as before [26]. The same holds true for σ_y . The resolution should be evaluated at the ALFA position, approximately at 1400 mm. The results are summarized for each combination of planes in Tab. 13. Weighted with their probability of occurrence a mean resolution of $\sigma_x = \sigma_y = 12.3 \mu\text{m}$ is obtained. For the resolution studies of ALFA the bad combination with $32 \mu\text{m}$ is excluded and a mean of $\sigma_x = \sigma_y = 7.6 \mu\text{m}$ is the result.

Active planes						Resolution [μm]
1	2	3	4	5	6	
1	1	1	0	0	0	32.2
1	1	0	1	0	0	8.2
1	0	1	1	0	0	8.4
0	1	1	1	0	0	9.1
1	1	1	1	0	0	8.2
1	1	0	0	1	0	7.0
1	0	1	0	1	0	7.1
0	1	1	0	1	0	7.5
1	1	1	0	1	0	7.0
0	1	0	1	1	0	5.9
0	1	0	1	1	0	6.5
1	1	0	1	1	0	5.6
0	0	1	1	1	0	7.4
1	0	1	1	1	0	5.8
0	1	1	1	1	0	6.2
1	1	1	1	1	0	5.6

Table 13: Resolutions of the extrapolated EUDET coordinate prediction. If a plane is active, it is marked with a 1, else with a 0.

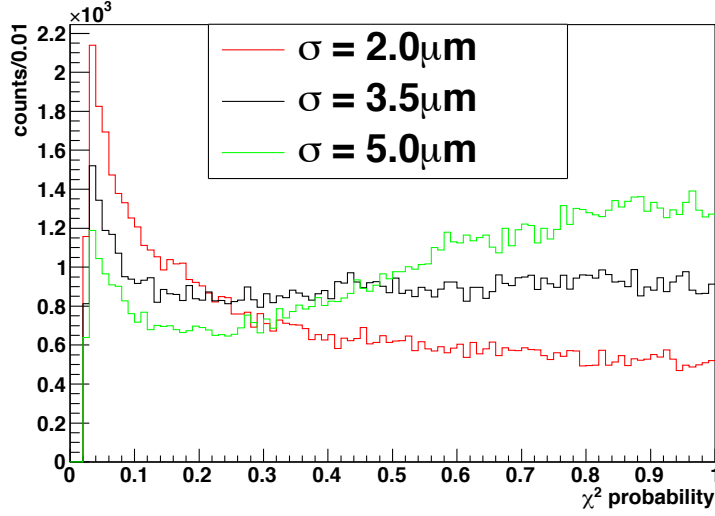


Figure 40: χ^2 probabilities distribution. If the error is overestimated the distribution will increase to the right. Should the error be underestimated it will increase to the left.

4.4 ALFA Resolution

The aligned ALFA EUDET data can be used to study the resolution of the ALFA detector. For this a look at the residual of

$$x_{\text{EUDET}} - x_{\text{ALFA}} \quad (52)$$

$$y_{\text{EUDET}} - y_{\text{ALFA}} \quad (53)$$

has to be taken, for both upper and lower pot. As an example the result is shown for x in Fig. 41 and summarized in Tab. 14. Yet the determined resolution is not the final resolution of ALFA alone but

$$\sigma = \sigma_{\text{ALFA}} \oplus \sigma_{\text{EUDET}} \quad (54)$$

the sum of the resolutions of EUDET and ALFA. The resolution of EUDET, as determined previously, has to be subtracted in order to get the plain ALFA resolution. Since the determined EUDET resolution is a bit over idealized, a more conservative $\sigma_{\text{EUDET}} = 10 \mu\text{m}$ is used. The spatial resolution determination was done using two runs, one central on the upper pot, one central on the lower pot. Yet there is much more data available from the different areas of the detector which should be looked at since the actual resolution also depends on the area of the detector which is covered.

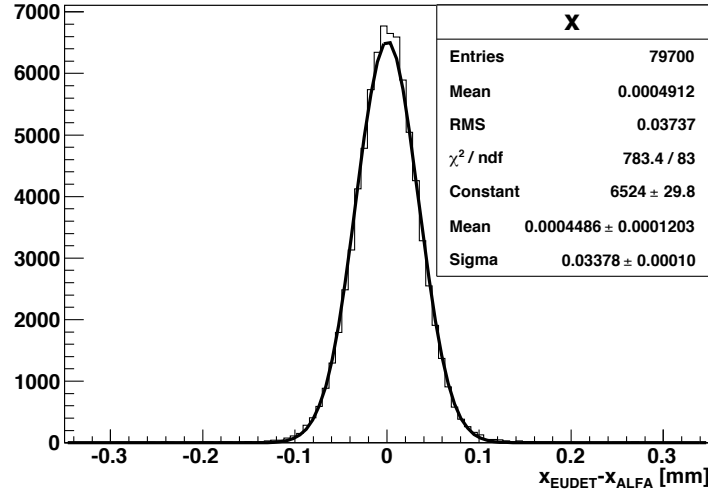


Figure 41: Resolution determination for the lower detector in the testbeam. As an example the x resolution determination is shown.

	including EUDET		EUDET contr. 10 μm	
	x [μm]	y [μm]	x [μm]	y [μm]
upper	38.2	38.3	36.9	37.0
lower	33.8	33.6	32.3	32.1

Table 14: Spatial resolutions as determined from the testbeam.

4.5 Metrology

One very interesting test concerns the quality of metrology. This can be done in a very simple way. The telescope delivers the information where the incident particle has struck the detector. Now for a specific fiber one can plot the distribution of incident positions whenever the fiber has seen light. This will ultimately give a picture of the fiber shape. The aforementioned picture can be rotated by 45° or -45° , depending on the layer, in order to get a vertical line of roughly $500 \mu\text{m}$ width. This line is sliced in y into eight parts. For each part the left and right edge is fitted using a smeared edge fit,

Eq. 55.

$$\text{EdgeFit}(x) = N \cdot \begin{cases} \left(1 + \text{Erf}\left(\frac{x - x_{\text{edge},r}}{\sqrt{2}\sigma_r}\right)\right) & , x > \frac{x_{\text{edge},l} + x_{\text{edge},r}}{2} \\ \left(1 + \text{Erf}\left(\frac{x - x_{\text{edge},l}}{\sqrt{2}\sigma_l}\right)\right) & , x \leq \frac{x_{\text{edge},l} + x_{\text{edge},r}}{2} \end{cases} \quad (55)$$

$$\text{Erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-\xi^2} d\xi \quad (56)$$

with $x_{\text{edge},l,r}$ the position of the edge, N a normalization factor and $\sigma_{l,r}$ the edge smearing. This fit will deliver the position of the edges. Finally from the mean of both edges the fiber center can be determined. The result is a pair $(x|y)$ which is rotated back and the resulting eight points represent the fiber. The abstract fiber parametrization is fitted using a straight line,

$$y = A \cdot x + b \quad (57)$$

which in the ideal case should be exactly the same as the one coming from metrology. In Fig. 42 the eight slices including smeared edge fit are shown for one specific fiber.

This procedure has been performed using the testbeam data. The results have been obtained using ALFA runs 1256761359 (EUNET 7908) for the upper pot and 1256983389 (EUNET 7956) for the lower one. For run 7908 only fibers with more than 3500 events were accepted. Here this corresponded to fibers 27-30 for odd layers, and fibers 32-36 for even layers. The run 7956 had twice the statistics and thus only fibers with more than 7000 events were accepted, here this corresponded to fibers 19-26 for odd layers and fibers 36-44 for even layers.

Due to the low statistics in each of the eight bins the fiber inclination is not really comparable with the one from metrology. The only thing that can be said is that the absolute value of the resulting inclination is very close to unity, like it should be. What has been compared is the difference in fiber offset b from the fiber equations, i.e.

$$\Delta b_i = b_{i,\text{fit}} - b_{i,\text{metr}} \quad (58)$$

The result for upper and lower pot can be seen in Fig. 43. For the upper pot this gives a nice Gaussian with a width of $17 \mu\text{m}$. In the lower pot the width is $38 \mu\text{m}$, but the distribution also shows a constant offset of $22 \mu\text{m}$. Yet the overall result is that the metrology corresponds very well with the results found from the testbeam. Still the fiber inclination should be checked, but for this runs with much higher statistics have to be used.

Another property under study is the sensitive width of the fibers as it came out of the fit procedure. The width of a fiber is defined as the distance

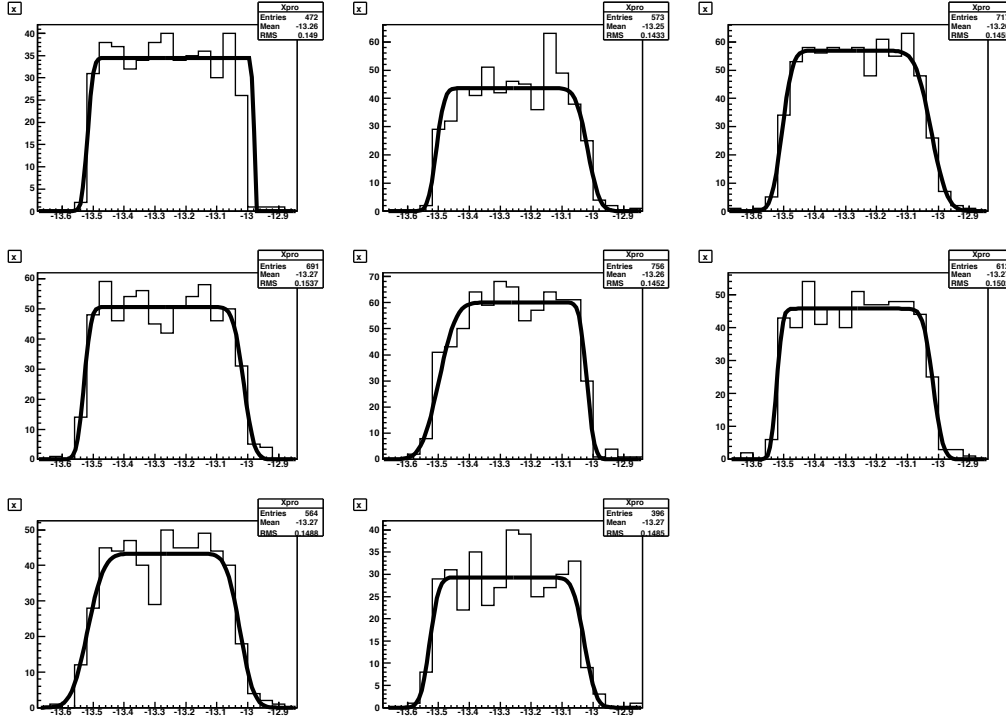


Figure 42: Example of fiber equation fit. Drawn are the fits of the eight slices the fiber is cut into. Each fit gives one pair $(x|y)$, in total eight pairs. These are fitted with a straight line, the fiber equation. Plotted on the x axis is the rotated fiber x position in mm.

between left and right edge resulting from the smeared edge fit. For each fiber the width is measured at eight points which are put into the histogram. This is why there might be some runaway values, when the smeared edge fit works quite well, yet still looks a little skewed. Nonetheless, the mean comes out almost perfect at $480 \pm 18 \mu\text{m}$ for the upper pot and $481 \pm 15 \mu\text{m}$ for the lower pot, as shown in Fig. 44. The ideal value is $500 \mu\text{m} - 2 \cdot 10 \mu\text{m} = 480 \mu\text{m}$.

The gained fiber equations can be used to check the fiber pitch. In the ideal case this should be

$$500 \mu\text{m} \cdot \sqrt{2} = 707 \mu\text{m} \quad (59)$$

The result is presented in Fig. 45. Again it comes out very well with $700 \pm 16 \mu\text{m}$ for the upper and $709 \pm 12 \mu\text{m}$ for the lower pot.

A last important check has been performed concerning the staggering. The staggering has been reviewed for the lower pot with run 7956. In principle

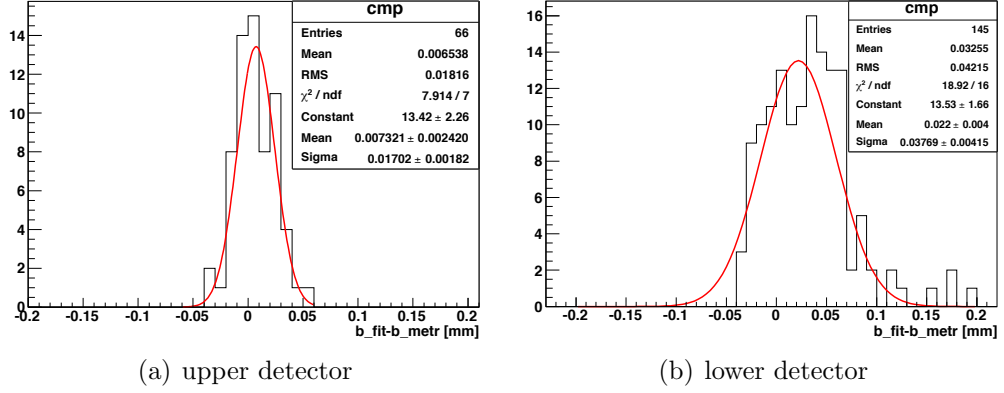


Figure 43: Comparison of fiber equation offset b from metrology with the b gained from the testbeam setup.

the upper pot could be used as well, but since the statistics was too low, a lot less fiber equations were calculated. Furthermore, for the staggering the fiber equations with a $\chi^2/\text{Ndf} > 20/8$ were excluded. This reduced the fibers available for tests again. For the calculation of the staggering layers 0 and 1 were used as reference. The staggering is the difference from each later fiber equation b to the reference fiber b . The agreement with theoretical values is quite good as can be seen from Tab. 15.

4.6 Layer and fiber efficiencies

The next point of interest is the efficiency of single layers and fibers. Using the external telescope information the fiber efficiency is calculated. It is given by the number of events where the fiber was active, given that the telescope predicted it to be active, divided by the number of events where the telescope predicted it to be active. The layer efficiency is defined in a similar fashion. The only difference is, that besides the predicted fiber, one of its two neighbors is allowed to be active. By this definition clearly the layer efficiency should be slightly higher than the fiber efficiency. Shown in Fig. 46 are the results for EUDET run 7956, on the lower pot. From the figure it is evident that the layer efficiency is above 90% for almost all layers. This is in very good agreement with the previous 2008 testbeam [27]. Layer 1 seems to have had a problem, having an efficiency of only 50%. The efficiency for a single fiber is slightly below 90% for most of the layers. Fig. 46(b) shows the small fluctuations of fiber efficiencies in a layer for some selected fibers.

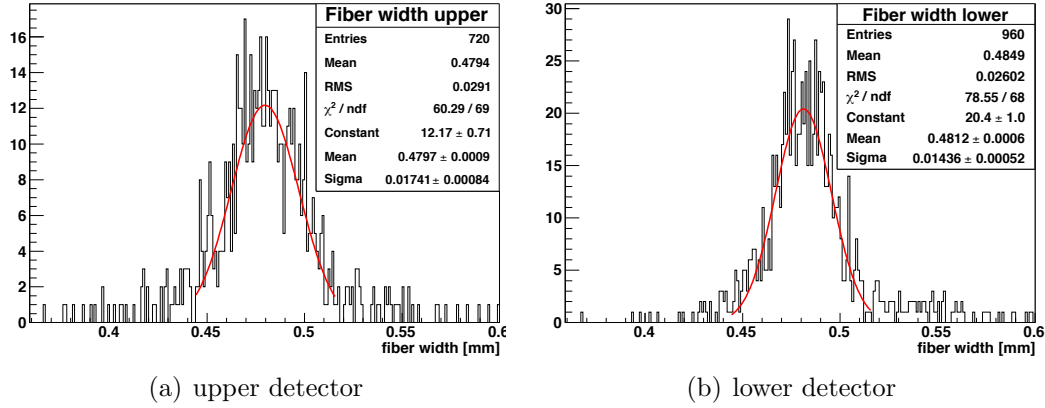


Figure 44: Fiber width for upper and lower detector as measured with EUDET runs 7908 and 7956. For each fiber the eight measured points enter the histogram.

4.7 Hit multiplicities

A view at the hit multiplicity distribution should be taken. For this two overnight high statistics runs were used. For the upper pot run 1256513069 (2 314 514 triggers), for the lower pot run 1256597780 (1 415 828 triggers) is analyzed. The integral result over all layers is shown in Fig. 47. Drawn is the normalized multiplicity distribution to make the two runs comparable. Interesting is the rise in very high multiplicities, 60 and above. This rise can partially be attributed to hadronic showers, but the greater part should be induced from electronics noise. Nicely visibly are the expected higher multiplicities the lower pot experiences.

The resulting multiplicities for each individual layer are shown in Fig. 48. For the lower pot the layer numbering has been reversed. This is due to the fact that, looking in beam direction, layer 20 is the first. Thereby it is easily comparable with the upper pot. Additionally two linear fits are drawn. One is fitted to the lower pot data, the other one to the upper pot data. From this it becomes very clear that the lower pot has the tendency to higher hit multiplicities as a result of the trigger in front of the main detector tiles. Furthermore the large non physical fluctuations are observable.

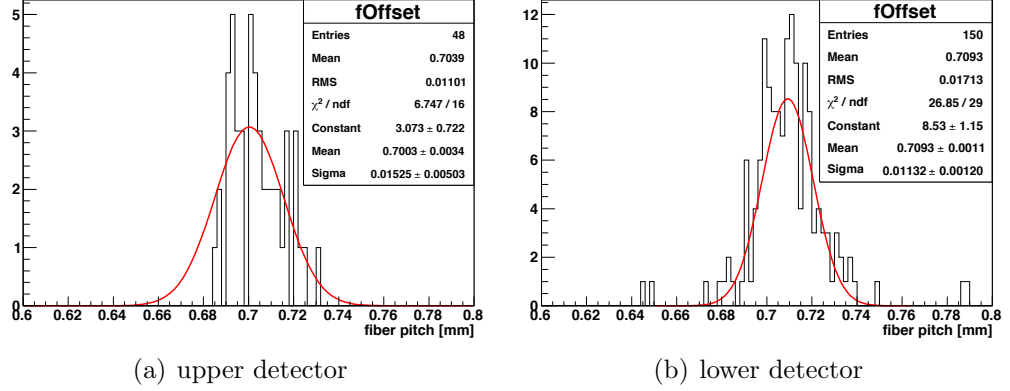


Figure 45: Calculated fiber pitch from the testbeam data. The theoretical value is given by $707 \mu\text{m}$.

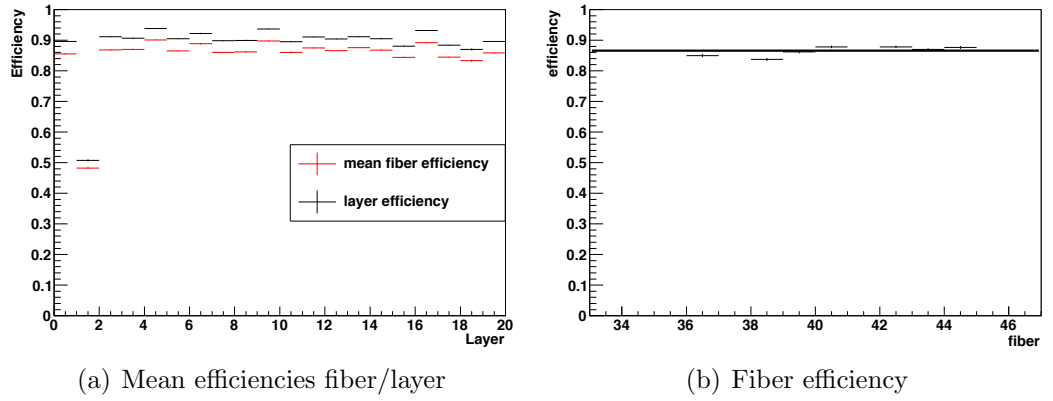


Figure 46: Efficiency study for layers and fibers with testbeam data.

step	nominal [mm]	measured [mm]	RMS [mm]
1	0.283	0.285853	0.0333591
2	-0.141	-0.114626	0.0217812
3	0.141	0.162667	0.0398345
4	-0.283	-0.29088	0.0448232
5	0.354	0.363073	0.0377752
6	-0.071	-0.0524545	0.0467685
7	0.212	0.23283	0.0412527
8	-0.212	-0.168494	0.0441037
9	0.071	0.113233	0.109444

Table 15: Staggering found in the testbeam for the lower detector in comparison with theoretical values.

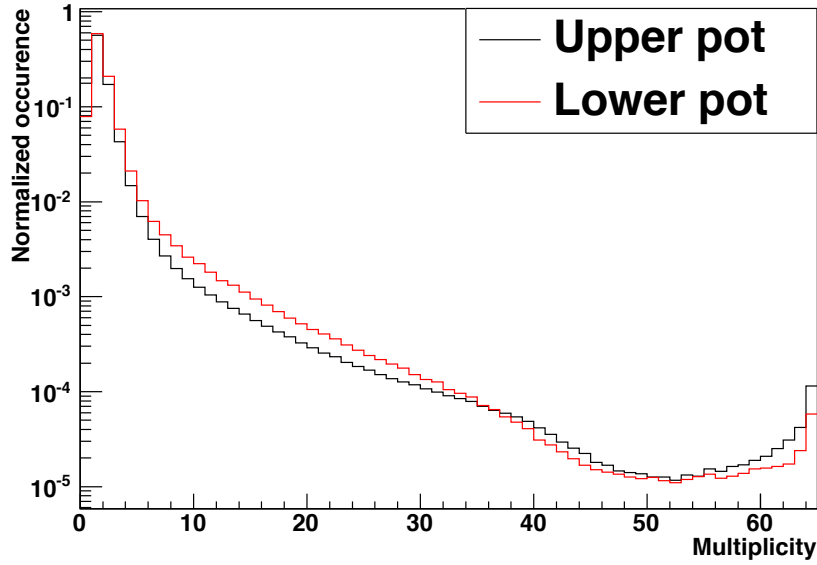


Figure 47: Multiplicity distribution as obtained from one testbeam sample. Nicely visible are the higher multiplicities the lower pot experiences as a result of showers from the additional trigger tile in front.

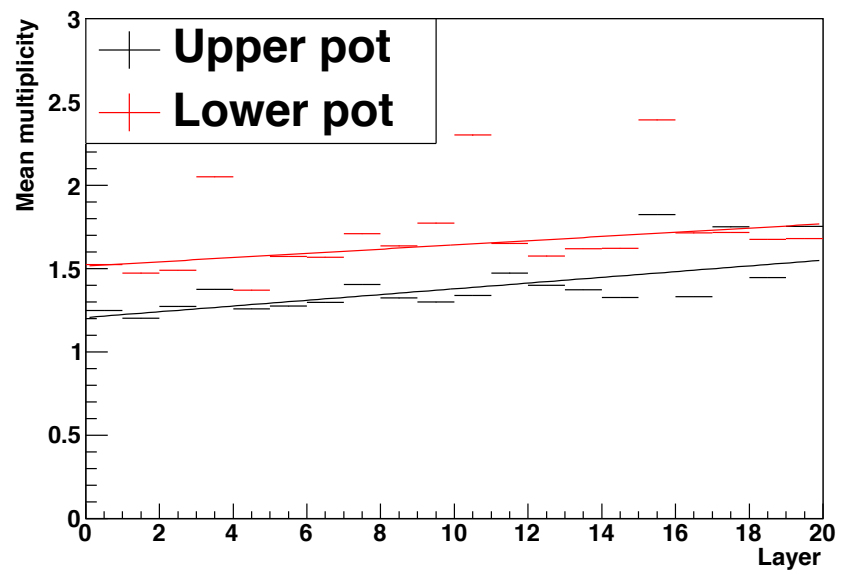


Figure 48: Mean multiplicity per layer as obtained from one testbeam sample. Special attention should be paid to the large fluctuations.

5 Comparison of testbeam and simulation

A lot of information has been extracted from the simulation and the testbeam. As a last important step both sources of information should be compared whenever possible. Furthermore the experimental data available should be used for the tuning of the Monte Carlo based simulations.

5.1 Influence of the beam pipe window

As a preliminary remark the influence of the 1 mm thick beam pipe window, hereafter called lid, shall be investigated [28]. It is made of stainless steel and closes the beam pipe on both sides to maintain a vacuum. Hence the lid and the beam pipe are added to the Geant setup and two otherwise identical runs executed. Both are centered on the lower pot and consist of 1×10^7 events. The influence on the hit multiplicities from additional showers can be seen from Fig. 49. Especially interesting is the rise in the green curve, which corresponds to the fraction of multiplicities resulting from the run with lid to the one without. In particular for multiplicities in the range around five to six there is an increase of about 20%. This is of special interest if one wants to investigate the applied reconstruction cuts. The standard maximum multiplicity allowed is at five per layer. For multiplicities above 15 there is only a very small noticeable increase and for the very high multiplicities the statistics is too low to be meaningful. The mean multiplicity per layer also increases, on average by about 2%.

The influence on the detector resolution is moderate. The resolutions found with lid are $\sigma_x = 34.4 \mu\text{m}$ and $\sigma_y = 32.4 \mu\text{m}$. For the run without lid $\sigma_x = 33.8 \mu\text{m}$ and $\sigma_y = 31.8 \mu\text{m}$ are found. Thus it can be concluded that the effect of the lid is negligible. However, for multiplicity cut studies it should be considered.

5.2 Main Detector

5.2.1 Resolution

In order to learn about the dependence of spatial resolution on the irradiated position on the detector, the position scan runs are analyzed. Since the EUDET data processing is not yet finalized the resolution calculated with telescope cannot be provided for every position. For the simulation the single ALFA runs are reconstructed and for each run the reconstructed particle position is taken as input into the Geant simulation. Since these positions also show an underlying digital pattern they are smeared with a Gaussian of

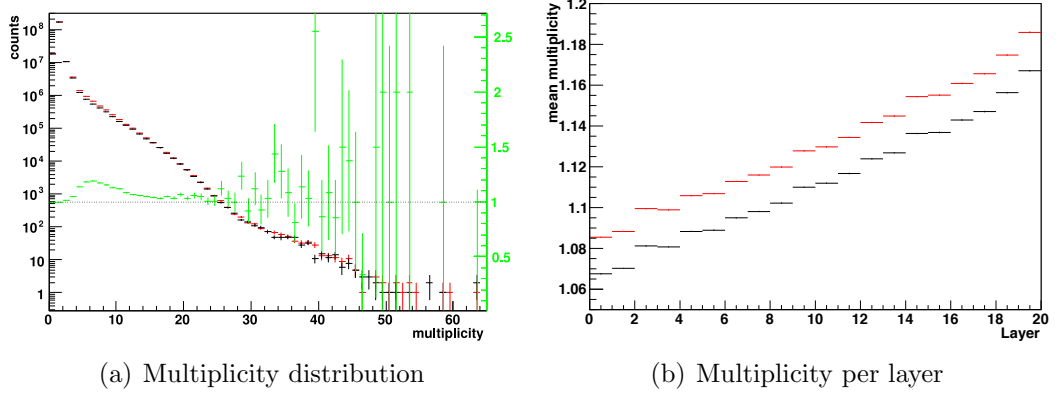


Figure 49: Influence of the flange lid on the detector. Red with lid, black without.
 (a) Multiplicity distribution, green fraction of red to black curve. (b) Mean multiplicity per layer.

width $\sigma = 50 \mu\text{m}$. The goal of this is to have a smooth particle distribution throughout the area where the detector is irradiated. For the lower pot, ALFA2, nine runs have been processed. The upper pot, ALFA1, has been investigated using ten runs. All runs and results are summarized in Tab. 16. For each run the corresponding irradiated position is indicated by a small symbol.

If now the values found from simulation are compared with the ones from the testbeam it is important to notice that the EUDET contribution has not yet been subtracted. The simulated resolution might even come off a little too good since no transverse momentum is applied, which should not make a big difference though.

Not for all processed position scan runs data from the telescope is available. Still, in order to be able to compare the simulated values with data from the testbeam, additionally the half detector resolution has been calculated for each of the position scan runs. For this the first five planes of the detector are used as telescope, and their reconstructed position is the reference value. The difference to the reconstructed position of the second half is taken and the resulting distribution is a Gaussian with width σ_H . One has to take care that the staggering for the five planes in use matches and is in steps of $141 \mu\text{m}$. With this information the theoretical half detector resolution for the ideal half detector is given by $\frac{100 \mu\text{m}}{\sqrt{12}} = 28.9 \mu\text{m}$. To conclude from the determined halfdetector resolution to the full detector resolution it is assumed that both halves have the same resolution. Furthermore that both have twice the resolution found for the full detector, which is a very idealized

	EUDET	Testbeam		Simulation		Half detectors		Half detectors sim		Res. extrapolation	
		σ_x	σ_y	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y
	7908	38.2	38.3	27.3	27.7	57.9	58.6	56.4	56.2	28.0	28.9
	7924			30.5	29.3	61.1	61.0	53.2	53.0	35.0	33.7
	7928			28.9	28.7	63.6	63.8	56.3	55.8	32.7	32.8
	7931			29.1	29.3	61.2	61.2	58.0	56.8	30.7	31.6
	7934	37.2	37.5	28.8	29.5	66.9	66.9	56.7	56.4	34.0	35.0
	7935			28.4	28.7	64.7	64.5	58.0	57.5	31.7	32.2
	7939			25.6	25.8	53.7	53.6	53.8	53.3	25.6	26.0
	7941			25.8	25.7	57.9	57.7	55.8	56.0	26.8	26.5
	7942			24.5	24.8	57.7	57.7	56.2	55.6	25.2	25.7
	7943			23.4	23.6	61.1	61.0	53.1	53.3	26.9	27.0
	7945	32.5	32.5	34.9	26.9	65.0	65.2	54.0	54.2	42.0	32.4
	7946			36.4	31.3	64.7	64.9	51.4	51.8	45.8	39.2
	7947			33.5	32.0	59.5	59.5	45.7	45.3	43.6	42.0
	7948			31.3	31.1	57.3	57.3	52.1	52.3	34.4	34.1
	7956	33.8	33.6	30.2	29.4	52.9	53.0	43.6	43.6	36.6	35.7
	7957	32.3	33.9	28.0	28.1	53.9	54.1	45.3	45.7	33.3	33.3
	7958	33.4	35.1	31.8	28.5	62.1	62.1	50.2	50.3	39.3	35.2
	7959	32.1	33.9	26.2	26.2	49.4	49.1	45.1	45.4	28.7	28.3
	7961	29.6	29.7	25.2	25.2	49.5	49.8	44.7	44.9	27.9	28.0

Table 16: Comparison of the position scan runs. Listed are the determined resolution with the telescope, the simulated resolution, the measured and simulated half detector resolution. Furthermore a predicted resolution is estimated based on extrapolation from the measured half detector resolution. From the testbeam values the EUDET contribution has not yet been subtracted. If no reconstructed EUDET data is available by now, this resolution is omitted. All resolutions are given in μm .

5 COMPARISON OF TESTBEAM AND SIMULATION

assumption. Then the resolution is given by

$$\sigma_H = \sqrt{\sigma_{H,1}^2 + \sigma_{H,2}^2} = \sqrt{4\sigma_{Full}^2 + 4\sigma_{Full}^2} = \sqrt{8} \cdot \sigma_{Full} \quad (60)$$

Thus in theory one could just divide σ_H by $\sqrt{8} \approx 2.83$ to get the full detector resolution. In reality it is not that simple since neither the staggering nor the fibers themselves are perfect.

The result of the comparison is that in the simulation the spatial resolution

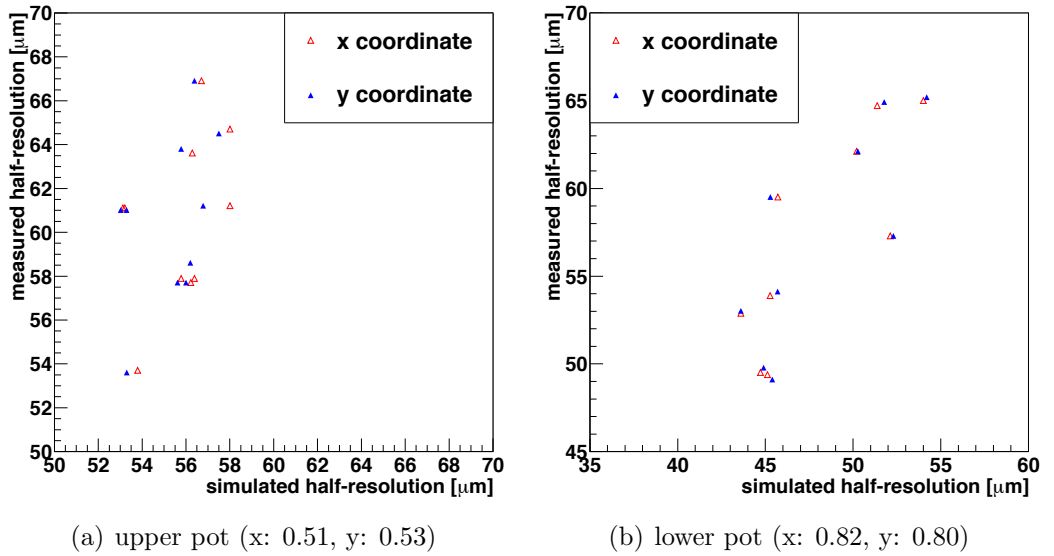


Figure 50: Correlation between simulated and measured half detector resolution for upper and lower pot. The correlation coefficients are denoted as well in braces.

of the lower pot comes off worse in most of the positions as compared with the upper. In general the overall picture is consistent, yet there are positions where data and simulation agree more, and others where they agree less. A nice correlation between measured half detector resolutions and simulated resolutions, as illustrated in Fig. 50, is obtained. Still the improvement in simulation from half to full detector resolution is not given by the theoretical $\sqrt{8}$. However, the “real” factor can be calculated from simulation and applied to the measured half detector resolution from the testbeam. From Tab. 16 the real conversion factor can be estimated by dividing the half detector resolution by the full detector resolution, both from simulation. For the upper pot this results on average in 2.05 ± 0.15 and for the lower in a factor of 1.60 ± 0.13 . Since the upper pot is closer to the theoretical value it can be concluded that the geometrical imperfection is less of a matter here.

The extrapolation to the full detector spatial resolution is also denoted in the summarizing table. Still this is only an estimate. The real resolution for each run should be extracted from the telescope data. Since there is no final telescope data available up to now, the extrapolation is an easy way to compare data and simulation.

5.2.2 Tomography plot

A very nice thing from the testbeam to compare with simulation is the so called “tomography plot”. Particles that have triggered the EUDET telescope might hit the ALFA pot support and create a shower of secondaries. One of these secondaries might trigger ALFA, which in turn will record an event, from which only a fraction will be detected. Now if a look at the incident particle distribution is taken, the pot support will nicely show up. This is particularly interesting for the runs focused on the detector edge and the overlaps at the same time. Here the thin bottom window and the surrounding material of the overlaps show up nicely. For comparison this is shown in Fig. 51. It is evident that the simulation is very well able to reproduce the plot resultant from the testbeam.

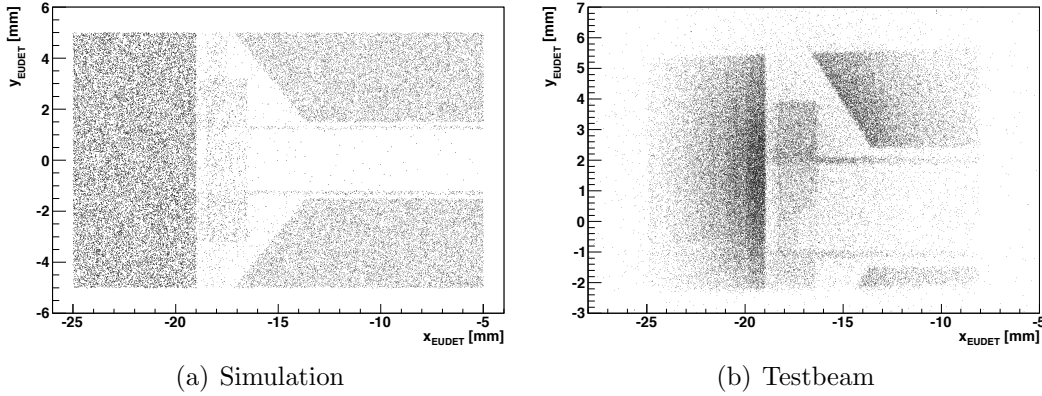


Figure 51: Tomography plot resulting from a run centered on the gap between the main and overlap detectors.

5.2.3 Layer and fiber efficiency

The layer and fiber efficiencies, as found from simulation, shall be compared with testbeam data. For this EUDET run 7931, central on the upper pot, was used as input to the simulation. The efficiencies of fibers and layers were calculated as explained earlier in Sec. 4.6. Whenever the telescope predicts a

5 COMPARISON OF TESTBEAM AND SIMULATION

particle to be geometrically within one fiber, the fiber is checked if it has seen light. For this the previously determined fiber equations from the smeared edge fit are used. The results are plotted in Fig. 52. Efficiencies found for the individual layers agree quite well with what was found in the testbeam - most layers are slightly above 90% efficiency. Yet the major difference apparent from Fig. 52(a) is that layer and fiber efficiency are almost the same. In the testbeam a bigger discrepancy between both was found. This means that in the simulation the fiber efficiency is higher than found in the testbeam. The main contribution to this difference is a result of the smearing by the

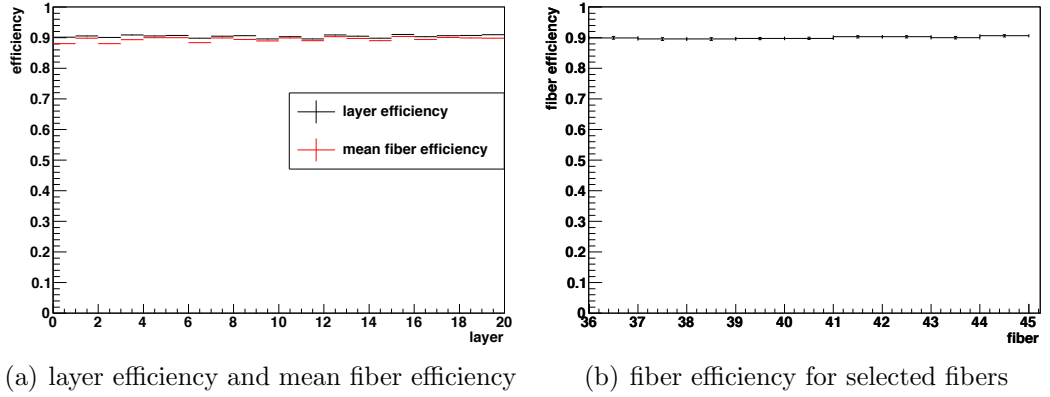


Figure 52: Efficiencies as calculated from simulation with input from testbeam data.

telescope. Lets assume a conservative $20\text{ }\mu\text{m}$ smearing of EUDET in x and y. Due to the 45° angle between the scintillating fibers and x and y, the total radial smearing relatively to one fiber turns out to be

$$\sigma_r = \sqrt{20^2\text{ }\mu\text{m}^2 + 20^2\text{ }\mu\text{m}^2} = 28.3\text{ }\mu\text{m} \quad (61)$$

Therefore, for a particle which really hits the sensitive detector area in $\hat{x}$ and $\hat{y}$, the telescope will predict a position Gaussian smeared around $(\hat{x}|\hat{y})$ with width $\sigma_r = 28.3\text{ }\mu\text{m}$. This gives the possibility to calculate the proportion of particles that were predicted to hit a fiber, when in fact they did not.

The calculation procedure is simple. A Gaussian of width σ_r is taken and shifted perpendicular to the fiber. Starting from the right fiber edge ($r := 0\text{ }\mu\text{m}$) it is shifted continuously until it has moved by $500\text{ }\mu\text{m}$. In each step the integral over the Gaussian in the limits of the fiber under investigation is taken, thus the entire fraction is given by

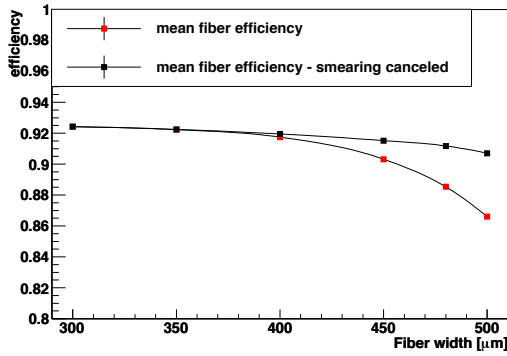
$$\mathcal{F} = \frac{1}{\sigma_r \sqrt{2\pi}} \cdot \int_{r'=0\text{ }\mu\text{m}}^{500\text{ }\mu\text{m}} \int_{-500\text{ }\mu\text{m}}^{0\text{ }\mu\text{m}} e^{-\frac{(r-r')^2}{2 \cdot \sigma_r^2}} dr dr' \quad (62)$$

This integral is the result of only one side of the fiber, the other side experiences the same contribution. In total this gives the proportion of particles that are actually outside the fiber, but are predicted by the telescope to be inside. Clearly this will reduce the calculated fiber efficiency. The calculation of Eq. 62 for a $500\text{ }\mu\text{m}$ core results in a total reduction by a factor of 0.955. Correction factors for different widths are summarized in Tab. 17. The procedure is illustrated in Fig. 53(b), in which the fraction of false positive particles is marked in red.

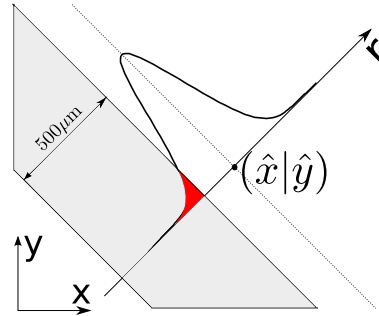
This effect can be checked experimentally. Therefore the fiber efficiencies are calculated again, but now with smaller assumed fiber cores down to $300\text{ }\mu\text{m}$. This safety margin is big enough to get rid of the smearing from the telescope. A summarizing plot is shown in Fig. 53(a) from which it is evident that the fiber efficiency will converge to smaller assumed fiber width, as the telescope contribution vanishes. For comparison the smearing cleaned fiber efficiency, calculated as the fiber efficiency divided by the result of Eq. 62 for the corresponding width, is plotted in black. At bigger fiber widths there is still some difference from the converged value, which can be attributed to cladding effects or ghost hits in the telescope from the long EUDET integration time.

Width [μm]	Factor
300	0.999 99
350	0.999 76
400	0.997 794
450	0.986 854
480	0.970 995
500	0.954 711

Table 17: EUDET smearing impact factors.



(a) Layer and fiber efficiencies for different assumed fiber widths.



(b) False positive calculation procedure.

Figure 53: Investigation of differences in layer and fiber efficiencies.

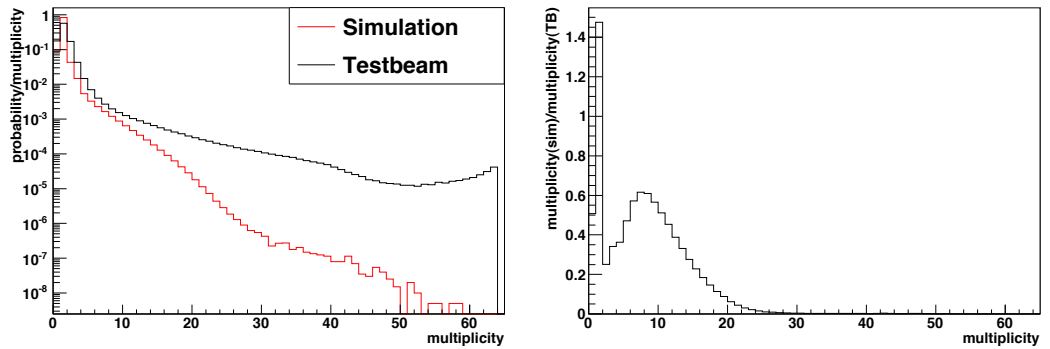
5.2.4 Hit Multiplicities

For the comparison of hit multiplicities the high statistics run 1256513069 (2314514 triggers) central on the upper pot was chosen. The same run has been put into simulation for comparison. For both cases the multiplicity distribution is plotted in Fig. 54. In order to make both comparable their integral is normalized to unity. The differences are quite astonishing. The simulation will only see half the amount of layers with zero hits as compared with the testbeam. In the simulation these are approximately 9%, whereas in the testbeam these account for almost 18%. For perfect fibers, i.e. 100% efficiency, and no applied cuts this should only be 4%, the cladding area. Clearly the simulation is more on the ideal case side.

For layers with one and more hits the differences are harder to explain. The simulation registers much more layers with one hit only and much less with more than one. For multiplicities below ten this can qualitatively be explained as crosstalk between fibers, which is not present in the simulation, but will shift multiplicities to higher values in the testbeam. For the differences in high multiplicities, ten and above, the dominant contribution should be a result from electronics noise since there no agreement between simulation and testbeam can be found.

Despite these differences it is good to know that the overlap algorithm works reliable in both cases. Again it is important to state the fact that certainly a run that matches simulation and testbeam data better could be found. There are large run to run differences in multiplicities found from the testbeam. Yet the overall shape is similar.

The very high multiplicity tails shall be subject of inspection next. Surely



(a) Comparison of multiplicities from simulation and testbeam (b) Proportion of multiplicities from simulation to testbeam

Figure 54: Multiplicities comparison from testbeam and simulation.

there is the possibility that a particle shower will light up all 64 fibers, yet

the probability is dimishingly small. From Fig. 26(a) it can be estimated to 10^{-7} , which is much smaller than observed in the testbeam with roughly 10^{-4} . To see the impact of this assumed electronics noise a simple cut will be applied. Naturally, if a shower develops the difference in multiplicities between two adjacent layers should not jump suddenly by an unreasonable amount. The definition of unreasonable has to be extracted from simulation. For this the multiplicity difference for all neighboring layers is taken. The result is shown in Fig. 55(a). It can be seen that, for both simulation and testbeam, the majority of differences are zero, like it should be for a clean track. Yet again there are big differences visible as to which amount the multiplicity differences occur.

The cut will finally reject an event if amongst the 19 differences between the 20 layers there is one which exceeds the cut value. The event is assumed to be flawed by electronics noise and therefore discarded. Hence it is important to have a look at the maximum differences distribution in Fig. 55(b). Here the simulation peaks at unity with roughly 75% of all events, whereas the testbeam peaks at two with roughly 50%. A look at the data explains why. For the simulation the majority of layers registers only one fiber, but due to cladding and photoelectron cuts there are also layers with zero. Hence the peak at one. In the testbeam the same holds true, but some layers will just jump to two “at random”. Therefore the peak at two. Apparently for the

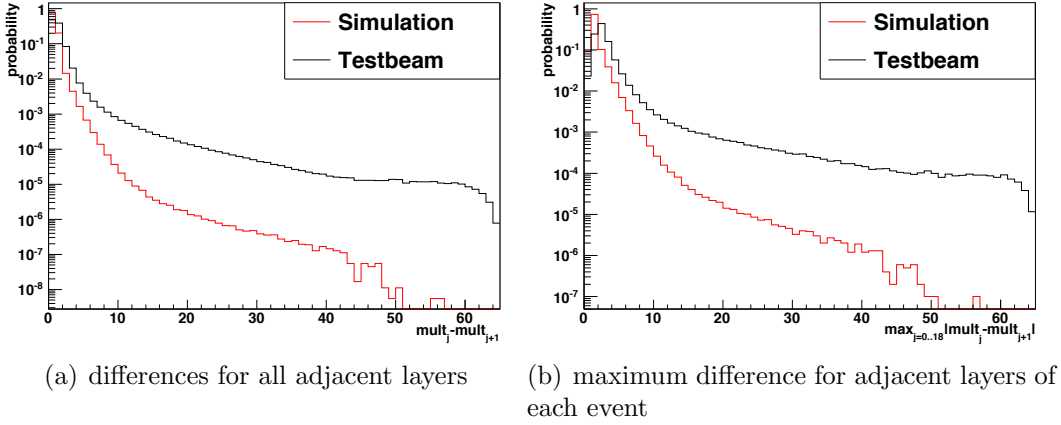


Figure 55: Multiplicity differences between adjacent layers of ALFA.

testbeam data there are events where even jumps of up to 64 between two adjacent layers are possible. Clearly this is nonphysical, which is why it does not appear in the simulated data. Now a cut on this maximum difference will be applied. Three cut values have been chosen, all of which affect way below 1‰ of all events according to the simulation. In the testbeam data it will cut

Cut value	Proportion lost	
	Simulation	Testbeam
20	0.000 139 222	0.009 797 49
30	$3.732\,53 \times 10^{-05}$	0.004 833 6
40	$8.483\,03 \times 10^{-06}$	0.002 480 98

Table 18: Effects of different cut values on the multiplicity distribution.

away up to 1% of all data, which is acceptable. A summary of the cuts can be found in Tab. 18. The result is that in the end, with a cut in maximum

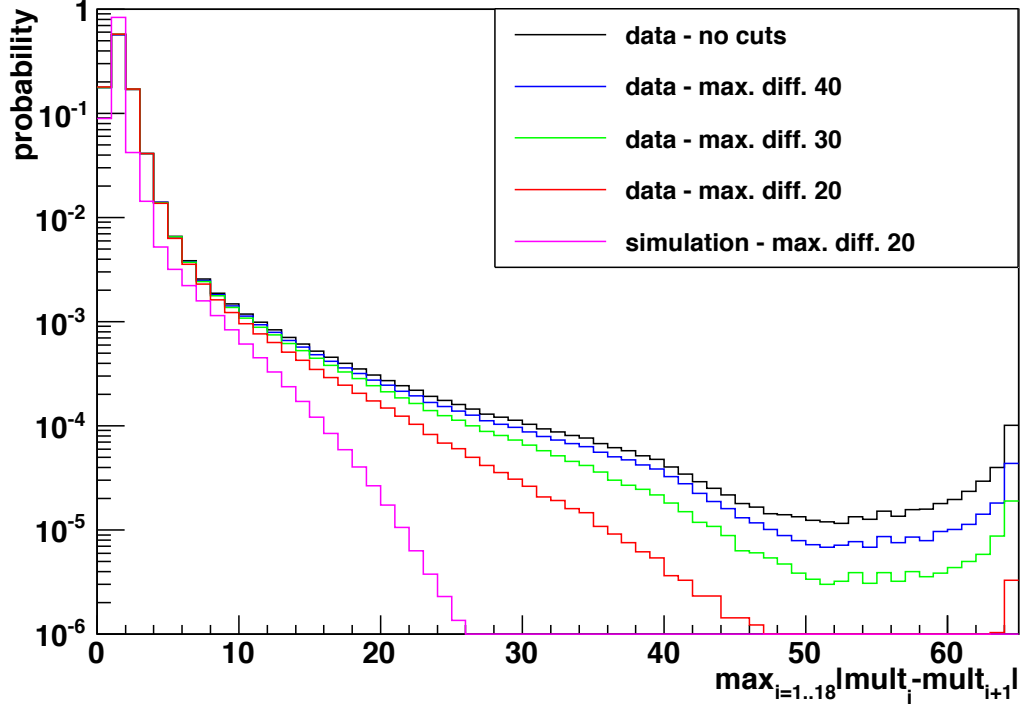


Figure 56: Cuts applied on the hit multiplicity distribution.

difference of 20, the resulting multiplicity distribution is very similar in shape to the simulated one. According to simulation the cut of 20 is still a very soft cut, affecting only about 1‰ of physical events. Yet, as shown in Fig. 56, it will clean up the entire long high multiplicity tail, which strengthens the assumption that these long tails are dominated by electronics noise effects. Fortunately the events with multiplicities below ten stay almost untouched

Input				Found values			
x0	y0	φ	z_{ALFA}	x0	y0	φ	z_{ALFA}
10	10	50	1200	9.993 ± 0.021	10.004 ± 0.082	48.2 ± 0.4	1197 ± 21
2	15	-25	1200	1.9909 ± 0.0003	15.00 ± 0.18	-26.6 ± 3.1	1196 ± 58

Table 19: Test of alignment setup with data from simulation. x0, y0 and z_{ALFA} given in mm, φ in mrad.

by any of the three cuts. This is a very important point, since it is outside of the range of the multiplicity cut (5) of the reconstruction. Meaning that the reconstruction will reject events with a higher multiplicity than 5 anyway. This still means that for the low multiplicities the differences as shown in Fig. 54 remain since they are caused by physics crosstalk.

As the differences in the low multiplicities persist, it is important to include crosstalk in later versions of the simulation. Also the addition of simulated electronics noise, as possible with Geant4, would be desirable.

5.2.5 Alignment tests

In order to check the performance of the developed alignment setup it has been tested with data from simulation. In the simulation the incident particle position is well known, and therefore a hypothetical track can be calculated for each event. The track parameters are chosen to match the tracks found with EUDET in the testbeam. In addition the incident particles position is smeared with a Gaussian to simulate the resolution of EUDET. After track calculation the reconstructed ALFA coordinates are rotated and shifted in x and y, as these are the available degrees of freedom. Finally everything is stored in a format which matches exactly the one coming from pre-alignment. Now this file is taken and put into the alignment script, which will return the desired parameters. For comparison the input values are denoted along with the resulting alignment values in Tab. 19. From this it can be concluded that the alignment works well and with a high precision. Also it is possible to reconstruct z_{ALFA} from this quite well. Here the chosen smearing of EUDET was set to $\sigma = 20 \mu\text{m}$. With this setting the convoluted resolution of ALFA and EUDET comes pretty close to what is found from testbeam data.

It should be said that this test simulation is over idealized, yet as a proof of concept it serves quite well.

5.3 Photoelectron calibration

In the Geant simulation sensitive volumes are defined, in which the deposited energy is recorded. Among these are for sure the sensitive fibers. However, in the end a conversion from deposited energy to photoelectrons has to be applied. The parametrization implemented first is given by

$$N = N_{\text{phot}} + \sqrt{N_{\text{phot}}} \cdot \text{Gauss}(0, 1) + 0.1 \cdot \text{Gauss}(0, 1) \quad (63)$$

$$N_{\text{phot}} = \text{Poisson} \left(E_{\text{dep}} \cdot \frac{\overline{N_{\text{phot}}}}{\overline{E_{\text{dep}}}} \right) \quad (64)$$

$$\text{Gauss}(x_0, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-x_0)^2}{2\sigma^2}} \quad (65)$$

$$\text{Poisson}(\mu) = \frac{\mu^k e^{-\mu}}{k!} \quad (66)$$

see [29]. Here Poisson and Gauss are meant as random numbers, drawn according to the denoted distribution. The mean deposited energy $\overline{E_{\text{dep}}} = 70 \text{ keV}$, determined from simulation, yields an average of $\overline{N_{\text{phot}}} = 4.11$ photoelectrons, measured in a previous testbeam. Thus the photoelectrons are mainly drawn according to a Poisson distribution with a mean at $E_{\text{dep}} \cdot \overline{N_{\text{phot}}}/\overline{E_{\text{dep}}}$ and then smeared with the statistical error $\sqrt{N_{\text{phot}}}$. This approximation works, yet can be improved. Therefore data from cosmic tests can be used and the photoelectron conversion calibrated accordingly.

Just after the testbeam, ALFA1 and ALFA2 were put in a cosmic setup. The advantage of this setup was, that here Orsay test motherboards with charge readout were available. This gives the possibility to gather information about the photoelectron spectra. The procedure consists of two steps. At first the calibration of the MAPMT with a low intensity LED is done. Thereby the pedestal and the one photo electron peak are found and calibrated. The pedestal is the position of the noise peak. The resulting data is fitted with

$$f(x) = N \cdot \left(\sum_{i=0}^1 \left[\frac{e^{-\mu} \mu^i}{i!} \frac{1}{\sqrt{2\pi} \sqrt{i\sigma_{1\text{PE}}^2 + \sigma_{\text{PED}}^2}} e^{-\frac{(x-i\cdot Q_{1\text{PE}}-Q_{\text{PED}})^2}{2\sqrt{i\sigma_{1\text{PE}}^2 + \sigma_{\text{PED}}^2}}} \right] \right) \quad (67)$$

and will deliver the charge and width of the one electron peak $Q_{1\text{PE}}$ and $\sigma_{1\text{PE}}$, as well as the position and width of the pedestal Q_{PED} and σ_{PED} . Here x is equivalent to Q , the charge measured by an ADC. An example calibration for one ADC channel is shown in Fig. 57(a).

In the second step this data is now used for the cosmic run data which is

Variable	Value
1 PE Mean [ADC counts]	258.65
1 PE width [ADC counts]	134.13
Pedestal [ADC counts]	1025.01
Pedestal width [ADC counts]	4.26
μ	3.95 ± 0.11
μ_{CT}	0.74 ± 0.12

Table 20: Values found from the cosmic data for the photoelectron spectra. Calculated as average over all 64 channels.

fitted with

$$f(x) = N \cdot \sum_{i=0}^n \left[\frac{e^{-\mu} \mu^i}{i!} \frac{1}{\sqrt{2\pi} \sqrt{i\sigma_{1PE}^2 + \sigma_{PED}^2}} e^{\frac{(x-i \cdot Q_{1PE} - Q_{PED})^2}{2\sqrt{i\sigma_{1PE}^2 + \sigma_{PED}^2}}} + \frac{e^{-\mu_{CT}} \mu_{CT}^i}{i!} \frac{1}{\sqrt{2\pi} \sqrt{i\sigma_{1PE}^2 + \sigma_{PED}^2}} e^{\frac{(x-i \cdot Q_{1PE} - Q_{PED})^2}{2\sqrt{i\sigma_{1PE}^2 + \sigma_{PED}^2}}} \right] \quad (68)$$

This is a Poisson distribution, where each term is smeared with a Gaussian. It is important to notice, that now the values from the one electron peak, Q_{1PE} and σ_{1PE} , are fixed as found previously from the calibration. Additionally a crosstalk term is added, with a Poisson mean of μ_{CT} . In the end a good estimate of the mean photoelectron number μ and a crosstalk estimate μ_{CT} are found [30].

The result is shown in Fig. 57(b) including all the different contributions from higher n-photon peaks. In the end an average of $\mu = 3.95$ photoelectrons and $\mu_{CT} = 0.74$ crosstalk photoelectrons are found. Previous measurements had found a mean of 4.11 photoelectrons, which is very close to the value found here, i.e. $0.74 + 3.95 = 4.69$. The values resulting from the cosmic test are summarized in Tab. 20. Due to the small width of the pedestal and its far distance from the one photoelectron peak, pedestal noise can be neglected in the simulation.

Since the calibration values from the cosmic test are available, the conversion of deposited energy to photoelectrons is tuned accordingly in the Monte Carlo. The only problem is the fact that the calibration is in ADC counts, not in energy deposit. Yet this can be circumvented, since it is known that 70 keV correspond to 4.11 photoelectrons. Therefore the deposited energy is converted to a mean number of photoelectrons which are to be expected.

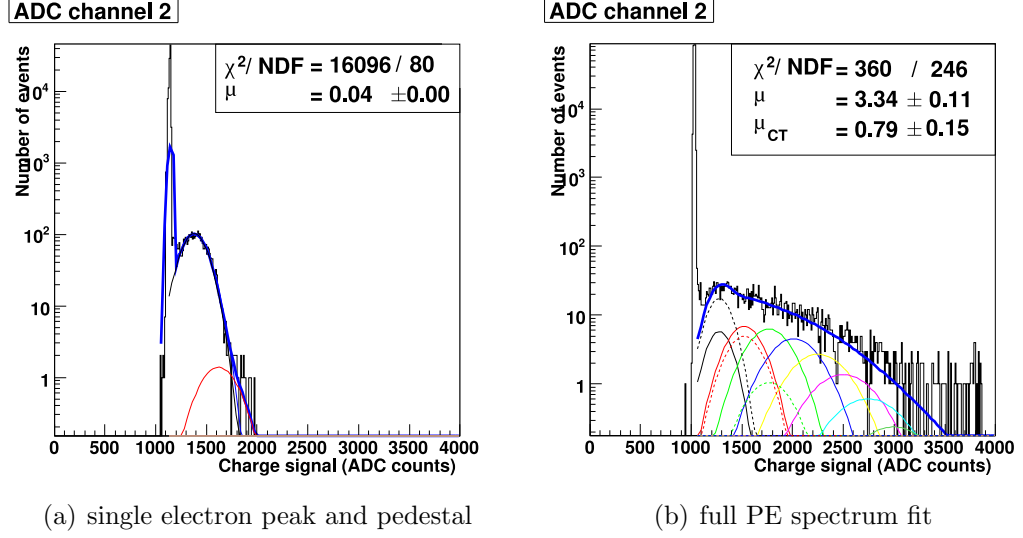


Figure 57: Finding the pedestal and one electron peak, as well as the full spectrum fit including crosstalk terms. The solid colored curves are the different n -photoelectron contributions, whereas the dashed colored lines correspond to the n -photoelectron crosstalk contributions.

This mean is used as μ in Eq. 68, which is implemented in root and used as probability density. The photoelectron number is drawn according to this density.

As a comparison Fig. 58 shows a spectrum obtained from the cosmic measurement (black), the result of a high statistics Monte Carlo run (red) with the new parametrization Eq. 68 and the old parametrization (green), Eq. 63. The Monte Carlo results are scaled down to match the low statistics cosmics sample. One can see that especially around the one electron peak the new parametrization fits the data much better. Here the old parametrization underestimated, while at higher values it overestimated the actual number of photoelectrons.

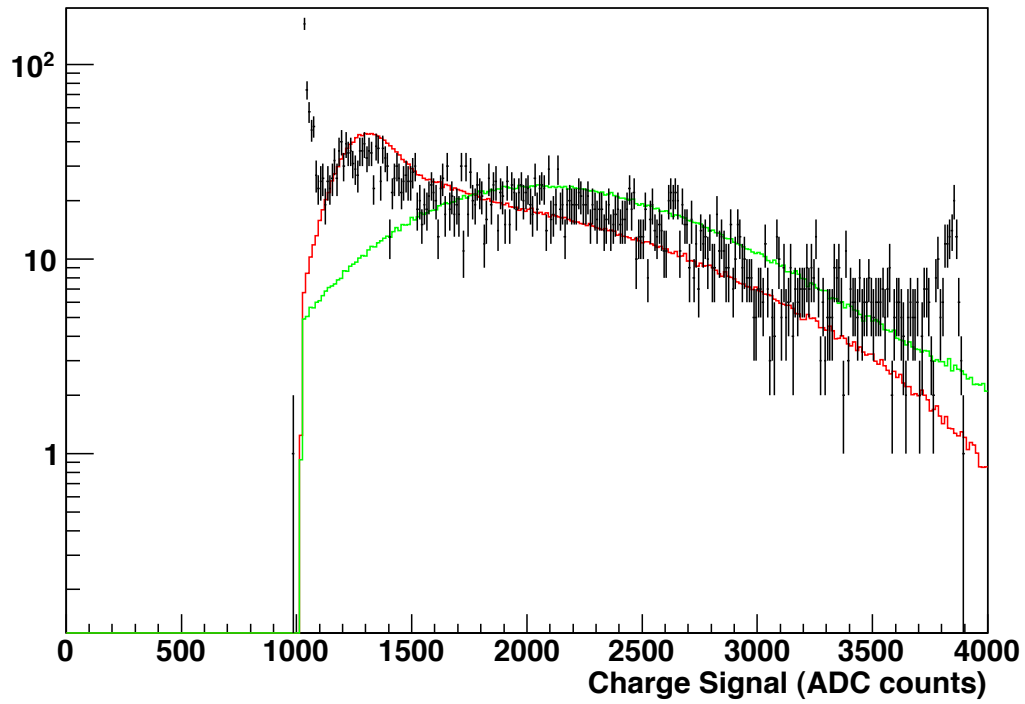


Figure 58: Comparison of the photoelectron spectra obtained from cosmics test (black), the parametrization from Eq. 68 (red) and the parametrization from Eq. 63 (green). The pedestal noise has not been simulated since it can be neglected.

6 Summary and conclusion

In this diploma thesis the performance of the ATLAS ALFA subsystem was estimated with a complete simulation and compared to testbeam measurements. The ALFA subdetector will determine an absolute luminosity calibration for ATLAS from the t spectrum of elastically scattered protons in special calibration runs. ALFA is a scintillating fiber detector, consisting of four stations, two on every side of ATLAS. Every station is comprised of two detectors, each mounted in a Roman Pot and approaching the beam from top and bottom respectively.

The event generation for the elastic process is achieved using Pythia8. Generated protons are transported along the LHC beamline via the beam transport program MadX. Once the protons have reached the location of ALFA, 240 m away from the Interaction Point, Geant4 is employed for detector simulation. Finally the reconstruction and analysis chain is applied and the luminosity determined.

Several scenarios have been simulated and analyzed. It was shown that the measured proton occupancy distribution in ALFA can be used to determine the beam spot at a higher precision than with the beam position monitors, i.e. better than $100\,\mu\text{m}$. The concept of the overlap detectors, whose task is the determination of the vertical detector distance, was evaluated in the simulation and found to be efficient. Even at low statistics the required precision of below $10\,\mu\text{m}$ is well obtainable. The system remains reliable, even if one of the three overlap planes is lost - clearly at higher, yet reachable, required statistics.

The main detector resolution was calculated from simulation for elastically scattered protons. Out of nine sets of modules to be assembled to detectors only one was found to have a resolution worse than $30\,\mu\text{m}$. The stability of the spatial resolution for the main detectors under rotations around the beamline was investigated. A qualitative agreement with previous testbeam measurements was obtained.

An important result is the observed impact of hadronic showers. A strong influence of hadronic showers from the first on the second pot is noticeable, decreasing the latter reconstruction efficiency by about 6%. More subtle details could be revealed considering the trigger tiles. There are two possible configurations in use. In the first the trigger tiles are mounted in front of the main detector sensitive area, in the second they are mounted behind, looking in beam direction. If a trigger tile is mounted in front of the sensitive main detector area the reconstruction efficiency for this pot will be decreased additionally by about 2% compared to the inversed order of trigger and tracking modules.

Despite all this the luminosity is well reconstructable with a statistical error of below 2% for a run with 1×10^7 events. Including systematical uncertainties a total error on L of less than 3% is attainable.

The data from the latest 2009 ALFA testbeam was partially analyzed for comparison with the simulation. In the testbeam an additional silicon pixel telescope was installed in front of ALFA to provide positional references. Software for alignment of the telescope with respect to ALFA was developed and tested. The spatial resolution of the telescope after track extrapolation to ALFA was estimated to 10-20 μm . Therewith the determined ALFA resolution is about 30 μm , depending on irradiated location on the detector.

The fiber equations describing the fiber positions are measured via optical metrology. For comparison these equations were calculated from testbeam data and found to be in good agreement with the optically measured ones. The efficiency of layers and single fibers was determined from testbeam data and found to be about 90%, in good agreement with previous testbeam campaigns. The hit multiplicity, i.e. the number of active fibers per layer and event, was evaluated. Large fluctuations between single runs and from layer to layer were observed. Furthermore a long tail of high multiplicities, predominantly from electronics noise, is present.

Whenever possible the results from the testbeam were compared with the simulation. The measured resolution was found to be consistent with the simulated one, yet at some sensitive detector regions discrepancies became clear. The efficiencies of layers and fibers were in agreement in testbeam and simulation, once the testbeam data was corrected from the positional smearing by the telescope. Larger discrepancies were found for the hit multiplicity distribution. The high multiplicity tails observed in the testbeam are not present in the simulation. Still, even for low multiplicities there are noticeable differences as a result of optical and physical crosstalk. Clearly the simulation is not able to reproduce the observed random multiplicity fluctuations on a layer to layer basis.

The photoelectron spectra resulting from the simulation were calibrated with data from a cosmics setup, which was installed shortly after the testbeam. The result is a very nice qualitative agreement of data and simulation.

In the overall picture the simulation is working nicely and is able to reproduce the important features of ALFA. Yet in detail there are deviations which could be downsized by the addition of some new items later on. First of all, electronics noise ought to be included to increase compliance in the high multiplicity tails observed in the testbeam. Secondly optical crosstalk would be a desirable addition to reach better agreement in the lower hit multiplicity range. Furthermore an important point to study and add to the simulation are events, where two protons traverse the detector at once. Here the pos-

sibility to distinguish the two tracks would be very interesting to examine. This has not been an issue for the testbeam, nevertheless in the LHC it will be.

The first ALFA pot has already been installed in the tunnel in early 2010, see Fig. 59. This will make first beam halo measurements possible in the near future. In order to test the performance of the remaining detectors the following testbeam campaign has already been scheduled for fall 2010. The remaining pots will be installed in the tunnel in the short technical LHC shut-down in December 2010. Starting at the restart of the machine in January 2011 luminosity measurements with ALFA will be possible.

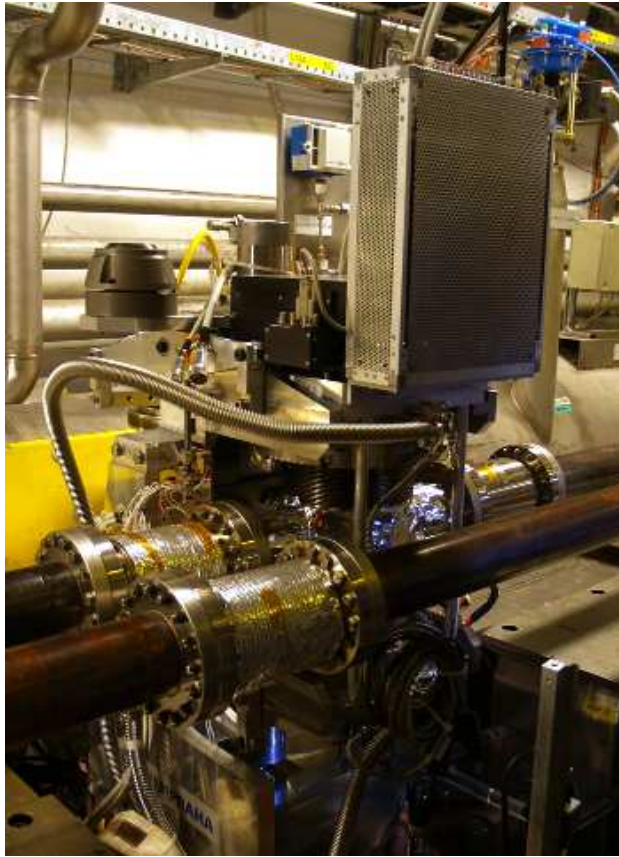


Figure 59: First ALFA pot installed in the LHC.

Acknowledgements There are a lot of people I would like to express my gratitude to:

- Michael Düren for all support and the possibility to work on a nice project on the HEP frontier.
- Hasko Stenzel for his open door and all the time he spent answering my questions and helping me with the thesis.
- Anatoli Astvatsatourov and Roberto Perez-Benito for the nice working climate in the office and the availability to questions.
- Thanks for proof-reading to Tobias Eissner, Anja Nicolai, Daniel Pelikan and Andreas Roth.
- The entire Düren group for the nice working climate and fun times.
- Sune Jakobsen for the permission to use his ALFA photos.
- Last but not least to my family and friends for all the support during the years.

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Erklärung

Ich versichere, dass ich diese Diplomarbeit selbständig geschrieben und deren Inhalt wissenschaftlich erarbeitet habe. Außer der angegebenen Literatur habe ich keine weiteren Hilfsmittel verwendet.

Giessen, den 09.04.2010