Measurements of ALFA Geometry and Correspoding Precision

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1 The ALFA Detector

A precise knowledge of luminosity is essential to physics analyses at collider experiments. The cross section of a physical process is one of the fundamental quantities that can be measured by such an experiment and its precise determination is a primary goal. To do this, precise knowledge of luminosity is needed. The total interaction rate is

$$R = \sigma_{tot} \times L, \tag{1}$$

where σ_{tot} is the total cross section of the collision and L is the luminosity provided by the accelerator. In order to determine the cross section of a specific process, σ_i, the rate at which that event occurs is counted and the luminosity must be measured. Due to the partonic nature of the proton, measuring luminosity is not a trivial task at the LHC or any other hadron collider. The ALFA (Absolute Luminosity For ATLAS) subdetector at the ATLAS experiment is designed to measure the elastic scattering rate in dedicated runs. This will then provide an absolute calibration for LUCID (Luminosity measurement using a Cherenkov Integrating Detector), the main luminosity measurement subdetector [1]. In turn, this will allow for precise determinations of the luminosity provided to ATLAS by the LHC.

1.1 Concept

The process of measuring luminosity via independent determination of the total cross section is a process which has been used before and is thus well described and studied [3]. The principle is to measured the elastic and inelastic collision rates separately, as well as to measure the elastic rate as a function of momentum transfer t. Using the optical theorem, the luminosity can be found.

Splitting the rate into elastic and inelastic parts, the total cross section is

$$\sigma_{tot} = \frac{1}{L}(R_{elas} + R_{inel}). \tag{2}$$

In scattering theory, the optical theorem relates σ_{tot} to the imaginary part of the forward scattering amplitude [4]. In terms of the quantities at hand, it states that

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{(1+\rho^2)}\frac{1}{L}\frac{dR_{elas}}{dt}|_{t=0}, \tag{3}$$

where ρ is the ratio of the real to imaginary parts of the forward scattering amplitude. One can then obtain a relation between the measured rates and the total cross section, independent of luminosity:

$$\sigma_{tot} = \frac{16\pi(\hbar c)^2}{(1+\rho^2)}\frac{1}{(R_{elas}+R_{inel})}\frac{dR_{elas}}{dt}|_{t=0}. \tag{4}$$

Having the total event rate and the total cross section thus yields the luminosity.

The measurement of elastic and inelastic rates is done separately. The inelastic rate is measured by the main detector, ATLAS, while the elastic rate is measured by an extremely forward detector, ALFA. ALFA is situated about 240 m from the ATLAS interaction region, surrounding the beamline. The ALFA detector uses position-sensitive scintillating fibers situated inside Roman Pots, a device which has been used several times before [1] and has been shown to allow a precise approach to the beam. These Roman Pot devices were pioneered by the CERN-Rome Collaboration when working to study elastic scattering at the ISR [2], from which they derive their name. They have since been used by several other experiments at various accelerators.

The ALFA detector relies on using the LHC dipole magnets as a spectrometer. When there are elastic collisions with low momentum transfer (t), the interacting protons will loose only a small amount of their energy. As the dipoles and RF cavities of the LHC are precisely tuned to the ideal proton momentum, this slight change will send the proton off course. The ALFA detector detects these protons. In the small t approximation, the relationship between momentum transfer, beam momentum and angular deflection is approximated to be

$$-t = (p\theta)^2. \tag{5}$$

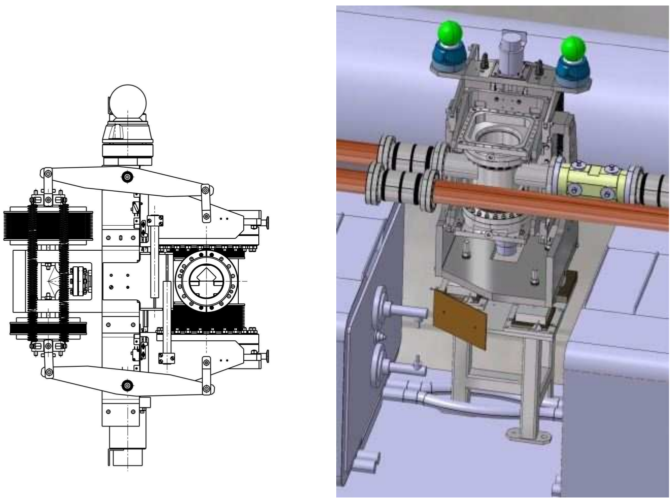
A 7 TeV proton that scatters at $-t = 0.005$, a typical low-t value, is deflected by ≈ 10 μrad, corresponding to a deviation of ≈ 2.4 mm from the beamline after a distance of 240 m. The Roman Pot housing allows a precise approach to the beam within this range.

The measurement of σ_{tot} with this method relies on extracting the differential of elastic scattering rate with respect to momentum transfer down to a momentum transfer of 0. Thus proton momentum must be measured over a range of t values. Doing this requires an extremely precise determination of the proton position in the ALFA detector. To resolve appreciable differences in values of t in this range it is anticipated that the ALFA detector needs an ultimate precision of $\sigma_x = \sigma_y = 30$ μm. This precision is one of the most important factors in the ALFA detector; indeed it is the main driving force in the design and implementation of the detector. Determination of this precision will be described herein.

1.2 Detector Layout

The ALFA detector will be briefly described here. The entire detector is described in [1, 5].

1.2.1 The Roman Pots



(a) A detailed sketch of a single pot.

(b) A simulation of a pot after integration with the LHC vacuum.

Figure 1: The ALFA Roman Pots.

The purpose of a Roman Pot is to allow a detector such as ALFA - housed within it - to be brought to within 1 mm of the beam. To do this, the pot must be integrated into the beam vacuum. The ALFA detector has components within the pot on either side of the beam. One of the benefits of the pot design is that it allows for independent control of each of the two sides for precision placement. A schematic of a Roman Pot can be seen in Fig. 1 (a) as well as a visualization of it integrated with the LHC beam vacuum in Fig. 1 (b). The positions of the pot with respect to the beam line is shown in Fig. 2 in both a retracted and working state. As the beam spot of the LHC will change from store to store, a precise dynamic positioning of the pots is necessary. The measurement of the pots' position is done using the overlap detector, which uses the same concept and a similar geometry as the one that is is used for the main detector.

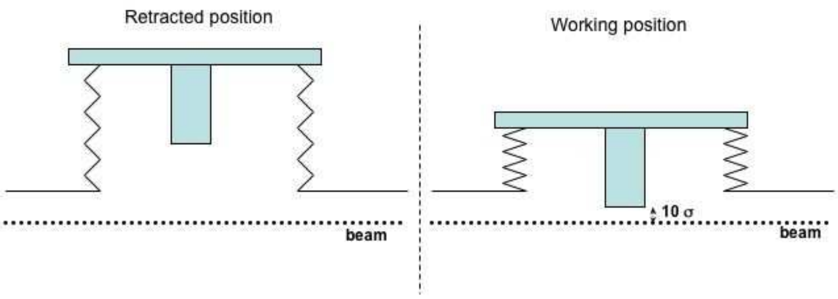


Figure 2: A schematic of the position of a Roman Pot with respect to the beam line in both close and near states.

1.2.2 Scintillating Fibers and Plate Geometry

Each side of the main detector within each Roman Pot contains a structure with a "UV" geometry comprised of ten plates which each contain two layers of 64 scintillating plastic fibers, visualized in Fig. 3. The fibers are glued to either side of the plate at 90° to one another. The ten plates are staggered with respect to one another at 0.5 mm / 10 $\times\sqrt{2}$ = 70.7 μm, yielding an effective fiber pitch of 50 μm. In principle this yields a spatial resolution of $\sigma_x = \sigma_y = 50$ μm / $\sqrt{12} = 14.4$ μm. Each layer on each plate is connected to a photo multiplier tube and an 8 $\times$ 8 pixel sensor, hence 64 fibers per layer.

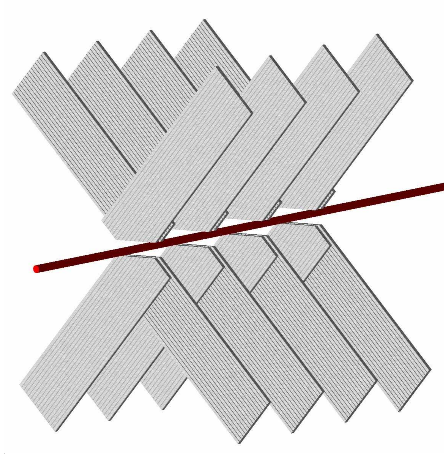


Figure 3: The geometry of a portion the ALFA plates on each side of every pot.

2 Metrology of ALFA Plates

In order to resolve proton position - and therefore momentum and momentum exchange - from the elastic collision a precision within 30 μm is needed. As stated earlier, the spatial resolution achievable using the ALFA detector with an ideal strip geometry is $\sigma = 14.4$ μm. It is therefore necessary to determine what the deviation from the ideal is and ensure that it is acceptable. Deviations from the ideal geometry have been found and are thought to arise from gaps between fibers which have an imprecise width [5]. The fibers are precisely 500 μm wide, however they are glued to the plates as well as to each other. The gap is on the order of 1/10 the width of the strips, ~ 50 μm. Variations in this gap size are believed to lead to a difference between ideal and real geometry. It is also possible that imprecise machining of the plates themselves could lead to shifted positions, notably if the angle between layers deviates from 90°. A detailed sketch of a single plate is given in Fig. 4.

To achieve the stated resolution, it is absolutely necessary that the position of each fiber is precise to within 70.7 μm, otherwise the staggering of plates becomes useless and the resolution sharply degrades. Much work on this has already been done [5] and a few points are considered here.

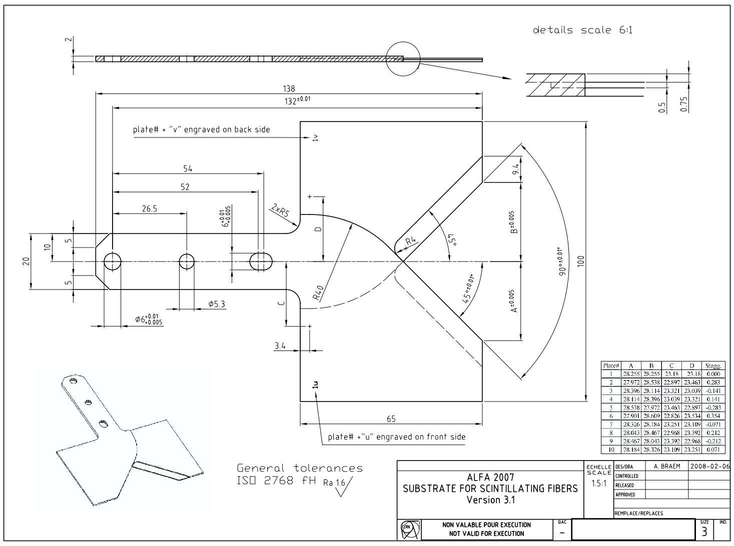


Figure 4: A detailed drawing of one side of a single plate used in the ALFA detector.

2.1 Measurement Devices and Method

There are two separate optical measurement systems being used to measure the strip position and plate geometry, one at CERN and one at DESY. The CERN microscope is out of the box, including software, while the DESY microscope is a custom design with software being written in Labview. Both microscopes use the same principle but are implemented differently. Each has variable light sources which can introduce an uncertainty to the measurements, as changing the light source changes the apparent size of the object.

2.1.1 Microscope at DESY

The FEC electronics clean room at DESY has provided a microscope. The lenses used in this setup are a Navitar 12x zoom lens, a Mitutoyo M Plan Apo 10x object lens and a 2x C-Mount adapter. The image is recorded using a Nikon DS-5M Digital Camera with 2560 $\times$ 1920 pixels (5 megapixels) and a 2/3" CCD. The apparatus is mounted on a 3-axis positioning table (x-y-z table). The table consists of two separate parts: A x-y-table (GT9-NSMA) and a z-table (LT8-LBMA) from Walter Uhl. The tables are driven by a step motor allowing for a positioning precision of 2-3 μm. The step motor is connected to a PCI-card in the PC and can be controlled through the LSTEP-PCI API by LANG [5].

Two light sources are available here: a moveable gooseneck light source and a ring light mounted to the microscope around the final objective. For the sake of consistency, now only the ring light is used and it is always used at full power.

2.1.2 Microscope at CERN

The team measuring the geometry of ALFA at CERN is using the SmartScope CNC 250 from OGP. According to the company, a precision of better than $(3 + 6L/1000)$ μm, where L is the measured length in mm, is achieved. The machine is equipped with a 12x zoom and variable light sources.

2.1.3 Measurement, Disagreement and Problem Resolution

In order to measure the fiber positions it is necessary to first determine a coordinate system. The measurements taken at both the DESY and CERN sites define the center of the coordinate system to be at the center of the lowest peg hole on the plate, visible in Fig. 5. The coordinate system assumed that the plate was not perfectly alligned and thus calculated an angle between the plate's coordinate and the table's. For the same plates using the same coordinate system the measurements at CERN and DESY displayed a systematic shift of $\approx$ 70 μm. Given that this is the same as the design staggering, one possible explanation was a mislabeling of data. This was not thought to be the case, and another cause of error has recently been identified.

At the CERN site, a low-zoom image of the peg hole is taken which the provided software uses to find the center and thus the origin of coordinates. In this method, the user then zooms in to measure the fiber positions. At the DESY site, eight points around the edge of the circle are taken, then a circle is fit and the center found. This is done at the same zoom (the least possible) as is used to take the fiber position measurement.

It is a well known phenomenon in photography that changing the zoom of a lens changes the center point, a form of optical aberration. In a zoom lens there are many internal lenses (generally 10-20) which move around to project the object image to a different distance before a final lens focuses

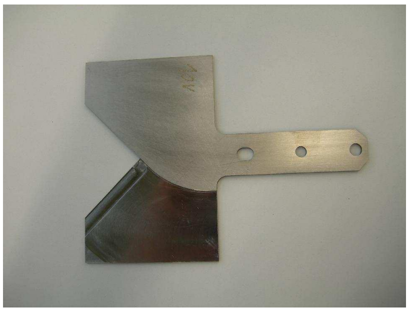


Figure 5: A photograph of an ALFA prototype 2 plate.

that image to the recording plane. This causes a small shift in the recorded image.

The company which built the CERN microscope, OGP, claims that it yields a sensitivity of better than $(3 + 6L/1000)$ μm. It is notable that the website also claims that the device uses proprietary mechanisms to reach such a fine precision and thus does not explain the method used. It was therefore not possible to tell if the microscope corrects for this optical aberration.

The possibility of this shift as a cause of the 70 μm disagreement was tested at CERN. Indeed the shift seen between the two zooms used is $\approx$ 70 μm. This is now assumed to be the source of the disagreement. A technician from OGP has recently visited CERN to recalibrate the machine. The two measurement systems at DESY and CERN respectively are now thought to both be calibrated.

2.2 Accuracy of Fiber Geometry

In order to determine the accuracy of ALFA's construction, the measured positions of the scintillating fibers must be compared to the ideal position. A simple geometric comparison is used to ensure that the measured position differs from the ideal by less than 70.7 μm. A program has previously been written that takes into account the actual effect of the geometry on the precision of the result of ALFA, and that program has been used with the measured geometry.

2.2.1 Measurements and Deviations

Larger than anticipated deviations have been found on certain layers. Each strip on each layer has been fit to a line. These line fits for ideal and measured geometry are compared on a strip-by-strip basis for each layer. The position visualization plots show the line fits of the two data sets, measured and ideal. The variations plot shows the differences between the a- and b-parameters from these line fits for the two layers, "U" and "V".

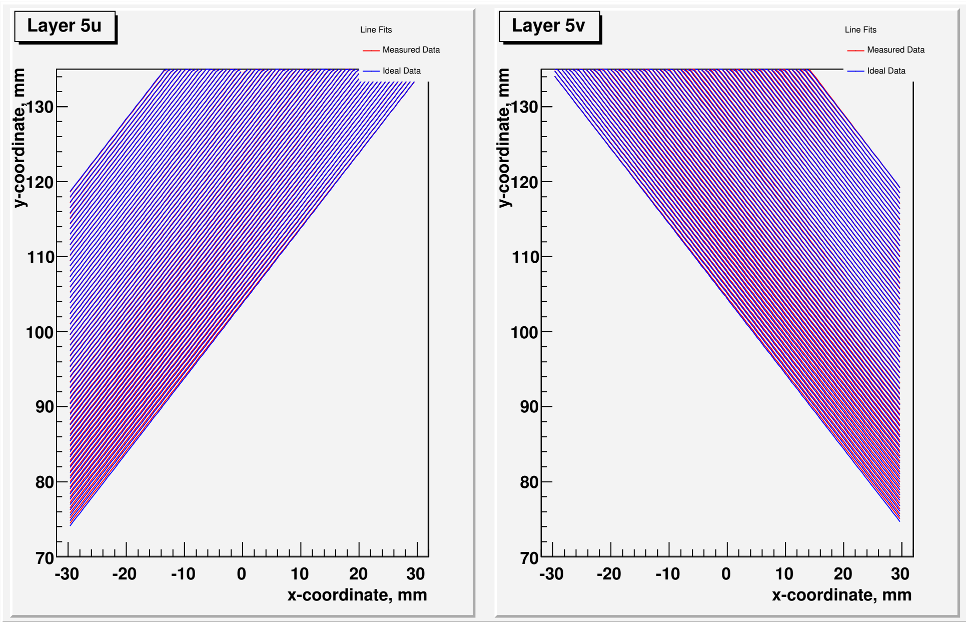


Figure 6: The reconstructed position of fibers in an ideal and measured geometry for one plate with relatively good agreement.

An example of the reconstructed fiber positions on a "good" plate is shown in Fig. 6. The two sets of lines, blue corresponding to ideal and red corresponding to measured are in decent agreement. Accordingly, the difference in position, shown in Fig. 7, between measured and ideal is close to the expected gaussian distribution, centered around 0 with a standard deviation below 30 μm.

An example of a plate with poor agreement is shown in Fig. 8. The lines are shown to be at an angle with respect to one another, with a select group of lines having a deviation in their b-parameter that is very large, shown in Fig. 9.

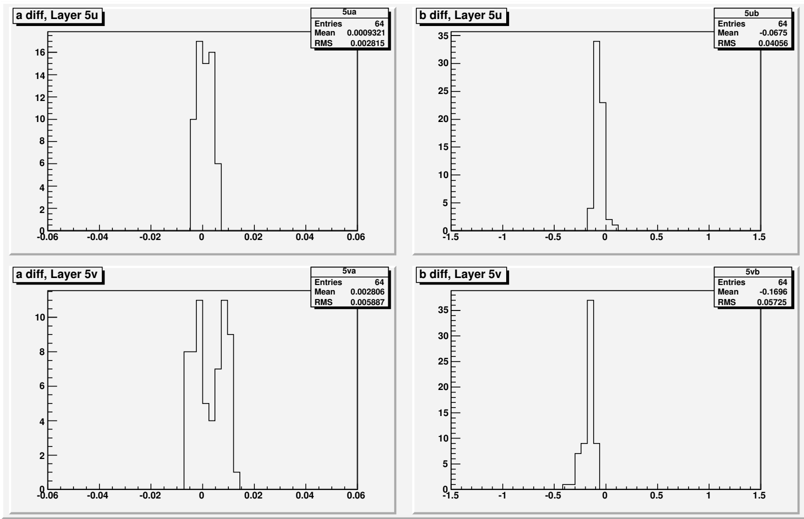


Figure 7: The differences between reconstructed positions of fibers in an ideal and measured geometry for one plate with relatively good agreement.

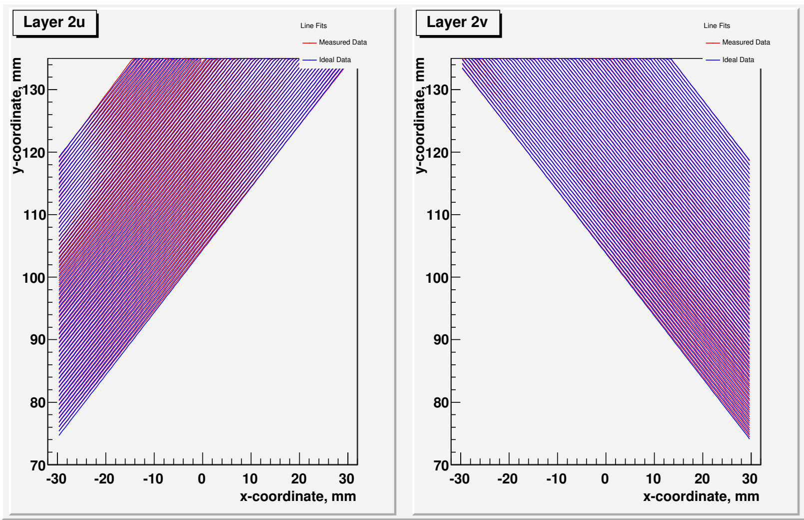


Figure 8: The reconstructed position of fibers in an ideal and measured geometry for one plate with relatively poor agreement.

Work done to verify the measurement methods used will be described in this article. Different methods are being used at the two test sites, and different methods are being tested at the DESY site as well. This will help to

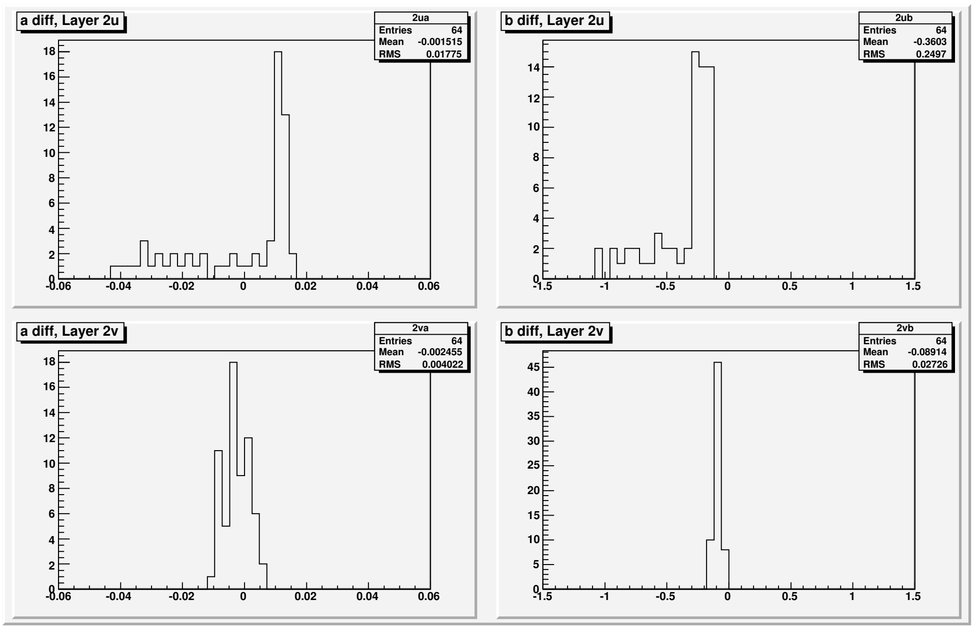


Figure 9: The differences between reconstructed positions of fibers in an ideal and measured geometry for one plate with relatively poor agreement.

determine whether the effects seen result from a poor measurement technique or are an accurate representation of an imprecise geometry.

3 Position Resolution of ALFA

A previously written program is used to estimate the effect of the fiber positions on the ultimate position resolution of a particle passing through.

3.1 Simulatied Precision with Ideal Geoemtry

A plot of the precision using ideal geometry is shown in Fig. 10. The left and right hand sides correspond to the x- and y-measurements. As one would expect, the resolution is the same in x as in y The top row shows the precision of position measurements in the main detector, which is $\sigma_m = 14$ μm for ideal geometry. The lower row shows the precision of the position measurement of the overlap detector, which is used to place the entire pot. In effect, the top plots show the precision a measurement with respect to its pot and the second shows the precision of the placement of the pot with respect to the beam. The overlap detector's precision with ideal geometry is $\sigma_o = 11$ μm. Adding in quadrature, the total uncertainty of a given position measurement using ideal geometry is $\sigma = \sqrt{\sigma_m^2 + \sigma_o^2} = 18$ μm.

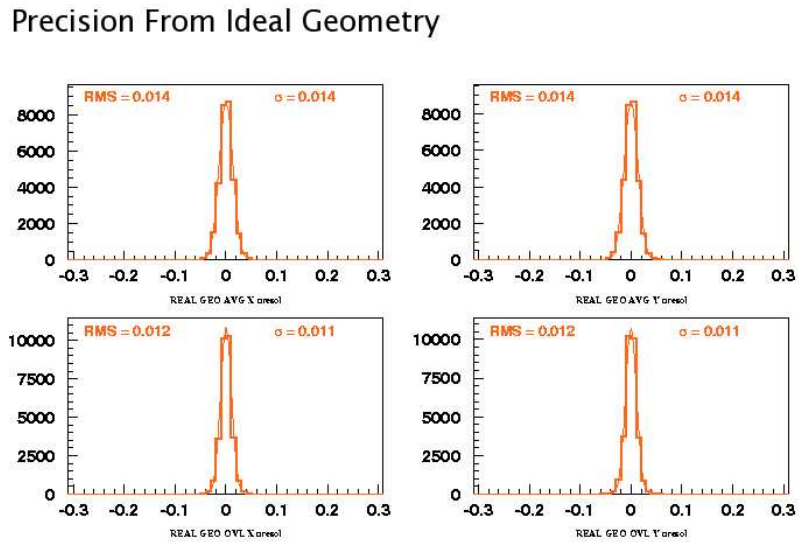


Figure 10: The precision of the ALFA fiber detector with ideal geometry. The top row shows the precision of a measured point with respect to the Roman Pot and the lower row shows the precision of the pot with respect to the beam.

3.2 Precision with Measured Geoemtry

While the measured position of the fibers deviates to large degrees as described earlier, the available precision is not degraded to such a dramatic degree. This has been simulated using the same code as above. The results are shown in Fig. 11. Just as in the plots shown above, the top row corresponds to the precision of an individual measurement with respect to the pot and the lower to the precision of the pot's placement. A symmetry between x- and y-values is seen here again. In this case however, the main detector has an uncertainty of $\sigma_m = 36$ μm and the overlap detector of $\sigma_o = 26$ μm. Adding in quadrature, $\sigma = \sqrt{\sigma_m^2 + \sigma_o^2} = 44$ μm.

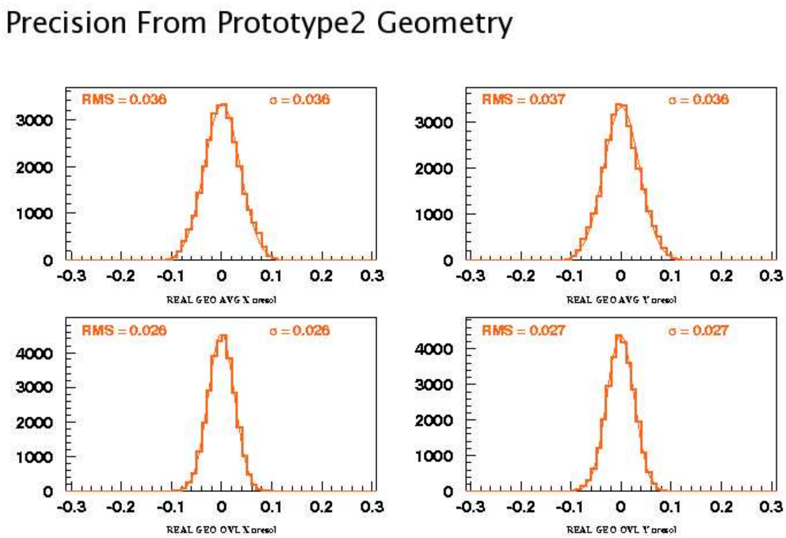


Figure 11: The precision of the ALFA fiber detector with the measured geometry of the Prototype 2 plates. The top row shows the precision of a measured point with respect to the Roman Pot and the lower row shows the precision of the pot with respect to the beam.

It should be noted that while $\sigma = 44$ μm is out of the acceptable range, there is room for improvement which can bring this value to within the desired 30 μm. This can be done by using more precise measurement techniques and perhaps an improved gluing technique. Improvement of this precision continues to be a central goal of the project.

4 Plate Edge Measurements

As has been shown, it was found that the measured geometry of the fibers on ALFA plates yielded a measurement precision that was outside of the acceptable range. It was decided that bare plates – with no fibres – should be measured in order to determine whether the shifts are a result of the plate geometry or a result of the fiber gluing method. It would also serve to help determine the precision of the measurements.

The most accurately defined nominal position is the corner where the diagonal edge meets the straight edge of the plate. This is expected to be staggered by 70.7 μm plate-to-plate. Due to the nature of machining, the corner is not a perfect corner but in fact is rather rounded. Thus, in order to determine the position of the corner points were measured along the diagonal edges and the top edges separately, lines fit and the intersection found. This method is used in the folowing analysis. The measurement of a single layer using this method is shown in Fig. 12. Both layers on each of five plates are taken as a representative sample.

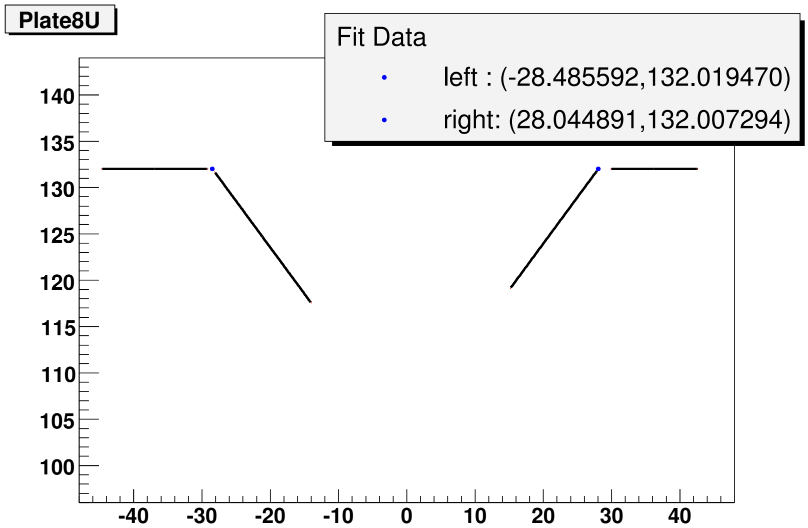


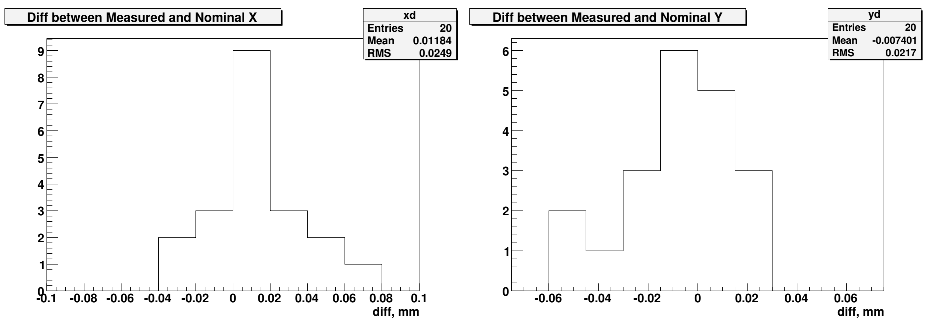
Figure 12: The reconstructed corner positions of a single layer, 8U. The method shows straight lines fit through the points measured along diagonal and top edges. The fit lines intersect at the dots and the position is shown in the legend. The nominal x-position for this layer is x = -28.467 for the left and x = 28.043 for the right. The nominal y-position is always 132.000. This plate shows differences of $\sim$ 20 μm in x and $\sim$ 10 μm in y.

4.1 New and Old Coordinate Measurements

It should be noted that a new method (new with respect to the older fiber position measurements) was used for the measurements discussed here. The old method, which took into account the angle between the plate and talbe, was thought to introduce inaccuracy and has been replaced by a method which fixes the plate to a rigid jig using a perfectly fitting pin. The goal is to eliminate the angle between the two coordinate system. This method makes it tougher to place and remove the plate but had been anticipated to remove inaccuracy and provide for surer agreement between the CERN and DESY measurements. Indeed it has been found to reduce inaccuracies. A single plate, 7, was measured using both methods. The difference to nominal was found to be about $\sim 50\ \mu$m in the old method and $\sim 10\ \mu$m. A second plate, 2, was measured in the old method to have deviations of $\sim 200\ \mu$m. That plate was not remeasured, but the deviations are generally a factor of 10 smaller in the new method.

4.2 Comparison to Nominal Positions

The difference between reconstructed and nominal position in both x- and y-coordinates is shown in Fig. 13.



(a) x-coordinate differences.

(b) y-coordinate differences.

Figure 13: Differences between nominal and measured position for the ALFA plates.

There is generally a decent agreement between the measured and reconstructed position. It should be immediately noted that both distributions are spread around a central value near to zero, implying that there is not a systematic shift. It should also be noted that the x-values are more broadly spread than the y-values. The two points with $\Delta y \approx 50\mu$m come from 7U and 3U, which should both be remeasured. Assuming a modecum of consistency from the team which machines the plates, these offsets do not seem to be the source of the large offsets in strip position seen earlier. The overall accuracy here seems to be $\lesssim 50\ \mu$m.

4.2.1 Precision of Plates and Measurements

It is also essential to determine precision. To do this, the distance from corner-to-corner is compared, done in two ways here. In order to determine the precision of the machining, the distance, AB, is compared from the nominal and measured data sets. This is shown in the top plot of Fig. 14. It is notable that the deviations are < 20 μm despite the fact that individual measurements in x differ by up to 60 μm. This implies that the machining is certainly precise while it may not be accurate. This is an extremely important matter. It implies that the angle between the two diagonal edges will still be very close to 90°. Deviations from 90° in the fiber positions are therefore also likely to stem from the gluing procedure, not plate fabrication.

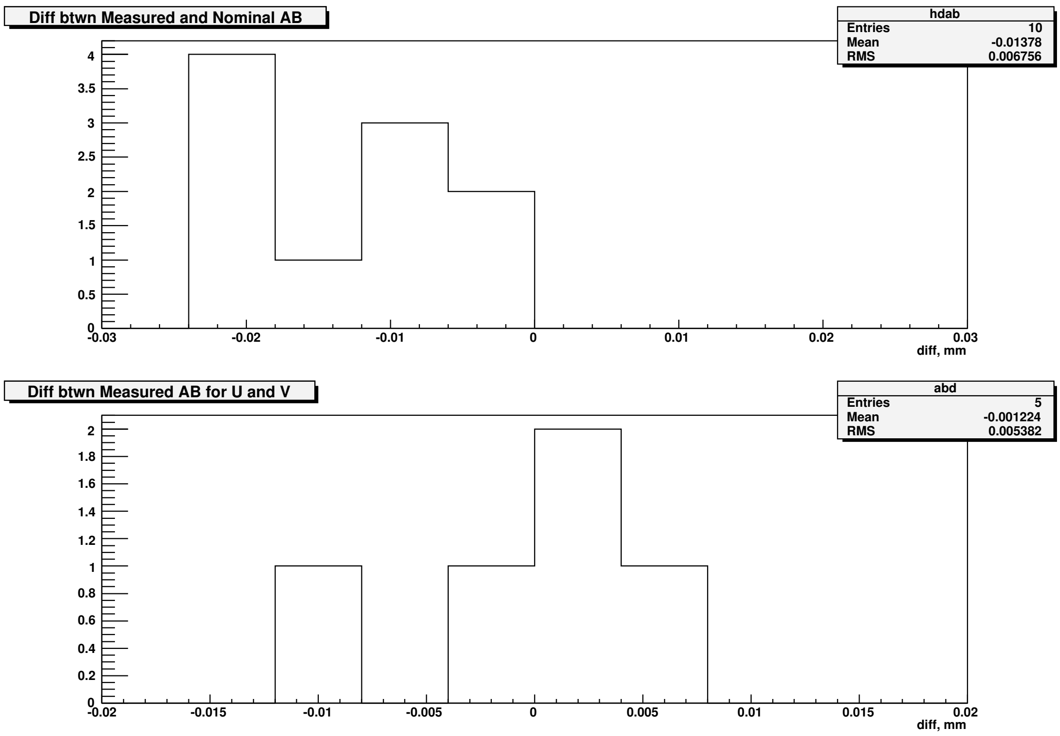


Figure 14: Comparions yielding machine (top) and measurement(bottom) precisions. The corner-to-corner distance, AB, is compared.

The precision of measurements done at the DESY site is shown to be < 10 μm, as shown in the bottom plot of Fig. 14. The distance AB measured on either side of a given plate, layers U and V, is compared. The devations are shown to mostly be $< 5\ \mu$m, with a single value being a factor of 2 coarser. This gives a good estimate of internal precision: in between the measurements of the two layers of a given plate the microscope is moved up and out, plate removed and flipped over, microscope returned to measurement postion and then refocused and remeasured. It seems that the combination of this process, other uncertainties and operator introduced error combine to $< 10\ \mu$m. This is an essential result, as it compares well with the quoted value of the OGP machine used at CERN.

5 Conclusions

Recent measurements of the plate edges imply that the earlier (large) offsets were not caused by poor machining of the plates; this is not however absolutely conclusive because the plates measured are different from those measured earlier. This leaves open two likely possibilities: that the fiber offsets are real – likely caused by the capilary gluing procedure – or that they are an articaft of the earlier measurement and coordinate method. The sharp increase in accuracy between the old and new measurement methods, seen directly in the measurements of Plate 7, implies a large inaccuracy in the earlier fiber measurements. However, measurements taken recently by the CERN team show that the first fiber is in the correct place and the last fiber is nearly correct while deviations to the nominal of 100-200 μm are seen in the middle. This agrees well with the hypothesis that the plates are machined accurately and the gluing procedure introduces inaccuracy.

It has been described in this article that the machining precision on the ALFA plates is $< 20\ \mu$m and the measurement precision is $< 10\ \mu$m. With deviations in the corner position to the nominal of $\lesssim 50\ \mu$m, one can conclude that the accuracy of the entire machining and measurement system is at least this good. If larger deviations are seen when fiber positions are remeasured, it will be logical to conclude that the deviations are real effects in the fiber geometry.

The data show a clear difference between accuracy and precision. In terms of the plates, this is most strikingly evidenced by the fact that the width of the corner-to-corner gap shows small deviations from the normal while individual corner measurements show relatively large deviations in x position. Likewise, the precision of the measurement methods is seen to be very good while the accuracy is much more difficult to determine. Given that both methods are precise it is difficult to conclude what the root of the observed inaccuracy is. The accuracy observed is, however, far better than that earlier observed on the fiber measurements. It therefore seems that the large deviations of fiber placement is resultant from the fiber attachment method, not from either the plate machining nor inaccurate measurements. To make this conclusive, the originally measured plate should be remeasured using the new methods.

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