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# High precision measurements with nuclear emulsions using fast automated microscopes

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**Abstract**

We report on the development of an automated scanning system for nuclear emulsions aiming at very precise spatial and angular measurements. An accuracy of 0.06 μm in position was achieved with the emulsion films used for the measurement. An accuracy of 0.4 mrad was achieved for tracks penetrating orthogonally the emulsion films while an accuracy of 1 mrad was obtained for tracks inclined by about 300 mrad with respect to the perpendicular direction. This result shows unprecedented position and angular resolutions achieved by automated measurements.
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## 1. Introduction

Nuclear emulsions have been largely used in high energy physics, leading to the discovery of new particles and to the measurement of their properties [1–4]. The high sensitivity and grain uniformity of nuclear emulsions make them capable of observing tracks of single particles with submicrometric space resolution and therefore they are especially suitable for the observation of short lived particles. The present use of the

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emulsion technique is linked to the impressive achievements in the development of automated scanning systems [5–8]. This allowed the design of a new generation of "hybrid" experiments [9–12], where nuclear emulsions are combined with electronic detectors.

The need for massive detectors has recently motivated the revival of the Emulsion Cloud Chamber (ECC) technique [13] for neutrino experiments aiming at the detection of the $\tau$ lepton [11,12]. The ECC consists of a sandwich structure made of thick metal plates (passive material) and thin emulsion layers (tracking device). This detector was successfully used in cosmic ray experiments, having the advantages of cost effectiveness and of particle identification capabilities. Most of the detector mass consists of metal plates, allowing for a substantial cost reduction (a few percent) compared with stacks of pure emulsions.

The use of metal plates in the ECC design prevents the recognition of short lived particles through the visual observation of their decay point, as done in experiments where only emulsion stacks are used as a target. This feature is replaced by the use of impact parameter techniques. For background rejection, one profits from better measurements of kinematical parameters through the showering and multiple Coulomb scattering measurements [14].

The intrinsic position resolution of the nuclear emulsions used is about $0.2/\sqrt{12}\,\mu m$, where $0.2\,\mu m$ is the diameter of the original AgBr crystal [15] for the used emulsions. The emulsion films used in this paper are made of two $44\,\mu m$ thick layers stuck on both sides of a $210\,\mu m$ plastic base. Given the level arm of $210\,\mu m$ between the two layers, the intrinsic angular accuracy is about 0.4 mrad.

Automated scanning systems aimed at achieving a maximal scanning speed (now reaching $20\,cm^2/h$ [8]) are not focused on fully exploiting the intrinsic resolution of the nuclear emulsions. In this paper we report on the realization of an automated microscope aimed at achieving a high resolution, with a somewhat slower scanning speed (about $0.1\,cm^2/h$). This system is meant to scan a limited number of events for which a very high precision is needed. Therefore, the scanning speed should be measured per track rather than per unit surface. A speed per track of 270 tracks/h has been achieved. We also report on the development of a dedicated measurement procedure.

## 2. The automated microscope

The automated scanning system consists of a microscope equipped with a computer-controlled motorized stage, movable in all three directions, a dedicated optical system and a CCD camera, on top of an optical tube. For each field of view, several tomographic images of the emulsions are taken at equidistant depths by moving the focal plane across the emulsion thickness ($Z$ direction). Images are grabbed and processed by a vision multi-processor board, hosted in the control PC together with the motor control board. Its design profits from the experience gained in the design of high speed microscopes developed in an R&D project in the framework of the OPERA experiment [8], with the addition of special features to enhance the precision of the measurements.

The mechanical stage is equipped with nano-step motors and optical encoders with a resolution of $0.1\,\mu m$ for the horizontal axes. The stage allows to cover a range of 20 cm on the horizontal axes and 5 cm on the vertical one. A modified optical bench hosts the illumination system and it is equipped with a granite arm bearing on the $Z$ stage and the optical system. The peculiar mechanical feature of this stage is the $Z$ stage with optical encoders achieving the accuracy of $0.05\,\mu m$. The optical system includes a trinocular tube, mechanically assembled to fit the $Z$ stage, and a magnification 50 oil-immersion objective with a working distance of $400\,\mu m$. The optical system is infinity-corrected and produces achromatic planar images through the whole thickness of the emulsion. A photograph of the system is shown in Fig. 1.

The image is formed on a CCD camera (Video Walls VWFT12I, type FTM12) capable of 30 frames per second with a sensor of $1024 \times 1024$ pixels and a size of $7.5 \times 7.5\,mm^2$. The resulting size of one microscope field of view is $150 \times 150\,\mu m^2$ yielding a pixel to micron conversion factor of $0.1477 \pm 0.0003\,\mu m/pixel$, a factor of

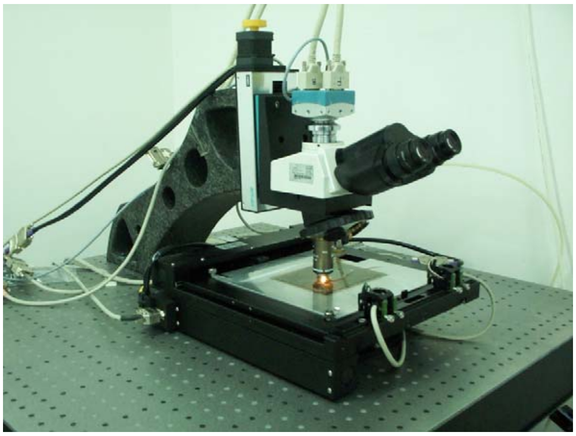

Fig. 1. Photograph of the automated scanning system developed in this work.

about 2 better than in the high speed system [8]. Images are filtered using a Matrox Genesis frame grabber and vision processor.

Nuclear emulsions are very sensitive to the variation of the environmental parameters like temperature and humidity. In order to achieve the desired accuracy, it is necessary to keep these parameters around the suggested values (about 24 °C and 60% relative humidity) with a few percent stability. This needs their continuous monitoring. We have designed and installed an acquisition system for the measurement and storage of the values read out from different sensors at fixed time intervals with a user friendly interface. The system uses FieldPoint control devices developed by National Instruments [16]. Resistive sensors are used for temperature monitoring while solid state sensors are employed in humidity monitoring. A control board with real-time functionality is used. The applicative program was developed under the LabView environment. The control unit takes the data on a memory and downloads them to the server. A Web access was also developed.

## 3. Data taking software

We developed a dedicated software to grab and process the images of nuclear emulsions. The software is divided into two independent parts: one is dedicated to image grabbing and cluster forming analysis (the so-called "clusterization"), the other one to tracking analysis ("segmentation").

The on-line program is written in the object-oriented C++ language and developed under the Microsoft Visual C++ environment as standard Windows application with an user-friendly interface. The program performs the following main operations: stage moving, image grabbing and processing, data storage. An input file containing the predicted track positions and slopes must be provided. These parameters come from previous measurements performed by a fast automated system.

The microscope stage is driven to the position of each predicted track. The number of repeated acquisitions as well as the vertical distance between grabbed layers can be selected by the user (the typical value is 40). The so-called tomographic analysis of emulsions is performed both in the top and in the bottom emulsion layer. For each level, a digital image of $1024 \times 1024$ pixels is saved and processed, i.e. filtered and binarized. The grabbing process is performed in asynchronous mode to increase the speed of the system. In this way the vertical axis moves through the emulsion without stopping and the storage of images is not synchronized with the end of its grabbing. All the saved frames are then ready to be processed. Images are filtered by applying a Finite Impulse Response (FIR) filter. This operation improves the discrimination between emulsion grains and background noise. The binarization is then performed by applying a gray level threshold to the filtered image. Thus, the resulting black and white image is the best separation between signal and background. A clustering operation is needed to recognize the emulsion grains. Clusters of pixels represent the physical grains produced by the passage of particles through nuclear emulsions.

The identification of clusters is made on binary images, while features of clusters (area and center of gravity) are calculated by using the pixel gray level. The center of gravity of all the pixels belonging to a given cluster provides the position of the grain. It is calculated by using the gray level of each pixel as weight. The number of pixels belonging to a cluster is by definition its area. Image processing is performed on-line by using the Matrox Vision

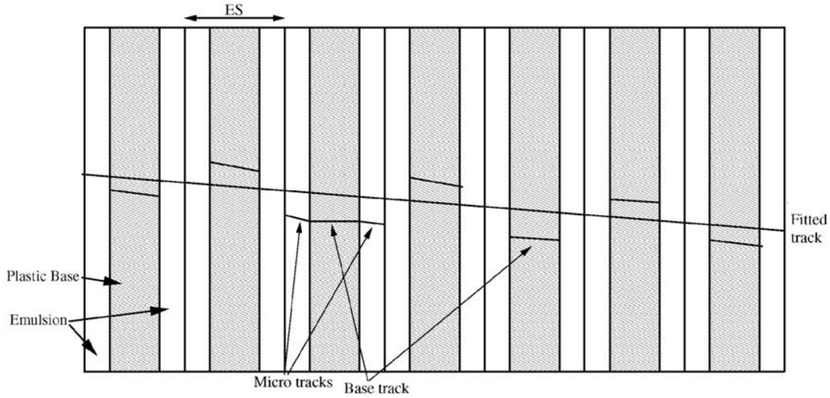


Fig. 2. Schematic drawing of the emulsion stack used for the measurements. The micro-track and base-track are defined.

processor. The scanning results are stored and processed by the FEDRA analysis framework [17] which operates in a ROOT [18] environment.

An off-line tracking procedure ("segmentation") is then applied. The tracking is independent of the clusterization procedure and can be used for any kind of "segmentation" analysis. This procedure can be compiled either under the Windows or the Linux operating systems.

The off-line tracking algorithm is based on the "layer-shifting" procedure described in the following. By superimposing all the digitized layers, a bi-dimensional histogram is produced with peaks corresponding to perpendicular tracks. For inclined tracks, peaks in the bi-dimensional histogram appear only after a layer shift proportional to the track slope. These shifts converted into slope units are used as input values for the fitting procedure. This procedure involves all the clusters with a distance from the track below a given threshold. In the current realization of the algorithm, the threshold is estimated by using the fact that the distance of clusters from the fitted line does not depend on the track slopes in the used "normalized" (to the measured error) space. The fitted line is the result of the tracking procedure.

## 4. Beam exposure

In order to test the performances of the scanning system, emulsion stacks were assembled and exposed to high energy particle beams. The stack used for the measurement reported here was made of seven consecutive emulsion sheets, as shown in Fig. 2. Unlike the ECC case, no metal plate was used, in order to minimize scattering effects which would prevent the evaluation of the precision reachable with nuclear emulsions, which is the purpose of this study.

The emulsion films were produced by the Fuji Film company.[1] They belong to the same batch of the nuclear emulsions used for the OPERA experiment [12].

The emulsion stack was exposed to the $\pi^-$ beam in the T7 experimental area of the CERN PS. Data were taken at a pion momentum of $8\,\mathrm{GeV}/c$. The uncertainty on the beam momentum is of the order of 1%. At this energy, the T7 pion beam shows an electron contamination of less than 10% [19]. In order to avoid irradiation of the emulsion layers by the electron-generated showers above an acceptable track density, we placed about 2.5 cm of lead ($\sim 5\ X_0$) upstream of the last focusing magnet. This reduced the electron contamination well below the per-mil level, as monitored by Cherenkov detectors. Its effect became completely negligible.

In order to determine the measurement accuracy as a function of the track angle, we made several beam exposures by rotating the emulsion stack in steps of 100 mrad (well above the beam angular

[1]Fuji Film, Minamiashigara, 250-0193, Japan.

spread), up to 300 mrad. The coincidence of two scintillation counters was used to monitor the incident flux and set the exposure time to obtain the desired statistical sample. The recorded track density was about 15 tracks per mm$^2$.

## 5. Position measurements

The basic idea of the tracking algorithm is that a track is a straight sequence of grains. A grain is defined as a cluster of about 15 pixels. A sequence of aligned grains in an emulsion layer defines the so-called ‘‘micro-track’’. From the two micro-tracks in the two emulsion layers of an emulsion sheet, the so-called ‘‘base-track’’ is formed, as shown in Fig. 2.

The angular measurement accuracy in the track fit depends on the accuracy of the angular measurement in each emulsion sheet. There are two contributions to the measurement of this so-called base angle: the first comes from the position accuracy, the second one comes from the accuracy of measuring the level arm, which is given by the plastic base thickness in the emulsion sheet used. A stage with high mechanical quality and a readout system with an excellent pixel to micron ratio is needed for precise position measurements.

The above mentioned base and emulsion thicknesses are nominal and fluctuations are expected, due also to environmental parameter instabilities beyond the value which can be kept under control. In order to make a precise measurement of the base thickness we used the following procedure. We took 40 images in each emulsion layer by sampling the thickness every 1.5 μm, which corresponds to the depth of field of the optical system. Given the fact that the nominal emulsion thickness is 50 μm, there are some empty frames. They are actually essential since they are used to determine the base thickness. The distribution of the number of clusters per frame is shown in Fig. 3. The upward and downward ramps of the profile give the position of the emulsion edges. A smoothing procedure is first applied, by using the formula

$$n_s(i) = \frac{1}{9}[n(i-2) + 2 \times n(i-1) + 3 \times n(i) + 2 \times n(i+1) + n(i+2)]$$

where $n(i)$ indicates the number of cluster in the $i$th frame and $n_s(i)$ is the smoothed one. The plot in Fig. 4 shows a more regular profile, as obtained after the smoothing procedure.

The derivative of the number of clusters is then evaluated. This is a flat distribution except at the edges where the derivative shows the maximum and minimum value, as it is shown in Fig. 5. The maximum and minimum of the derivative define the edges of the emulsions. We have measured a Gaussian fluctuation of these values with a standard deviation of 1.7 μm. Therefore, instead of using the extreme values of the derivative, we

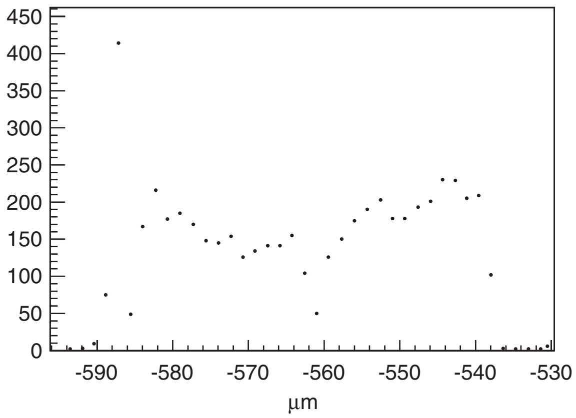


Fig. 3. Measured profile of the number of clusters as a function of the $z$ (μm) coordinate of the frame.

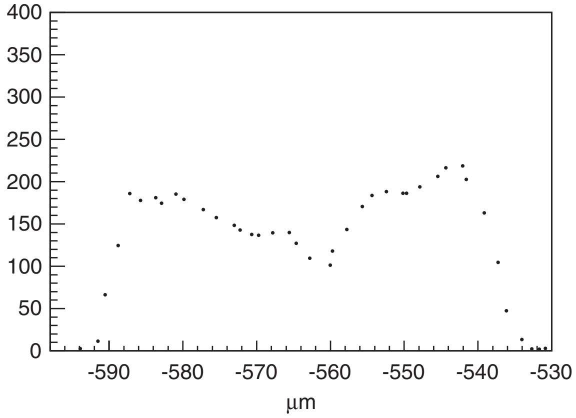


Fig. 4. Profile of the number of clusters as a function of the $z$ (μm) coordinate of the frame after the smoothing procedure is applied.

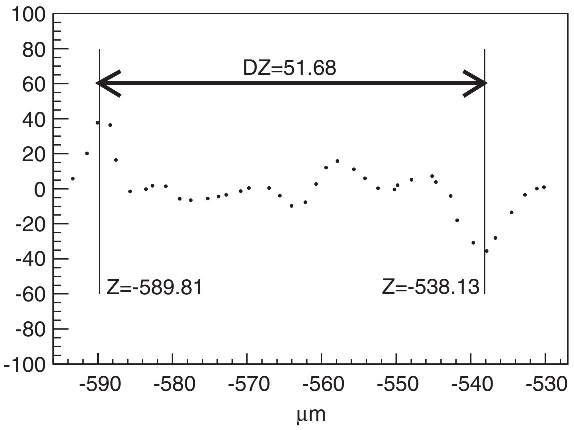


Fig. 5. Profile of the derivative of the number of clusters as a function of the $z$ (μm) coordinate of the frame for one emulsion sheet.

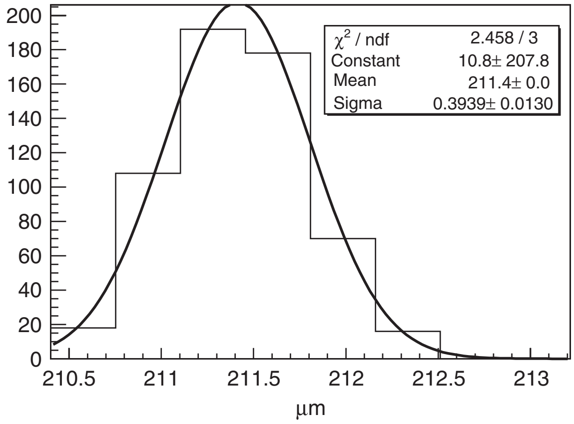


Fig. 6. Base thickness (μm) distribution, showing an achieved accuracy better than 0.2%.

take the mean value of the derivative distribution computed over a ±5 μm region around the extremes. This procedure provides a thickness of about 52 μm for the emulsion considered, as shown in Fig. 5.

This procedure is repeated for both emulsion layers. The thickness of the base, which is relevant for the measurement of the base track angle, is obtained as the distance between the emulsion edges close to it. A relative accuracy of 0.2% is achieved, as shown in Fig. 6.

The position accuracy of our measurement is defined by the difference between the grain position and the fitted micro-track position at the same longitudinal depth in each emulsion sheet (residual). The residuals of the position measurement are shown in Figs. 7 and 8 for the $X$ and $Y$ projections, respectively. An accuracy of 0.05 μm is achieved.

Given the position resolution achieved and the measured accuracy for the base thickness, we expect an angular resolution in each cell of about 0.4 mrad.

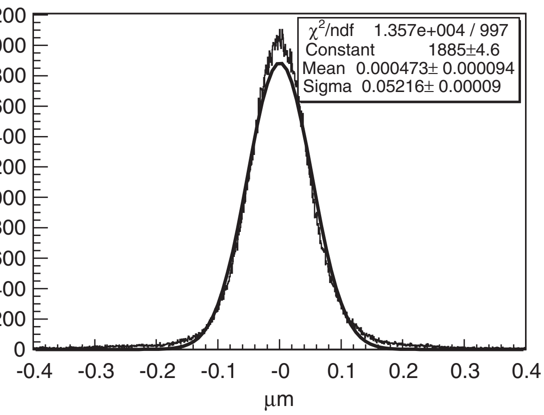


Fig. 7. Position accuracy for the $X$ projection (μm).

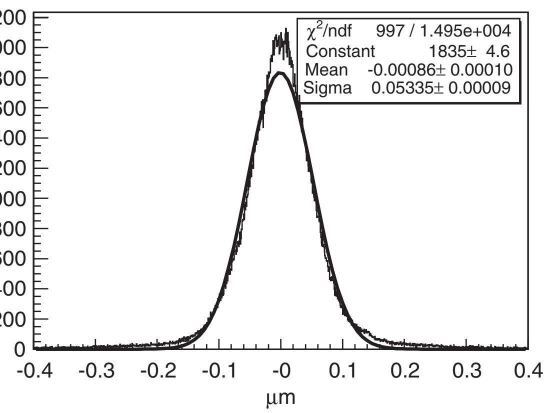


Fig. 8. Position accuracy for the $Y$ projection (μm).

## 6. Angle measurements

In order to achieve a very precise angular measurement it is necessary to reduce as much as possible the systematic errors which would spoil the statistical accuracy achieved with the data taking procedure described in the previous sections.

The main systematic effects in the analysis of nuclear emulsions are the non-planarity of two consecutive emulsion films, due to the thickness variation of the passive material or separator, and the local distortion of the sheets. The first effect becomes relevant only on emulsion surfaces of several square centimeters. The local distortion, instead, has a scale of a few square millimeters and is therefore the leading one.

Distortion effects on such thin emulsions are as large as a few milliradiants, which would completely overcome the statistical error. In order to suppress such an effect, the average trajectory of other penetrating tracks of beam particles in a surrounding area of a few square millimeters is used as reference trajectory so that the relative trajectory is built for each track. It is therefore necessary to collect enough penetrating tracks. Given that the track density in the exposure is about 15 tracks/mm$^2$, an area of $2 \times 2\,\mathrm{mm}^2$ is suitable for this purpose. The size of the area should, of course, match the size of the effect. The use of the relative trajectory produces an almost total cancellation of the above systematic effects.

After measuring the base track in one emulsion sheet, we followed the tracks along the seven consecutive sheets. The track following is done by means of the inter-calibration of consecutive emulsion sheets. The inter-calibration is performed by matching track patterns in consecutive sheets, one pair after the other. After following the track in all consecutive sheets, we performed the track fit. The difference of the track fit and the base angle measurement (residual) in each emulsion sheet provides the accuracy of our measurement.

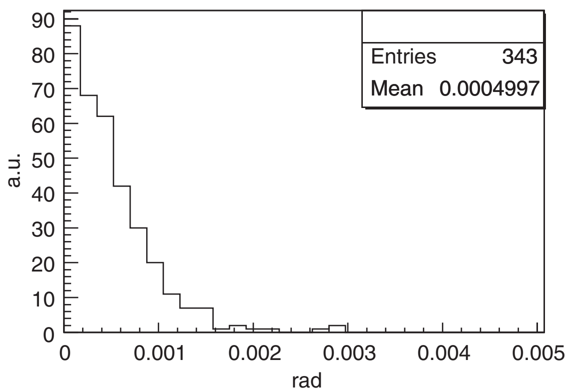

Fig. 9. The angular accuracy for perpendicular tracks. The median of the distribution is 0.40 mrad.

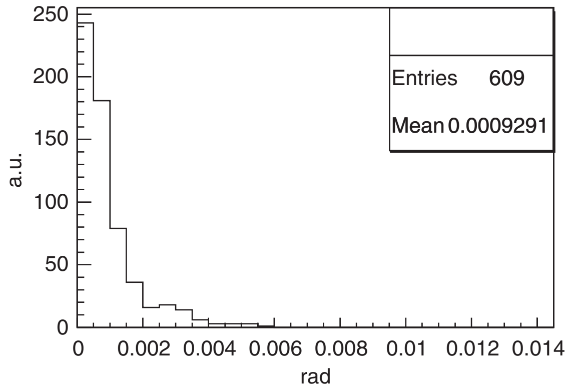

Fig. 10. The angular accuracy for tracks inclined of about 200 mrad. The median of the distribution is 0.64 mrad.

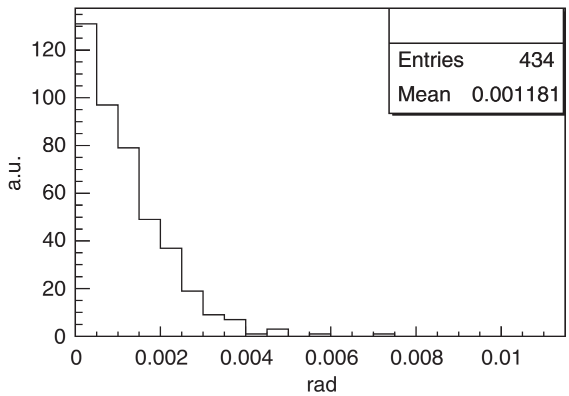

Fig. 11. The angular accuracy for tracks inclined of about 300 mrad. The median of the distribution is 0.95 mrad.

The residuals of the angle measurement are shown in Fig. 9. An average value of 0.5 mrad is obtained. Given the asymmetric shape of the distribution, the median provides a better estimate of the accuracy. The median value is 0.4 mrad.

We performed the same analysis also for inclined tracks. Usually the measurement accuracy degrades with the angle. In Fig. 10 we show the residuals for tracks inclined by 200 mrad while in Fig. 11 the residuals of 300 mrad inclined tracks are shown. The median is about 0.6 mrad for 200 mrad tracks while it is still below 1 mrad for 300 mrad tracks.

## 7. Conclusions

We have developed an automated scanning system aiming at very precise spatial and angular measurements. The system is designed for the analysis of rare events where the accuracy is the main issue rather than the scanning speed. We have developed a new data taking and analysis procedure to measure the track angles and we have achieved unprecedented results: 0.06 μm for the position measurement, 0.4 mrad for low angle tracks (around 50 mrad) and 0.95 mrad for 300 mrad inclined tracks.

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