EUDET-Memo-2007-06

# Simulation study for the EUDET pixel beam telescope using ILC software

T. Klimkovich*

January 31, 2007

**Abstract**

A pixel beam telescope which is currently under development within the EUDET collaboration will provide a test environment for different pixel sensor technologies as well as for large tracking devices such as TPC. The telescope will consist of 4-6 sensor planes. There will be a possibility to operate the telescope inside a solenoidal magnetic field of up to 1.2 Tesla. The setup will initially be installed at a 1-6 GeV/c electron beam line at DESY in Hamburg, however, it will be flexible to be used at other beam lines.

In order to achieve the required impact position of beam particles on the device under test (DUT) plane of 3 $\mu$m at 5 GeV/c it is necessary to find the optimum configuration of the telescope mechanics. For this purpose a simulation study using the International Linear Collider (ILC) simulation package Mokka has been done. In this paper the intermediate results of the simulation study for different telescope configurations are presented.

*DESY, Hamburg, Germany

# 1 Introduction

EUDET is a coordinated European effort towards research and development for the next generation of large-scale particle detectors. It is intended to develop infrastructures to facilitate experimentation and to enable the analysis of data using shared equipment and common tools. The project covers different activities for vertexing, tracking, calorimetry as well as networking activities which support information exchange. The JRA1 subgroup is dedicated to develop a test beam infrastructure and a pixel beam telescope. The planes of the beam telescope will be equipped with monolithic active pixel detectors constructed in CMOS technology. The objective of the future device is to achieve a precision of the predicted impact position of beam particles on the DUT plane of less than 3 $\mu$m at 5 GeV/c. To fulfil this requirement it is necessary to find an optimum configuration of the telescope mechanics. For this purpose a simulation study of different telescope geometries has been done. In this paper the intermediate results of this study are presented.

# 2 Beam telescope geometries

The general layout of the considered beam telescope geometries is shown in Fig. 1-2. Symmetric geometry (Fig. 1) consists of 2, 4 or 6 planes, situated symmetrically around the DUT and placed inside a box for electrical and thermal shielding with aluminium windows for the beam. In asymmetric geometry (Fig. 2) the DUT is shifted in the direction of the beam source providing enough space for the electronics. The asymmetric setup consists of three separate insulating boxes (for two telescope arms and the DUT), which allows better flexibility for the overall setup. In the cases of 2- and 4-plane geometries the closest telescope planes to the DUT have been considered. The thickness of the telescope planes has been assumed to be 110 $\mu$m which corresponds to the thickness of the thinned sensors. The DUT is assumed to be 300 $\mu$m thick.

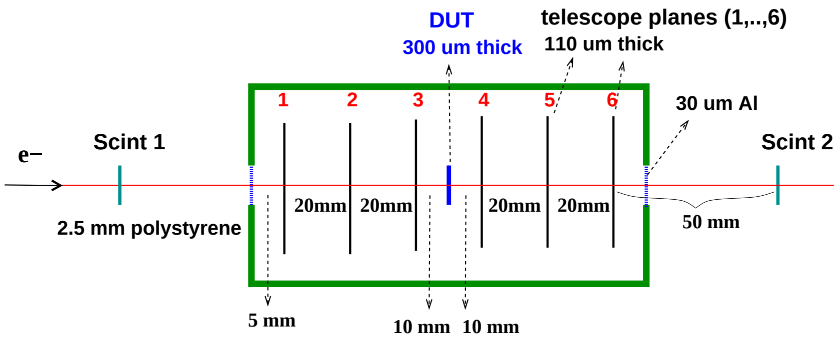


Figure 1: Symmetric geometry of the pixel beam telescope.

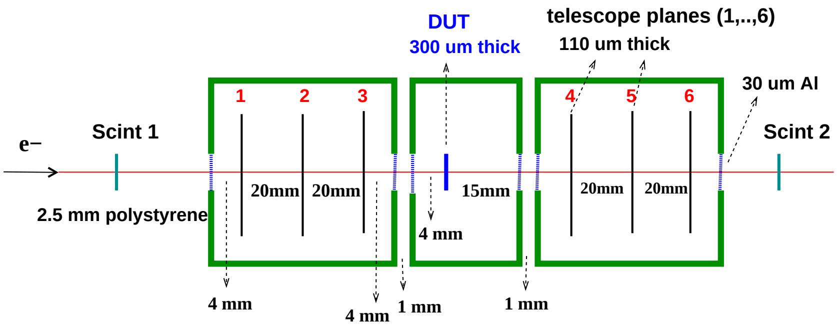


Figure 2: Asymmetric geometry of the pixel beam telescope.

# 3 Software tools

The simulation of the beam telescope has been done using the package Mokka 06.00 [1], which is a Geant4-based simulation program for a future linear collider. All parameters for different detector models have been stored in a MySQL database. The output files are in LCIO format [2, 3]. For the analysis of simulated data the linear collider analysis framework Marlin 00.09.04 [4] as well as C++ and ROOT software have been used.
For every detector setup 50000 events have been simulated (without magnetic field) with an electron beam momentum from 1 GeV/c to 6 GeV/c. In the simulation the effects of multiple scattering have been taken into account. For every event hit positions and deposited energies in every telescope plane and the DUT have been stored. An intrinsic resolution of 3 $\mu$m for every telescope plane has been assumed. For this purpose in the analysis every hit position in telescope planes has been smeared.

# 4 Validation of multiple scattering model

Charged particles passing through a medium undergo deflection due to Coulomb scattering from nuclei. For small scattering angles a Gaussian approximation is used to describe the width of the projected angular distribution of scattered particles [5]:

$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right], \tag{1}$$

where $\theta_0$ is defined as

$$\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{2}} \theta_{\text{space}}^{\text{rms}}. \tag{2}$$

In (1) $p$, $\beta c$ and $z$ are momentum, velocity and charge number of the incident particle, respectively, and $x/X_0$ is the thickness of the scattering medium in radiation lengths. To verify the description of the multiple scattering in the simulation a silicon wafer of 300 $\mu$m thickness has been modelled using Mokka, and 100000 electrons of 1 GeV/c have been used as incident particles. For these events the projection of the scattering

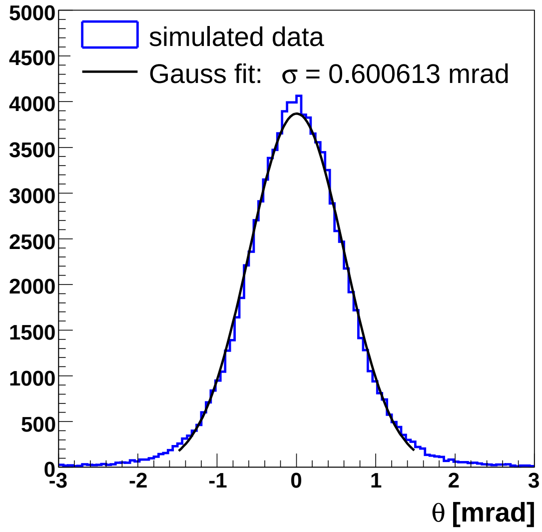


Figure 3: The projection of the scattering angle $\theta$ of electrons.

angle $\theta$ has been calculated (Fig. 3). Fitting a Gaussian function to the distribution gives a standard deviation of $\theta$ distribution $\theta_0 = 0.601 \pm 0.002$ mrad which is in good agreement with calculated according to (1) value $\theta_0^{theor} = 0.602$ mrad.

# 5 Analysis of the beam telescope simulation

The analysis procedure is done as follows. Through the hits in the telescope planes a straight line as a track model using a least squares fit has been fitted [6]. The telescope planes have been considered as perfectly aligned. To reduce the effects of multiple scattering the following track selection has been used:

- $\chi^2_{\text{track}} < 30$ for 6-plane geometry, $\chi^2_{\text{track}} < 10$ for 4- and 2-plane geometries;
- track slope $< 2$ mrad;
- distance $= \sqrt{(x_{\text{DUT}} - x_{\text{pred}})^2 + (y_{\text{DUT}} - y_{\text{pred}})^2} < 200\ \mu$m,

where $(x_{\text{pred}},\ y_{\text{pred}})$ is the position of the intersection of the track with the DUT plane and $(x_{\text{DUT}},\ y_{\text{DUT}})$ is the real hit position in the DUT. Track selection efficiencies for different detector configurations and electron beam momenta are listed in Table 1.
The residuals in the DUT plane $r_{x\ \text{DUT}}$ and $r_{y\ \text{DUT}}$ are calculated as the difference between the DUT hit position predicted by the extrapolated track and the real hit position in the DUT:

$$r_{x\ \text{DUT}} = x_{\text{pred}} - x_{\text{DUT}},$$

$$r_{y\ \text{DUT}} = y_{\text{pred}} - y_{\text{DUT}}.$$

| Momentum | 2-pl.sym. | 4-pl.sym. | 6-pl.sym. | 2-pl.asym. | 4-pl.asym. | 6-pl.asym. |
|---|---|---|---|---|---|---|
| 1 GeV/c | 81% | 36% | 27% | 79% | 28% | 21% |
| 2 GeV/c | 97% | 77% | 74% | 97% | 71% | 67% |
| 3 GeV/c | 99% | 89% | 90% | 99% | 86% | 87% |
| 4 GeV/c | 99% | 93% | 95% | 99% | 92% | 94% |
| 5 GeV/c | 100% | 95% | 97% | 100% | 94% | 97% |
| 6 GeV/c | 100% | 96% | 98% | 100% | 96% | 98% |

Table 1: Track selection efficiencies for different detector configurations and electron beam momenta.

After fitting a Gaussian function to the DUT residual distributions $r_{x\ \mathrm{DUT}}$ and $r_{y\ \mathrm{DUT}}$ the standard deviation values $\sigma_x$ and $\sigma_y$ have been extracted. The dependence of $\sigma_x$ on the electron beam energy is shown for different telescope configurations in Fig. 4. At low energies the contribution of multiple scattering (MS) is large and, therefore, the 2-plane configuration gives better results. With increasing energy the 4-plane geometry is an optimal variant. The asymmetric geometry gives worse results in comparison with the symmetric one due to larger multiple scattering from the aluminium windows of the shielding boxes.

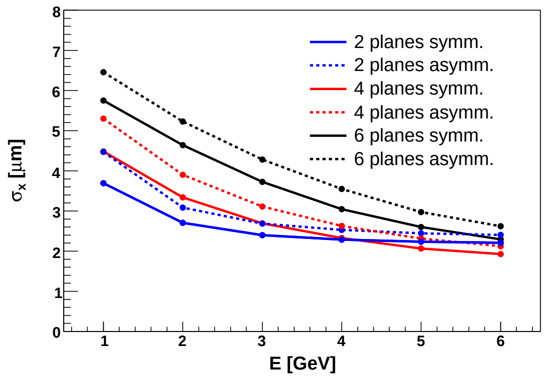


Figure 4: Standard deviation value of the residual distributions in the DUT plane $\sigma_x$ as a function of the electron beam energy for symmetric geometries (solid lines) and asymmetric geometries (dashed lines).

To investigate the dependence of the telescope precision on the distance of the telescope planes to the DUT the closest planes have been put 5 mm from the DUT (close setup) instead of 10 mm like it is in the standard symmetric configuration. The result is shown in Fig. 5 which indicates that the performance improves significantly if the telescope planes are situated as close as possible to the DUT.
For the case of the availability of two closest to the DUT telescope planes of higher resolution (1.5 $\mu$m), which can be achieved by using sensors with smaller pixel size, the

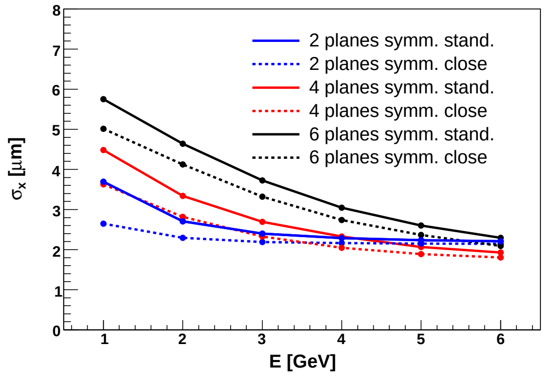


Figure 5: Standard deviation value of the residual distributions in the DUT plane $\sigma_x$ for symmetric geometry as a function of the electron beam energy for standard setup (solid lines) and close setup (dashed lines).

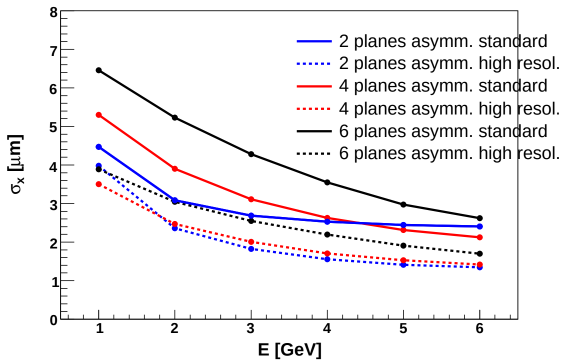


Figure 6: Standard deviation value of the residual distributions in the DUT plane $\sigma_x$ for standard asymmetric setup (solid lines) and high resolution asymmetric setup (dashed lines) as a function of the electron beam energy.

performance of the telescope will improve significantly (Fig. 6).

# 6 Pion beam

The present telescope setup is foreseen to be used in different test beam environments. The performance of the telescope within hadronic beams has been investigated by simulating a pion beam of 100 GeV/c. The same intrinsic plane resolution of 3 $\mu$m is assumed. The results of the study are presented in Fig. 7. As is expected, the 6-plane geometry will show the best performance due to negligible multiple scattering effects in comparison with low energy electron beams. The increase of material in the asymmetric geometry has almost no influence on the results.

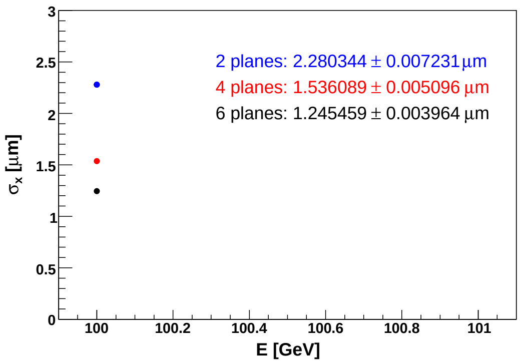


Figure 7: Standard deviation value of residual distributions in the DUT plane $\sigma_x$ as a function of the pion beam energy for asymmetric geometry.

# 7 Non-thinned sensors

To consider the possibility of using non-thinned silicon sensors at the "demonstrator" stage of EUDET beam telescope project a performance of symmetric setup with sensor planes of 500 $\mu$m thickness has been investigated in comparison with 110 $\mu$m thickness planes. The analysis has been done for 4- and 6-plane symmetric configurations. The efficiencies of track selection explained in Section 5 are shown in Table 2 for both standard setup and non-thinned setup.

| | 4-plane symm. | | 6-plane symm. | |
|---|---|---|---|---|
| Momentum | 110 $\mu$m | 500 $\mu$m | 110 $\mu$m | 500 $\mu$m |
| 1 GeV/c | 36% | 11% | 27% | 4% |
| 2 GeV/c | 77% | 50% | 74% | 35% |
| 3 GeV/c | 89% | 72% | 90% | 63% |
| 4 GeV/c | 93% | 83% | 95% | 80% |
| 5 GeV/c | 95% | 88% | 97% | 88% |
| 6 GeV/c | 96% | 92% | 98% | 92% |

Table 2: Track selection efficiencies for different detector configurations and electron beam momenta. The standard setup has 110 $\mu$m sensor thickness and the non-thinned setup – 500 $\mu$m.

The results of the analysis are shown in Fig. 8 where standard deviation values of residual distributions in the DUT plane $\sigma_x$ for symmetric beam telescope geometry after track selection are shown as a function of the electron beam energy. A setup with non-thinned sensor planes is represented by solid lines and a standard setup – by dashed lines. The plot shows that with increasing width of telescope sensors a performance of the telescope degrades rather significantly. Adjusting selection cuts one can find an optimal situation for improving the results without big loss in efficiency.

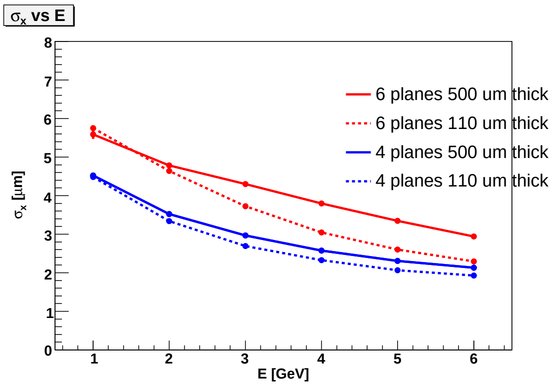


Figure 8: Standard deviation value of residual distributions in the DUT plane $\sigma_x$ for symmetric beam telescope geometry as a function of the electron beam energy after track selection described in Section 5. Solid lines: a setup with non-thinned sensor planes of 500 $\mu$m thickness, dashed lines: standard setup with 110 $\mu$m plane thickness.

# 8 Alignment

When the detector is ready a proper software alignment will be an important issue for telescope precision. Therefore it is useful to test different alignment procedures in order to arrange the setup in such a way as to make alignment later on easy. A popular alignment program in use is Millepede [7] which is widely exploited in H1, ZEUS and CMS experiments for tracker alignment. The package is based on a linear least squares fit and especially suited for systems with big numbers of fitted parameters. There are two types of parameters used in the fit:

- local parameters: track parameters (here, track slopes and curvatures);
- global parameters: alignment coefficients (here, $x$ and $y$ shifts).

For testing the package 50000 events for 6 GeV/C electron beam have been simulated for the 6-plane symmetric telescope geometry without the DUT. A misalignment has been introduced into the analysis by randomly shifting hit positions in telescope planes. Very preliminary results of the alignment procedure are shown in Fig. 9 for $x$ shifts (left plot) and $y$ shifts (right plot). Blue dots indicate true shifts which have been introduced in the analysis and red dots represent the output of the alignment package Millepede. In general good performance of the program is demonstrated however more detailed and systematic study is needed e.g. for taking into account rotations of the telescope planes as well as finding a minimal number of events necessary for precision alignment.

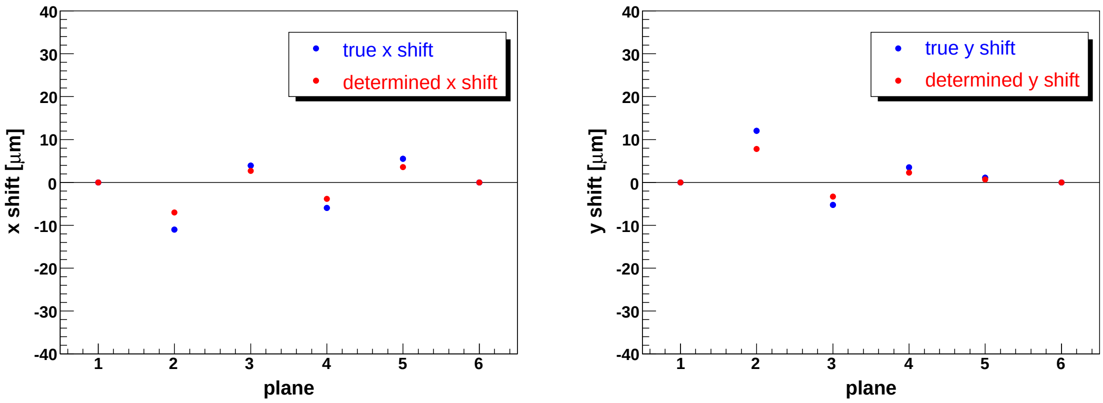


Figure 9: The results of alignment procedure for $x$ shifts (left plot) and $y$ shifts (right plot) as a function of the plane number. Blue dots indicate true shifts and red dots represent the output of the alignment package Millepede.

# 9 Conclusions and outlook

In this study the intermediate analysis results of the simulation of different beam telescope configurations are presented. The simulation has been done using the ILC simulation package Mokka. The simulation included modelling of multiple scattering effects. A straight line has been considered as a track model during a track reconstruction. Under this assumption in general all telescope geometries show satisfactory results. For low energy electron beam a 4-plane geometry gives the best performance. For high energy pion beam (100 GeV/c) a 6-plane geometry shows the best results. The next steps in this study will be to perform a track reconstruction taking into account the effects of multiple scattering, e.g. using Kalman filter methods.

For low energy electron beam the analysis has shown that the telescope planes should be situated as close as possible to the DUT. Moreover, the telescope performance will profit significantly from increasing the resolution of the two planes closest to the DUT, especially at lowest energies.

The possibility of using non-thinned silicon sensors for the "demonstrator" stage of the EUDET beam telescope project has been investigated by performing a simulation with the sensors of the thickness of 500 $\mu$m instead of 110 $\mu$m. It has been found that by choosing the right track selection it will be possible to achieve satisfactory results with reasonable track selection efficiency. The results can be improved by performing a track reconstruction taking into account multiple scattering effects.

For the telescope software alignment a first try has been done using the Millepede program and considering only transverse plane shifts. This test has shown a satisfactory performance of the package. The next step will be a more systematic study of the alignment procedure, also taking into account rotations of the telescope planes.

As planned initially there would be a possibility to operate the telescope inside a solenoidal magnetic field of up to 1.2 Tesla. Therefore there is also an interest in per-

forming a simulation of the telescope inside a magnetic field and developing a track reconstruction using specific track models.
Another effort will be to develop a common analysis framework for the telescope operation within test beams comprising all the steps of data analysis and possibility of its comparison with simulation.

# References

[1] P. Mora de Freitas, *Prepared for International Conference on Linear Colliders (LCWS 04), Paris, France, 19-24 Apr 2004*

[2] F. Gaede, T. Behnke, N. Graf and T. Johnson, *In the Proceedings of 2003 Conference for Computing in High-Energy and Nuclear Physics (CHEP 03), La Jolla, California, 24-28 Mar 2003, pp TUKT001* [arXiv:physics/0306114].

[3] F. Gaede, *Prepared for International Conference on Linear Colliders (LCWS 04), Paris, France, 19-24 Apr 2004*

[4] F. Gaede, Nucl. Instrum. Meth. A **559** (2006) 177.

[5] W. M. Yao *et al.* [Particle Data Group], J. Phys. G **33** (2006) 1.

[6] V. Blobel, E. Lohrmann, "Statistische und numerische Methoden der Datenanalyse", Stuttgart and Leipzig, Teubner (1998).

[7] V. Blobel, a program description for Millepede and the code is available from `http://www.desy.de/~blobel/`.