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EUDET-Pixel Telescope

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A 500 GeV electron-positron linear collider is the next great international project in High Energy Physics. In order to achieve that goal, an intense international planning effort with a number of R&D projects has started. EUDET is one project within that context with the aim to improve the infrastructure for doing detector R&D for the future international linear collider. EUDET is partially funded by the European union as a so-called "Integrated Infrastructure Initiative" within its 6^{th} Framework Programme for Research and Technological Development.
One of this infrastructures is a high resolution pixel telescope. The demonstrator telescope is only the first phase of this project, a full scale telescope will follow in 2009. This demonstrator telescope does not satisfy the final requirements (see section 2) with respect to readout speed. But this first test facility was quickly available to satisfy immediate and urgent test needs of various research groups working on pixel detectors in Europe. In this presentation the first test beam results of the pixel beam telescope will be discussed. The results show that the demonstrator telescope is working according to the requirements in terms of resolution and operation. The final telescope will be constructed using sensors with fully digital readout, integrated correlated double sampling (CDS) and data sparsification.

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1. Introduction

A 500GeV electron-positron linear collider is the next great international project in High Energy Physics. In order to achieve that goal, an intense international planning effort with a number of R&D projects has started. EUDET is one project within that context with the aim to improve the infrastructure for doing detector R&D for the future international linear collider EUDET is partially funded by the European Union as a so-called “Integrated Infrastructure Initiative” within its 6th Framework Programme for Research and Technological Development. It covers a number of different activities related to tracking, calorimetry and pixel R&D as well as so called networking activities which support information exchange. In this paper we shall discuss only one activity, namely the construction of a pixel beam telescope to be operated at DESY and CERN. The here described analogue telescope ("demonstrator") is only the first phase of this project; a full scale telescope will follow in spring 2009. This first test facility is already available for users since one year to satisfy the urgent test needs of various research groups working on pixel detectors in Europe. In this presentation the high resolution beam telescope based on pixel sensors will be described. Design aspects to ease users interfacing to the general purpose mechanical setup and the data acquisition will be explained. Also a modular analysis package has been developed and used to analyse the data. Users can integrate at different levels of the analysis chain. Also the performance of the telescope in the different user test beam period will be summarised and the results will be discussed. The audience will learn how to apply for the use of this telescope and which tools are ready for the community.

2. Telescope Requirements

The beam telescope is to be used for a wide range of R&D applications and quite different devices under test (DUT), from small (a few millimetres) to large (up to one meter) size. Depending on the project and on the size of the device the requirements as to precision and coverage are quite different. Still, the system should be easy to use so that a high efficiency in the use of the facility can be achieved.

Due to the limited energy of the electron beam from DESYII ($1-6$ GeV) the precision that can be reached in any device is limited by the multiple scattering. However, with a careful optimisation of the telescope setup with respect to dead materials and positioning of the telescope planes the precision of the predicted impact position of beam particles on the DUT plane should reach less than 3 μm at 6 GeV. This is achieved by reducing the amount of material in individual planes while maintaining point precision on the telescope planes of around $2-3$ μm. It is also foreseen to place a high resolution plane ($\sigma \approx 1$ μm) in front of the DUT to improve the precision of the telescope.

The mechanical setup should allow for a wide range of different configurations from a very compact one useful for pixel sensors to a two-arm layout with sufficient adjustable space in between the arms to accommodate the DUT. The lateral dimensions of the active area should be large enough to cover high precision pixel devices without mechanical movement of the device under test. Obviously, for larger devices mechanical actuators will have to be used. The speed of the device should allow to take full advantage of the beam rates and hence should be able to operate at readout rates of up to

1000 frame/sec.
Finally, the overall setup of the telescope should be flexible enough to make it transportable in order to use it at other beam lines outside of DESY, e. g. at higher energy hadron beam lines.

3. Sensors

The sensors for the telescope have to provide a single point resolution of $2-3\mu$m with a minimum of material. Also, a reasonable lateral coverage is required and the readout has to be fast enough to reach a telescope frame rate of 1 kHz.
R&D towards an ILC vertex detector is actively being pursued on a number of different sensor technologies such as CCDs [1], DEPFETs [2] and CMOS [3] sensors and a number of prototypes emphasising different aspects of these devices have been built. Most of these prototypes are too small for the planned telescope.
The CNRS-IPHC institute in Strasbourg, France [4] has also successfully developed, fabricated and tested a number of monolithic active pixel sensors (MAPS) with large enough arrays for the telescope. The MimoTel prototype, was chosen for the demonstrator telescope. The chip has been designed and produced in an engineering run in AMS 0.35 OPTO; this technology allows the chip designer to choose among two different epitaxial layer thickness (14 and 20 μm) in order to better suit with light detection. In order to explore this technology feature prototypes with both the epitaxial thickness have been produced and tested either in laboratory with sources and on beam. The sensor is divided in 4 sub-arrays of 64×256 pixels each readout in parallel. With a pixel pitch of 30×30 μm^2 this results in an active area of 7.7×7.7 mm^2. This is not fulfilling the final telescope requirements, but suitable for the demonstrator. While the chip shows a good signal-to-noise ratio and high point precision, its architecture based on the self biased structure is simple and not integrating any data reduction, signal processing and parallelisation.

4. DAQ System

The heart of the DAQ system is a general purpose acquisition board called EUDRB (EUDET Data Reduction Board). This is featuring two I/O buses: the VME64x for high throughput data transfer and synchronous operation with other devices and the USB 2.0 for standalone and bench top testing. To maximize its flexibility a mother- / daughter- board scheme has been followed, in order to have all the computing and memory elements common to all possible configurations on the motherboard, while the sensor specific requirements have been implemented on removable and interchangeable daughter cards.
For each sensor in the telescope there is a corresponding EUDRB board in the DAQ system and the two are linked via three connections named as follows:

- **Analog link**. This is the analog line connecting the pixel chip to the readout board. It is made by a CAT-5e ethernet cable with one pair of conductors for each sub-array.

- **Digital link**. This line is dedicated to the chip steering and synchronization. Again it is made using a network cable.

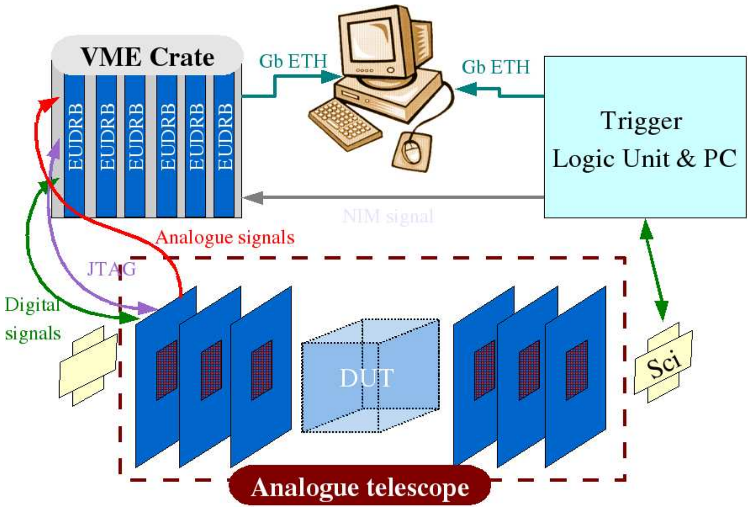


Figure 1: Schematic layout of the DAQ system.

- **JTAG link**. This line is used to send to and receive from the chip its configuration. The EUDRB board is generating the JTAG pattern in single–ended mode and a level adapter is needed to enter the MimoTel chip that is accepting differential signals.

The EUDRB is named after one of its most important feature: the possibility to reduce on the fly the data volume. Two different readout modalities have been implemented so far:

1. **Fully transparent mode**, mainly for debug purpose, in which all pixel signals are transferred to the equipment computer;

2. **Zero suppressed mode (ZS)**, in which the DAQ board is performing online the Correlated Double Sampling (CDS) and transferring to the computer only the signal and the address of pixels above a certain user–defined threshold.

Another important element of the DAQ system is the Trigger Logic Unit; this can be considered as the replacement of a NIM crate with all the most commonly used modules. In fact it accepts as input the output signal of the trigger scintillators and produce any kind of coincidence / anti coincidence the user wants to use to trigger the system. For each trigger, the TLU is also generating an incrementing event number and assigning a time stamp. The TLU is connected through Gb ETH to a control PC that is its turn connected to the main DAQ PC.
A schematic layout of the DAQ system is shown in Fig. 1.

To control the different tasks, a custom DAQ system (EUDAQ, [10]) has been implemented in C++. Several producer tasks communicate with a global run control using sockets (see Figure 2). These producer tasks connect to the hardware of the beam telescope, to the TLU and eventually to the DUT. Data from all producers is sent to the central data collector and can be monitored by several processes. An online monitor based on the ROOT framework showing online data quality monitoring histograms as well as a process to collect log messages are available. EUDAQ runs on MacOS, Linux and Windows using cygwin.

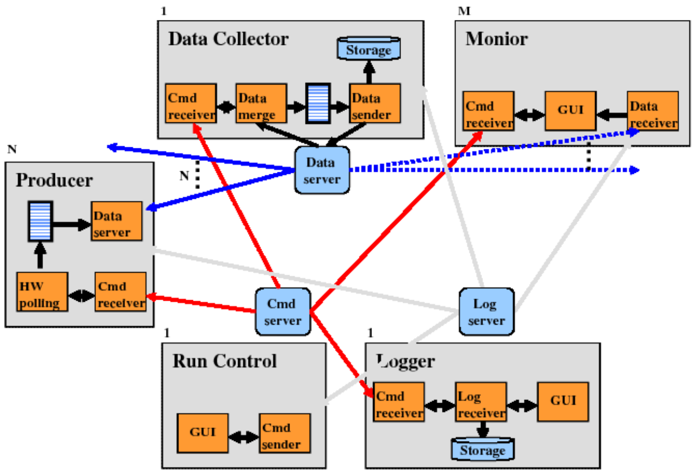


Figure 2: The EUDAQ software scheme.

5. Telescope Mechanical Design

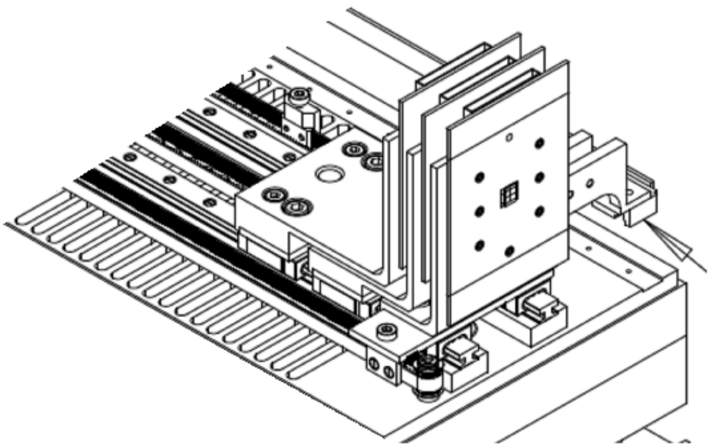
It is foreseen that the beam telescope will be operated in widely varying R&D applications with very different DUTs. Some telescope parameters are particularly relevant in this context. These are the number of measurement planes, the active area, longitudinal size and layout of the telescope, the mechanical support for the DUT and the environmental conditions such as gas flow and temperature.
The demonstrator telescope provides 6 telescope planes for redundancy and flexibility. The telescope is subdevided into two arms to allow more flexibility without limiting the size of the DUT which will be located between the two arms. In Fig. 3(a) the mechanics of the telescope is illustrated. Three sensor jigs (L-piece) are positioned on a track system. The minimal distance between the first and the third layer is 2 cm, the maximum level arm is 15 cm. Each L-piece holds one proximity board housing the sensor. The further electronics is placed close to the telescope.

6. Test beam effort

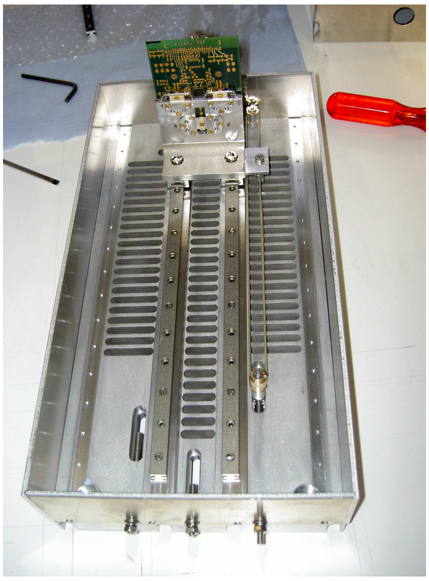
So far, the pixel telescope has been installed three times on a beam line. In the following sections a brief description of the performed tests is outlined.

6.1 The integration test

The first test beam has been done on the TB–24 electron beam line in DESY and it was meant to be an integration test, with only one telescope arm (three sensor planes). This was the first time ever all the different pieces of hardware were connected together and steered by the general DAQ software. The system performed well since the beginning without any major problem, even if some minor issues were identified and corrected on site. A textual version of the DAQ software was used and the requirements on the online monitoring task have been drafted. More than 100 thousand tracks with 3 GeV electrons were acquired in fully transparent mode in order to have some real data sample to be used with the offline analysis and reconstruction software.



(a)



(b)

Figure 3: (a) Technical drawing of one arm of the telescope mechanics. (b) A picture of the actual implementation.

6.2 Telescope characterization test

The second test beam was once again on the TB–24 beam line at DESY with the main goal to characterize the telescope itself. Since the final mechanical support was not yet ready, an ad hoc structure hosting five sensor planes in a single box was installed on the beam line. A close-packed configuration with 20 mm distance between to consecutive planes was used in order to minimize the effect of the multiple scattering on the spatial resolution. A fair amount of tracks have been acquired with five detector planes both in fully transparent and in zero suppressed mode with 3 and 6 GeV electrons to study the energy dependency of the spatial resolution. An improved version of the DAQ software more stable and with a graphical user interface has been used. This was also the first time ever where all the offline analysis and reconstruction software could be deeply tested with real data; data were stored on the DESY storage element and processed using the GRID computing elements made available to the ILC virtual organization. The overall characteristics of the telescope system were evaluated and results were found to be very close to the expectations. The measured intrinsic resolution of each single detector plane is found to be of the order of 3 μm very well in agreement with the design specification.
The spatial resolution of the system was measured taking into account also the multiple scattering contribution using an analytic approach [8] in the fitting procedure. The basic idea underlying this fitting procedure is that the contribution to the χ^2 by the i-th sensitive plane is given by the following

$$\Delta\chi_i^2 = \left(\frac{x_i - p_i}{\sigma_i}\right)^2 + \left(\frac{\Theta_i - \Theta_{i-1}}{\Delta\Theta_i}\right)^2 \tag{6.1}$$

where

$$\Theta_i = \frac{p_{i+1} - p_i}{x_{i+1} - x_i}$$

is the scattering angle, x_i and p_i are respectively the fitted and the measured position on the i-th plane, σ_i is the intrinsic resolution of the i-th plane and $\Delta\Theta_i$ is the width of the multiple scattering angle distribution [9]:

$$\Delta\theta_i = \frac{13.6\mathrm{MeV}}{\beta c p} z \sqrt{\frac{dx}{X_0}}[1 + 0.038\ln(\frac{dx}{X_0})] \tag{6.2}$$

where p, βc and z are the momentum, velocity and charge of the incident particle, and dx/X_0 is the thickness of the scattering medium in radiation lengths.

6.3 Integration of the first device under test

For the last test beam, the pixel telescope was mounted on the H8 line at the SPS facility at CERN and the system performance were evaluated using 120 GeV positive pions. The main goal of this test, apart from studying the ultimate spatial resolution using a multiple scattering free beam, was the integration of an alien (Device Under Test) sensor in the middle of the telescope setup. In this specific case two DEPFET sensors [2] have been integrated in the DAQ system. The integration went through two steps:

1. The first phase was accomplished having the two DAQ systems synchronized at the trigger level via the TLU. The two systems were sharing the same trigger signal and the overall busy

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signal was the logical OR of the telescope and the DUT one. When running in this modality the two DAQ systems were saving the output data streams into two different files, and the event reconstruction has to be done by the offline software. The two output files should be already synchronized by the trigger / busy logic, but it was preferred to add a further level of redundancy and both the telescope and the DUT events are labeled with the run and event number distributed by the TLU. Moreover this is adding another degree of freedom because the two data streams can underwent different analysis procedures and then merged afterwards at any points. This is by far the easiest way to integrate any external device in the telescope system.

2. The second phase was accomplished having the DUT system steered by the DAQ software. In this respect the high modularity of the telescope DAQ software played a crucial role. The key issue is given by the *DataProducer* / *DataCollector* client / server relationship. A global instance of the DataCollector is running on the main DAQ computer and its task is to gather all the data from all the DataProducer running on the client equipment. The DataProducer is the part of the DAQ software responsible to interface any piece of hardware in the system that is producing some data to be saved in the output file. Every different DataProducers have to describe all the operations that should be performed on the corresponding hardware during the system initialization, for each event and when closing the acquisition cycle. At the end of each event, the DataProducer is making available to the DataCollector the data stream to be saved in the output file or to be passed to all the on line monitoring task requiring it. Even if this level of integration is requiring a little of coding by the DUT user, it is safer from the point of view of the data integrity because the DAQ is recognizing the DUT as a part of the system and no more as an alien device and, moreover, the DUT data output is saved in the same file the telescope stream is written. Unfortunately, because of a lack of beam time, this modality could not be tested even if all the necessary code was written already.

During the whole data taking period, more than 4 million tracks were acquired with the telescope and the DEPFET sensors.
The final mechanical structure has been used and to get advantage from the lever arm, the sensor planes within one arm were displaced by 10 cm and in between the two arms a region 34 cm long was reserved for the DUT. The first arm was made by 14 μm thick epitaxial layer sensors, while the second one was made by 20 μm thick sensors. In this second arm, only two out of three planes were actually readout because of an electrical failure of one readout board.

7. Test beam results

The test beam analysis is quite advanced, but the results presented here are still preliminary as minor details of the analysis are still under discussion.

7.1 Sensor plane characterization

The first result one can obtain exposing the telescope to a Minimum Ionizing Particle (MIP) beam is the characterization of the sensor planes themselves. This does not require any particularly complicated analysis, alignment procedure or track fitting but, nevertheless it is opening up

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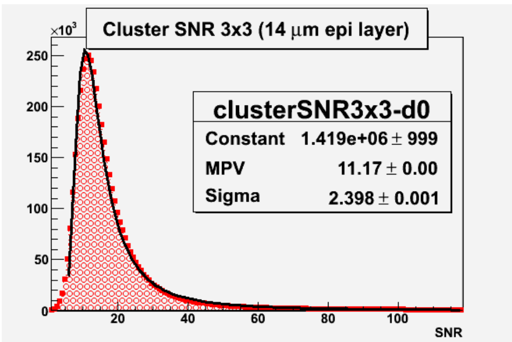
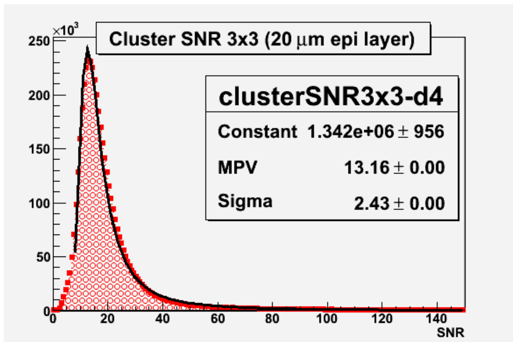
Table 1: Sensor plane characterization. Most probable values of the Landau fit for the cluster signal (in ADC counts) and signal to noise ratio and for the seed pixel.

Plane	**Epi layer [μm]**	**Seed pixel**		**Cluster w. 4 pixels**		**Cluster w. 3 $\times$ 3 pix.**	
		Signal [ADC]	**SNR**	**Signal [ADC]**	**SNR**	**Signal [ADC]**	**SNR**
#0	14	47.2	12.5	104.4	14.0	131.0	11.2
#1		46.2	12.2	103.0	13.6	129.0	10.9
#2		47.3	12.8	105.0	14.3	130.3	11.3
#3	20	47.5	10.9	112.8	13.0	151.4	11.0
#4		46.3	12.6	109.7	15.0	147.6	13.2



(a) 14 μm epi layer



(b) 20 μm epi layer

Figure 4: The SNR distribution for one thin (a) and one thick (b) epitaxial layer sensors.

the possibility to estimate how well the overall system will behave especially in terms of tracking efficiency and purity, and spatial resolution.

Every particle crossing the detector is producing a cloud of electrons along its trajectory in the sensor epitaxial layer and due to the MAPS working principle, this is shared among several neighboring pixels where a non zero output signal is detected. A clustering procedure to group together close pixels with signals above a certain minimum threshold is then required. In the CERN test beam setup the two families of MimoTel prototypes, with 14 and 20 μm thick epitaxial layer, were both used and a comparison between the two is then possible. In principle the thicker epitaxial layer sensor should provide a higher signal because the particle is crossing a larger amount of sensitive material, but on the other hand, being a diffusion based sensor, this could result in a greater spread of the charge and in a lower charge collection efficiency because of charge recombination.

In Table 1 the most probable values of the Landau fit for the seed pixel, the cluster with the four highest pixels and the one made by the three by three pixels around the seed are shown. Looking at the signal column for the three different quantities, it is clear that the charge collected by the seed pixel is the same for the two families of sensors while a larger charge is collected by the clusters

in the thick epi sensors denoting a greater signal production but also a larger charge spread. The signal to noise ratio must be considered carefully, because plane 3 has a mean single pixel noise 20% higher than all the other, making its performance very similar to plane number 4. The reason for this higher noise is not due to the detector itself but to a misbehavior of the acquisition and sampling electronics. For both sensor families the mean cluster size, once a threshold of 2.5 times the pixel noise is set, is around 8 pixels. It is worth to remember that the telescope was operated with a moderate cooling aimed to keep the sensors with a temperature ranging from 20 to 22 degrees centigrade.
These very good performance at the sensor level are clear also at the system level and they are supporting the still preliminary evaluation of the tracking efficiency found to be in excess of 99%.

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7.2 Detector plane alignment

The mechanical structure of the telescope was designed to offer a high level of stability of the system and, to a certain extent, also a good plane to plane alignment. No surveys were done to make any preliminary alignment corrections and the final alignment was done using particle tracks. At the CERN test beam, a rather small number of events (few thousands) with very low hit multiplicity (typically 2 tracks per event) was acquired with the explicit purpose of performing a preliminary alignment. With such a low multiplicity, the track finding criteria can be relaxed and then consequently a minimization procedure can be applied to each detector plane but the first one that was taken as a reference. For each detector plane two shifts in the beam orthogonal plane and three rotation angles were determined. Using these alignment constants, the track finding criteria can be made harder and then the minimization procedure can be applied also to data sample with a higher multiplicity statistically improving the results.
The telescope setup at CERN was such that the DUT reserved space in between the two arms was of 34 cm; in this a configuration the alignment was initially performed on the first arm allowing a track fitting over these three planes; the track is consequently extrapolated on the second arm and then the distance between the expected and the measured position is minimized to align also the second arm.
In Table 2 the initial shifts in the beam orthogonal plane are listed for each detector plane along with the corresponding mean values of the residual distribution after the alignment procedure. In

Table 2: Detector shifts before alignment to be compared with the mean value of the residual distribution after the alignment procedure.

Plane	**Before alignment**		**After alignment**	
	x shift [μm]	**y shift [μm]**	**Resi. mean x [μm]**	**Resi. mean y [μm]**
#0	REFERENCE PLANE		-0.23	-0.41
#1	334.7	-395.3	0.26	0.68
#2	438.5	-345.9	-0.05	-0.26
#3	871.5	-547.4	-0.38	-0.04
#4	54.7	-285.9	-0.31	-0.01

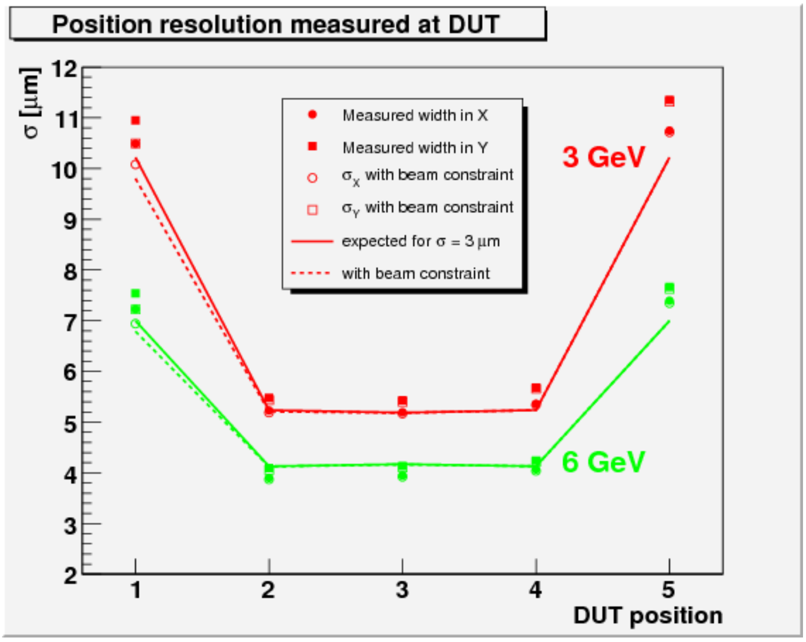

Figure 5: Measured and expected residual distribution widths for different configuration. The number on the x axis represents the position of the sensor plane used as DUT.

the case of high energy pion beam as in the CERN test beam, the alignment procedure was a simple minimization algorithm based on the assumption that the particle trajectory is following a straight line. For the DESY data instead, where electrons with a maximum energy of only 6 GeV are available, the alignment procedure is more complicated and taking into account multiple scattering contribution is required. In this case an iterative procedure was used in which the analytical fitting was repeated several times interactively adding shifting constants to center around zero the residual distribution and varying the detector angles to flatten the residual distribution versus the hit position.

7.3 Spatial resolution studies

Spatial resolution studies have been performed both on the high energy pion data taken at CERN and on the 3 and 6 GeV electron data taken at DESY. While for the former a simple straight line fitting can be used, for the latter a more complicated tracking procedure able to take the multiple scattering contribution in consideration has to be adopted. In both cases, four sensor planes have been used as references and the track is then extra-/inter- polated onto the fifth sensor. In the case of the DESY data all five possible configurations have been studied while for the CERN data only the configuration with the DUT in the center has been considered so far. Figure 5 is a summary plot showing the measured residual distribution widths with 3 and 6 GeV electron beam compared with the expected ones assuming that the reference sensor planes have an intrinsic resolution of 3 μm. A part from the configurations in which either the first or the last sensor is used as a DUT, a measured width around 5 μm and 4 μm is found for 3 and 6 GeV electrons respectively.
For the π^+ data the residual distribution is much narrower because the multiple scattering is neg-

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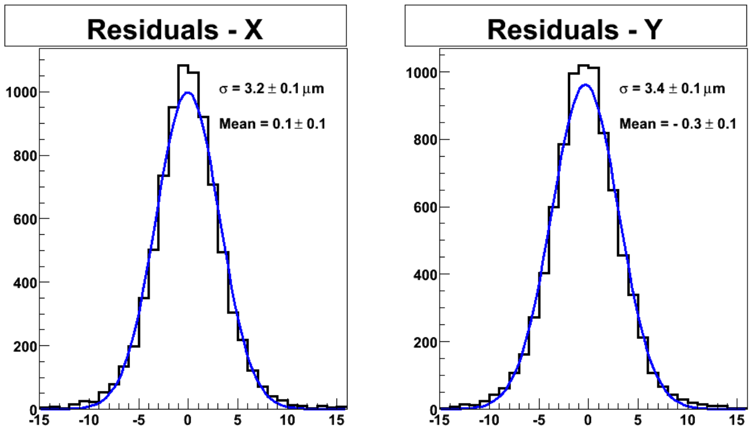

Figure 6: Residual distributions along X and Y for the CERN pion data onto the central plane used as DUT.

ligible as it is shown in Figure 6. In this case the expected fit precision considering the lever arm and the intrinsic plane resolution is around 1.5 μm, proving that the telescope system is working according to the required specifications.

8. Conclusion and Outlook

This paper presented the first test beam results obtained exposing the EUDET pixel telescope in a medium energy electron beam at DESY and in a high energy hadron beam at CERN. The data analysis is still on going but the results already available are very promising and confirming that the system specifications required for the telescope demonstrator can be fulfill. Nevertheless further improvements are possible in particular for what the acquisition rate is concerned and pixel sensor

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