A Pixel Telescope for Detector R&D

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***Abstract*— A high resolution (σ <3 μm) beam telescope based on pixel sensors is being developed within the EUDET collaboration, a coordinated detector R&D programme for a future international linear collider. The telescope will consist of up to six sensor planes and can be operated inside a solenoidal magnetic field of up to 1.2 T. A general purpose cooling, positioning and readout infrastructure will be available. The telescope and the magnet will initially be installed at a 6 GeV electron beam line at DESY in Hamburg. However, the setup will be sufficiently flexible to be moved to higher energy hadron beam lines, for instance at CERN, in the future. Thus the telescope will provide a test environment for a wide variety of pixel-lated sensor technologies, while at the same time acting as a realistic test bed for tracking studies for a vertex detector at a future linear collider. In this presentation the status of the first demonstrator telescope will be summarised. The mechanical concept as well as the DAQ system will be presented.**

***Index Terms*— Silicon Pixel Detectors, ILC, Telescope, Testbeam**

I. Introduction

A 500 GeV electron-positron linear collider is the next great international project in High Energy Physics. The current plan foresees that the machine would have to be approved in 2010 and possibly commence operation not earlier than 2017.

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.

EUDET covers a number of different activities relating to tracking, calorimetry and pixel R&D as well as networking activities which support information exchange. In this presentation only one activity, namely the construction of a pixel beam telescope to be operated initially at the DESYII 6 GeV electron test beam facility, will be discussed. In order to minimise the risk, the construction of the telescope will proceed in two stages. In the first stage (demonstrator telescope) existing CMOS pixel sensors with an analogue readout will be used. Analog-to-digital conversion and signal processing will be realised using fast processors in the readout electronics. This first telescope will not satisfy the final requirements (see section II) with respect to readout speed. But a first test facility will be available quickly to satisfy immediate and urgent test needs of various research groups working on pixel detectors in Europe. The final telescope will be constructed using sensors with fully digital readout and integrated correlated double sampling (CDS) and data sparsification.

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II. 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. 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 $3\ \mu$m at 5 GeV. This is achieved by reducing the amount of material in individual planes while maintaining point precision on the telescope planes of around $2-3\ \mu$m. It is also foreseen to place a high resolution plane ($\sigma \approx 1\ \mu$m) 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 space in between the arms to accommodate TPC or calorimeter prototypes. 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. A minimum size of 20 mm in one lateral dimension is adequate. The second dimension could possibly be smaller. 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.

III. 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

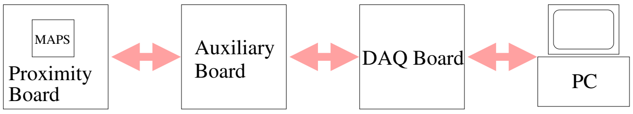

Fig. 1. Schematic layout of the DAQ system.

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.

However, 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 Mimostar3M prototype, developed for the STAR micro-vertex upgrade [5] was chosen for the demonstrator telescope. This chip is designed in the AMS 0.35 OPTO process [6] with an epitaxial layer of 12 μm. The sensor is divided in 4 sub-arrays of 64×256 pixels each. With a pixel pitch of 30×30 μm^2 this results in an active area of 7.7×7.7 mm^2, not fulfilling the final telescope requirements, but suitable for the demonstrator. The sensors are designed to stand more than 10 kGy dose at room temperature. While the chip shows a good signal-to-noise ratio and high point precision, its architecture is simple without integrated data reduction or parallelisation.

The final telescope will be equipped with a follow up of the MIMOSA-16 sensor. This is a translation of the fully characterised Mimosa-8 chip into the AMS 0.35 OPTO radiation tolerant process. 800×800 pixels with 25×25 μm^2 pitch will result in the required active area of 20×20 mm^2. Fully digital readout, CDS and data sparsification will be implemented. Additionally a high resolution sensor will be developed. This is an extension of the Mimosa-8 chip with integrated ADCs. The expected single point resolution is ≤ 2 μm. Both new sensors will be available in early 2008.

IV. DAQ System

A schematic layout of the planned DAQ system is shown in Fig. 1. The sensor is mounted on a PCB which includes digital and analogue signals bufferisation : the Proximity Board. This test board is controlled by the DAQ board which provides digital signals to drive the chip and to acquire analogue outputs. JTAG protocol is generated by software and is interfaced to a PC parallel port.

Sensors are connected to the signal conditioning and digitising module installed on the front end board. An FPGA on the front end board is used to process the digitised data stream from the sensor to achieve common mode suppression and data sparsification. The sparsified data are then transferred, upon reception of a readout trigger signal, over the VME-64x bus, to a PC for event building and archiving.

A. Development of a VME 64x based DAQ Card

The DAQ Card developed by INFN (EUDRB) will consist of:

- One mother board, hosting an ALTERA Cyclone II FPGA and the core resources (SRAMs, FIFOs, VME64x interface, trigger port, diagnostic UART). A 32 bit soft (NIOS II) microcontroller implemented in the Cyclone II FPGA handles tasks like on board diagnostics, on-line calculation of pixel pedestal and noise (not interfering with data taking operations), and remote configuration of the FPGA via RS-232, VME, and USB2.0. The clock rate of the FPGA is 80 MHz (40 MHz for the NIOS II processor), and the clock rate of the A/D converter is up to 20 MHz.
- One analog daughter card with 4 independent signal processing and digitising stages
- One digital daughter card, featuring a standard PCI Mezzanine Card interface to the mother board. It drives/receives control/status signals for the detectors and it features a USB 2.0 link.

The EUDRB also implements the interface to the EUDET trigger bus and a VME64X slave interface capable of 2e-VME transfers (for a peak bandwidth of about 80 to 100 MB/s).

The whole system can run in two readout modes:

- Zero Suppressed readout to minimise the readout deadtime while in normal data taking.
- Non Zero Suppressed readout of multiple frames for debugging or off-line pedestal and noise calculations.

1) Full Frame readout mode:: The card responds to a trigger by sending out all raw pixel data for at least three frames: the frame being acquired at trigger time, the preceding one and the following one, for a total of 6 MB per event. The TRIGGER BUSY is set as soon as the trigger is received and released when data has been transferred to the host PC.

2) Zero Suppressed readout mode:: The card responds to a trigger by sending out a formatted block which includes a header and a trailer identifying the event number and the number of hits. Processing of a trigger in this mode does not stop the scan of the detector and therefore no data are lost due to trigger processing. The trigger processing time is at least one frame time. The TRIGGER BUSY is set as soon as the trigger is received and released when data has been transferred to the host PC.

The boards were delivered end of July 2006 and initial hardware tests were successfully. Testing of the operation of the EUDRB connected to a sensor (e.g. MimioStar) is under way. The EUDRB should be ready for the telescope integration beginning of 2007.

B. DAQ Integration Concept

The main challenge of this telescope is integration of the different DAQs. The typical telescope users will bring their own DAQ and should not need to invest time in rewriting code or reconfiguring the hardware. A "plug-and-play" system would be desirable. Therefore it was decided to use different hardware

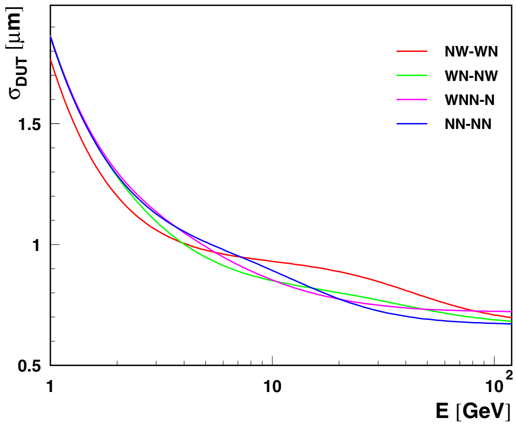

Fig. 2. Precision of particle position determination at DUT plane for different telescope configurations (assuming 6 sensor planes including one high-resolution planes) as a function of beam energy.

and DAQ for the DUT and the reference planes, and to integrate the two systems on the trigger level. Synchronisation will be done with the Trigger, Busy and Reset signals. The Readout Software, DAQ and data storage is provided by the DUT user. The events are then combined offline. The additional hardware in order to combine DUT and telescope is the trigger logic unit (TLU) which receives the trigger and passes it into the telescope and DUT. It vetoes further triggers and records the timestamp. The TLU was developed and tested and is available for the integration.

V. Simulations

In order to find the optimum configuration of the telescope mechanics an analytic method for track fitting with multiple scattering has been developed and verified using GEANT 4 simulation [8].

The best configuration depends on the beam energy, number of telescope planes, as well as sensor and DUT parameters. In all cases, configuration with 6 sensor planes results in better position determination than 4 planes, although significant improvement is obtained only for high energies.

Position resolutions which can be obtained for different telescope configurations, for 6 sensor planes including one high-resolution plane, are compared in Fig. 2, as a function of beam energy. Gaussian position measurement error of $1\mu m$ is assumed for one high-resolution plane placed in front of DUT, whereas for other sensor planes it is 2 μm. Thickness of telescope sensors is 120 μm, whereas for DUT thickness of 500 μm is assumed. For low energies the best performance is obtained in a configuration with two long measurement "arms" (Fig. 3), which allow to constrain the multiple scattering in DUT plane best. Also at highest energies this configuration results in the position resolution which is close to optimal.

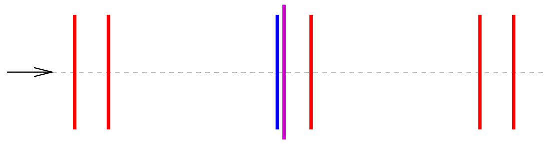

Fig. 3. Configuration NW-WN with two long measurement "arms".

VI. Layout, Mechanics and Cooling

It is foreseen that the beam telescope will be operated in widely varying R&D applications with very different DUTs. Four 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. It is planned to provide up to 6 telescope planes for redundancy and flexibility. For large DUTs mechanical actuation is foreseen in order to move the device through the active area of the telescope.

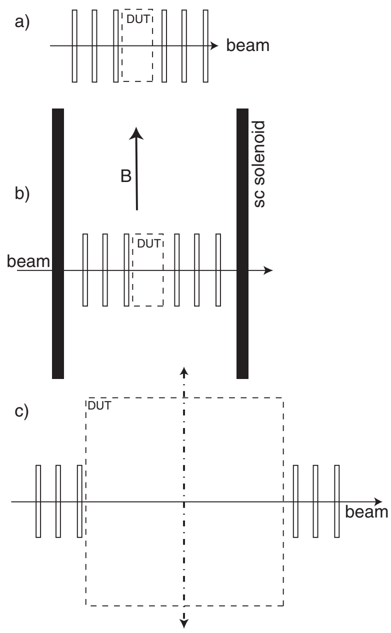

Fig. 4. Three foreseen layouts for the beam telescope; (a) a compact layout for characterisation of high precision devices, (b) a compact layout inside a magnetic field and (c) a two-arm geometry for the use with larger DUTs.

Fig. 4 shows three foreseen layouts for the pixel telescope. Version (a) is very compact and will typically be used for characterising high precision devices. In this configuration one of the telescope planes should be built such that it can be moved very close to the pixel DUT in order to limit the effects of multiple scattering. Layout (b) inside a $1.2\ T$ superconducting solenoid can be used for internal tracking. In this configuration the telescope acts as a small slice of a future vertex detector. Finally, layout (c) will be used with large devices such as TPC and calorimeter prototypes.

In Fig. 5 the mechanical concept is illustrated. Three "boxes"

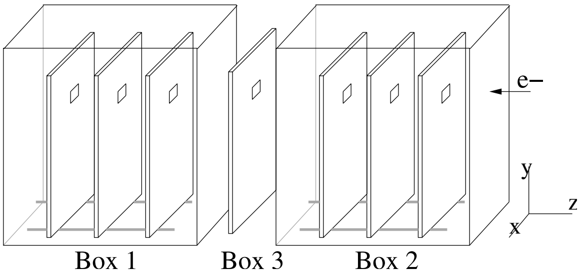

Fig. 5. Mechanical concept with three separate areas for the two reference arms and the DUT.

will be the main part. The box 1 is in a fixed position,an optical bench guides the three reference planes of the arm in front of the DUT. The box is temperature controlled. The wall to the DUT can be removed. The second box is movable in z-direction to ease the installation of the DUT as well as to give the possibility of larger DUT devices. Also here the wall to the DUT side can be removed. The third box is the space between the boxes 1 and 2. A cover over this gap will ensure thermal enclosure. By removing the wall to the DUT, one thermal volume can be built.

The DUT will be positioned on a XYϕ table which is positioned underneath the telescope. The mechanical interface between XYϕ table and DUT needs to be designed by the user. The three boxes with reference planes can be positioned inside the 1.2 T magnet. Due to cost reasons, the positioning with the magnet with a XYϕ table is not foreseen.

VII. CONCLUSION

In this presentation the status of a high resolution beam telescope based on pixel sensors was summarised. This is a project within the EUDET initiative, partially financed by the EU. The chosen sensors for the reference planes were introduced as well as the DAQ concept described. Extensive simulations indicated the best configuration of such a telescope in order to get the highest resolution at different beam energies. A flexible mechanical setup is foreseen to allow for a wide range of DUTs and beam energies. A first version of this high resolution telescope will be available in summer 2007.

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