THE ADENUIM TELESCOPE - A new beam telescope for the DESY II Test Beam Facility

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ABSTRACT: A high-resolution beam telescope is one of the most important and equally demanding infrastructure at any test beam facility. Its main purpose is to provide reference particle tracks from the incoming test beam particles to the test beam users, which allows to measure the performance of the so-called device-under-test (DUT). We present the development of the ADENUIM beam telescope (ALPIDE sensor based DESY Next testbeam Instrument). The ADENUIM beam telescope is equipped with vary number of telescope planes depending on testbeam measurement by users. The telescope planes are framed by plastic scintillators. The coincident signal of all scintillators is used as trigger and distributed to the entire system, including all the telescope planes and any devices under test from test beam users. Both the data acquisition and offline reconstruction software are kept being compatible to the EUDET-style beam telescope. This allows an telescope hardware replacement, without forcing users to migrate their data acquisition system. The biased residual distribution is studied as a function of the beam energy, pixel layers distance and sensor threshold. The measure pointing resolution of reconstructed tracks is better than $6 \mu m$. The design trigger rate is up to 100 kHz. The number of fake hits is negligible after applying an masking of a few defect pixels.
1 Introduction

Due to the high complexity of particle detectors in modern high energy physics experiments, it is crucial to demonstrate and validate performance of the detector during development of the detector prototype. Particle beam lines with a well defined momentum spread, energy and particle rate can be used to study the detector performance. DESY Hamburg operates a test beam facility, DESY II Test Beam Facility [1], with three independent beam lines at the DESY II synchrotron. It is one of the world-wide facilities providing test beams in the GeV range.

A beam telescope is a reference tracker which is used to tag the presence of a particle and reconstruct its trajectory. The measurement of the detector’s characteristics, such as hit efficiency, intrinsic spatial resolution, Lorentz angle and timing resolution can be carried out at test beam line equipped with a reference beam telescope. As part of the main infrastructure equipment for user, the EUDET-style beam telescopes [2] were developed as a precise reference beam telescopes in the last decade, matching the requirements posed by different communities. After serving a growing user community successfully more than ten years, the EUDET-style beam telescopes are going to reach the life time in the next few years and a successor needs to be developed.
A high resolution beam telescope based on the ALPIDE sensors was developed at DESY as an upgrade for current EUDET-style beam telescopes which have served more than ten years as the primary in-beam particle tracker for many groups at various beam lines. The new beam telescope is equipped with six pixel planes using the ALPIDE [3] sensors. The portable design of the readout out electronic and mechanical enables the telescope planes being feasible arranged depending on the testbeam user requirement. A typical setup of this telescope consists of six telescope planes, grouped into two arms, and are framed by plastic scintillators. The coincident signal of all scintillators is used as a trigger and distributed to the entire system, including all the telescope pixel planes and any devices under test from test beam users. Both the data acquisition and offline reconstruction software are kept be compatible to the recent maintained EUDET-style beam telescope. This allows the planned telescope hardware replacement being transparent to all users of EUDET-style beam telescope.

2 DESYII Beam Facility

The DESY II electron/positron synchrotron at the DESY site in Hamburg has a circumference of 292.8 m supplying beam to three test beam areas. Its dipole magnets operate in a sinusoidal ramping mode with a frequency of 12.5 Hz. Therefore, one DESY II cycle takes 80 ms, and the bunch length is around 30 ps. The DESY II synchrotron is equipped with movable carbon fibres. If positioned in the beam, bremsstrahlung photons are created, escaping the beam line tangentially. Subsequently, the photons are converted to electron/positron pairs on a secondary metal target. Their energy distribution reaches up to 6 GeV. Using a dipole magnet, this secondary electron/positron beam is spread out. It offers electron and positron beam with adjustable momenta from 2 to 6 GeV/c. Variable size of collimators can be used to select certain energy ranges of the beams reaching the experimental halls. Each of TB21, TB22 and TB24 beam is recently equipped with a EUDET-style beam telescope which is going to be updated by this presented work. A more detailed description of the test beams at DESY II Test Beam Facility can be found in reference [1].

Figure 1: DESY II Test Beam Facility
3 Telescope Plane

In general, the detector sensor equipped at each telescope plane is required to have high granularity, low material and large sensitive region covering the intersection on way where the beam particles pass. The detector sensor also required to be fine time resolution and high speed readout. To be robust and feasible, the sensor readout of the telescope plane which can be operated standalone is preferred. A few standalone telescope planes, along with independent sensor readout systems, will be grouped as a beam telescope and supervised by the beam telescope DAQ software.

3.1 Detector Sensor Selection

CMOS Image Sensor (CIS) technology was adapted to provide the detector sensor for beam telescope, such as the Mimosa sensor for the EUDET-style telescopes. Over last decade, CIS technology has made impressive progress, and gradually becomes more available and affordable via most advanced commercial foundries. CIS sensor allows detecting minimum ionising particles (MIPs) by collecting the charge liberated when traversing the thin, almost undepleted, epitaxial layer implemented above the wafer substrate. Since MIP generates typically 80 electron-hole pairs per micrometer in the tens micrometer thick epitaxial silicon, the signal charge a few thousand electrons. The CIS sensor offers remarkable performance in terms of intrinsic resolution, material budget and readout electronics. The excellent intrinsic resolution follows from the high granularity achievable, combined with the cluster charge sharing due to thermal diffusion. The low material budget comes from the thin sensitive volume, which enables thinning the sensors down to a few tens of micrometres. The nature of CIS technology enables high density integrated circuit, with a powerful signal processing capability, closed to the sensitive volume.

Table 1: the design specification of Alpide sensor chip [4]

| Parameter               | Specification               |
|-------------------------|-----------------------------|
| Chip size               | 15 mm × 30 mm               |
| Chip thickness          | 50 µm to 100 µm             |
| Pixel pitch             | 26.88 µm × 29.24 µm         |
| Pixel matrix            | 512 × 1024 pixel cell       |
| Detection efficiency    | >99%                        |
| Fake-hit rate           | <10⁻⁶ pixel⁻¹ event⁻¹       |

The Alpide CIS sensor is an excellent candidate with it design specification in table 1 good meeting on requirement of the test beam telescope. Its design was guided for the upgrade of the inner tracker of the ALICE experiment at the CERN Large Hadron Collider where the sensor chip is required to read out Pb-Pb interactions at 100 kHz with detection efficiency above 99 %, fake-hit probability below 10⁻⁵ and a spatial resolution of 5 µm. The Alpide sensor is implemented with 180 nm CIS process and fabricated on substrates with a high resistivity 25 µm p-type epitaxial layer on a p-type substrate. It measures roughly 15 mm × 30 mm and contains a matrix of 512 × 1024
pixels with amplification, shaping, discrimination and three-events-buffering inside each individual pixel covering 26.88 µm × 29.24 µm.

The in-pixel circuit works in global shutter mode, which eliminates the rolling shutter effect. It is a significant improvement comparing to the rolling shutter Mimosa sensor of EUDET-style beam telescopes. Due to the power efficient design of its hit driven on chip circuit and very limited number of beam particle hits to telescope planes, the heat generation is negligible. The passive cooling is sufficient and extremely reduces the complexity of the mechanical design.

3.2 Telescope Plane Readout

A telescope plane only contains a single sensor, even though the sensor is slightly smaller than the maximum collimator window of the DESY II beam line, which is up to 20 mm × 20 mm. Therefore, the telescope plane readout is equivalent to the single sensor readout. The development of sensor readout is the main task of this beam telescope project. It is involved with the development of front-end electronic hardware, firmware and software.

The beam telescope is designed to be a disturbed readout system on Ethernet network. Equipping with its own sensor readout, each telescope plane runs as independent network node. Therefore, the beam telescope is basically a duplicated of a few telescope planes with its own standalone readout. The number of telescope planes can vary depending the final beam telescope settings. It simplifies the readout electronic and speed-ups the development project. No dedicated hardware component is required as a center control node. The front-end electronic forms the full readout electronic to operate a telescope plane.

Three components form the front-end electronic: a sensor carrier board, a main readout board and a small passive bridge board. The sensor carrier board is offered by ALICE ITk upgrade community. Reusing the same sensor carrier board helps to speed-up the front-end electronic design. The sensor chip is glued and wire bonded onto the carrier board. PCB material, overlapping the sensor’s sensitive region, was removed during the PCB fabrication to minimize the material budget for the beam particle. The main readout board is custom-mode at USTC, carrying a Xilinx Kintex-7 field-programmable gate array (FPGA) chip as the core component [5]. The main board offers a dedicated Mezzanine Card (FMC) connector for detector sensor and optical fiber SFP connector for Ethernet connection. A bridge board is designed, with FMC and PCIe connectors at each end, to bridge between the main readout board and sensor carrier board. The bridge board optionally accepts external trigger thought HDMI interface.

Configured by a custom firmware, the FPGA operates the sensor chip and runs the server as node on Ethernet, via IP/TCP. Power and clock signal are provided by main readout board to sensor and bridge board. During the earlier phase of the telescope development, a simple DAQ software is implement to the validate the functionality of telescope plane readout. Written in C++, it is basic network capable software working above the POSIX sockets API. It later services as underlying software library for the telescope DAQ software which supervises all telescope planes.

3.3 Telescope Plane Assembly

A telescope plane consists of a detector sensor, front-end electronic and housing mechanical jig. The sensor carrier board is fixed on an aluminium jig which has window to avoid the overlap on
the sensor. The Kapton polyimide film, 25 um thickness, covers the both window from both sides to protect it from dust. The jig is able to be clip mount on a support telescope rail. An aluminium frame, fitting the main board, prevents the mechanical bending and the electronic connection broken. After the assembly, the telescope plane becomes a solid piece and feasible to mount in preferred arrangements by the user decision. Due to very limited heat deposition, mainly from the FPGA, the cooling is just passive.

4 Telescope Integration

The beam telescope is integrated with grouped planes, trigger system and telescope supervised DAQ software. When a user DUT (Device Under Test) detector to be measured is present, the DUT also needs to be integrated, either fully or partly, with the beam telescope.

4.1 Plane Arrangement

The identical support mechanics as for EUDET-style telescope is used. There are two telescope rails along the particle beam direction. The telescope planes can be grouped into either dual arms, i.e. a upstream and a downstream arm, or a single arm, as shown in Figure 3. In principle, the number of telescope planes in one telescope arm is subject to no restriction.

Typically, the dual arms grouping can deliver particle trajectories with better spatial resolution under the assumption that the DUT does not introduce significant multiple scattering to the particles
due to the presence of its material. In particular, if the DUT is a scintillator-based calorimeter
detector, a downstream arm becomes meaningless because the Electromagnetic process of the
particle with the detector can generate bunches of secondary particles. Therefore, a single upstream
arm with more telescope planes is recommended in such case.

![Diagram](image)

Figure 3: Telescope planes grouped into (a) dual arms (b) single arm. The DUT (gray box) can
be mounted on a high precision $xy\phi$-stage table (not shown here) for the dual arms grouping, and
a large $xy$-stage table (not showed here) for the single arm grouping. Assuming the beam (red
line with arrow) is coming from the right-handed side, the telescope planes are numbered with
consecutive integers starting from 0 from right to left. The distances between the planes (green
lines with arrows) are denoted by $D$

Both arms are adjustable in the beam direction to ease the installation of the DUT as well as
to enable the usage of possibly large DUT. A DUT cooling box with a thickness up to 40 cm can
be installed. A high precision $xy\phi$-stage table consisting of a vertical, a horizontal, and a rotation
stage can be used to move the DUT through the active area of the telescope. The telescope planes
are guided on a rail. The rail for each arm allows for a distance of up to 1.3 m between the two
outermost planes. A photograph of the setup of the telescope installed at DESY test beam is shown
in Figure 4.

4.2 Trigger Sharing

An AIDA2020 TLU [6] (Trigger Logic Unit) together with variable pieces of scintillator-PMT
(Photo Multiplier Tube) modules serves as a global trigger device for the full telescope system. The
TLU has 4 channels to power the PMT and accept its signal caused by a particle hit on scintillator.
To decide on a valid trigger according to the scintillator-PMT modules, the TLU can be configured
from the software side to coincide a specific set of the PMT signals. There are in total 4 trigger-out
channels, which can be configured to 4 different modes. The so-called AIDA-mode-with-id, used
for the beam telescope, sends trigger pulse, clock, and trigger number via HDMI. The trigger can
be vetoed when busy signal is asserted. Typically, to measure the DUT sitting in between the
upstream and downstream arms, scintillator-PMT modules are installed in front of the upstream
arm and behind of the downstream arm with 2 pieces of scintillator-PMT modules at each position
to suppress the PMT noise.
4.3 DAQ Software and Data Processing

The EUDAQ [7] software is a data acquisition framework, written in C++, and designed to be modular and cross-platform. It was written primarily to run the EUDET-style beam telescopes. Since the EUDAQ software framework is widely used by testbeam users of EUDET-style beam telescopes, the new telescope software is able to be integrated into EUDAQ. A so-called Producer, by definition of EUDAQ specification, is implemented for the telescope. The Producer is basically a client to all telescope planes, via IP/TCP. Running as one of EUDAQ network components, the Producer will be operated by remote EUDAQ control node incorporating with other EUDAQ components located in the same network. The data processing, status monitoring and data saving are handled by EUDAQ software in its own manner. According to EUDAQ specification, a so-called DataConverter is also implemented. The DataConverter, as a plugin route by the EUDAQ software, helps to converter the telescope to EUDAQ standard format as well as LCIO format [8].

To process and analysis the telescope data offline, the telescope data can be converted to LCIO format which then allows for analysing the data using the EUTELESCOPE package [9].

The telescope DAQ software has a built-in particle trajectory tracking route based on a combinatorial Kalman Filter tracking algorithm developed by ACTS project [10]. The built-in tracking
route can be enabled at data-taking time to process telescope data directly after arrival of the full data belonging to the same trigger. The reconstructed particle trajectories can stored in the same file along with original telescope readout. Meanwhile, the telescope DAQ software has built-in 3D graphic window to visualise the reconstructed trajectories at real-time. Figure 5 presents two reconstructed trajectories which belong to a single trigger when beam energy is set at 2.0 GeV with a high electron rate.

4.4 Integration with User Detector

The principle of the testbeam beam telescope operation is to measure the same beam particle by both the DUT and the beam telescope simultaneously. The DUT should receive the same trigger signals and trigger sequence ID numbers (TLUID) as those received by the beam telescope. It allows for data synchronization based on the trigger sequence numbers.

With one trigger channel occupied by the telescope, the AIDA2020 TLU offers extra 3 triggers channel to DUTs to inform the arrival of a particle. The physical interface must comply with the specification of AIDA2020 TLU. The trigger with its TLUID is send to DUT, and the DUT hardware should be able to extract the TLUID from the trigger lanes and tag its detector data with that number. In case that the DUT also provides its own trigger signal, the AIDA2020 TLU is also capable to accept it and evaluate it together with scintillator signal to generate an eventual trigger.

It is thoroughly upon to the telescope user, either integrating DUT’s DAQ software into EUDAQ software framework or simply running the DUT’s DAQ in a standalone manner. If integrated, the EUDAQ control node offers single operation panel to configure, start and stop the telescope and DUT simultaneously, and the data from both telescope and DUT stream can be synchronized in the same data file.

5 Performance Studies

A bunch of measurements were made to verify the functionality of the telescope and characterization its performance with and without the presence of beam electrons. This section presents results of a series of studies with the telescope planes placed as in Figure 3, i.e. the hit efficiency and cluster size of individual telescope planes are studied with the dual arm setup of the telescope, whereas the DUT is also a telescope plane, and the track extrapolation precision of the telescope is studied with the single arm setup. Note that all sensors are currently configured with identical settings, which can be further optimized with sensor-wise settings.

5.1 Timing and Trigger Rate

While the TLU is capable to trigger at a rate up to 10 MHz, which offers a fine-grained time stamp with 1.56 ns timing resolution, the sensor chip has the dominant impact on the trigger rate of the full telescope system. The analogy front-end in-pixel circuit has a typical peak-up time at about 10 us. This means the next particle coming within the last peak-up time will be non-distinguishable by the same pixel. The DESY II beam is far from reaching an luminosity resulting in double hits in the same pixel within 10 us. However, since all pixels in the same sensor chip is clocked and sampled at the same pace, trigger rate is again limited to 100 kHz due to the analogy circuit’s peak-up time. At DESY II testbeam, a maximum trigger rate of 40 kHz is observed by the scintillator-PMT module
without additional veto. Therefore, the telescope is not considered to be the bottleneck to limit the testbeam measurement speed for any potential DUT.

5.2 Noise and Hit Efficiency

Due to inconsistency of silicon chip manufacture, the sensor chips and its pixels could have slightly different noise levels among each other even if identical configuration is applied. A pixel scoring route is adapted. It issues a million TLU self-triggers to all telescope planes for pixel sampling when test beam is off. Ignoring the negligible environment radiation, the noise occupancy of all individual pixels can be measured by counting the fired pixels. Pixels are categorized depending on the noise occupancy (Table 2). The DAQ software can then take the categorized pixel lists which are part of configuration file to disable the grade B and grade C pixels which are more noisy than others.

| Grade | Noise Occupancy | Plane #0 | Plane #1 | Plane #2 | Plane #3 | Plane #4 | Plane #5 |
|-------|-----------------|---------|---------|---------|---------|---------|---------|
| A     | \(< 10^{-6}\)   | -       | -       | -       | -       | -       | -       |
| B     | \(10^{-6} < N < 10^{-3}\) | 0.022% | 0.002% | 0.008% | 0.024% | 0.029% | 0.011% |
| C     | \(> 10^{-3}\)    | 0.003% | 0.000% | 0.001% | 0.003% | 0.004% | 0.001% |

The hit efficiency is also measured. For this purpose, particle trajectories traversing multiple telescope planes are reconstructed from the telescope data. When a particle is not detected by a telescope plane, the reconstructed trajectory does not contain a fired cluster at its expected intersection with the plane. The effect of multiple scattering is taken into account when matching the hit to the trajectory. The detection efficiency of different telescope planes is shown in Table 3. The slightly lower efficiencies at lower electron energy could be due to a broader kink angle distribution which is not fully covered by the hit matching window.

| Beam energy | Plane #0 | Plane #1 | Plane #2 | Plane #3 | Plane #4 | Plane #5 |
|-------------|---------|---------|---------|---------|---------|---------|
| efficiency @5.6 GeV | 0.99916 | 0.99762 | 0.99865 | 0.99978 | 0.99916 | 0.99489 |
| efficiency @2.0 GeV  | 0.99900 | 0.99556 | 0.99817 | 0.99945 | 0.99836 | 0.98792 |

5.3 Hit Cluster

Due to the effect of charge sharing, neighbour pixels could response to a single particle hit at the same time. The number of pixels belonging to a hit cluster, i.e. cluster size, mainly depends on the particle incident angle as well as its position in a pixel.
Figure 6: The percentage of clusters with different cluster size (denoted by the stacked histograms) at different telescope planes. The mean cluster size is 2.71, 2.56, 2.61, 2.99, 2.81, 2.86 and 2.91 pixels at the seven telescope planes, respectively.

For single pixel cluster, the intrinsic resolution of the sensor is estimated to be 7.76 um and 8.44 um in the x and y dimension, respectively, using the formula: $d/\sqrt{12}$, where $d$ is the sensor pixel pitch at each dimension. For cluster with multiple hits, the incident position can be evaluated by the weighted center of all pixel positions.

The charge sharing can improve the sensor intrinsic resolution beyond $d/\sqrt{12}$. The Figure 6 presents the percentage of clusters with different cluster size at each telescope plane. The mean cluster size is 2.78 pixels per cluster and varies within 0.22 among different sensors. It can be optimized and adjusted to equivalent value, via on-sensor register configuration such as sensor global threshold.

5.4 Track Extrapolation Precision

With properly aligned detector geometry, the built-in analysis route of the DAQ software in the standalone mode is able to reconstruct the particle trajectories on-the-fly, and also predict intersections of the trajectories with the DUT planes through track extrapolation.

The extrapolated position of a track reconstructed using measurements on the telescope planes to the DUT plane can be compared to the measured hit position. Figure 7 shows the distributions of residual, i.e. the difference between the measured hit position and the extrapolated track position on the local plane of the detector plane in the $x$ and $y$ direction, for a sample of 500 k electrons at 5.6 GeV with the telescope setup as Figure 3a. The track extrapolation precision could be estimated from the width of the residual distributions. Two Gaussian fits to the residuals give rise to $\sigma = 5.87 \pm 0.01 \ \mu m$ and $\sigma = 5.74 \pm 0.01 \ \mu m$ in the $x$ and $y$ dimension of the DUT plane, respectively.
The dependency of the track extrapolation precision on both the beam energy and placement of the telescope planes is shown in Figure 8, where the Figure 8a and Figure 8b show the results with the dual arms setup and single arm setup, respectively. It’s observed that the track extrapolation precision gets better when the beam energy increases. This is in agreement with the expectation considering that higher beam energy results in less multiple scattering. The dependency of the track extrapolation precision on the distances between the telescope planes can be observed as well, i.e. smaller distances between the planes result in better precision on the DUT. This is considered to be a result of the fact that shorter track extrapolation path means not only less material effects but also smaller transportation covariance between the planes.

Figure 7: Distributions of residual in the (a)\(x\) and (b)\(y\) dimension of the DUT plane for a sample of 500k electrons at 5.6 GeV. The six telescope planes with additional telescope plane taken as the DUT are grouped as Figure 3a, where the distances between the planes are \(D_{10} = D_{21} = D_{43} = D_{54} = D_{12} = D_{13} = 38\ m\). The black dots are data, and the red (blue) lines are Gaussian fits to the data.

(a) \(x\) direction (pixel pitch is 29.24 um)  
(b) \(y\) direction (pixel pitch is 26.88 um)

(a) Dual arms. Telescope planes are grouped as Figure 3a where the distances among the planes are measured \(D_{10} = D_{21} = D_{43} = D_{54} = 38\ mm\) and \(D_{12} = D_{13} = D_{32}/2\)  
(b) Single arm. Telescope planes are grouped as Figure 3b where the distances among the planes are measured \(D_{10} = D_{21} = D_{32} = 38\ mm\).

Figure 8: Resolution of point prediction. An extra telescope plane is added as DUT.
6 Summary

A high resolution telescope, as upgrade and compatible replacement of old EUDET-style telescope, is developed and tested. It reaches track spatial resolution better than 6 \(\mu\text{m}\) with trigger rate up to 100 kHz. The existing EUDET-style telescope users can switch to new telescope transparently without additional effort. The compact readout electronics allows more feasible arrange of telescope planes. The telescope design, include the senor readout electronic, DAQ software and data analysis software, is also a basic framework and reference design for beam telescope equipped with other detector sensors.

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