

2 **ADENIUM - A demonstrator for a next-generation beam**
3 **telescope at DESY**

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12 **ABSTRACT:** High-resolution beam telescopes for charged particle tracking are one of the most
13 important and equally demanding infrastructure items at test beam facilities. The main purpose of
14 beam telescopes is to provide precise reference track information of beam particles to measure the
15 performance of a device under test (DUT). In this report the development of the ADENIUM beam
16 telescope (ALPIDE sensor based DESY Next test beam Instrument) as a demonstrator and prototype
17 for a next-generation beam telescope is presented. The ADENIUM beam telescope features up to
18 six pixelated reference planes framed by plastic scintillators for triggering. ADENIUM is capable
19 of replacing the currently used EUDET-type beam telescopes without impacting existing DUT
20 implementations due to the integration of the telescope DAQ into EUDAQ2.

21 In this report the concept and design of the ADENIUM telescope as well as its performance
22 are discussed. The telescope's pointing resolution is determined in different configurations. For an
23 optimal setup at an momentum of 5.6 GeV with an ALPIDE as DUT, a resolution better than 3 μm
24 has been extracted. No rate limitations have been observed at the DESY II test beam.

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42 **1**

Introduction

43 Due to the high complexity of detectors for modern particle physics experiments, it is crucial to
44 demonstrate and validate their performance during all steps of the development and commissioning.
45 Test beams with a well defined momentum and particle rate can be used to study the detector
46 performance. DESY Hamburg operates the DESY II Test Beam Facility [1] with three independent
47 beam lines at the DESY II synchrotron. It is one of the few facilities providing test beams in the
48 GeV range worldwide.

49 A beam telescope is a reference tracking system to reconstruct particle trajectories. It enables
50 measurements of detector characteristics, such as hit detection efficiency and intrinsic spatial
51 resolution at test beam lines. The EUDET-style beam telescopes [2] have served as precise
52 reference beam telescopes at the DESY II Test Beam Facility for more than ten years. They consist
53 of six telescope planes, grouped into two arms, which are framed by plastic scintillators to generate
54 a trigger signal. A trigger-logic-unit [3] distributes this trigger signal to the telescope and user
55 devices. The mechanical support for the telescope is optimized to be easily adjustable for detectors
56 of different sizes. The EUDET-style beam telescopes are about to reach their end of life and a
57 successor is needed.

58 The ADENIUM telescope is a key step towards the development of the next generation beam
59 telescope. It features a modular and modern DAQ system and is based on ALPIDE [4] sensors,
60 which have been identified as best suited currently available sensors. ADENIUM can be used
61 interchangeably with EUDET-style telescopes without impacting existing device integration. In
62 this report an overview of the ADENIUM telescope implementation is given and its performance
63 at the DESY II Test Beam Facility is discussed.

64 **2 The DESY II Test Beam Facility**

65 DESY operates a test beam facility at the DESY II synchrotron with three beam lines for detector
66 testing purposes as outlined above. The DESY II synchrotron operates in a sinusoidal ramping
67 mode with a frequency of 12.5 Hz. A single electron bunch with a length of 30 ps hits a thin
68 carbon fibre serving as primary target in the beam and generates Bremsstrahlung photons. They are
69 converted back into electron-positron pairs on a metal plate (secondary target). The particles pass
70 a momentum selecting magnet and are delivered to the test beam areas. Users can chose momenta
71 between 1 and 6 GeV and the particle polarity.

72 Each of the three test beam areas is equipped with a EUDET-style beam telescope. A more
73 detailed description of the DESY II Test Beam Facility can be found in reference [1].

74 **3 ADENIUM Telescope Overview**

75 The ADENIUM beam telescope consists of six ALPIDE planes that are selected for their good
76 spatial resolution and low material to allow precise particle tracking at low momenta particle beams
77 such as the DESY II electron beam. ADENIUM has to be capable of processing particle rates of a
78 few 10 kHz to match the DESY II test beam rates.

79 **3.1 Sensor**

80 Monolithic Active Pixel Sensors (MAPS) are ideal for high resolution tracking telescopes at low
81 momentum beam lines. Mimosa26 sensors [5, 6] had been chosen for the EUDET-style telescopes,
82 since they provide an excellent intrinsic resolution that stems from the fine pixel pitch of 18.4 μm ,
83 combined with diffusion based charge collection in an up to 20 μm thick epitaxial layer. Removal
84 of the inactive silicon minimizes the amount of material the particle has to pass.

85 As the long term availability of the Mimosa26 is not clear, the highly available ALPIDE
86 sensor [7] is chosen for the ADENIUM telescope. The ALPIDE sensor is implemented in an
87 180 nm CIS process and fabricated on wafers with a 25 μm thick high resistivity p-type epitaxial
88 layer on a p-type substrate. Table 1) compares the main parameters of the two sensors. ALPIDE has
89 a slightly larger pitch, but offers a larger active area as well as significantly shorter readout times.

90 Additionally, the power-efficient design of the chip results in a negligible heat generation,
91 allowing for passive cooling, which reduces the complexity of the mechanical design significantly
92 compared to the existing MIMOSA26 planes.

Table 1: Main parameters of the Mimosa26 [5, 6] and ALPIDE sensor [7].

	Mimosa 26	ALPIDE
Chip size	21.2 mm \times 10.6 mm	15 mm \times 30 mm
Chip thickness	50 μ m to 70 μ m	50 μ m to 100 μ m
Pixel pitch	18.4 μ m \times 18.4 μ m	26.88 μ m \times 29.24 μ m
Pixel matrix	1152 \times 576	512 \times 1024
Detection efficiency	>99 %	>99 %
Fake-hit rate	$\sim 10^{-6}$ pixel $^{-1}$ event $^{-1}$	$< 10^{-6}$ pixel $^{-1}$ event $^{-1}$
Typical frame readout time	115.2 μ s	10 μ s

3.2 Telescope Plane

Each telescope plane can be operated standalone as an independent network node, maximizing the system flexibility. An ADENIUM reference plane, compare Figure 1, consists of three hardware components: the sensor carrier board, the main readout board and a small passive bridge board:

- The **main readout board** is custom-made at USTC. It features a Xilinx Kintex-7 field-programmable gate array (FPGA) chip as the core component [8] running a custom firmware to operate the chip and run a server on an ethernet network node. In addition, an optical SFP interface is provided. The connection to the sensor carrier board is realized via a dedicated Mezzanine Card (FMC) connector. Power and clock signals for the chip are provided by the main readout board to the sensor over the bridge board.
- 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 provides an optional interface with the AIDA-2020 Trigger Logic Unit (TLU) [9] via an HDMI connector.
- The **sensor carrier board** is provided by the ALICE collaboration [4], with the sensor chip glued and wire bonded to it. Below the sensor the PCB has an opening to minimise the material to reduce multiple scattering when particles pass through the sensor. Besides the mechanical support for the sensor, the board provides passive electronics for powering, noise reduction and signal coupling.

3.3 DAQ Software and Data Processing

The telescope DAQ is realized as a client to all connected telescope planes communicating over a TCP/IP-based interface. The data flow is summarized in Figure 2: the telescope DAQ receives data from all planes, synchronizes it by trigger ID and performs hit clustering.

A EUDAQ2 [10] component, called Producer, provides the interface between the telescope and EUDAQ2. EUDAQ2 globally controls all components and logs the data flow including the telescope. Detector synchronization on hardware level is realised with the AIDA-2020 trigger-logic-unit [9]. The central Run Control of EUDAQ2, with an optional graphical user interface, is

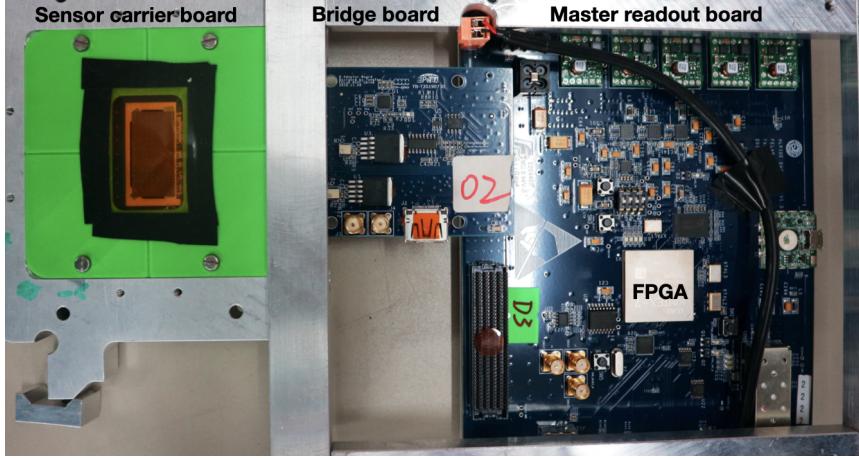


Figure 1: An assembled readout electronic of a telescope plane showing sensor carrier board, bridge board and main readout board.

119 able to control the telescope and start/stop its readout via standardized commands processed by the
 120 Producer. In this concept the reference planes of the telescope are treated the same way as any
 121 device under test (DUT) [11].

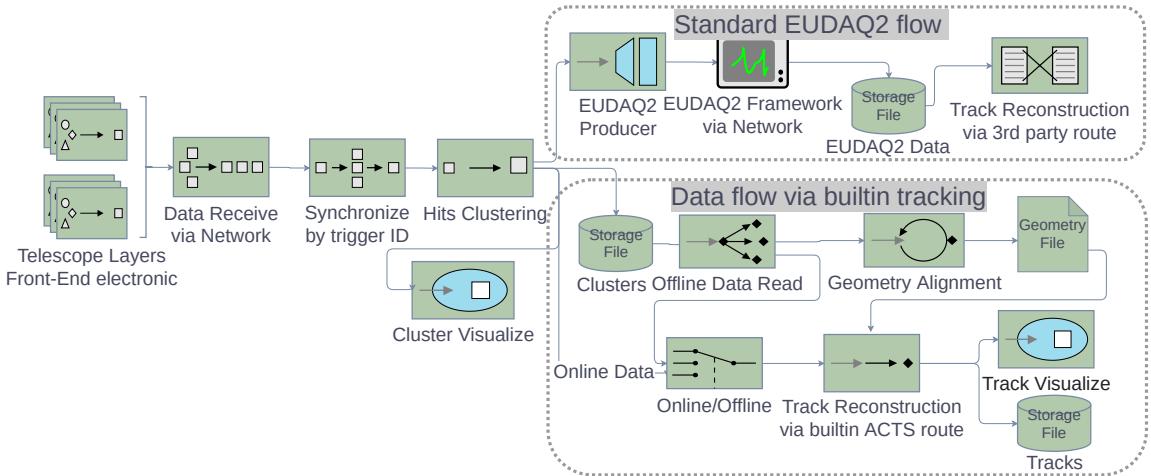


Figure 2: The data flow in ADENIUM from the individual sensor planes to the user analysis.

122 According to EUDAQ2 specification, a so-called **DataConverter** is implemented. A **DataConverter**
 123 plugin in EUDAQ@ converts the raw ADENIUM telescope data to a EUDAQ2 native format or
 124 the LCIO format [12]. Either the built-in tracking discussed below or third party software, like
 125 the **CORRYVRECKAN** package [13] or the **EUTELESCOPE** package [14] can be used for the particle
 126 trajectory reconstruction.

127 **3.3.1 Trigger Implementation**

128 An AIDA-2020 Trigger Logic Unit (TLU) [9] serves as a global trigger distribution system for all
129 connected devices. A trigger itself is usually generated by a set of scintillator-PMT modules when
130 a particle passes them. ADENIUM uses the *AIDA-mode-with-id*. In this mode the TLU sends a
131 trigger, a 40 MHz clock, and a trigger ID via an HDMI cable. A busy from the telescope vetos
132 potential additional triggers during readout.

133 **3.4 Telescope Mechanics**

134 The telescope mechanics reuses the support structure of the EUDET-type telescopes. Rails for
135 mounting the sensor planes are arranged in two arms parallel to the beam axis (see Figure 3). This
136 design allows for maximum flexibility when integrating user setups. Placing DUTs in the center
137 of the telescope yields the best pointing resolution as the particle trajectories are confined on both
138 sides.

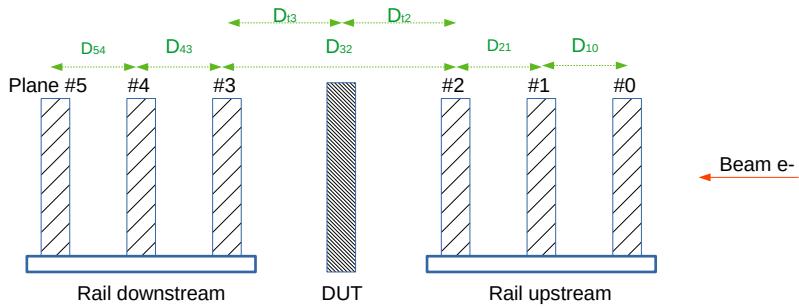


Figure 3: Typical arrangement of the ADENIUM Telescope planes. The beam direction (red line with arrow) is from right to left and the DUT is indicated as a grey box. The telescope planes are numbered with consecutive numbers starting from 0 from right to left. The distances between the planes (green lines with arrows) are denoted by D_{ij} .

139 The distance between the two arms is adjustable and can measure up to 50 cm allowing for
140 larger scale DUT setups. The two outermost telescope layers can span a distance of 1.3 m maximum.
141 A high precision $xy\phi$ -stage table can move the DUT and adjust its position with respect to the active
142 area of ADENIUM. A photograph of the telescope installed at the DESY II Test Beam Facility is
143 shown in Figure 4.

144 The sensor carrier board is fixed on an aluminium jig with a cutout that minimises the amount
145 of material in the beam. The openings are covered by 25 μm thin polyimide sheets on both
146 sides to protect the sensor from dust. This jig is fastened on the EUDET-style rail system. The
147 main board is mounted at the top of the jig to an aluminium aluminium frame. Each plane
148 can be moved independently on the rails allowing for a flexible layer arrangement. No active
149 cooling is implemented in this mechanical support as the overall heat dissipation of the sensor as
150 well as the adjacent electronics is relatively low. The power consumption of ALPIDE is below
151 40 mW/cm² [15]. Passive cooling through the jig is sufficient to maintain reasonable temperatures
152 during operation.

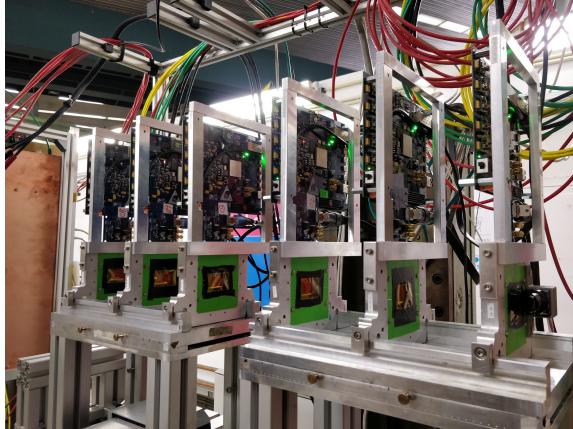


Figure 4: The ADENIUM telescope installed at the DESY II Test Beam Facility

153 3.5 Integration and synchronization of user detectors

154 Correlating the reference trajectories from the telescope with data from DUTs is an essential part of
 155 test beam measurements. Hence, it has to be ensured that the telescope and DUT data streams are
 156 synchronized. The AIDA-2020 TLU takes care of this on hardware level by sending a global trigger
 157 signal, typically generated by a scintillator coincidence, to all connected detectors. Up to four
 158 detectors can be connected to a single AIDA-2020 TLU. One channel is occupied by ADENIUM,
 159 leaving three free slots for user devices. The physical interface must comply with the specification
 160 of the AIDA-2020 TLU [16]. Alongside the trigger signal, the AIDA-2020 TLU sends a trigger ID,
 161 which gets included in the telescope data stream. By including it also in the DUT's data stream the
 162 synchronisation gets more robust. The data from both telescope and DUT can be stored in the same
 163 file, optionally already sorted by trigger ID. In addition to the scintillator-based trigger detectors
 164 installed by default, user devices can also trigger the AIDA-2020 TLU. It features six trigger inputs
 165 with configurable coincidence logic generating the global trigger signal. A precise timestamp of
 166 the trigger is recorded by the TLU and can be added to the data stream.

167 An optional full integration of the user device in EUDAQ2 allows for synchronized configuring,
 168 starting and stopping of the telescope's and DUT's DAQs. Data can be saved in the EUDAQ2
 169 native data format, where an event package is the fundamental storage structure, which contains
 170 the trigger ID, timestamp, telescope data, and DUT hit data belonging to a single trigger. The
 171 size of an event package per trigger varies and depends on the telescope's occupancy and the DUT
 172 data defined by the user. Typically, at the DESY II Test Beam Facility less than three clusters are
 173 recorded per telescope plane and trigger. In this case, without a DUT, the size of the event package
 174 is about 1 kByte.

175 3.6 Built-in Track Reconstruction Module

176 The ADENIUM DAQ software features built-in track reconstruction based on a combinatorial
 177 Kalman Filter (CKF) tracking algorithm developed as a part of the ACTS project [17]. The latter
 178 provides a toolkit for track reconstruction in a generic, framework- and experiment-independent
 179 software package. The fast CKF algorithm of the built-in tracking module can run online and offline

180 (see Section 4). In online mode each trigger event is processed instantaneously. The offline mode
181 can be used with a refined software alignment of the telescope planes.

182 Since multiple beam particles could potentially pass through the telescope in the same trigger
183 window, the CKF algorithm is configured to take all clusters in the first telescope plane as seed
184 of potential track candidates. For each seed, the CKF algorithm performs the forward track
185 propagation into the next telescope plane. Clusters in the following telescope plane are scored using
186 the predicted χ^2 obtained by comparing the Kalman filter prediction and the measured cluster center
187 with the resolution of the cluster taken into account [18]. The cluster with the highest score within
188 a search window is added to the track. The track parameters are then updated for next forward
189 track propagation. The CKF algorithm is tolerant to imperfect trajectory with missing clusters,
190 due to either sensor inefficiency or that the trajectory is partially outside of the sensitive region
191 (misalignment). A backward track parameter smoothing performed afterwards to further improve
192 the precision. The reconstructed particle trajectories can be stored in the same file alongside the
193 original telescope pixel hit and cluster data. The telescope DAQ software has built-in 3D graphic
194 window, implemented using OpenGL, to visualise the reconstructed trajectories in real-time. The
195 graphical display shows only the last reconstructed event. Figure 5 shows two reconstructed
196 trajectories which belongs to a single trigger with a beam energy of 2.0 GeV and high beam rate.

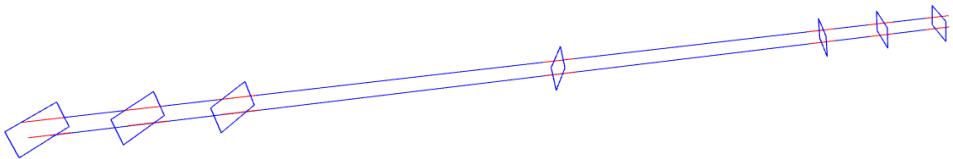


Figure 5: A 3D visualization of reconstructed double trajectories belonging to a single trigger (beam energy at 2.0 GeV) by the DAQ software. The blue rectangles are the sensitive areas of the telescope. The red segmented lines crossing the sensitive areas denote the measured hit clusters by the telescope planes. The telescope planes are placed as in Figure 3 where the distances between the planes are $D_{10} = D_{21} = D_{43} = D_{54} = 38 \text{ mm}$ and $D_{t2} = D_{t3} = D_{32}/2 = 150 \text{ mm}$.

197 To not deteriorate the precision of the reconstructed tracks, the geometry of the telescope, i.e. the
198 position and orientation of the telescope planes, must be precisely known. The built-in tracking
199 module provides tools to perform a track based alignment using the MILLEPIDE-II [19] package,
200 which can significantly improve the precision of the telescope geometry after several iterative runs.
201 For the time being, the alignment procedure is standalone and supposed to be executed prior to the
202 track reconstruction. The generated geometry file with misalignment corrected is then fed into the
203 online track reconstruction.

204 4 Performance Studies

205 A series of measurements was performed to verify the functionality of the ADENIUM telescope and
206 to characterize its performance in terms of timing and rate capability, noise, hit detection efficiency,
207 cluster sizes and pointing resolution. The telescope arrangement shown in Figure 3 was used. Note

208 that all sensors are currently configured with identical settings, hence the results can be further
 209 optimized with sensor-specific settings.

210 4.1 Timing and Trigger Rate

211 While the TLU is capable to trigger up to a rate of 10MHz and provides a precise time stamp
 212 with 781 ps binning, the overall trigger rate of the telescope is limited by its sensors. Their analog
 213 circuit has a peaking time of about 2 μ s [20]. A readout time of ca. 10 μ s is chosen accordingly to
 214 ensure that the hit that corresponds to the trigger is read out. Therefore, the maximum processable
 215 trigger rate is about 100 kHz - far more than can be achieved with the DESY II test beams. At the
 216 DESY II Test Beam Facility a maximum trigger rate of 40 kHz was measured and no rate dependent
 217 limitations of ADENIUM were observed. Note that multiple hits can be recorded per trigger and
 218 the telescope is not able to resolve them in time, since no on-chip time stamping is provided. Such
 219 ambiguities can be resolved by incorporating one additional tracking plane consisting of a detector
 220 with high spatial and time resolution.

221 4.2 Noise and Hit Detection Efficiency

222 Due to variations in CMOS processes, the sensors have slightly different noise levels at identical
 223 configurations. A pixel scoring approach has been used to classify the pixel quality.

Table 2: The fraction of pixels per plane belonging to the three noise-occupancy categories

Grade	Noise Occupancy	Plane #0	Plane #1	Plane #2	Plane #3	Plane #4	Plane #5
A	$< 10^{-6}$	99.975%	99.998%	99.991%	99.973%	99.967%	99.988%
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%

224 With the beam turned off, the TLU issues a million triggers to all telescope planes to sample
 225 all pixels. Ignoring the negligible impact of the natural background, the noise occupancy of all
 226 individual pixels can be measured by counting the noise hits per pixel. Pixels are then categorized
 227 depending on their noise occupancy (see Table 2). The grade B and grade C pixels can be added
 228 to a configuration file to disable them.

Table 3: The hit efficiencies for each telescope plane at two beam energies

Energy	Plane #0	Plane #1	Plane #2	Plane #3	Plane #4	Plane #5
5.6 GeV	(99.92 \pm 0.01)%	(99.76 \pm 0.02)%	(99.87 \pm 0.01)%	(99.98 \pm 0.00)%	(99.92 \pm 0.01)%	(99.48 \pm 0.02)%
2.0 GeV	(99.90 \pm 0.01)%	(99.56 \pm 0.02)%	(99.82 \pm 0.02)%	(99.95 \pm 0.01)%	(99.84 \pm 0.01)%	(98.79 \pm 0.04)%

229 The hit detection efficiency is measured using the ratio of reconstructed tracks with no hit
 230 on the plane under test to all reconstructed tracks. "No hit" is defined here as no cluster being

231 found with the distance less than 0.5 mm to the expected intersection of the track, taking the effect
 232 of multiple scattering into account when matching the hit to the tracks. The hit efficiency of the
 233 different telescope planes is shown in Table 3.

234 4.3 Hit Cluster

235 Due to charge sharing, several neighbouring pixels may respond to a single particle hit at the same
 236 time. The number of pixels belonging to a hit cluster, i.e. the cluster size, depends on the incident
 237 angle of the particle as well as its hit position within the pixel.

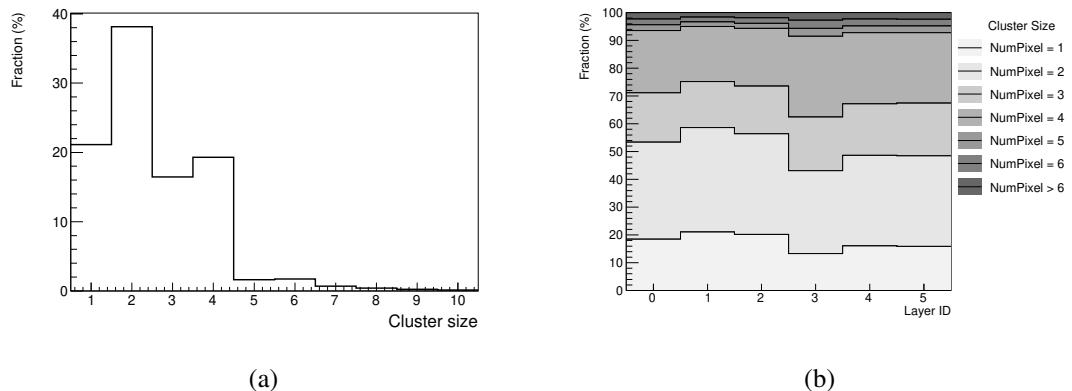


Figure 6: (a) Fraction of cluster sizes for one telescope plane (layer ID = 1). (b) Fraction of clusters with sizes 1 to 6 for the six telescope planes. The mean cluster sizes for the individual planes are 2.71, 2.56, 2.61, 2.99, 2.81, and 2.86.

238 For single-pixel clusters, the intrinsic resolution of the sensor can be estimated as $7.76\text{ }\mu\text{m}$ and
 239 $8.44\text{ }\mu\text{m}$ in the x and y dimension, respectively, using the formula: $d/\sqrt{12}$, where d is the pixel
 240 pitch. Charge sharing can improve this resolution when the cluster center is used as the measured
 241 hit position. Figure 6b shows the percentage of clusters with different sizes for each telescope plane.
 242 The mean cluster size is 2.78 pixels per cluster and varies within 0.22 among different sensors. This
 243 can be further optimized and adjusted to a uniform value for all sensors, e.g. via the comparator
 244 thresholds.

245 The average cluster size of all sensors is independent of beam energies ranging from 2.0 GeV
 246 to 5.6 GeV, hence the intrinsic resolution at the DESY II beam lines is constant, as expected.

247 4.4 Track Interpolation

248 With a properly aligned detector geometry, the built-in analysis module of the DAQ software
 249 (see Section 3.6) in the stand-alone mode is able to reconstruct the particle trajectories and their
 250 intersection points with DUT planes online. At each propagation step of the CKF algorithm, the
 251 predicted χ^2 is expected to follow a distribution with two degrees of freedom for the each telescope
 252 plane. A cut of 13.816 is imposed on the predicted χ^2 when the clusters are associated to the track
 253 in the CKF algorithm. This corresponds to accepting hits steaming from the correct particle with
 254 a probability of 99.9%. The interpolated position of a reconstructed track on the DUT plane can
 255 be compared to the measured DUT hit. Figure 7 shows these distributions of unbiased residuals,

256 i.e. excluding the DUT hits from the track fit, for a sample of 500k electrons at 5.6 GeV with the
 257 telescope setup as shown in Figure 5. Two Gaussian fits to the unbiased residuals show a width
 258 of $\sigma = 5.87 \pm 0.01 \mu\text{m}$ and $\sigma = 5.74 \pm 0.01 \mu\text{m}$ in the x and y dimension of the DUT plane,
 259 respectively.

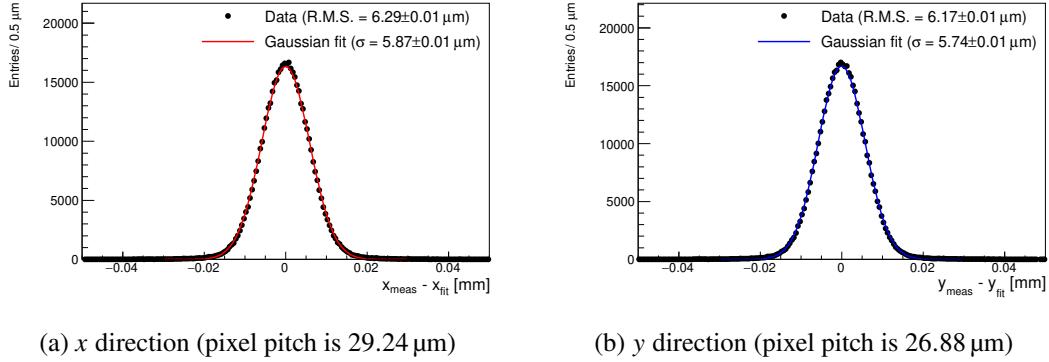


Figure 7: Distributions of residual in the (a) x and (b) y dimension of the DUT plane for a sample of 500k electrons at 5.6 GeV. The six telescope planes with additional telescope plane taken as the DUT are grouped as shown in Figure 3, where the distances (D_{ij}) between the planes are $D_{10} = D_{21} = D_{43} = D_{54} = D_{t2} = D_{t3} = 38 \text{ mm}$. The black dots are data, and the red (blue) lines are Gaussian fits to the data

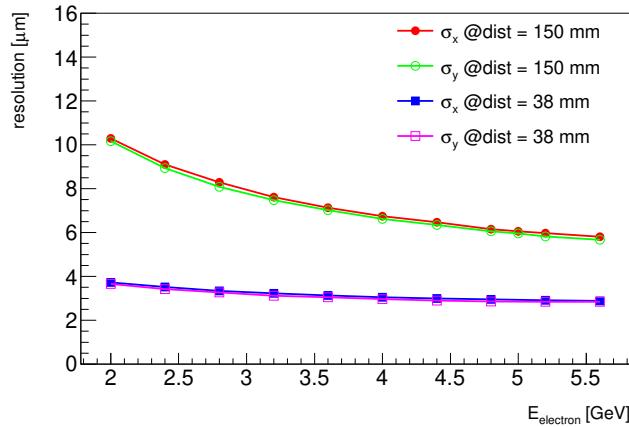


Figure 8: Resolution of the telescope at an additional telescope plane acting as DUT with distances between the planes of $D_{10} = D_{21} = D_{43} = D_{54} = 38 \text{ mm}$ and $D_{t2} = D_{t3} = D_{32}/2$. The different markers represent different distances to the innermost telescope planes (D_{t2}, D_{t3}). The slight difference in resolution along x/y is due to the difference in pixel pitch.

260 The resolution of the telescope for different spacing as a function of the momentum is shown
 261 in Figure 8. As expected, the resolution improves with increasing momentum since the impact
 262 of multiple scattering is reduced. The dependency of the tracking precision on the distances

263 between telescope planes can be seen as well, i.e. smaller distances between the planes result in
264 a higher precision on the DUT. This can be explained by less air that has to be passed as well as
265 smaller uncertainties on the propagation. In the optimal setup, a resolution of $\sigma_x = 2.89 \mu\text{m}$ and
266 $\sigma_y = 2.84 \mu\text{m}$ at 5.6 GeV could be determined.

267 5 Summary and Outlook

268 A demonstrator of a high resolution telescope, as upgrade and drop-in replacement of the EUDET-
269 style telescopes, was developed and tested. It reaches pointing resolution below 3 μm and shows no
270 performance limitations at the maximum trigger rates that can be reached at the DESY II test beams
271 (ca. 40 kHz). It is compatible with the existing EUDET-style infrastructure, so users can switch
272 to the new telescope easily without additional integration effort. The compact readout electronics
273 allow a flexible arrangement of the telescope planes. The demonstrated performance justifies the
274 choice of the sensor and the DAQ layout. An upgrade of all EUDET-style pixel beam telescopes
275 in the near future will be based on the presented system. The next development for a long-term
276 version of the ADENIUM telescope is on-going. A more compact readout electronic based on a
277 Xilinx Zynq SOC has been designed and manufactured. It will allow the implementation of more
278 advanced features including running the DAQ software on the front-end Zynq SOC itself.

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288 References

- 289 [1] R. Diener et al., *The DESY II Test Beam Facility*, *Nucl. Instrum. Meth.* **A922** (2019) 265.
- 290 [2] H. Jansen et al., *Performance of the EUDET-type beam telescopes*, *Eur. Phys. J. Tech. Instr.* **3** (2016) 7.
- 292 [3] D. Cussans, *Description of the JRA1 Trigger Logic Unit (TLU)*, v0.2c, *EUDET-MEMO 2009-04* (2009) .
- 294 [4] ALICE collaboration, *The ALPIDE pixel sensor chip for the upgrade of the ALICE Inner Tracking* System, *Nucl. Instrum. Meth.* **A845** (2017) 583.
- 296 [5] J. Baudot, G. Bertolone, A. Brogna, G. Claus, C. Colledani, Y. Degerli et al., *First test results of* MIMOSA-26, *a fast CMOS sensor with integrated zero suppression and digitized output*, in *Nuclear Science Symposium Conference Record (NSS/MIC)*, 2009 IEEE, pp. 1169–1173, Oct, 2009, DOI.

299 [6] C. Hu-Guo et al., *First reticule size MAPS with digital output and integrated zero suppression for the*
 300 *EUDET-JRA1 beam telescope*, *Nucl. Instrum. Methods Phys. Rev. A* **623** (2010) 480.

301 [7] ALICE collaboration, *ALPIDE: the Monolithic Active Pixel Sensor for the ALICE ITS upgrade*,
 302 *Nuovo Cimento C* **41** (2018) 91. 3 p.

303 [8] C. Yang, C. Feng, J. Liu, Y. Teng, S. Liu, Q. An et al., *A prototype readout system for the alpide pixel*
 304 *sensor*, *IEEE Transactions on Nuclear Science* **66** (2019) 1088.

305 [9] P. Baesso, D. Cussans and J. Goldstein, *The AIDA-2020 TLU: a flexible trigger logic unit for test*
 306 *beam facilities*, *Journal of Instrumentation* **14** (2019) P09019.

307 [10] Y. Liu, M. Amjad, P. Baesso, D. Cussans, J. Dreyling-Eschweiler, R. Ete et al., *EUDAQ2—a flexible*
 308 *data acquisition software framework for common test beams*, *Journal of Instrumentation* **14** (2019)
 309 P10033.

310 [11] P. Ahlborg et al., *EUDAQ—a data acquisition software framework for common beam telescopes*, *JINST*
 311 **15** (2020) P01038 [[1909.13725](https://arxiv.org/abs/1909.13725)].

312 [12] F. Gaede, T. Behnke, N. Graf and T. Johnson, *LCIO: A Persistency framework for linear collider*
 313 *simulation studies*, *eConf* **C0303241** (2003) TUKT001 [[physics/0306114](https://arxiv.org/abs/physics/0306114)].

314 [13] D. Dannheim et al., *Corryvreckan: A Modular 4D Track Reconstruction and Analysis Software for*
 315 *Test Beam Data*, *JINST* **16** (2021) P03008 [[2011.12730](https://arxiv.org/abs/2011.12730)].

316 [14] T. Bisanz, H. Jansen, J.-H. Arling, A. Bulgheroni, J. Dreyling-Eschweiler, T. Eichhorn et al.,
 317 *EUTelescope: A modular reconstruction framework for beam telescope data*, *Journal of*
 318 *Instrumentation* **15** (2020) P09020.

319 [15] M. Mager, *Alpide, the monolithic active pixel sensor for the alice its upgrade*, *Nuclear Instruments*
 320 *and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated*
 321 *Equipment* **824** (2016) 434.

322 [16] AIDA2020 project homepage, “Aida2020: Advanced european infrastructures for detectors at
 323 accelerators.” <http://aida2020.web.cern.ch/>.

324 [17] X. Ai, C. Allaire, N. Calace, A. Czirkos, I. Ene, M. Elsing et al., *A common tracking software project*,
 325 2021.

326 [18] R. Frühwirth, *Application of Kalman filtering to track and vertex fitting*, *Nucl. Instrum. Meth.* **A262**
 327 (1987) 444.

328 [19] V. Blobel, *Software alignment for tracking detectors*, *Nucl. Instrum. Meth. A* **566** (2006) 5.

329 [20] G. Aglieri Rinella, *The alpide pixel sensor chip for the upgrade of the alice inner tracking system*,
 330 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers,*
 331 *Detectors and Associated Equipment* **845** (2017) 583.