Full Length Article

TELEPIX2: Full scale fast region of interest trigger and timing for the EUDET-style telescopes at the DESY II test beam facility

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ARTICLE INFO

ABSTRACT

With increasing demands by future and current upgrades of particle physics experiments on rate capabilities and time resolution, the requirements on test beams are also increasing. The current infrastructure at the DESY II TEST BEAM facility includes particle tracking telescopes with long integration times, no additional timing but excellent spatial resolution. This results in readouts with multiple particles per trigger, causing ambiguities in tracking and assigning particles to triggers. Also, it is likely not to trigger on particles that pass through a small device under test, leading to inefficient data taking. These issues can be solved by adding TELEPIX2 as a timing and flexible region of interest trigger layer. TELEPIX2 is a full scale HV-CMOS chip based on the successful small scale prototype TELEPIX. The DAQ system and the sensor's performance featuring efficiencies above 99 % and a time resolution of 3.844(2) ns are presented. The integration into EUDAQ2 and the AIDA-TLU to seamlessly work in the test beam environment as well as into the analysis chain is described. First successful use cases are highlighted to conclude that TELEPIX2 is a well-suited timing and trigger layer for test beams.

1. Introduction

Developing new detectors for particle physics experiments is crucial for improving the understanding of fundamental forces and interactions. Characterization of novel detectors under conditions as close as possible to the final experiment can be done at test beams, where minimum ionizing particles are provided for tests. Precise reference systems – so-called beam telescopes – are used to tag the spatial and temporal presence of a particle. DESY hosts a test beam facility [1] at the DESY II accelerator with three independent beamlines of which two are equipped with EUDET-style beam telescopes [2], based on MIMOSA-26 sensors [3,4] with an active area of approximately $2 \times 1\,\mathrm{cm}^2$. Copies of these telescopes can also be found at CERN. These telescopes have an integration time of up to $230\,\mu\mathrm{s}$, no time-stamping and are read out in externally triggered rolling shutter mode. The telescope is fully integrated with EUDAQ2 [5] and the AIDA-TLU [6], allowing users to integrate devices under test (DUT) with minimal effort.

Under typical operation conditions, up to 6 electrons pass through the telescope in a single readout frame. This causes ambiguities in track reconstruction. In addition, it is likely not to trigger the particle passing through potentially small DUTs, which results in inefficient data taking. A pixelated timing layer with a configurable trigger region resolves both issues by assigning a timestamp to each particle passing through the telescope and only triggering the telescope readout if the selected region is hit. Previously used hybrid approaches [7] have reduced timing capabilities, are operated in 40 MHz LHC-like readouts and add significant material. The time resolution of a suitable layer has to be below $1\,\mu\mathrm{s}$ to be able to discriminate particles coming from different circulations of the primary beam and below 5 ns to provide insight into the timing for LHC like detectors. The active area should correspond to the telescope's active area. TELEPIX2 is the successor of a small-scale

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Fig. 1. Schematic diagram of TelePix2.

Fig. 2. Schematic drawing of the in-pixel functionality.
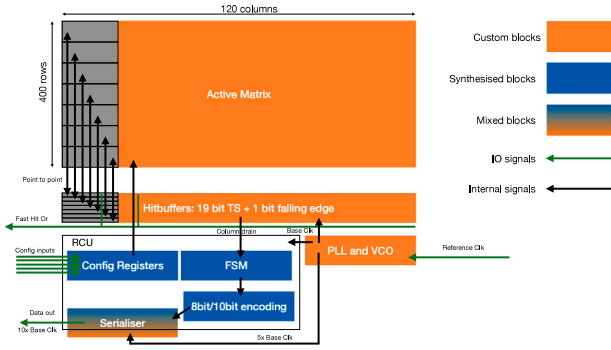
prototype TELEPIX [8], that has already fulfilled all requirements except for the size.

2. TELEPIX2

TELEPIX2 is a system-on-chip pixel detector produced in a $180\,\text{nm}$ HV-CMOS process and is based on the developments within the Mu3e and ATLAS context [9,10]. It has an active area of $2 \times 1\,\text{cm}^2$ to match the active area of the MIMOSA-26 chips. The matrix consists of 120×400 pixels with a pitch of $165 \times 25\,\mu\text{m}^2$. The chip consists of repeated columns, where one column has 400 pixels, point-to-point connected to 400 hit digitizers, and an end-of-column multiplexer. Each pixel can store a 20-bit time stamp as well as a 10-bit time-over-threshold. A layout of the chip is sketched in Fig. 1.

Hit data is streamed zero-suppressed via a differential link to the readout system typically running at $1.25\,\text{Gbit/s}$. The chip periphery additionally hosts a readout control unit, a clock generator based on a phase-locked loop, configuration registers, DACs and IO pads.

TELEPIX2 is implemented on a p-type Czochralski substrate with resistivity in the range $200 - 400\,\Omega\text{cm}$ instead of the standard wafer to enhance the depleted region and hence charge collection.

A pixel diode is formed by a deep n-well implant which is reversely biased towards the substrate. The pixel is designed to have a breakdown voltage of about 120 V. The used technology offers 7 metal layers, with a thick top metal layer used for the distribution of power and time-critical signals. The active pixel matrix extends to three die borders making the chip three-side abuttable.

All configuration register cells are triple redundant and followed by majority logic making it tolerant to single-bit flips caused by ionization (single-event upset). The cells have an auto-refresh feature to allow for the automated repair of single-event upsets. These registers store settings for the DACs that generate bias-, threshold-, baseline- and injection voltages.

Pixel cell

The main parts of the active pixel cell are the sensor diode — implemented as a large fill factor n-well electrode, the AC-coupled charge sensitive amplifier (CSA) and the comparator. The negative signal charge is collected by the n-well and amplified by an inverting CSA. No pixel reset is required since the feedback capacitor (p+ diffusion to n-well capacitance of the node AmpOut in Fig. 2) of the amplifier is continuously discharged. The comparator compares the positive amplifier output signal to a threshold, which is fine-tunable via a 3-bit differential current-steering DAC. The DAC value is stored in three in-pixel SRAM cells. The comparator output signals are transmitted to the hit digitizers at the bottom of the chip using long signal lines.

An additional test signal circuit allows the injection of a defined charge into the n-well by discharging a metal–metal capacitor enabling
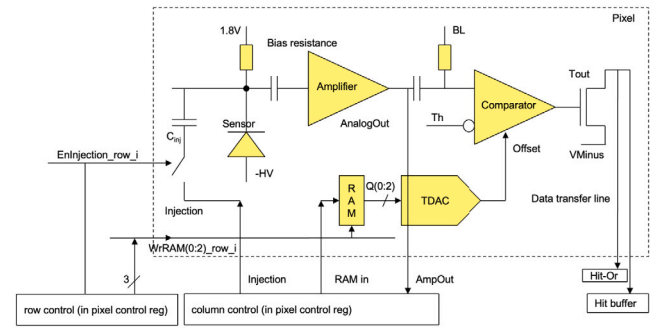
electrical tests without ionizing particles. It is produced at the chip periphery, its amplitude can be varied by an on-chip DAC with 8 bits. The test signal is distributed to all pixels but can be enabled/disabled per pixel. The block diagram of the pixel is shown in Fig. 2.

Hit digitization

The in-pixel discriminator signal is transmitted to the hit digitizers, where the rising edge is sampled with a 19-bit Gray counter running at the rising reference clock (typically $125\,\text{MHz}$) edge together with a falling clock edge 1-bit counter, allowing for time stamping with twice the clock speed. An additional 10-bit time stamp samples the threshold crossing of the falling signal edge to determine the time-over-threshold. Additionally, the address of the hit is generated. The layout of the hit digitizer is full custom and has an area of $165 \times 4.2\,\mu\text{m}^2$.

Digital periphery

The readout process is governed by a synthesized readout control unit (RCU) which comprises configuration registers, the readout state machine, an 8b10b encoder and the first stages of a data serializer realized in a binary tree structure. The final stage of the serializer is implemented in custom electronics and allows to send out the data at nominally $1.25\,\text{GBit/s}$, sending out a bit on the rising and falling edge of the fast base clock. This fully custom part, which also provides clocking, is implemented using differential current mode logic (DCL) instead of CMOS logic. TELEPIX2 has a clock generator based on a ring oscillator and a phase-locked loop (PLL). The PLL receives an externally generated reference clock and generates a 5 times faster base clock from which all other required clock signals are derived. The RCU timing is verified up to a reference clock speed of 160 MHz.

2.1. Data acquisition system

The data acquisition system is based on the Heidelberg HV-MAPS laboratory and test beam DAQ system [11,12]. TELEPIX2 is glued and wire-bonded to a carrier PCB with power filtering, see Fig. 3. The chipboard connects directly to a power supply providing low voltage to operate the chip with. Additionally, it connects to a generic motherboard, which hosts an LVDS repeater to enhance the quality of the differential data stream over a longer cable to the readout FPGA, that is connected via PCIe to the readout computer. Data is transferred via direct memory access to the PC's RAM and further processed in the DAQ software: Data is decoded and packed into a frame structure and stored on disk. A fraction of data blocks is forwarded to a monitoring system. The DAQ is steered with a Qt-based graphical user interface (GUI), which is described in [13].
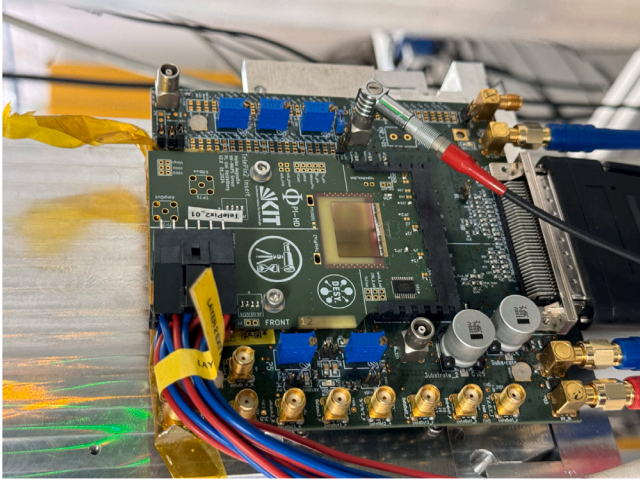
Fig. 3. Photograph of the TELEPIX2 chipboard, mounted to the motherboard. The red Lemo cable connects the fast hit-or, the Molex connector powers the chip, and the SCSI-III cable connects to the readout FPGA.
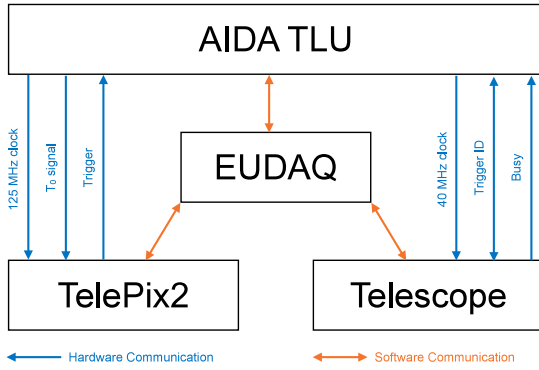

Fig. 4. Typical test beam setup. TELEPIX2 connects to a DUT interface of the AIDA-TLU and receives a 125 MHz clock and T_0 at run start while providing a trigger output. The MIMOSA telescope operates in the EUDET mode to exchange the trigger ID, while ADENIUM [14] runs in AIDA+trigger ID mode. EUDAQ2 is used to steer the data taking. External DUTs are not shown.

3. Telescope integration

Data taking setup

To integrate TELEPIX2 with beam telescopes at the DESY II TEST BEAM facility, it must interface with the AIDA-TLU and be integrated with the EUDAQ2 framework. The latter is achieved via a custom Producer that can be activated via the systems' GUI. Since the data is directly stored on disk, no additional data collectors are required in EUDAQ2. Synchronization with the telescope is realized in the synchronous AIDA mode [6], where the AIDA-TLU provides a 125 MHz clock to the TELEPIX2 DAQ, which is forwarded to the chip. At run start a T_0 signal is sent to TELEPIX2 which resets all internal counters. This allows for fully synchronous data-taking without additional interactions between the TLU and TELEPIX2. The telescopes at DESY exchange a trigger ID with the AIDA-TLU, which stores the timestamp for each trigger. The fast Hit-OR with a rising leading edge, an amplitude of approximately $1.2\,\mathrm{V}$ and a signal length corresponding to the time-over-threshold can be directly fed into a trigger input of the AIDA-TLU. A sketch of a typical test beam setup is shown in Fig. 4.
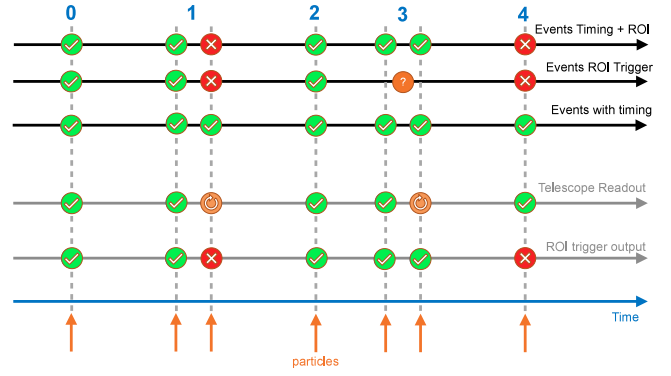

Fig. 5. Sketch of the event building with a timing and/or trigger plane. Green check marks indicate correctly assigned particles, red crosses wrongly assigned track time stamps or events that will be rejected, orange question marks ambiguities and the orange loading symbol indicates that a second particle hit is read out in the telescope's frame.

Event building with TELEPIX2

TELEPIX2 can be used as a region of interest (ROI) trigger or timing plane or both simultaneously. Depending on the usage, the event building, illustrated in Fig. 5, works as follows:

- **Region of interest trigger:** No additional timestamp information is provided; therefore, only the AIDA-TLU timestamp can be used. In this case, it is essential to record only a single particle per event in the region of interest. An example of a failure of this is shown in event 3 in Fig. 5.
- **Timing plane:** TELEPIX2 is used as a timing plane, assigning a time stamp to each hit. This causes efficient suppression of ambiguities but can result in unnecessary triggering, like for event 4 in Fig. 5.
- **ROI trigger and timing plane:** In this mode, the full potential of TELEPIX2 is being exploited. Particles outside the ROI will not trigger a telescope readout and hence increase data-taking efficiency. If two particles cross the ROI in one event, the time tagging will allow for correct assignment of these tracks.

For user convenience, a custom corryvreckan [15] EVENTLOADER is provided to access data for reconstruction. Three exemplary user stories highlighting each of the possible use cases are shown in Section 5.

4. Results

During a test beam campaign at DESY a single TELEPIX2 has been studied in detail using a $4\,\mathrm{GeV}$ electron beam as a compromise between particle rate and scattering in the telescope. Data recorded is used to study the key performance figures efficiency and time resolution of the full matrix and the timing of the fast Hit-OR. Analysis has been carried out with corryvreckan. ADENIUM [14], an ALPIDE based telescope provided by DESY has been used as a particle tracking reference system. Since no additional timing plane has been present during data taking with ADENIUM, all TELEPIX2 hits within the integration time of the reference telescope are accepted for spatial matching. A conservative elliptical cut of $495 \times 75\,\mathrm{\mu m^2}$ is applied to assign clusters to tracks. All presented studies have been performed with a single set of configuration DACs and a supply voltage of $1.8\,\mathrm{V}$, corresponding to the nominal operating voltage of the process, unless otherwise stated. The chip has been operated without pixel trimming.

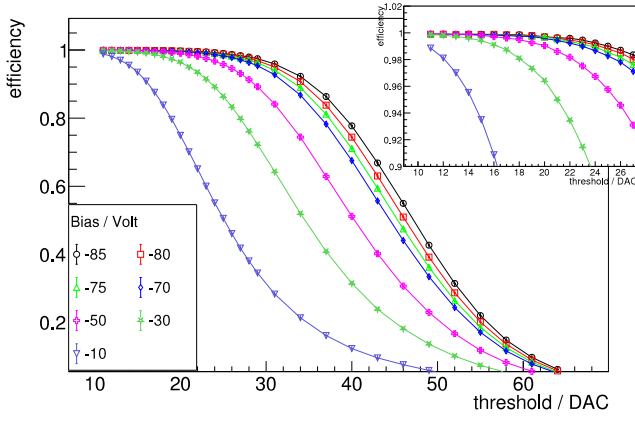**Fig. 6.** Efficiency as a function of the threshold for different bias voltages. Statistical error bars are too small to be seen.
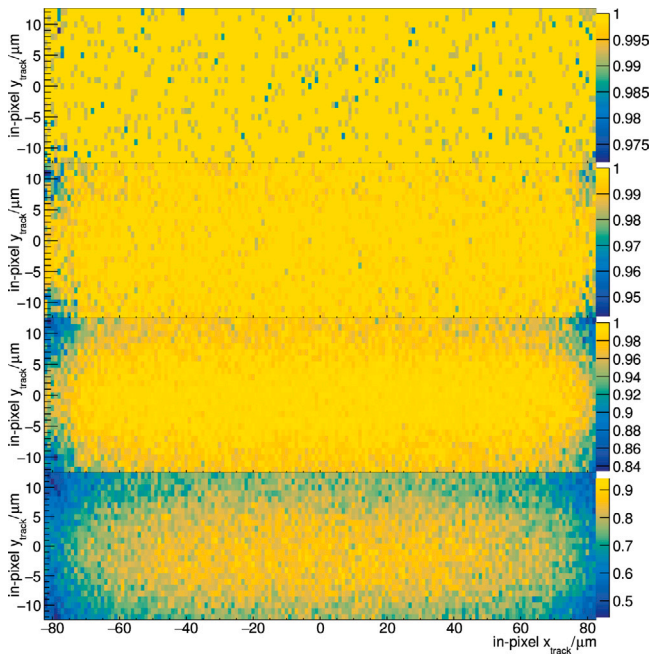

Fig. 7. In pixel efficiency of TᴇʟᴇPɪx2 at a bias of −85 V. Thresholds from top to bottom: 16, 21, 28, 40. Please note the change in the z-scale.

Hit detection efficiency

The hit detection efficiency is determined as the ratio between the number of reconstructed tracks with an assigned TᴇʟᴇPɪx2 cluster over the total number of tracks intersecting the chip. The hit detection efficiency for different bias voltages is summarized in Fig. 6.

As expected, higher bias increases the threshold range in which the chip can be operated efficiently. The improvement is less dominant at higher bias voltages as the expected growth in active depleted thickness scales with $\sqrt{HV}$. At low thresholds, the hit detection is homogeneous over the pixel area and no position-dependent effects are visible. With increasing threshold, the efficiency reduces in the corners first, at the edges second and finally all over the pixel as depicted in Fig. 7. The initial reduction is explained by charge sharing between up to four pixels in the corners and two at the edges.

Time resolution

The time resolution is determined relative to a trigger scintillator sampled with a 781.25 ps timestamp by the AIDA-TLU. Only clusters
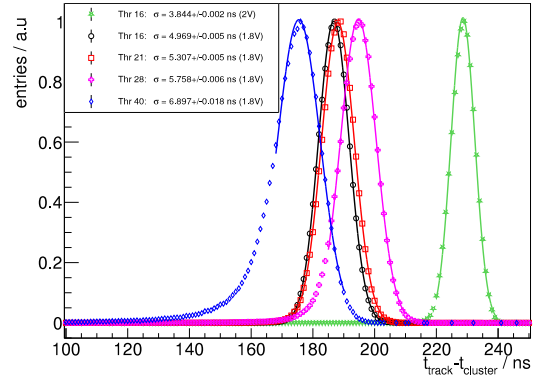

Fig. 8. Time difference between reference trigger and TᴇʟᴇPɪx2 cluster time.
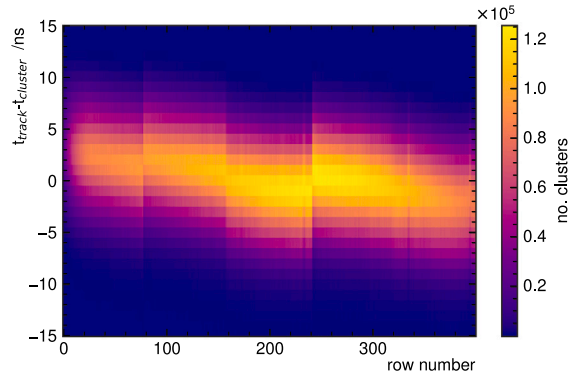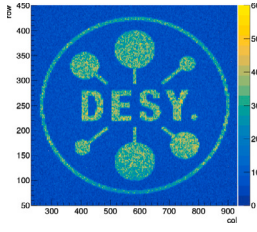

Fig. 9. Time difference between reference trigger and TᴇʟᴇPɪx2 cluster time versus the row number.

assigned to a track are used, while the cluster time stamp is defined by the pixel timestamp with the largest ToT in a cluster. The time resolution of the complete sensor is shown in Fig. 8 for different detection thresholds. A Gaussian fit to the core of the distribution leads to a σ of 3.844(2) ns at a detection threshold of 16 and a supply voltage of 2 V.[1] This is unprecedented for a large area chip in this technology and well within the specifications for a timing layer for the DESY II ᴛᴇsᴛ ʙᴇᴀᴍ. Data taken at the default 1.8 V supply voltage show systematically worse timing performance. At threshold 16 a σ of 4.970(5) ns is determined at a larger absolute delay. With increasing threshold, the time resolution is worsening as expected due to the increased impact of time walk. At lower thresholds, better time resolution is expected at the price of increased noise, which is likely not desired if operated as reference sensors and is currently under investigation. Studying the row dependency of the time residuals, compare Fig. 9, two effects are observed: Firstly, four sharp cuts are visible. These cuts correspond to rows where changes in the metal layers for signal routing occur, which results in different capacitance. Secondly, the small slope might be caused by longer transmission lines or voltage drops. Correction for these effects and time-walk is a work in progress and will be presented elsewhere.

Region of interest triggering

The region of interest trigger mode has been evaluated with a supply voltage of 2 V. The possibility of selecting an arbitrary pixel arrangement is showcased by only enabling the fast Hit-OR for pixels

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[1] No impact on long term operation has been observed so far and a small voltage drop over the chip board is expected.

(a) Hitmap of a telescope plane with TELEPIX2 as trigger. A DESY logo is programmed to the fast Hit-OR.
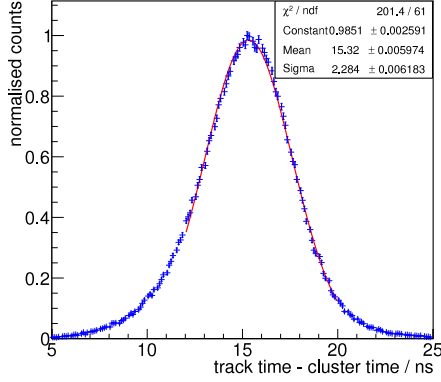
(b) Time difference between reference trigger and TELEPIX2 hit-or at a threshold of 16.

Fig. 10. The fast Hit-OR of TELEPIX2.

(a) Spatial correlations of H2M with (red) and without (blue) TELEPIX2 region of interest trigger along x.

(b) Temporal correlations between TELEPIX2 fast Hit-OR and H2M.

Fig. 11. Spatial and temporal correlations of H2M TELEPIX2.

assembling a DESY logo and reading out a triggered telescope reference pixel sensor; compare Fig. 10(a). Furthermore, the time resolution of the fast Hit-OR is gauged by comparing it with a scintillator signal coupled to a PMT and read out via an oscilloscope. The result is depicted in Fig. 10(b) as an example for a quasi noise-free threshold of 16. A Gaussian fit to the distributions' core yields a σ of 2.28(1) ns, sufficient for precise triggering at test beams. The absolute delay of the trigger compared to the scintillator is 15.32(1) ns, which is an acceptable latency for test beam operation.

5. User stories

TELEPIX2 is in user operation and utilized by multiple groups to enhance data taking efficiency and suppress ambiguities. In the following, three examples using the different operating modes are discussed and the improvement due to TELEPIX2 is highlighted.

### H2M - region of interest trigger mode

The H2M (Hybrid-to-Monolithic) is implemented in a 65 nm CMOS imaging process as proof of concept for a digital-on-top design workflow. It ports a hybrid pixel-detector architecture, with digital pulse processing in each pixel, into a monolithic chip. The chip matrix consists of 64×16 square pixels, each with a size of $35{\times}35\,\mu m^2$, and a total active area of approximately $1.25\,mm^2$. A 100 MHz clock is used for non-simultaneous Time-over-Threshold (ToT) or Time-of-Arrival (ToA) measurements.

H2M has been tested in the DESY II TEST BEAM facility using the ADENIUM telescope. TELEPIX2 is used as region of interest trigger plane. A region of interest of approximately $3\,mm^2$ is left unmasked in TELEPIX2 matching the H2M area with a safety margin.

Fig. 11(a) compares the correlations in X between H2M and the reference plane with data taken from a small region of interest and the entire TELEPIX2. While a one order of magnitude higher background of uncorrelated events is observed for the full region, for the small region, most of the events are correlated. The latter reduces the number of
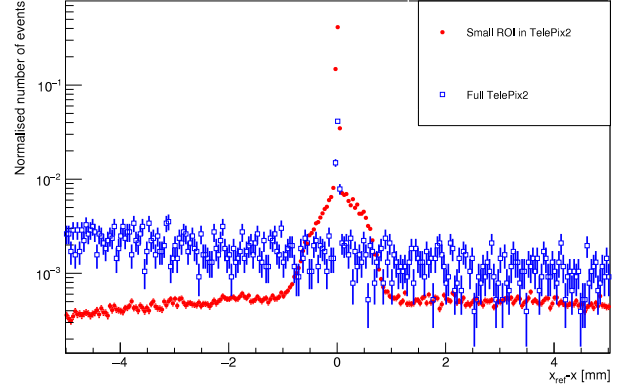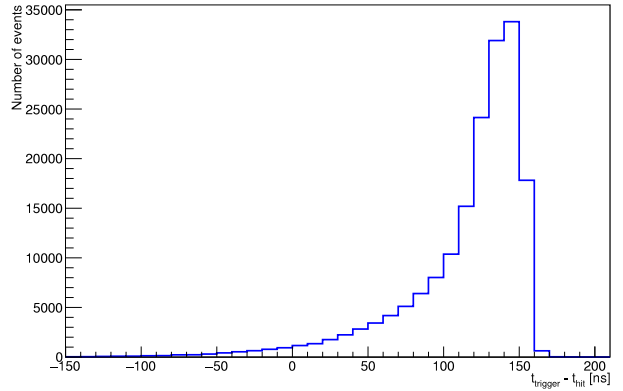
empty readout frames of H2M and highly improves the data taking efficiency. Moreover, time studies have been performed based on TELEPIX2. Fig. 11(b) shows the time residuals between the TELEPIX2 fast Hit-OR and H2M time stamps. The tail to the left is caused by time-walk of H2M.

ATLAS ITk strips - timing plane mode

The ATLAS inner tracker (ITk) [16] is a full silicon detector upgrade of the ATLAS tracking system for the high luminosity phase of the Large Hadron Collider (HL-LHC). To keep the tracking performance in the expected harsh environment and balance the cost, micro-strip modules are used in the outer barrel and end-cap layers of ITk, operated in a binary readout mode. The modules are required to have an operating threshold window with hit detection efficiency above 99 % at a noise occupancy below 0.1%. Different types of modules have been tested in the DESY II TEST BEAM facility. Already 1 % of fake tracks causes modules to not fulfil this stringent requirement. As the modules are significantly larger than the ADENIUM telescope's active area, only the track timing feature of TELEPIX2 is used in the analysis. Fig. 12 shows the comparison of the measured efficiency with and without TELEPIX2 as timing plane as a function of the detection threshold of an non-irradiated short strip module. In the low threshold region, an improvement in the determined efficiency of above 1 % is observed, resulting in a significant operating region, that would be hidden without the timing capabilities of TELEPIX2.
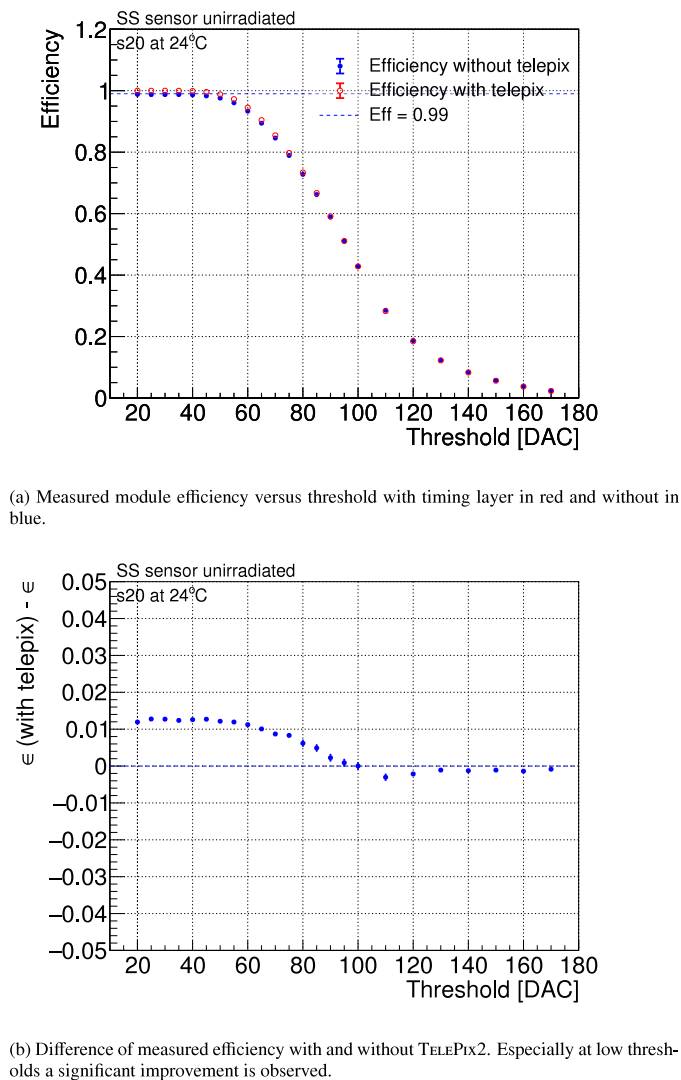
(a) Measured module efficiency versus threshold with timing layer in red and without in blue.

(b) Difference of measured efficiency with and without TELEPIX2. Especially at low thresholds a significant improvement is observed.

Fig. 12. Comparison of measured efficiency with and without TELEPIX2.

RD50-MPW4 - region of interest trigger and timing mode

The *RD50-MPW4* [17] is an HV-CMOS pixel sensor fabricated in a 150 nm process by *LFoundry*. It consists of a 64×64 pixel matrix with a pitch of $62 \times 62\,\mu m^2$, resulting in an active area of $\approx 4 \times 4\,mm^2$. The pixels are equipped with a time-stamping logic, which allows for 25 ns time binning. The performance was evaluated in a test beam at the DESY II TEST BEAM facility utilizing the ADENIUM telescope and the AIDA-TLU. As the ALPIDE sensors are substantially larger than the RD50-MPW4, an ROI trigger as input for the TLU over the "standard" operation employing scintillators was favourable, as otherwise, most tracks would not intersect the DUT and therefore occupy unnecessary storage and slow down the data analysis. Furthermore, the timing performance of the sensor should be assessed. TELEPIX2 is suited well for both by providing a region of interest trigger and allowing for track timestamping during offline analysis.

All pixels of TELEPIX2 that did not overlap with the DUT were masked and the fast Hit-OR enabled for all others. The effect of the ROI trigger operation is clearly visible in the hitmaps in Fig. 13. The correlations between the hit position at the DUT and the one at the telescope plane, adjacent to the DUT, in Fig. 14(a) show minimal background. TELEPIX2 can be used during analysis in track reconstruction to further suppress ambiguities and increase the on-DUT tracking efficiency. Requiring a

hit on TELEPIX2 for a track to be accepted, 80 % of all tracks intersect the DUT, compared to 63 % indicating, that there are still events with additional particles that did not pass through the trigger window of TELEPIX2, that is slightly larger than the DUT allowing for high statistics also at the edges of the DUT. TELEPIX2 efficiently suppresses these unwanted tracks. Assigning the timestamp of the TELEPIX2 hit data to the tracks and comparing it to the DUT time stamp allows to determine the temporal resolution of the DUT, by evaluating the time residuals, see Fig. 14(b). The observed value is slightly higher than the basic estimation of $25\,ns/\sqrt{12} \approx 7.2\,ns$. This is currently under investigation profiting largely from the TELEPIX2 track time stamping.

6. Conclusion

TELEPIX2 shows excellent performance with efficiencies above 99 % over a large threshold range and a time resolution of 3.844(2) ns without applying any threshold trimming or offline corrections. The fast Hit-OR which can be configured to any pixel arrangement has a time resolution of 2.28(1) ns with an absolute delay of 15.32(1) ns compared to a trigger scintillator. It is fully integrated with EUDAQ2 and the AIDA-TLU. The system is successfully provided to first users serving as timing and region of interest trigger layer. Including TELEPIX2 in the data taking and analysis improves their results and data taking efficiency. By overcoming previous limitations of the telescopes at the DESY II TEST BEAM facility, TELEPIX2 will be key to support future test beam characterizations of novel sensors.

Offline time corrections as well as systematic optimization of chip settings to maximize the performance are ongoing and are likely to further improve the presented results. In parallel, the radiation tolerance is studied. Future test beams at CERN are planned to show the feasibility to utilize TelePix2 at other facilities.

CRediT authorship contribution statement

L. Huth: Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **H. Augustin:** Writing – review & editing, Software, Investigation, Conceptualization. **L. Dittmann:** Writing – review & editing, Investigation. **S. Dittmeier:** Investigation. **J. Hammerich:** Writing – review & editing, Investigation. **Y. He:** Writing – original draft, Formal analysis. **A. Herkert:** Writing – review & editing. **D.M. Immig:** Supervision, Methodology. **D. Kim:** Writing – review & editing. **U. Krämer:** Investigation. **R. Kolb:** Writing – review & editing. **I. Perić:** Writing – original draft, Validation, Resources, Methodology, Conceptualization. **B. Pilsl:** Writing – original draft, Formal analysis. **S. Ruiz Daza:** Writing – review & editing, Writing – original draft, Formal analysis. **T. Senger:** Software. **A. Schöning:** Resources, Project administration. **M. Stanitzki:** Funding acquisition. **B. Weinläder:** Investigation. **A. Wintle:** Writing – review & editing, Visualization, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

(a) Hitmap of the *RD50-MPW4*.

(b) Hitmap of TₑₗₑPₓ2 with active ROI.

(c) Hitmap of the most downstream telescope plane.
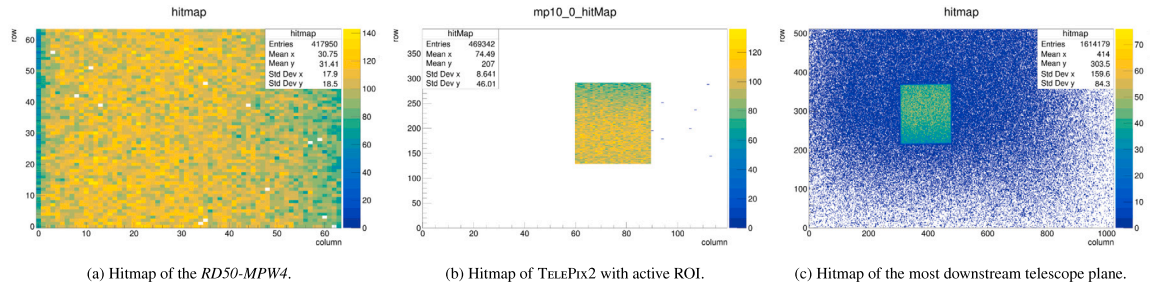
Fig. 13. Hitmaps of various sensors in the setup showcasing the effect of the ROI trigger operation of TₑₗₑPₓ2.

(a) Spatial correlations in X of the DUT with the telescope reference plane and ROI triggering

(b) Difference between the hit-time at the DUT and the time of the track, which is assigned from the TₑₗₑPₓ2 timestamp.
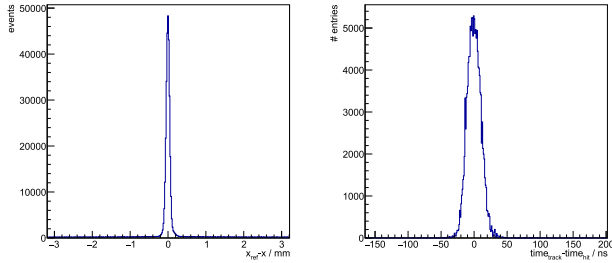
Fig. 14. Test beam results of the RD50-MPW4 highlighting the benefits of employing the TₑₗₑPₓ2 as an additional telescope plane.

Data availability

Data will be made available on request.

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