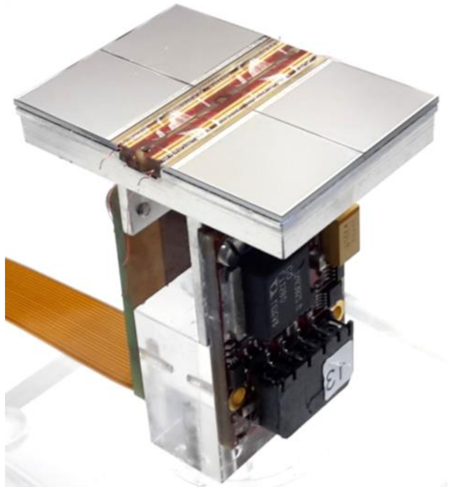
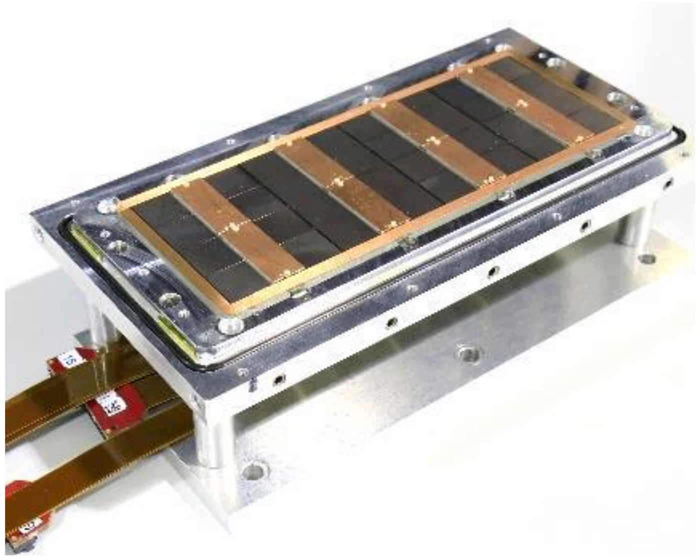
Pixelated TPC technology for the future e$^+$e$^-$ collider

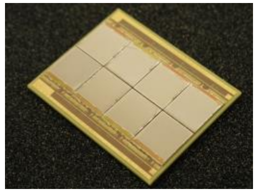
Yevgen Bilevych, Klaus Desch,
Harry van der Graaf, Fred Hartjes,
Jochen Kaminski, Peter Kluit,
Naomi van der Kolk,
Cornelis Ligtenberg,
Gerhard Raven, and
Jan Timmermans



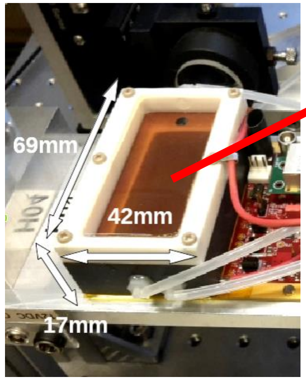


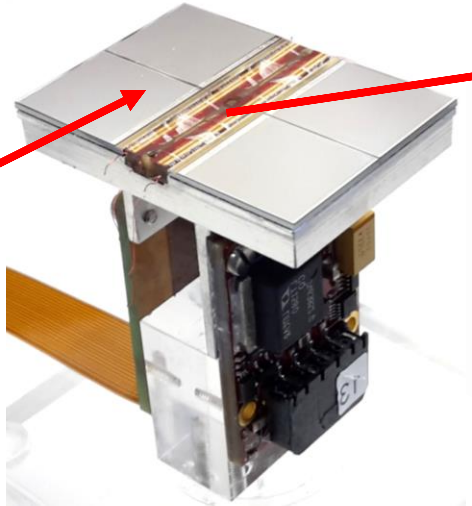
IAS HEP2023 Honk Kong 23 February 2023

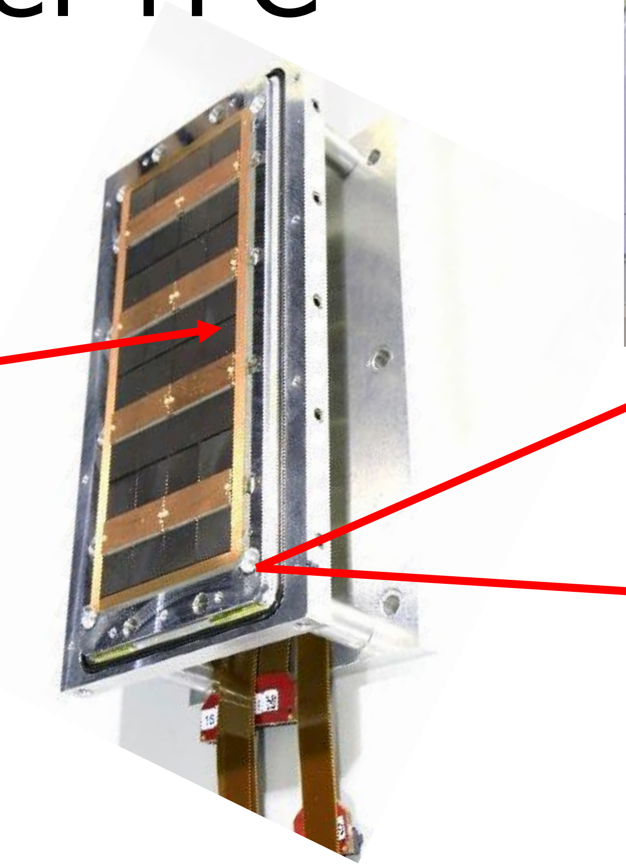
Pixel TPC

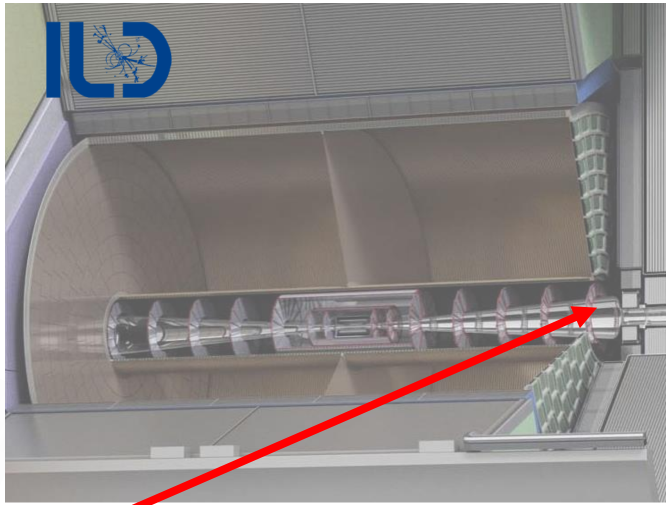


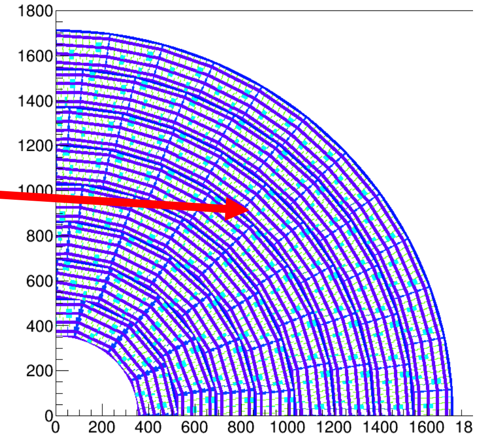
(Octopuce)





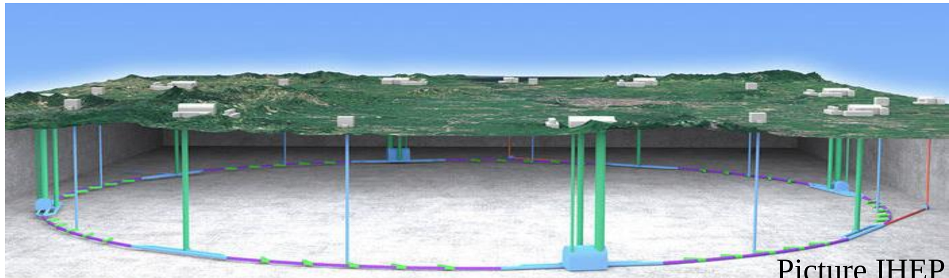






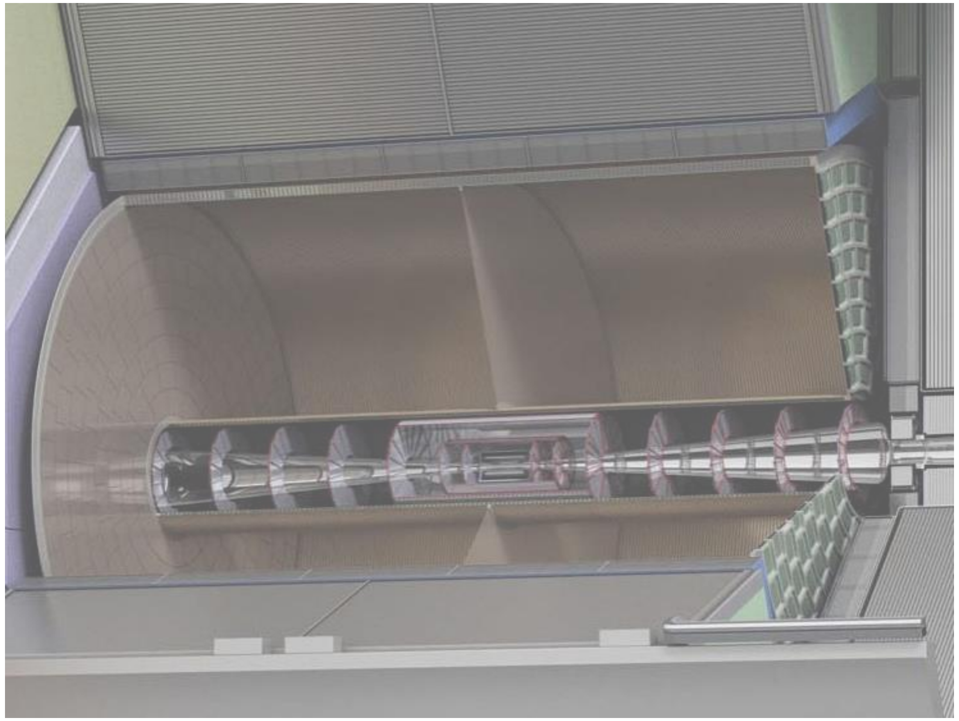
(TimePix1) TPX3 chip Quad Module TPC plane

(2007-14) 2017 2018 2019

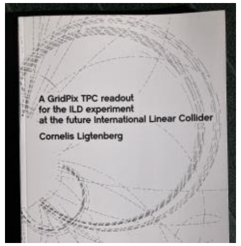


Picture IHEP

ILD Pixel TPC



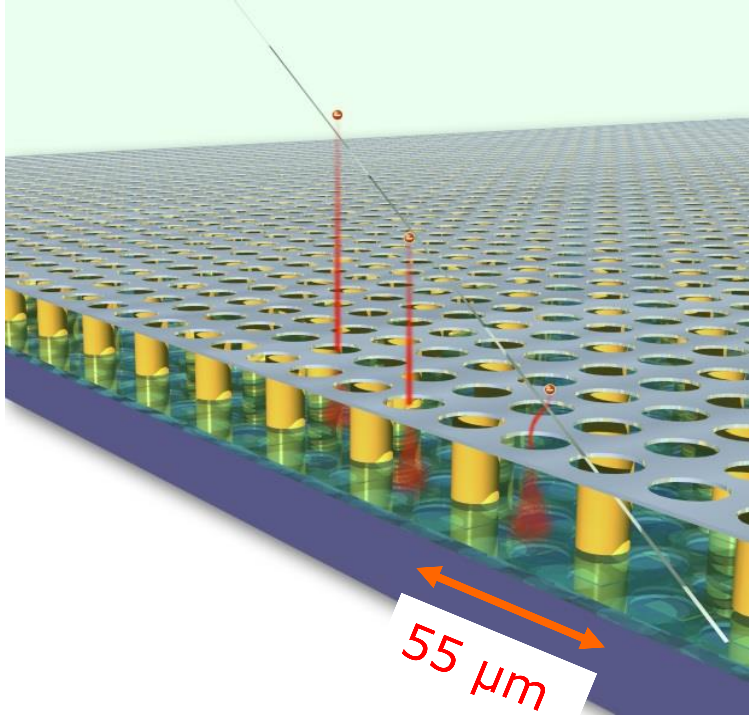
- Material budget is
  - 0.01 X_0 TPC gas
  - 0.01 X_0 inner cylinder
  - 0.03 X_0 outer cylinder
  - < 0.25 X_0 endplates (incl readout)
- Note the very low budget in the barrel region. Material budget can be respected by different technologies like GEM, MicroMegas and Pixels
- TPC is sliced between silicon detectors VTX, SIT and SET
- pixel readout is a serious option for the TPC readout plane @ ILC/FFC-ee/CLIC/CEPC colliders

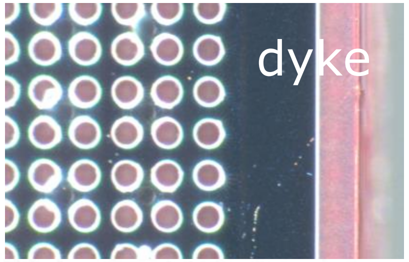


https://www.nikhef.nl/pub/services/biblio/theses_pdf/thesis_C_Ligtenberg.pdf

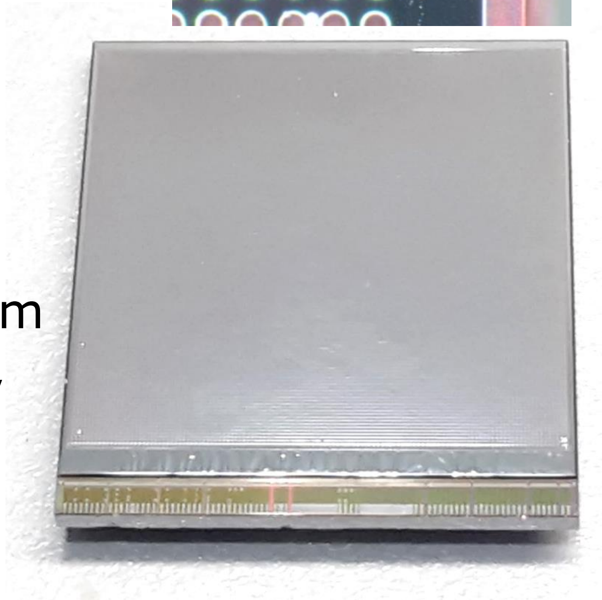
GridPix technology

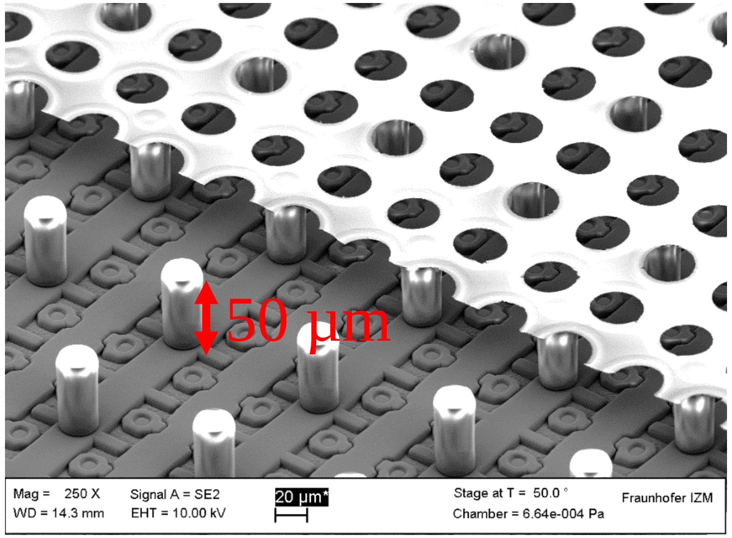
- Pixel chip with integrated Grid (Micromegas-like)
- InGrid post-processed @ IZM
- Grid set at negative voltage (300 – 600 V) to provide gas amplification
- Very small pixel size (55 μm)
- detecting individual electrons





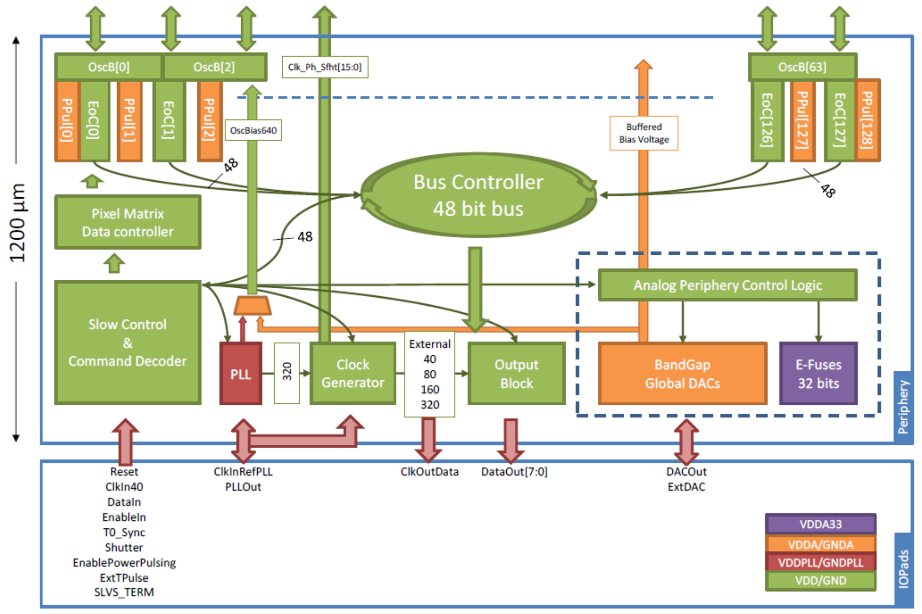
- Aluminium grid (1 μm thick)
- 35 μm wide holes, 55 μm pitch
- Supported by SU8 pillars 50 μm high
- Grid surrounded by SU8 dyke (150 μm wide solid strip) for mechanical and HV stability

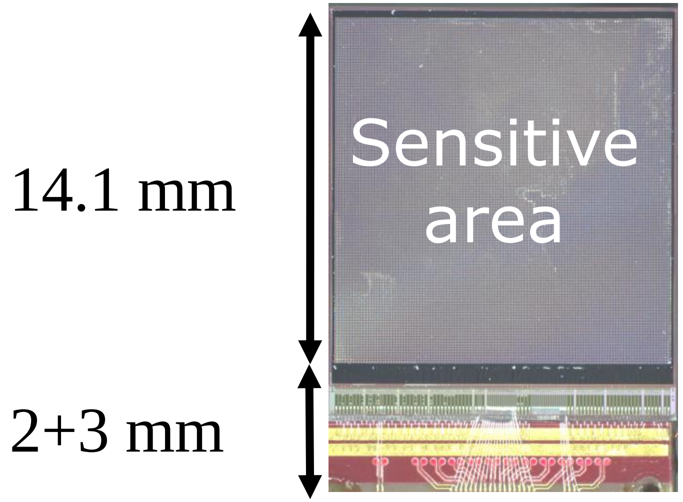




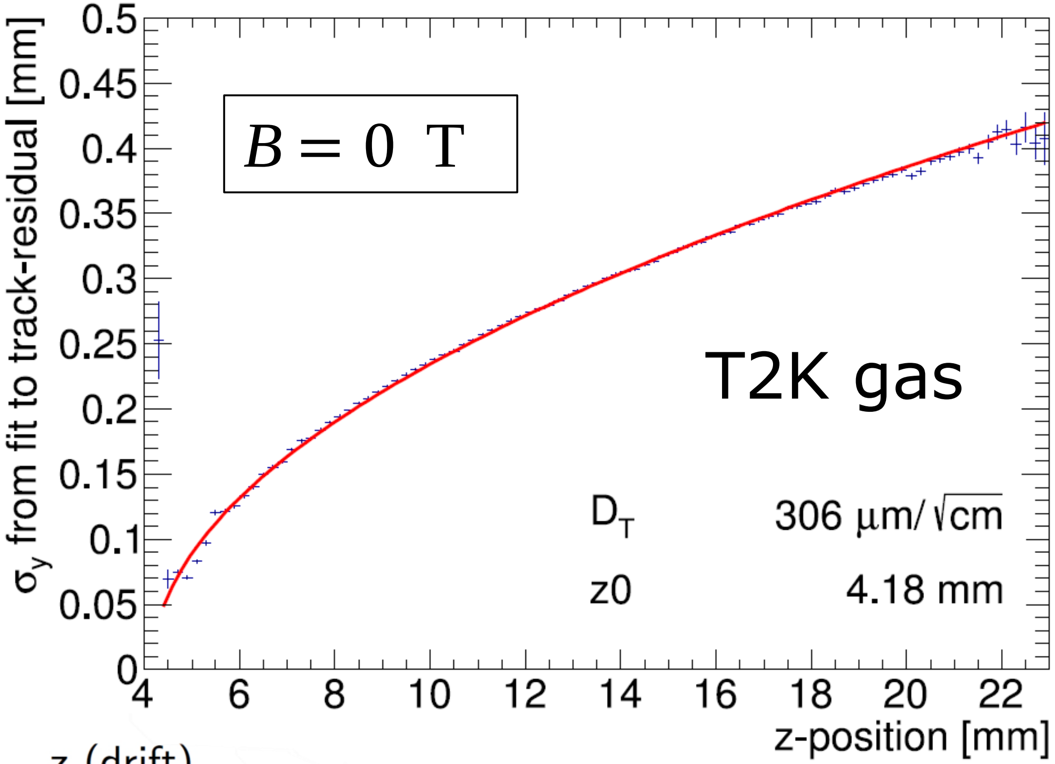
Pixel chip: TimePix3

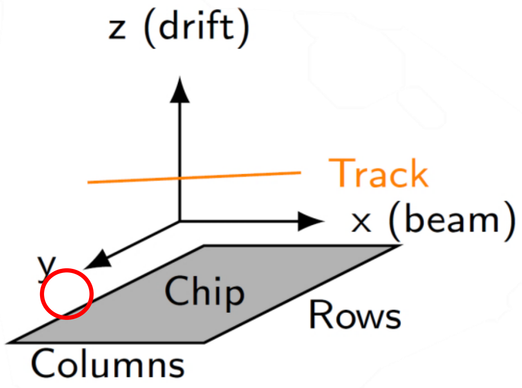
- 256 x 256 pixels
- 55 x 55 µm pitch
- 14.1 x 14.1 mm sensitive area
- TDC with **640 MHz clock** (1.56 ns)
- Used in the data driven mode
  - Each hit consists of the **pixel address** and **time stamp** of arrival time (ToA)
  - Time over threshold (ToT) is added to register the signal amplitude
  - compensation for time walk
  - **Trigger** (for t_0) added to the data stream as an additional time stamp
- Power consumption
  - ~1 A @ 2 V (2W) depending on hit rate
  - good cooling is important





Single hit resolution in transverse direction





$D_T = 306\ \mu\text{m}/\sqrt{\text{cm}}$

$(318 \pm 7\ \mu\text{m}/\sqrt{\text{cm}}$ expected)

Results from Bonn-Elsa testbeam in 2017
https://doi.org/10.1016/j.nima.2018.08.012

Single hit resolution in pixel plane:

$$\sigma_y^2 = \sigma_{y0}^2 + D_T^2(z - z_0)$$

Depends on:

- σ_{y0} = pixel size $/\sqrt{12}$
- Diffusion D_T from fit

Note that:

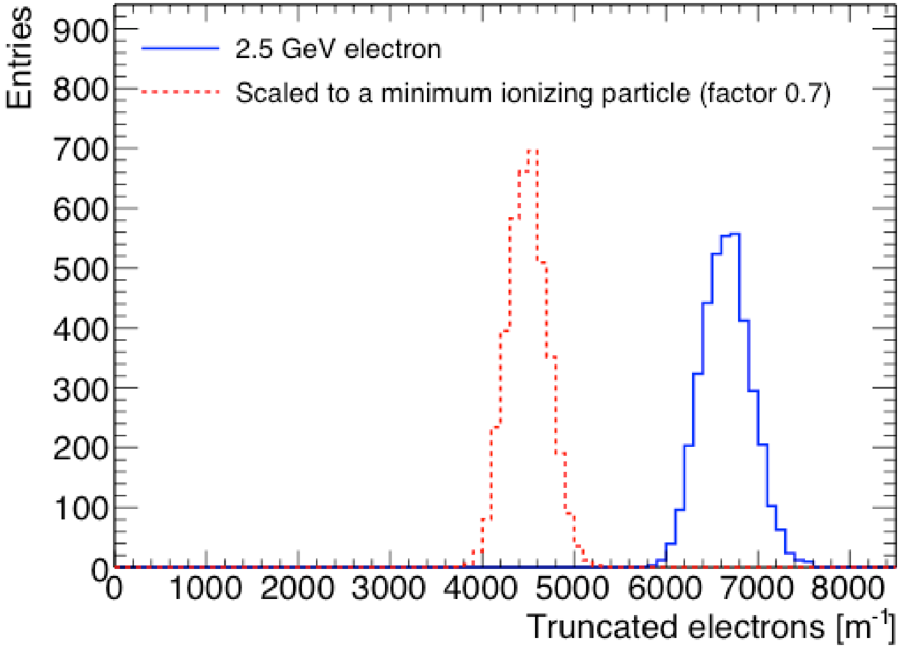
- A hit resolution of ~250 μm is ~25 μm for a 100-hit track (~ 1 cm track length)
- At $B = 4$ T , $D_T = 25\ \mu\text{m}/\sqrt{\text{cm}}$

Pixel dE/dx performance

- dE/dx resolution with truncated mean
  - From the single chip tracks; 1 m long tracks are made;
  - nr of electrons counted in slices of 20 pixel and reject 10% highest slices
  - Distances along track are scaled by 1/0.7 to get an estimation for the dE/dx of a MIP
  - Resolution is 4.1% for a 2.5 GeV electron and 4.9% for a MIP
- Separation $S = (N_e - N_{MIP})/\sigma_e$
- 8σ MIP-e separation for a 1 meter track

https://doi.org/10.1016/j.nima.2018.08.012

- A pixel readout can in principle within the resolution (diffusion) separate primary from secondary clusters. dE/dx can be measured by cluster counting and performance separation enhanced.

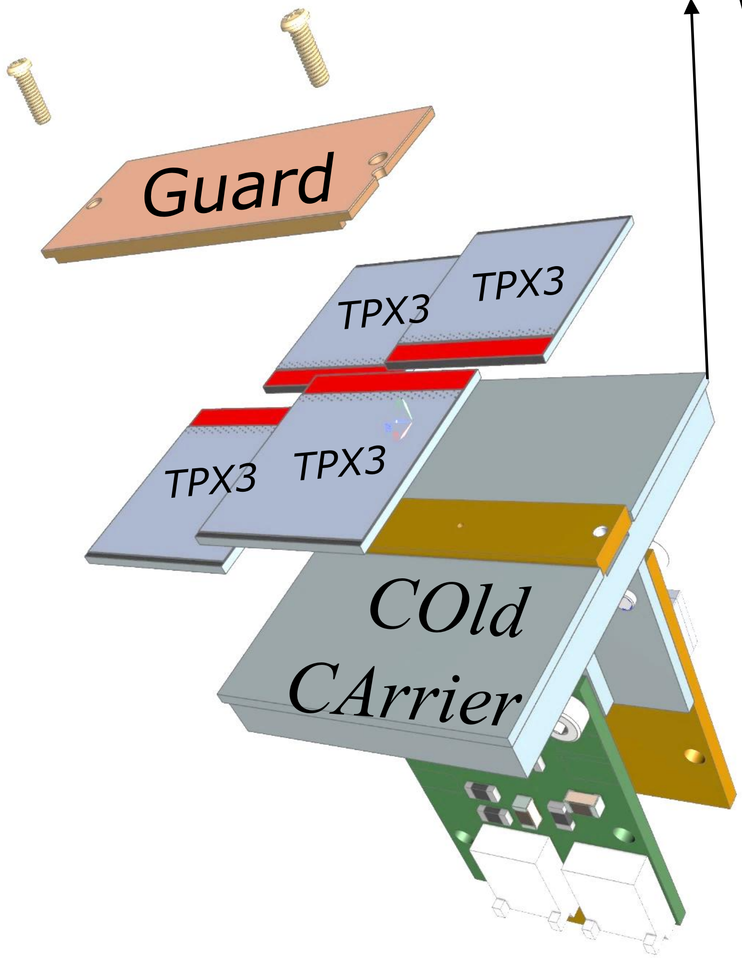


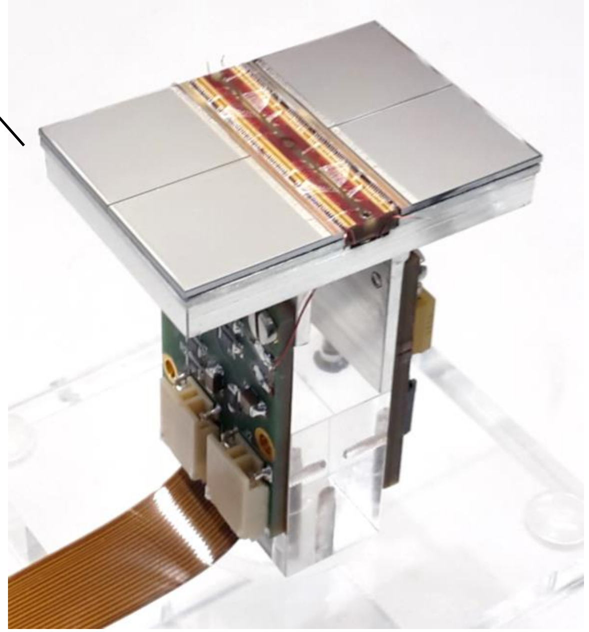
QUAD design and realization

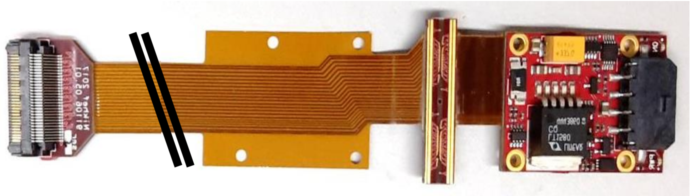
- Four-TimePix3 chips
- All services (signal IO, LV power) are located under the detection surface
- The area for connections was squeezed to the minimum
- Very high precision 10 μm mounting of the chips and guard
- QUAD has a sensitive area of 68.9%
- DAQ by SPIDR

39.6 x 28.38 mm

series of QUADs





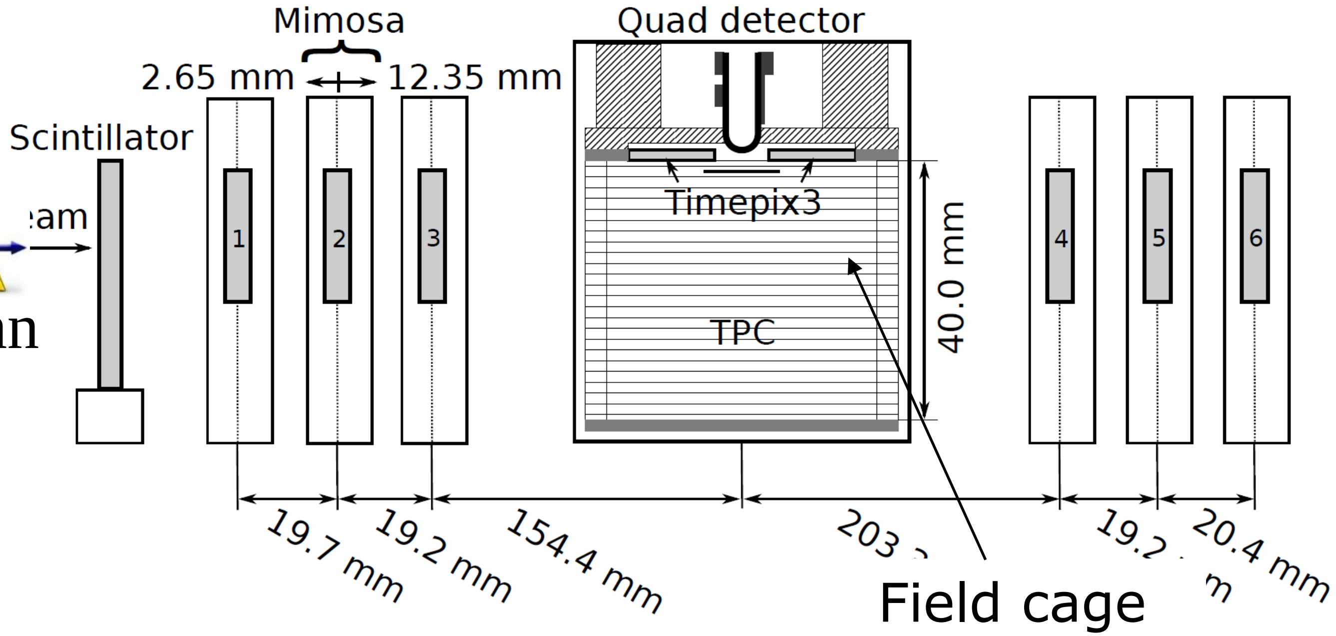


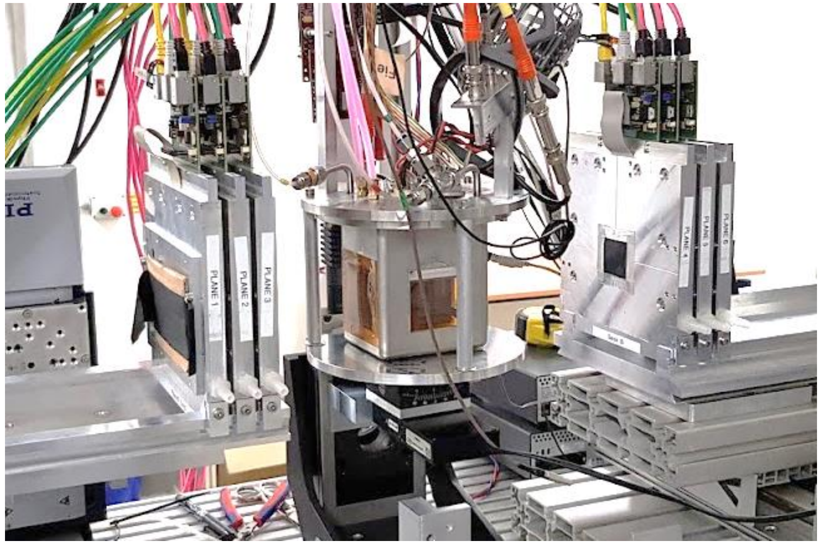
QUAD test beam in Bonn (October 2018)

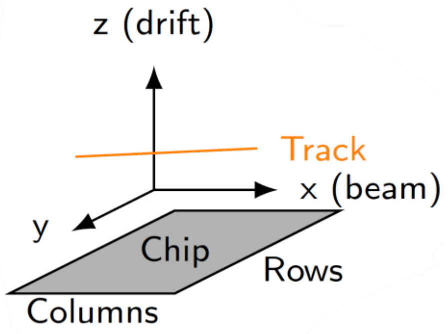
- ELSA: 2.5 GeV electrons
- Tracks referenced by Mimosa telescope
- QUAD sandwiched between Mimosa planes
  - Largely improved track definition
  - 6 planes with 18.4 μm × 18.4 μm sized pixels
- Gas: $Ar/CF_4/iC_4H_{10}$ 95/3/2 (T2K)
- E_d = 400 V/cm, V_{grid} = -330 V
- Typical beam height above the chip: ~1 cm

Published NIMA
https://doi.org/10.1016/j.nima.2019.163331

@Bonn

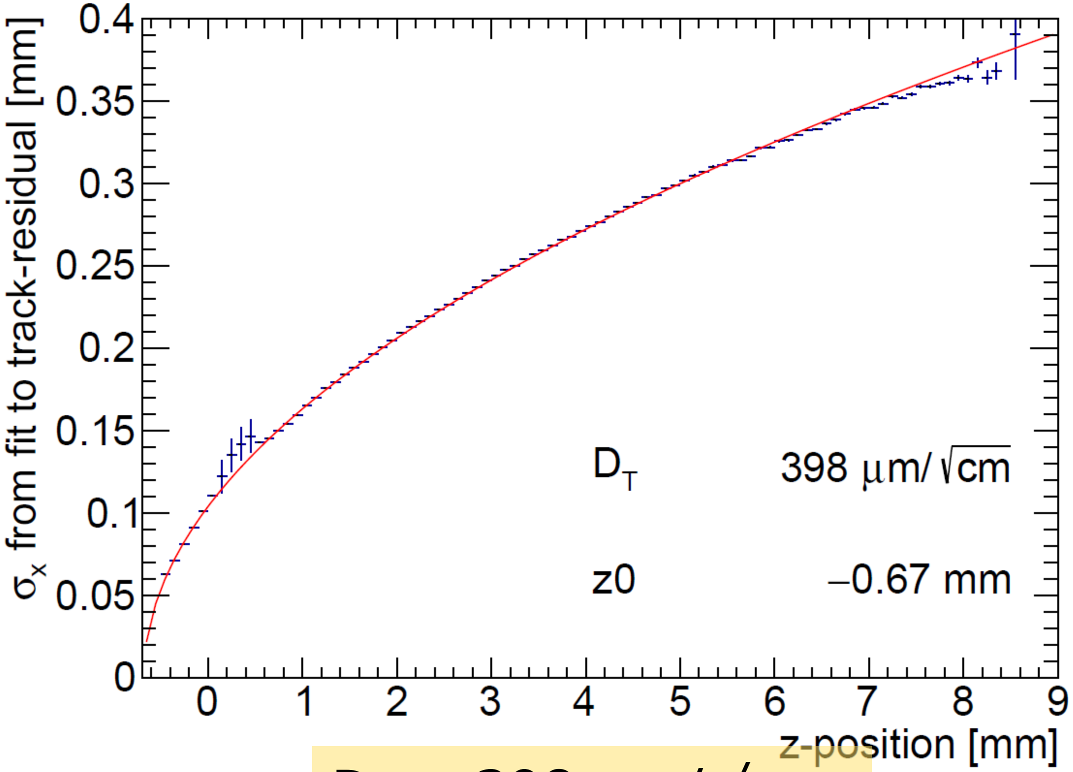






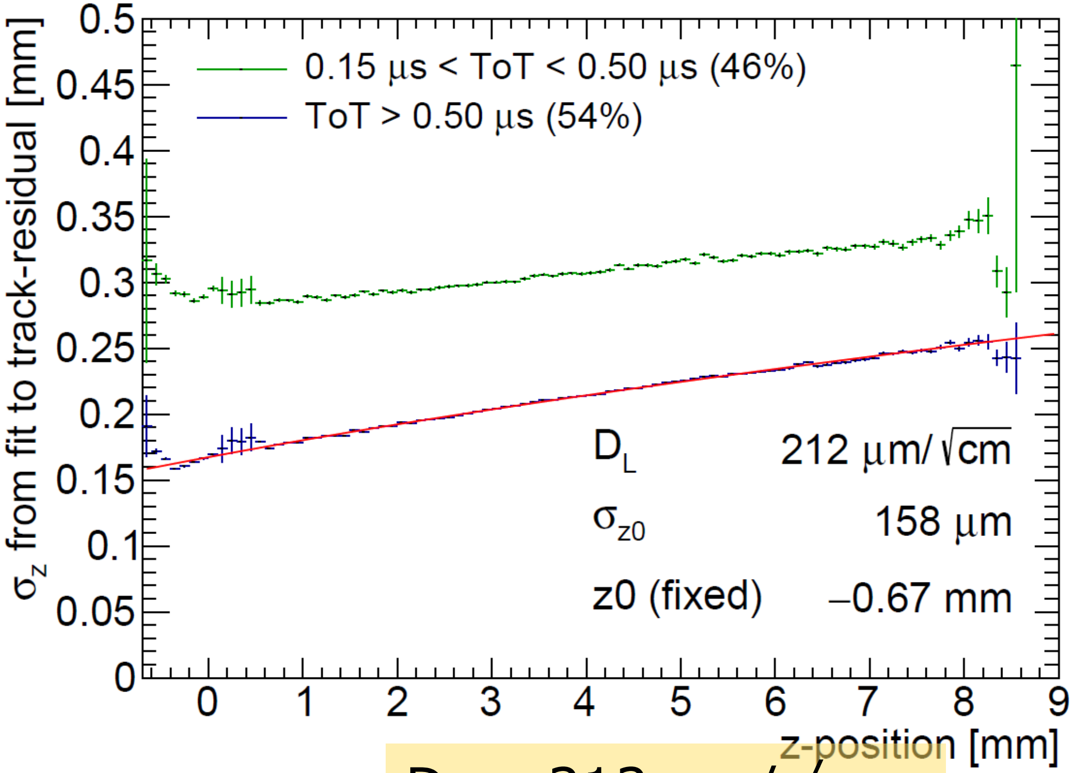
QUAD single hit resolution

Transverse



D_T = 398 μm/√cm

Longitudinal

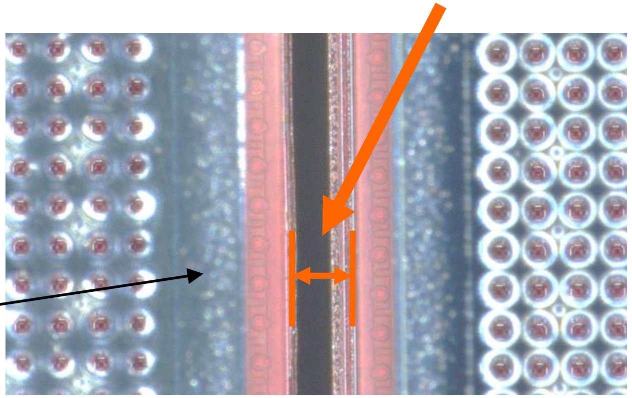


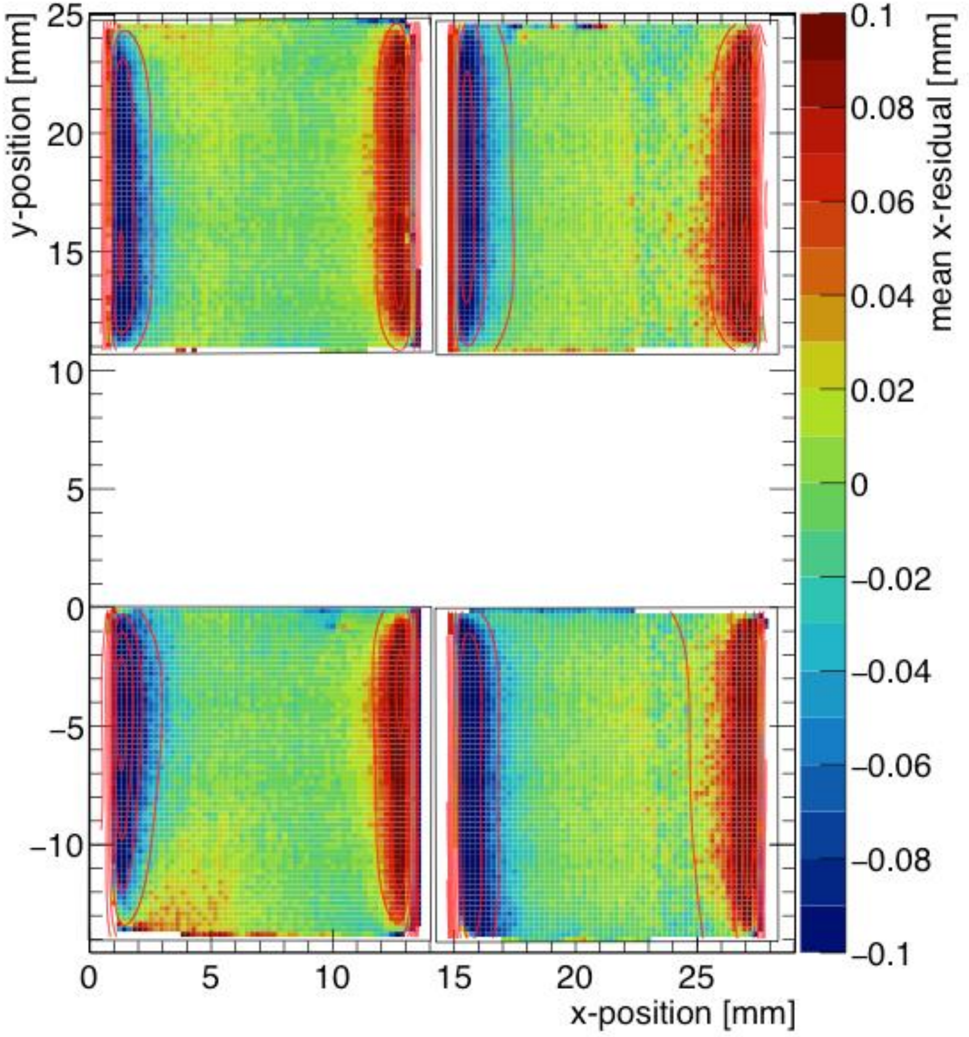
D_L = 212 μm/√cm

The D_T value is rather high due to an error in the gas mixing (too low CF4)

QUAD edge deformations (XY)

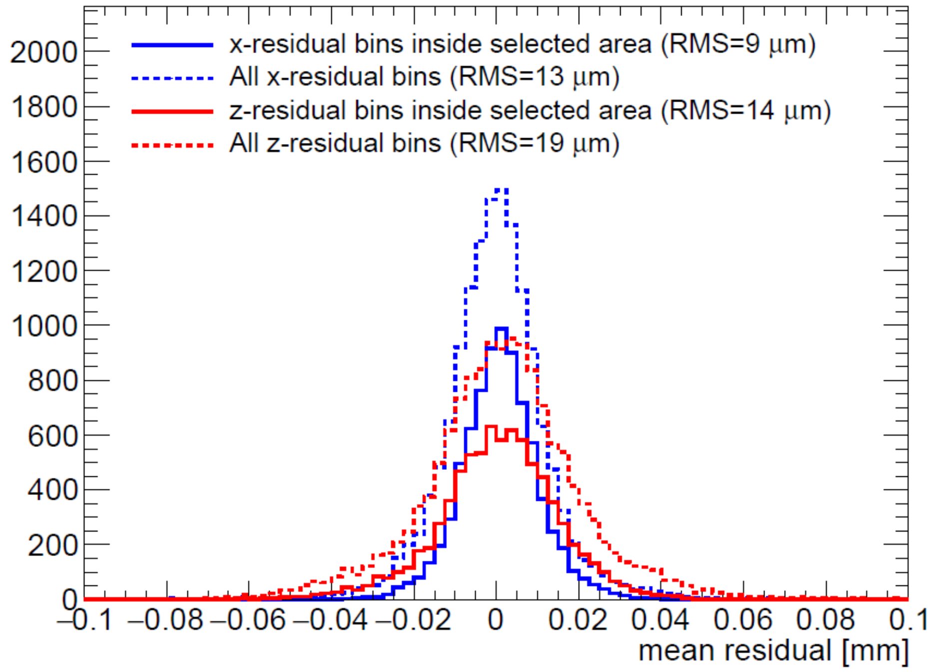
- Small deformations due to
  - Dead zone between chips
  - Grounded region between chips
- Are corrected by:
  - fitted correction function
  - adding proper guard wire electrode

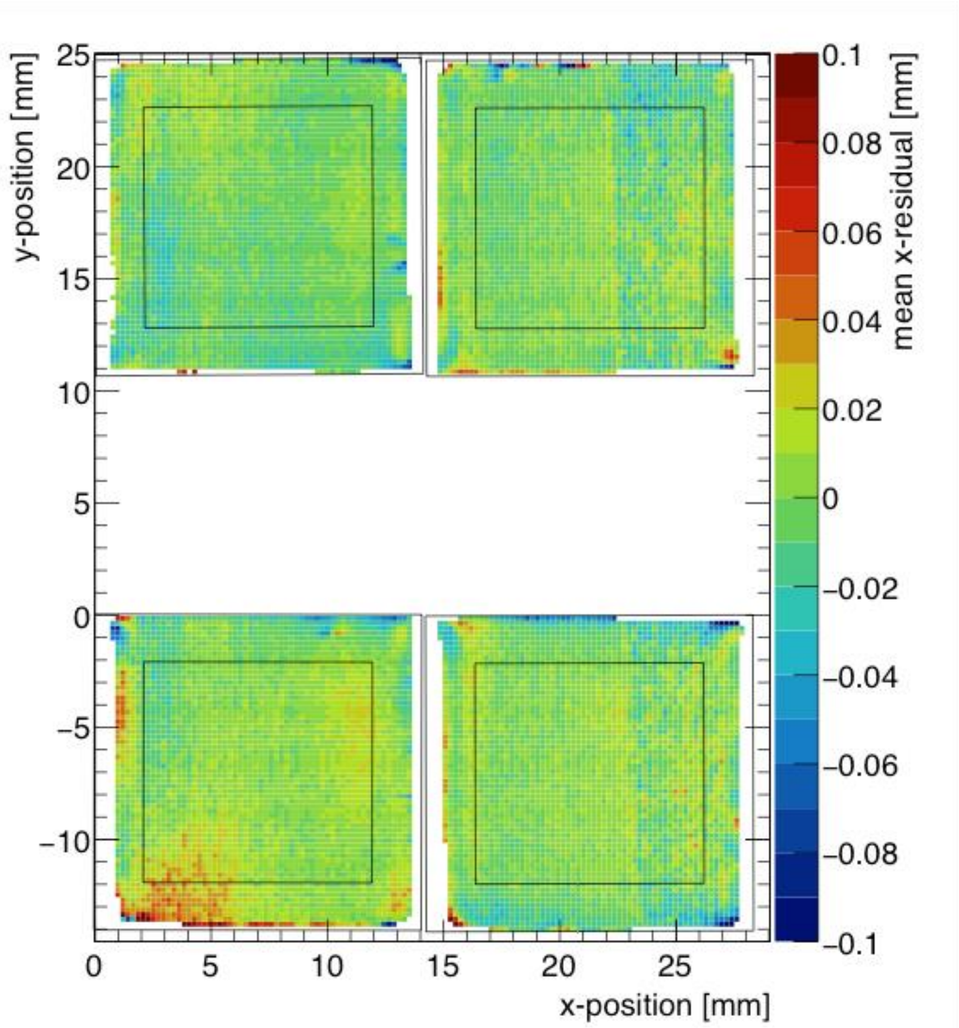




QUAD deformations in transverse plane (XY)

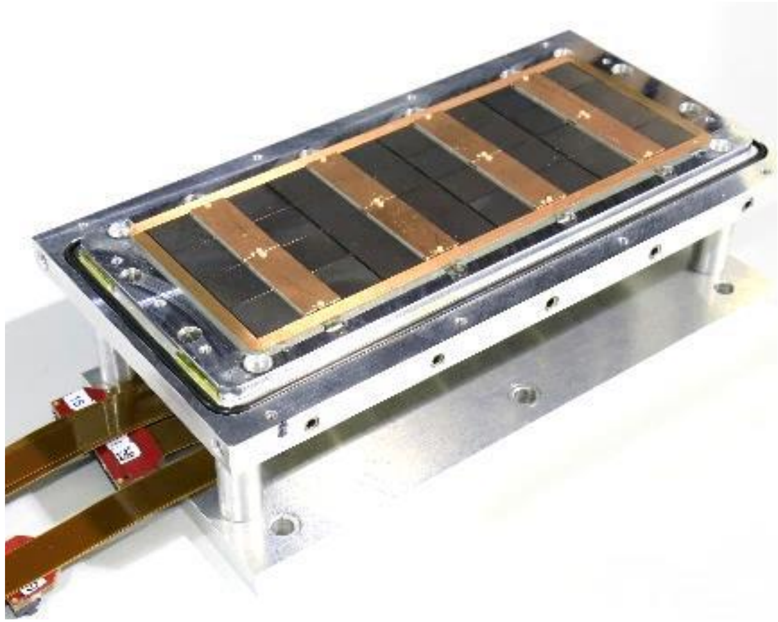
- After applying fitted edge corrections
- RMS of the mean residuals are 13 μm over the whole QUAD

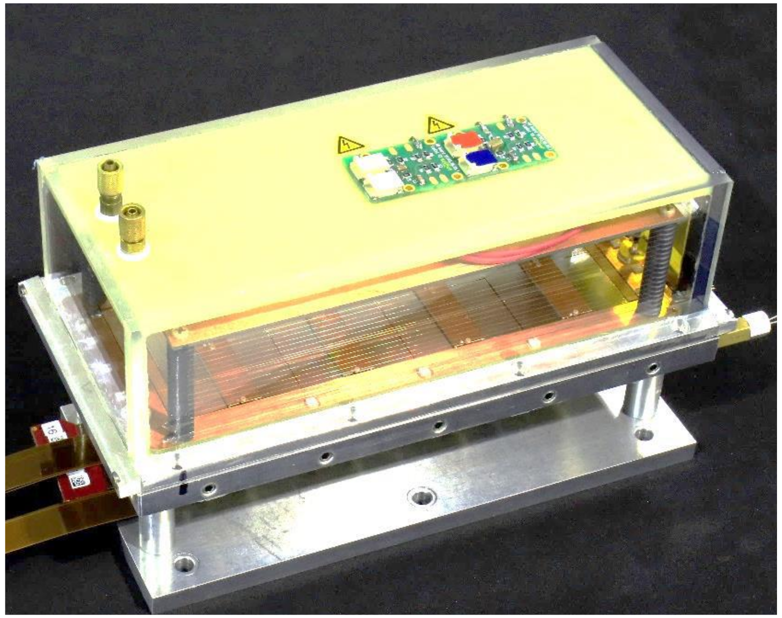


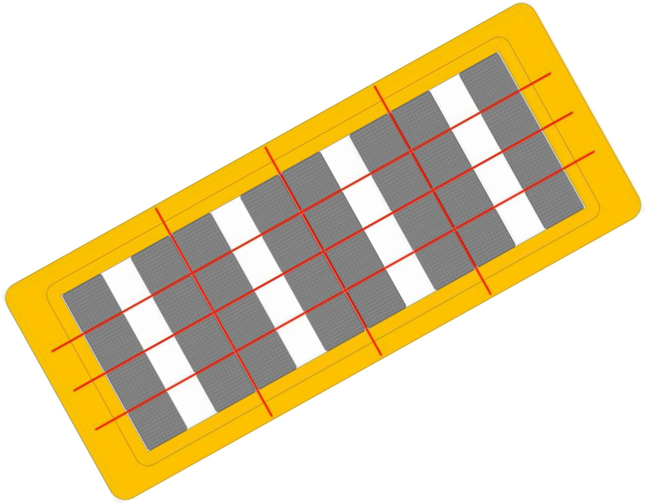


QUAD as a building block

8-QUAD module (2x4 quads) with field cage

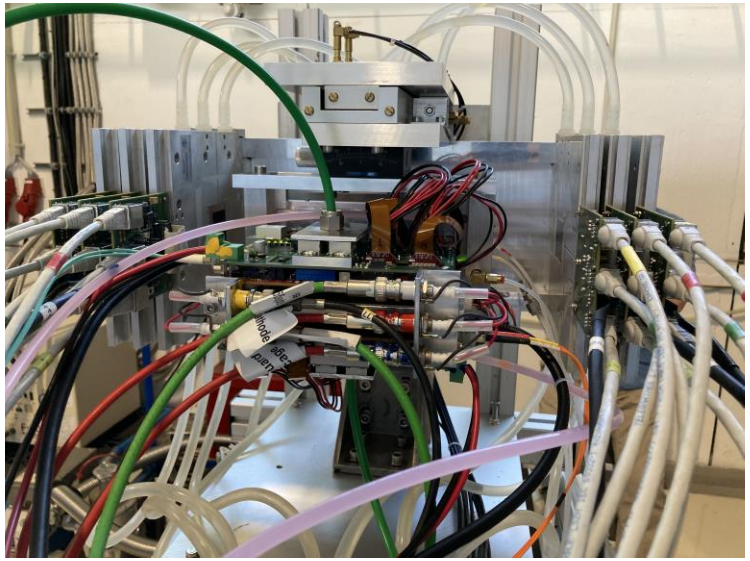


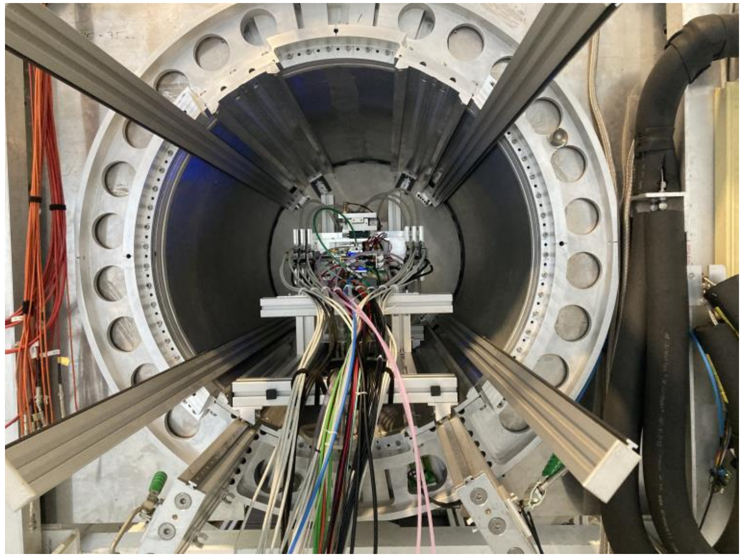




in red guard wires

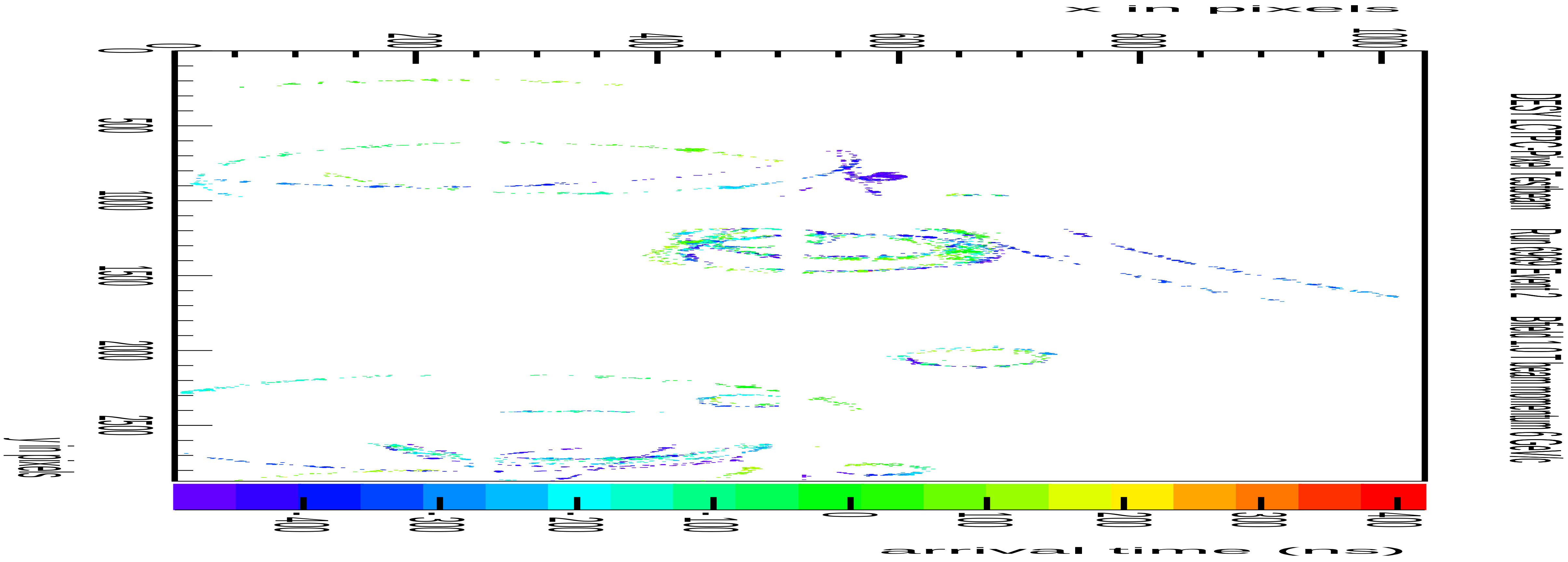
DESY testbeam June 2021



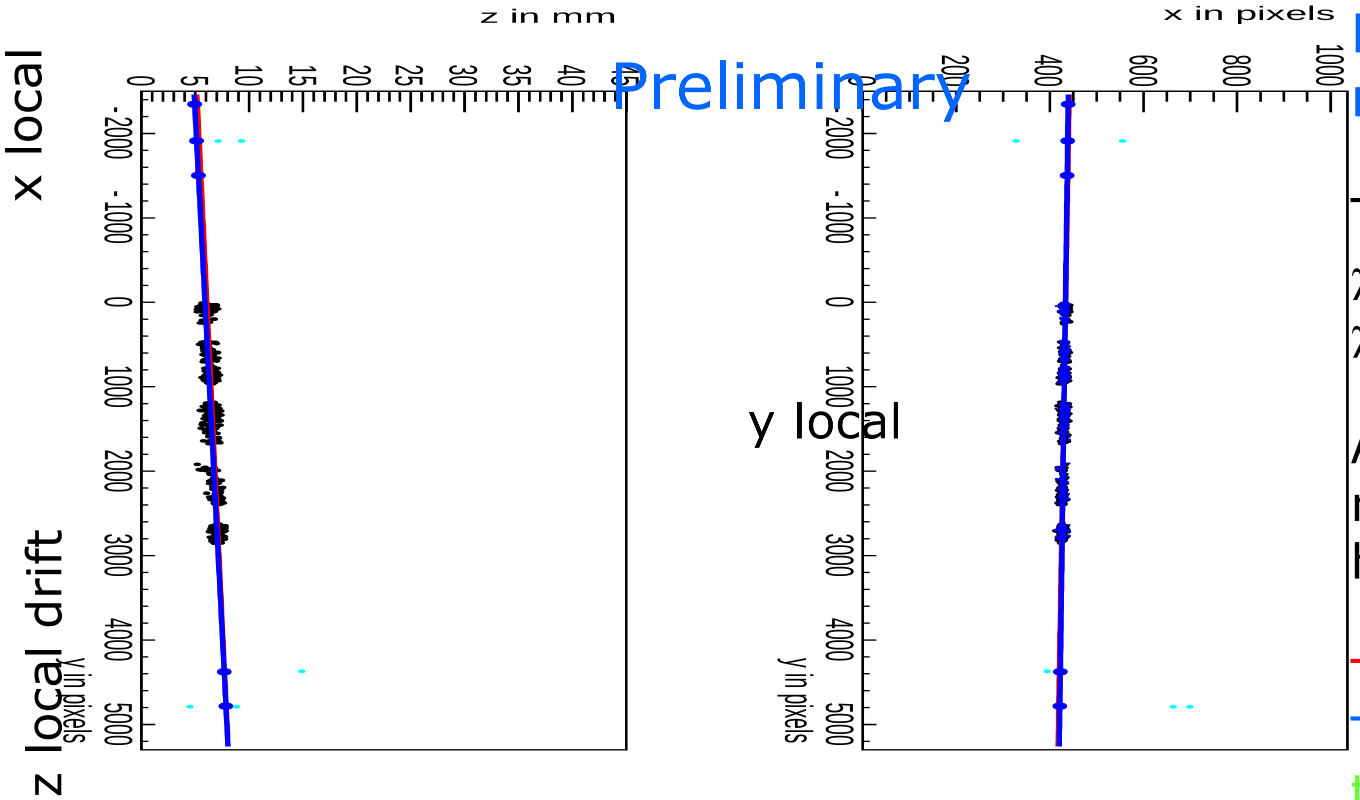


Mounting the 8 quad module between the silicon planes
sliding it into the 1 T PCMAG solenoid

DESY testbeam June 2021



DESY testbeam Module Analysis



Event display with module and telescope

TPX3 track 1130 hits
χ^2_{xy} = 677.5/1128
χ^2_{z} = 775.9/1069

Asymmetric tail outlier removal applied 1071 hits in z kept.

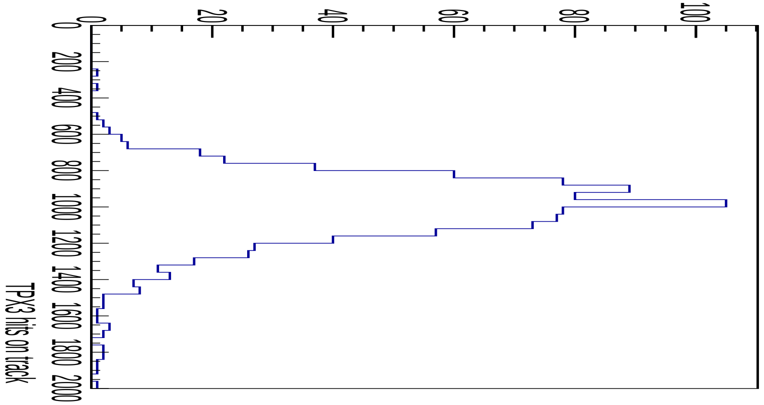
TPX3 track hits
Telescope track hits (off track green)

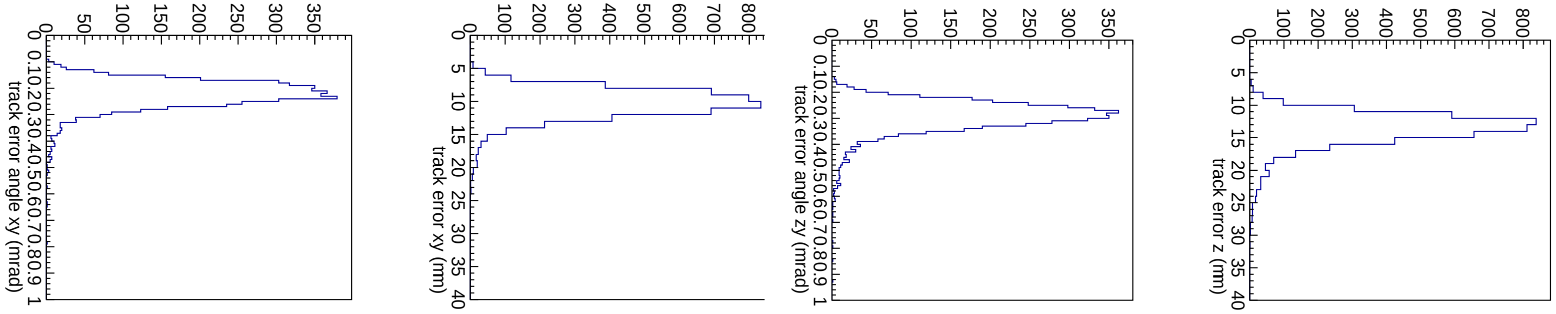
y local

DESY testbeam Module Analysis

Run 6916 B=0 T p =6 GeV

Preliminary





964 selected tracks
Impressive 1009 hits / track

8-quad module Tracking precision:

position 9 μm (xy) 13 μm (z)
angle 0.19 mrad (dx/dy) 0.25 (dz/dy) mrad
module tracklength = 157.96 mm

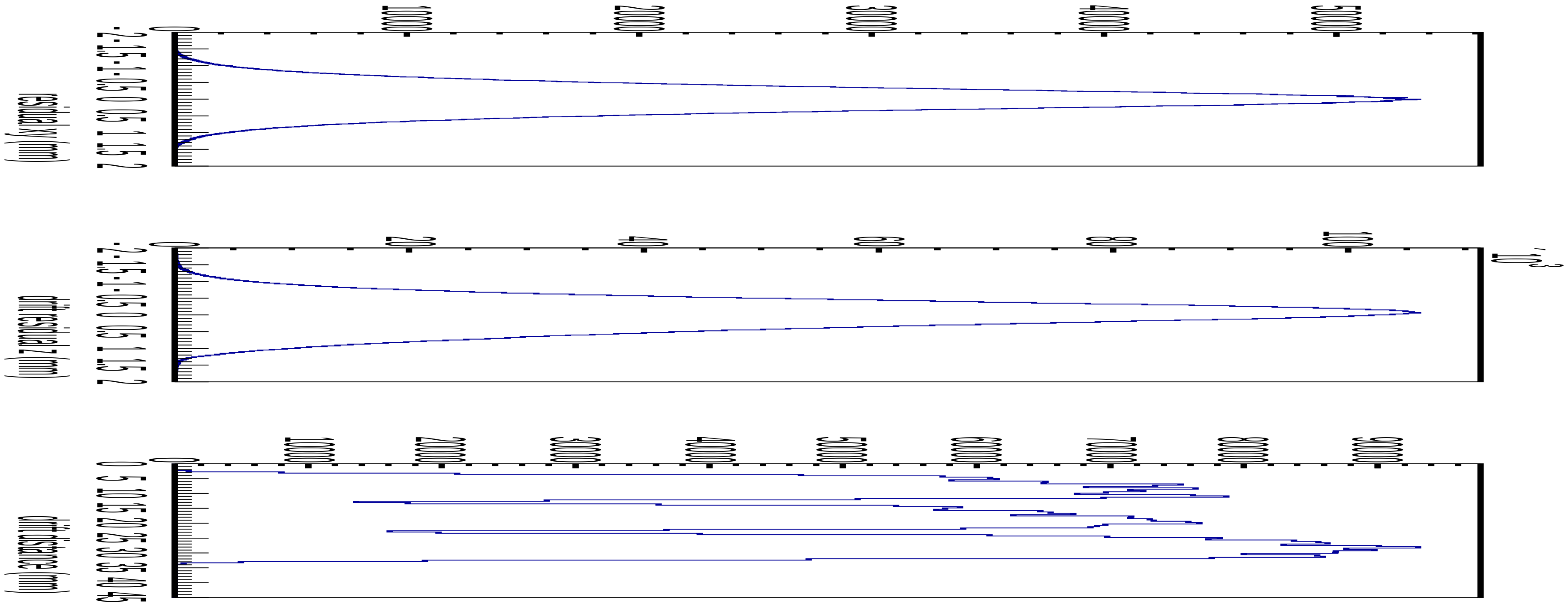
Note that in a B field because of the reduced diffusion the tracking precision will improve substantially

DESY testbeam Module Analysis

Run 6916-6918 B=0 T p=6 GeV

Three runs at different drift distances

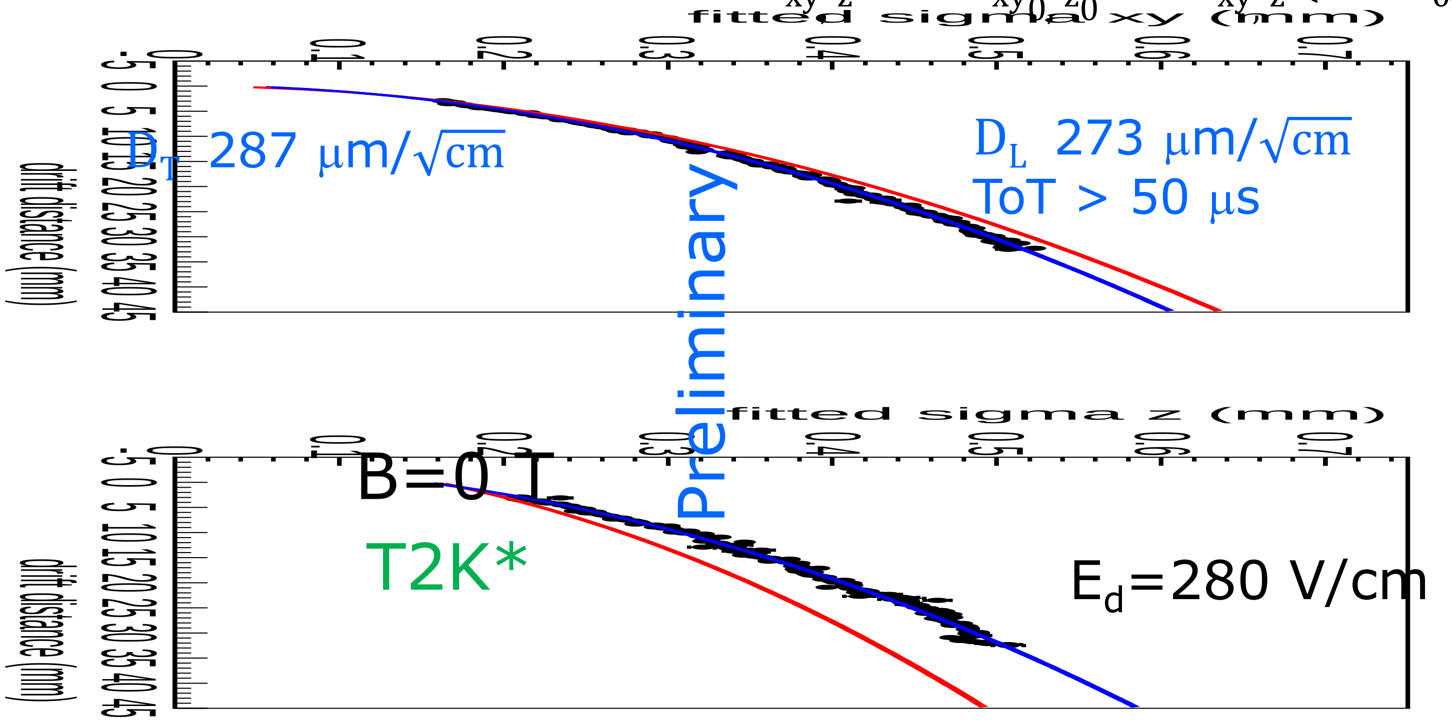
Preliminary



DESY testbeam Module Analysis

Run 6916-6918 B=0 T p=6 GeV

Fitted resolution $\sigma_{xy\ z}{}^2 = \sigma^2_{xy_0\ z_0} + D^2_{xy\ z}(z - z_0)$



$\sigma^2_{xy0} = \sigma^2_{pixel} + \sigma^2_{xy\ tele}$

$\sigma^2_{pixel} = 55^2/12\ \mu m^2$

$\sigma_{xy\ tele} = 35\ \mu m$

In red the curve published single chip results

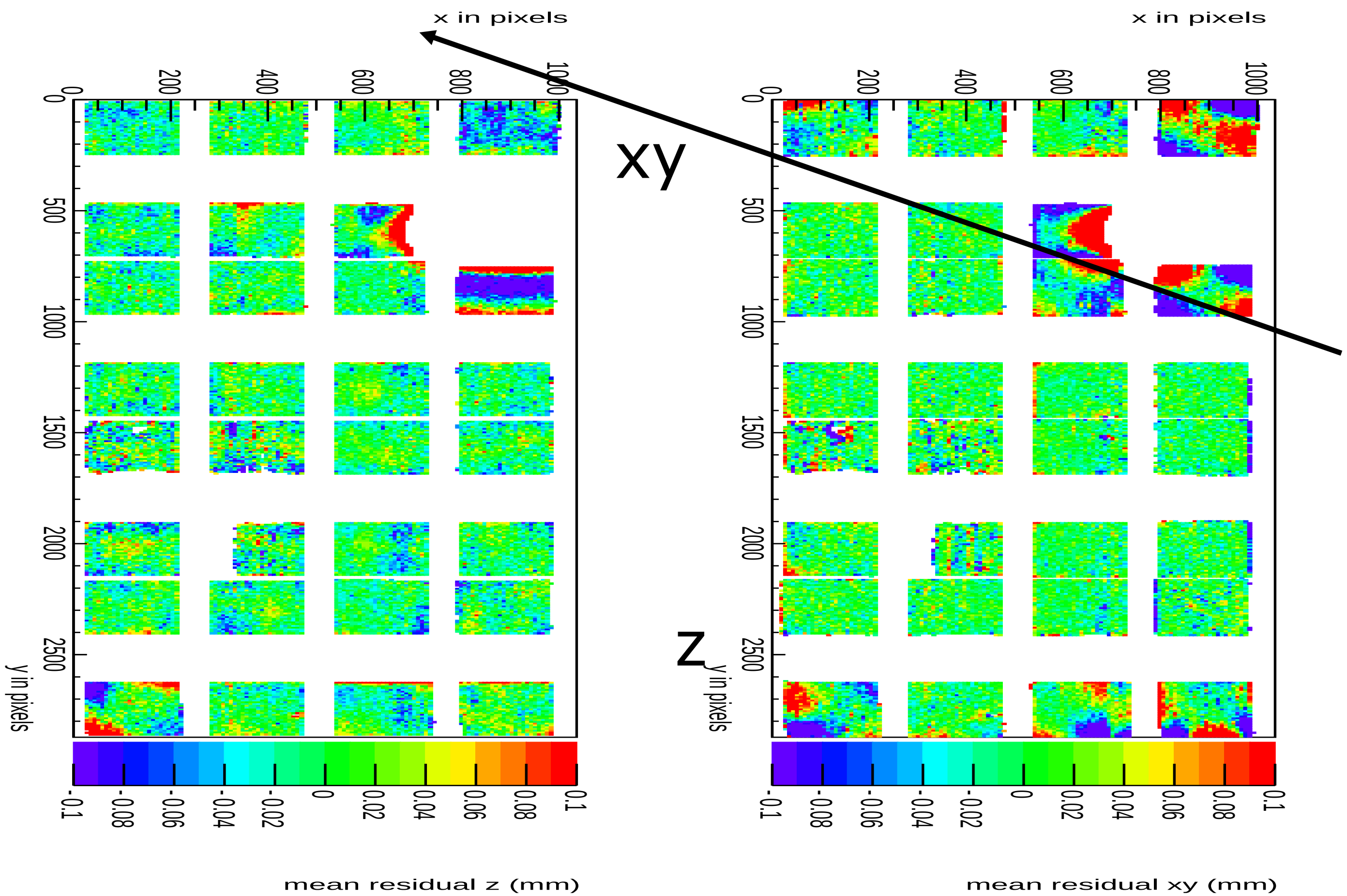
T2K* = T2K gas with O_2 and H_2O

DESY testbeam Module Analysis

Runs 6909, 6916-17, 6934-35 B=0 T p =6,5 GeV

Mean residuals in the module plane with acceptance cuts

Preliminary



Vertical white bands guards

There are clear deformations in xy for the chips in the 4 corners.

The field around chip 11 (no grid HV) is affected.

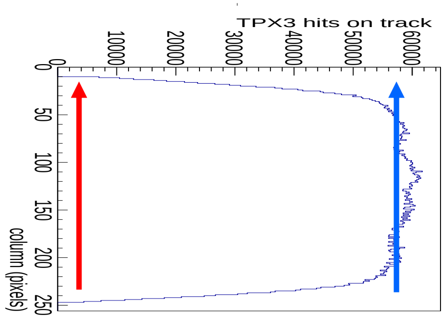
The Efield defined by the field cage is in these areas not homogenous enough

DESY testbeam Module Analysis

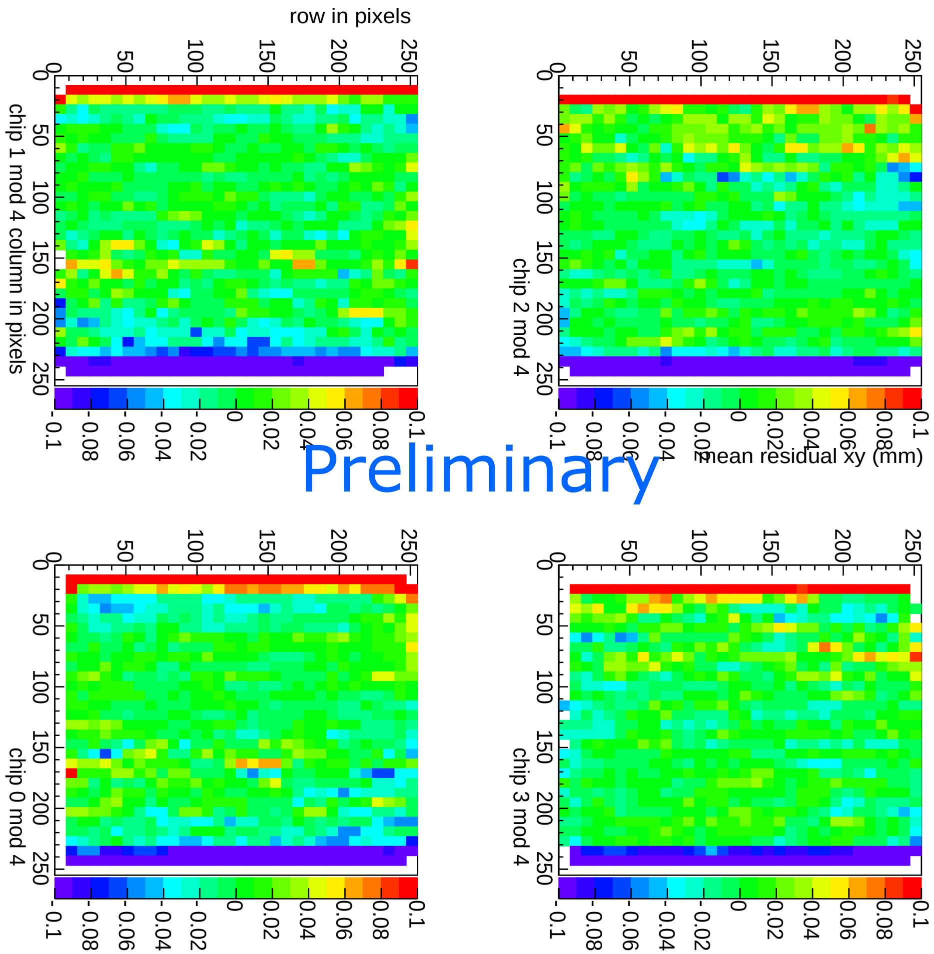
Runs 6909, 6916-17, 6934-35 B=0 T p =6,5 GeV

Mean residuals xy in the quad plane no acceptance cut

Columns horizontal

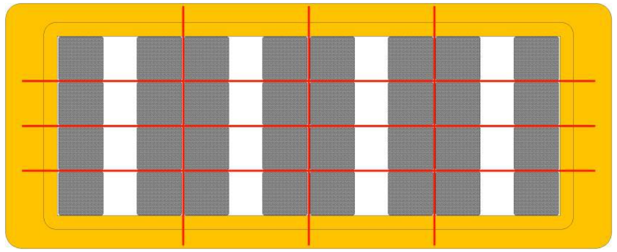


At the column edges the efficiency drops and introduces a bias (in local x).



Granularity 8x8 pixels

Only small deformations at the chip column edges. This means that the guard and guard wires are reasonably well tuned.



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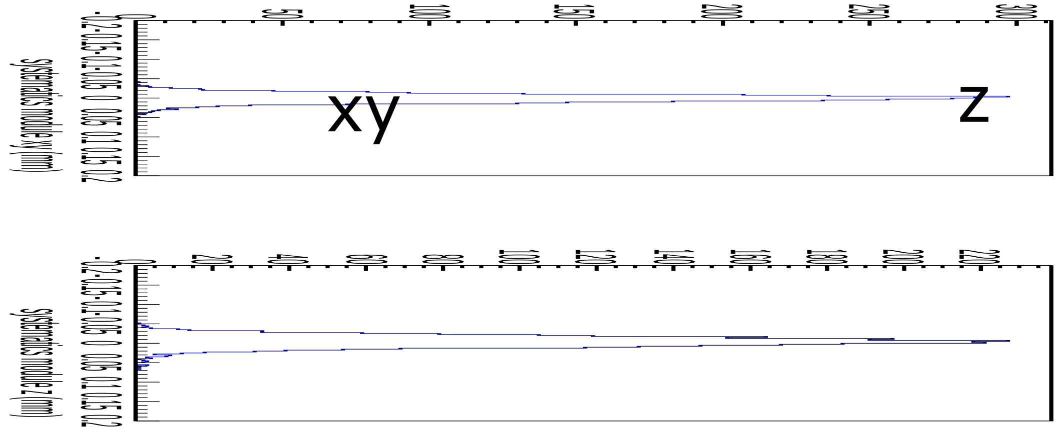
DESY testbeam Module Analysis

Runs 6909, 6916-17, 6934-35 B=0 T p =6,5 GeV

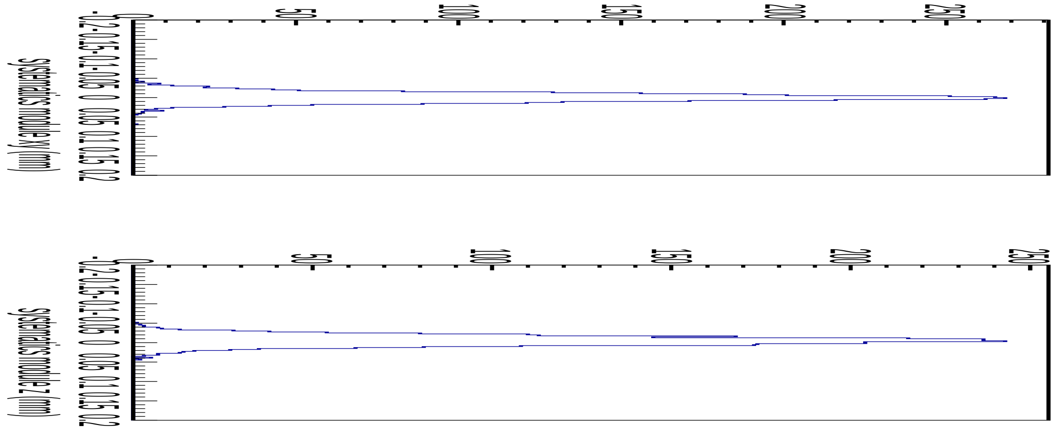
Distribution of mean residuals in the plane

Preliminary

Method row



Method column



See back up slide for the two methods that group the module plane

method	rms (stat) xy	bins xy	rms (stat) z	bins z
row	10 (6) μm	2881	14 (8) μm	2850
column	12 (7) μm	2901	13 (8) μm	2843

We did not include the 4 corner chips and (11), 14, 8, 13 and 19. These are affected by the field cage and the short in chip 11.

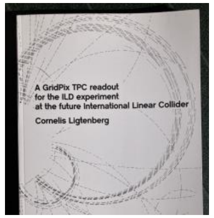
Preliminary conclusions on module

- Preliminary results of the 8 Quad Module in the DESY test beam in June 2021 have been presented
- One chip (nr 11) out of 32 was disconnected due to a short*
- In run 6916 e.g. 964 tracks were selected with 1009 hits on track
- The tracking precision: position 9 (xy) 13 μm (z) in angle 0.19 (dx/dy) 0.25 (dzdy) mrad for a module or tracklength is 157.96 mm
- The diffusion coefficients at B=0 T $D_{xy} = 287\ \mu m/\sqrt{cm}$ $D_z = 273\ \mu m/\sqrt{cm}$
- Results for the module showed that:
  - the HV of the guard wires was well tuned
  - rms residuals xy 12 μm and z 14 μm; Deformations xy are below 12 μm
  - The results are compatible with (very) high stats quad measurement

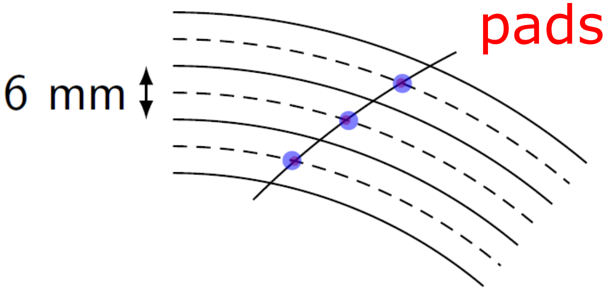
*the chip was successfully repaired in 2023 Bonn see backup slide

Simulation of ILD TPC with pixel readout

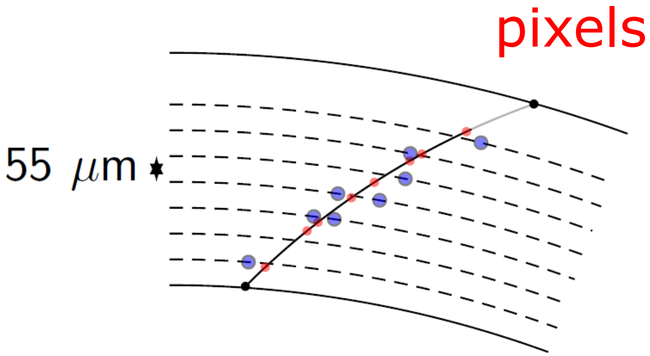
- To study the performance of a large pixelized TPC, the pixel readout was implemented in the full ILD DD4HEP (Geant4) simulation
- Changed the existing TPC pad readout to a pixel readout
- Adapted Kalman filter track reconstruction to pixels



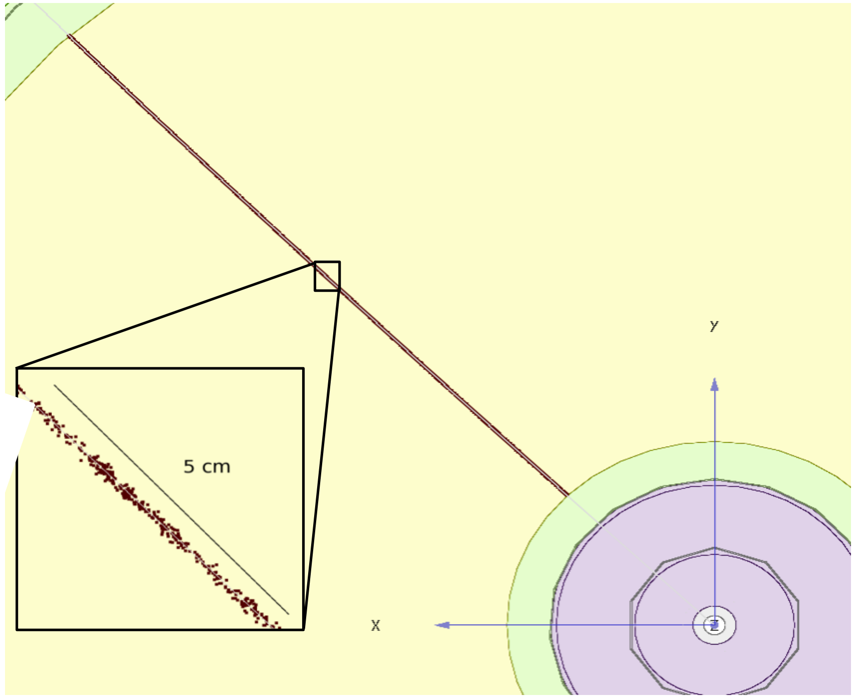
details: PhD thesis
Kees Ligtenberg



22 electrons / hit
~ 200 hits / track



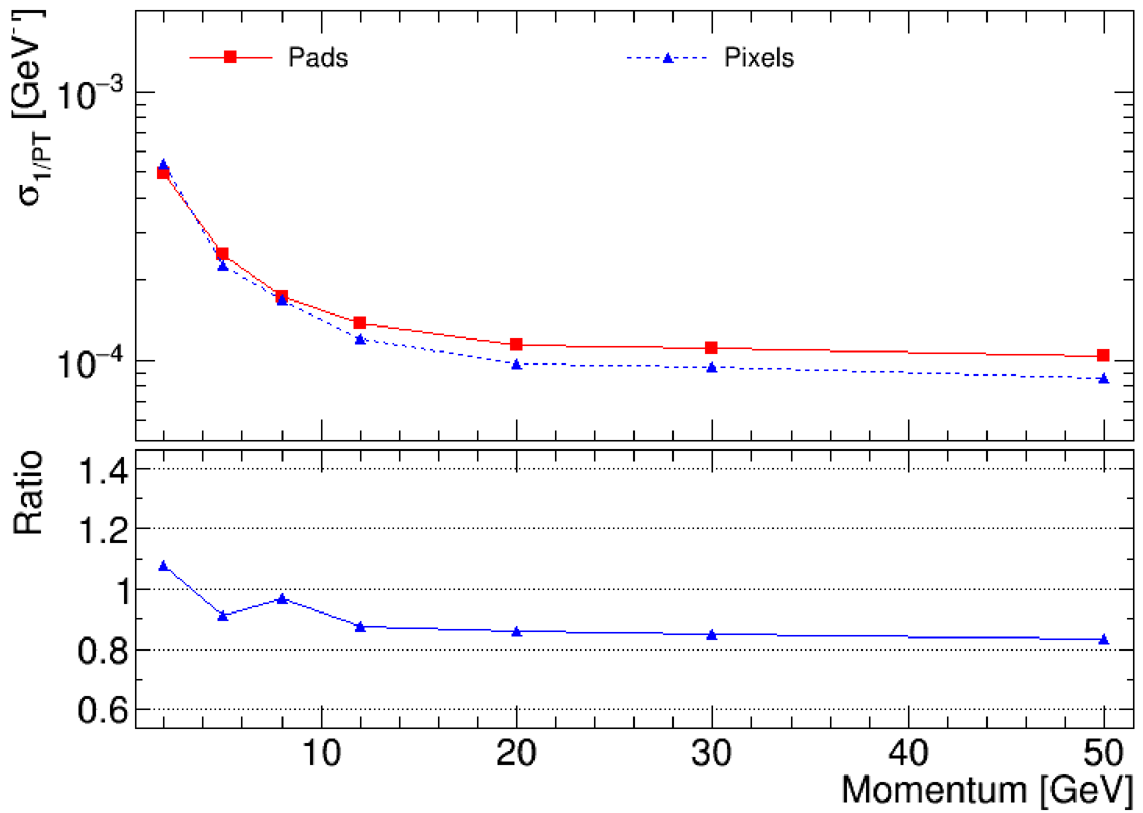
1 electron / hit
~ 10 000 hits / track

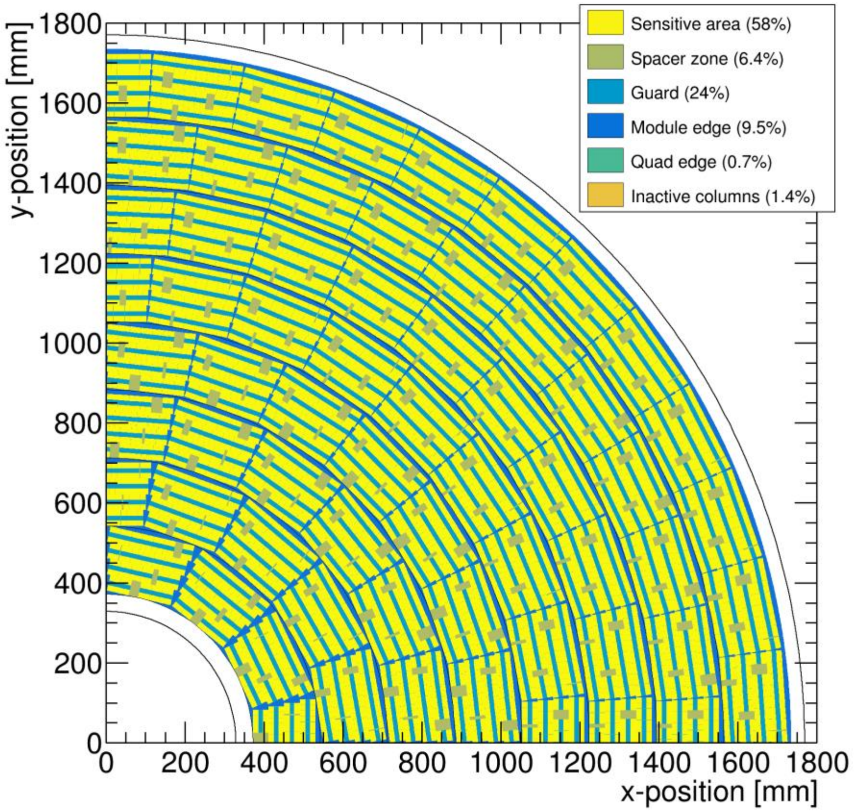


50 GeV muon track with pixel readout

Performance of a GridPix TPC at ILC

- From full simulation the momentum resolution can be determined
- Momentum resolution is about 15% better for the pixels with realistic coverage (with the quads arranged in modules coverage 59%) and deltas.



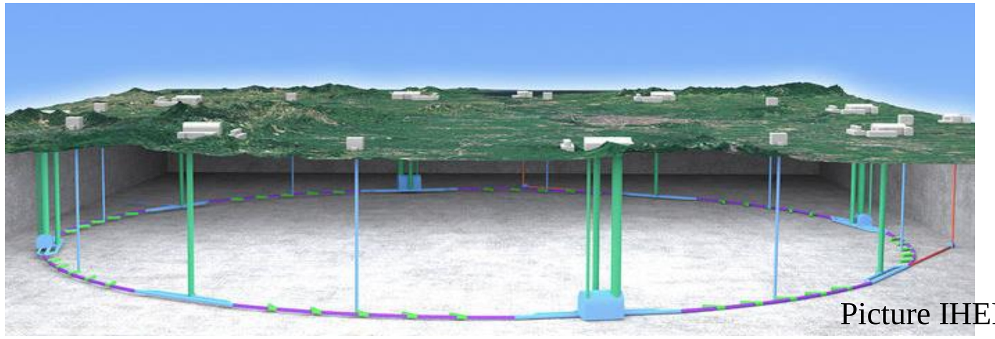


Summary of the Pixel TPC performance

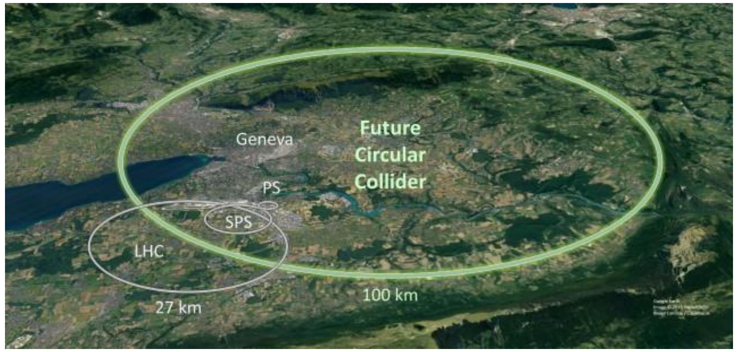
- A single chip GridPix detector was reliably operated in a test beam in 2017
  - Single electron detection => the resolution is primarily limited by diffusion
  - Systematic uncertainties are low: < 10 μm in the pixel xy plane
  - dE/dx resolution for a 1 m track is 4.1%
- A Quad detector was designed and the results from the 2018 test beam shown
  - Small edge deformations at the boundary between two chips are observed
    - added guard wires to the module to obtain a homogeneous field
  - After correcting the edges, deformations in the transverse plane shown to be < 15 μm
- An 8-Quad module has been designed with guard wires
- Preliminary test beam results are excelllent deformations (in xy or z) < 15 μm
- A test beam @ FermiLab with the module in a TPC is planned (US Grant EIC)
- A pixel TPC has become a realistic viable option for experiments
  - High precision tracking like ILD@ILC in the transverse and longitudinal planes, dE/dx by electron and cluster counting, excellent two track resolution, digital readout that can deal with high rates

A Pixel TPC at CEPC or FCC-ee

The most difficult situation for a TPC is running at the Z.
At the Z pole with $L = 200\ 10^{34}\ cm^{-2}\ s^{-1}$ Z bosons will be produced at ~60 kHz



Picture IHEP



- Can a pixel TPC reconstruct the events?
  - The TPC total drift time is about 30 μs
  - This means that there is on average 2 event / TPC readout cycle
  - YES: The excellent time resolution: time stamping of tracks < 1.2 ns allows to resolve and reconstruct the events
- Can the current readout deal with the rate?
  - Link speed of Timepix3 (in Quad) is 80 Mbps: 2.6 MHits/s per $1.41 \times 1.41\ cm^2$
  - YES: This is largely sufficient to deal with high luminosity Z running
  - NB: Data size is not a show stopper as e.g. LHCb experiment shows using the VeloPix chip

A Pixel TPC at CEPC or FCC-ee

- What is the current power consumption?
  - No power pulsing possible at these colliders (at ILC power pulsing was possible)
  - Current power consumption TPX3 chip ~2W/chip per 1.41×1.41 cm^2
  - So: good cooling is important but in my opinion no show stopper
  - For Silicon detectors lower consumption for the chips and cooling is an important point that needs R&D (e.g. microchannel cooling).
  - Note that the TPX3/4 chips can be run in LowPowerMode
- Can one limit the track distortions?
  - There are two important sources of track distortions:
    - the distortions of the TPC drift field due to the primary ions
    - the distortions of the TPC drift field due to the ion back flow (IBF)
  - At the ILC gating is possible; for CEPC or FCC-ee this is more involved

A Pixel TPC at CEPC or FCC-ee

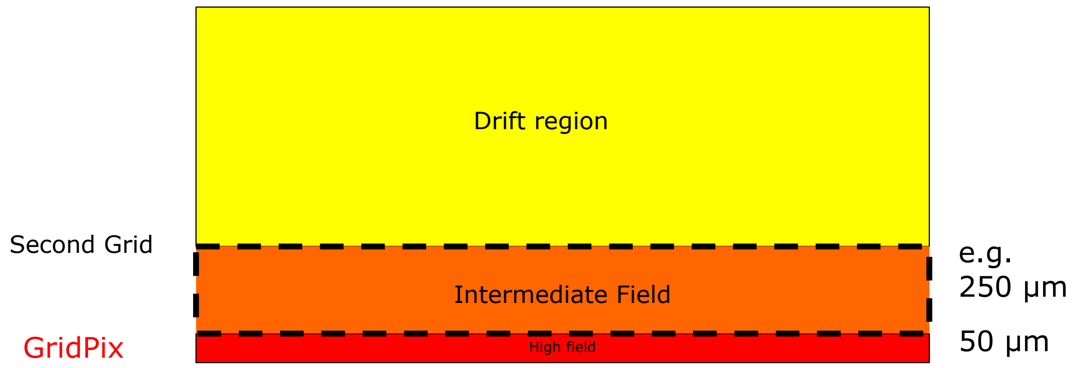
- Is it possible to reduce the IBF for a pixel TPC?
  - IDEA: by making chip with a double grid structure (see next slide)
  - This idea was already realized as a TWINGRID NIMA 610 (2009) 644-648
  - For GEMs for the ALICE TPC this was also the way – several GEMs on top of each other to reduce IBF
  - For the Pixel the IBF can be easily modelled and with a hole size of 25 μm an IBF of 3 10^{-4} can be achieved and the value for IBF*Gain (2000) would be 0.6.
  - YES: the IBF can be reduced to 0.6 but this needs R&D
  - In the new detector lab in Bonn it is possible to make and study this device
- What would be the size of the TPC distortions?
  - Recent Tera-Z studies by Daniel Jeans and Keisuke Fuji show that for FCC-ee or CEPC this means: distortions from Z decays up to < O(100) μm
  - Beam strahlung gives (now) a factor 200 more background. Detector optimization and shielding is important for TPC and Silicon detectors to reduce pair background.
  - Recently I argued that in an ILD like detector the distortions can be mapped out using the VTX-SIT/SET detectors.

Reducing the Ion back flow in a Pixel TPC

The Ion back flow can be reduced by adding a second grid to the device.

It is important that the holes of the grids are aligned. The Ion back flow is a function of the geometry and electric fields. Detailed simulations – validated by data - have been presented in LCTPC WP #326.

With a hole size of 25 µm an IBF of $3\ 10^{-4}$ can be achieved and the value for IBF*Gain (2000) would be 0.6.



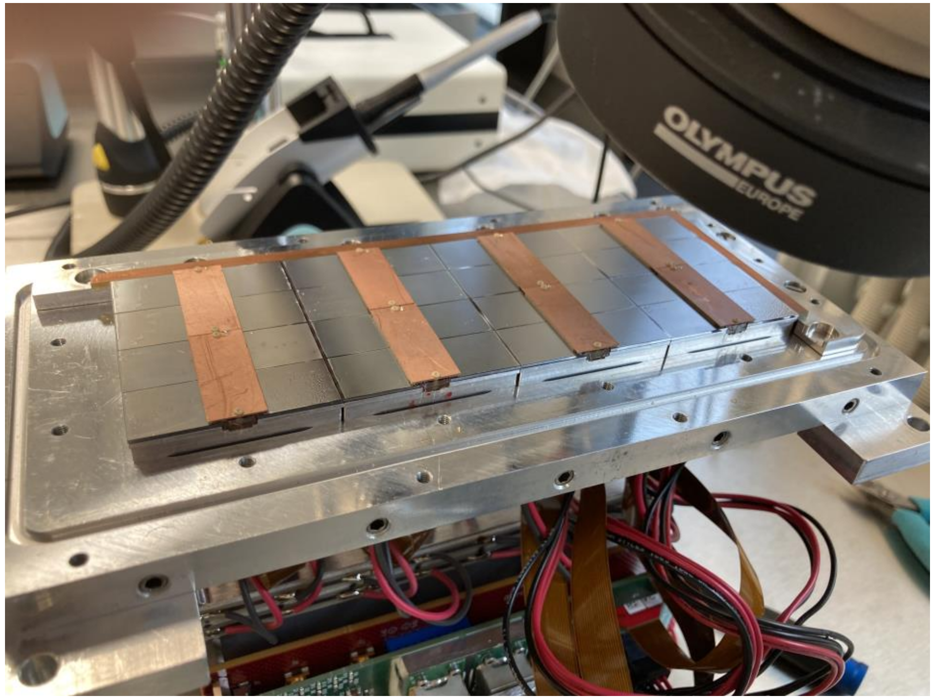
Ion backflow	Hole 30 µm	Hole 25 µm	Hole 20 µm
Top grid	2.2%	1.2%	0.7%
GridPix	5.5%	2.8%	1.7%
Total	$12\ 10^{-4}$	$3\ 10^{-4}$	$1\ 10^{-4}$
transparancy	100%	99.4%	91.7%

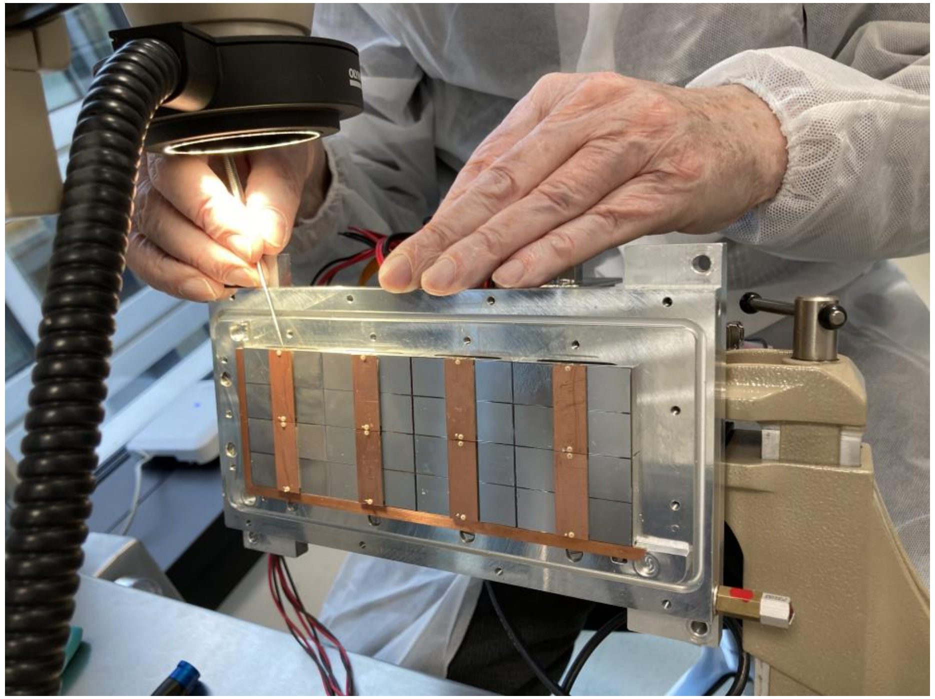
Conclusions: Pixel TPC at CEPC

- YES: a pixel TPC can reconstruct the Z events in one readout cycle
- YES: the current readout of the Timepix3 chip can deal with the rate
- The current power consumption is 1W/cm^2. So good cooling is important but in my opinion no show stopper; but needs extensive R&D.
- Track distortions in the TPC drift volume are a concern at high lumi Z running:
  - Track distortions from Z decays in TPC are O(100) μm
  - It is possible to reduce the IBF for a pixel TPC by making a device with a double grid
  - This needs dedicated R&D that can be performed in the new lab in Bonn
- The Z physics program at FCC-ee or CEPC with an ILD-like detector with a Pixel TPC (with double grid structures) sliced between two silicon trackers (VTX-SIT and SET) can be fully exploited. The reduction of beamstrahlung needs more study.
- A pixel TPC can perfectly run at WW, ZH or tt energies where track distortions are several orders of magnitude smaller

Backup

Pictures of repair work in Bonn for the EIC TPC project





The short in chip 11 was succesully repaired by Fred Hartjes

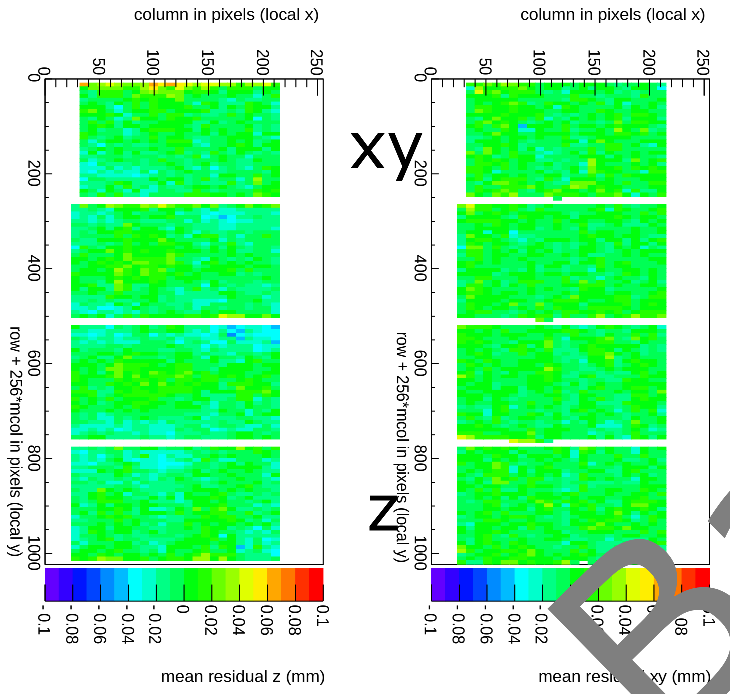
DESY testbeam Module Analysis

Runs 6909, 6916-17, 6934-35 B=0 T p =6,5 GeV

Mean residuals (module) row

(module) column

column 256 pixels

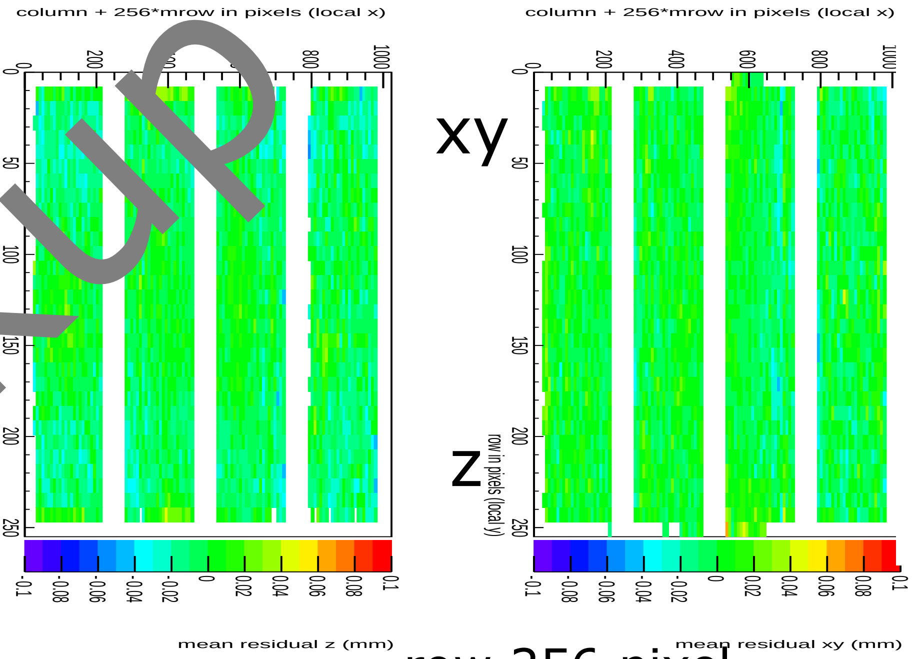


row 4x256 pixels

Preliminary

Backup

column 4x256 pixels



row 256 pixel

Regrouping the module plane to increase stats

Granularity 8x8 pixels

acceptance cut
entries > 1500

For the row plot the data is projected keeping 4 bins in local y (one follows the track)

For the column plot the 4 chip rows are kept separately (that is why there are white bands)