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

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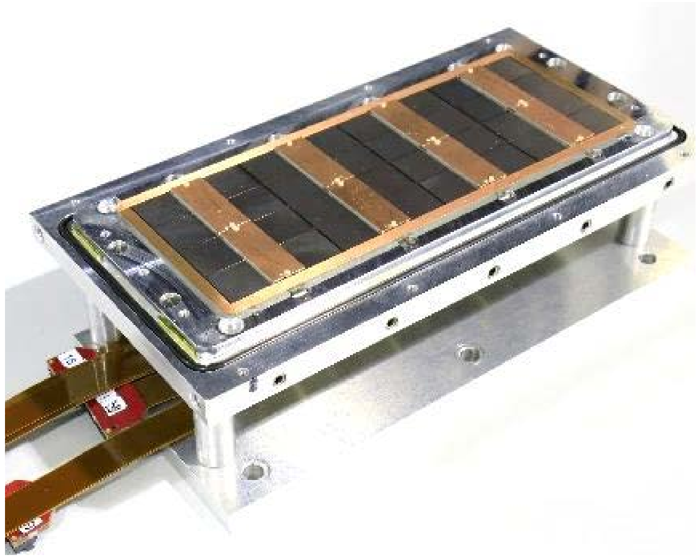
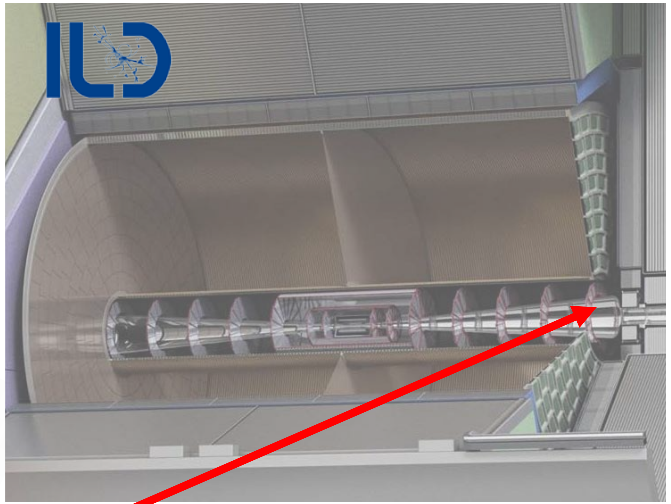
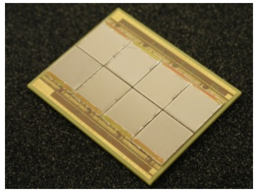


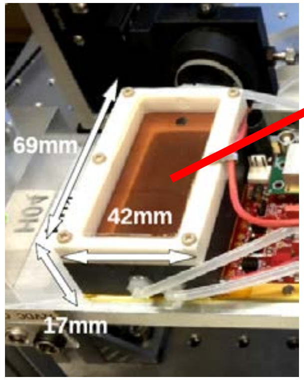
CEPC meeting 26 October 2022

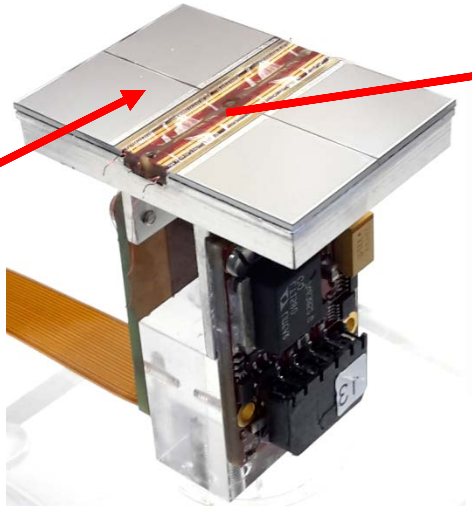
Pixel TPC

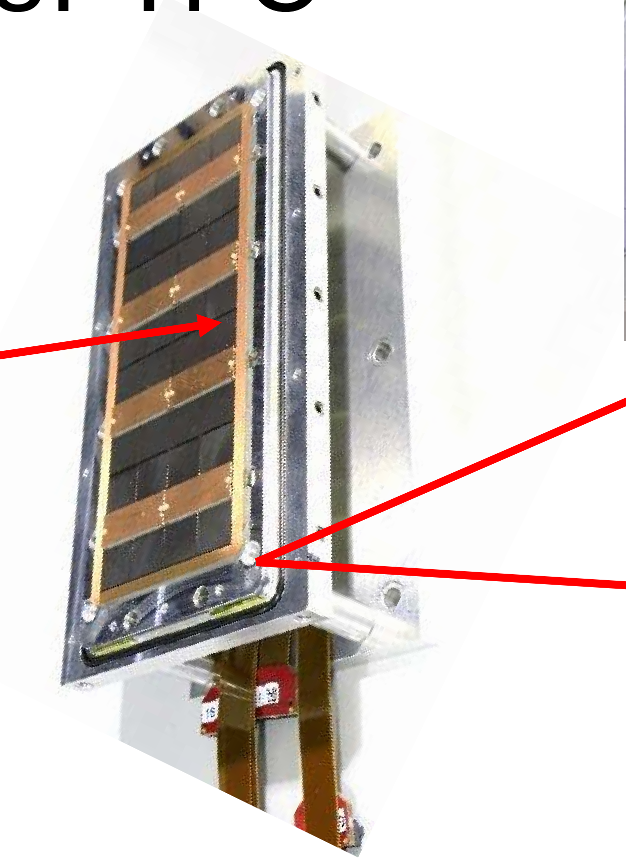


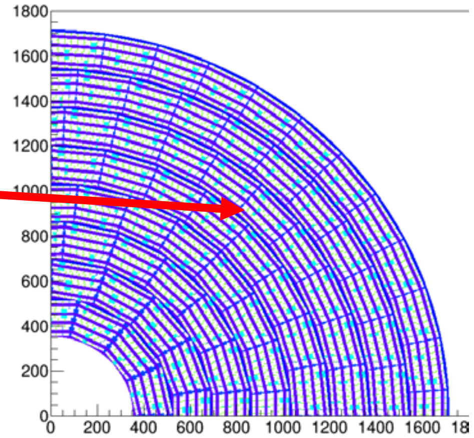


(Octopuce)



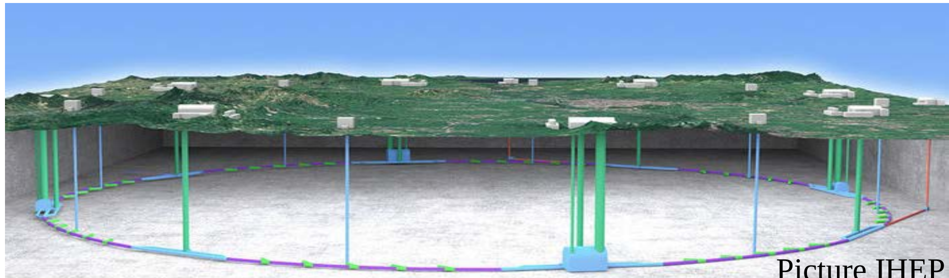




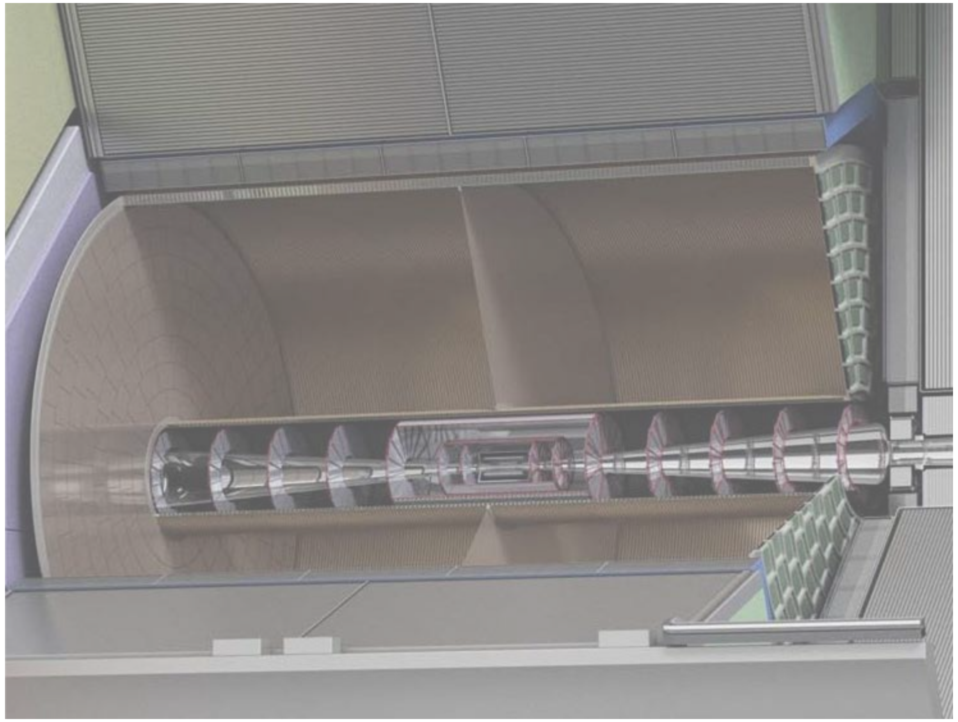


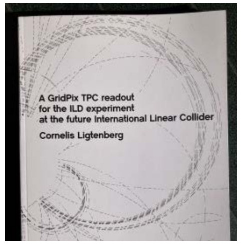
(TimePix1) TPX3 chip Quad Module TPC plane

(2007-14) 2017 2018 2019



Pixel TPC



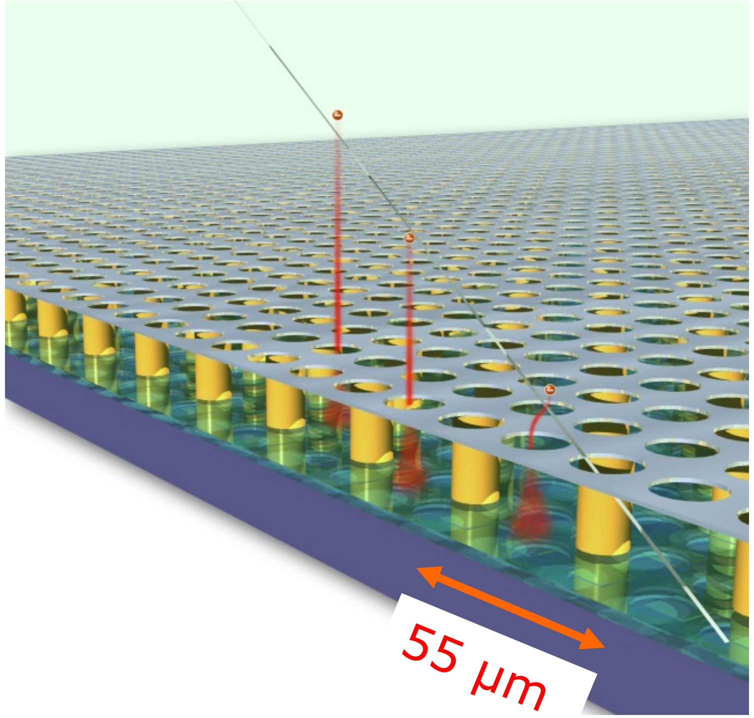


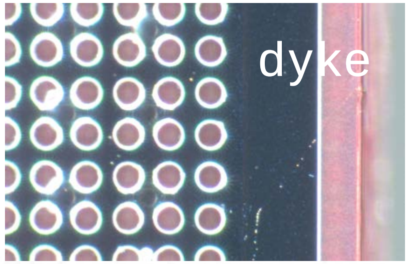
- Material budget is
  - 0.01 X_0 TPC gas
  - 0.01 X_0 inner cylinder
  - 0.03 X_0 outer cylinder
  - < 0.25 X_0 endplates (incl readout)
- Note the very low budget in the barrel region. Material budget can be respected by different technologies like GEM, MicroMegas and Pixels
- TPC is sliced between 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

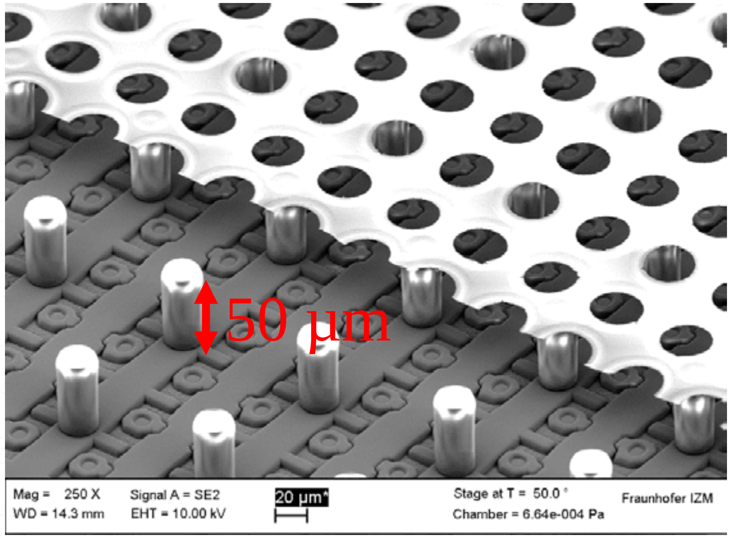
GridPix technology

- 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



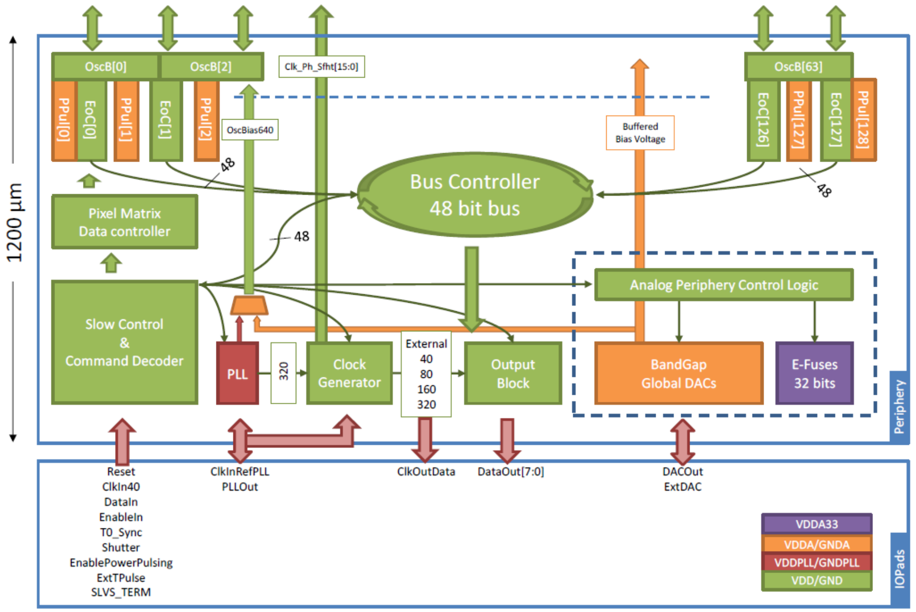


- Aluminium grid (1 µm thick)
- 35 µm wide holes, 55 µm pitch
- Supported by SU8 pillars 50 µm high
- Grid surrounded by SU8 dyke (150 µm wide solid strip) for mechanical and HV stability



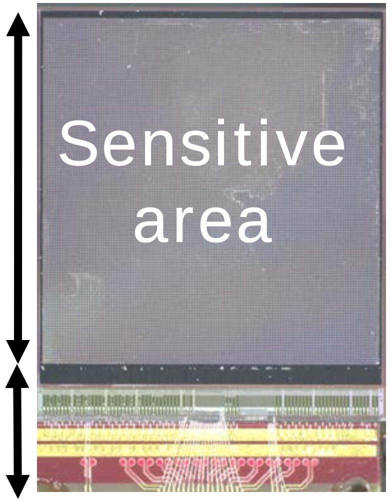
Pixel chip: TimePix3

- 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

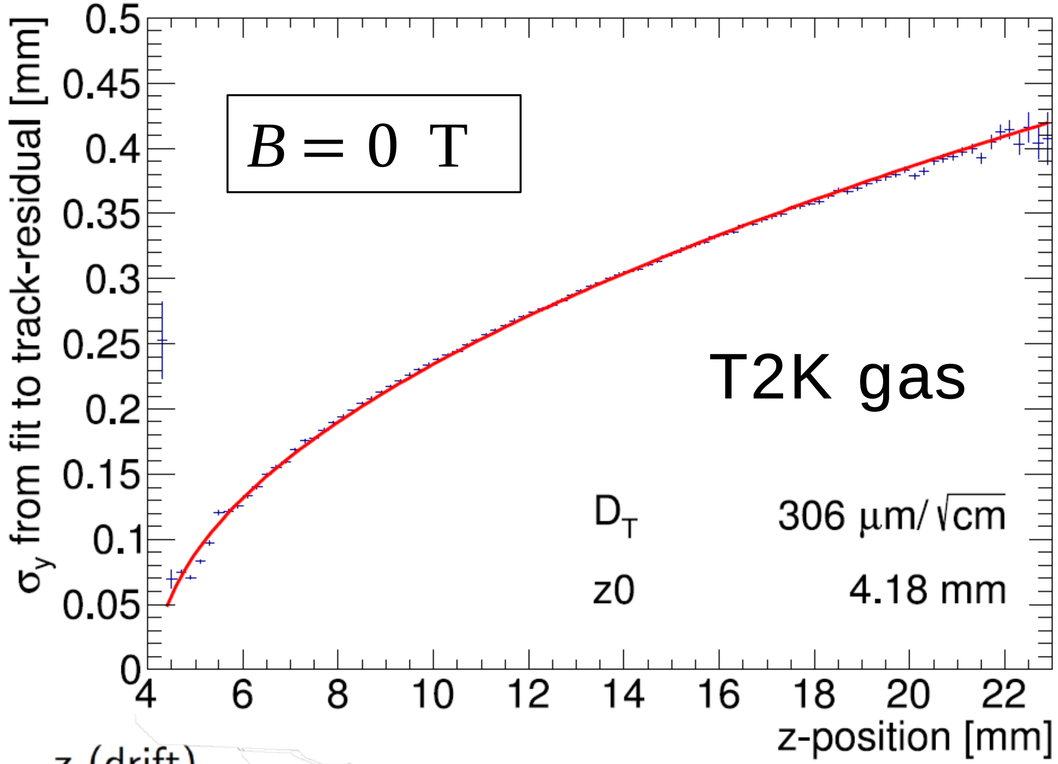


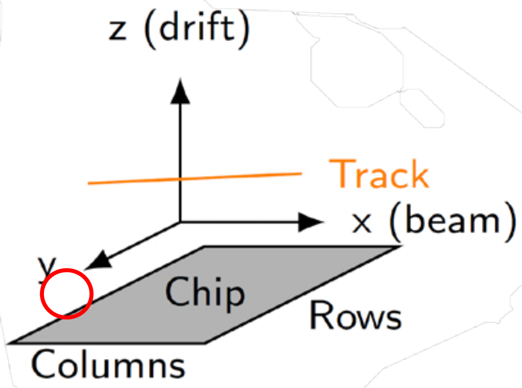
14.1 mm

2+3 mm



Single hit resolution in transverse direction





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

($318 \pm 7\ \mu\mathrm{m}/\sqrt{\mathrm{cm}}$ 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:

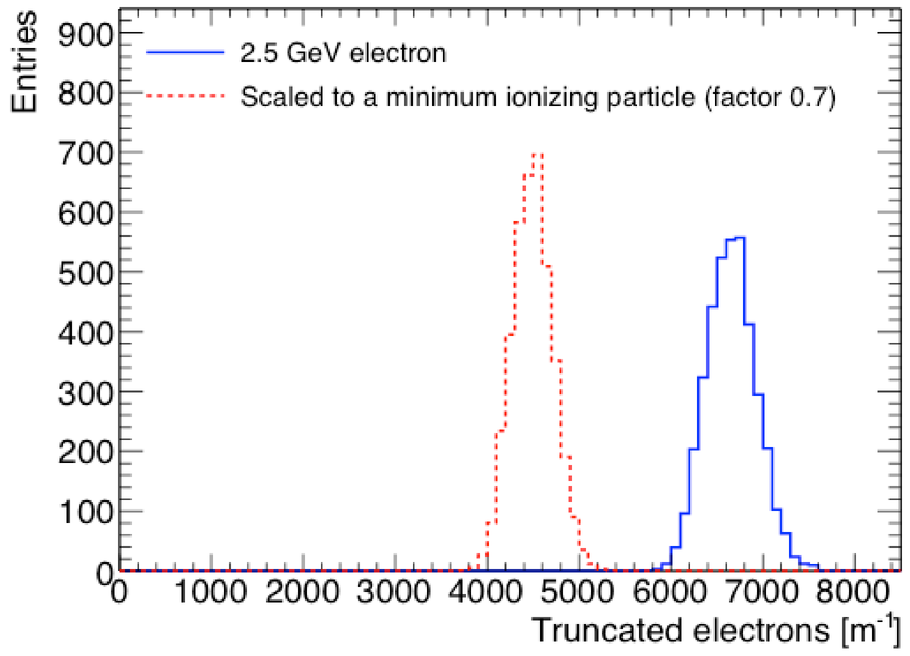
- A hit resolution of ~250 µm is ~25 µm for a 100-hit track (~ 1 cm track length)
- At $B = 4$ T , $D_T = 25\ \mu\mathrm{m}/\sqrt{\mathrm{cm}}$

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

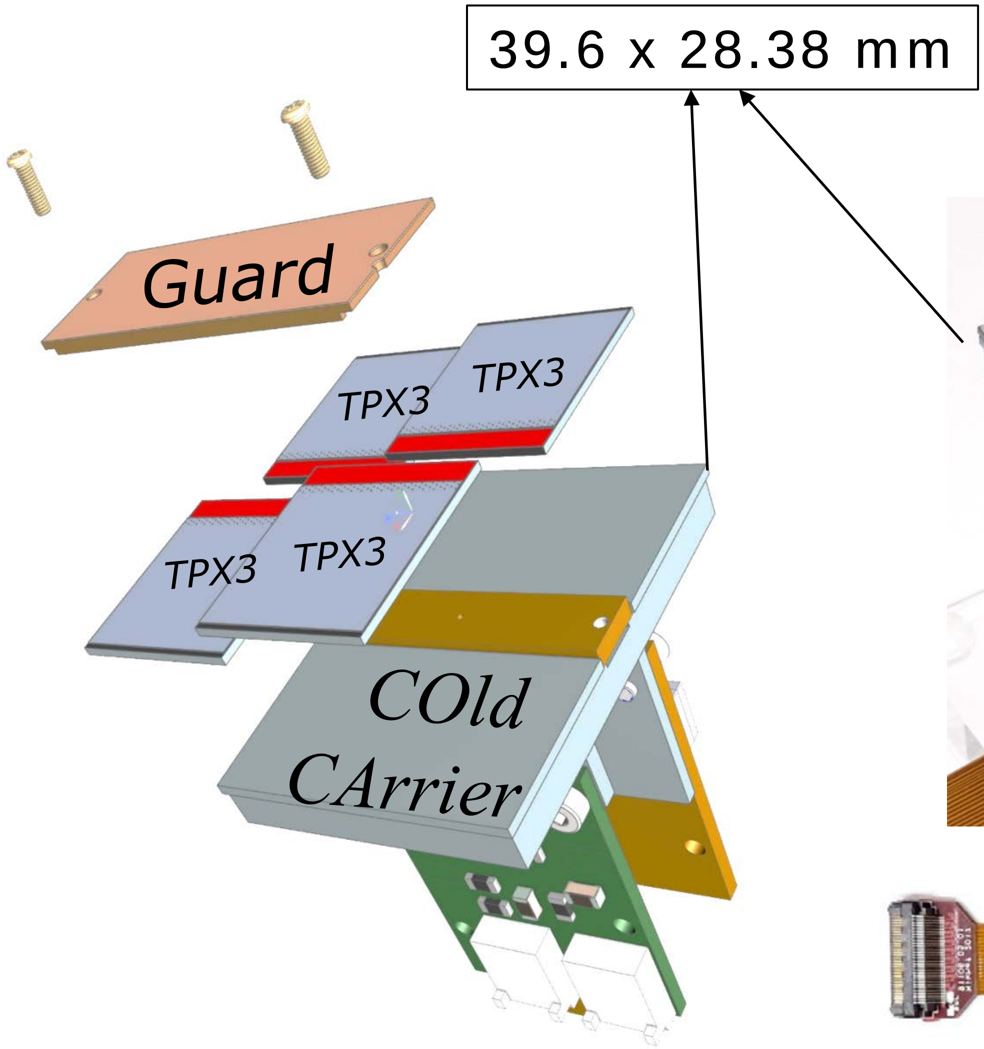
- A pixel readout can in principle within the resolution (diffusion) separate primary from secondary clusters. dE/dx can be measured by cluster counting and performance separation enhanced.

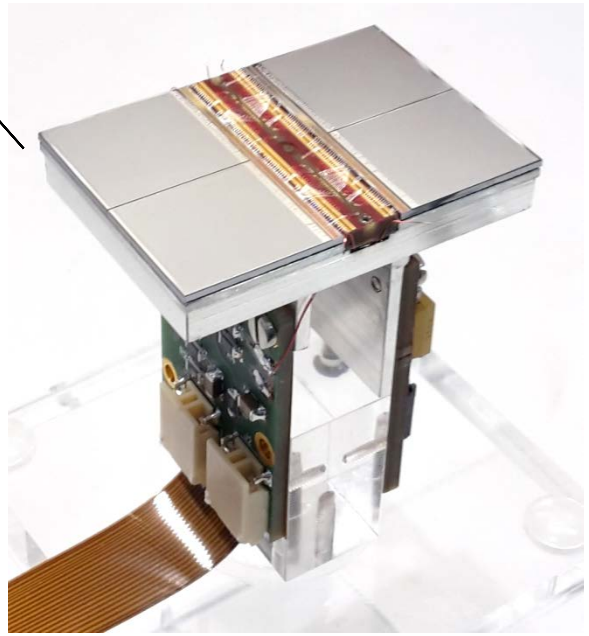


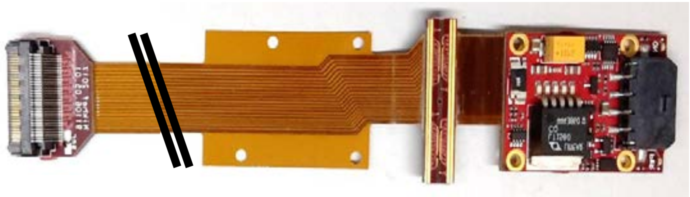
QUAD design and realization

series of QUADs

- 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



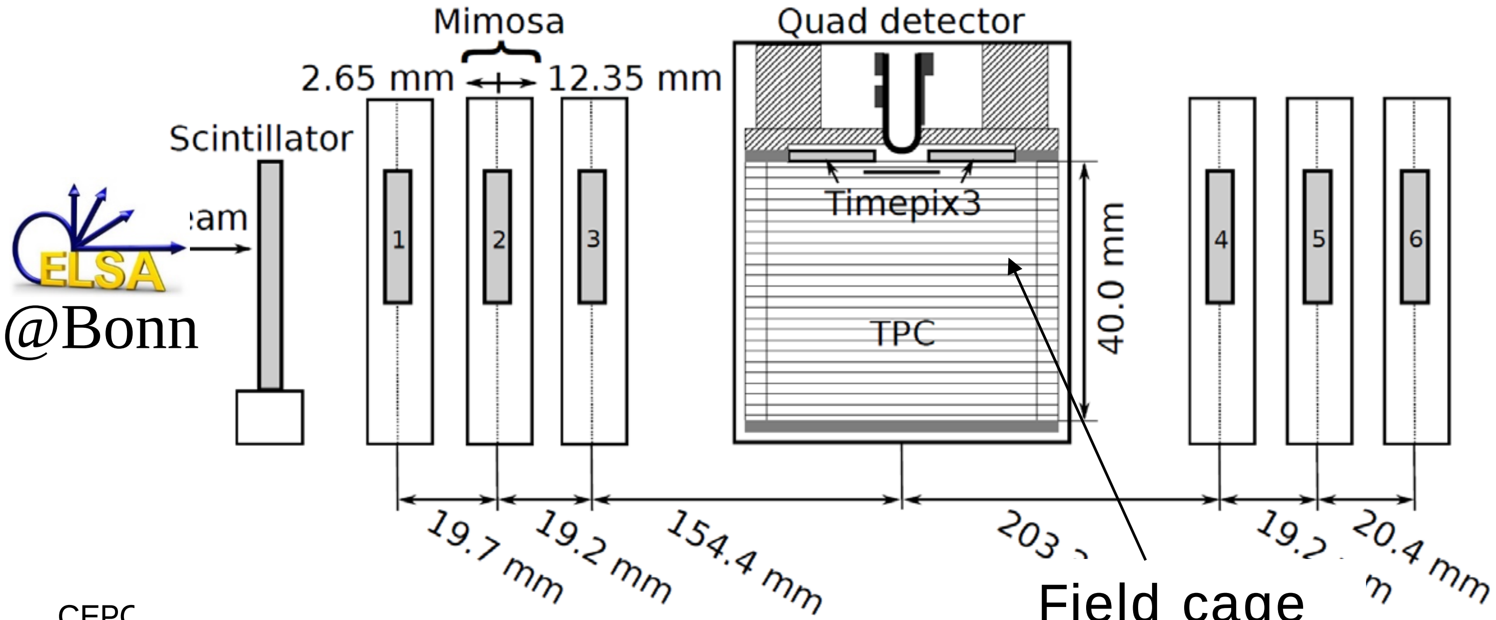


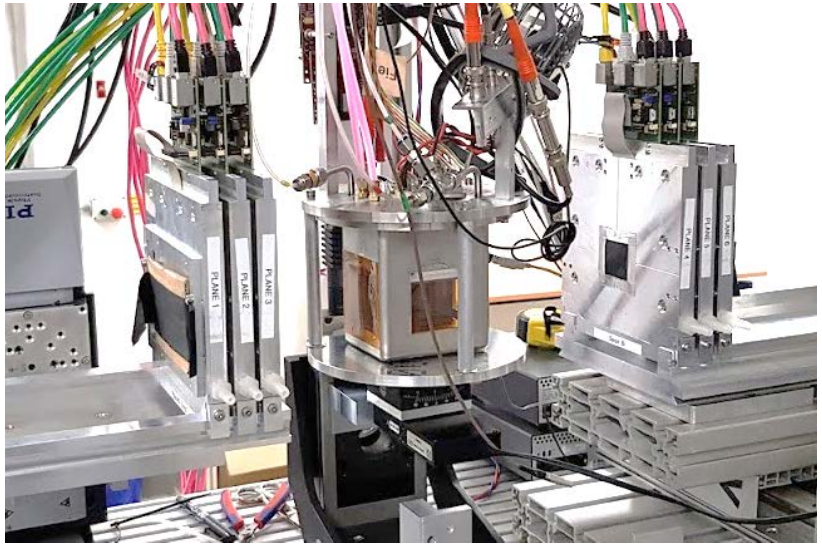


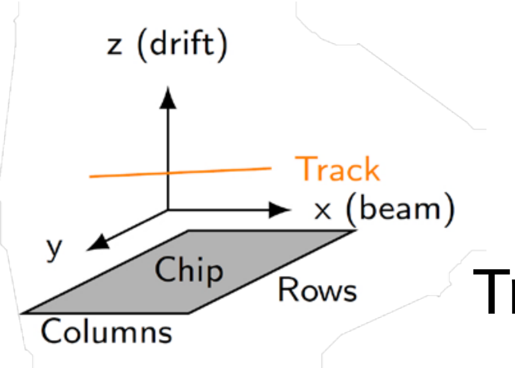
QUAD test beam in Bonn (October 2018)

- 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

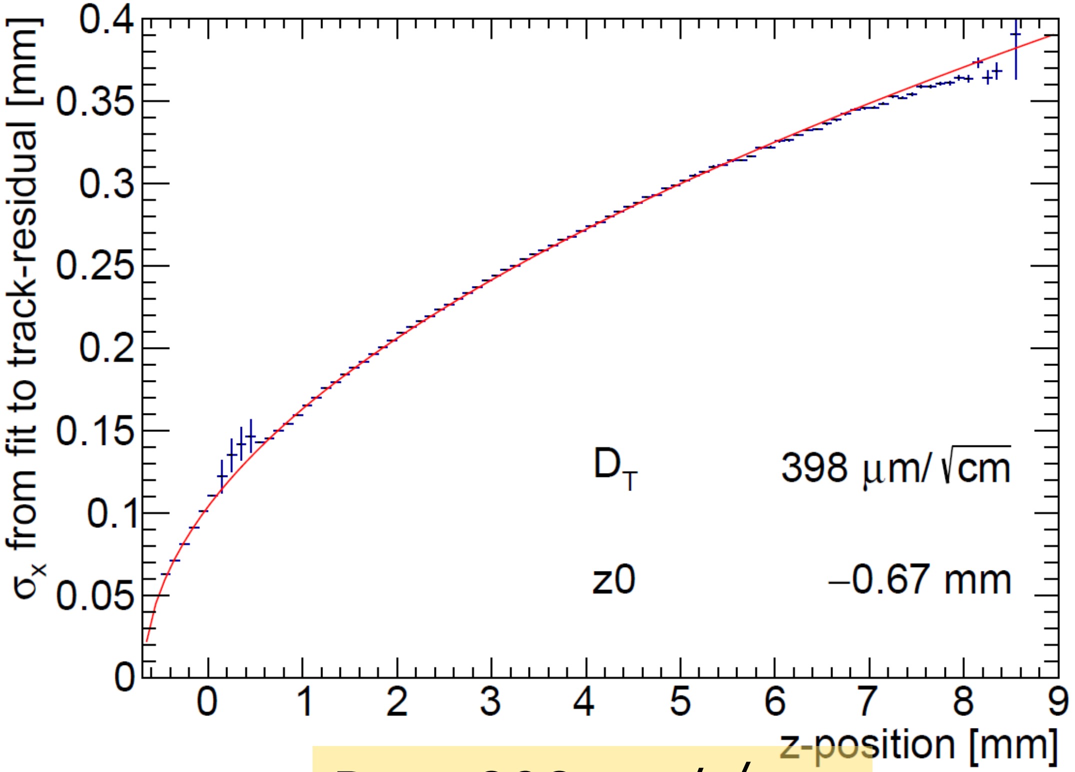






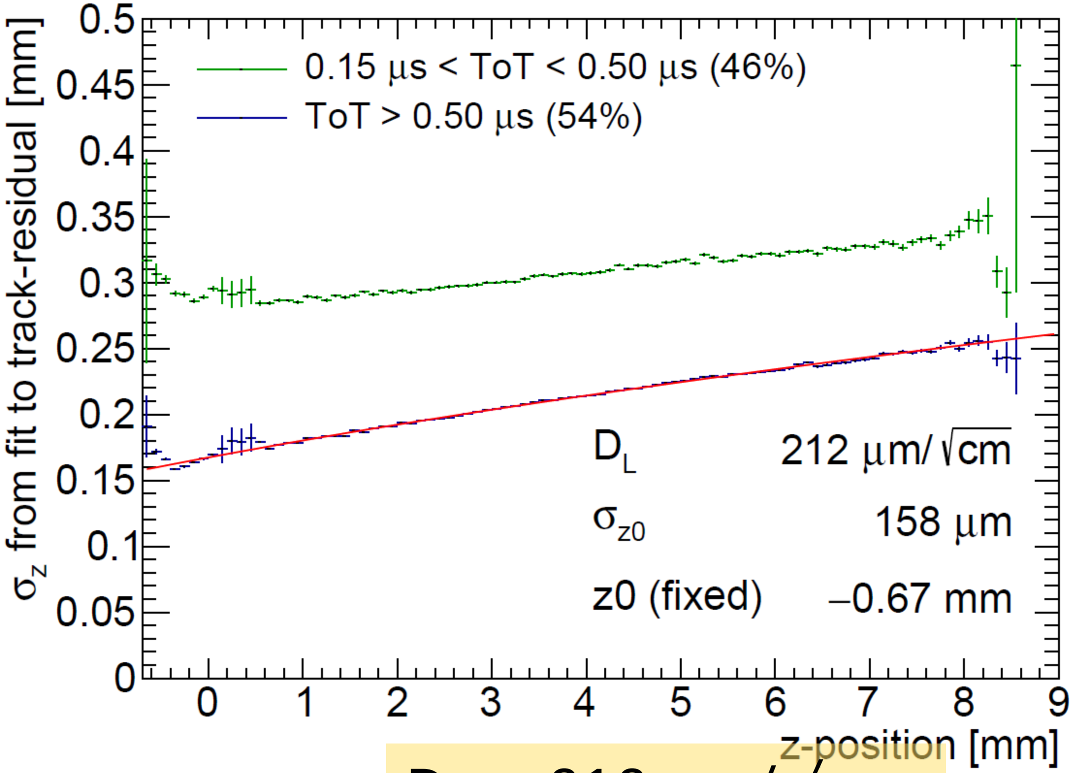
QUAD single hit resolution

Transverse



D_T = 398 µm/√cm

Longitudinal

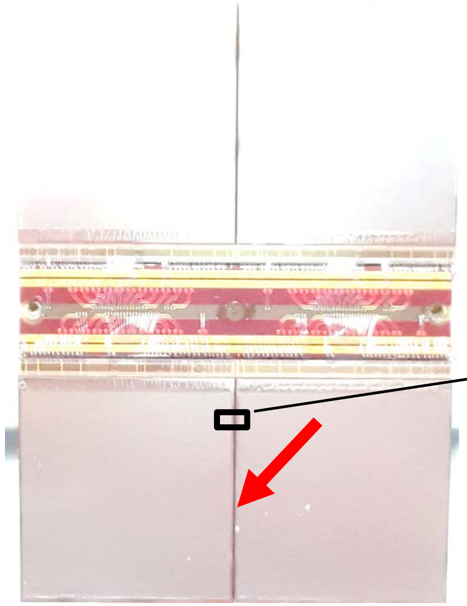


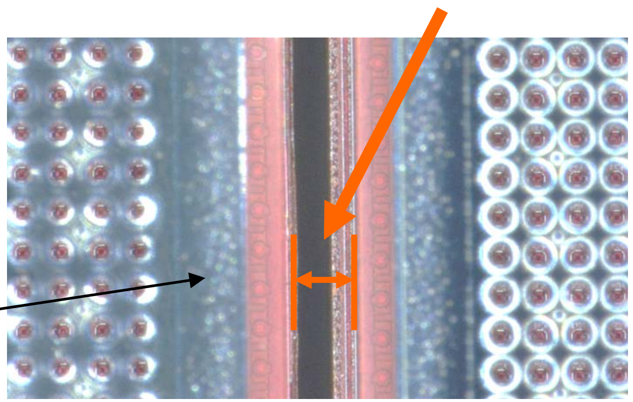
D_L = 212 µm/√cm

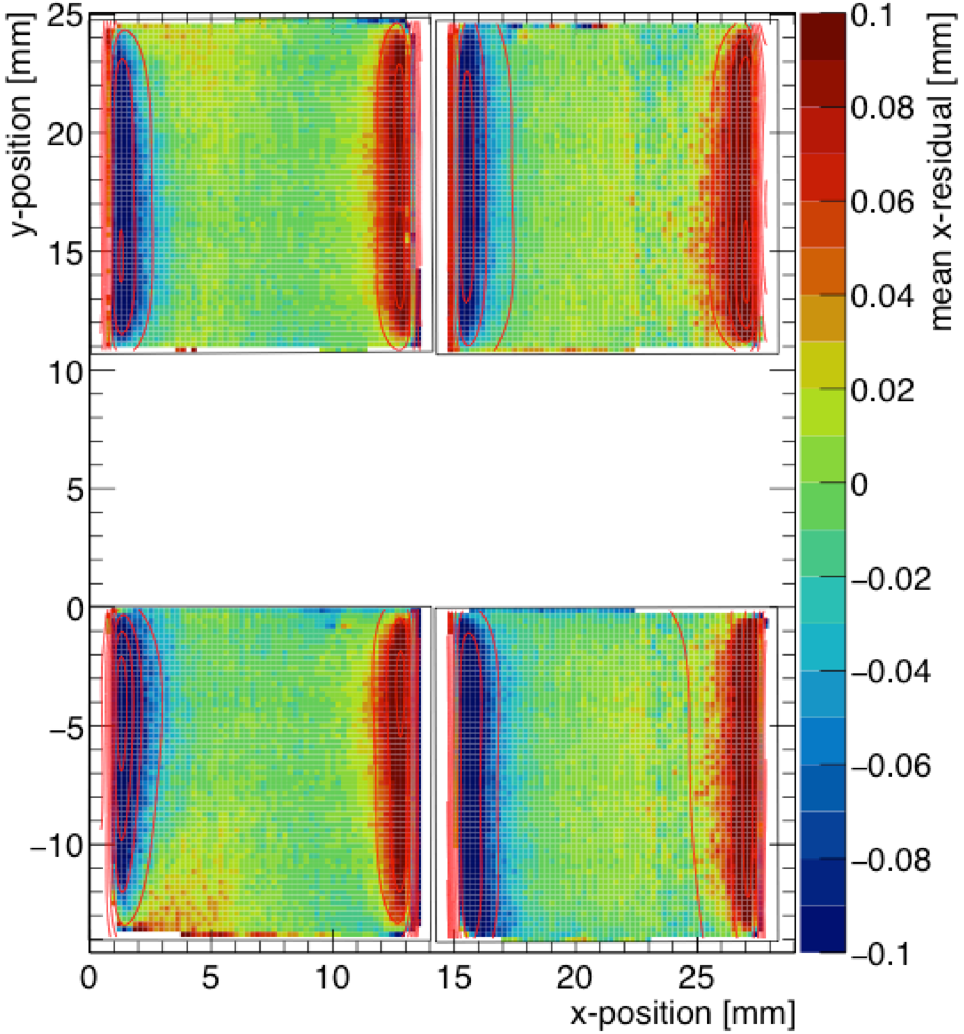
The D_T value is rather high due to an error in the gas mixing (too low CF4)

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

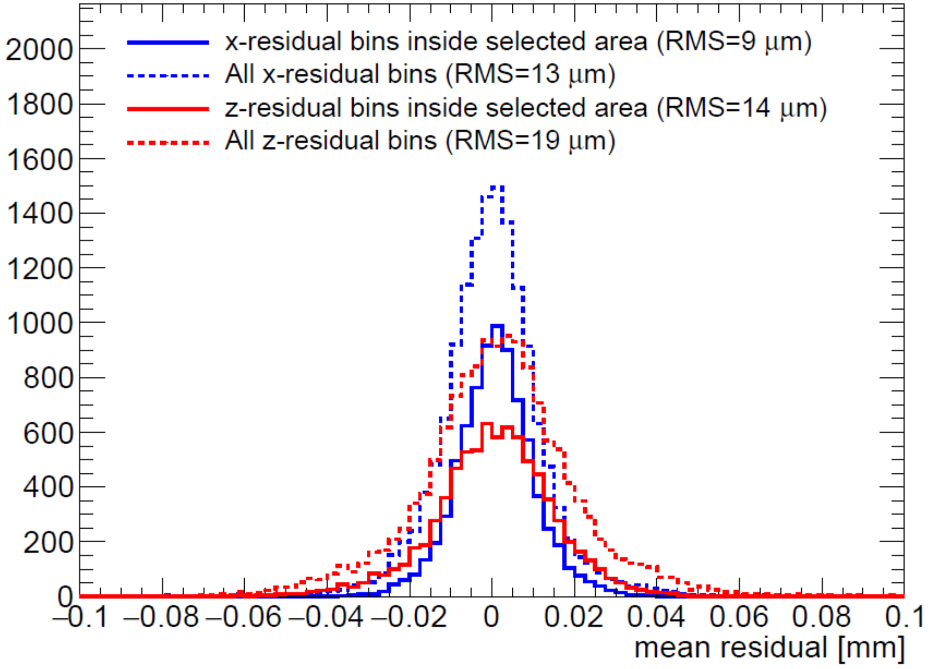


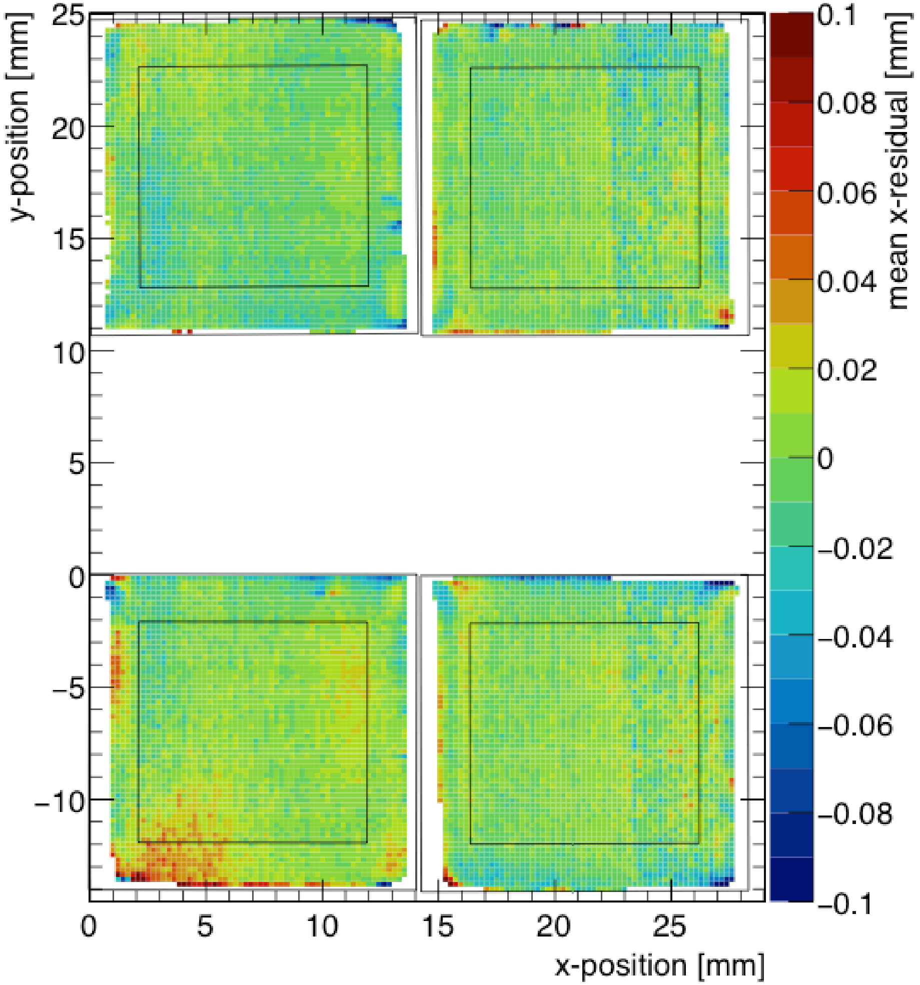




QUAD deformations in transverse plane (XY)

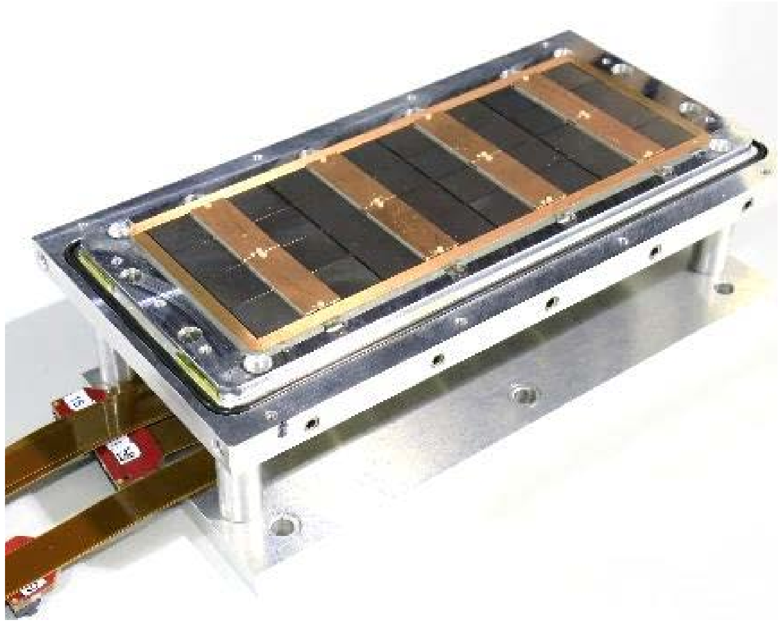
- After applying fitted edge corrections
- RMS of the mean residuals are 13 μm over the whole QUAD

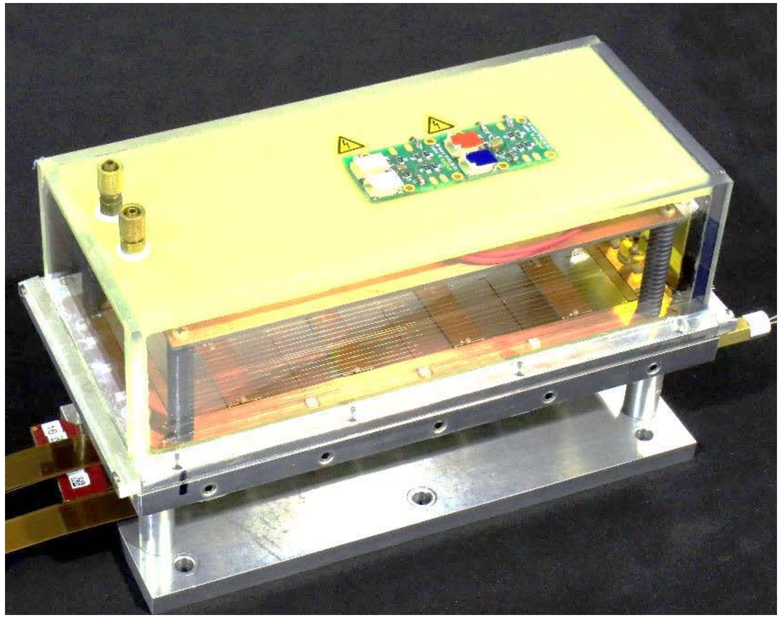


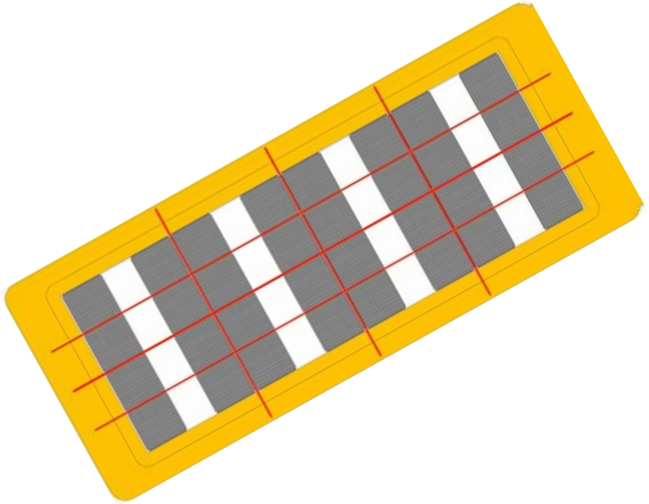


QUAD as a building block

8-QUAD module (2x4) with field cage

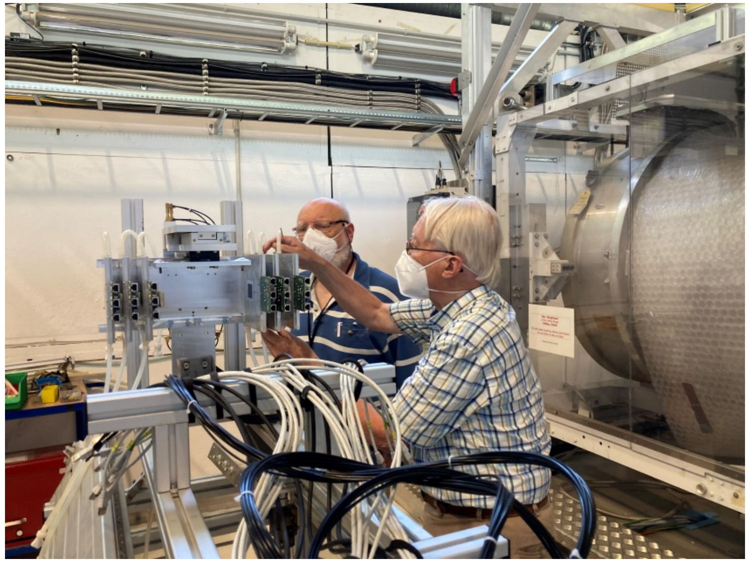
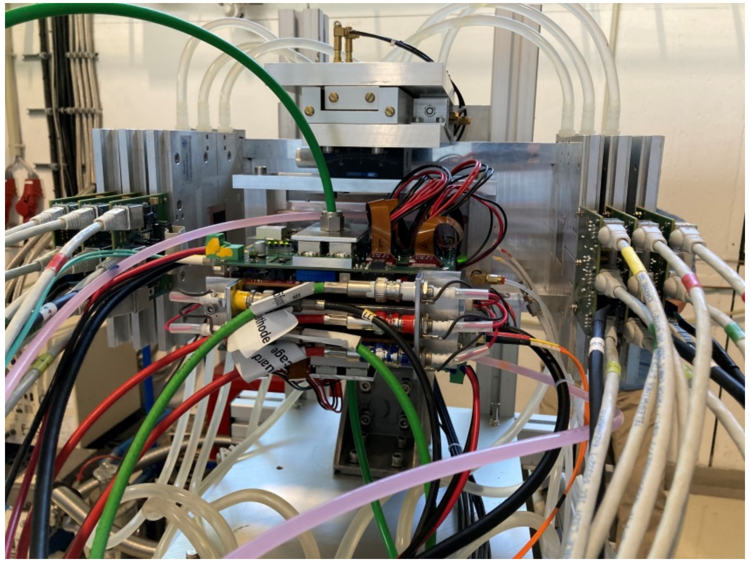
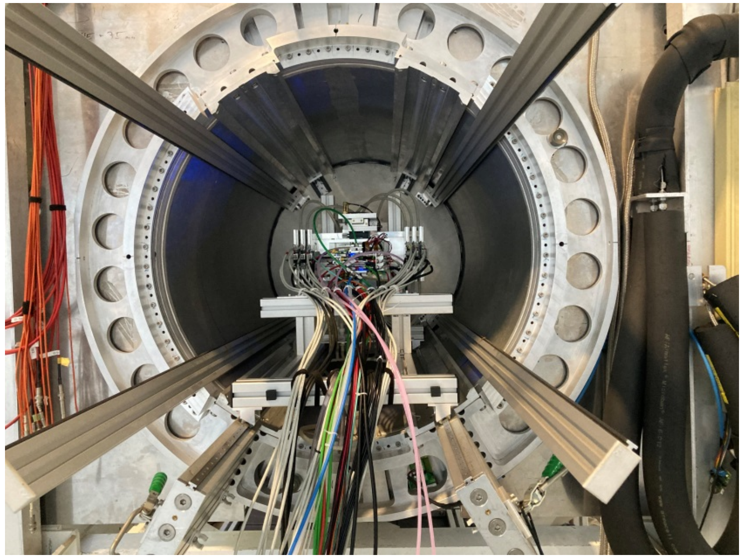






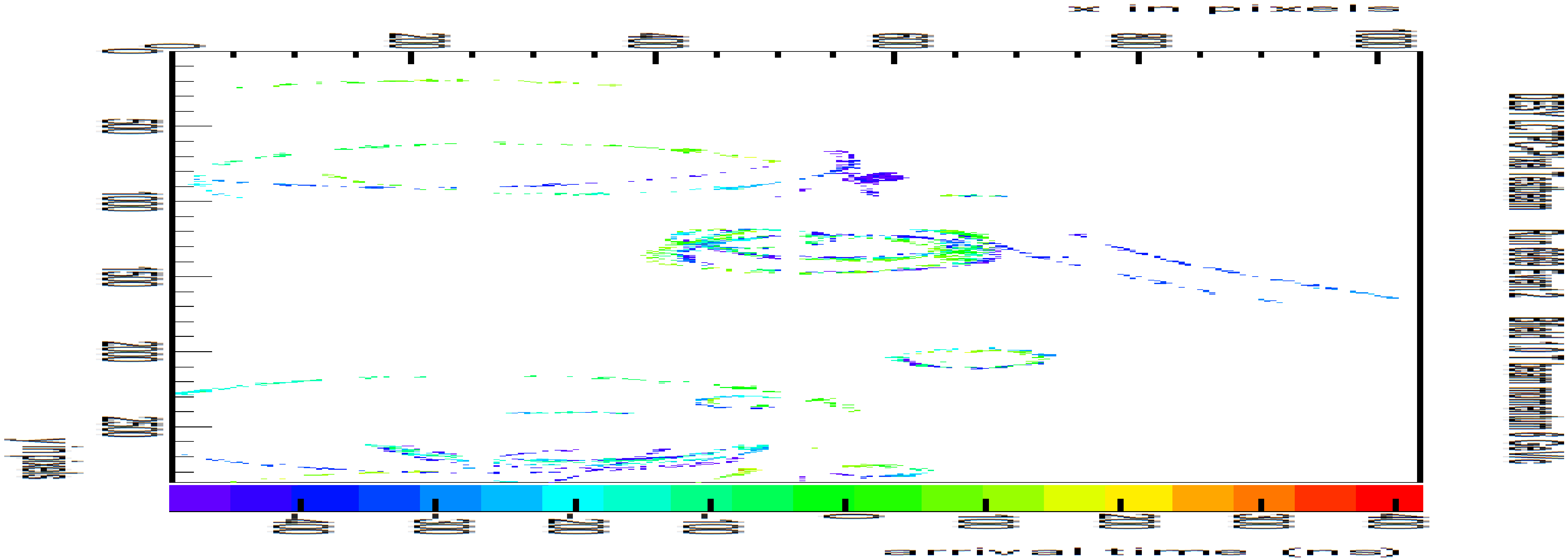
in red guard wires

DESY testbeam June 2021

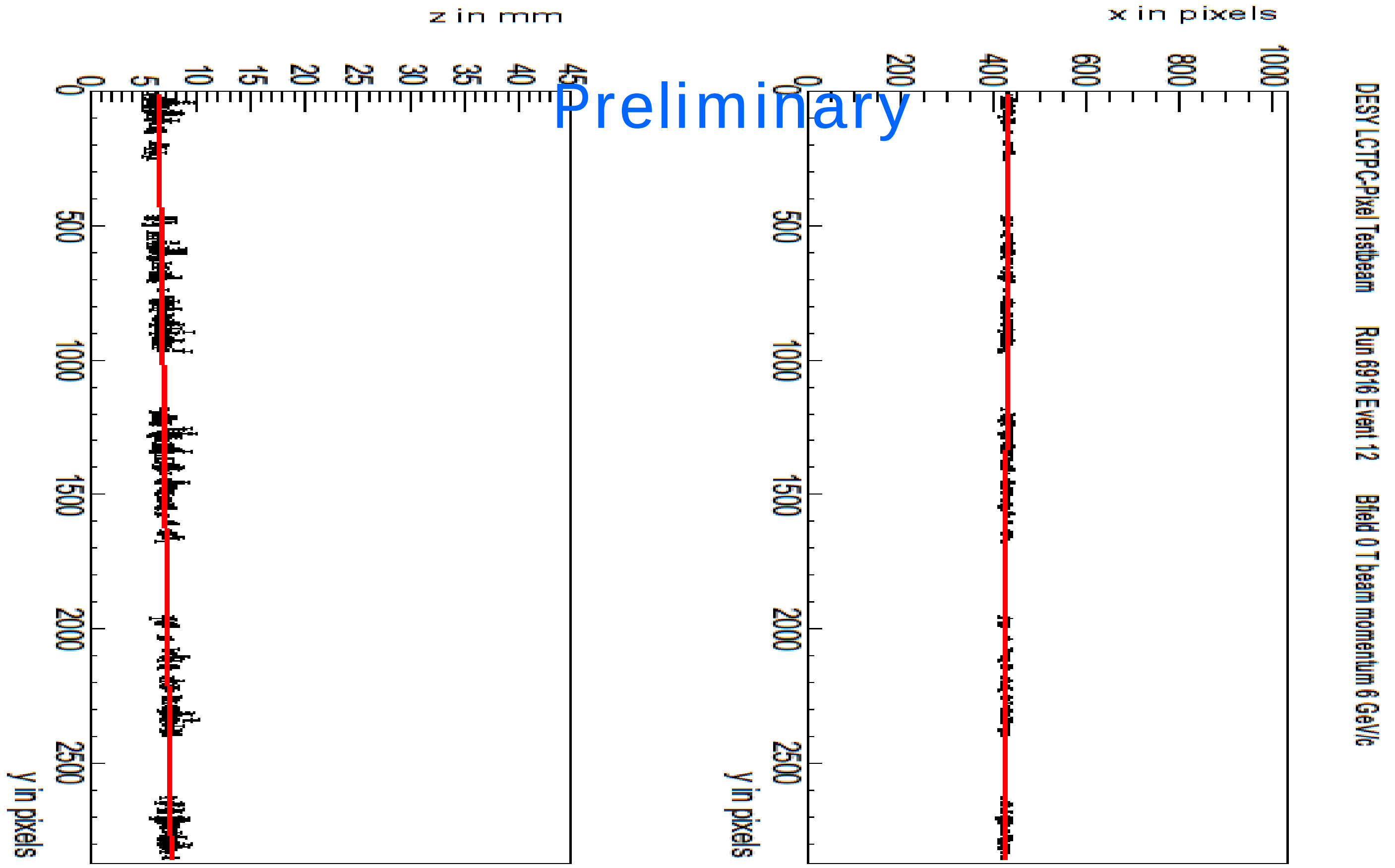




Mounting the 8 quad module between the silicon planes
sliding it into the 1 T PCMAG solenoid

DESY testbeam June 2021



DESY testbeam Module Analysis



Track 1050 hits

χ^2_{xy} = 912/1048

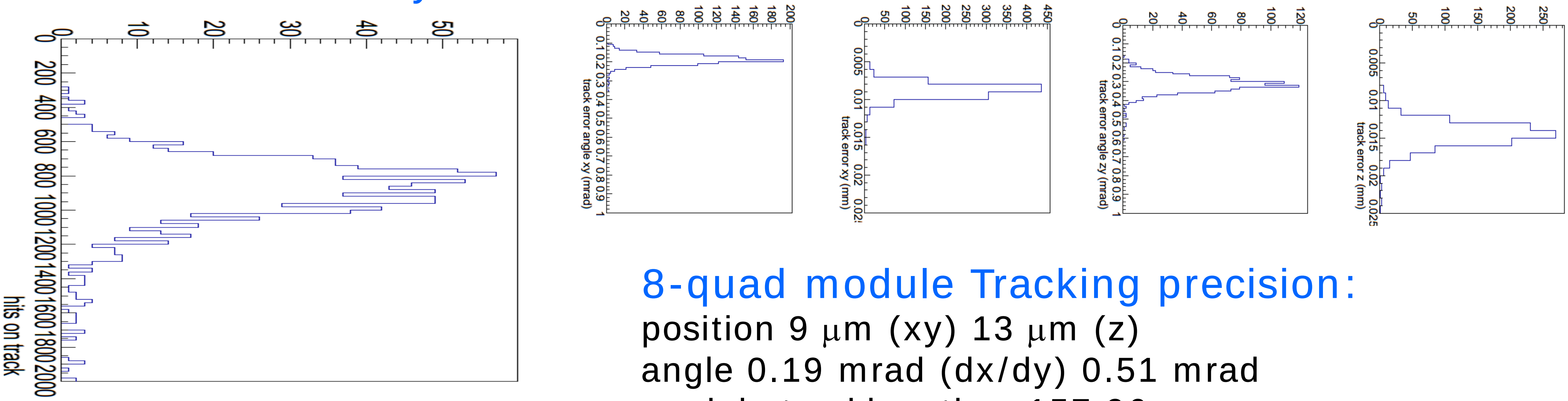
χ^2_z = 1740/1048

(no asymmetric tail (z time slewing) or outlier removal applied yet)

DESY testbeam Module Analysis

Run 6916 B=0 T p =6 GeV

Preliminary



1060 selected tracks
Impressive 900 hits / track

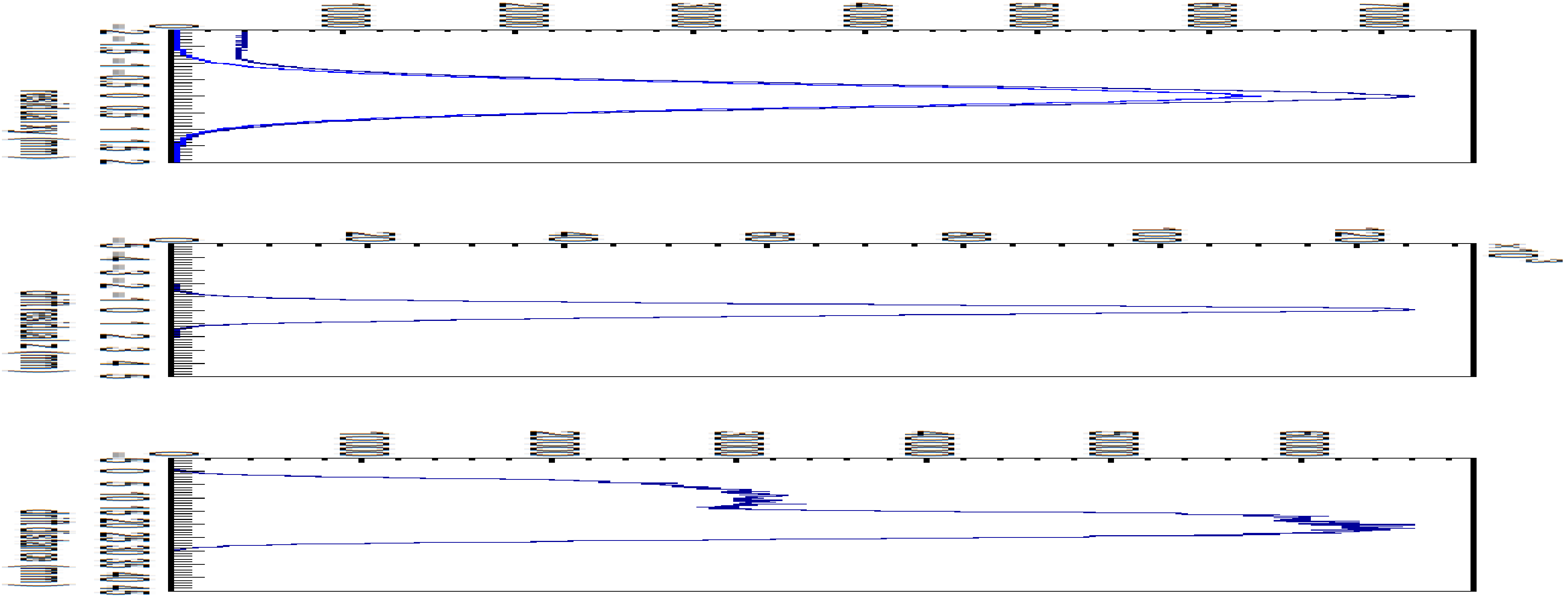
8-quad module Tracking precision:

position 9 μm (xy) 13 μm (z)
angle 0.19 mrad (dx/dy) 0.51 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 B=0 large stats

Preliminary



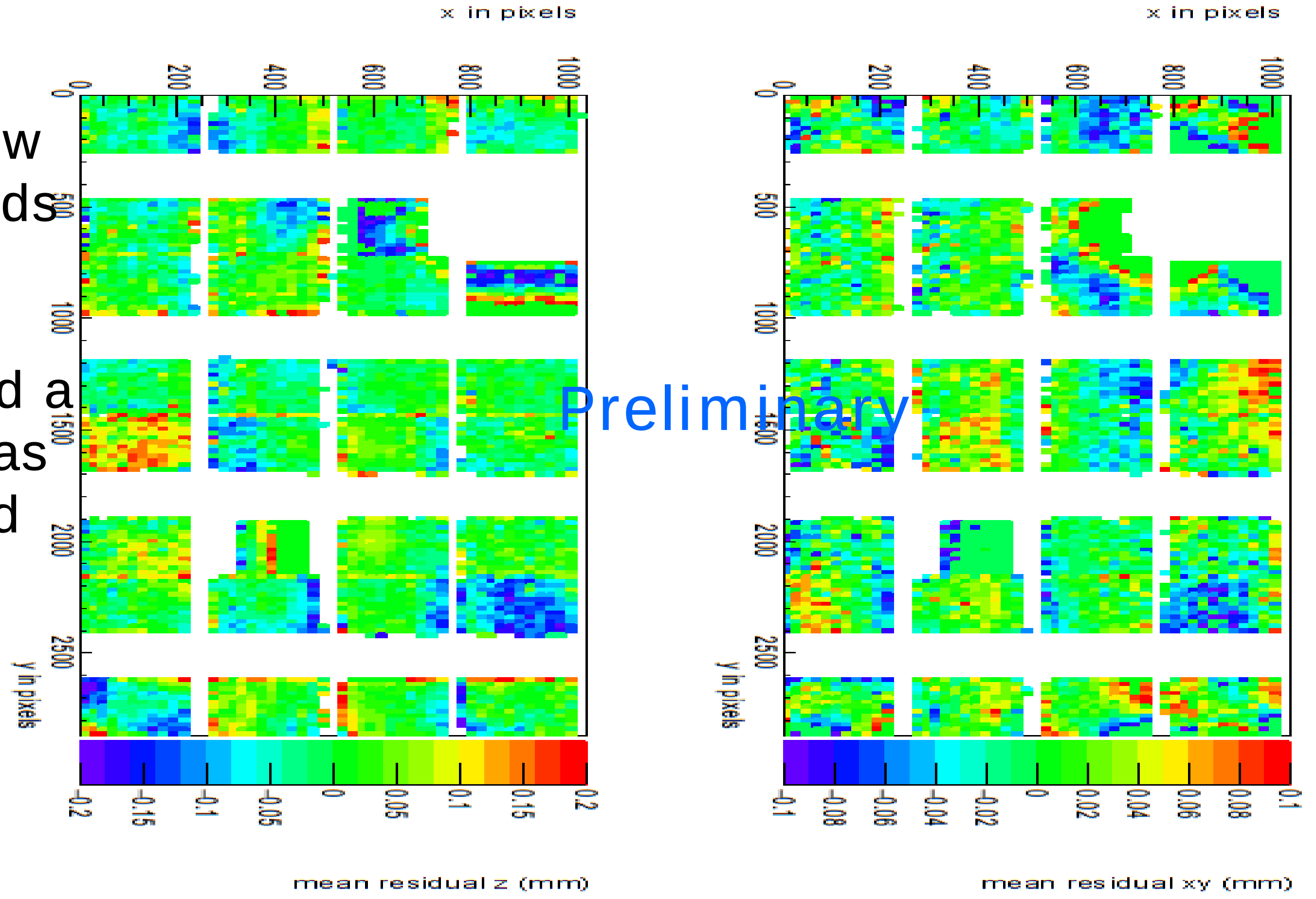
Before and after selection

DESY testbeam B=0 deformations

Here top view of the 8 quads (31 chips)

One chip had a short and was disconnected

beam



Mean residuals in xy (bottom plot z) in 20x20 pixel bins using the TPX3 track fit

All alignment and other corrections come from Telescope track residuals

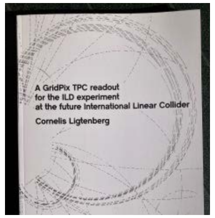
Results look fine

Only 6k tracks, need to analyse more data

Vertical white bands => guards

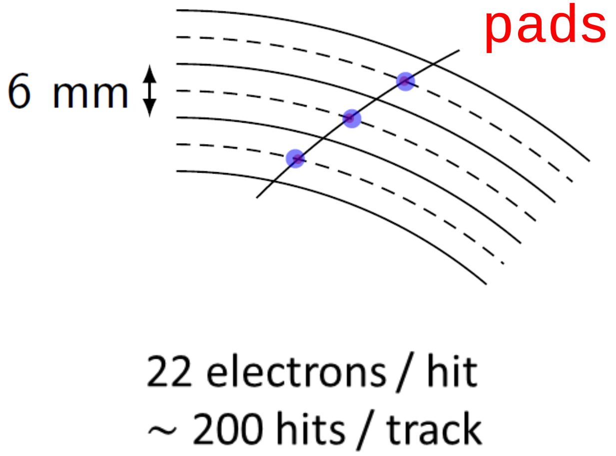
Simulation of ILD TPC with pixel readout

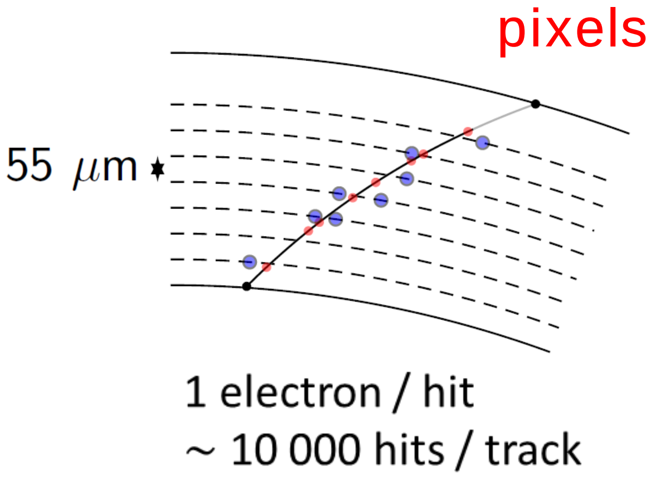
- To study the performance of a large pixelized TPC, the pixel readout was implemented in the full ILD DD4HEP (Geant4) simulation
- Changed the existing TPC pad readout to a pixel readout
- Adapted Kalman filter track reconstruction to pixels

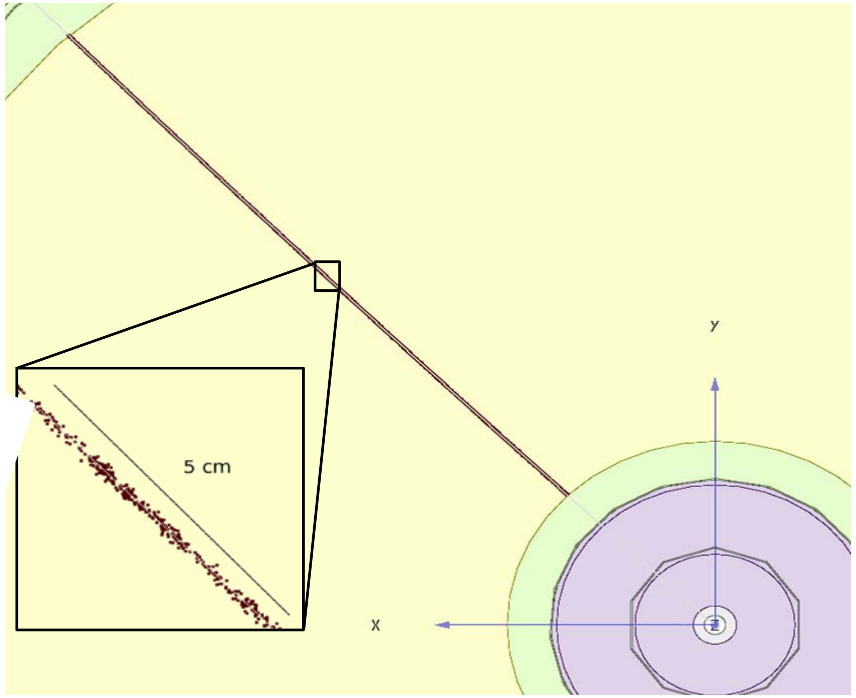


details: PhD thesis
Kees Ligtenberg

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



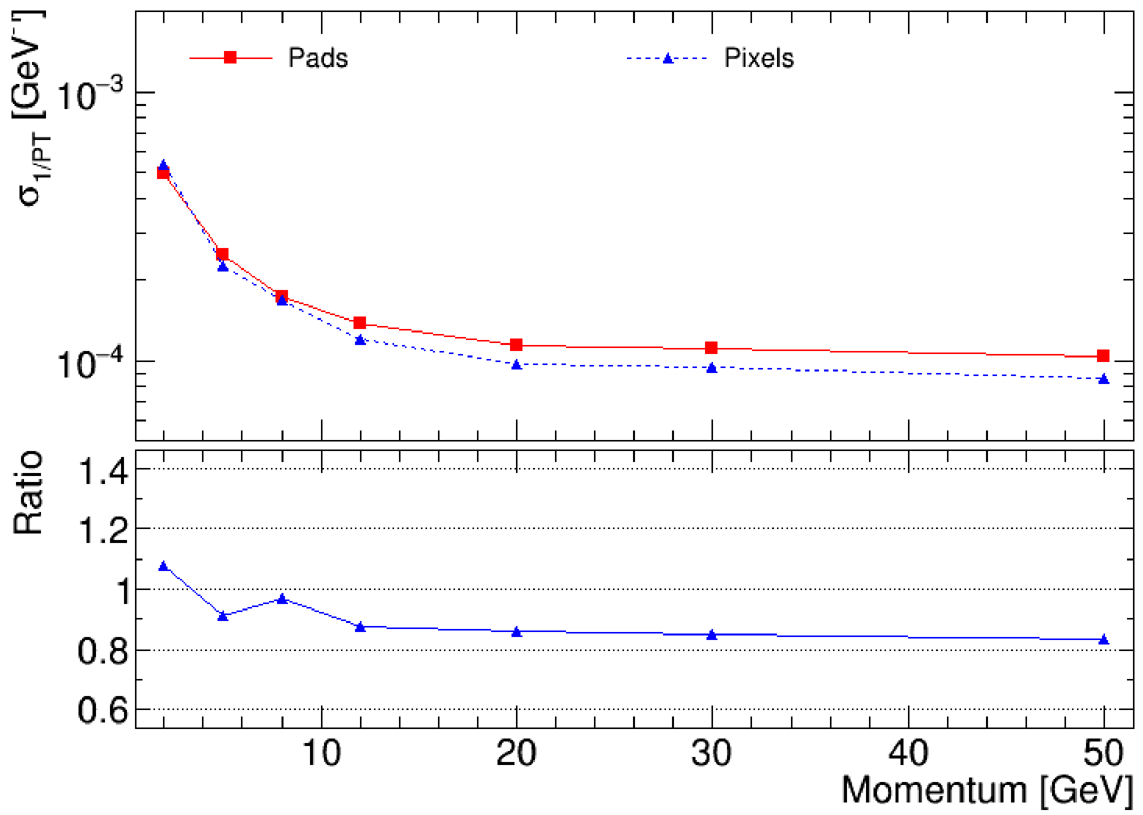


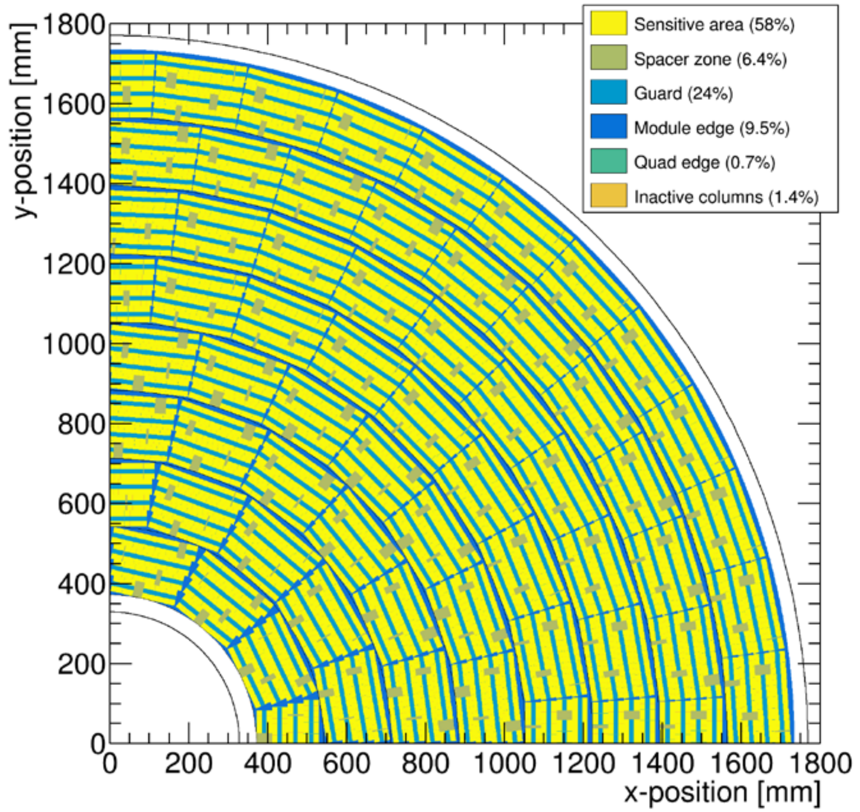


50 GeV muon track with pixel readout

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.



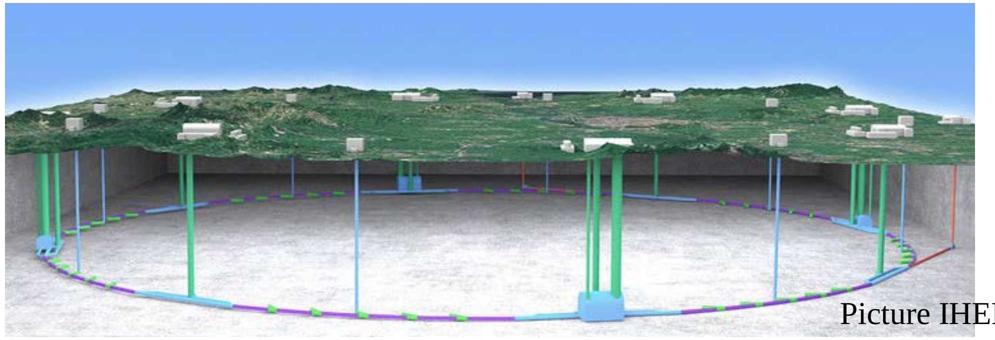


Summary of the Pixel TPC performance

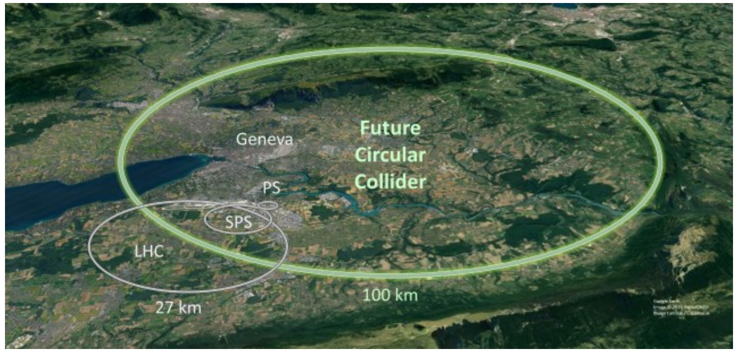
- A single chip GridPix detector was reliably operated in a test beam in 2017
  - Single electron detection => the resolution is primarily limited by diffusion
  - Systematic uncertainties are low: < 10 µm in the pixel xy plane
  - dE/dx resolution for a 1 m track is 4.1%
- A Quad detector was designed 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
- Test beam data taken at DESY in 2021: results on precision tracking presented
- 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

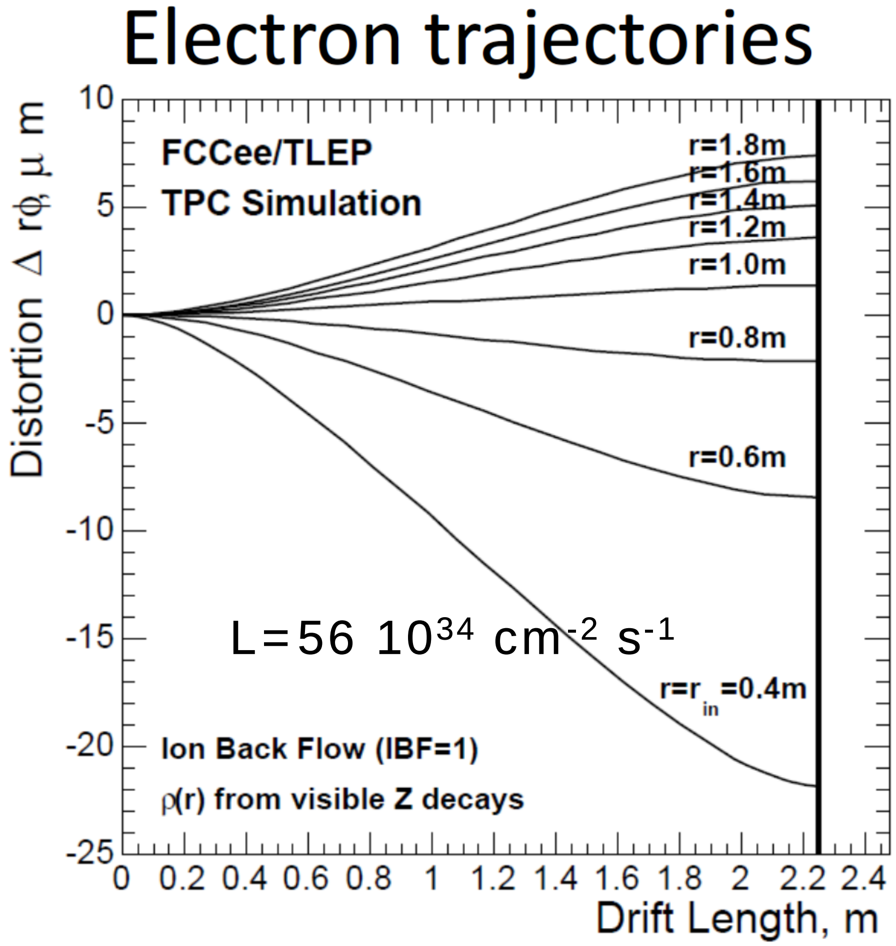


- Can a pixel TPC reconstruct the events?
  - The TPC total drift time is about 30 μs
  - This means that there is on average 2 event / TPC readout cycle
  - YES: The excellent time resolution: time stamping of tracks < 1.2 ns allows to resolve and reconstruct the events
- Can the current readout deal with the rate?
  - Link speed of Timepix3 (in Quad) is 80 Mbps: 2.6 MHits/s per 1.41 × 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).
- 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
    - For running at the Z at FCC-ee or CEPC, gating will significantly affect the data taking efficiency. Gating is NOT a good option
    - For running FCC-ee or CEPC at the WW, ZH or top gating is an option, but it is rather involved (as one needs e.g. a fast trigger) and needs study and thought

A Pixel TPC at CEPC or FCC-ee



Philippe Schwemling

What is the size of the track distortions?

- The distortions for IBF*Gain=1 according to the TLEP studies (see plot) range up to < 22 μm
- In LCTPC WP 370 meeting the extrapolation to 200 10^{34} cm^{-2} s^{-1} is performed (correcting the factor 4 lumi; factor 2.5 ions/cm; factor 1.67 in ion drifttime. In total a factor 16.7.

- For FCC-ee or CEPC this means: distortions < 370 μm at r = 40 cm
- The ion back flow of the current quad is measured to be 1.3% at a gain of ∽2000. So IBF*Gain is ∽25.
  - This means that this would lead to distortions up to 8 mm.
- Note that distortions can be corrected for on average. It will lead to a broadening of the track parameters and worsening of the momentum resolution.

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 for 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 distortions?
  - For FCC-ee or CEPC this means: distortions up to < 370 μm
  - ILD like detector the distortions can be mapped out using the VTX-SIT/SET

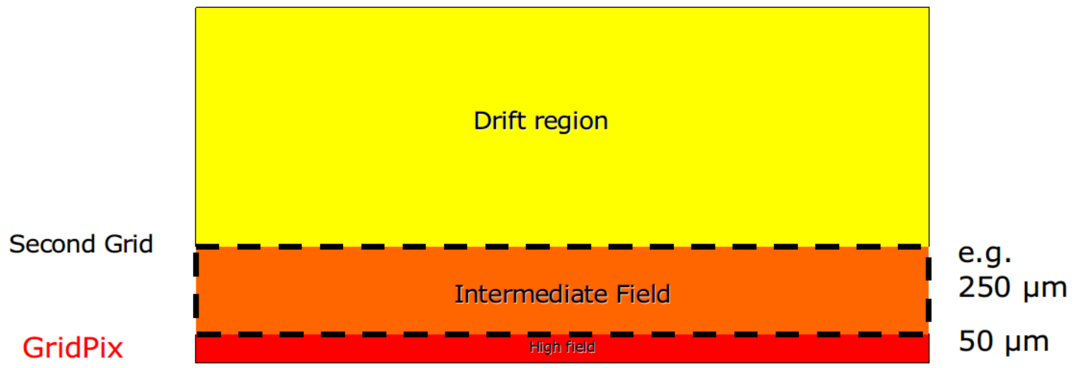
The Z physics program at CEPC or FCC-ee with an ILD-like detector with a Pixel TPC (with double grid structures) sliced between silicon trackers (VTX-SIT and SET) can be fully exploited. This statement needs more quantitative studies.

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

Running CEPC or FCC-ee at the Z pole with a L of 200 10^{34} cm^{-2} s^{-1}:

- 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:
  - It is possible to reduce the IBF for a pixel TPC by making a device with a double grid
  - One can limit the track distortions to stay within maximally 370 μm (R=40 cm)
  - This needs dedicated R&D that can be performed in the new lab in Bonn
- The above listed items need detector R&D to do the best job
- 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. This statement needs more quantitative studies.
- A pixel TPC can perfectly run at WW, ZH or tt energies where track distortions are several orders of magnitude smaller