Pixelated Time Projection Chamber Tracker Detector Technology

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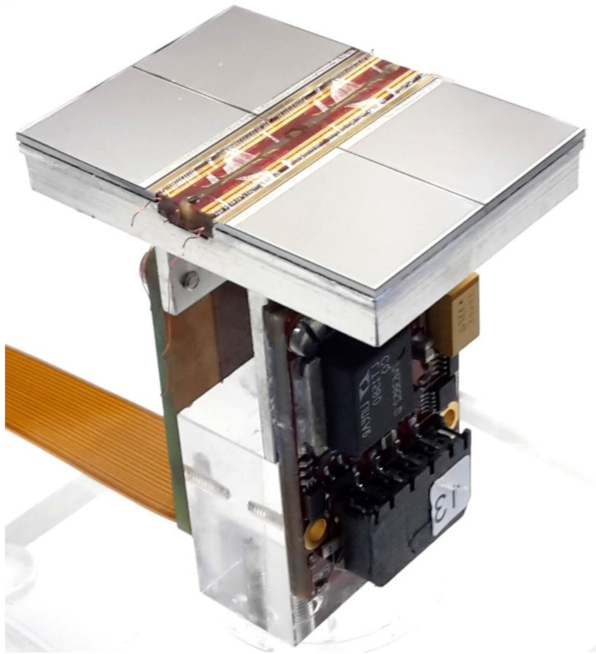
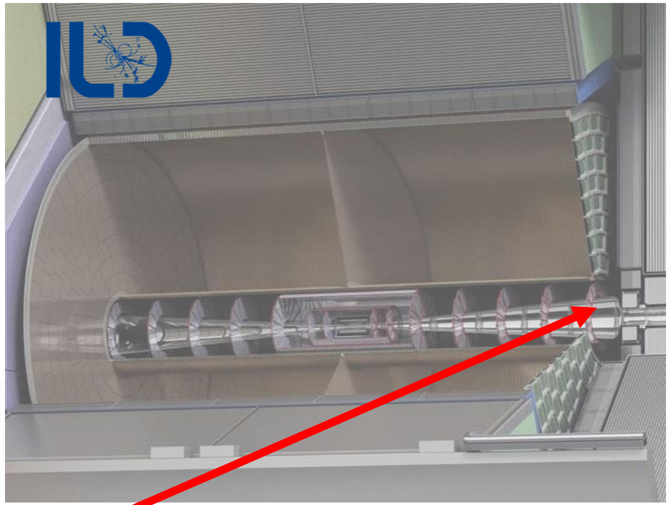
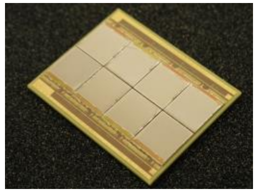


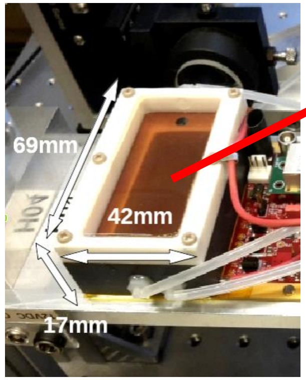
IAS HEP Hong Kong 2022

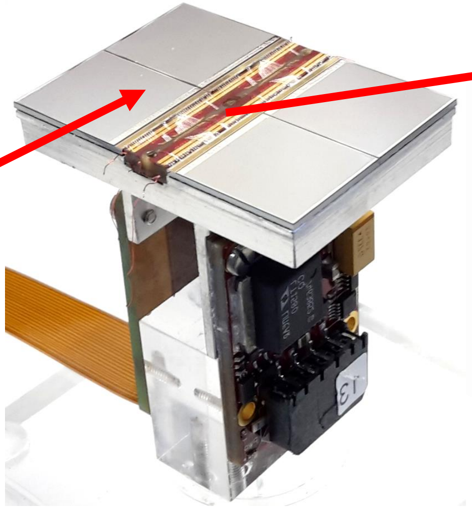
Pixel TPC

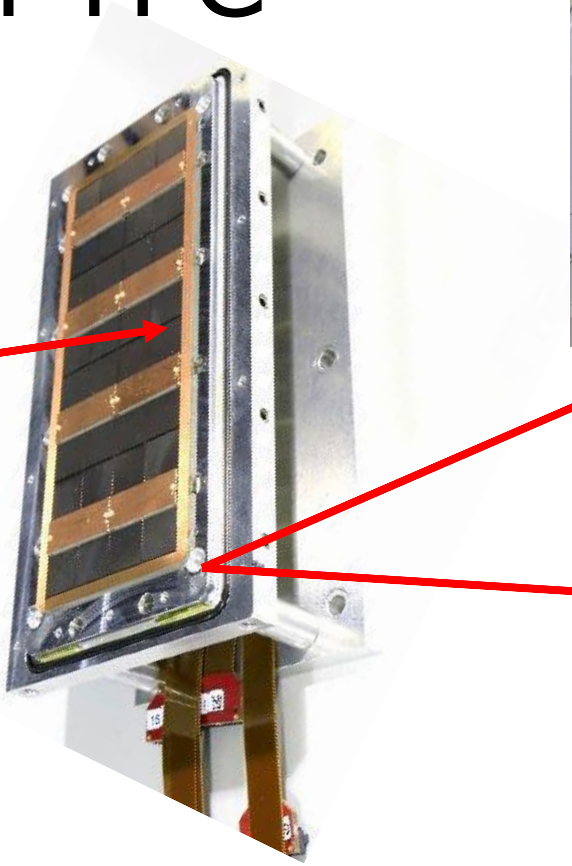


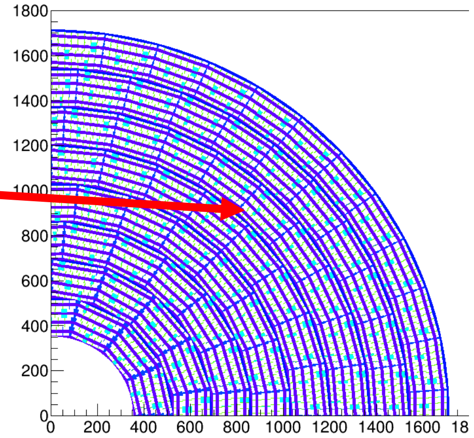


(Octopuce)



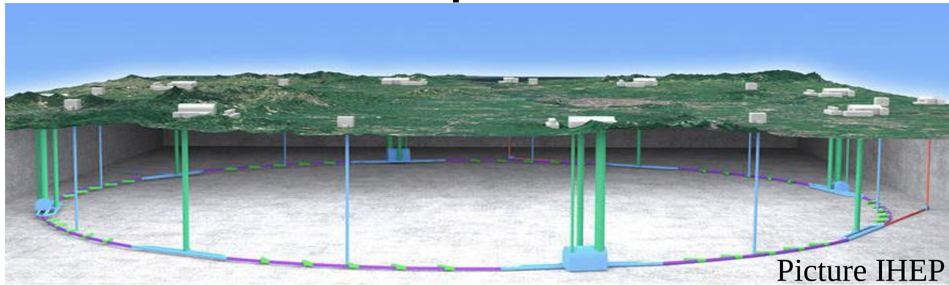






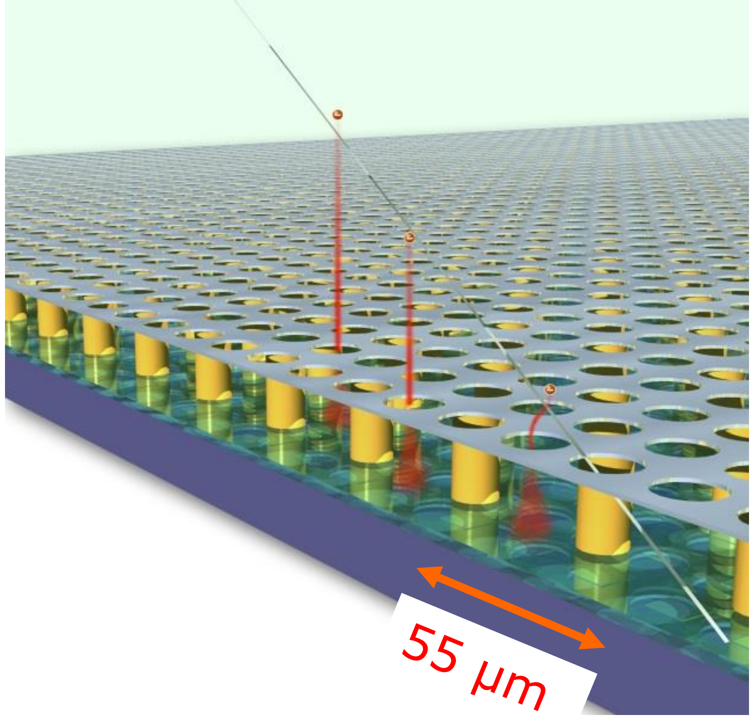
(TimePix1) TPX3 chip Quad Module TPC plane

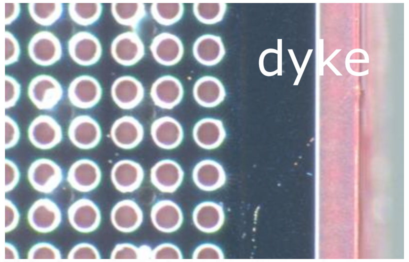
(2007-14) 2017 2018 2019



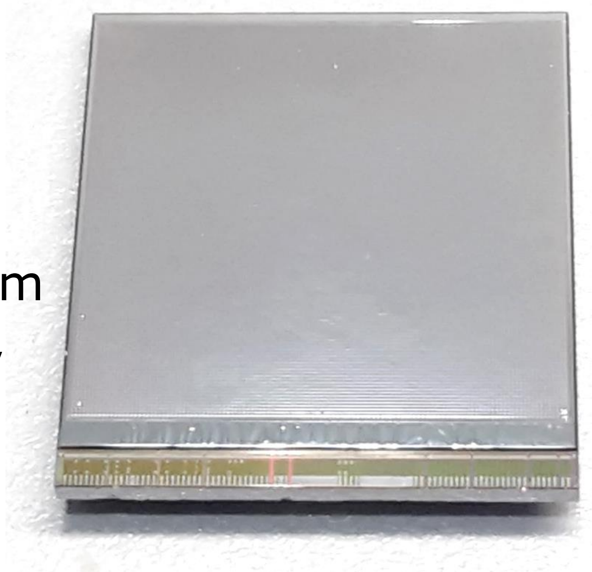
GridPix technology

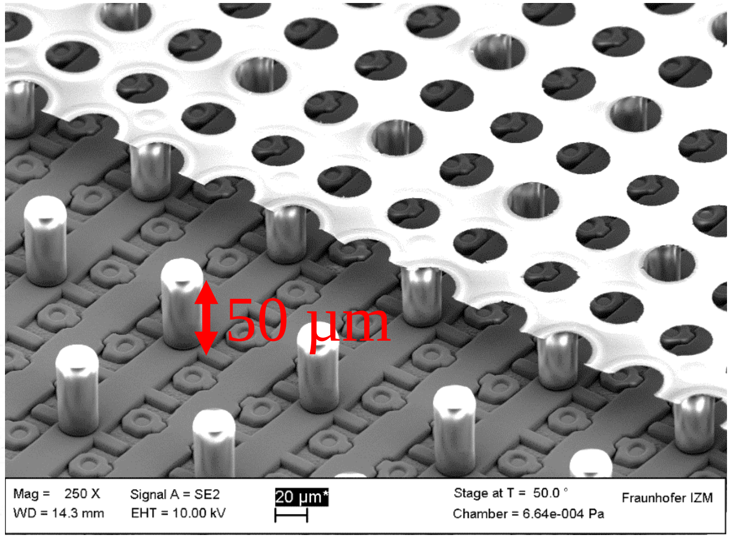
- Pixel chip with integrated Grid (Micromegas-like)
- InGrid post-processed @ IZM
- Grid set at negative voltage (300 – 600 V) to provide gas amplification
- Very small pixel size (55 μm)
- detecting individual electrons





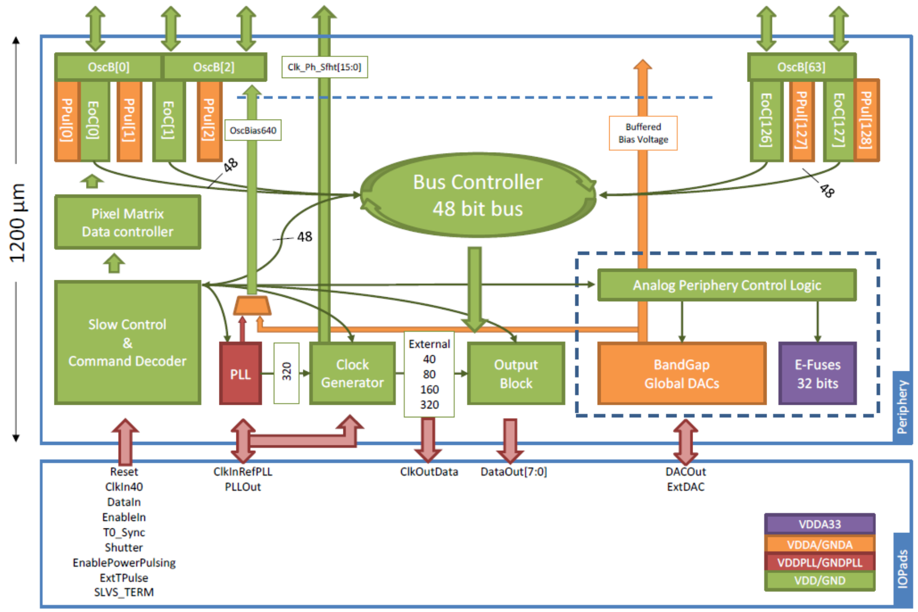
- Aluminium grid (1 μm thick)
- 35 μm wide holes, 55 μm pitch
- Supported by SU8 pillars 50 μm high
- Grid surrounded by SU8 dyke (150 μm wide solid strip) for mechanical and HV stability

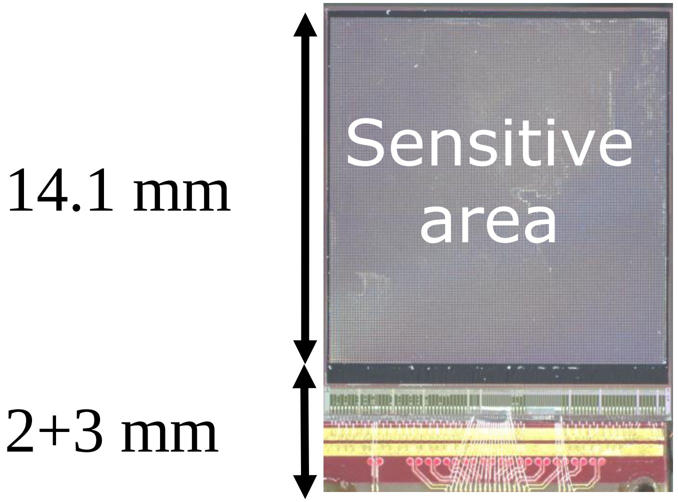




Pixel chip: TimePix3

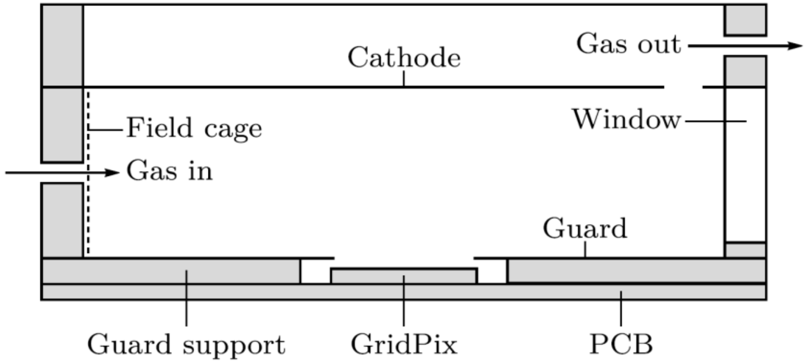
- 256 x 256 pixels
- 55 x 55 μm pitch
- 14.1 x 14.1 mm sensitive area
- TDC with **640 MHz clock** (1.64 ns)
- Used in the data driven mode
  - Each hit consists of the **pixel address** and **time stamp** of arrival time (ToA)
  - Time over threshold (ToT) is added to register the signal amplitude
  - 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

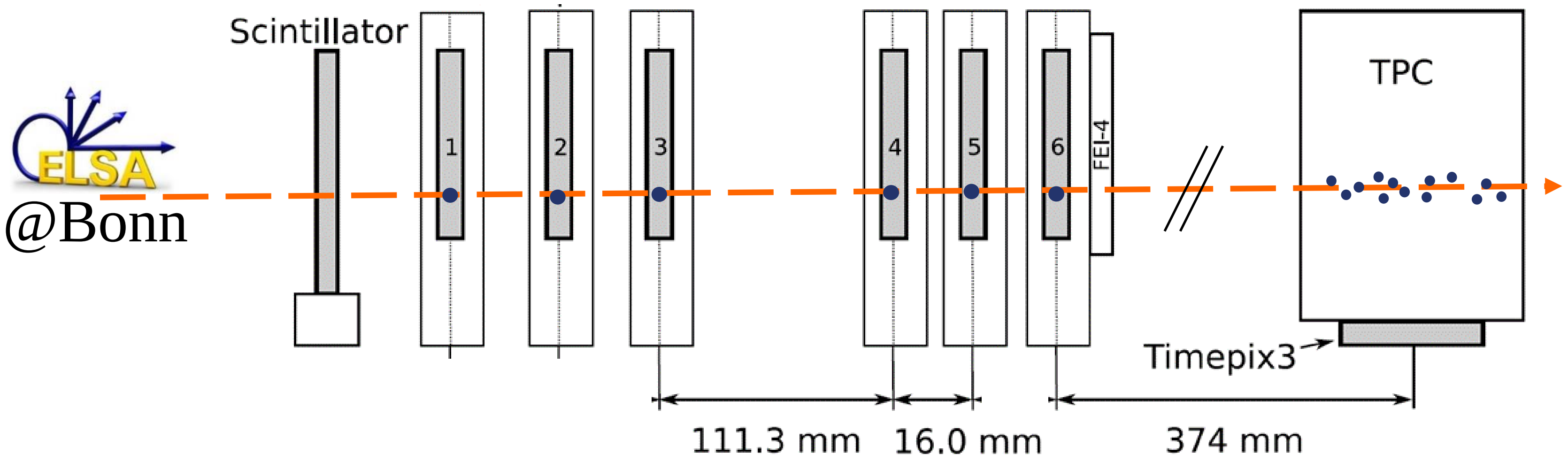




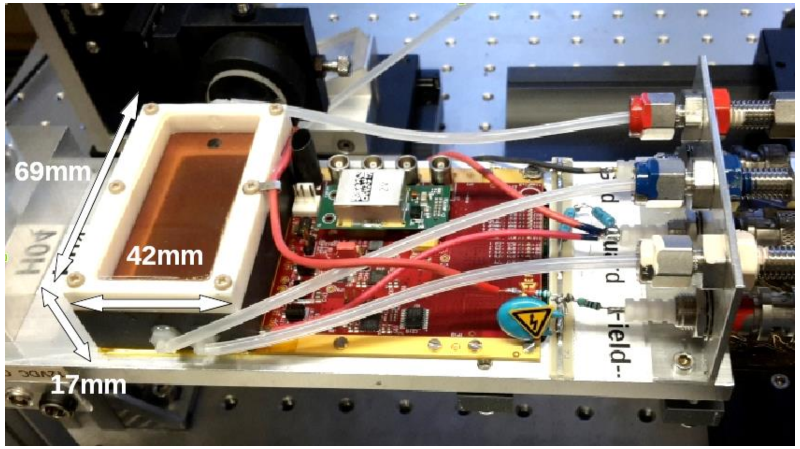
Single chip test in test beam Bonn (June 2017)

- ELSA: 2.5 GeV electrons
- Tracks referenced by Mimosa telescope
- Gas: $Ar/CF_4/iC_4H_{10}$ 95/3/2 (T2K)
- Electrons: ~100 e/cm
- E_d = 280 V/cm, V_{grid} = -350 V



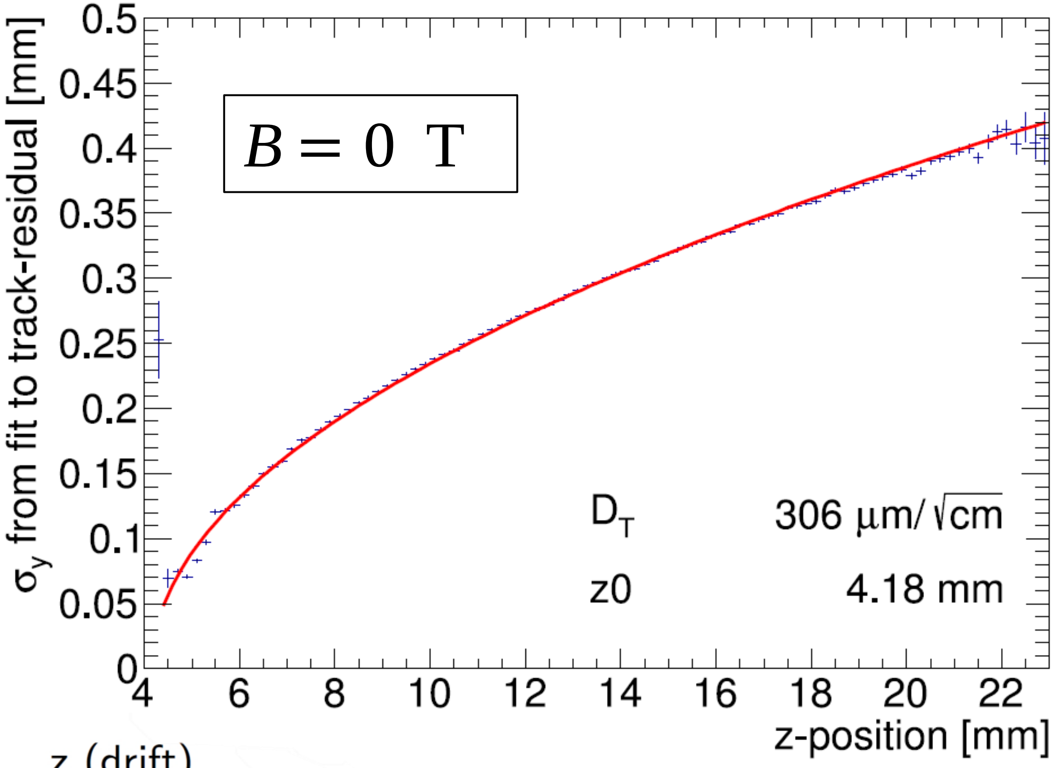


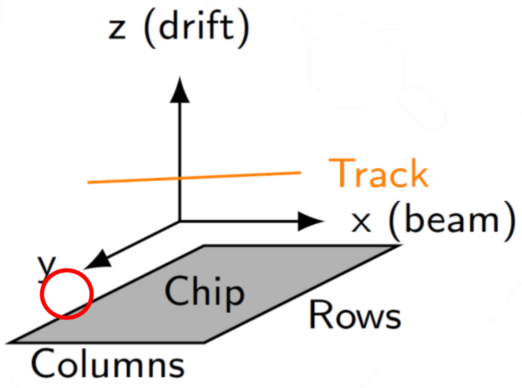
Detector with guard and field shaper



Published paper on 2017 testbeam: https://doi.org/10.1016/j.nima.2018.08.012

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)

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

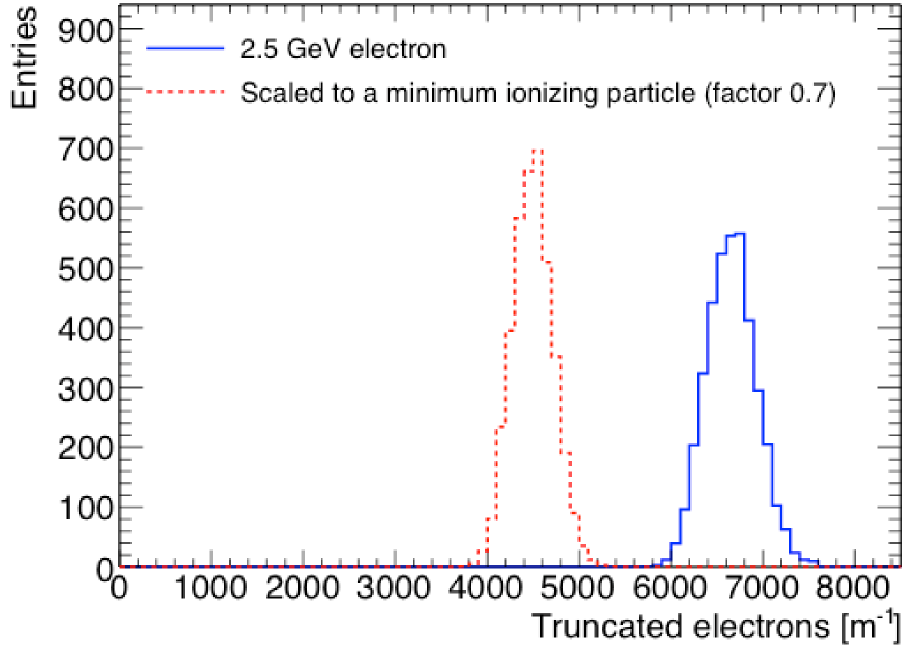
Note that:

- 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

- 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.

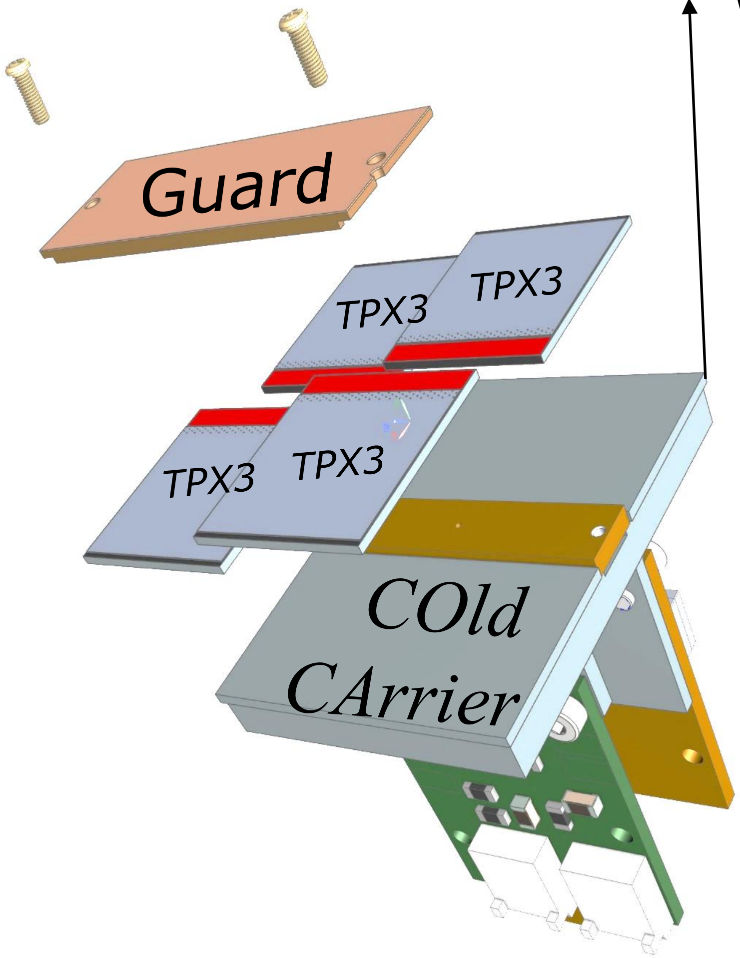


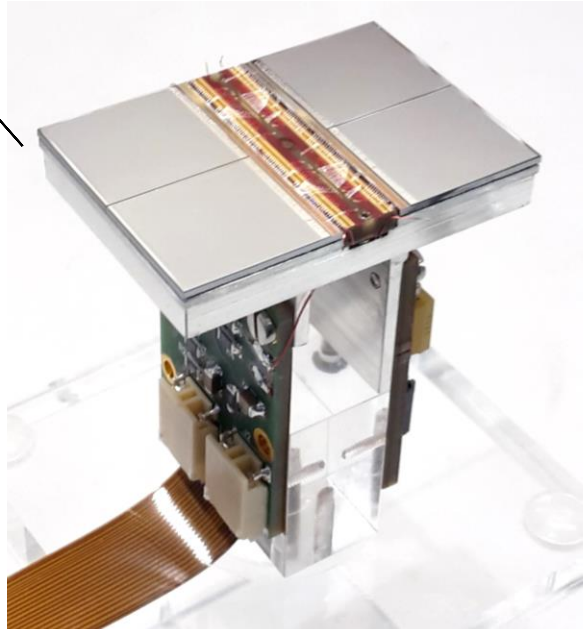
QUAD design and realization

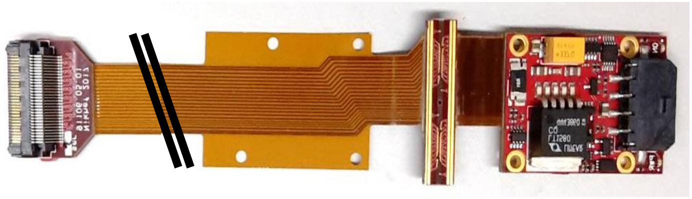
series of QUADs

- 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

39.6 x 28.38 mm



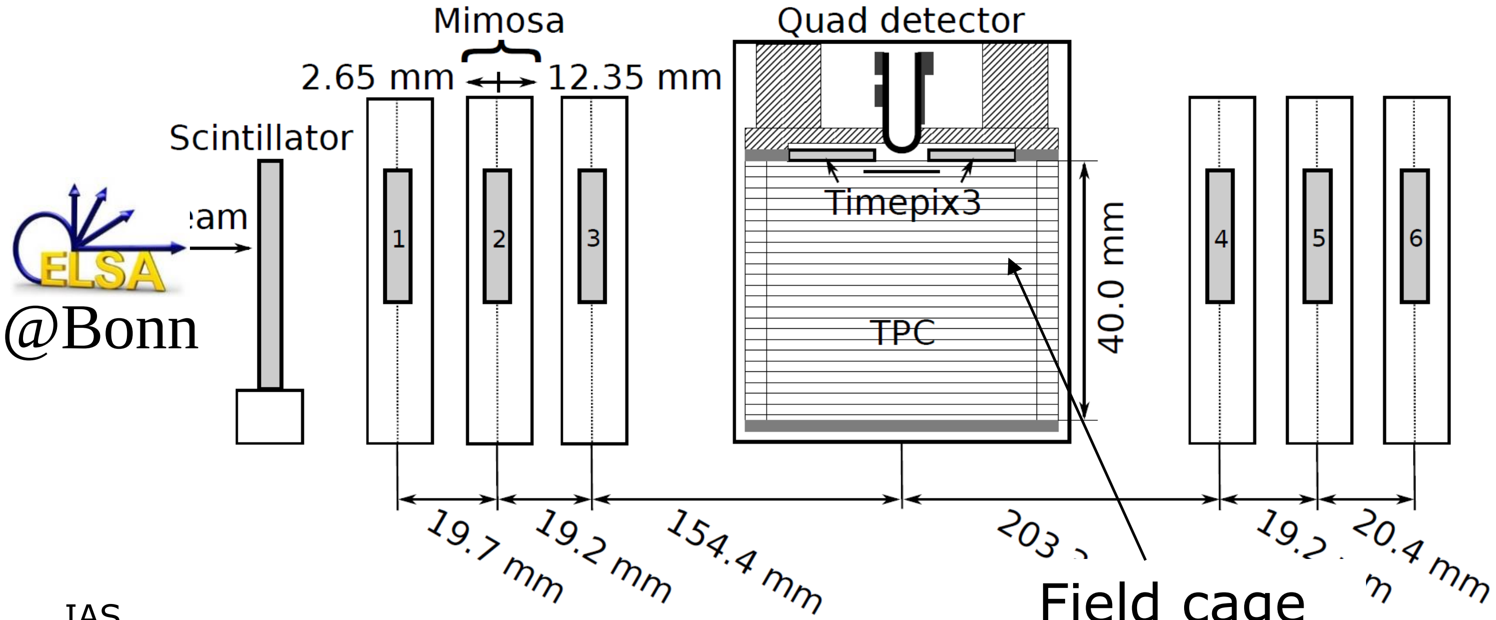


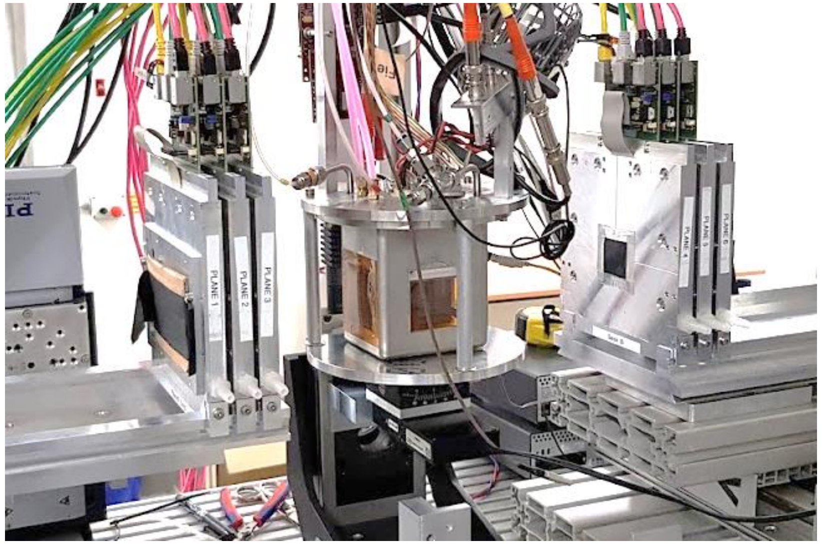


QUAD test beam in Bonn (October 2018)

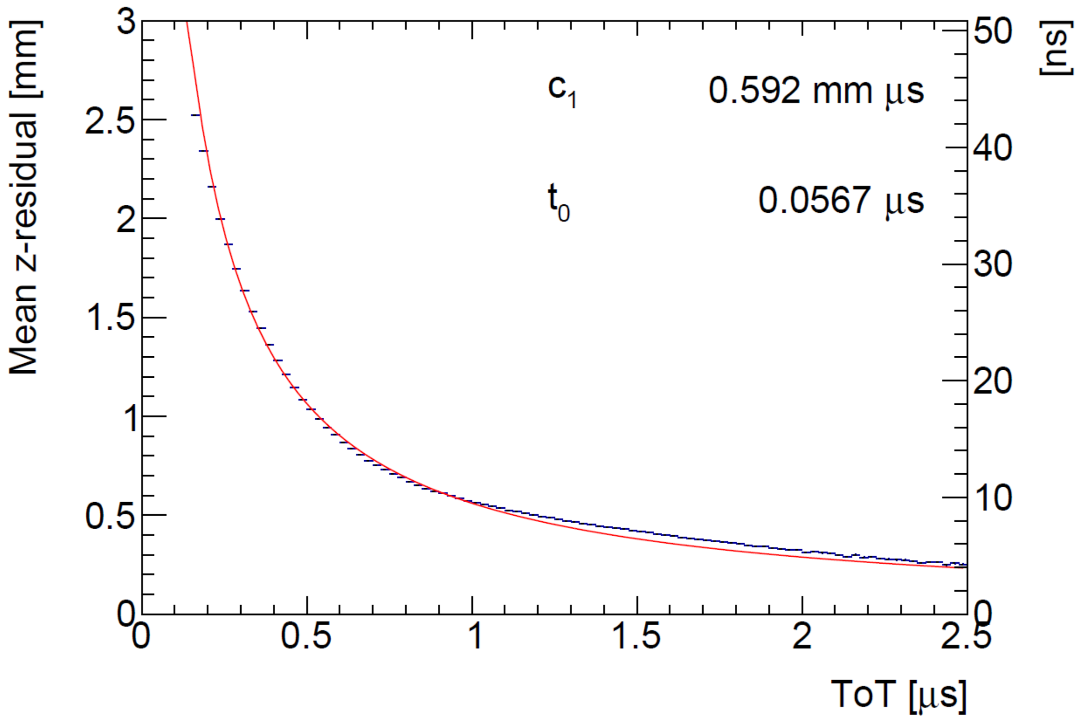
- ELSA: 2.5 GeV electrons
- Tracks referenced by Mimosa telescope
- QUAD sandwiched between Mimosa planes
  - Largely improved track definition
  - 6 planes with 18.4 µm × 18.4 µm sized pixels
- Gas: $Ar/CF_4/iC_4H_{10}$ 95/3/2 (T2K)
- E_d = 400 V/cm, V_{grid} = -330 V
- Typical beam height above the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

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

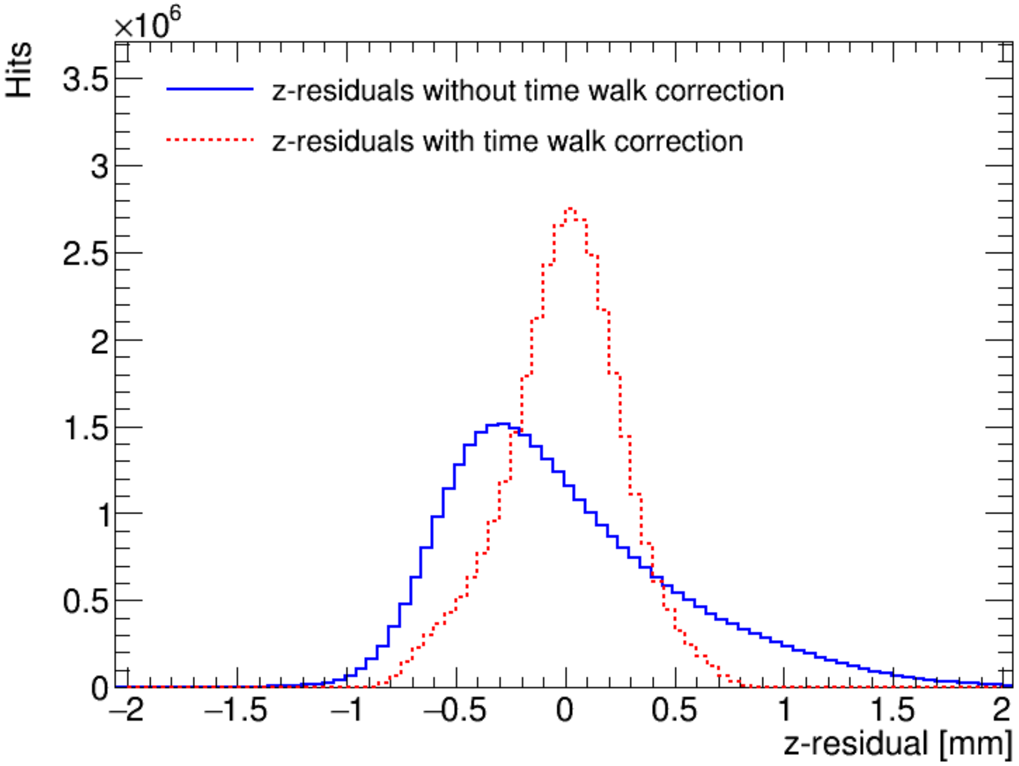




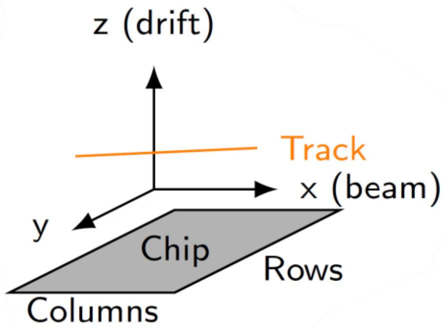
QUAD time walk results



$$\delta z_{\text{timewalk}} = \frac{c_1}{t_{\text{ToT}} + t_0} + z_0$$

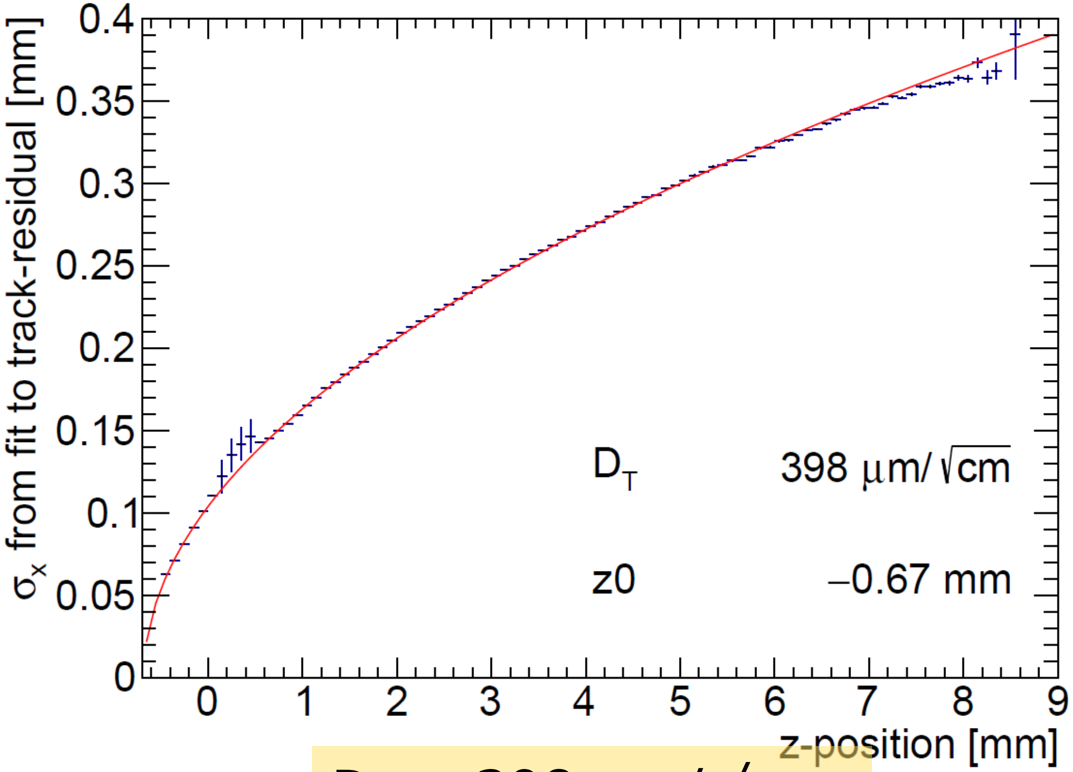


- Time walk correction works well
- Applied for all analysis results



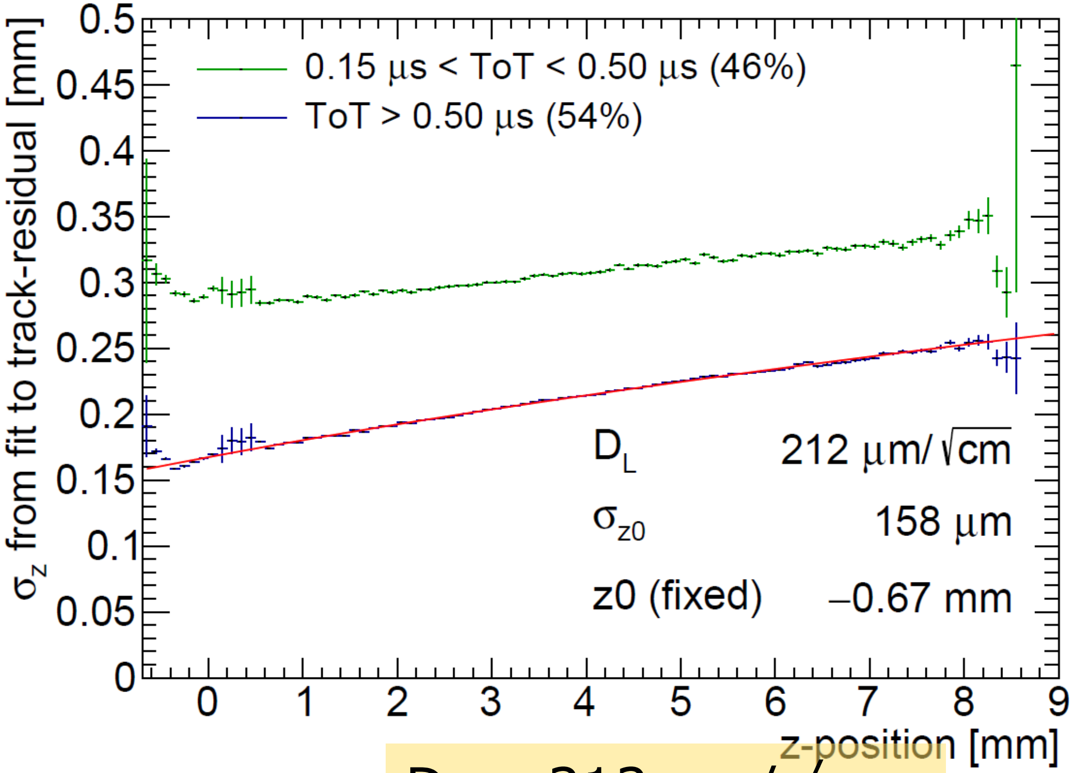
QUAD single hit resolution

Transverse



D_T = 398 µm/√cm

Longitudinal



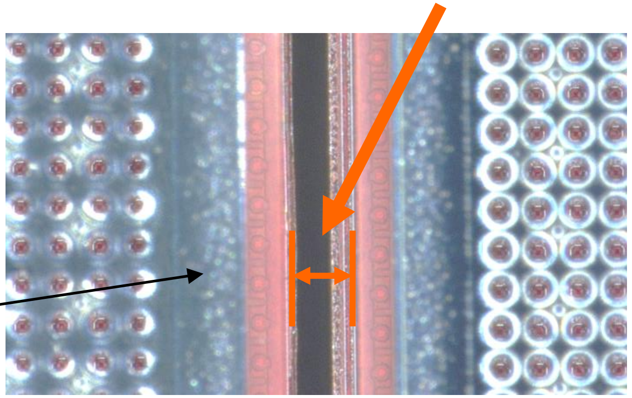
D_L = 212 µm/√cm

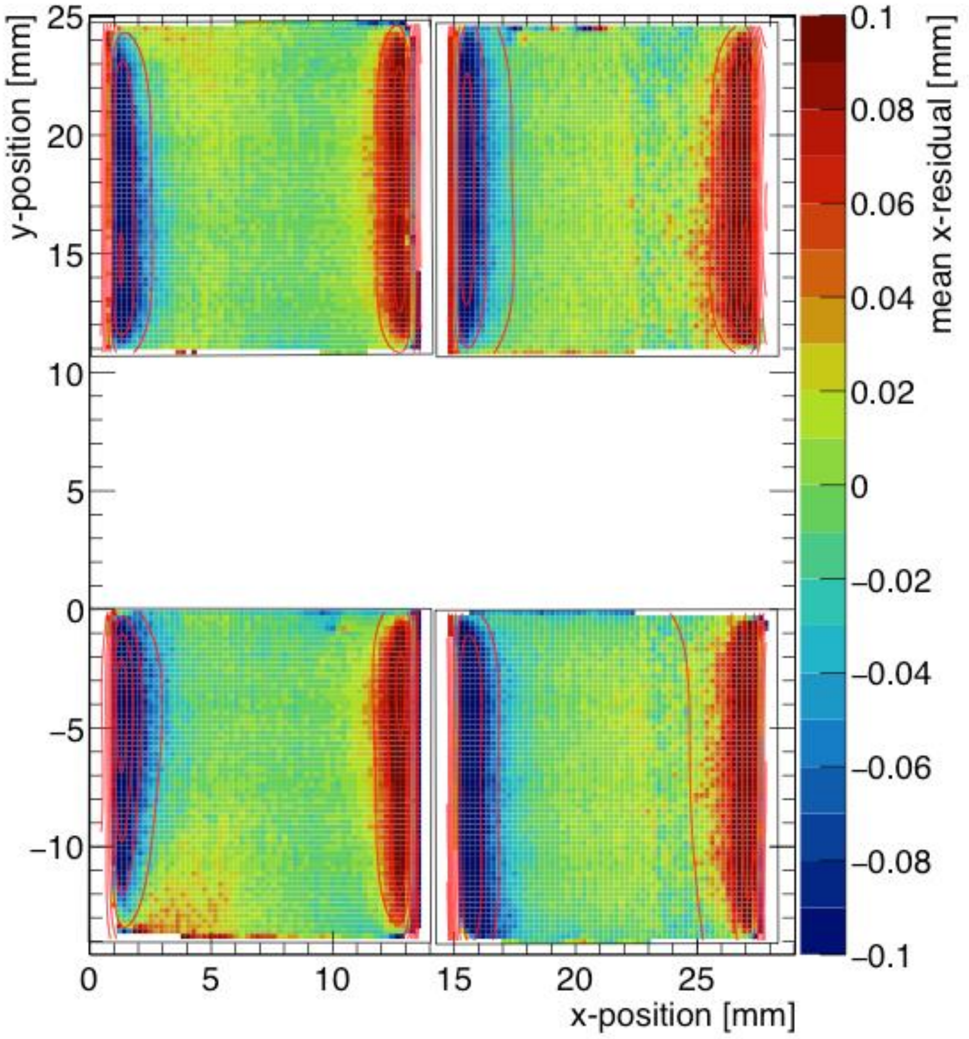
The D_T value is rather high due to an error in the gas mixing (too low CF4)

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

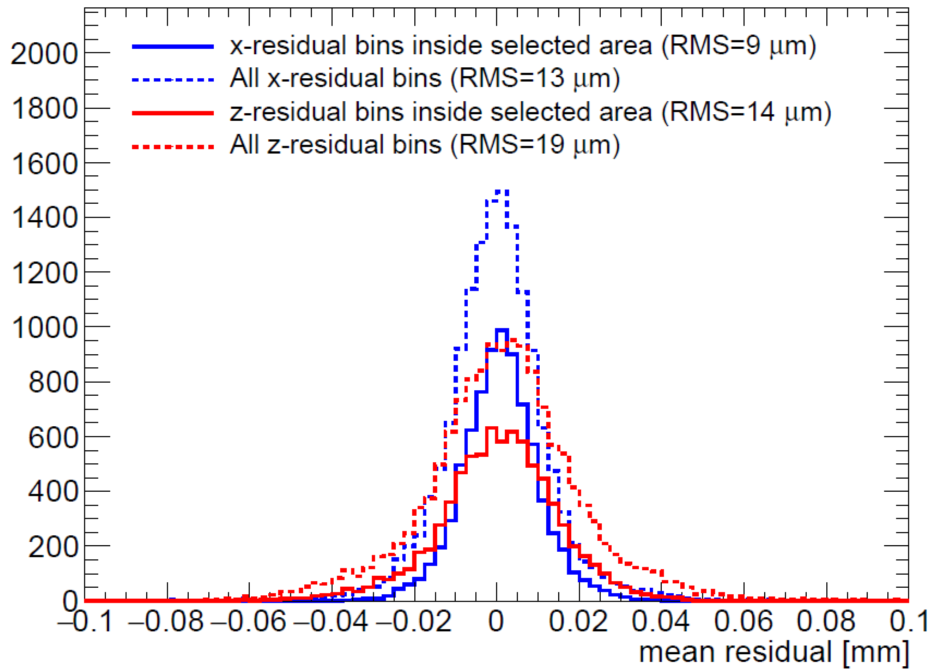
Grounded region

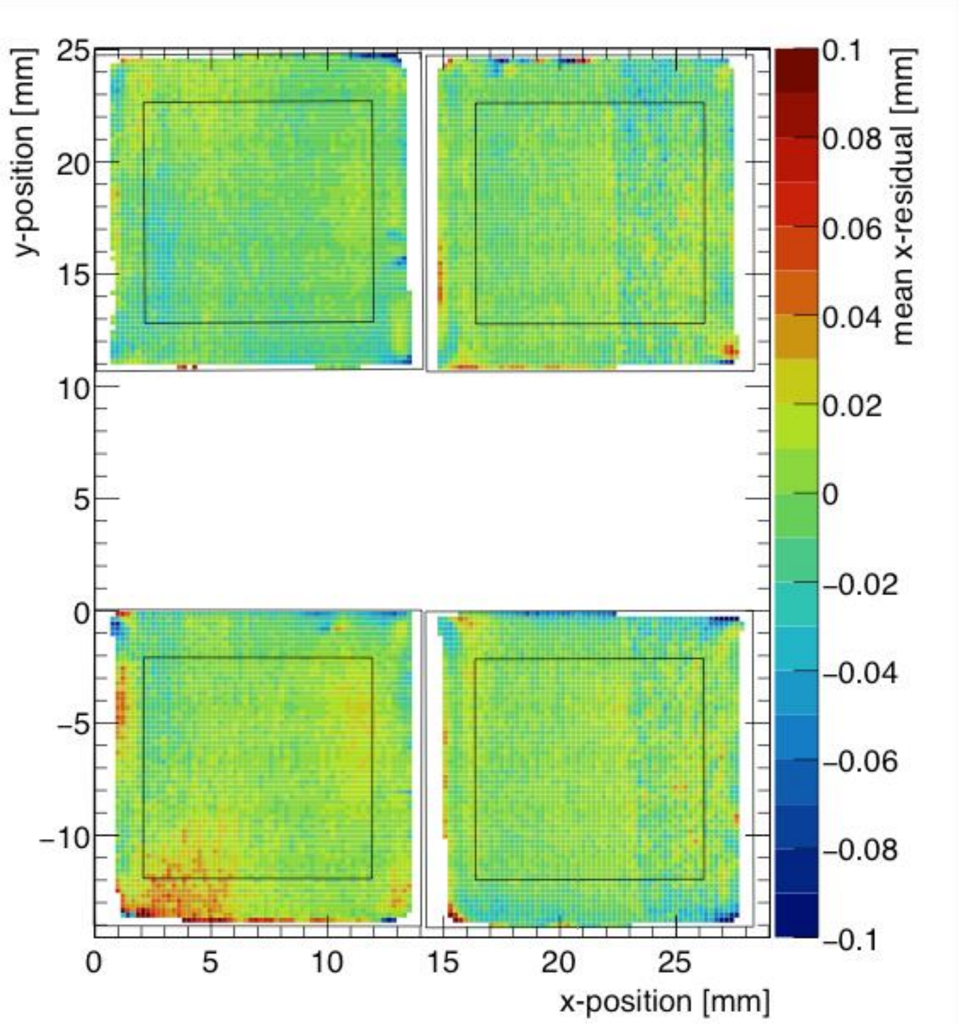




QUAD deformations in transverse plane (XY)

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

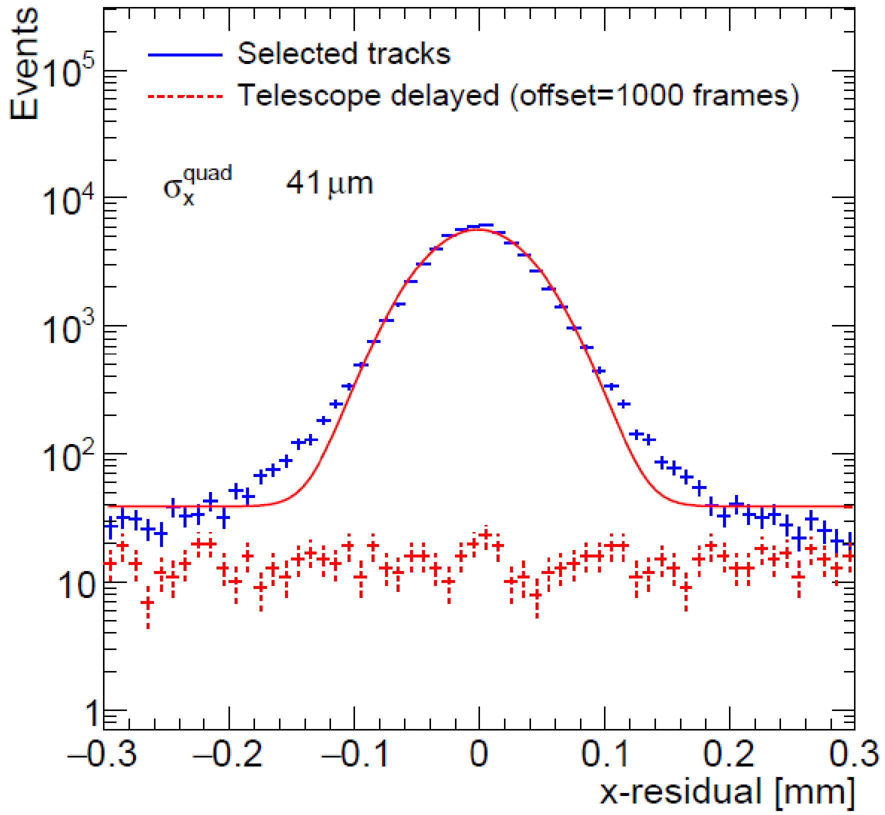




Combined resolution (XY) of a QUAD

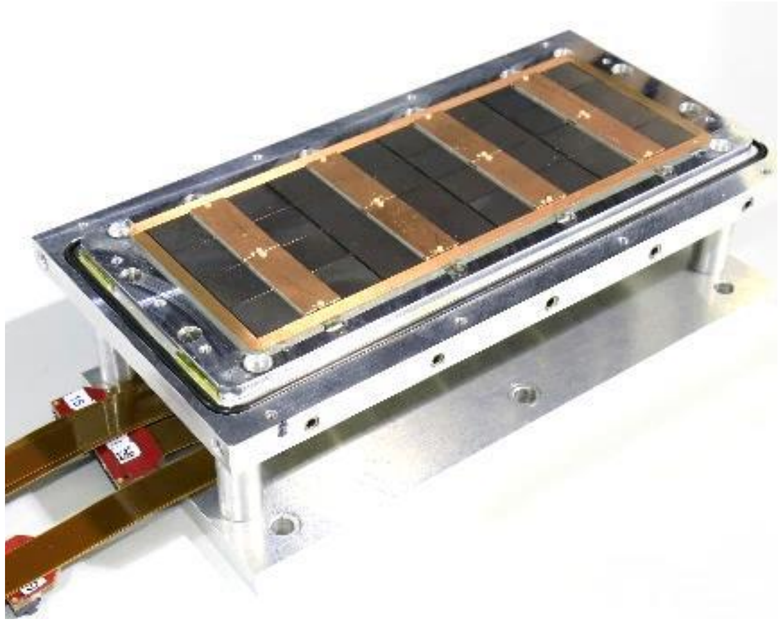
- Below a breakdown of the uncertainties and sources is given
- The observed resolution can be understood if an additional contribution of 14 μm is added

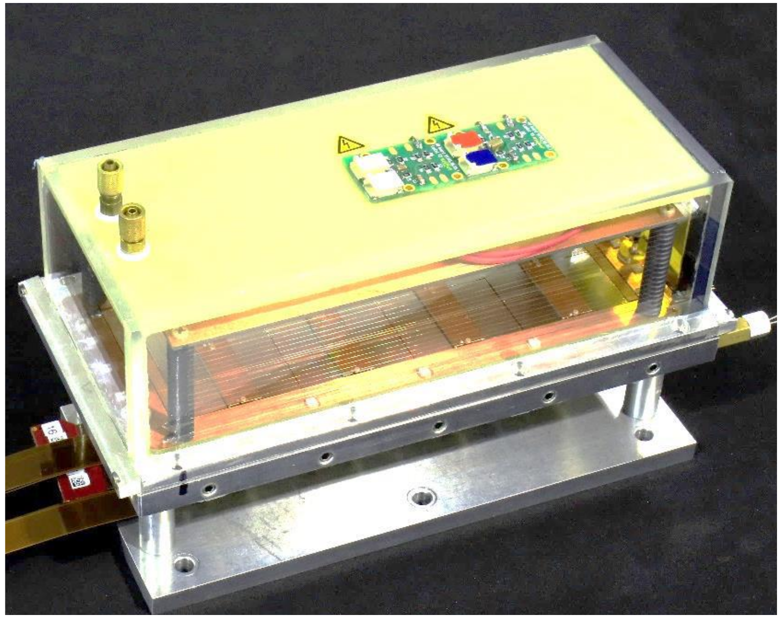
Observed standard deviation	41 μm
Statistical errors	25 μm
Systematic errors in the pixel plane and drift direction	19 μm
Multiple scattering	22 μm
Unidentified systematic error	14 μm

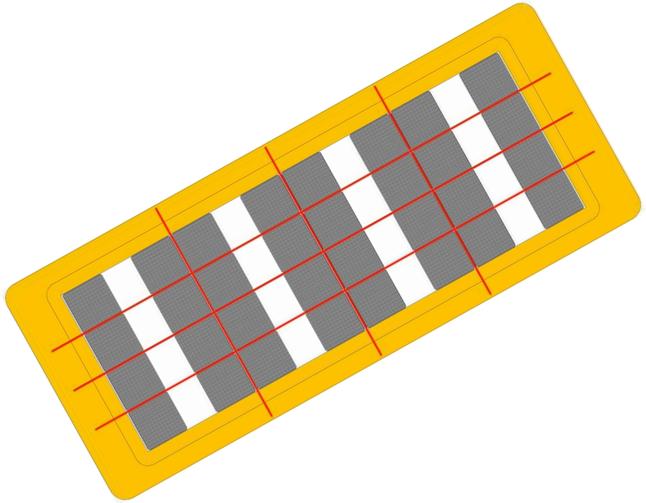


Next: QUAD as a building block

8-QUAD module with field cage

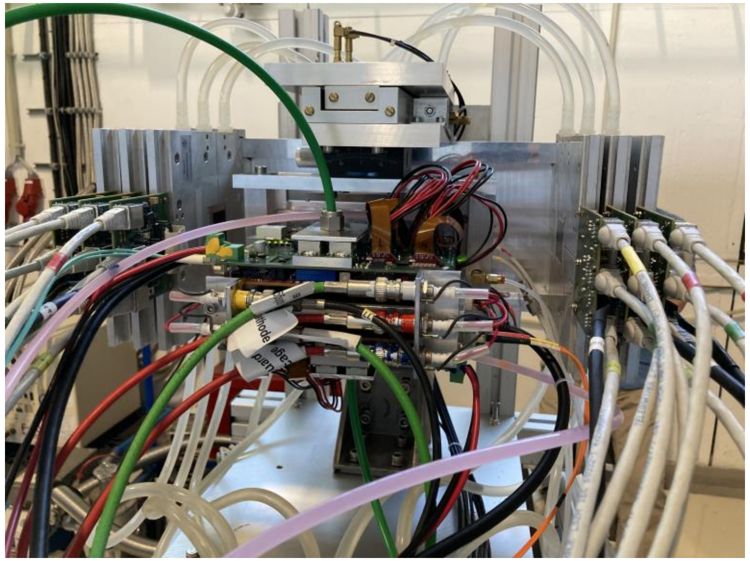
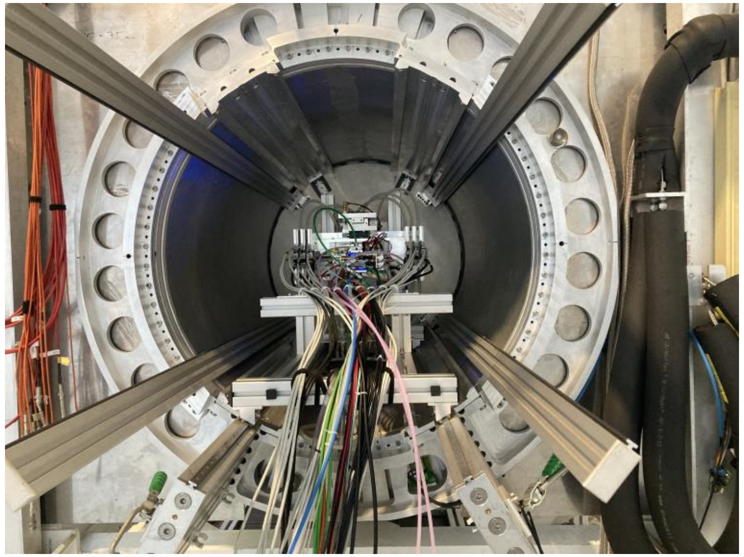






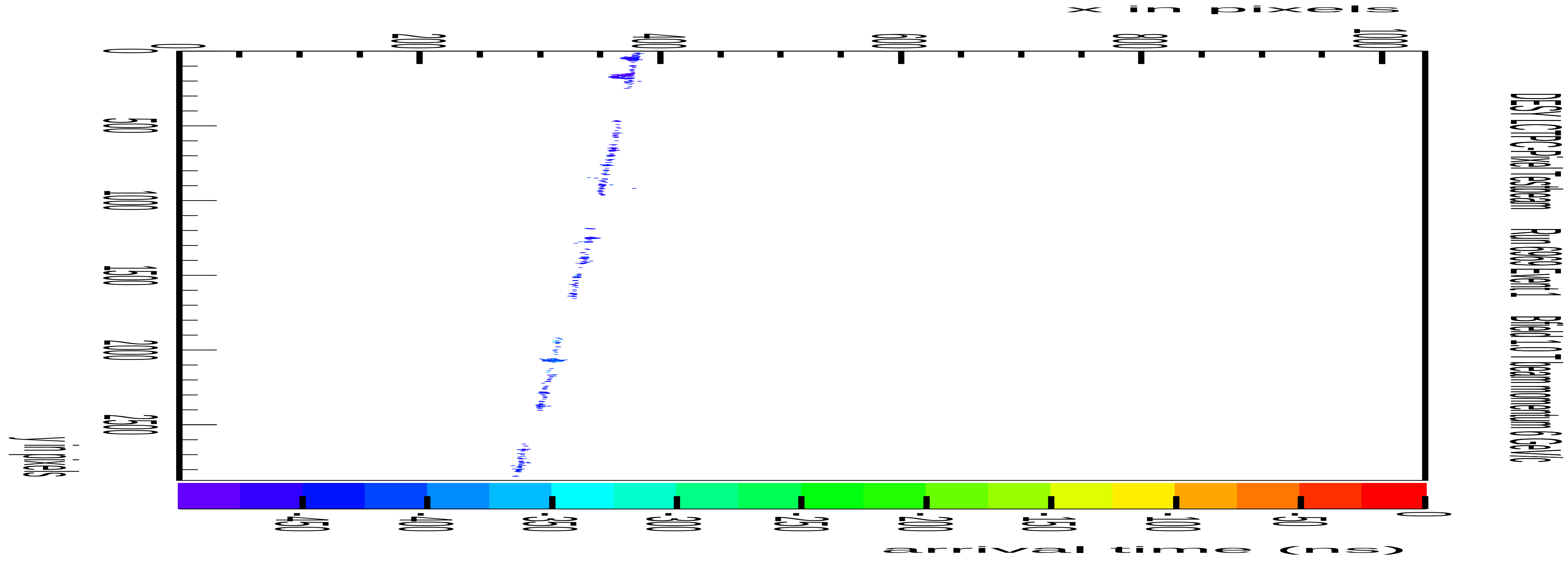
in red guard wires

DESY testbeam June 2021

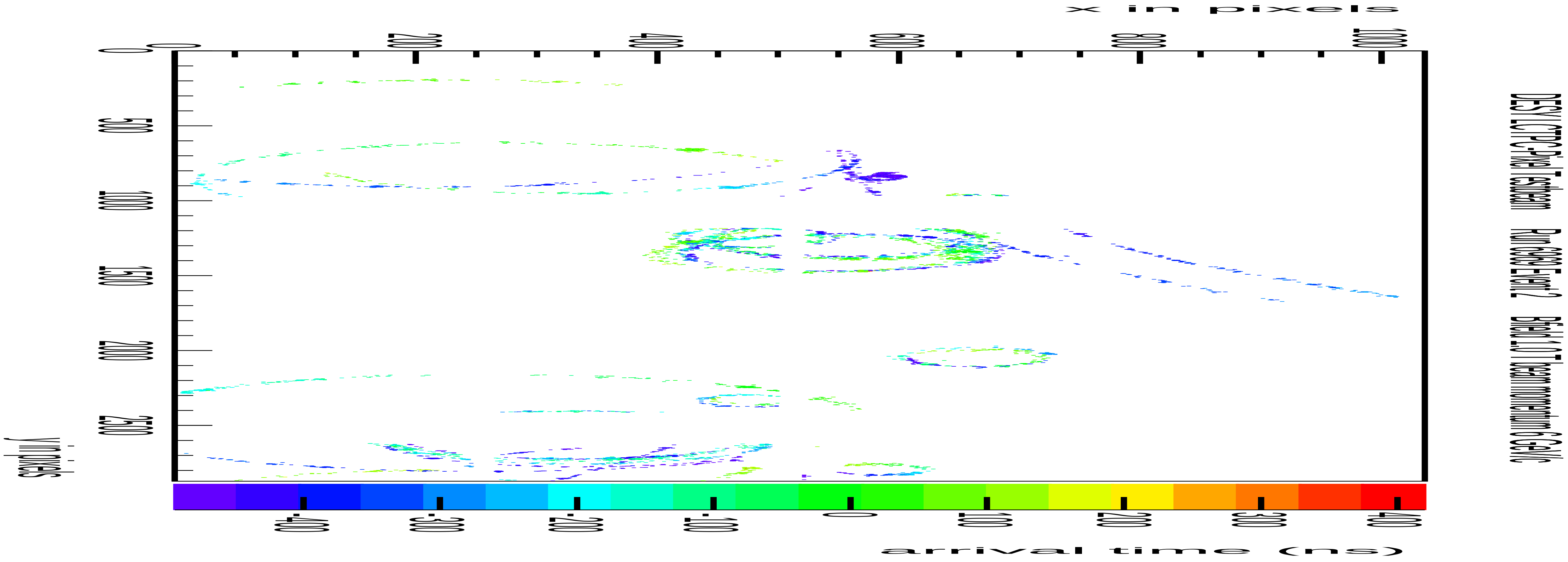




Mounting the 8 quad module between the silicon planes
sliding it into the 1 T PCMAG solenoid

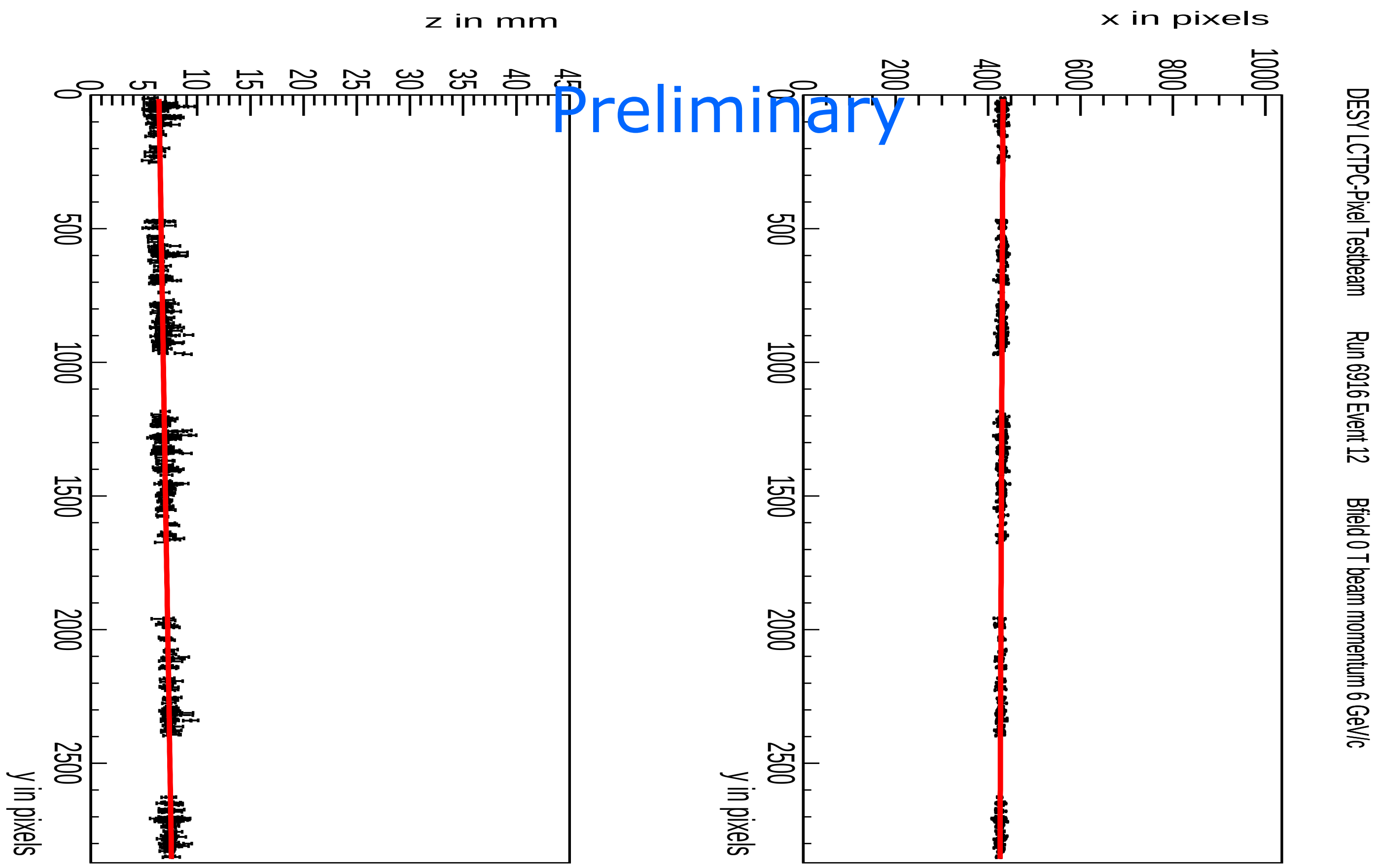
DESY testbeam June 2021



DESY testbeam June 2021



DESY testbeam Module Analysis



Track 1050 hits

$\chi^2_{xy} = 912/1048$

$\chi^2_z = 1740/1048$

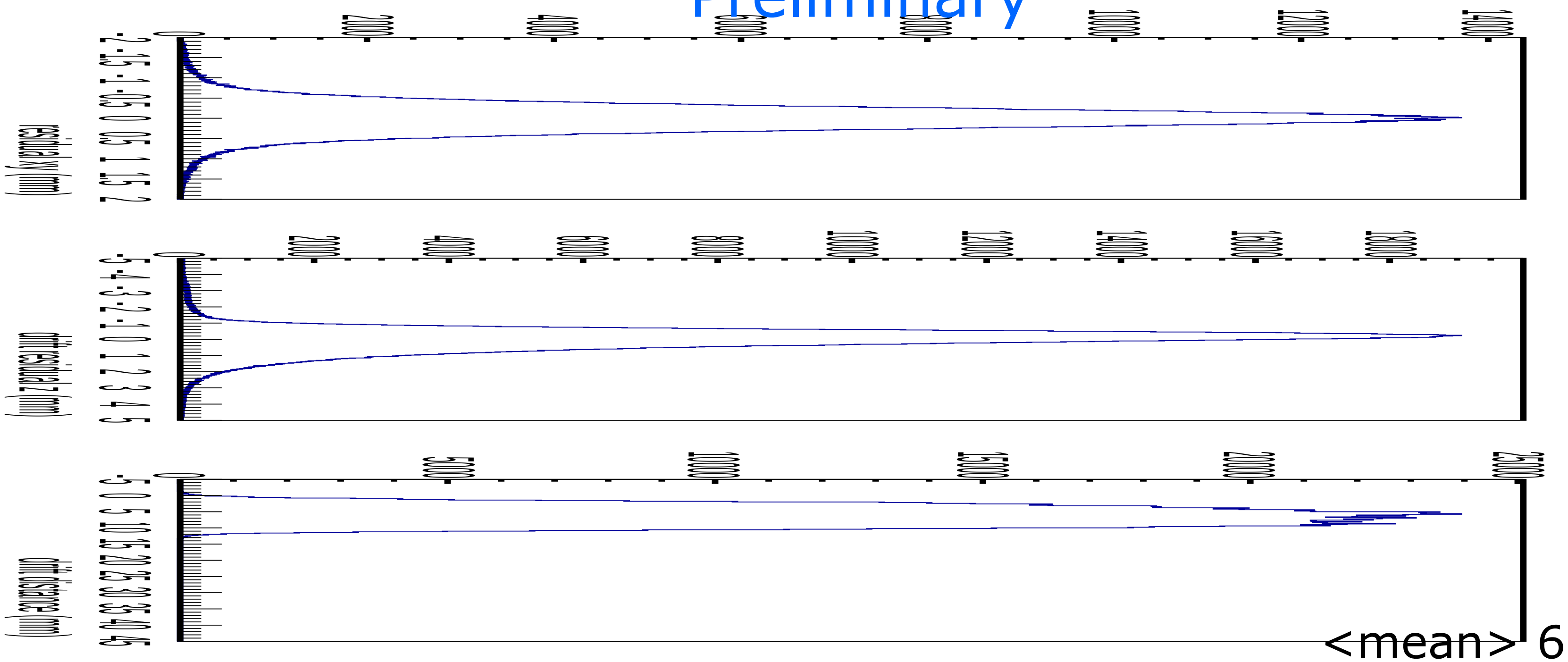
(no asymmetric tail (z time slewing) or outlier removal applied yet)

DESY testbeam Module Analysis

Run 6916 B=0 T p =6 GeV

σ_{xy} =250 μm and σ_z =425 μm   1M hits

Preliminary

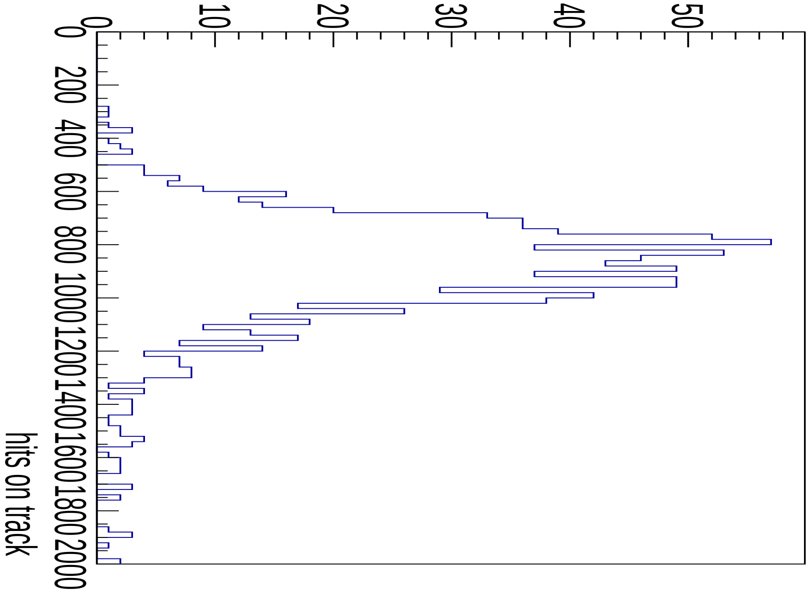


<mean> 6.4 mm

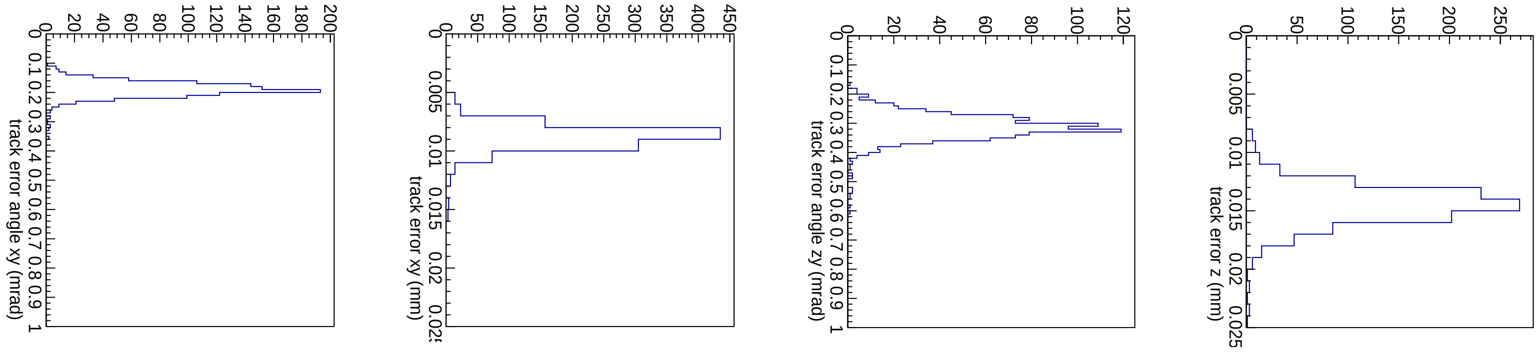
DESY testbeam Module Analysis

Run 6916 B=0 T p =6 GeV

Preliminary



1060 selected tracks
Impressive 900 hits / track



Tracking precision:

position 9 μm (xy) 13 μm (z)
angle 0.19 mrad (dx/dy) 0.51 mrad
module tracklength = 157.96 mm

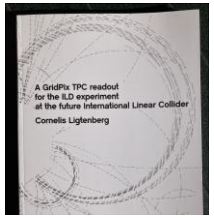
Note that in a B field because of the reduced diffusion the tracking precision will improve substantially

DESY testbeam data analysis

- High statistics data taken with different B fields
- The Silicon telescope has been aligned and gives excellent track predictions
- A beautiful data set and we look forward to study further the performance (resolutions and deformations)
- Opportunity to exploit pixel TPC high precision tracking and particle identification with dE/dx using single electrons

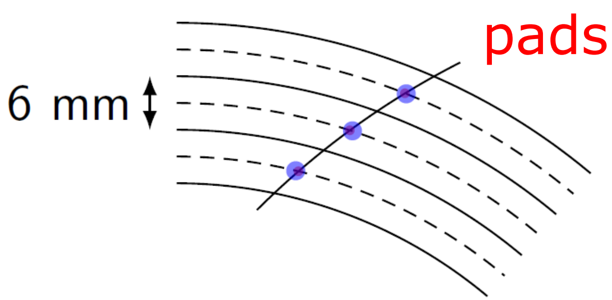
Simulation of ILD TPC with pixel readout

- 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

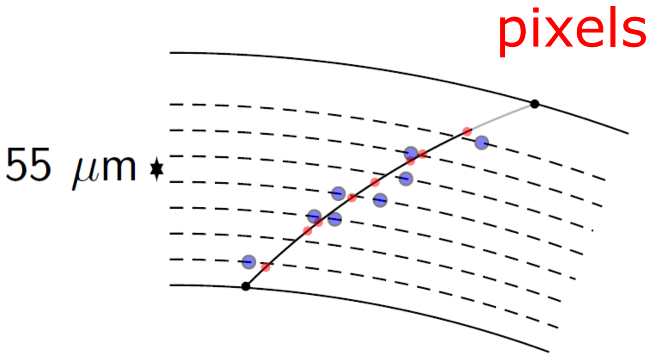


PhD Kees Ligtenberg

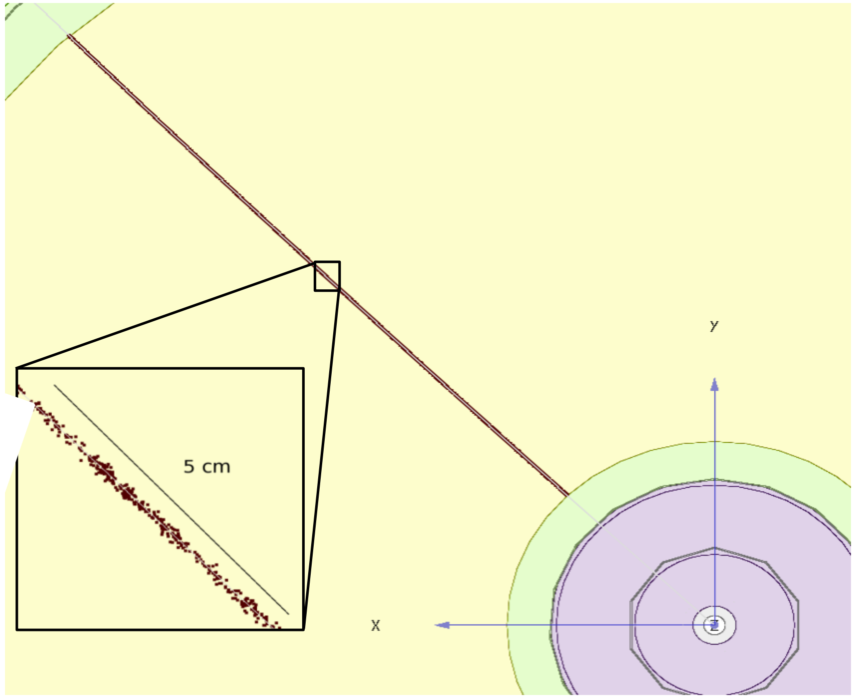
https://www.nikhef.nl/pub/services/biblio/theses_pdf/thesis_C_Ligtenberg.pdf



22 electrons / hit
~ 200 hits / track



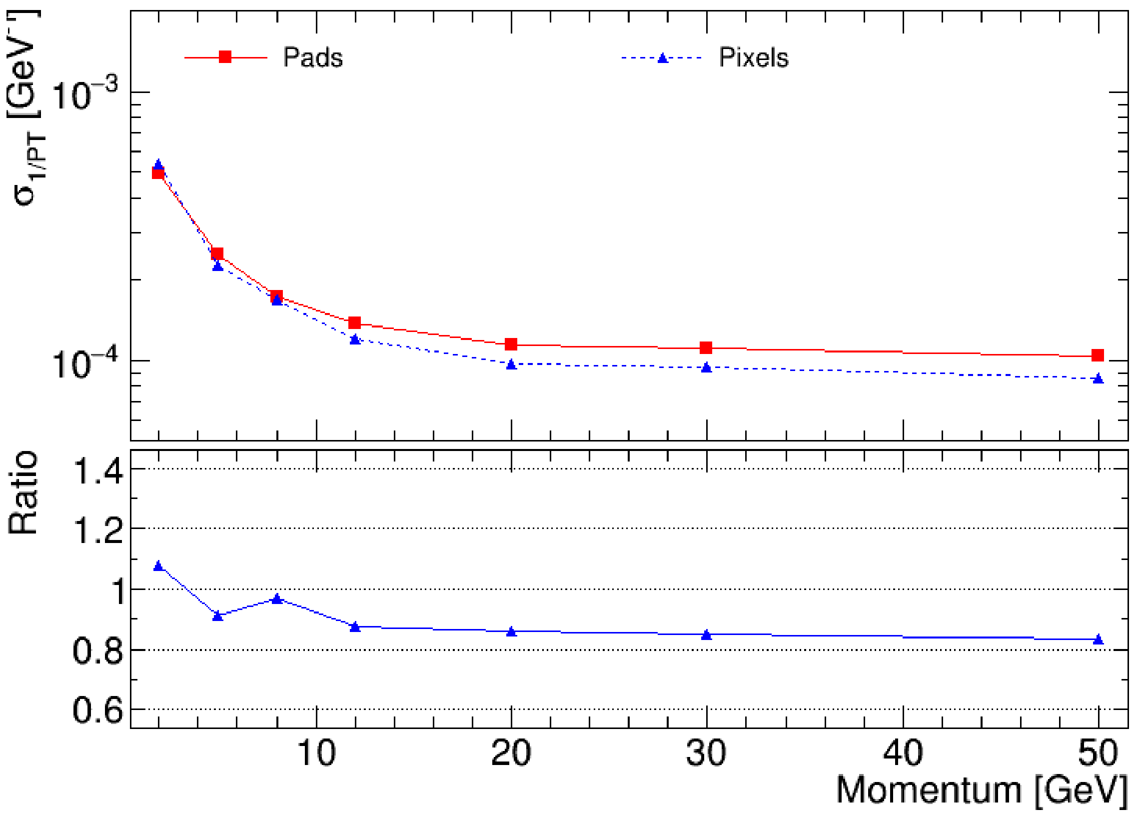
1 electron / hit
~ 10 000 hits / track

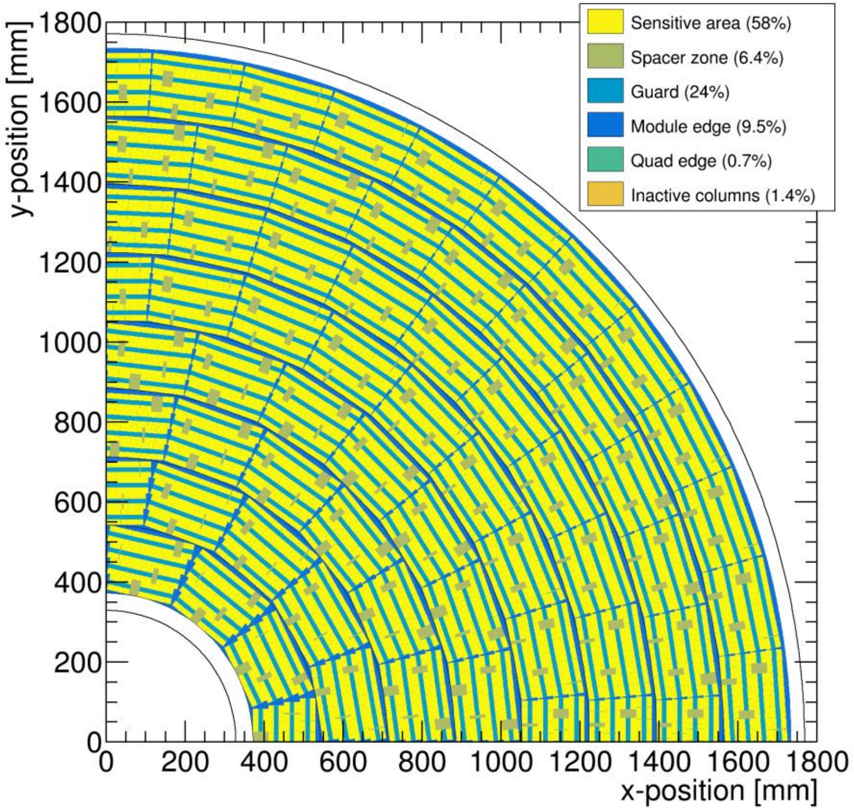


50 GeV muon track with pixel readout

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 59%) and deltas.





A Pixel TPC at the CEPC?

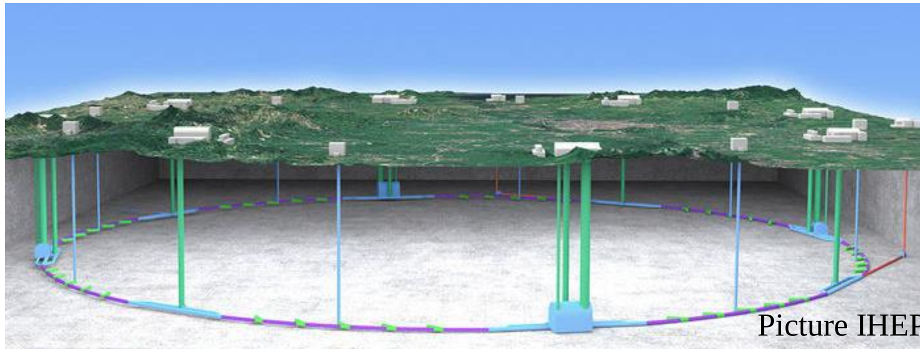
CEPC running above the Z (WW, Higgs) there are no critical issues

A Pixel TPC can deal with the high beam rates at the CEPC

- At the Z pole the CEPC with L = 34 10^{34} cm^{-2} s^{-1} will produce Z bosons at ~10 kHz
- Link speed of Timepix3 (in Quad) is 80 Mbps: 2.6 MHits/s per 1.41 × 1.41 cm^2
- Excellent time resolution: time stamping of tracks < 1.2 ns
- Power consumption ~2W/chip depends on hit rate
  - No power pulsing possible at the CEPC
  - Good cooling is important
- Ion back flow of the quad is measured to be 1.3%

  at a gain of ~2000. So IBF*Gain is ~25.

  NB: to limit the distortions in de drift volume one needs to achieve < 4

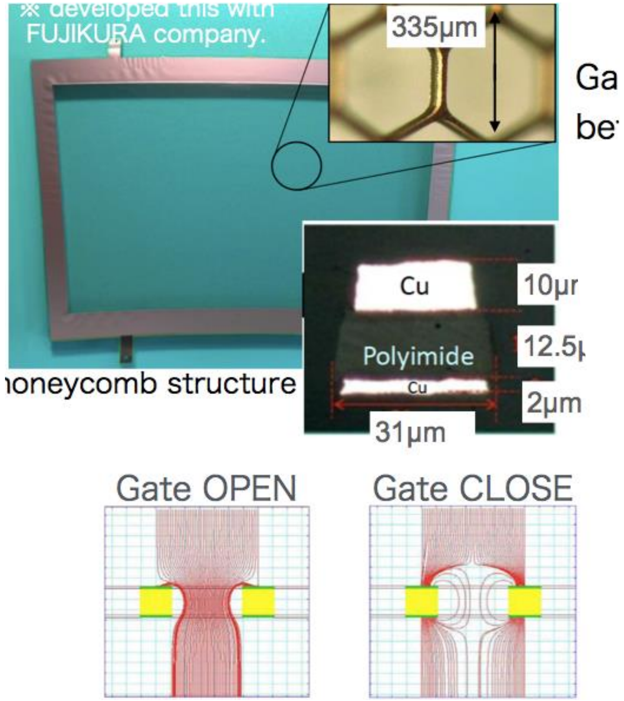


LCWS 2019 Sendai talk Huirong Qi

Reducing the Ion back flow in a (Pixel) TPC

The Ion back flow can be reduced – while running at the Z:

- By installing a gating device and closing the gate after a trigger.
  E.g.the Gating GEM as developed in the contect of the ILD experiment



- LCWS19 presentation ILD gating GEM by Yumi Aoki (KEK)

Can one apply gating in Z collisions?
High luminosity CEPC L = 32-50 10^{34} $cm^{-2}s^{-1}$.
Time between Z interactions 120-60 μs TPC drift takes 30 μs. So events are separated in the TPC; gating is possible.
Gate length of 20-60 μs would stop the ions in triggered mode.

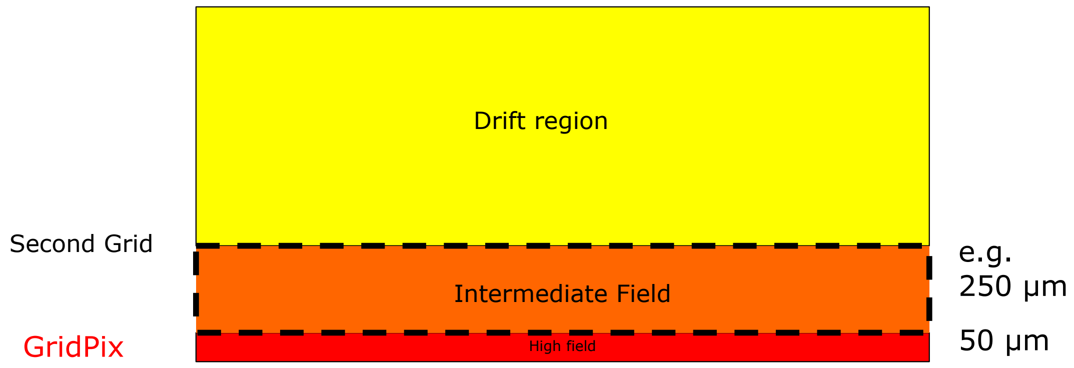
Problem is that the gating will lead to dead time and a data taking efficiency at high luminosities of ~85%-65% (for a 20 μs gate length).

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. Well below the specifications.



We plan to test this idea

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

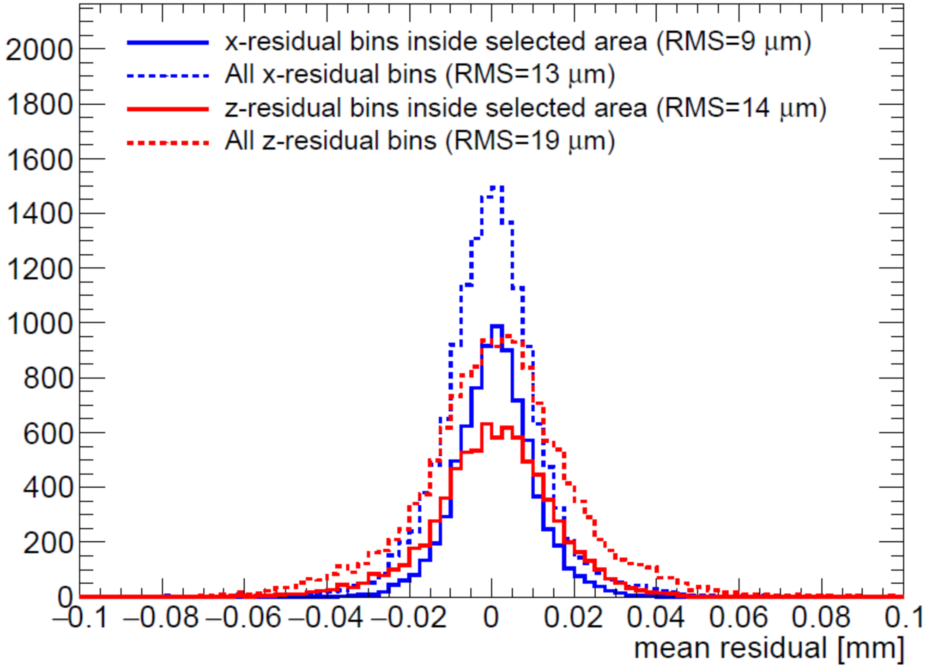
- A single chip GridPix detector was reliably operated in a test beam in 2017
  - Single electron detection => the resolution is primarily limited by diffusion
  - Systematic uncertainties are low: < 10 μm in the pixel xy plane
  - dE/dx resolution for a 1 m track is 4.1%
- A Quad detector was designed and the results from the 2018 test beam presented
  - 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
  - Deformations in the transverse plane for one quad are shown to be < 15 μm
- Test beam data taken at DESY in 2021: first results on precision tracking presented
- A pixel TPC has become a realistic viable option for experiments
  - High precision tracking 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 double grid will allow to reduce the Ion back flow distortions substantially

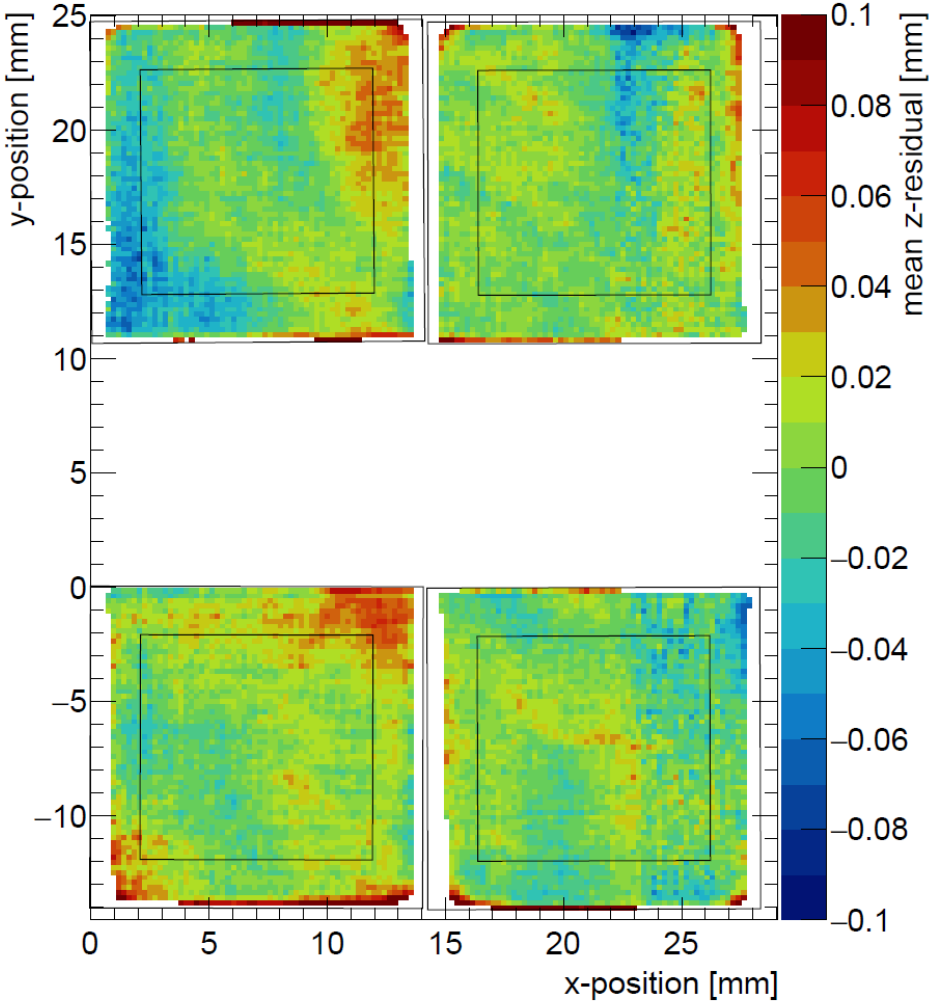
(Backup) Test beam summary

- First preliminary results of the 8 Quad Module in the DESY test beam in June 2021 have been presented
- The run 6916 B=0 T with p=6 GeV has been analysed
- The Mimosa telescope has been aligned using the corryvrecan software and tracks fitted with the GBL package
- The 8 quad module data is decoded and matched to the tracks
- The single electron resolution is:
  - σ_{xy} =250 μm and σ_z =425 μm (mean drift distance of 6.4 mm)
- In total 1060 tracks were selected with 900 hits on track
- The tracking precision: position 9 μm (xy) 13 μm (z) in angle 0.19 mrad (dx/dy) 0.25 mrad
- Note that the module or tracklength is 157.96 mm
- This is very promising: more precise results can be extracted

QUAD deformations in drift plane (Z)

- After applying fitted edge corrections
- RMS of the mean residuals are 19 µm over the whole QUAD





8-quad module deformations laser measurements

- One of the quads inside the 8-quad modules has been measured using laser tracks
- No edge corrections are applied
- The result is encouraging; the guard wires that run over the quad edges define a homogeneous field
- The RMS in the large rectangular area (near the edges) is only 14 μm

- Current plan is to do a test beam at DESY and Bonn as soon as all 8-quads can be read out simultaneously