Status Pixel TPC R&D

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Cornelis Ligtenberg,
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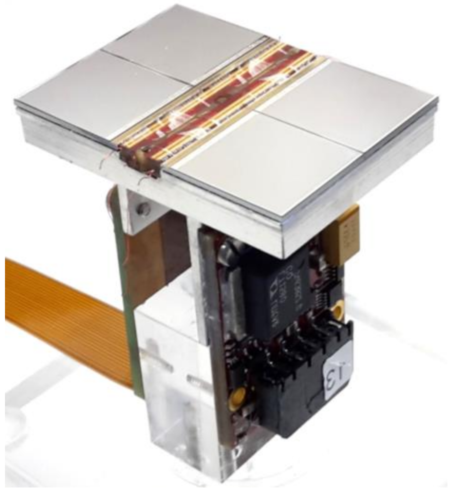
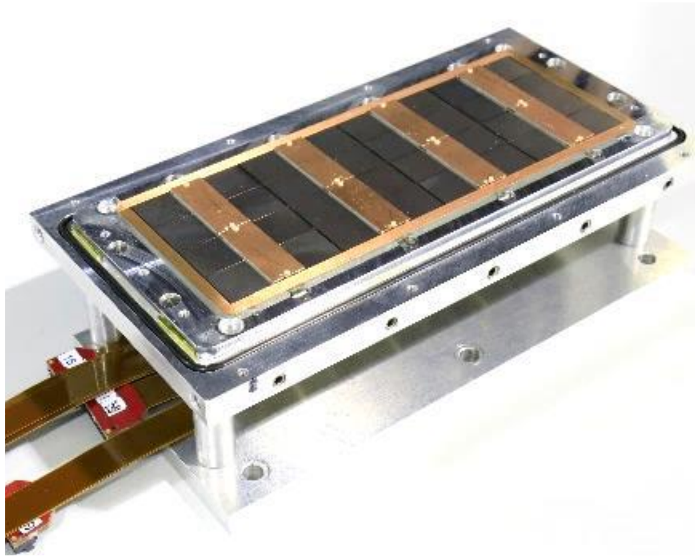
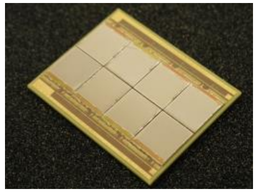




ILD meeting 15 January 2024

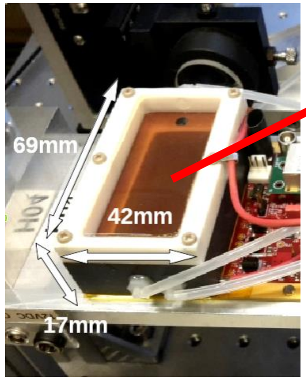
Pixel TPC



(Octopuce)

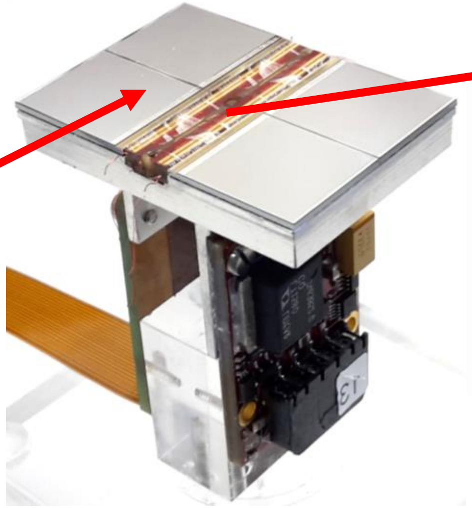
(TimePix1)

(2007-14)



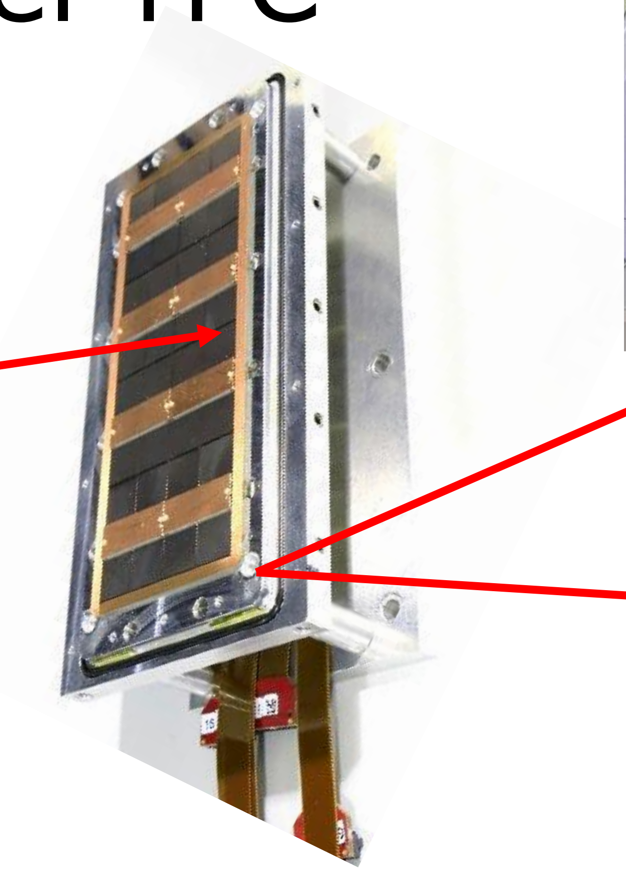
TPX3 chip

2017



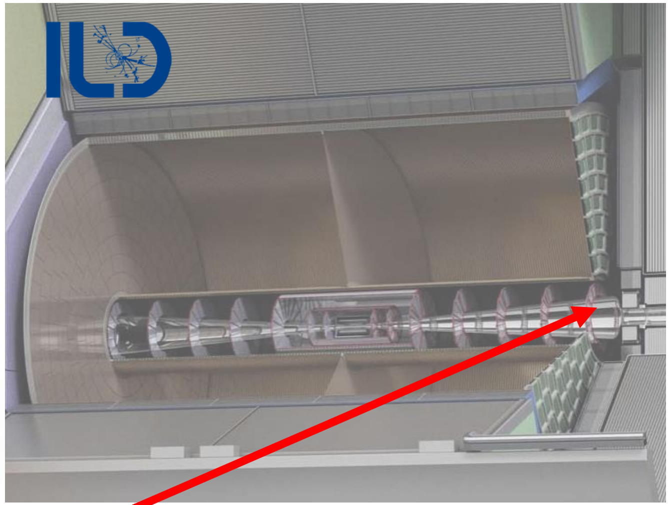
Quad

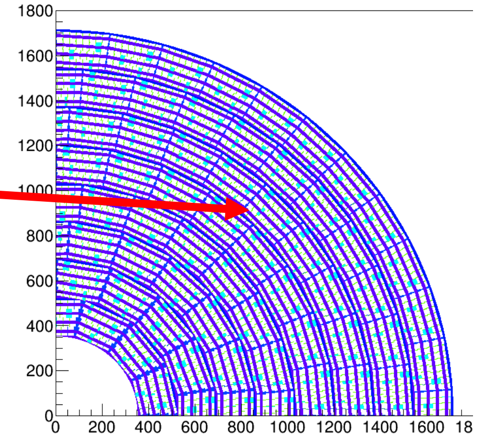
2018



Module

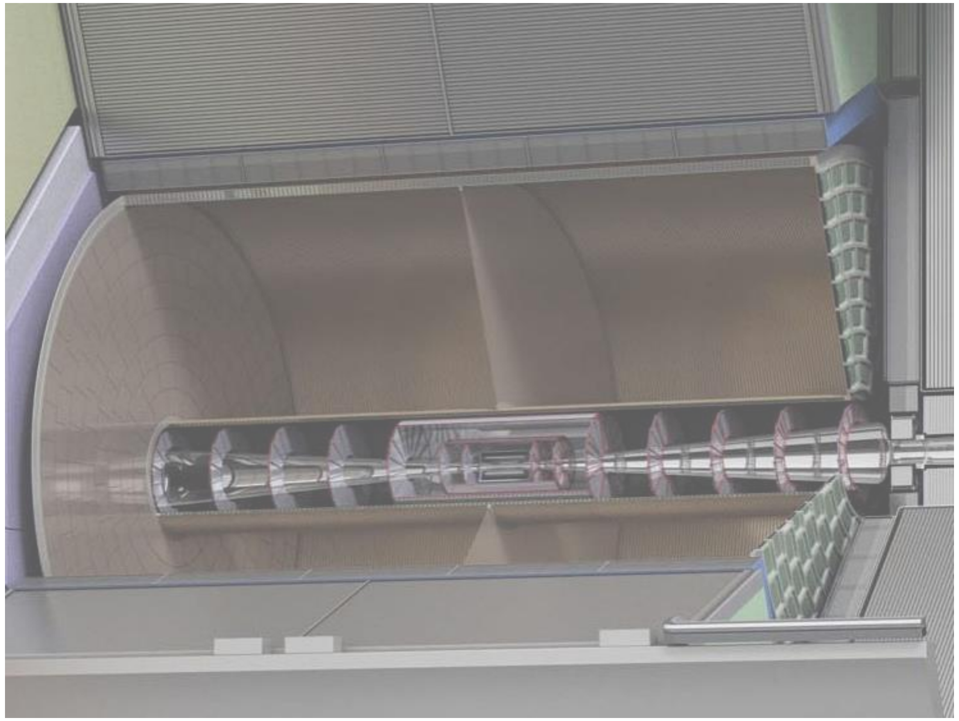
2019



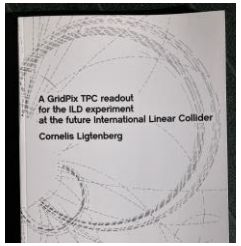


TPC plane

Pixel TPC



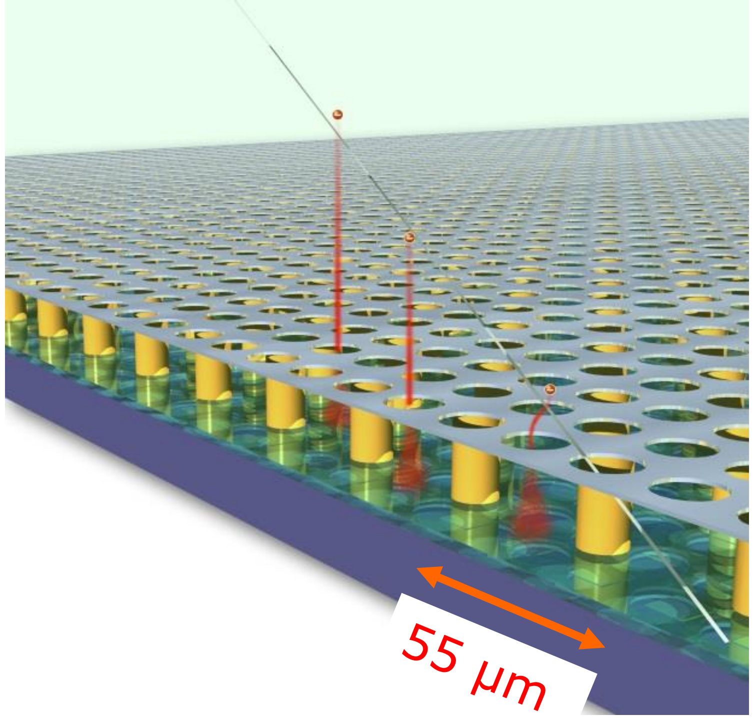
- Material budget is
  - 0.01 X_0 TPC gas
  - 0.01 X_0 inner cylinder
  - 0.03 X_0 outer cylinder
  - < 0.25 X_0 endplates (incl readout)
- Note the very low budget in the barrel region. Material budget can be respected by different technologies like GEM, MicroMegas and Pixels
- TPC is sliced between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

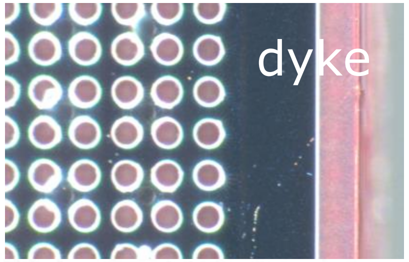


https://www.nikhef.nl/pub/services/biblio/theses_pdf/thesis_C_Ligtenberg.pdf

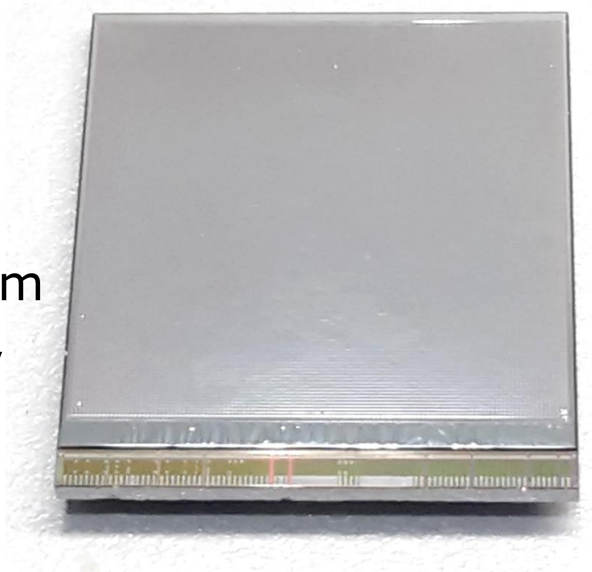
GridPix technology

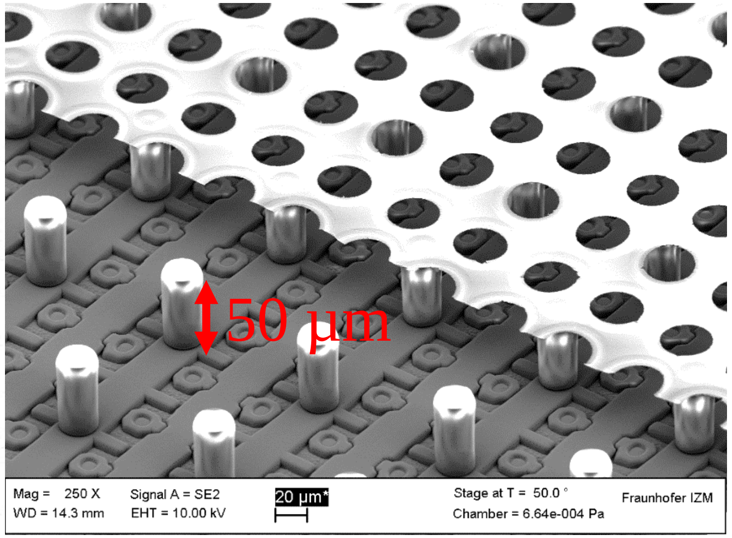
- Pixel chip with integrated Grid (Micromegas-like)
- InGrid post-processed @ IZM
- Grid set at negative voltage (300 – 600 V) to provide gas amplification
- Very small pixel size (55 μm)
- detecting individual electrons





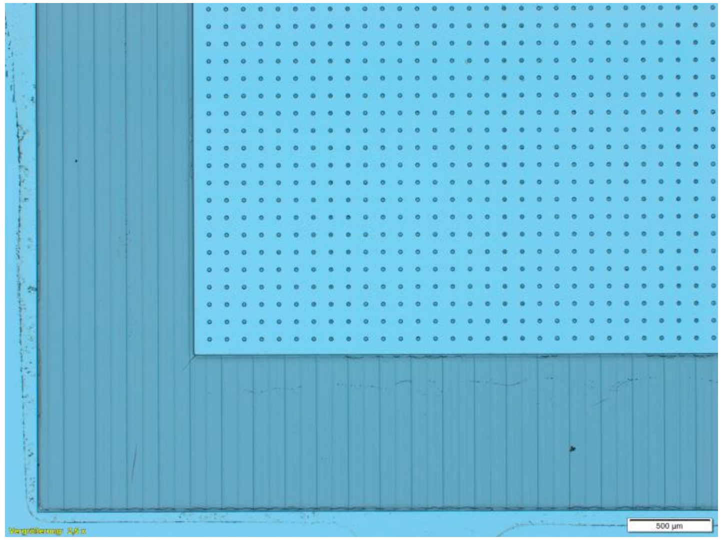
- Aluminium grid (1 μm thick)
- 35 μm wide holes, 55 μm pitch
- Supported by SU8 pillars 50 μm high
- Grid surrounded by SU8 dyke (150 μm wide solid strip) for mechanical and HV stability

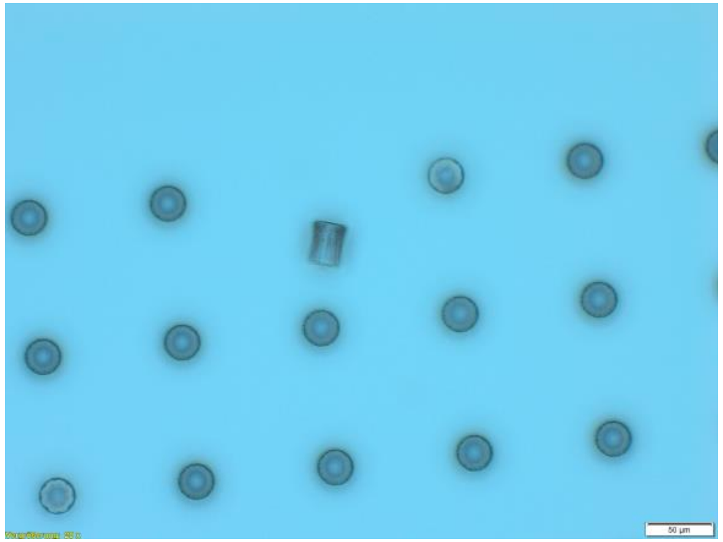




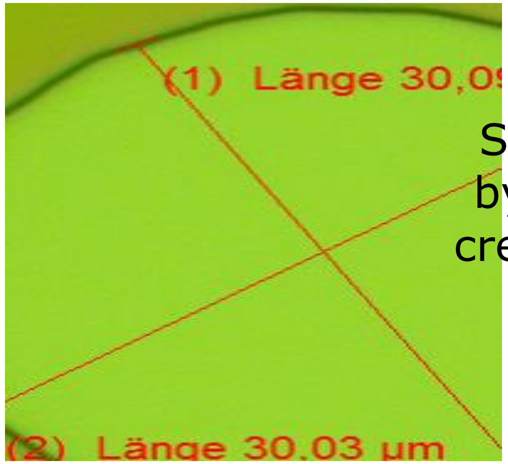
First Steps Towards
"GridPixes made in Bonn (2023)"

First structures made of SU8: 30μm high pillars and dykes

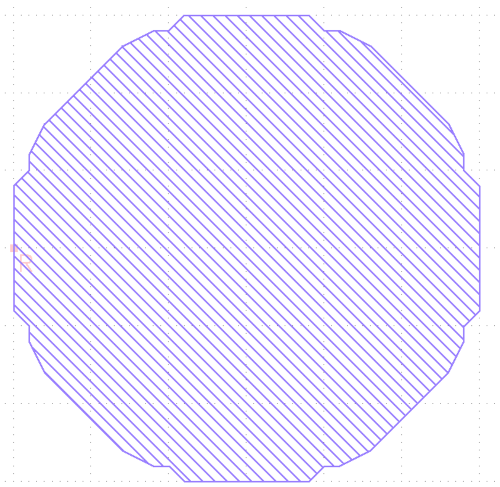




Holes in SU8 layer

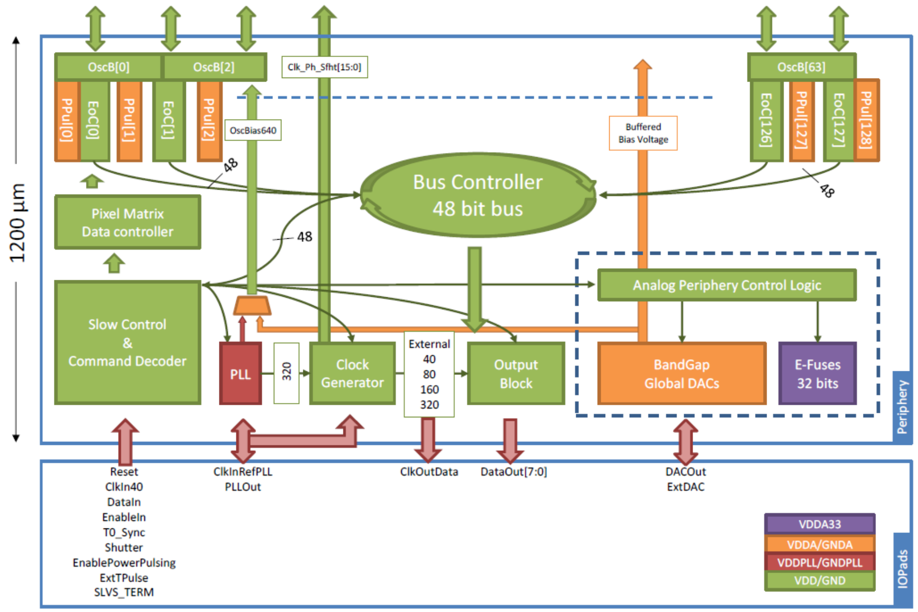


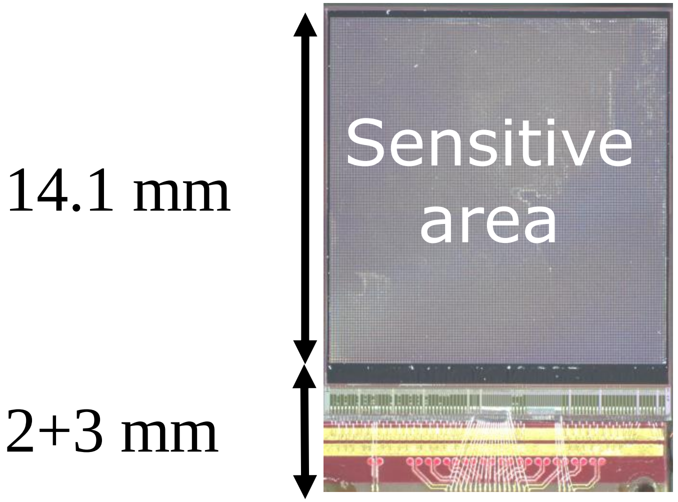
Shape caused by software to create the mask



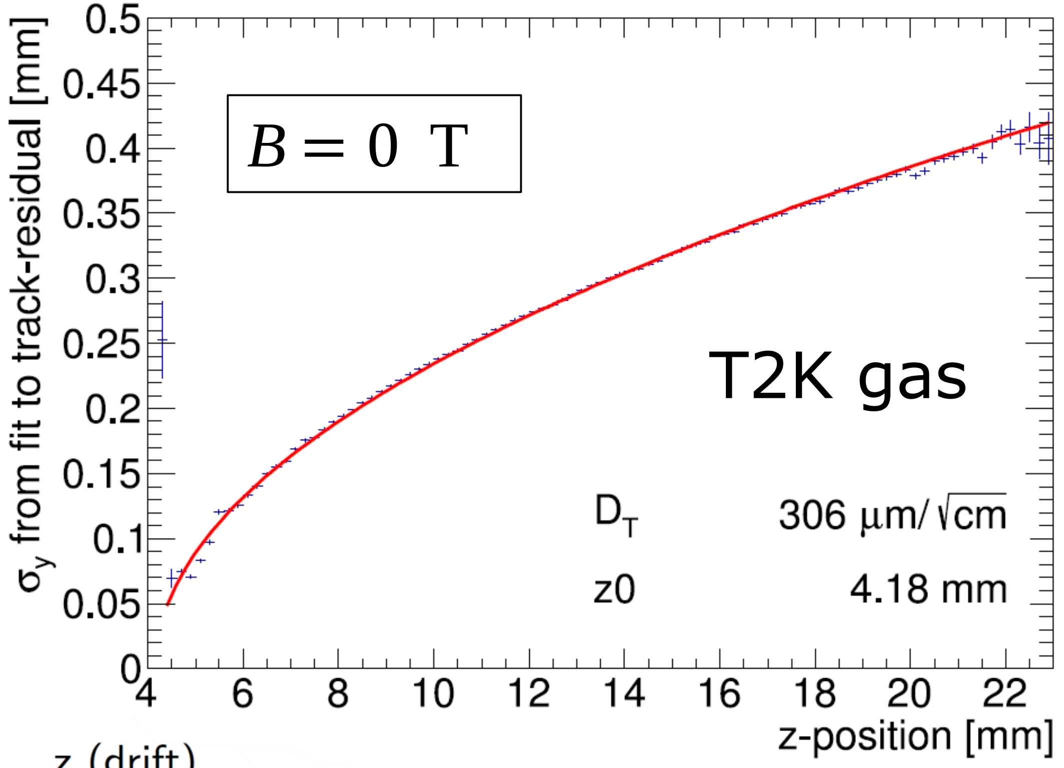
Pixel chip: TimePix3

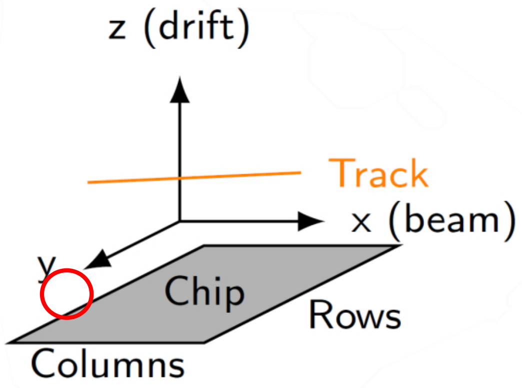
- 256 x 256 pixels
- 55 x 55 µm pitch
- 14.1 x 14.1 mm sensitive area
- TDC with **640 MHz clock** (1.56 ns)
- Used in the data driven mode
  - Each hit consists of the **pixel address** and **time stamp** of arrival time (ToA)
  - Time over threshold (ToT) is added to register the signal amplitude
  - 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:

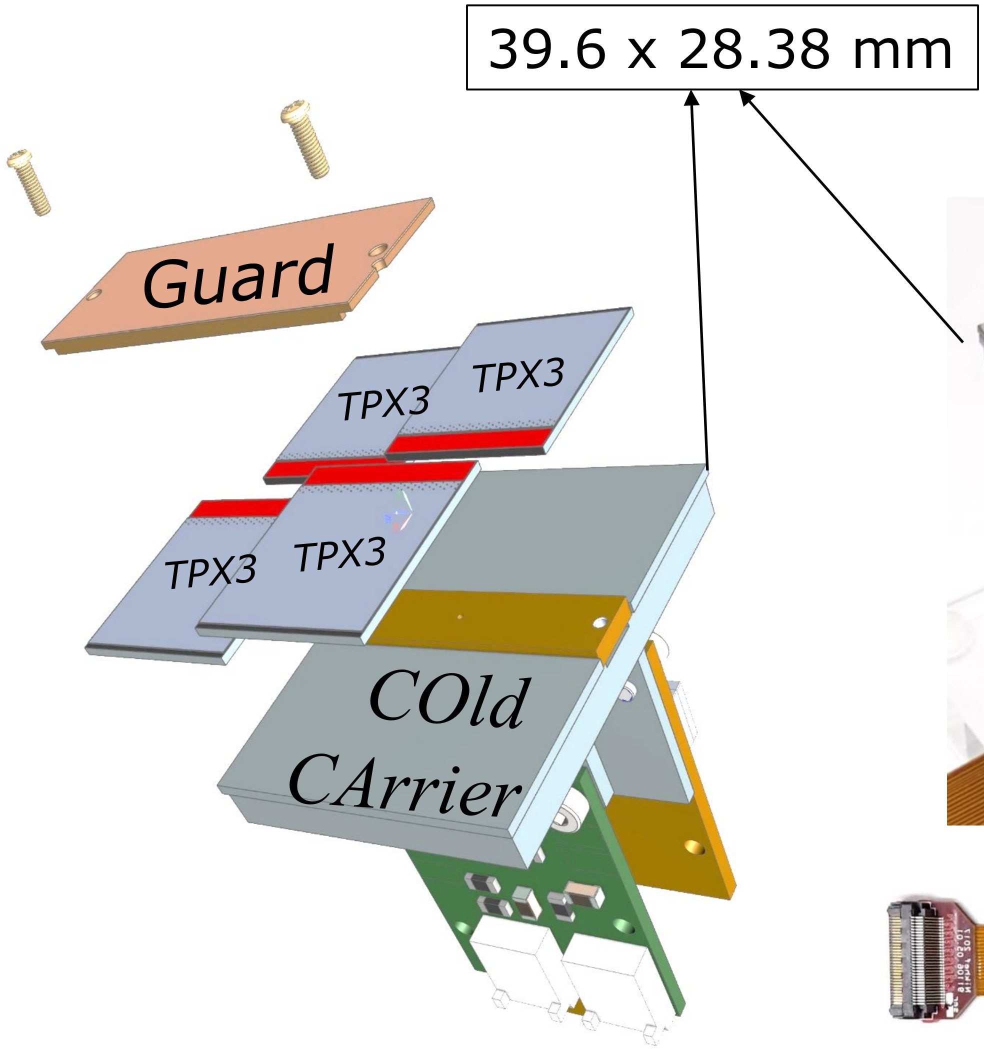
- σ_{y0} = pixel size $/\sqrt{12}$
- Diffusion D_T from fit

Note that:

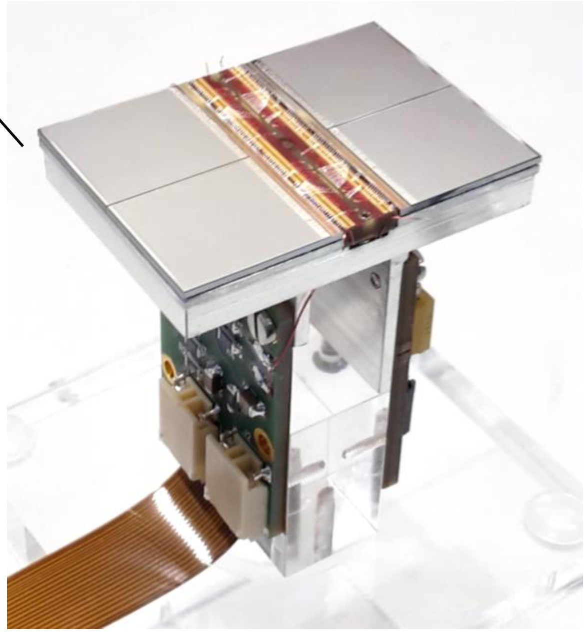
- A hit resolution of ~250 µm is ~25 µm for a 100-hit track (~ 1 cm track length)
- At $B = 4$ T , $D_T = 25\ \mu\text{m}/\sqrt{\text{cm}}$

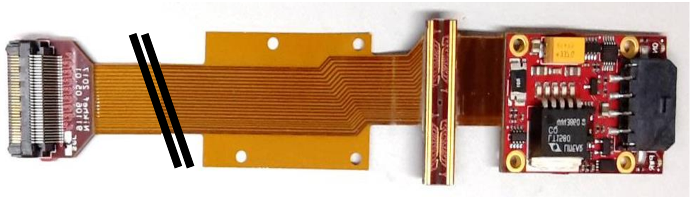
QUAD design and realization

- 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



series of QUADs



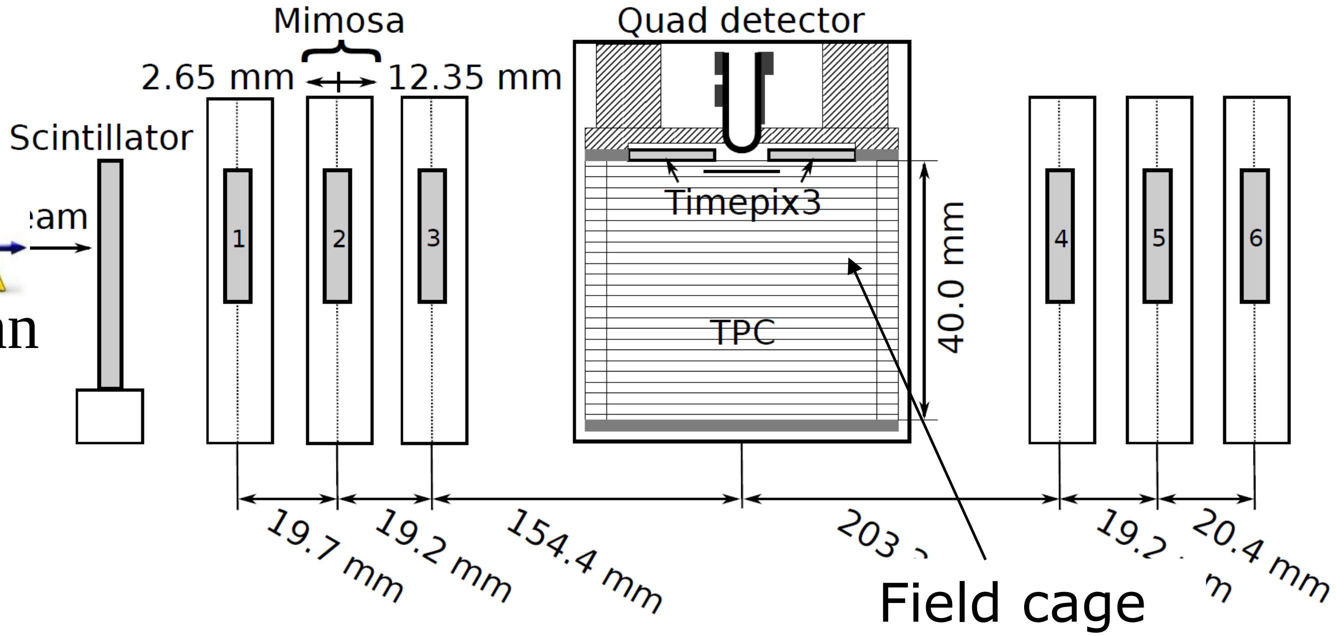


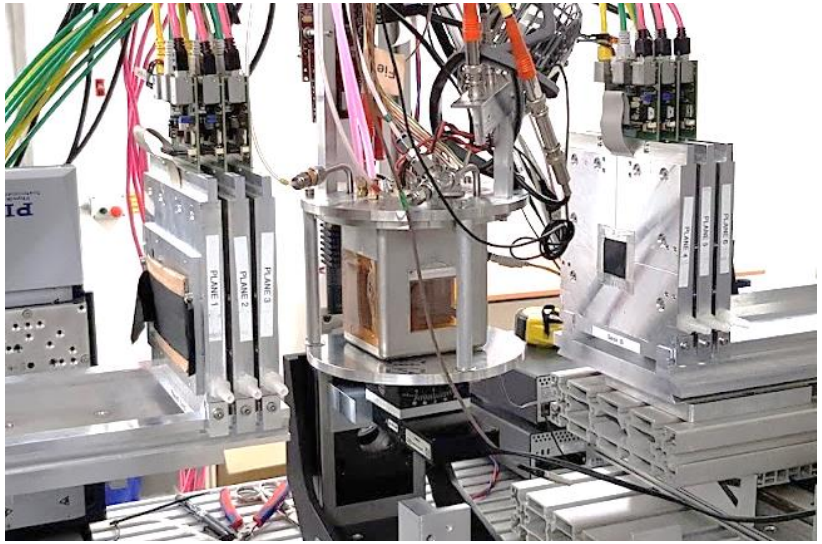
QUAD test beam in Bonn (October 2018)

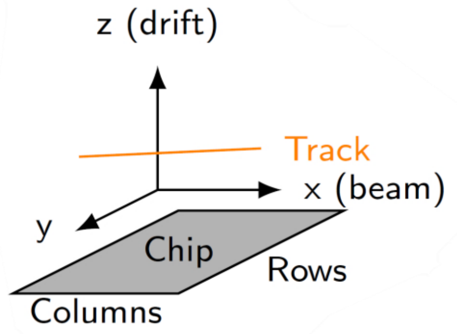
- ELSA: 2.5 GeV electrons
- Tracks referenced by Mimosa telescope
- QUAD sandwiched between Mimosa planes
  - Largely improved track definition
  - 6 planes with 18.4 μm × 18.4 μm sized pixels
- Gas: $Ar/CF_4/iC_4H_{10}$ 95/3/2 (T2K)
- E_d = 400 V/cm, V_{grid} = -330 V
- Typical beam height above the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

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

@Bonn

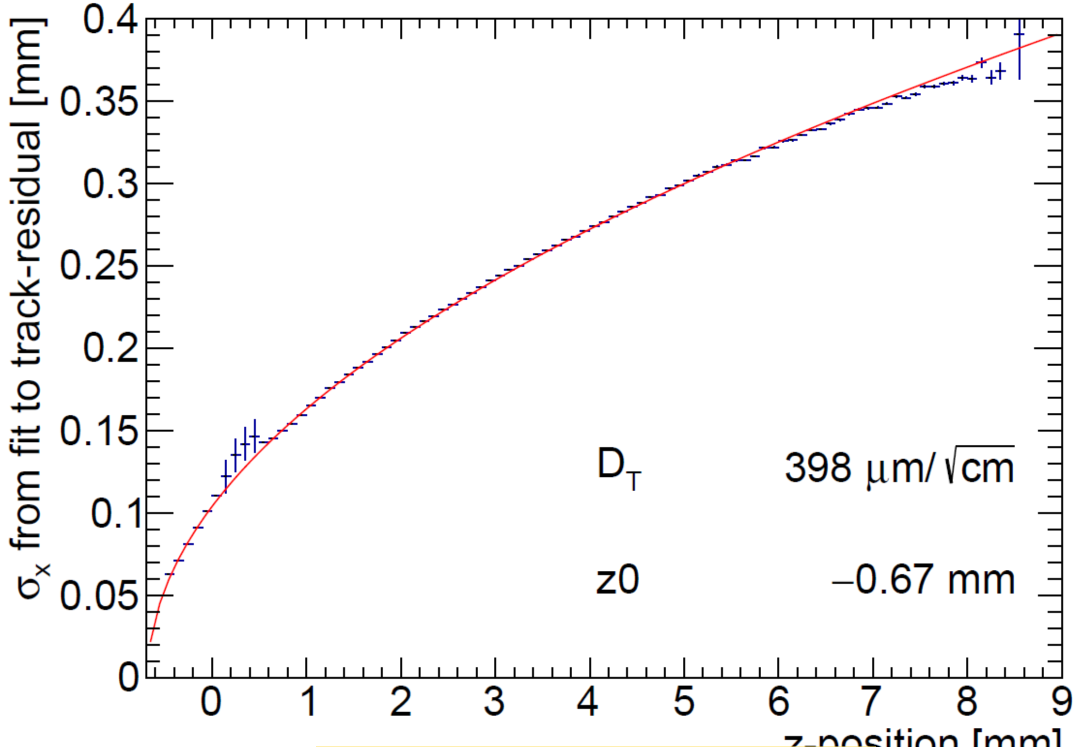






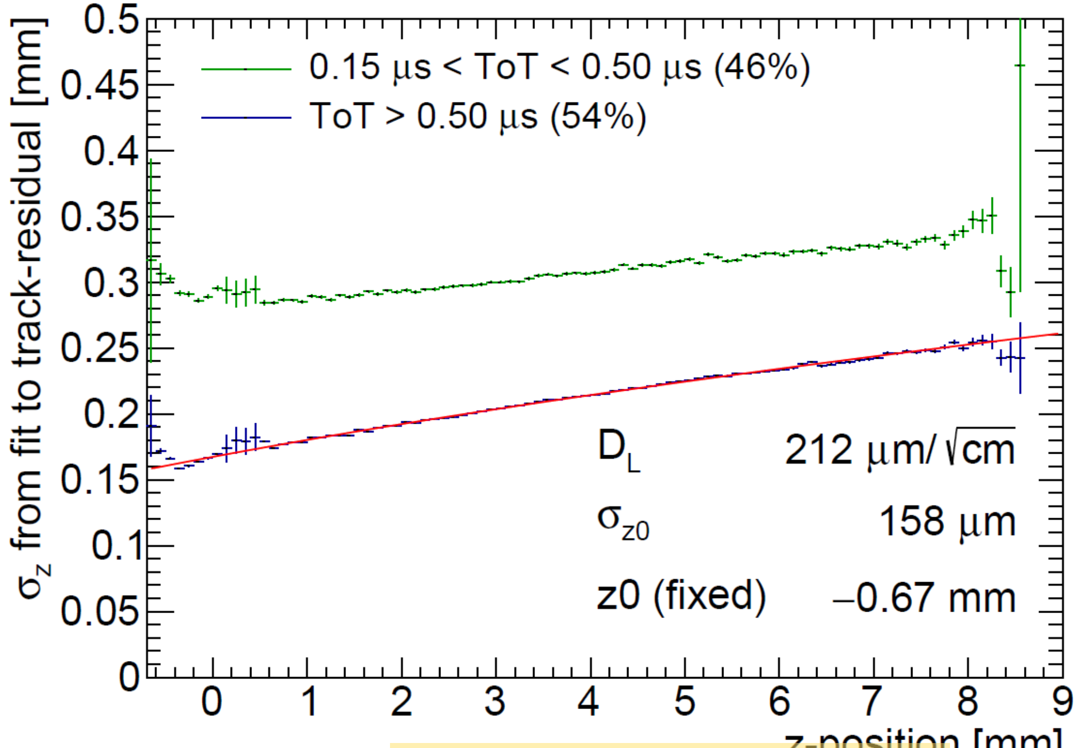
QUAD single hit resolution

Transverse



D_T = 398 µm/√cm

Longitudinal

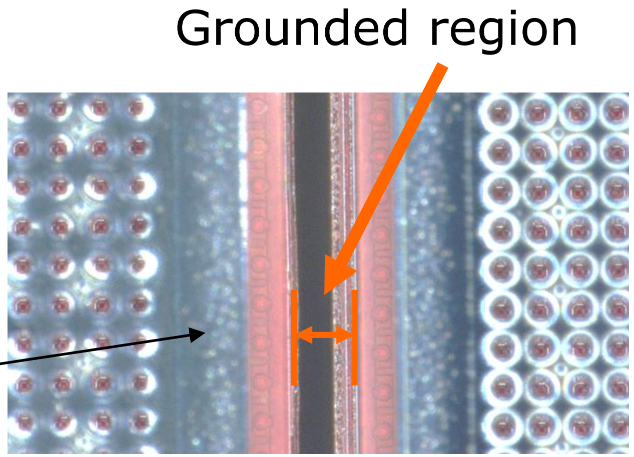


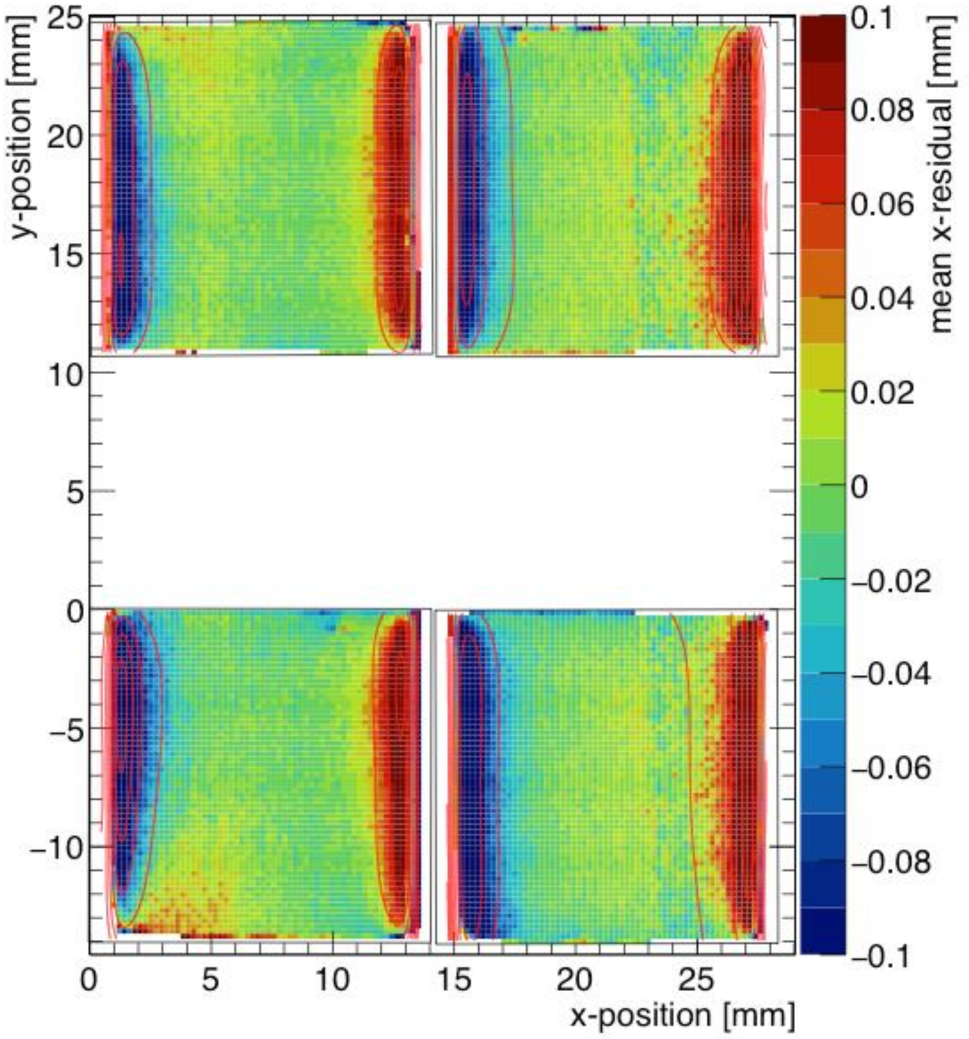
D_L = 212 µm/√cm

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

QUAD edge deformations (XY)

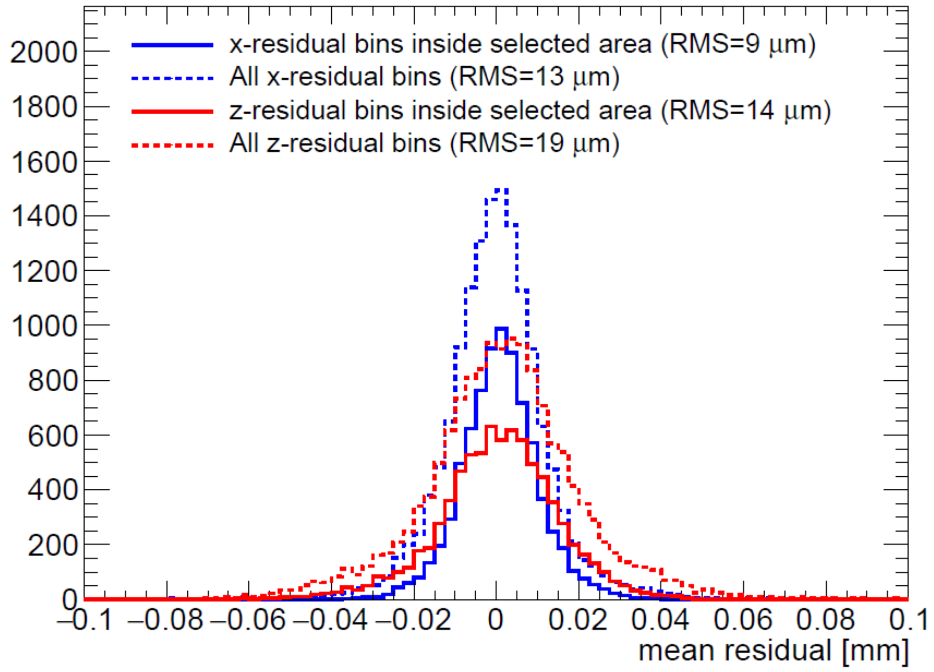
- Small deformations due to
  - Dead zone between chips
  - Grounded region between chips
- Are corrected by:
  - fitted correction function
  - adding proper guard wire electrode

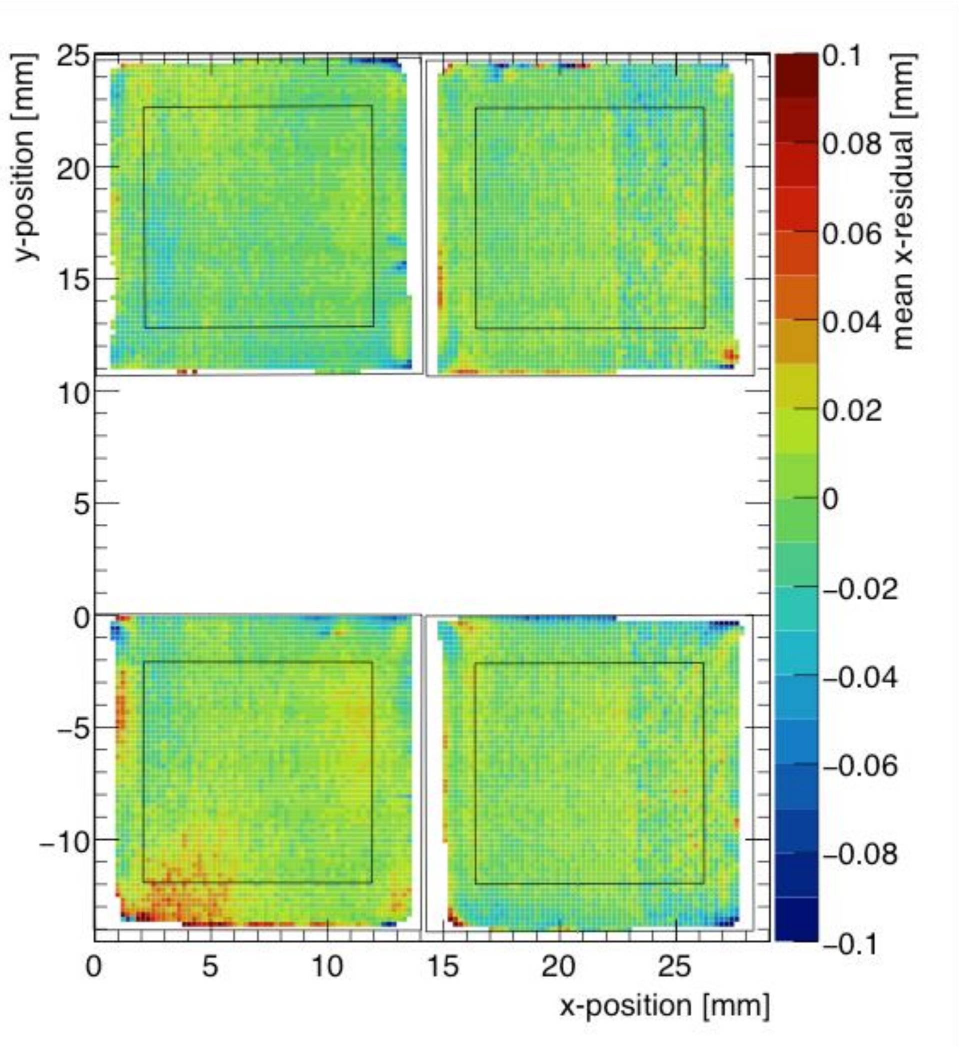




QUAD deformations in transverse plane (XY)

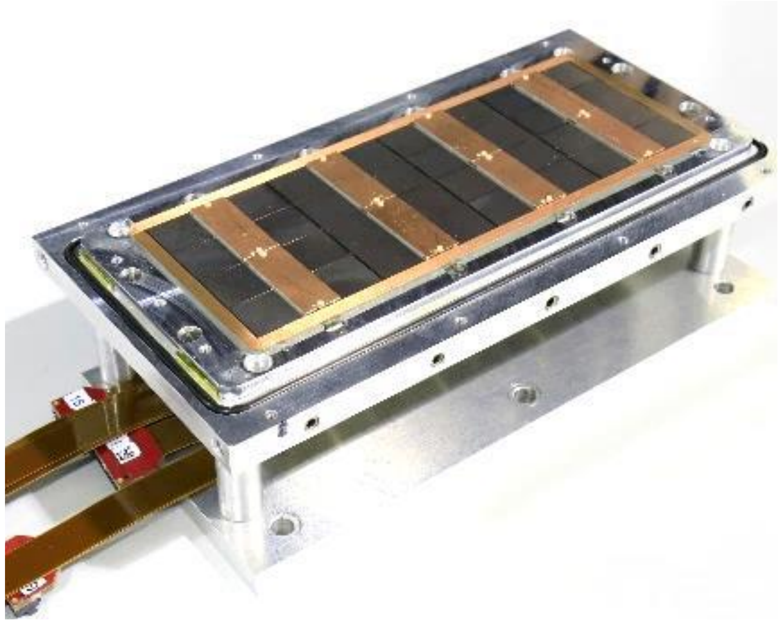
- After applying fitted edge corrections
- RMS of the mean residuals are 13 μm over the whole QUAD

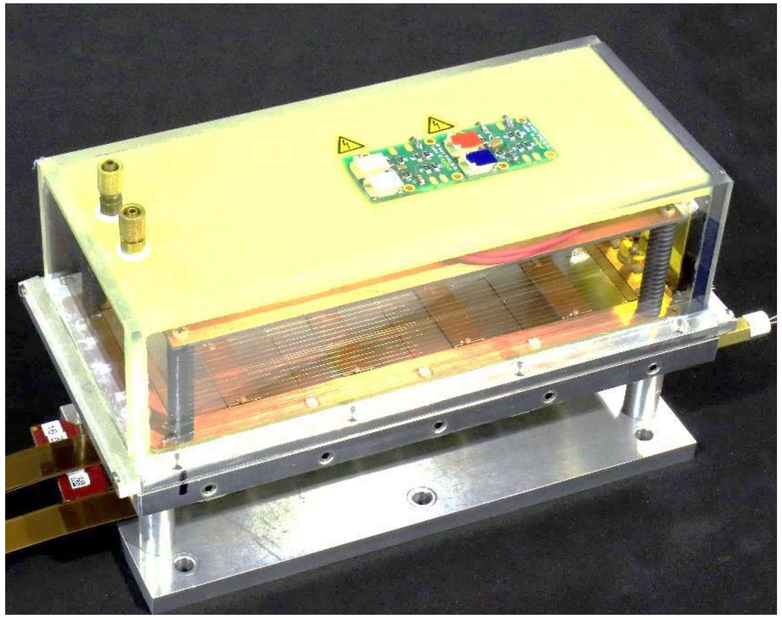


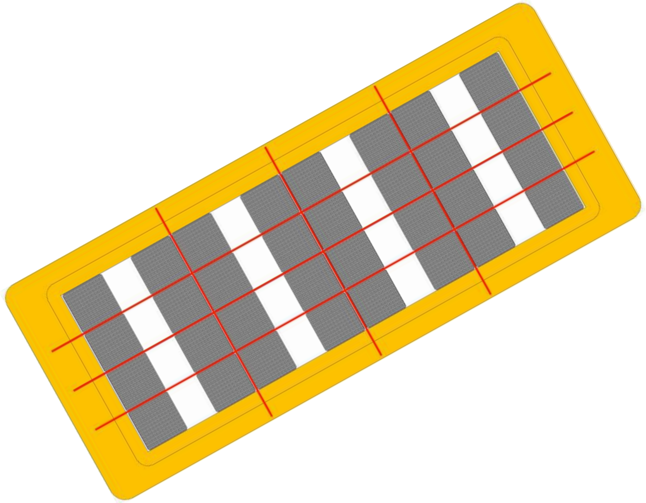


QUAD as a building block

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

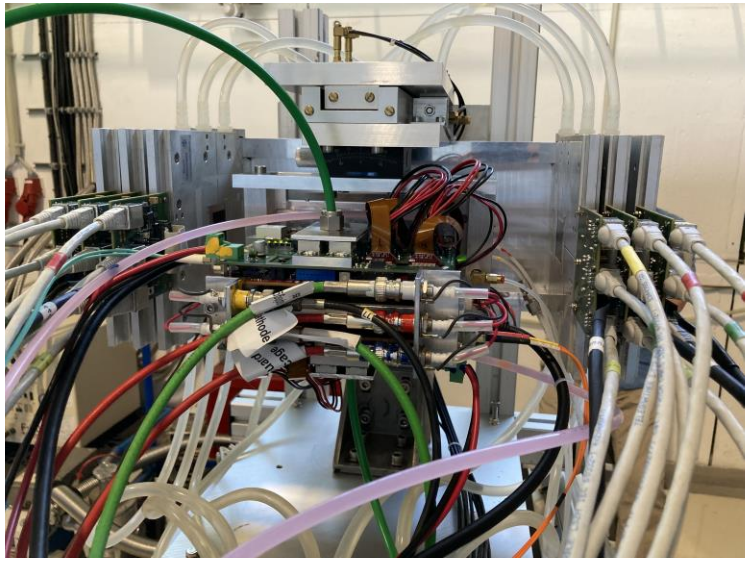


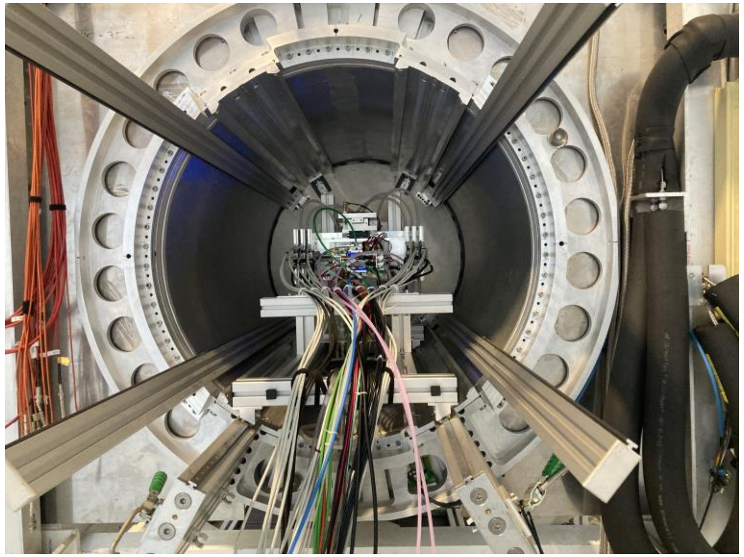




in red guard wires

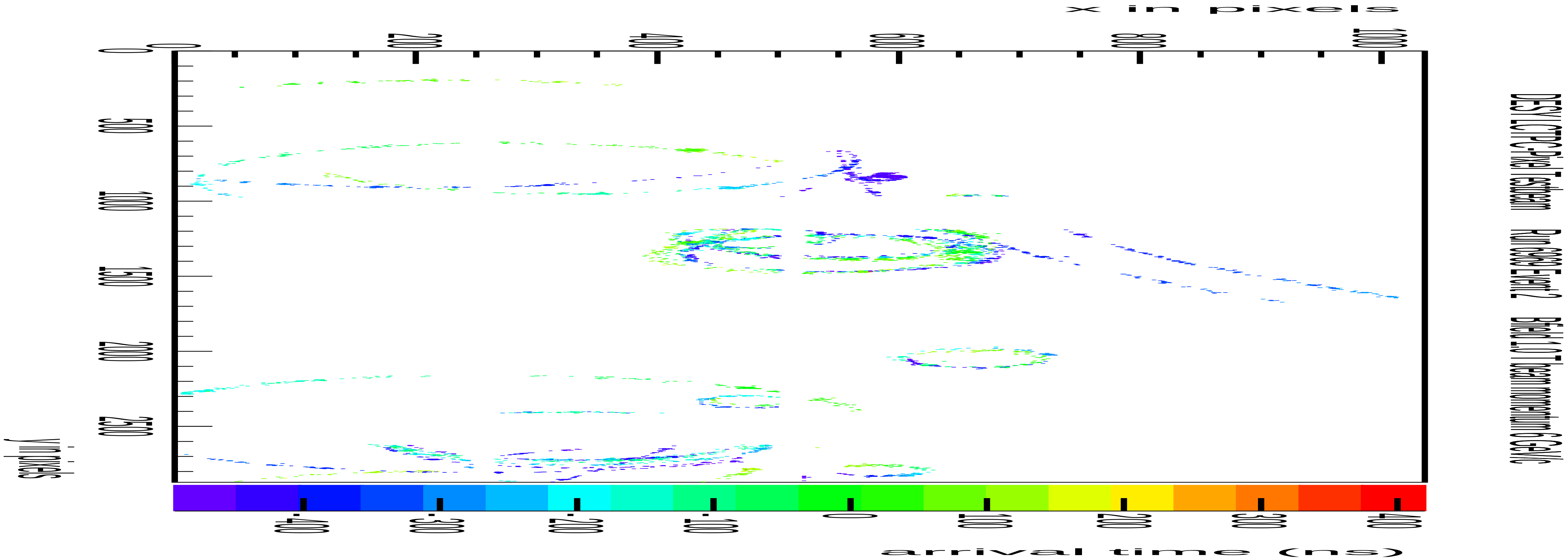
DESY testbeam June 2021





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

x global

z global

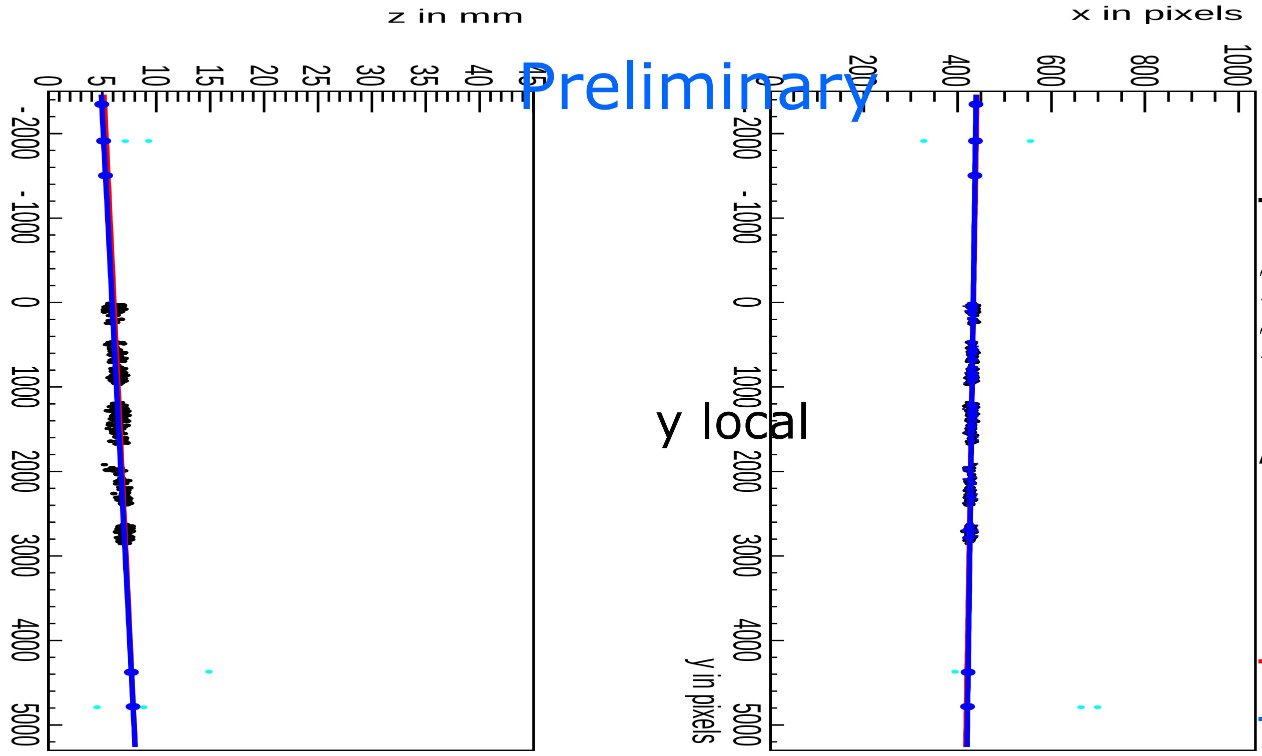
z global

y global

x local

z local drift

y local



y local

Event display with module and telescope

TPX3 track 1130 hits

$\chi^2_{xy} = 677.5/1128$

$\chi^2_{z} = 775.9/1069$

Asymmetric tail outlier removal applied 1071 hits in z kept.

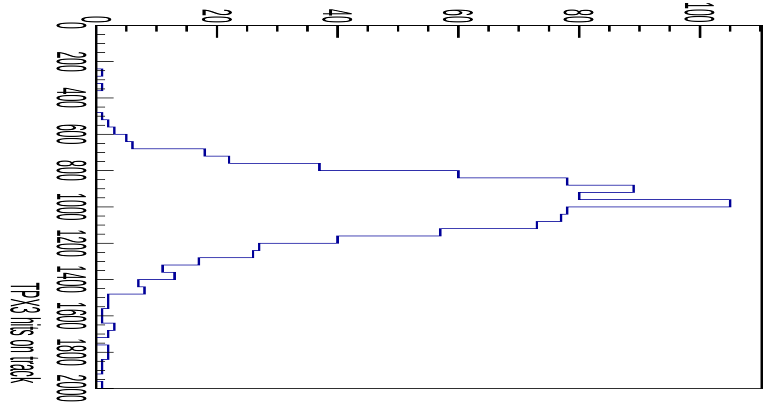
TPX3 track hits

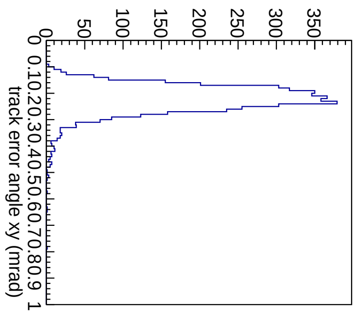
Telescope track hits (off track green)

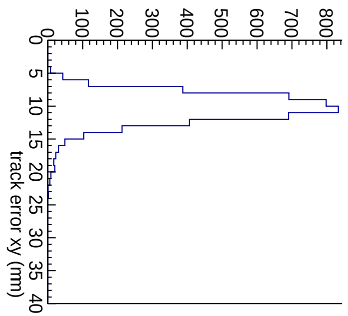
DESY testbeam Module Analysis

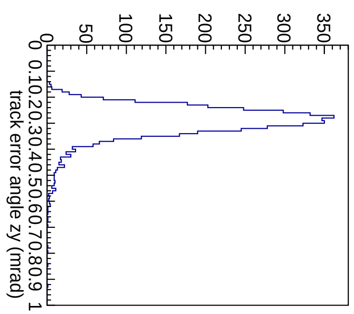
Run 6916 B=0 T p =6 GeV

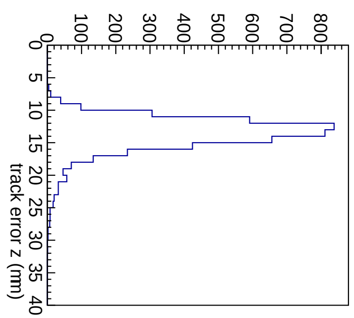
Preliminary











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

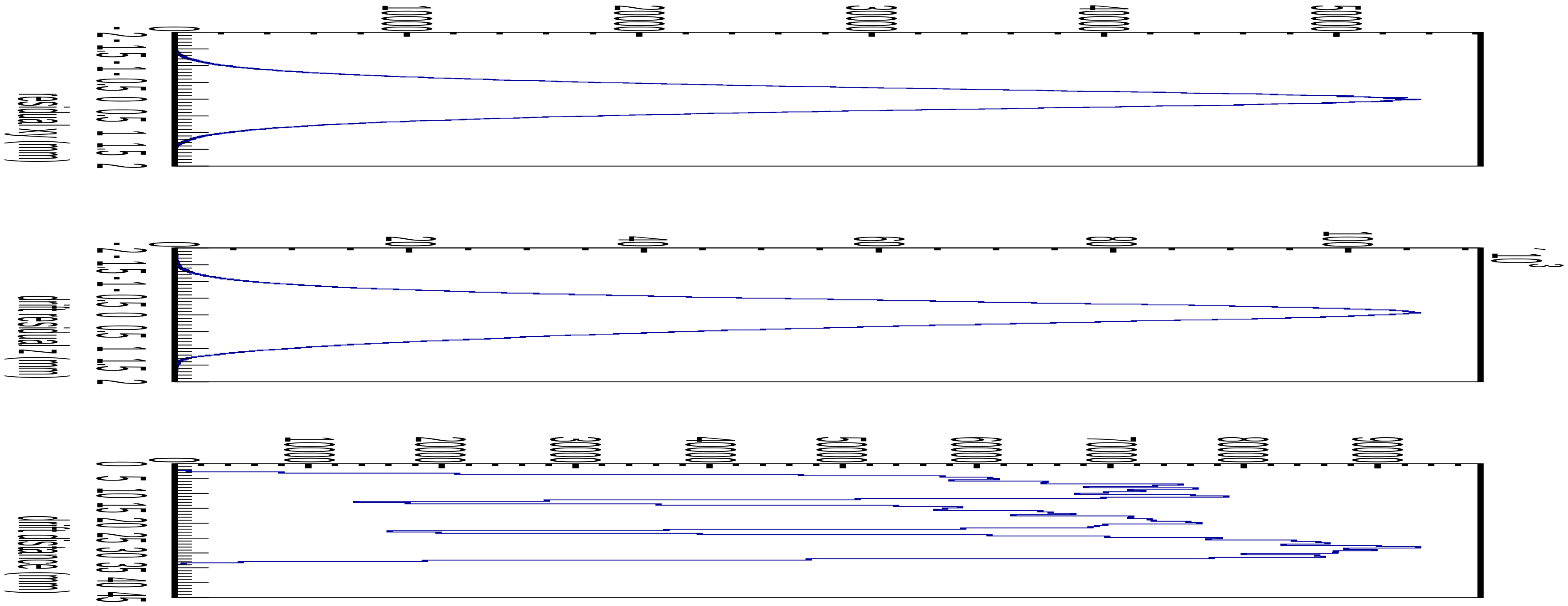
Note that in a B field because of the reduced diffusion the tracking precision will improve substantially

DESY testbeam Module Analysis

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

Three runs at different drift distances

Preliminary

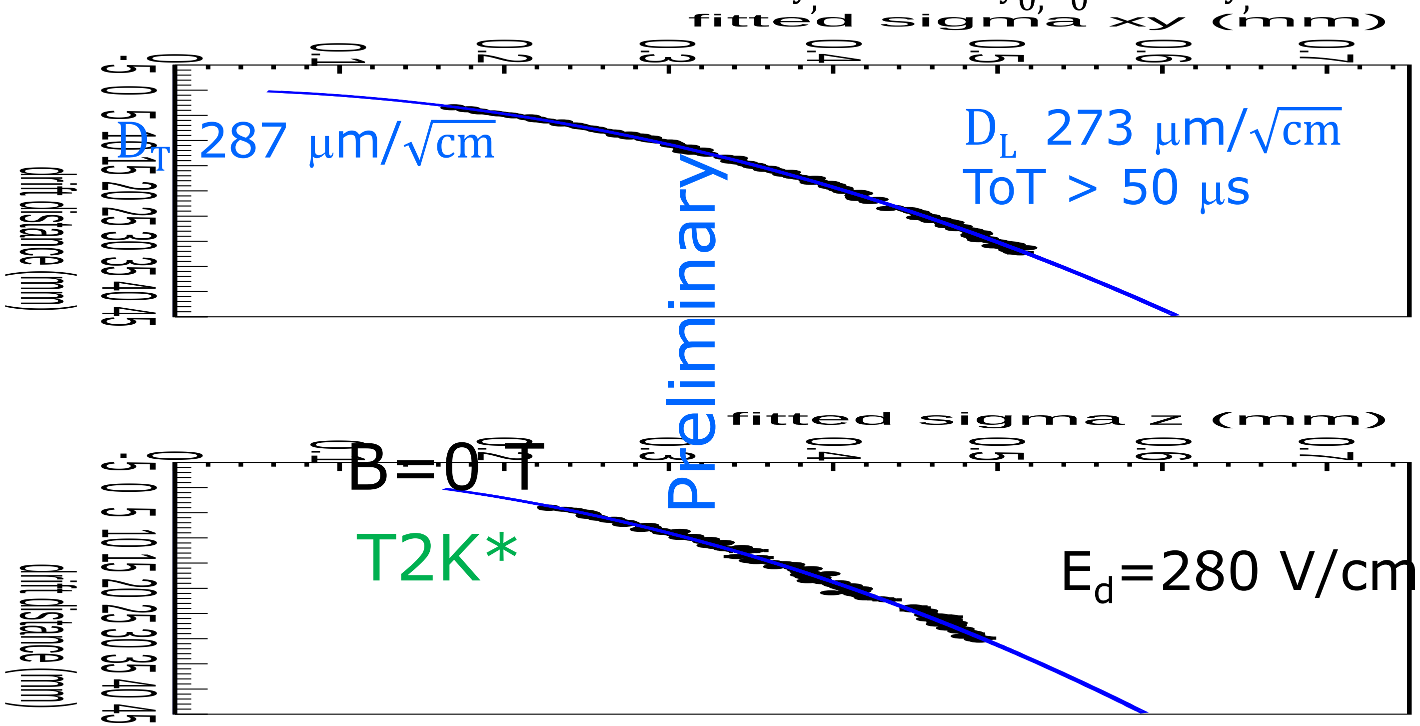


DESY testbeam Module Analysis

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

Fitted resolution

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



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

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

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

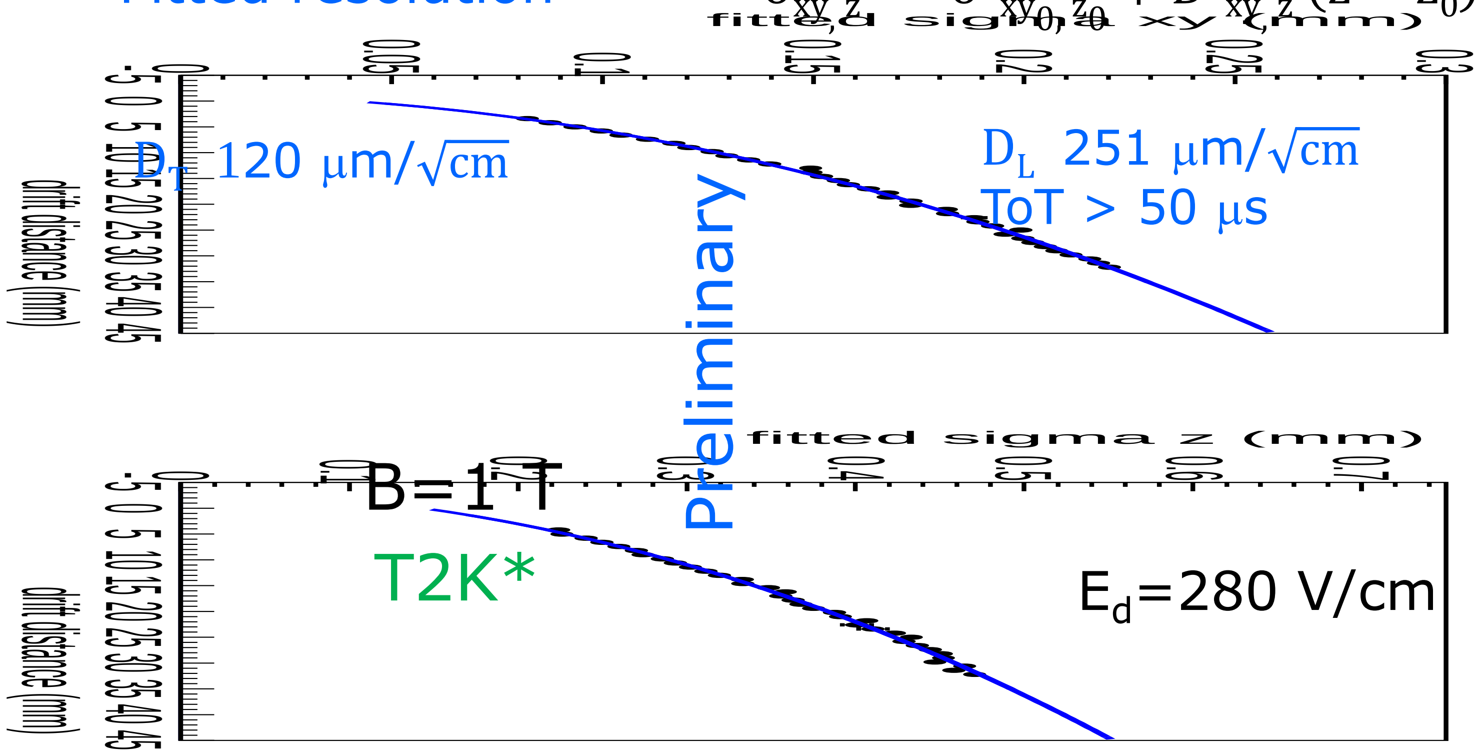
Magboltz gives D_T 287 μm/√cm

T2K* = T2K gas with O_2 and H_2O

DESY testbeam Module Analysis

Run 6983-6990 B=1 T p=5 and 6 GeV

Fitted resolution $\sigma_{xy,z}^2 = \sigma^2_{xy0,z0} + D^2_{xy,z}(z - z_0)$



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

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

$\sigma_{xy\ tele} = 42\ \mu m$

Magboltz gives for $D_T = 121\ \mu m/\sqrt{cm}$

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

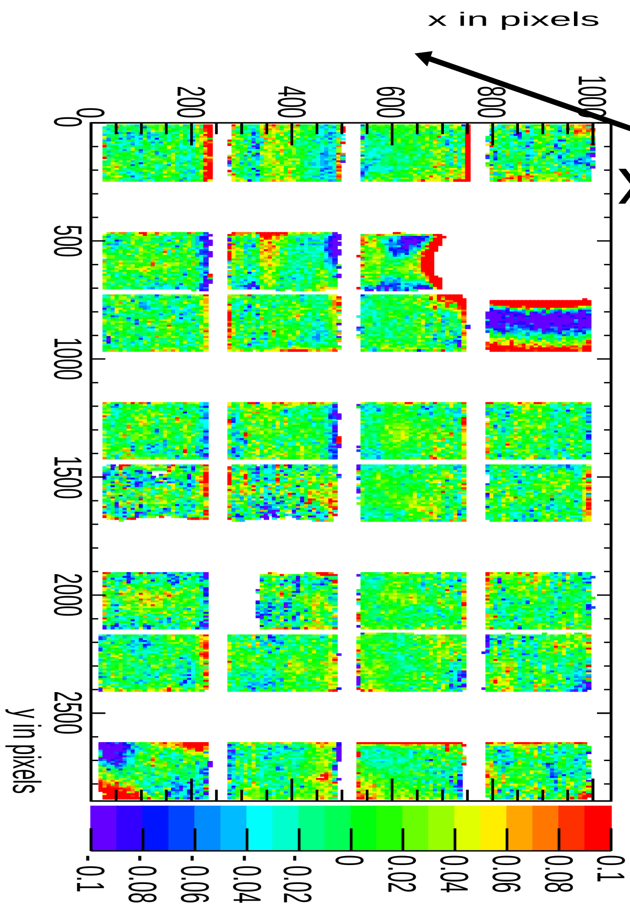
Mean residuals in the module plane with acceptance cuts

B=0 T situation

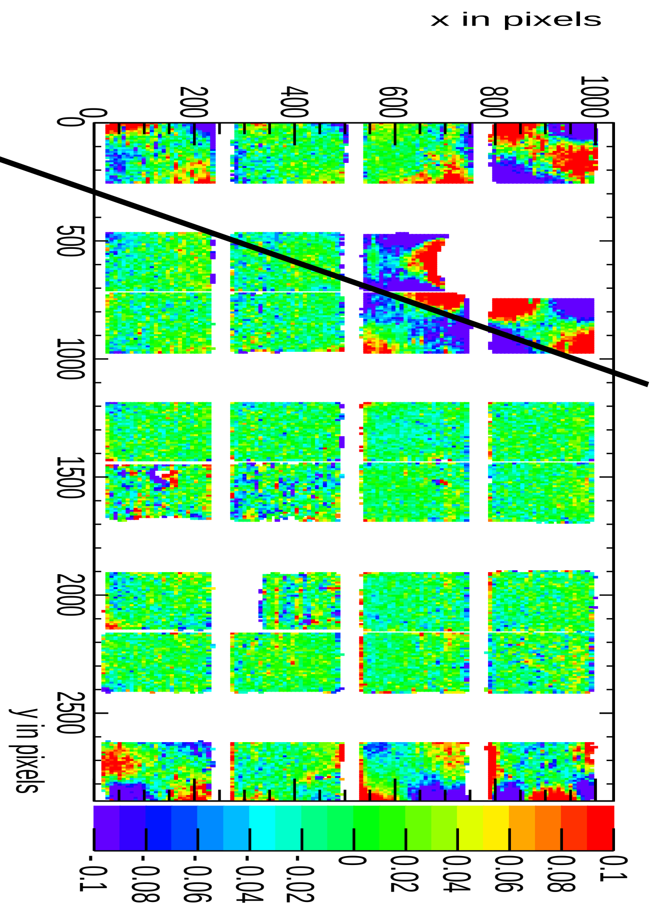
Preliminary

Vertical white bands guards

xy



z



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

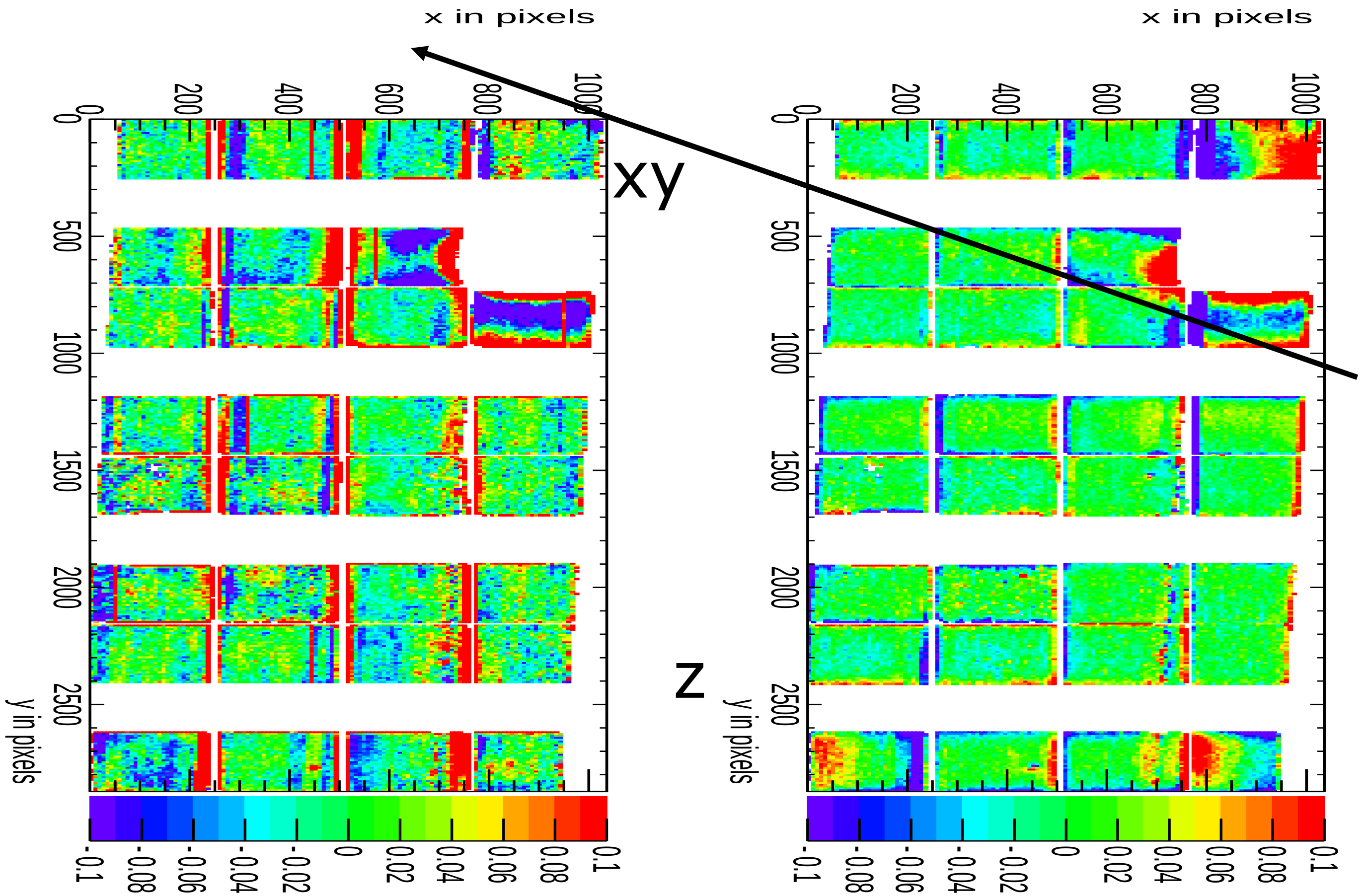
Runs 6981-6988 B=1 T p=5 GeV

Mean residuals in the module plane with acceptance cuts

B=1 T situation

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

ILD 2024

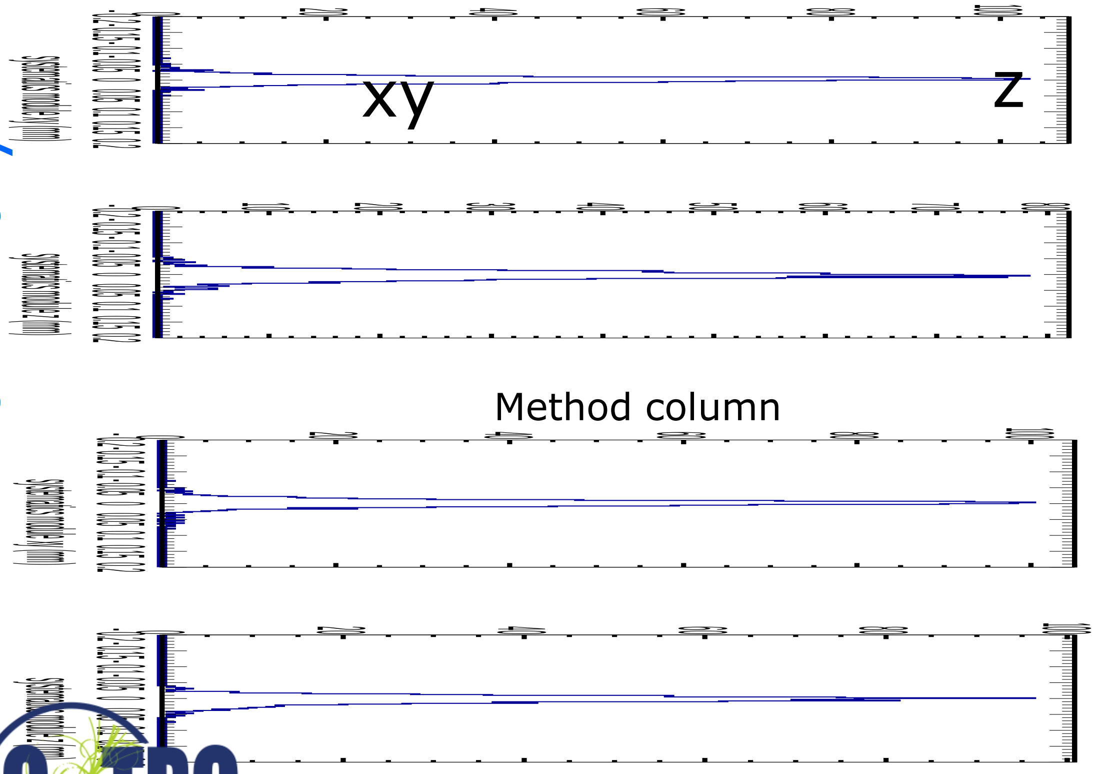
DESY testbeam Module Analysis

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

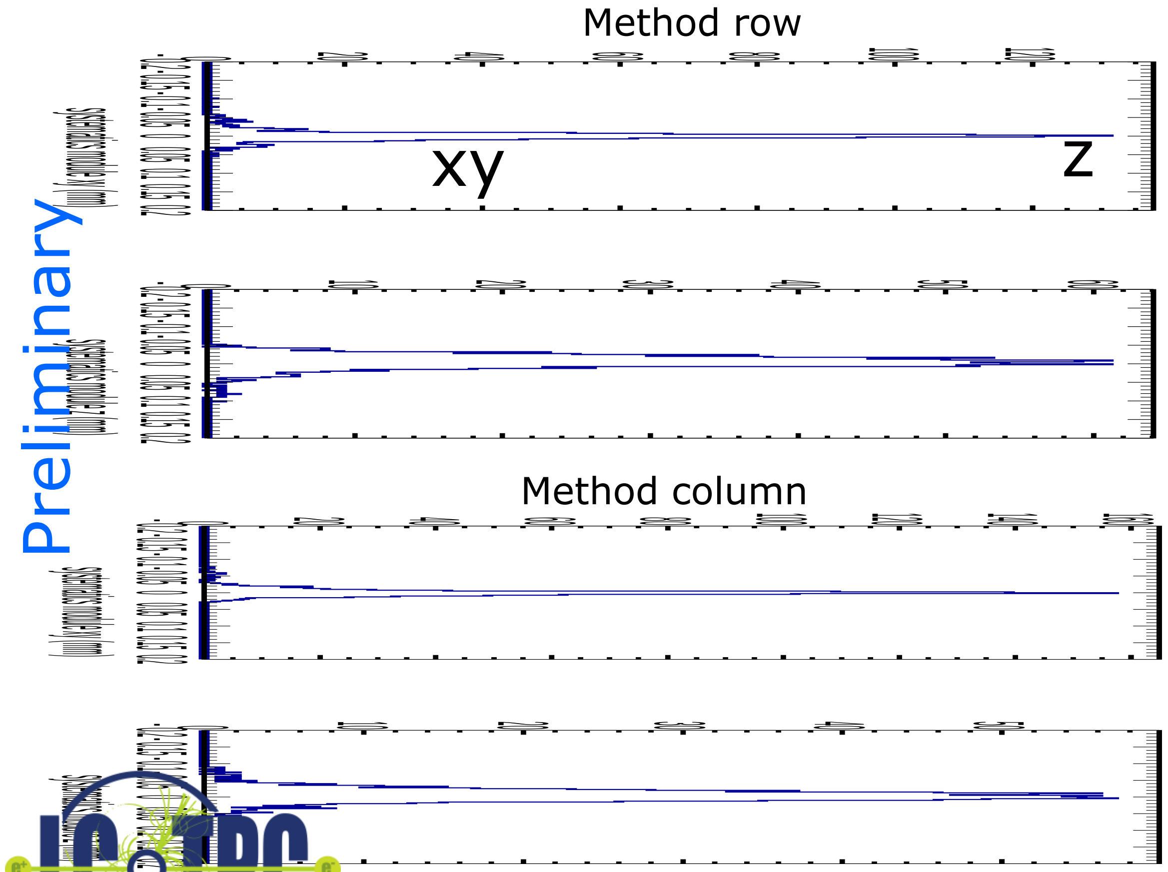
method	rms (stat) xy	bins xy	rms (stat) z	bins z
row	11 (5) μm	896	15 (5) μm	891
column	13 (5) μm	895	13 (5) μm	892

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.

DESY testbeam Module Analysis

Runs 6983-6988 B=1T p=5 GeV

Distribution of mean residuals in the plane



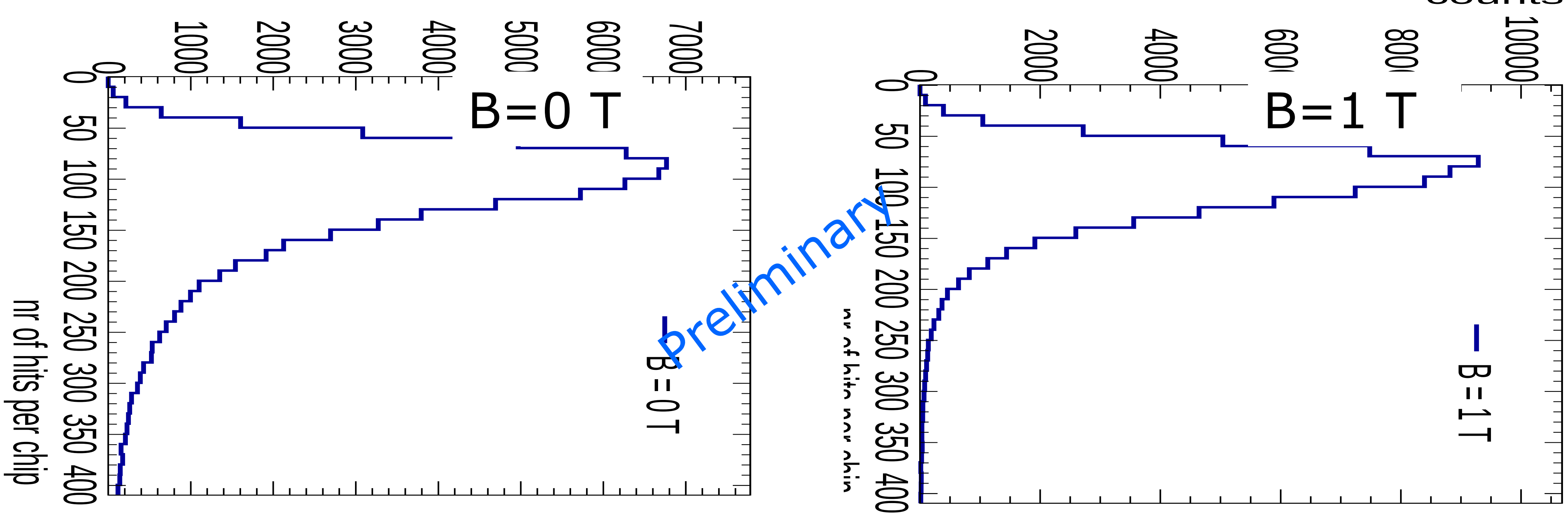
B=1 T situation

method	rms (stat) xy	bins xy	rms (stat) z	bins z
row	13 (2) μm	896	19 (5) μm	896
column	11 (2) μm	880	20 (5) μm	880

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.

DESY testbeam Module Analysis

Performance of dEdx



- B=0 T has a large Landau tail
- B=1 T smaller Landau tail and a more gaussian distribution
- An electron crossing 8 chips in the module has about 1000 TX3 hits

DESY testbeam Module Analysis

Performance of dEdx

The dEdx resolution for MIPs (70% of the electron dE/dx) from data by combining tracks to form a 1 m long track with realistic coverage ~60% coverage (corrected for the e-MIP scale).

Preliminary

Method	B=0 Resolution (%)	B= 1 T Resolution (%)
(1) dEdx 90 tail	7.7	5.3
(2) Fit slope	6.8	4.2

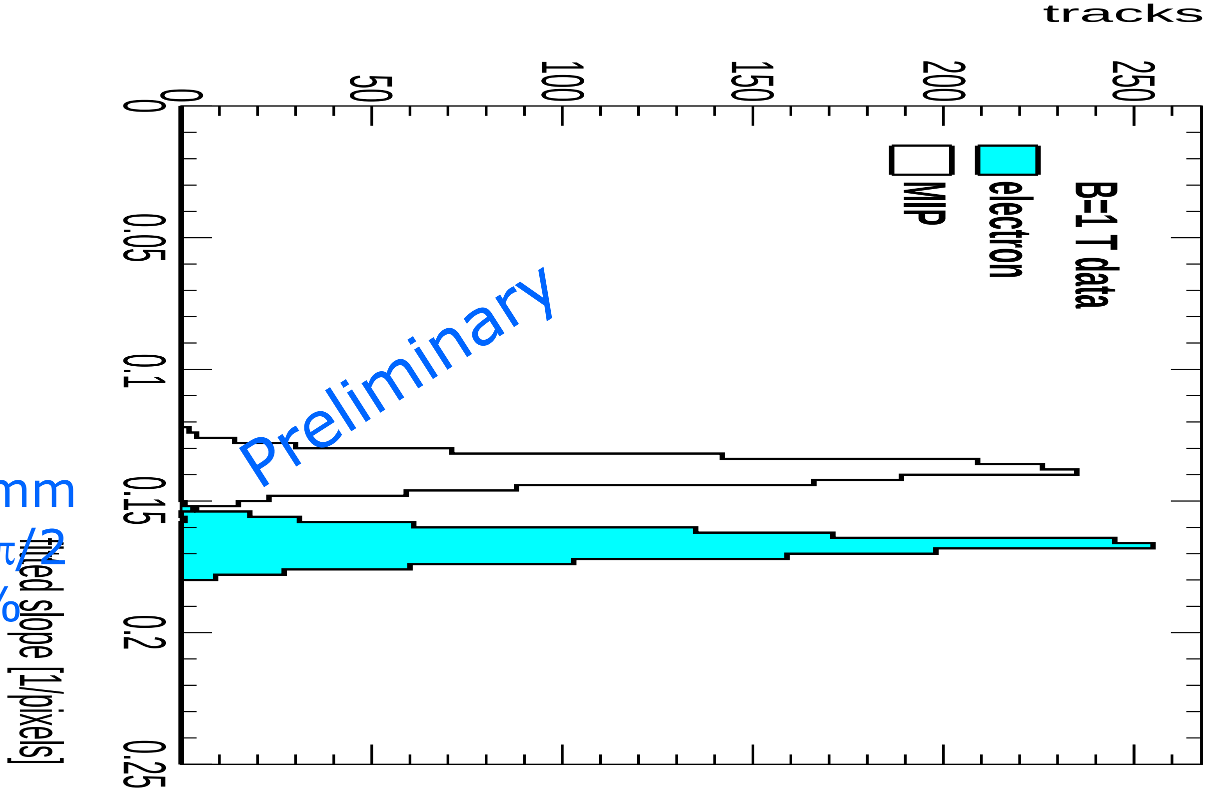
The "dEdx 90 tail" method is truncation at 90% where large clusters are identified and removed (tail reduced)
For the "Fit slope" method (2) an exponential distribution (with the slope and amplitude as free parameters) is fitted to the distance between the hits

DESY testbeam Module Analysis

Performance of dEdx fit slope method for B=1T

MIP scale corrected
resolution 4.2%
[electron has 2.9%]
1 m track 60% and
coverage

ILD detector with
rInner = 329 rOuter = 1770 mm
MIP resolution = 3.6% at $\theta=\pi/2$
electron resolution = 2.5%



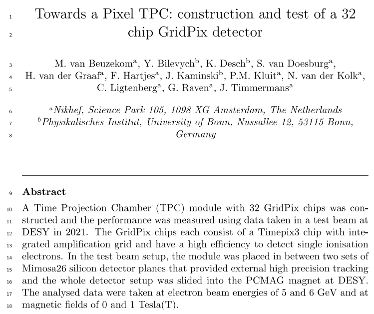
DESY testbeam Module Analysis

Preliminary

Measured efficiency at a high hit rates

- In the test beam also data at high hit rates was taken and analysed to study the change of efficiency of the GridPix
- This was done by comparing low and high rate runs

- It is demonstrated that running at hit rates up 1.2 kHz per chip gives at most a reduction of 0.6% in the relative efficiency.



Towards a Pixel TPC: construction and test of a 32 chip GridPix detector

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Abstract

A Time Projection Chamber (TPC) module with 32 GridPix chips was constructed and the performance was measured using data taken in a test beam at DESY in 2021. The GridPix chips each consist of a Timepix3 chip with integrated amplification grid and have a high efficiency to detect single ionisation electrons. In the test beam setup, the module was placed in between two sets of Mimosa26 silicon detector planes that provided external high precision tracking and the whole detector setup was slided into the PCMAG magnet at DESY. The analysed data were taken at electron beam energies of 5 and 6 GeV and at magnetic fields of 0 and 1 Tesla(T).

Other topics for the NIM paper:

- Study and characterization of bursts i.e. large numbers of hits due to highly energizing particles (e.g. delta's)
- Extraction of the resolution as a function of the incident angle using circles (helixes)

Conclusions on module performance

- 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 μm/$\sqrt{\text{cm}}$ D_z = 273 μm/$\sqrt{\text{cm}}$
- The diffusion coefficients at B=1 T is D_{xy} = 120 μm/$\sqrt{\text{cm}}$ D_z = 251 μm/$\sqrt{\text{cm}}$
  - In agreement with Magboltz D_{xy} = 121 μm/$\sqrt{\text{cm}}$

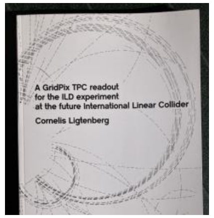
*the chip was successfully repaired in 2023 Bonn see backup slide

Conclusions on module performance

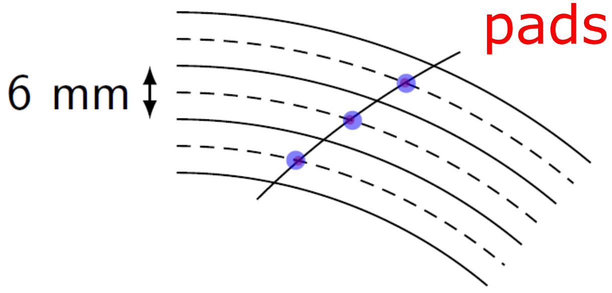
- Results for the module showed that:
  - the HV of the guard wires was well tuned
  - B=0 T rms residuals in the module plane xy 13 μm and z 15 μm
  - The results are compatible with (very) high stats quad measurement
  - B= 1 T rms residuals in the plane xy 13 μm and z 20 μm;
- High tracking precision is demonstrated with small systematics
  - deformations xy stay below 13 μm
- Particle identification dEdx based on the numbers of hits and their distance.
  - the "Fit slope" method gives a MIP resolution of 4.2% for a 1 m track with realistic ~60% coverage of the readout plane in a 1 T B field
  - this is much better than our single chip dEdx result at B=0 T.

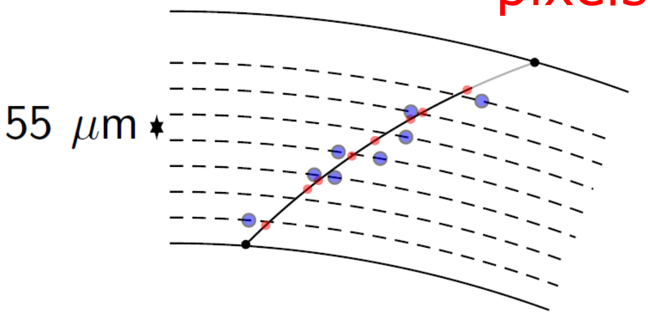
Simulation of ILD TPC with pixel readout

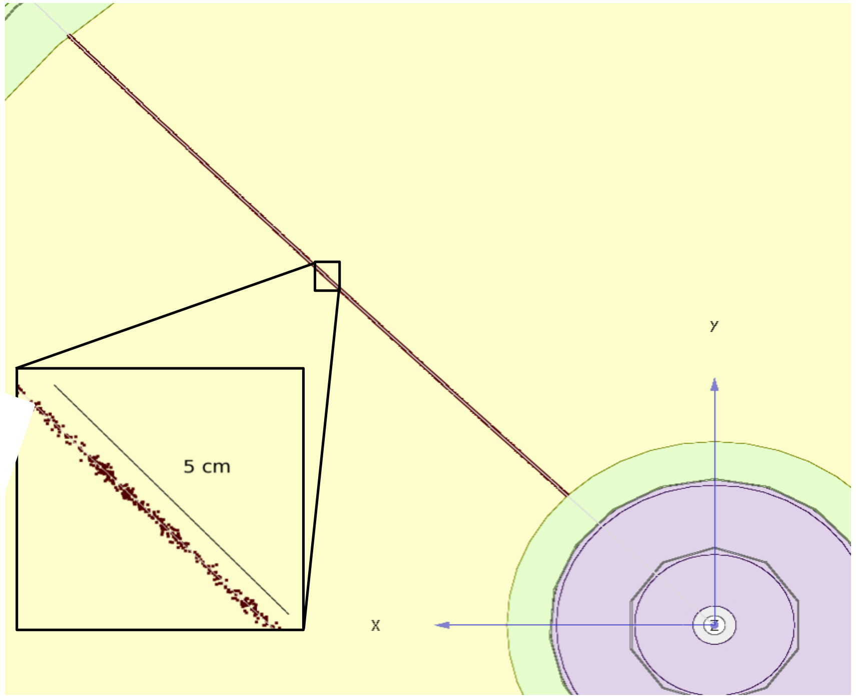
- To study the performance of a large pixelized TPC, the pixel readout was implemented in the full ILD DD4HEP (Geant4) simulation
- Changed the existing TPC pad readout to a pixel readout
- Adapted Kalman filter track reconstruction to pixels



details: PhD thesis
Kees Ligtenberg



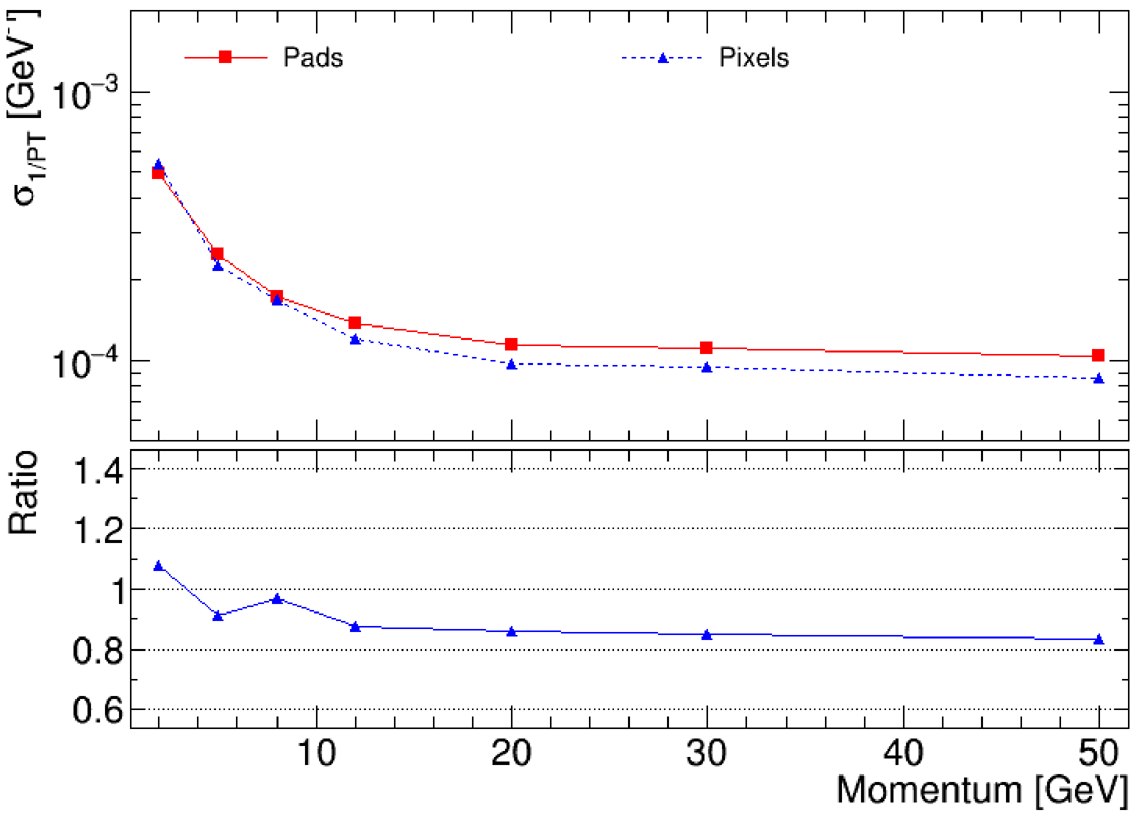


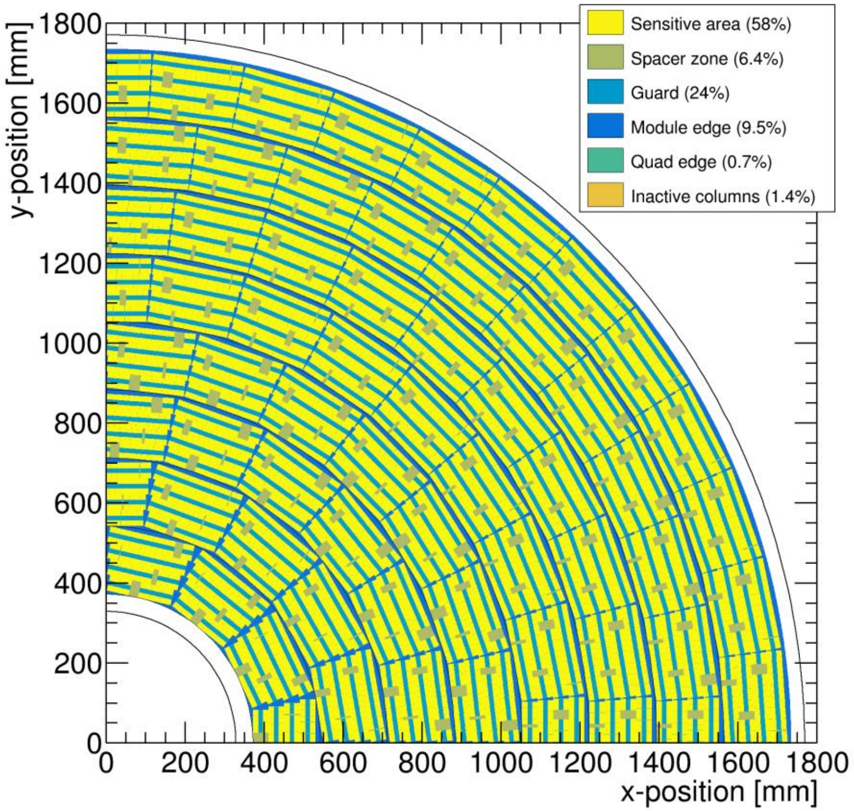


50 GeV muon track with pixel readout

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.





GridPix TPC: Track fitting at the edge

- In case of the a realistic geometry with detector edges, Kees Ligtenberg observed a worsened momentum resolution and momentum biases. This was traced down to be caused by biases in the residuals at the edge of the detector
- The conclusion was that the track fit should be updated to take into account the biases in the residuals at the detector edge(s)
- Recently, a master student (computational physics) at the UvA, Peter Voerman, has written a track fit that corrects the biases in one pass: “Track fitting at the edge”.
- The technique can also be applied to fit hits from other gaseous or non-gaseous detectors:
  - a centre of gravity technique is used (with measured charges over multiple strips near the edge)
  - in case of silicon detector hits near the boundaries of the sensitive volume

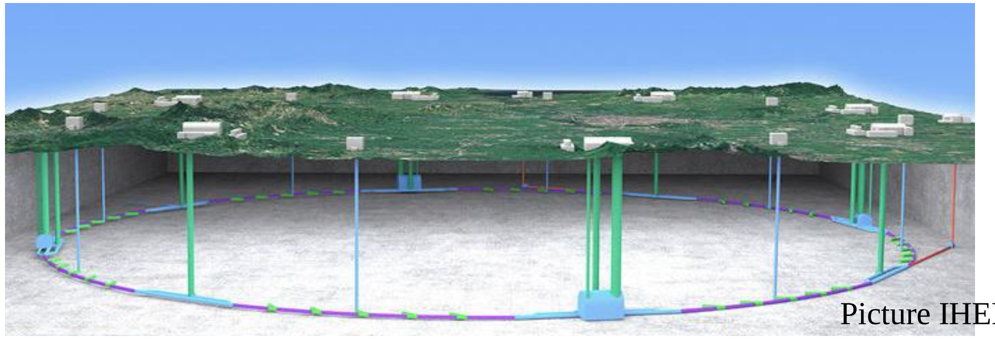
Summary of the Pixel TPC performance

- 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
- A Quad detector was designed and the results from the 2018 test beam shown
  - After correcting the edge: 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 excellent
  - High tracking resolution 9 (xy) 13 μm (z) for a tracklength is 157.96 mm (B=0 T)
  - High precision at B=1 T: $D_{xy} = 120\ \mu m/\sqrt{cm}$ and deformations in xy < 15 μm
  - dE/dx resolution for a MIP of 1 m track length with 60% coverage is 4.2% (at 1 Tesla)
- A test beam @ FermiLab with a quad in a TPC is planned (2024, US Grant EIC)

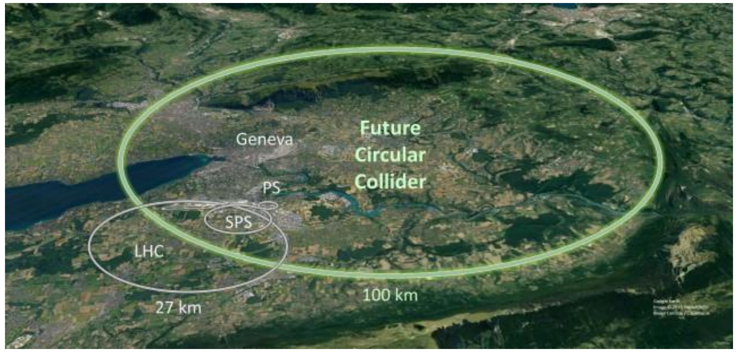
  also an EIC R&D program for CO2 cooling is funded (2023) (Yale, Stony Brook, Purdue, Bonn, Nikhef)
- A pixel TPC has become a realistic viable option for experiments
  - High precision tracking like ILD@ILC in the transverse and longitudinal planes, dE/dx by electron and cluster counting, excellent two 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 $L = 200\ 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ 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 $1.41 \times 1.41\ \mathrm{cm}^2$
  - 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).
  - To save power the TPX3/4 chips can be run in LowPowerMode: reduction factor 10.
- 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 a Pixel TPC a double grid is the best solution (see next slide)

A Pixel TPC at CEPC or FCC-ee

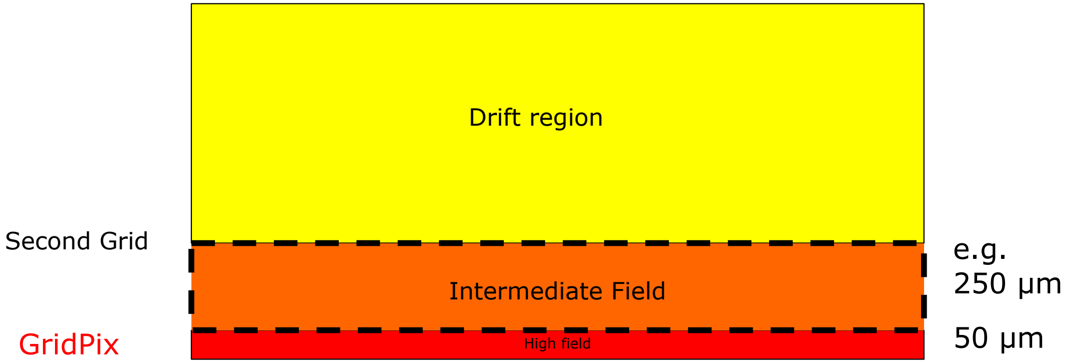
- Is it possible to reduce the IBF for a pixel TPC?
  - IDEA: by making chip with a double grid structure (see next slide)
  - This idea was already realized as a TWINGRID NIMA 610 (2009) 644-648
  - For GEMs for the ALICE TPC this was also the way – several GEMs on top of each other to reduce IBF
  - 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?
  - 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.
  - It was 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%

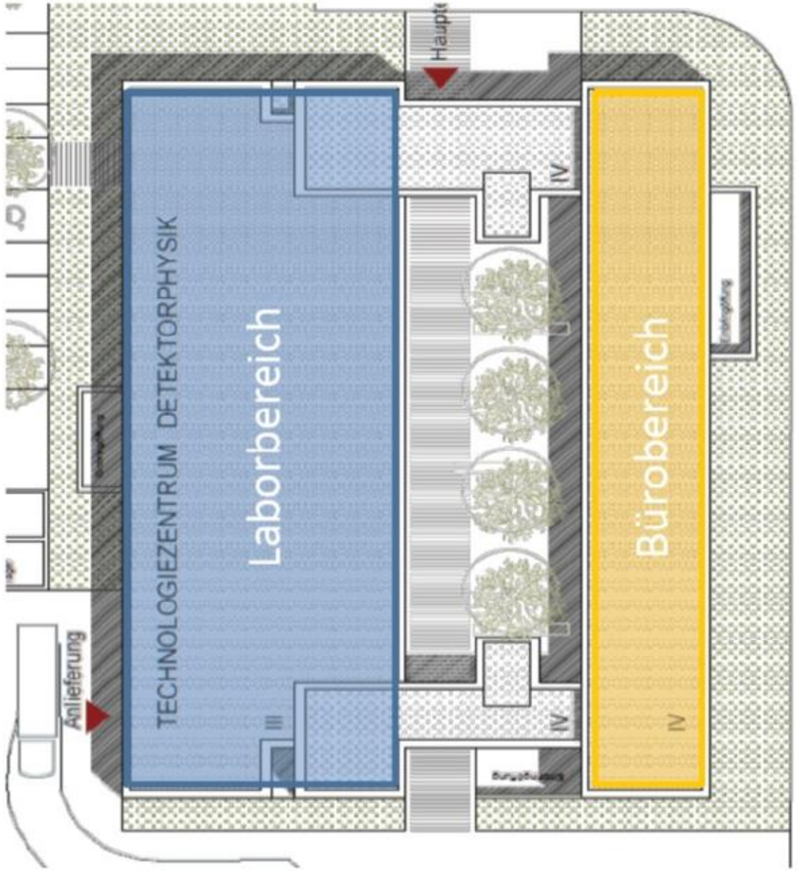
Conclusions: Pixel TPC at a circular collider

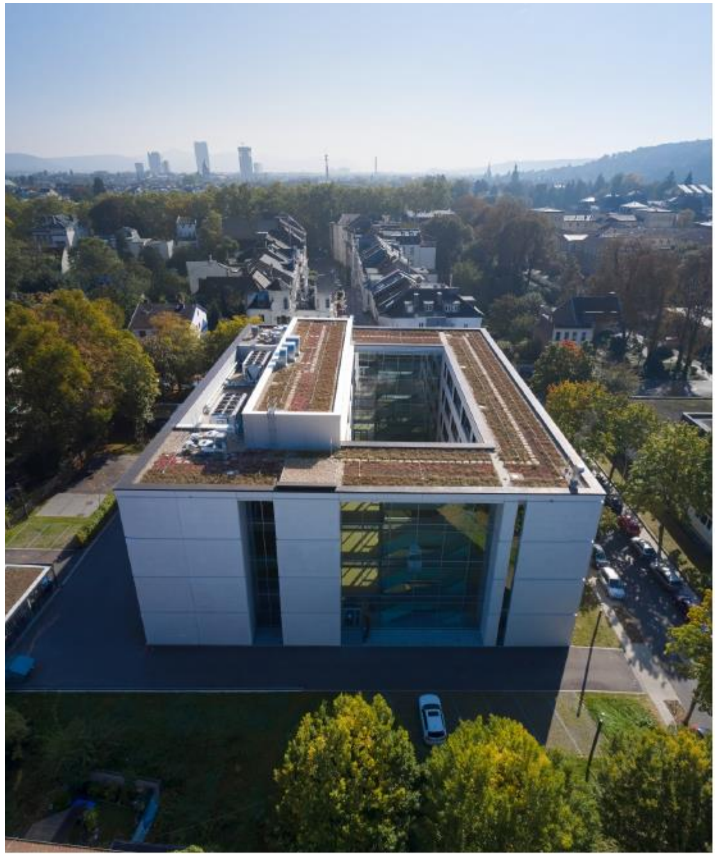
- YES: a pixel TPC can reconstruct the Z events in one readout cycle
- YES: the current readout of the Timepix3 chip can deal with the rate
- The current power consumption is 1W/cm^2. By running the TPX chips in low power mode this can be reduced by a factor of 10. Still good cooling is important no 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
  - A double grid 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

Forschungs- und Technologiezentrum Detektorphysik

Backup

First stone laying ceremony 2.11.2016
Inauguration ceremony 8.11.2021





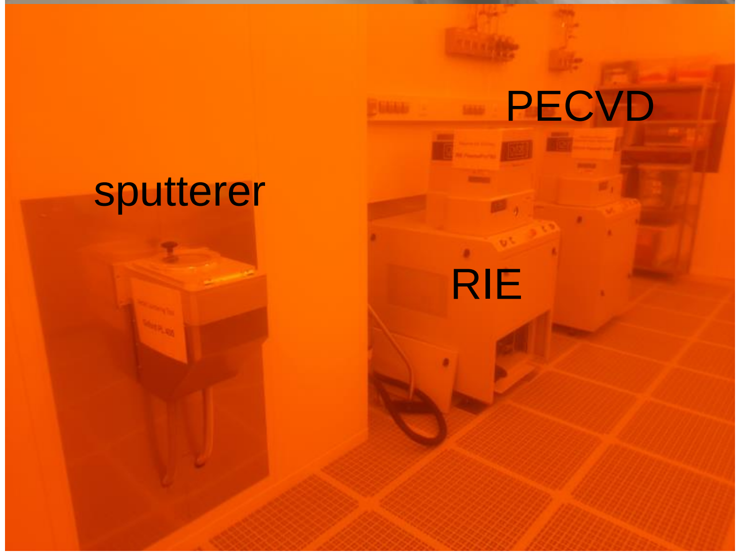
Office space:
- 880 m^2
- 4 Floors

Lab space
- 2010 m^2
- 4 Levels + Underground Laboratory
- 360 m^2 clean rooms (ISO 5, 6, 7)

Cleanroom

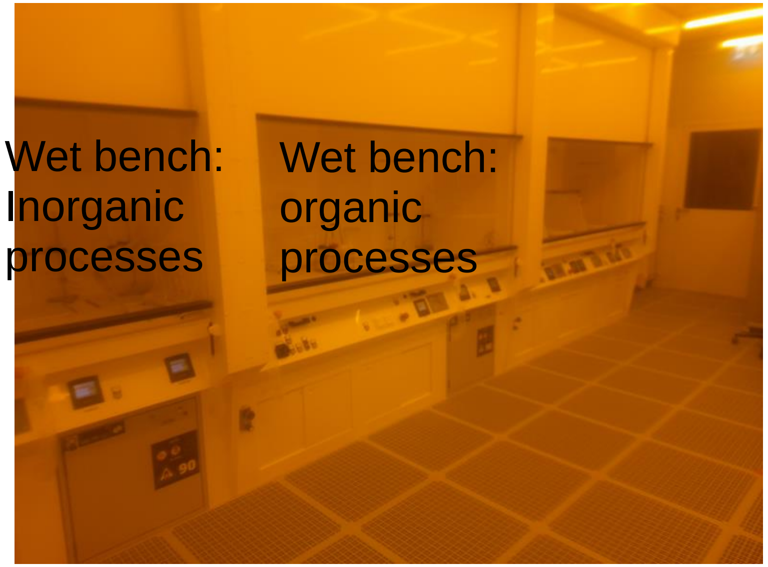
ISO 7

ISO 6



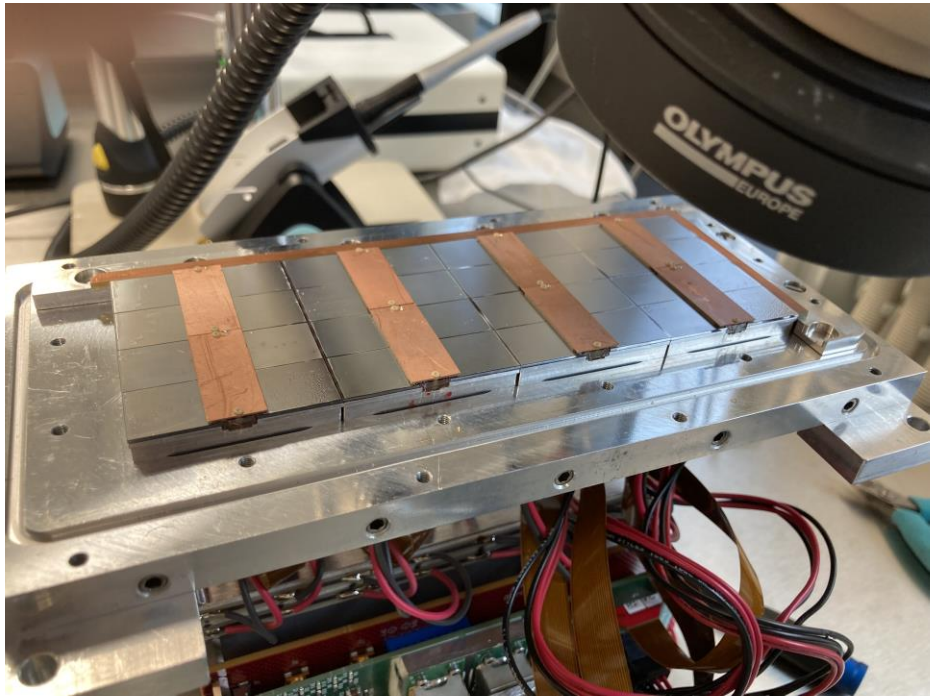
Maskless Aligner

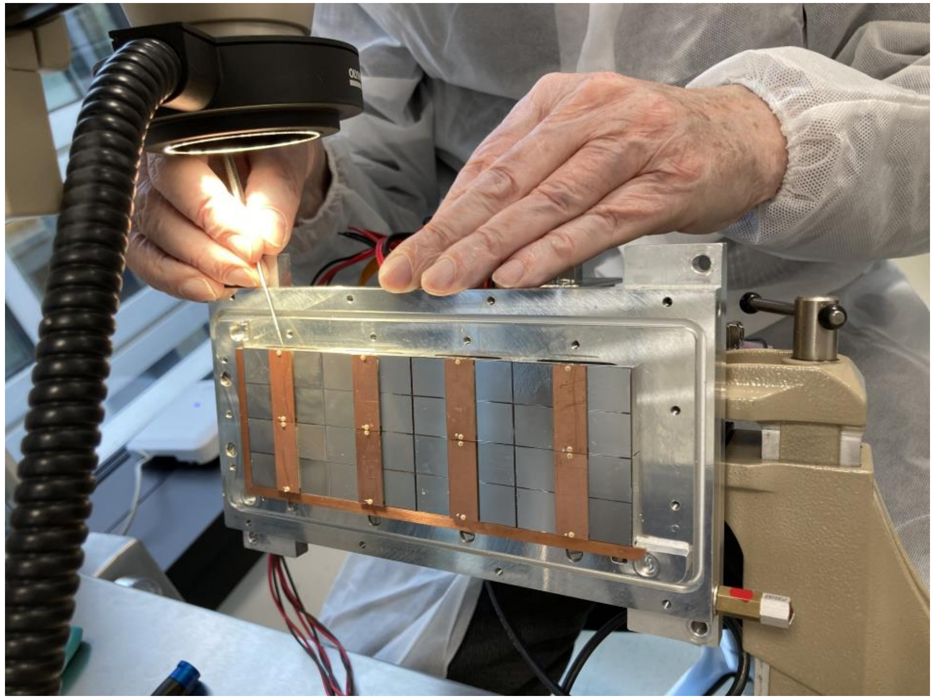
ISO 5



Backup

Pictures of repair work in Bonn





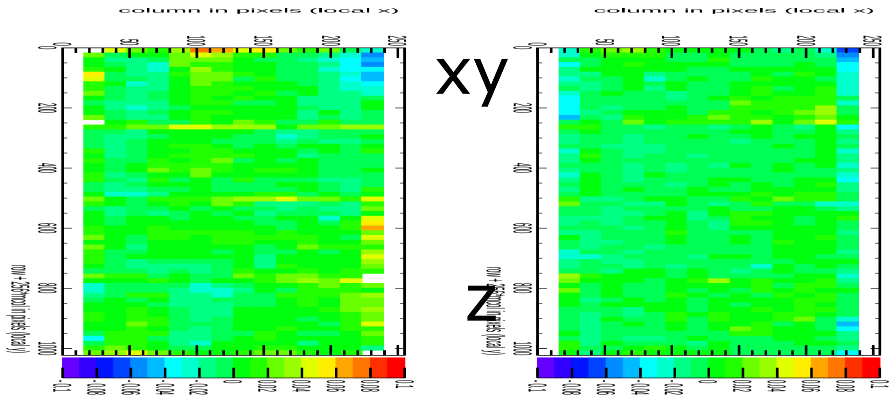
The short in chip 11 was succesully repaired by Fred Hartjes

DESY testbeam Module Analysis

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

Mean residuals (module) row

column 256 pixels



row 4x256 pixels

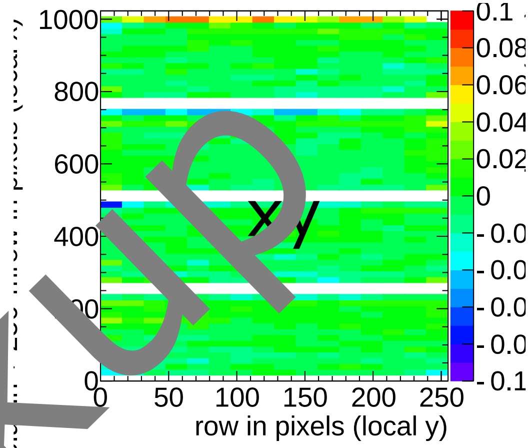
For the row plot the data is projected keeping 4 bins in local y (one follows the track)

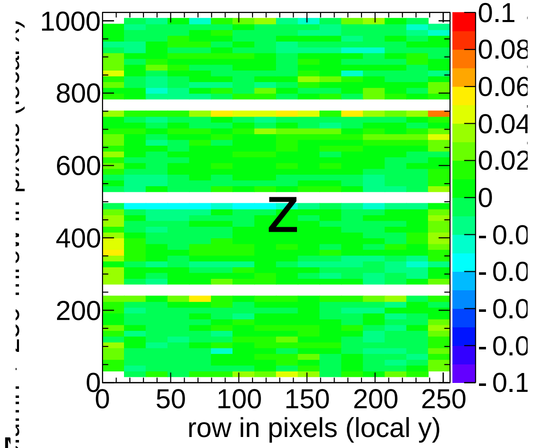
Preliminary

Backup

(module) column

column 4x256 pixels





row 256 pixel

Regrouping the module plane to increase stats

Granularity 8x8 pixels

acceptance cut entries > 1500

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