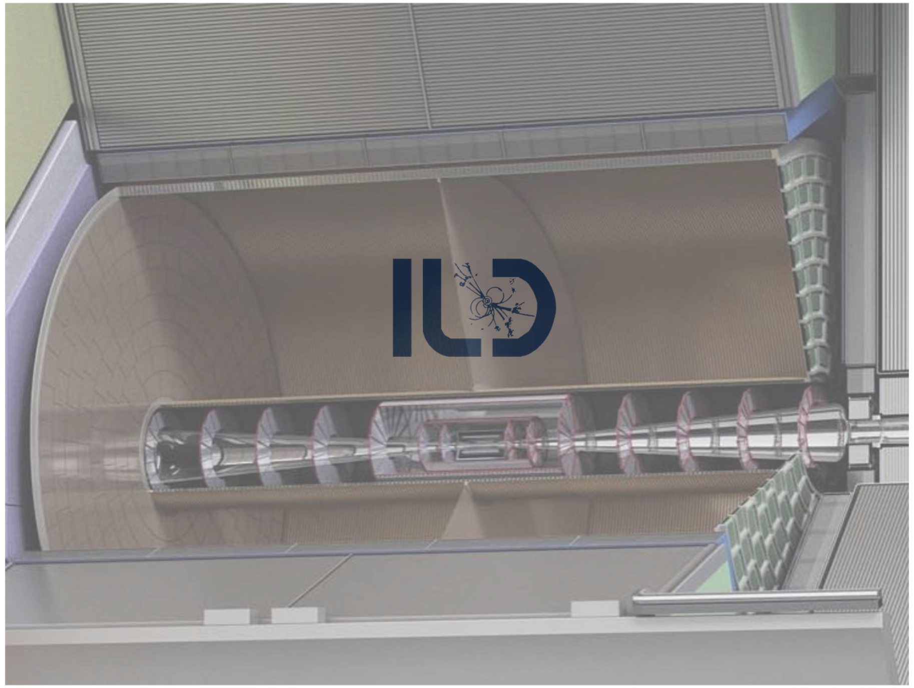
TPC Development for the ILD Detector at ILC



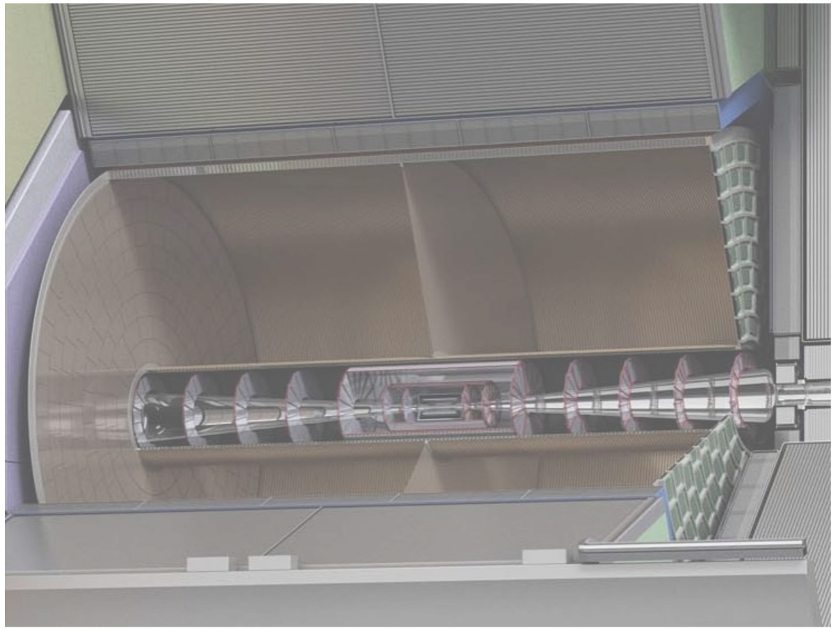
Peter Kluit,

On behalf of the LCTPC Collaboration

LCWS 2023 at SLAC May 2023

ILD TPC requirements

The R&D on a TPC for a Linear Collider is done in the LCTPC collaboration

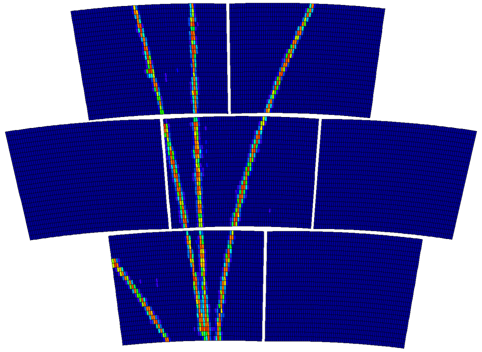


Requirements for a TPC ILC TDR

Table, large TPC, for pad/*pixel* electronics

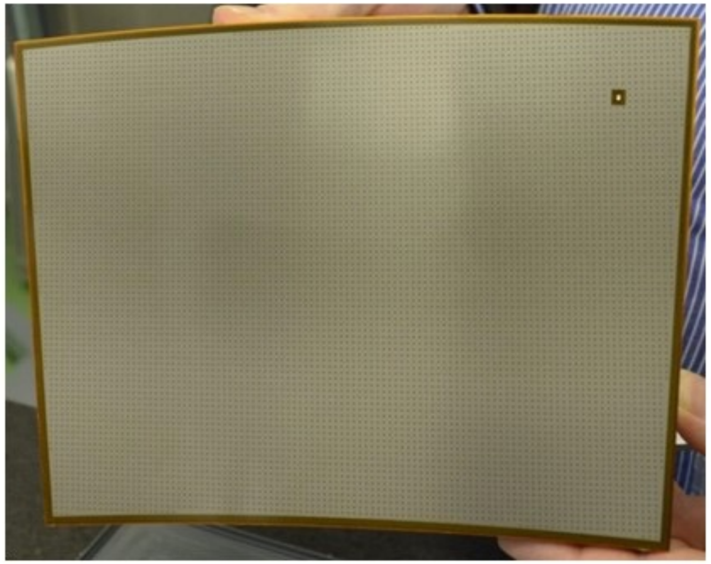
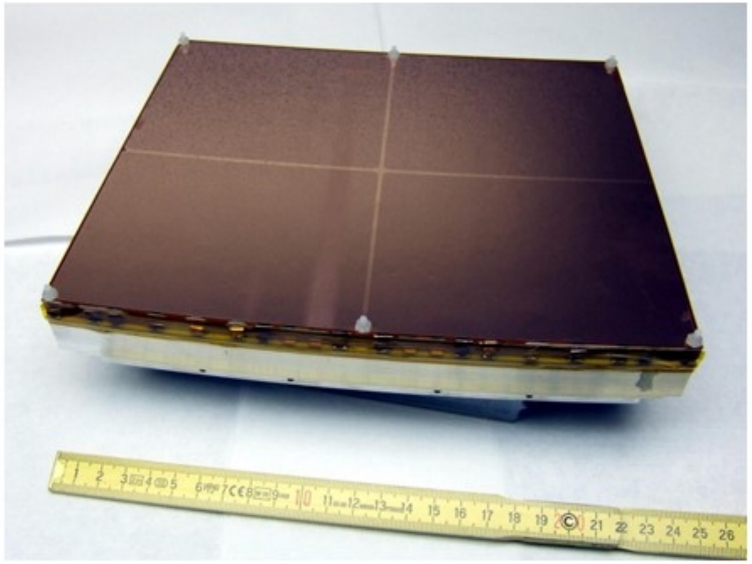
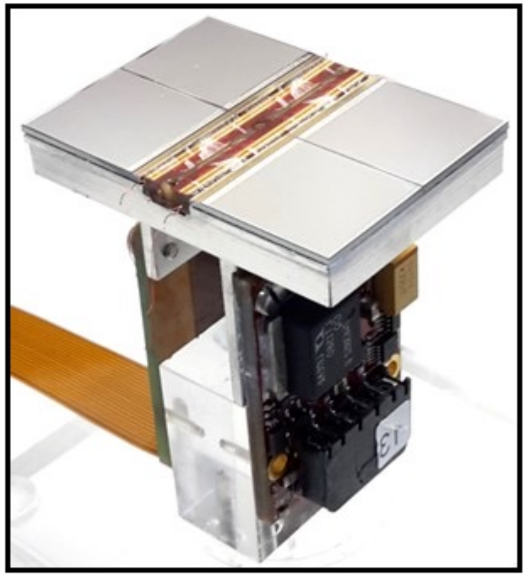
Parameter	
B-field	3.5T
Geometrical parameters	r_{in} 329 mm, r_{out} 1808 mm, z $\pm$ 2350 mm
Solid angle coverage	Up to $\cos\theta \simeq 0.98$ (10 pad rows)
TPC material budget	$\simeq 0.05\ X_0$ including outer fieldcage in r $< 0.25\ X_0$ for readout endcaps in z
Number of pads/timebuckets	$\simeq 10^6/1000$ per endcap
Number of pixels/timebuckets	*$\simeq 10^9/1000$ per endcap*
Pad pitch/ no.padrows	$\simeq 1\times 6\ \text{mm}^2$ / 213
σ_{point} in $r\phi$	$\simeq 60\ \mu$m for zero drift, $< 100\ \mu$m overall
σ_{point} in $r\phi$	*$\simeq 0.055\text{mm}/\sqrt{12}$ for zero drift,0.4mm for max drift*
σ_{point} in rz	$\simeq 0.4 - 1.4$ mm (for zero – full drift)
2-hit separation in $r\phi$	$\simeq 2$ mm
2-hit separation in rz	$\simeq 6$ mm
dE/dx resolution	$\simeq 5$ %
dE/dx resolution	*$\simeq 4$ %*
Momentum resolution at B=3.5 T	$\delta(1/p_t) \simeq 10^{-4}$/GeV/c (TPC only)
Momentum resolution at B=3.5 T	*$\delta(1/p_t) \simeq 0.8\times 10^{-4}$/GeV/c (60% cov, TPC only)*

ILD TPC read out technologies



There are 3 main options for the readout :
Micromegas with a resistive anode (ERAM), GEM, and Gridpix.
Feasibility and performance has been demonstrated in ILC conditions.

New ILD strategic goal is to adapt to conditions at high luminosity colliders.

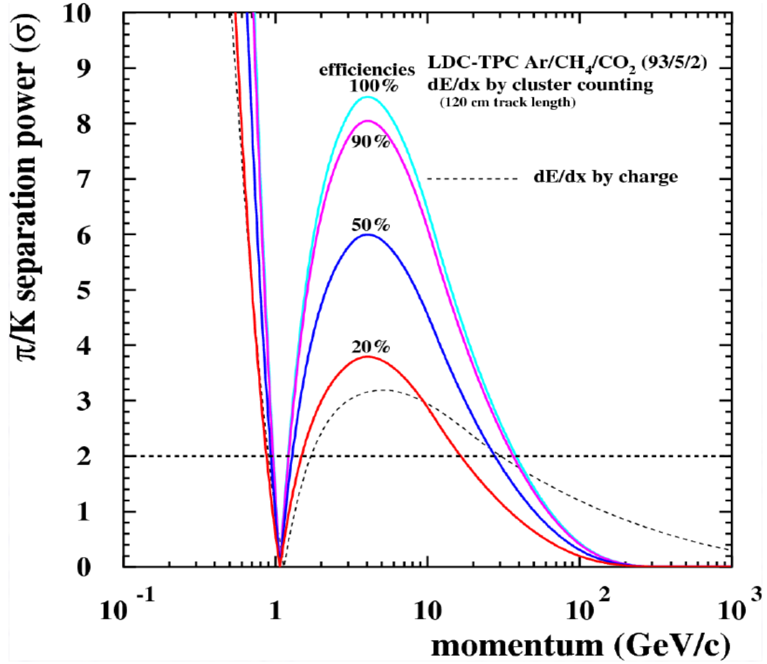
Micromegas	GEM	GridPix
		

ILD TPC particle identification and material

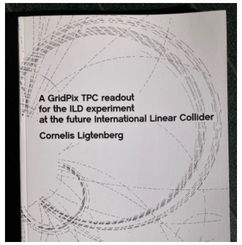
- Excellent tracking device with low material budget
  - 0.01 X_0 TPC gas
  - 0.01 X_0 inner cylinder
  - 0.03 X_0 outer cylinder
  - < 0.25 X_0 endplates (incl readout)
- Material budget can be respected by different technologies like GEM, MicroMegas and Pixels
- TPC between silicon detectors VTX, SIT and SET

- Excellent particle identification

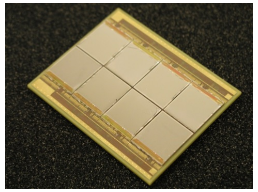
M. Hauschild: dE/dx and Particle ID Performance with Cluster Counting; ILC Workshop Valencia 2006



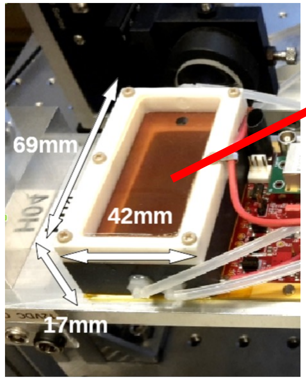
Pixel readout is a serious option for the TPC readout plane @ ILC or other colliders. Thesis Ligtenberg on a Pixel TPC.

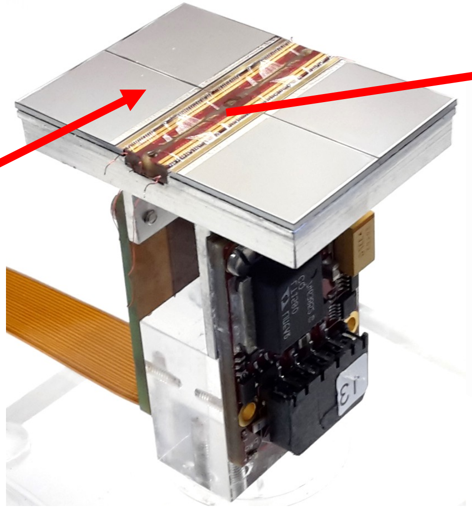


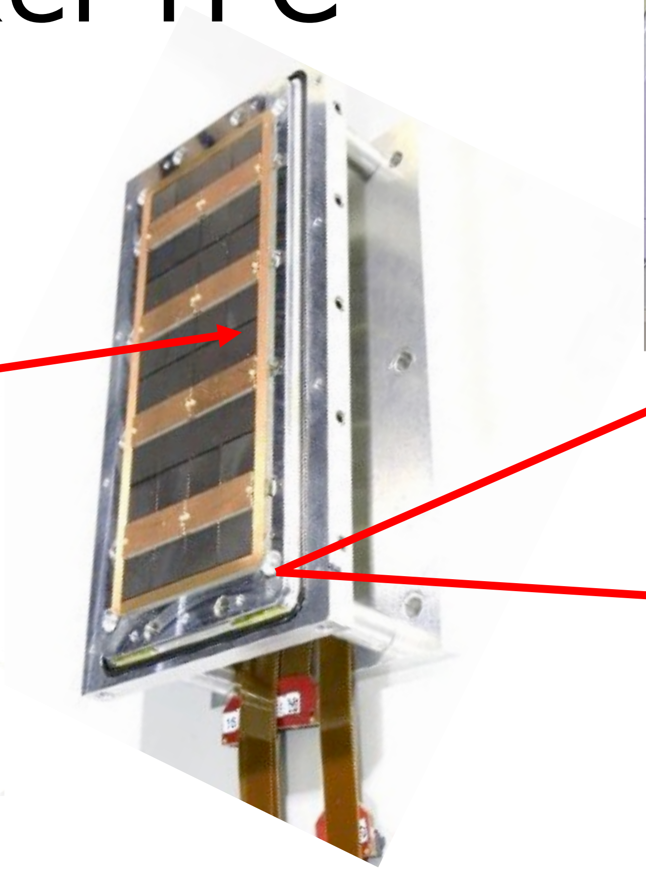
Pixel TPC

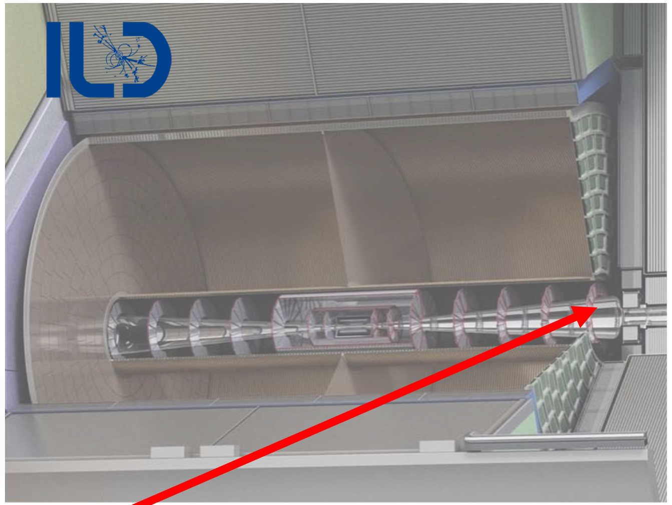


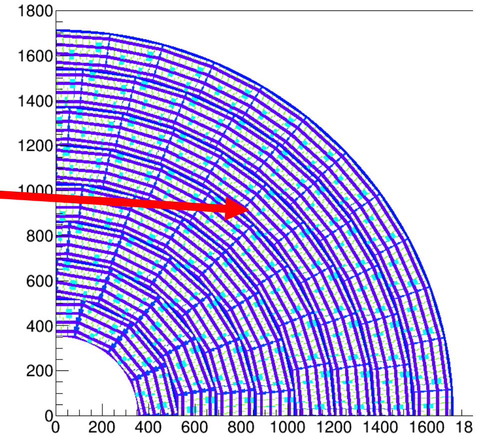
(Octopuce)









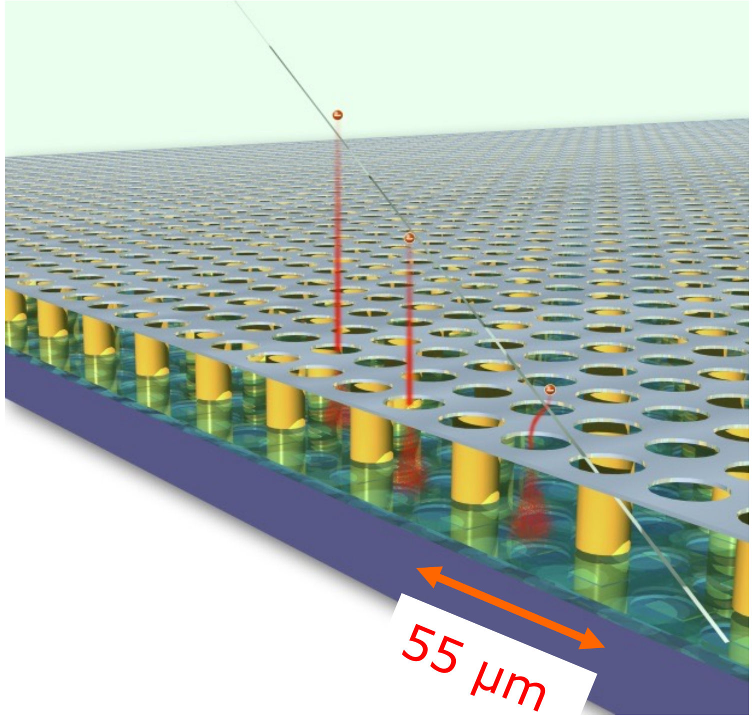


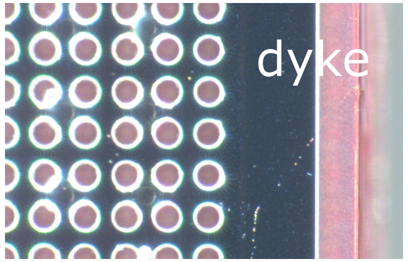
(TimePix1) TPX3 chip Quad Module TPC plane

(2007-14) 2017 2018 2019

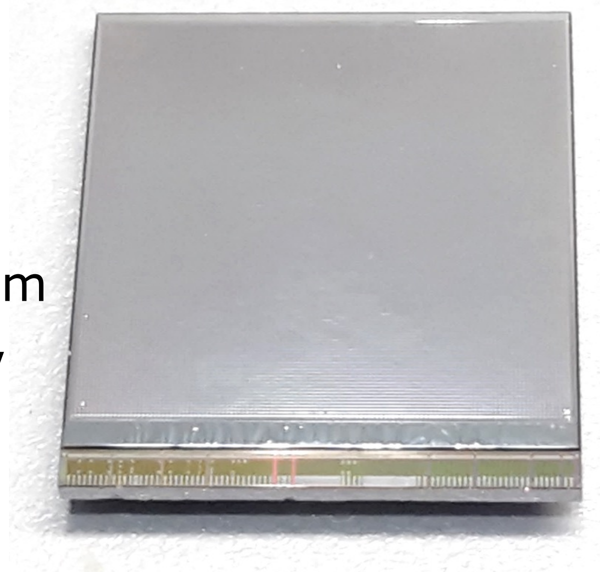
GridPix technology

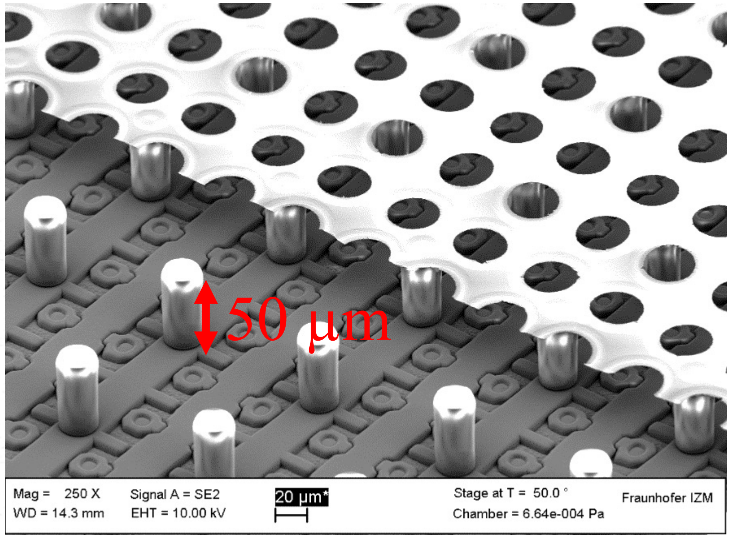
- Pixel chip with integrated Grid (Micromegas-like)
- InGrid post-processed @ IZM
- Grid set at negative voltage (300 – 600 V) to provide gas amplification
- Very small pixel size (55 μm)
- detecting individual electrons





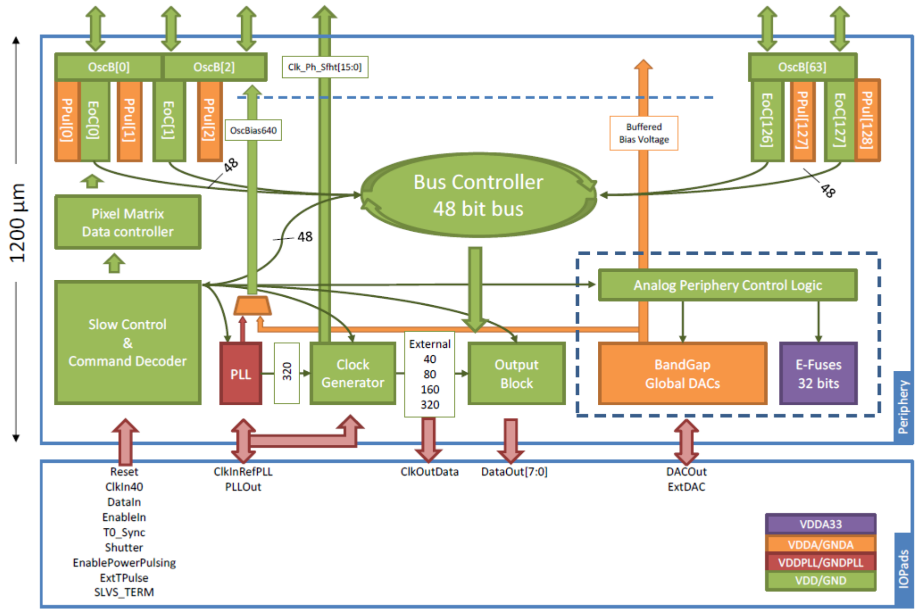
- Aluminium grid (1 μm thick)
- 35 μm wide holes, 55 μm pitch
- Supported by SU8 pillars 50 μm high
- Grid surrounded by SU8 dyke (150 μm wide solid strip) for mechanical and HV stability

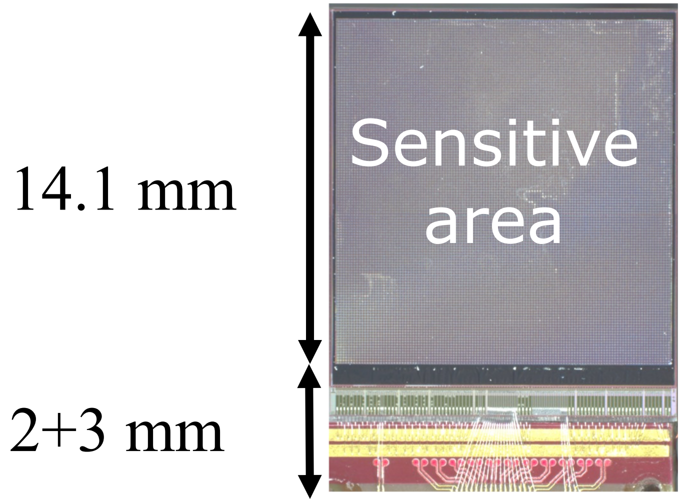




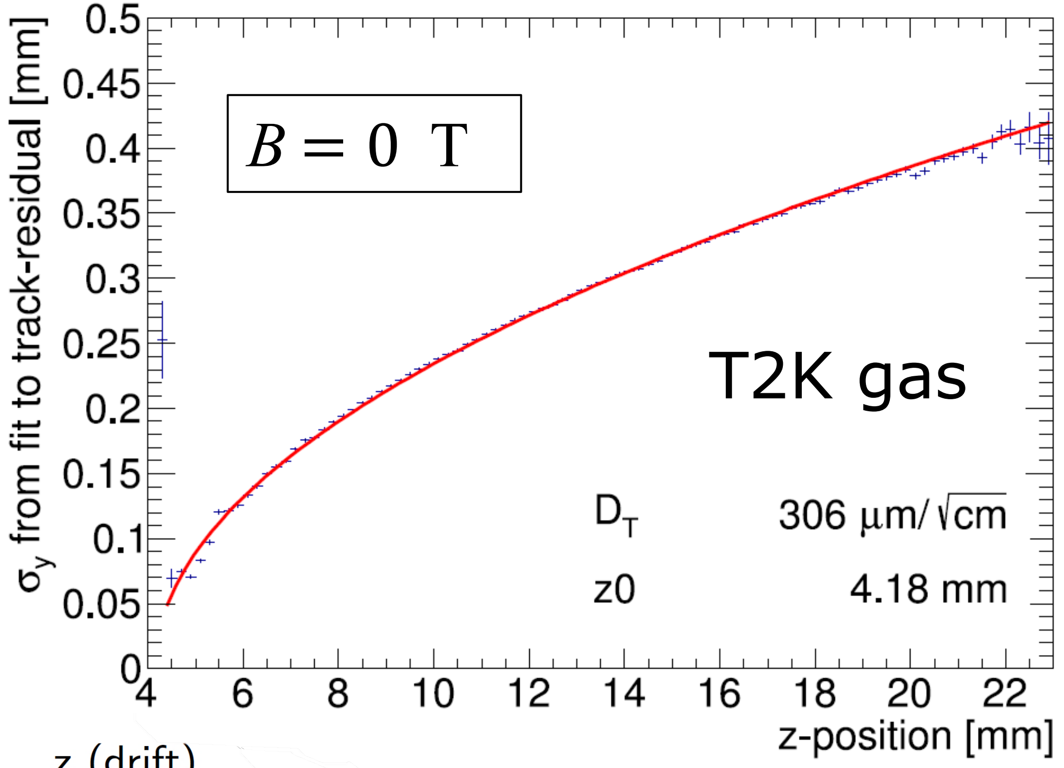
Pixel chip: TimePix3

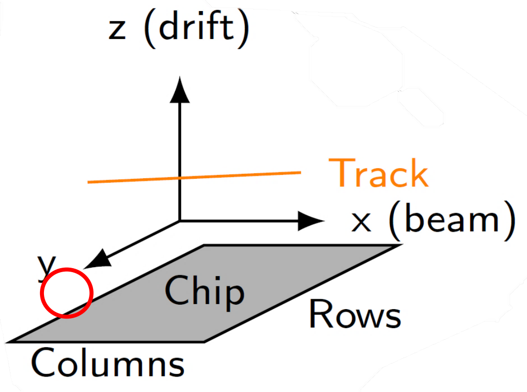
- 256 x 256 pixels
- 55 x 55 μm pitch
- 14.1 x 14.1 mm sensitive area
- TDC with **640 MHz clock** (1.56 ns)
- Used in the data driven mode
  - Each hit consists of the **pixel address** and **time stamp** of arrival time (ToA)
  - Time over threshold (ToT) is added to register the signal amplitude
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





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 electron resolution in pixel plane:

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

Depends on:

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

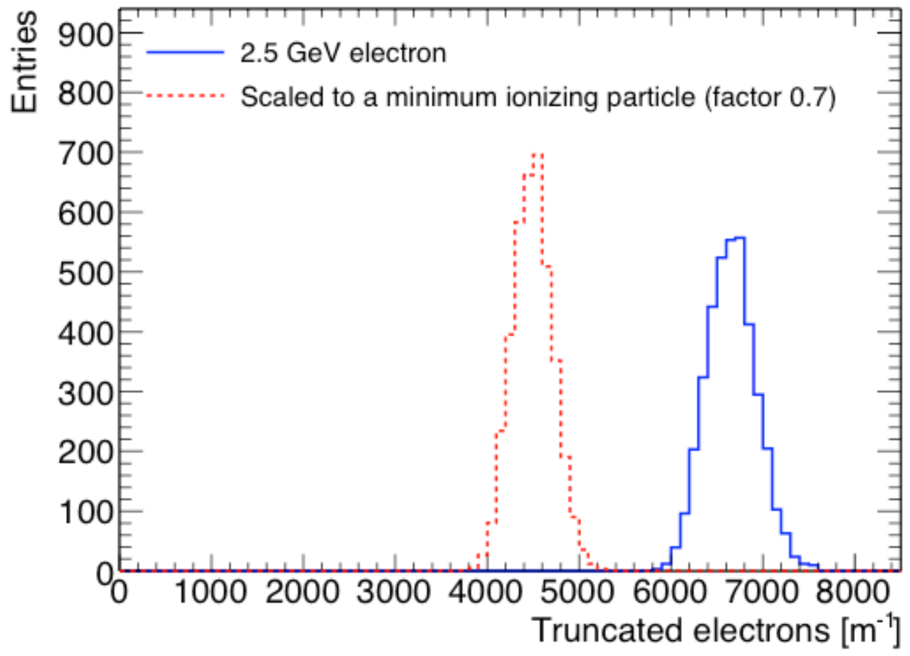
Note that:

- 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 measured with truncated mean technique
  - 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
  - Track-lentgh 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.

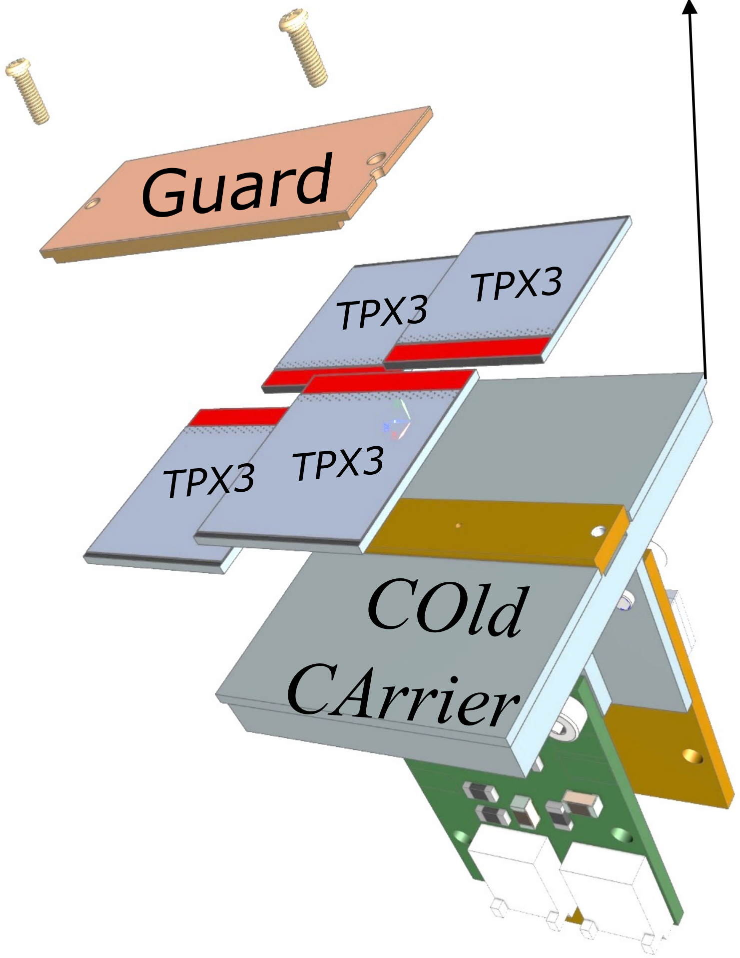


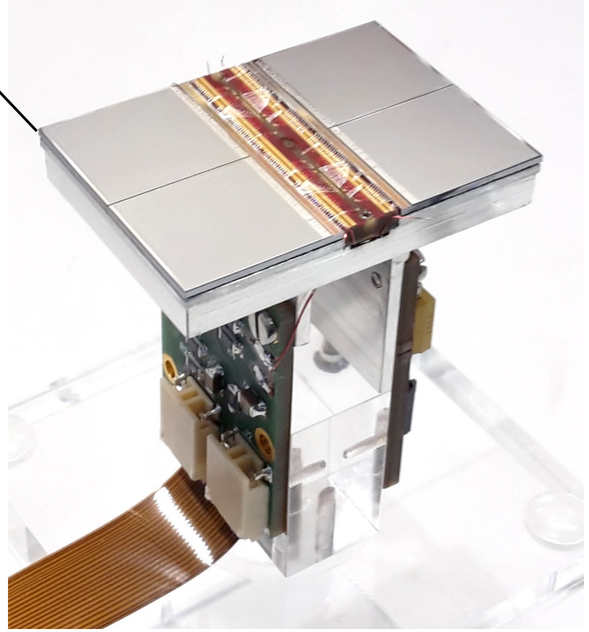
QUAD design and realization

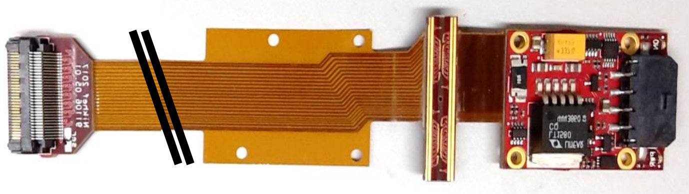
- Four-TimePix3 chips
- All services (signal IO, LV power) are located under the detection surface
- The area for connections was squeezed to the minimum
- High precision 10 μm mounting of the chips and guard
- QUAD has a sensitive area of 68.9%
- DAQ by SPIDR


series of QUADs

39.6 x 28.38 mm





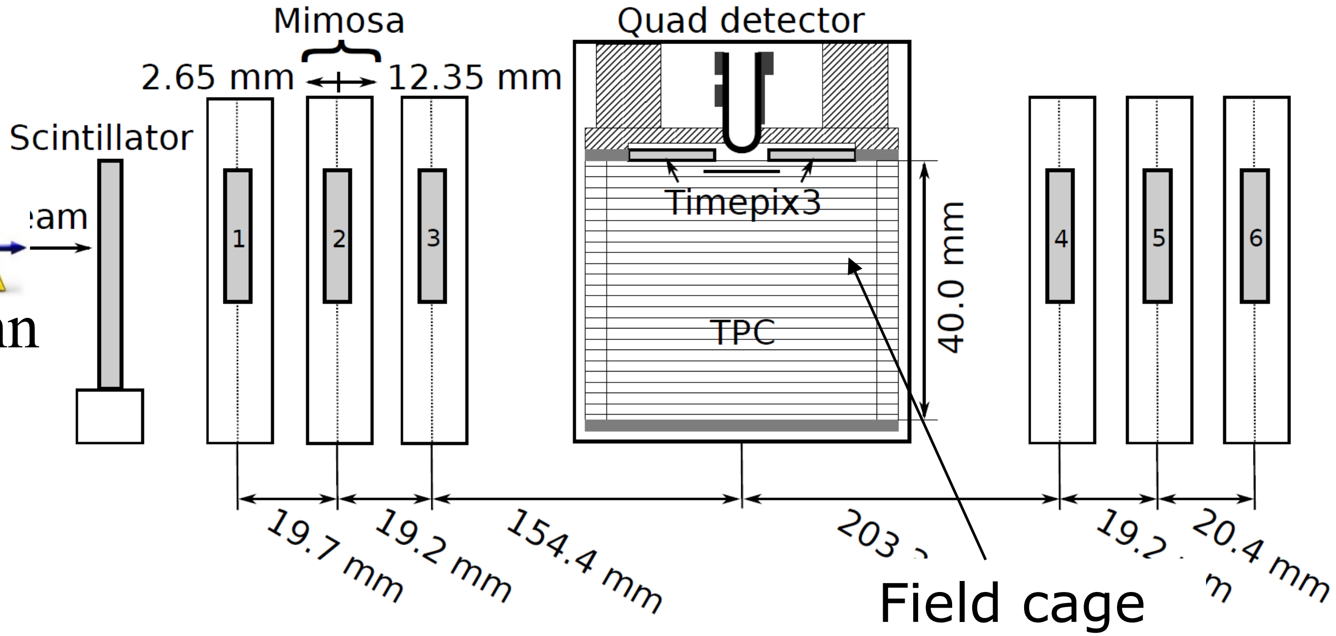


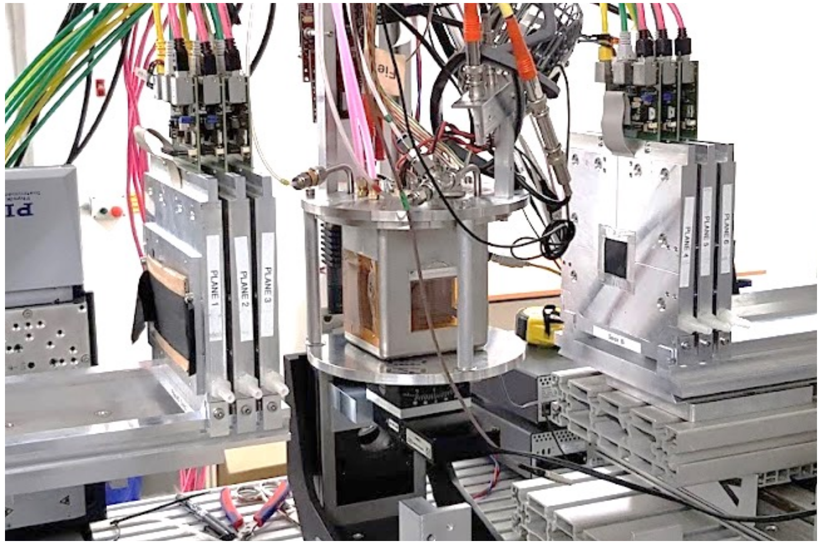
QUAD test beam in Bonn (October 2018)

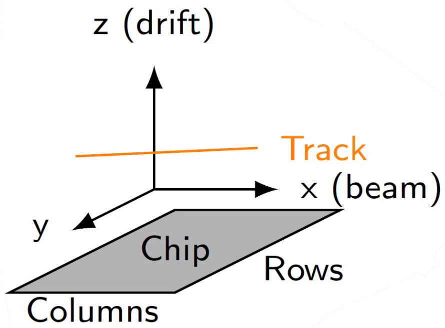
- ELSA: 2.5 GeV electrons
- Tracks referenced by Mimosa telescope
- QUAD sandwiched between Mimosa planes
  - Largely improved track definition
  - 6 planes with 18.4 μm × 18.4 μm sized pixels
- Gas: $Ar/CF_4/iC_4H_{10}$ 95/3/2 (T2K)
- E_d = 400 V/cm, V_{grid} = -330 V
- Typical beam height above the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

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

@Bonn

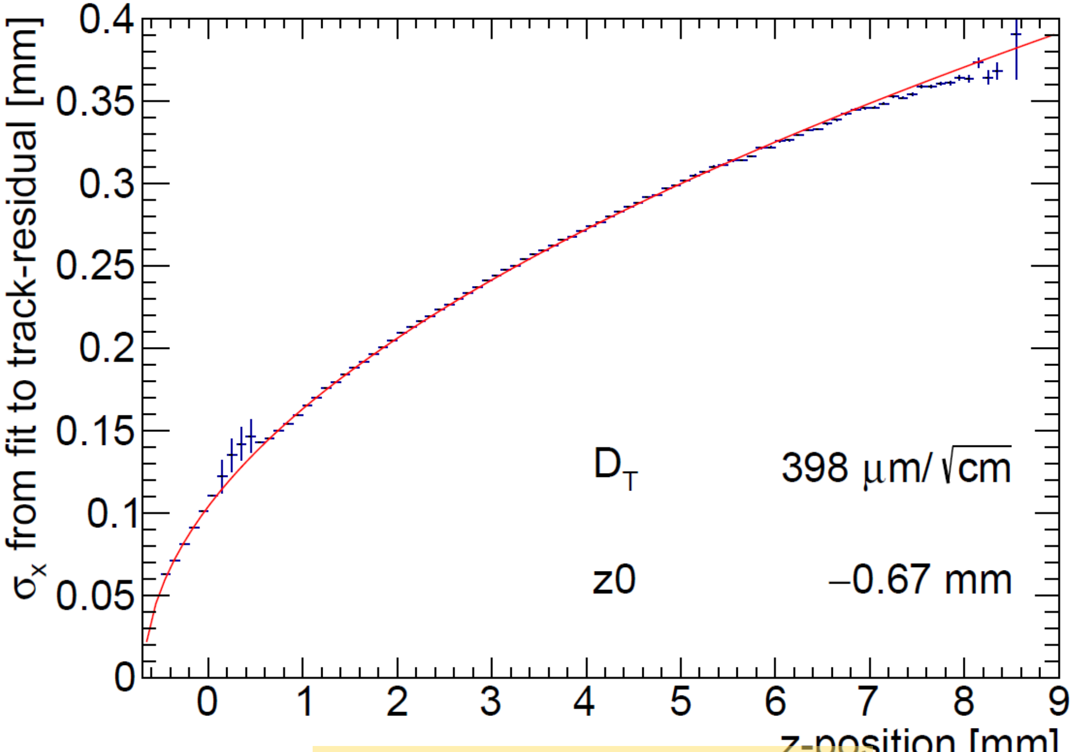






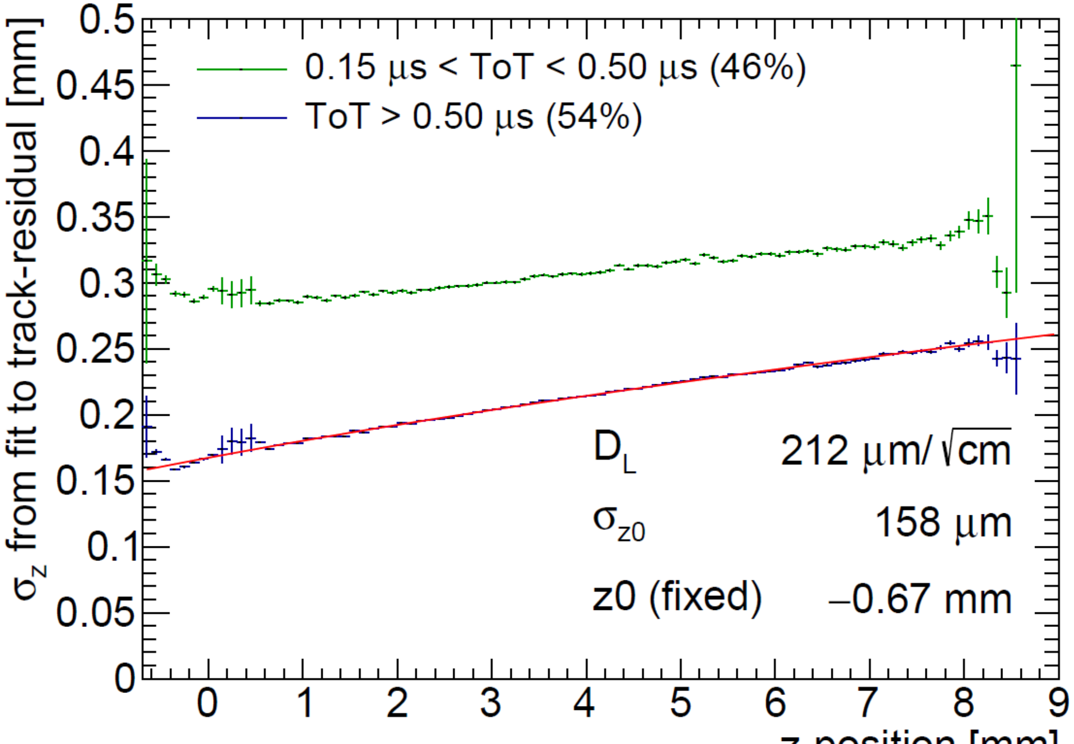
QUAD single hit resolution

Transverse



D_T = 398 μm/√cm

Longitudinal

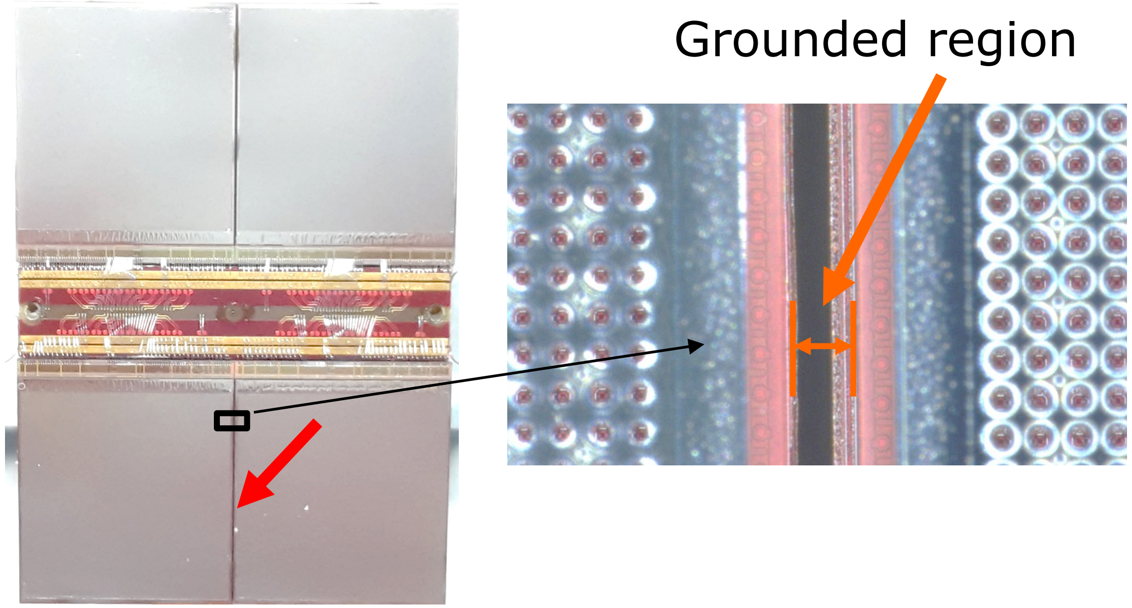


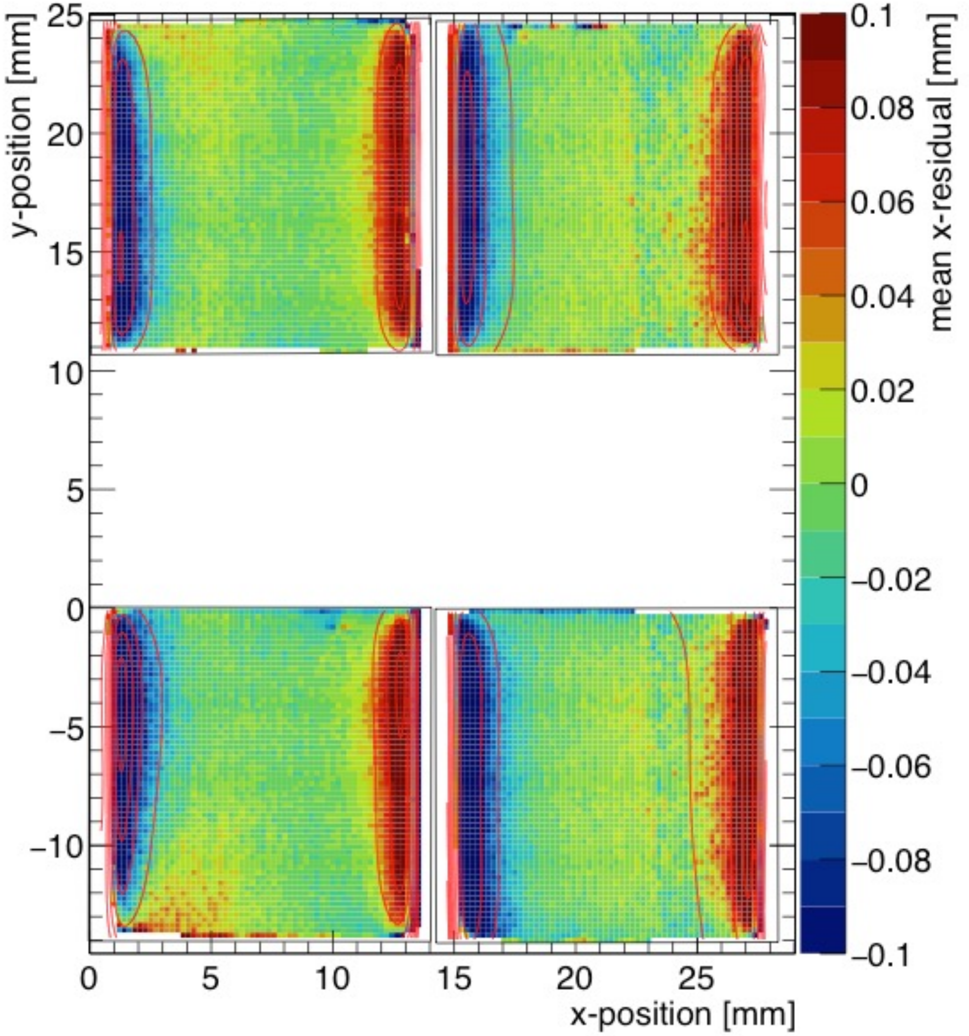
D_L = 212 μm/√cm

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

QUAD edge deformations (XY)

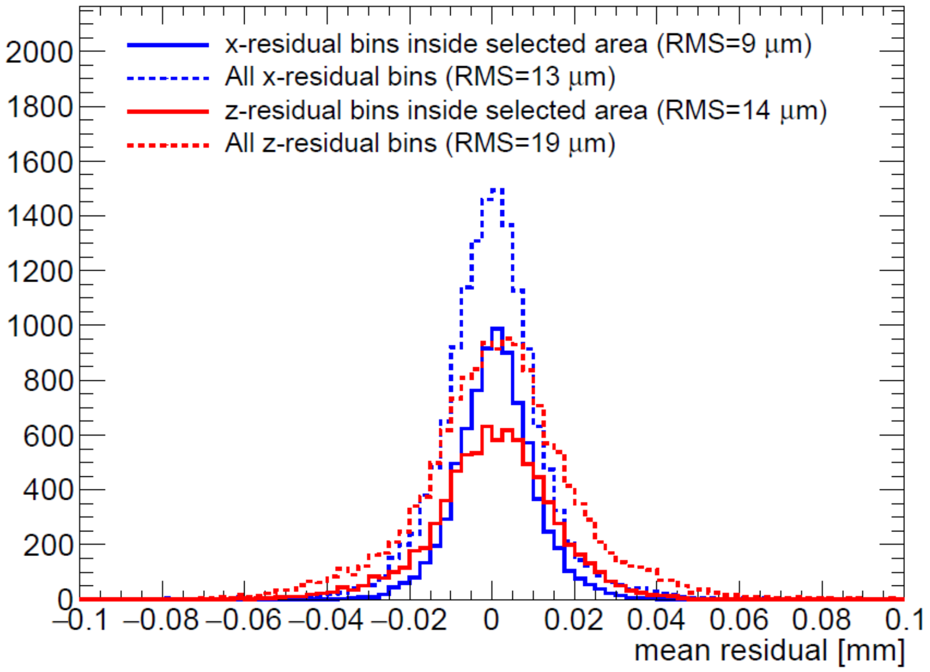
- Small deformations due to
  - Dead zone between chips
  - Grounded region between chips
- Are corrected by:
  - fitted correction function
  - adding proper guard wire electrode

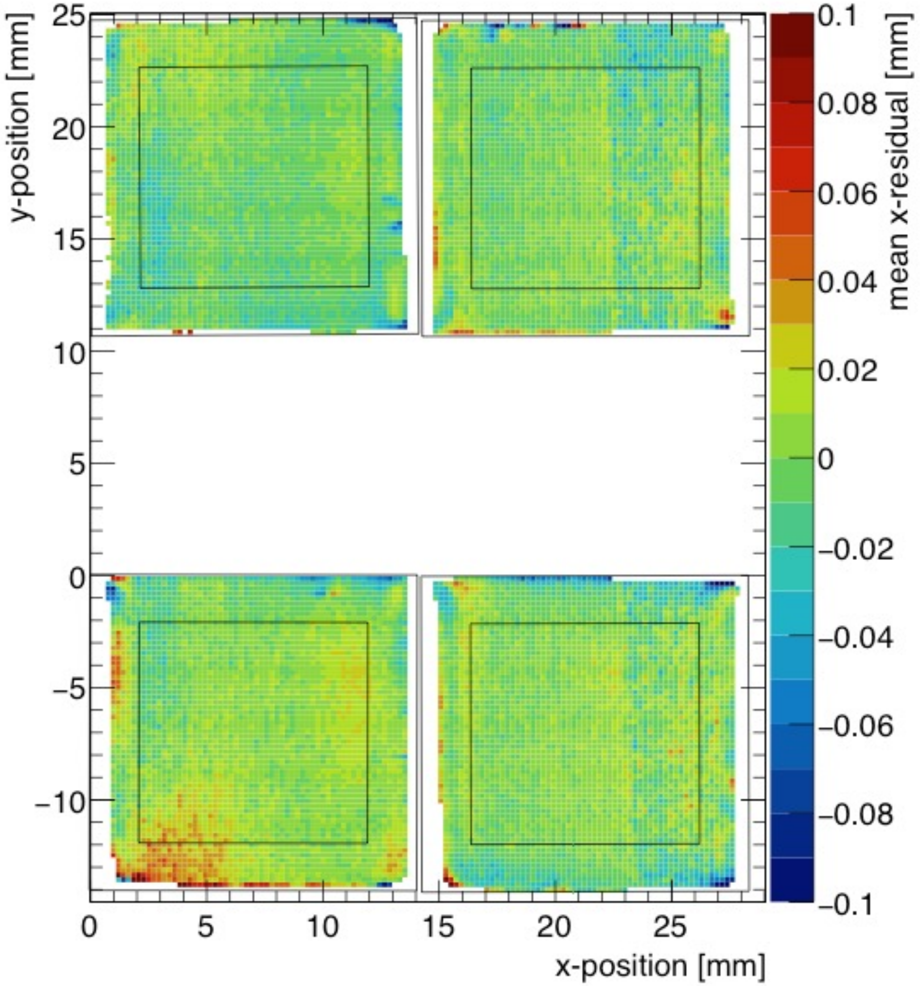




QUAD deformations in transverse plane (XY)

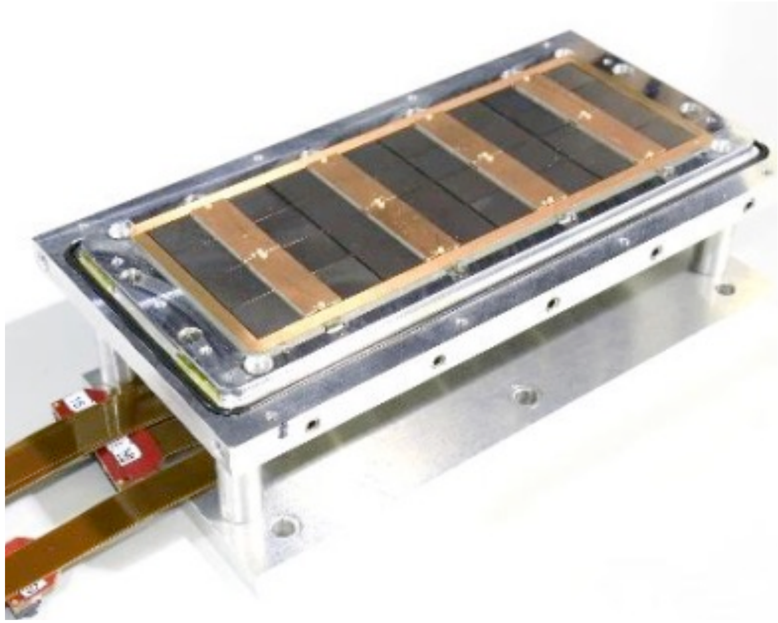
- After applying fitted edge corrections
- RMS of the mean residuals are 13 μm over the whole QUAD

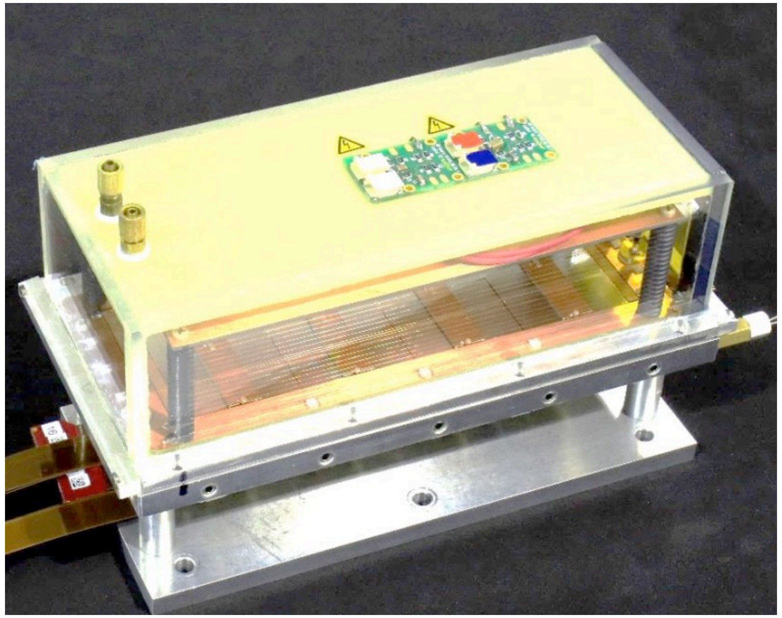


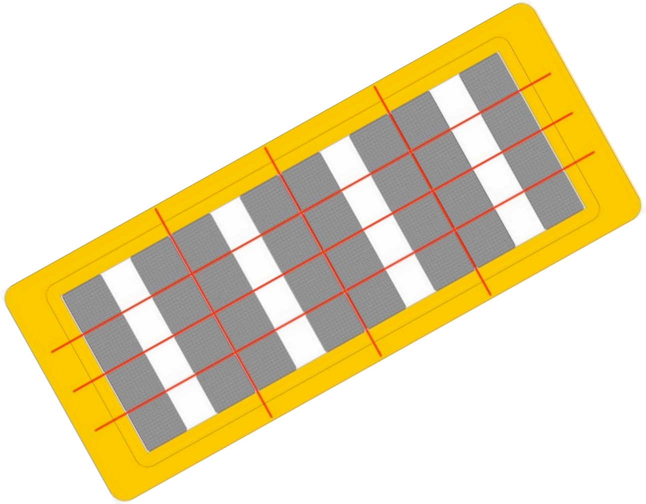


Next: QUAD as a building block

8-QUAD module (2x4) with field cage

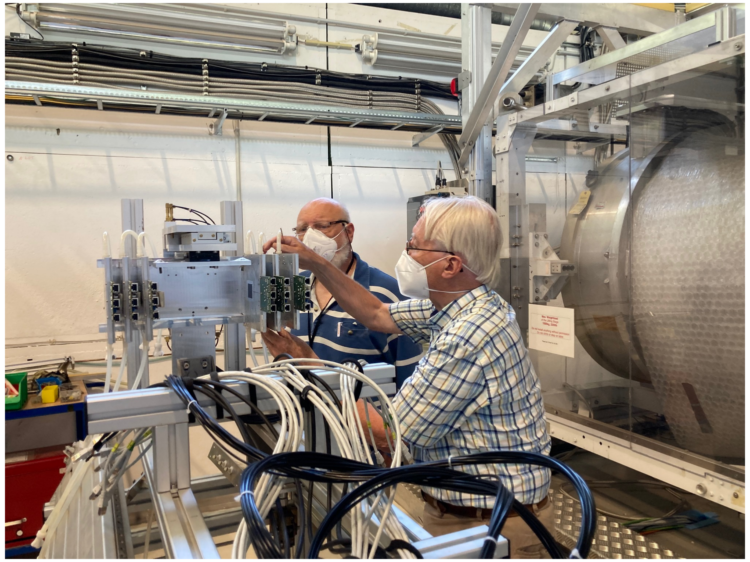
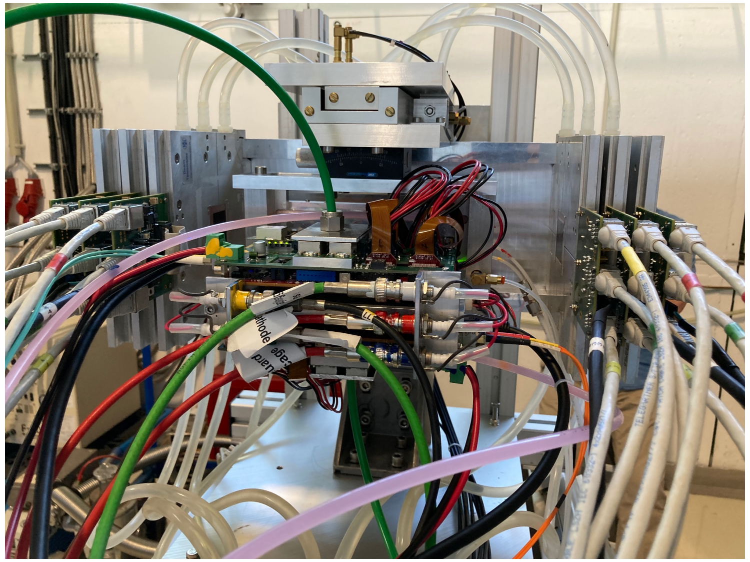
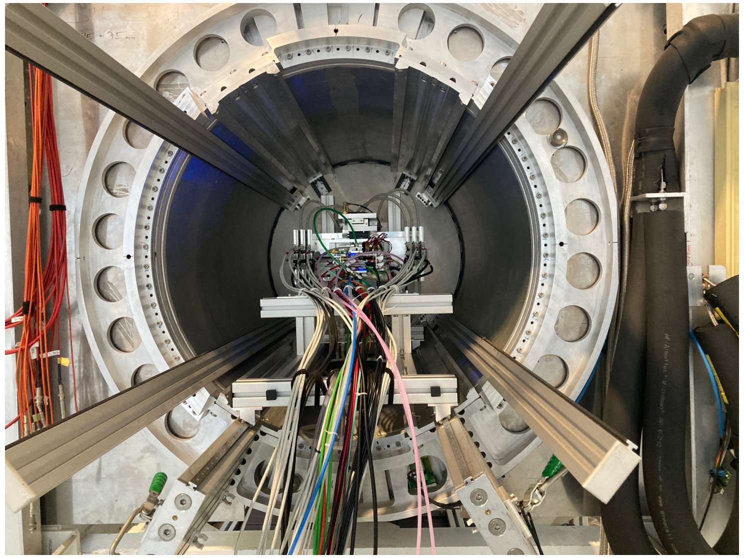






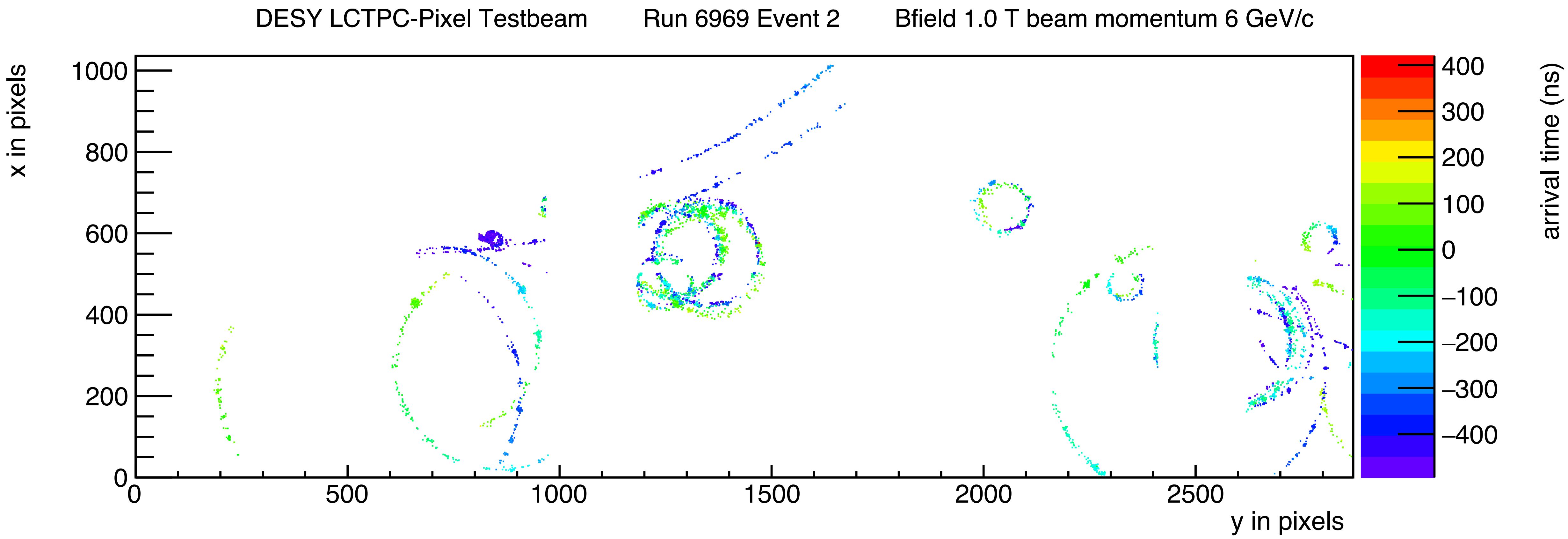
in red guard wires

DESY testbeam June 2021

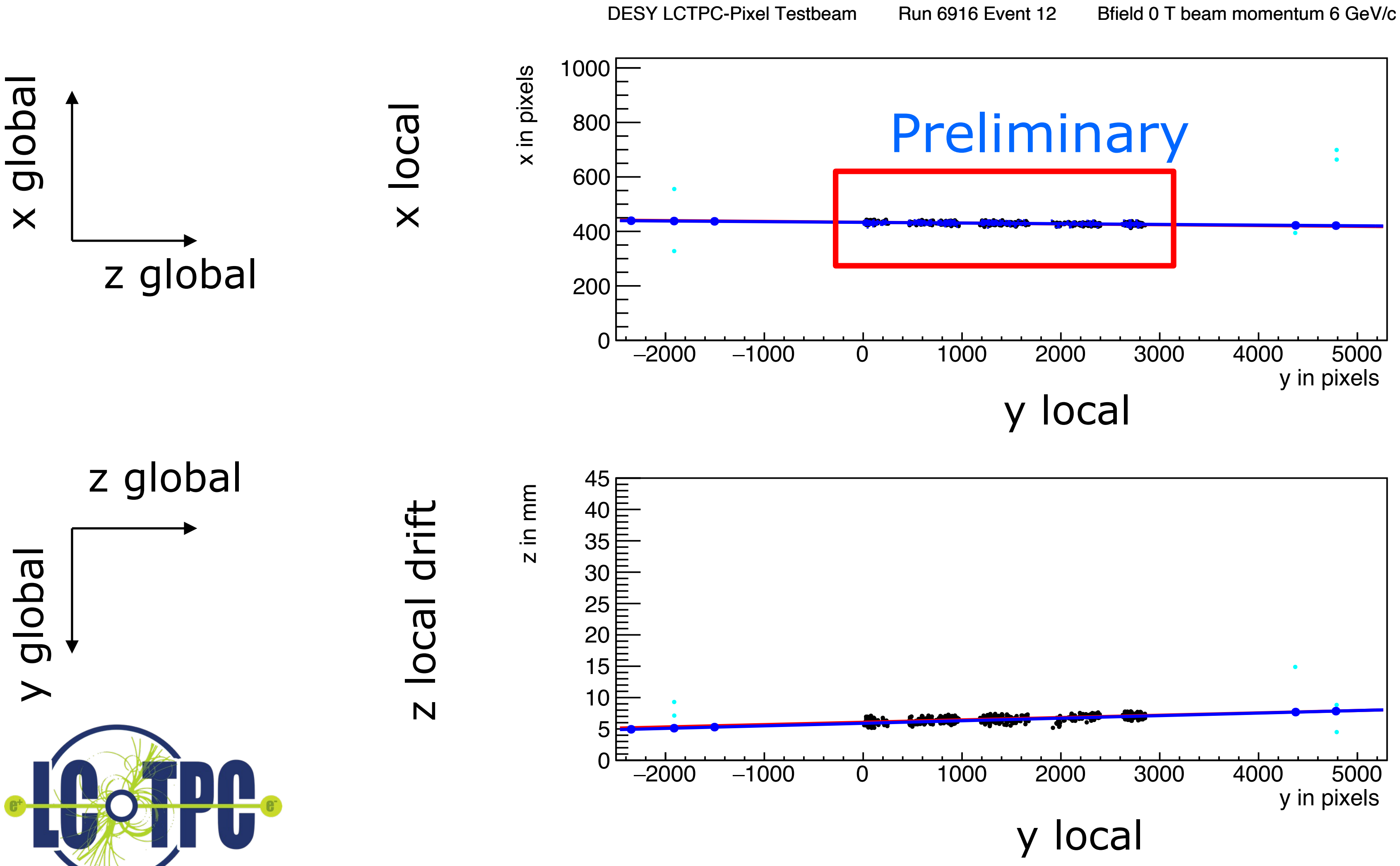




Mounting the 8 quad module between the silicon planes
sliding it into the 1 T PCMAG solenoid

DESY testbeam June 2021



DESY testbeam Module Analysis



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.

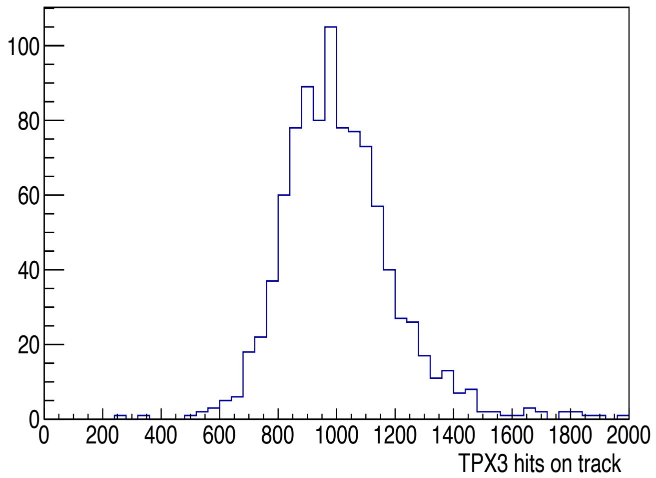
TPX3 track hits

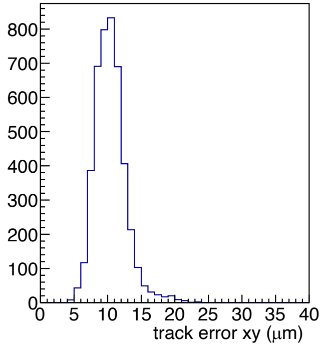
Telescope track hits (off track green)

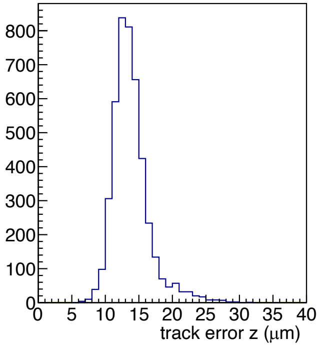
DESY testbeam Module Analysis

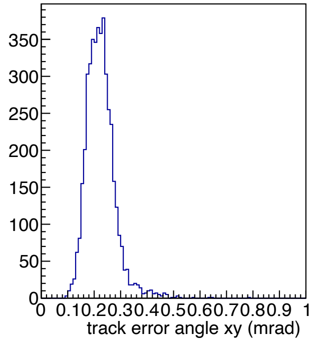
Run 6916 B=0 T p =6 GeV

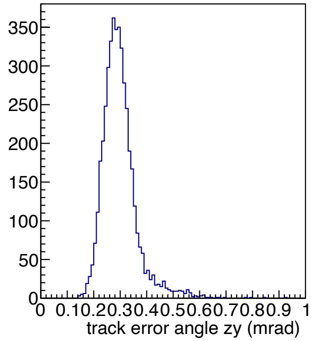
Preliminary











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

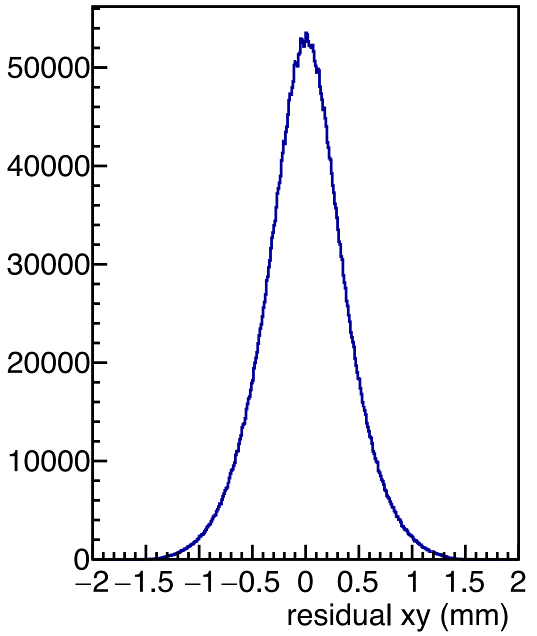
Note that in a B field because of the reduced diffusion the tracking precision will improve substantially

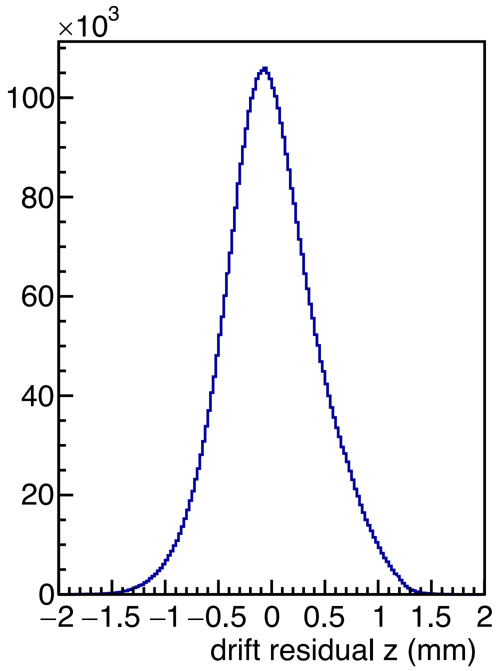
DESY testbeam Module Analysis

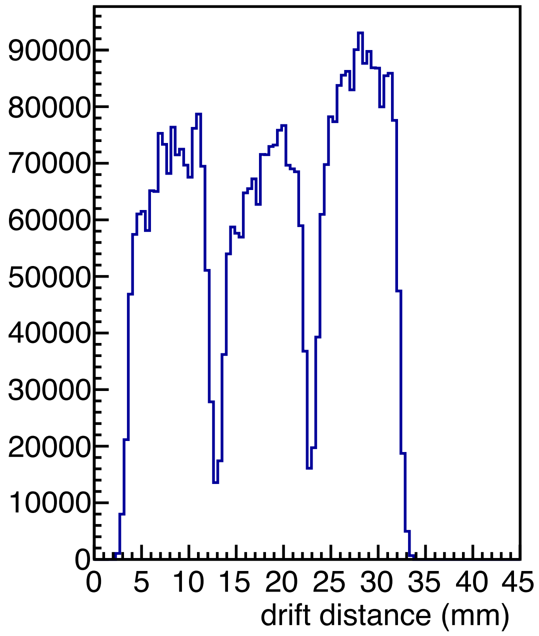
Run 6916-6918 B=0 T p=6 GeV

Three runs at different drift distances

Preliminary





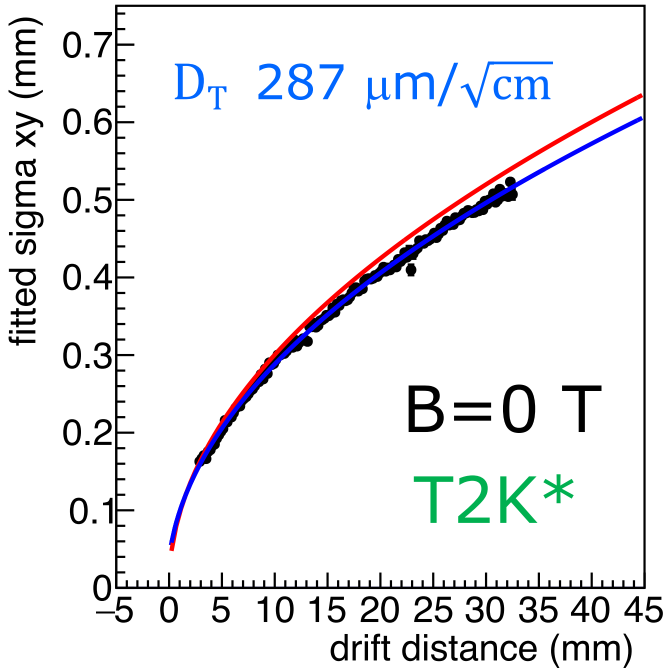


DESY testbeam Module Analysis

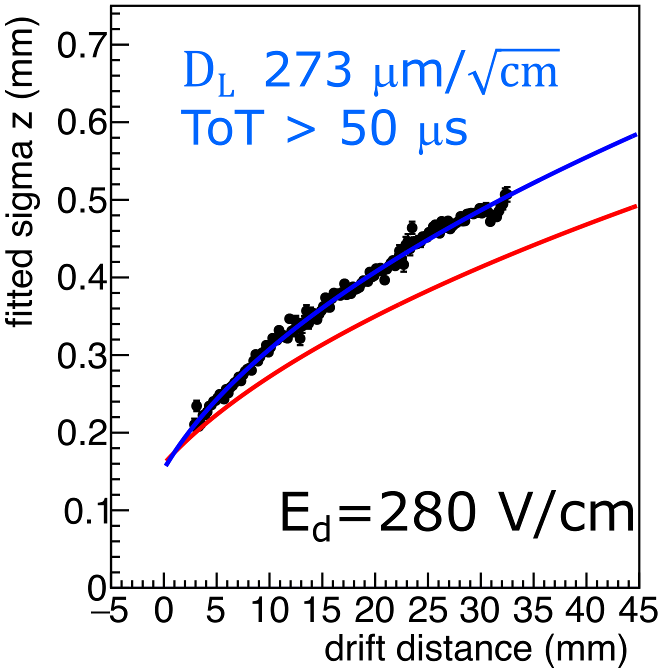
Run 6916-6918 B=0 T p=6 GeV

Fitted hit resolution

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



Preliminary



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

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

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

In red the curve published single chip results

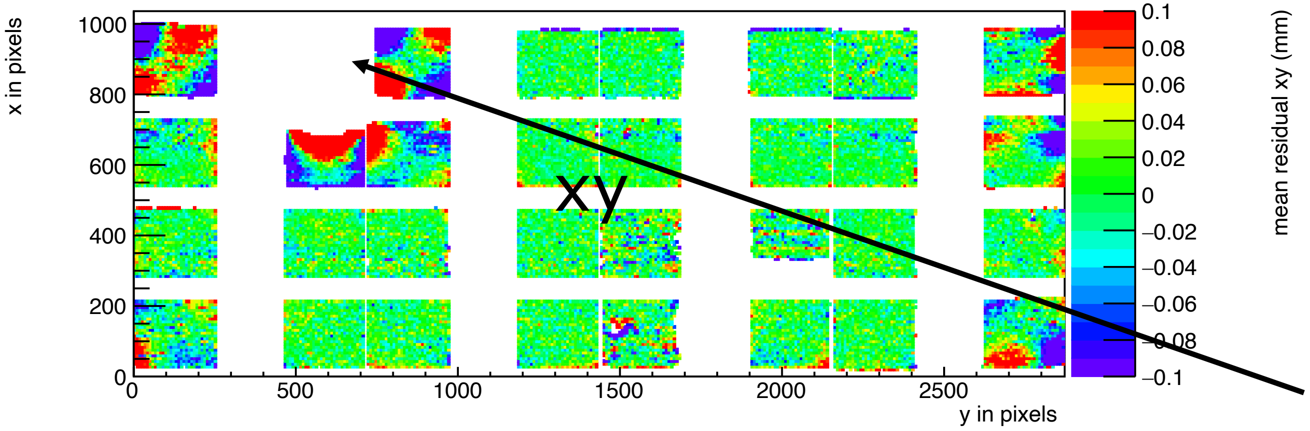
T2K* = T2K gas with admixture of O_2 and H_2O

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

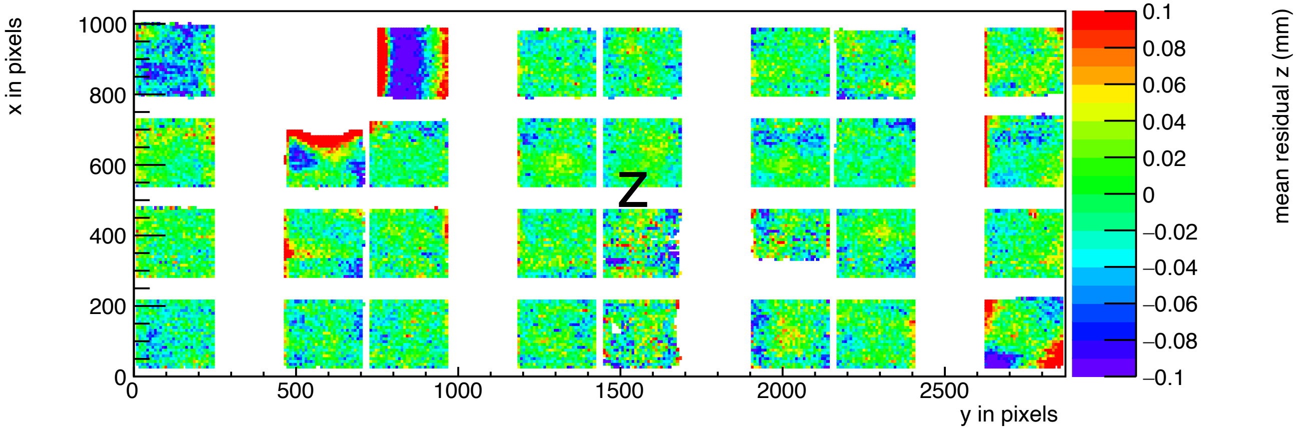
Preliminary



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

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

Vertical white bands guards



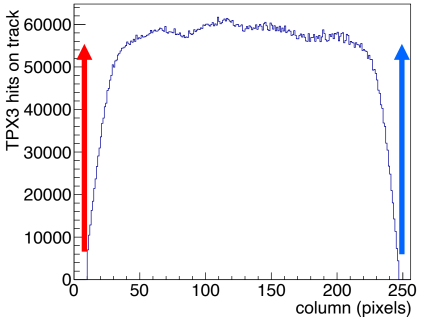
The Efield defined by the field cage is in these areas not homogenous enough

DESY testbeam Module Analysis

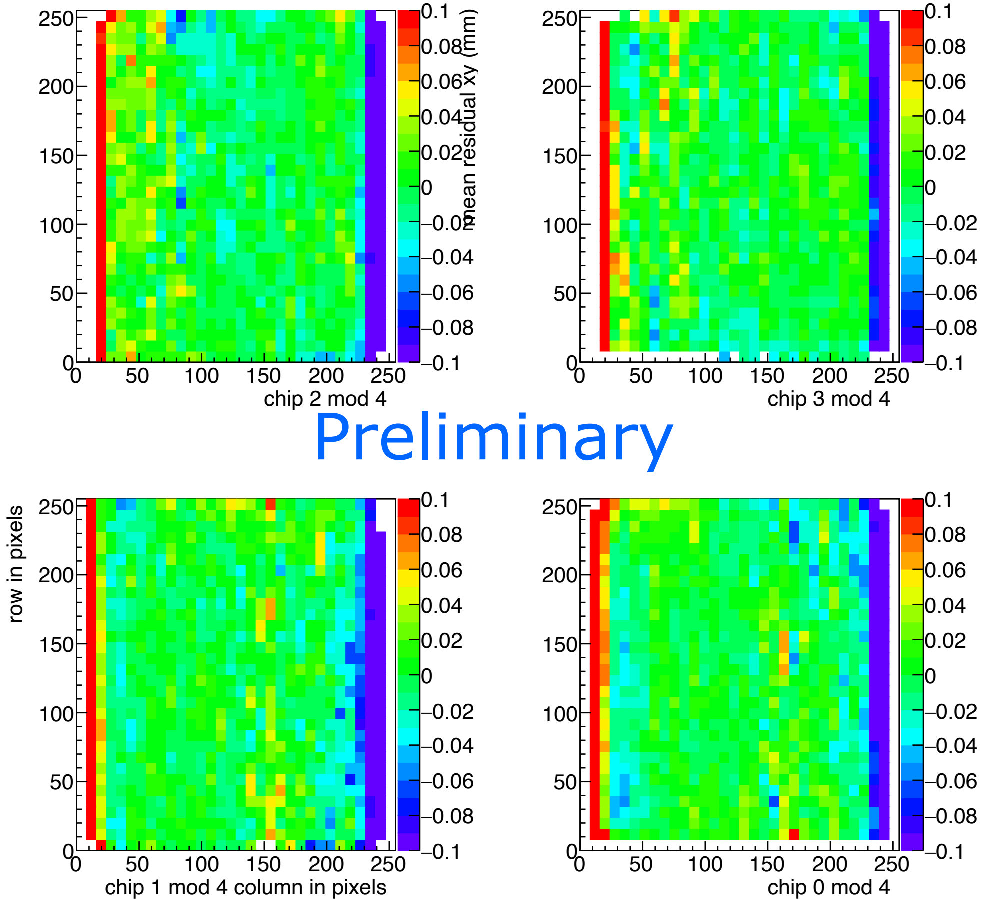
Runs 6909, 6916-17, 6934-35 B=0 T p =6,5 GeV

Mean residuals xy in the quad plane no acceptance cut

Columns horizontal



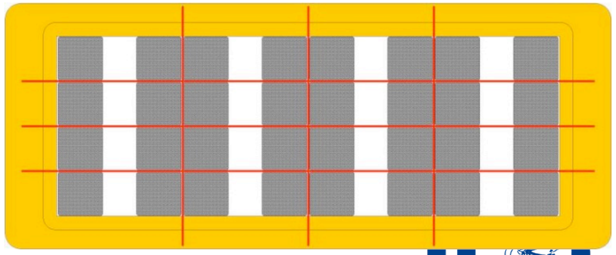
At the column edges the efficiency drops and introduces a bias (in local x).



Preliminary

Granularity 8x8 pixels

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



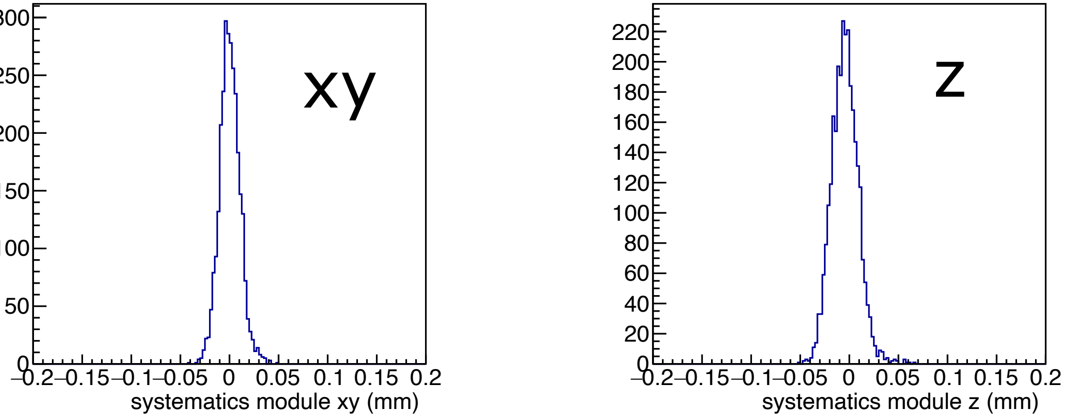
DESY testbeam Module Analysis

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

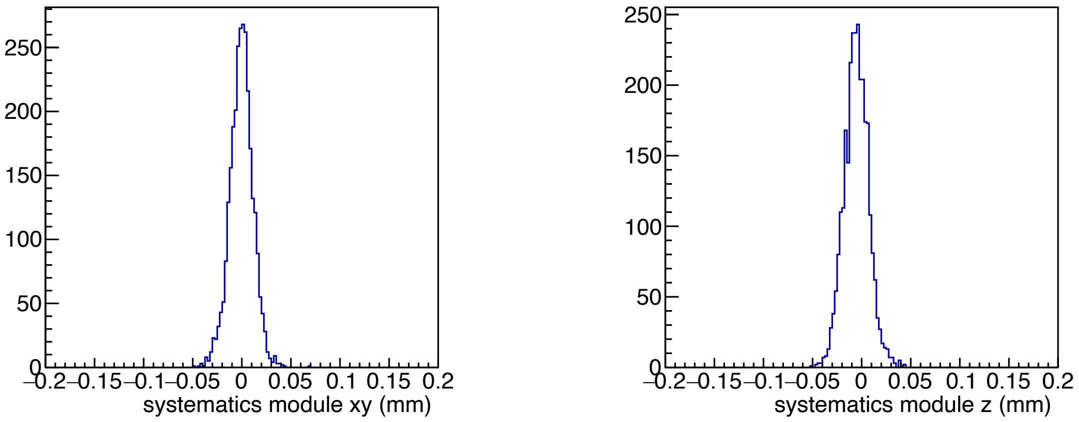
Distribution of mean residuals in the plane

Preliminary

Method row



Method column



Two methods (row/column) that group the module plane were used

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

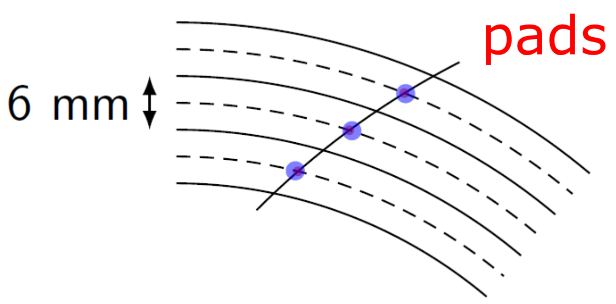
- Preliminary results of the 8 Quad Module in the DESY test beam in June 2021 have been presented
- One chip (nr 11) out of 32 was disconnected due to a short*
- In run 6916 e.g. 964 tracks were selected with 1009 hits on track
- The tracking precision: position 9 (xy) 13 μm (z) in angle 0.19 (dx/dy) 0.25 (dzdy) mrad for a module with tracklength of 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

*Chip 11 was successfully repaired in 2023 in Bonn

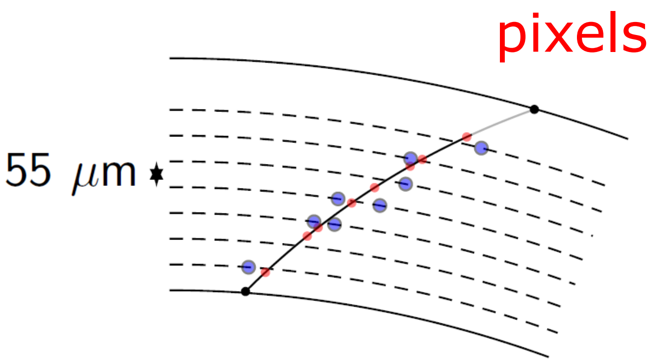
Simulation of ILD TPC with pixel readout

- 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

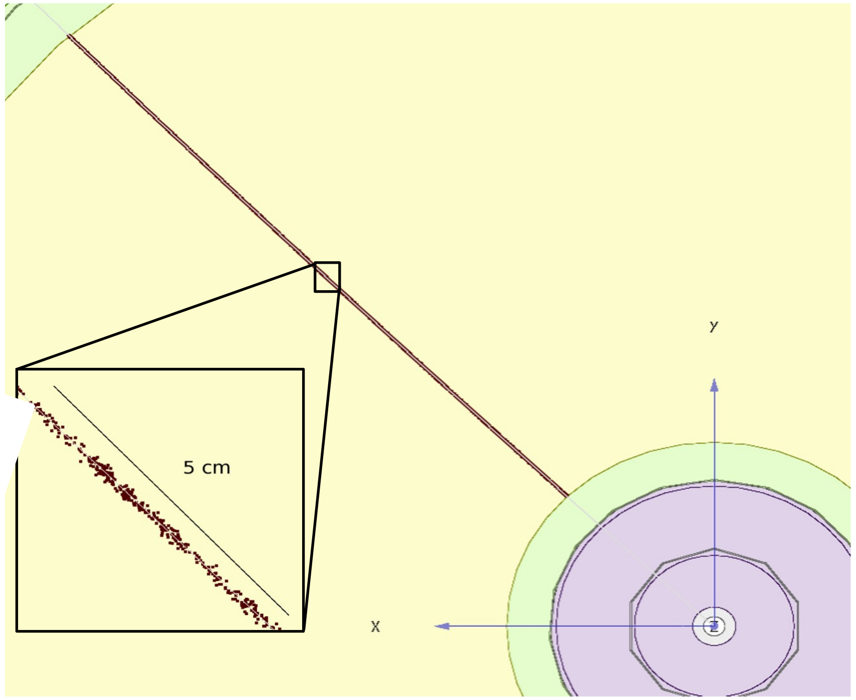
details: PhD thesis Kees Ligtenberg



22 electrons / hit
~ 200 hits / track



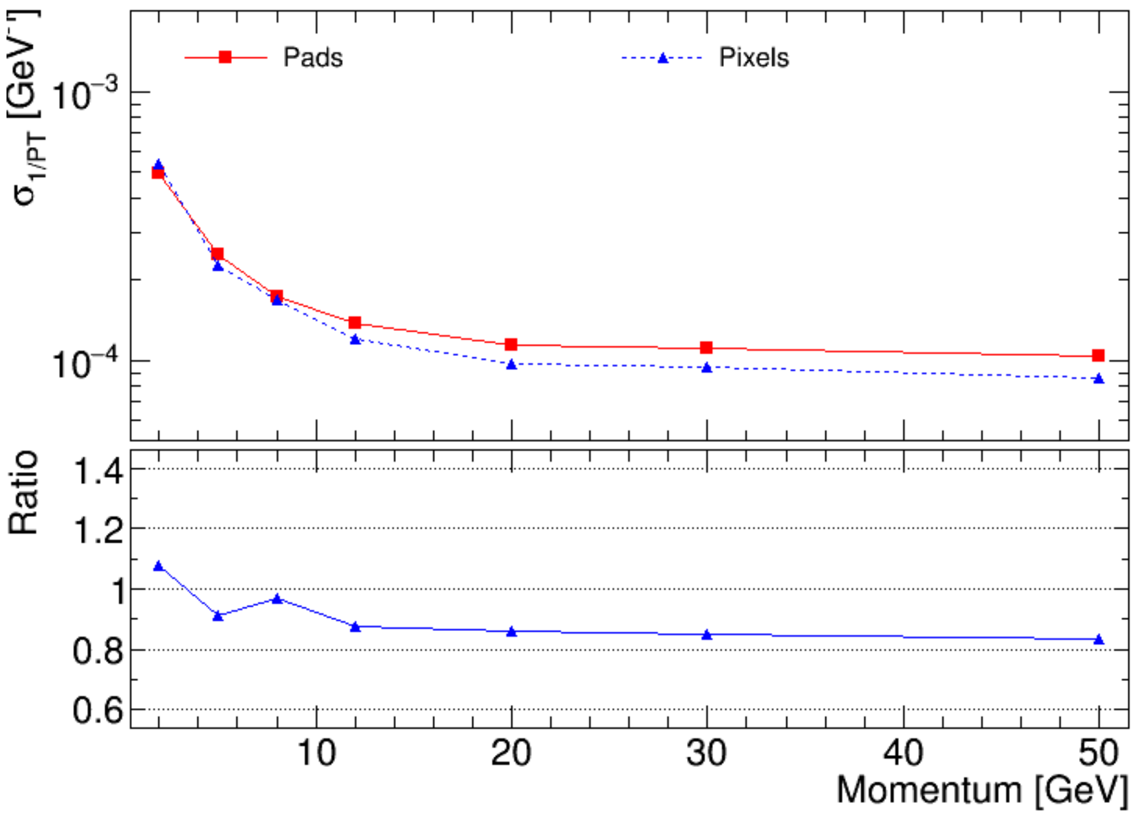
1 electron / hit
~ 10 000 hits / track

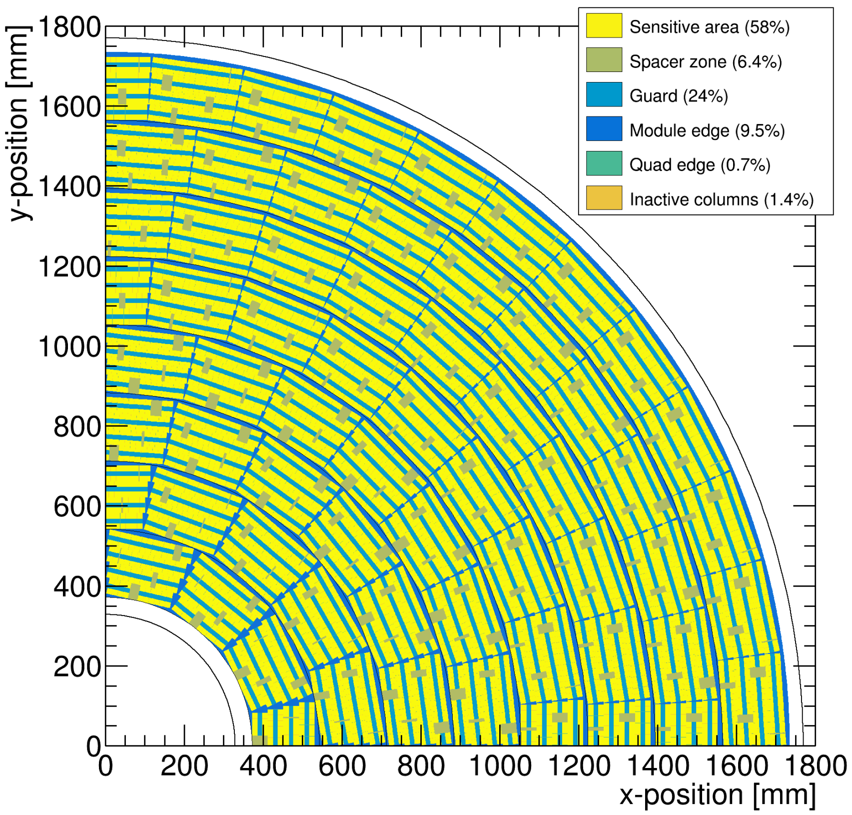


50 GeV muon track with pixel readout

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.



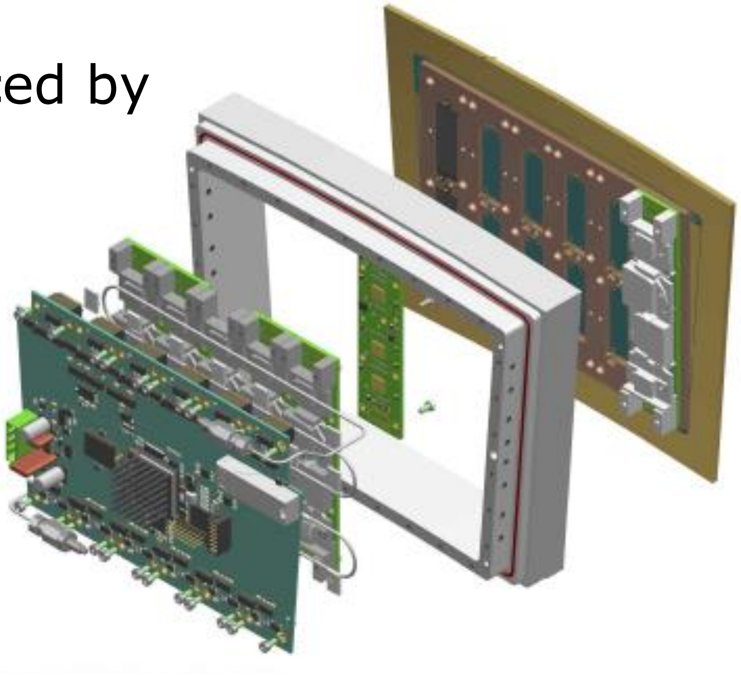


Power consumption and cooling

The power consumption of the TPX3 chip is ~1 W/cm^2.

At the ILC – due to the beam structure - the chip can be ran in power pulsing mode. Reducing the power consumption by more than a factor of 10.

The power consumption of the TPX3 chip can be reduced by a factor of 5-10 by using different DAC settings.



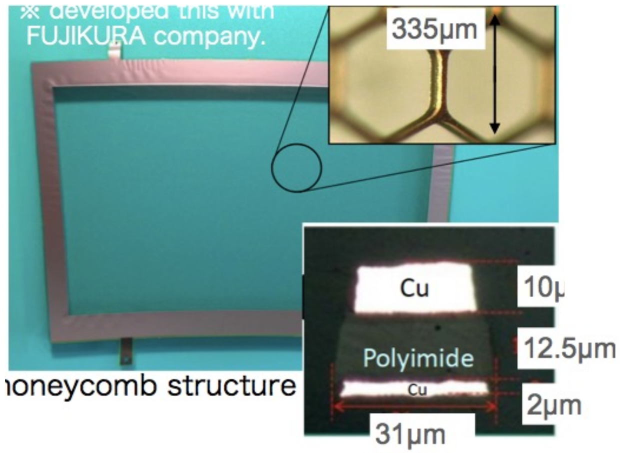
Cooling remains important.

A test of the CO2 cooling of Micro Megas integrated modules showed it works fine.

Reducing the Ion back flow in a TPC

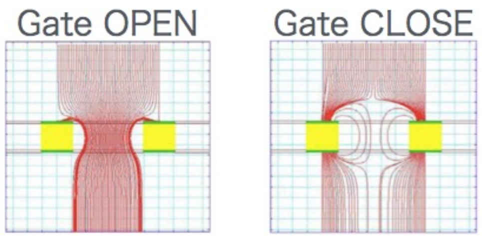
Part of the ions created in the avalanche drift back in the TPC drift volume will cause (limited) distortions.

The Ion back flow can be reduced at ILC by using a gating GEM gating device placed above the read out module. The gate is opened and closed based on the beam structure.



For a Pixel TPC a double grid structure will be developed (see backup slide) that reduces the ion back flow without the need of gating.

This will also allow operation with a more continuous beam (FCC-ee/CEPC).



LCWS19 by Yumi Aoki (KEK))

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 2021 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

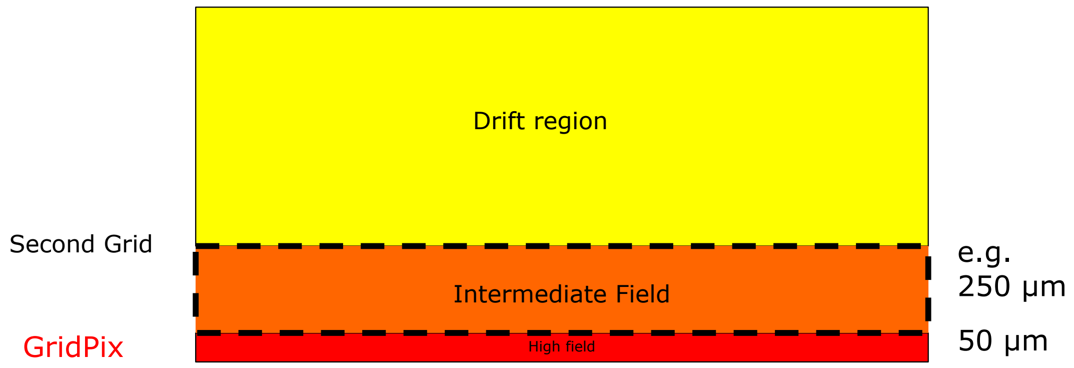
Back up slides follow

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%