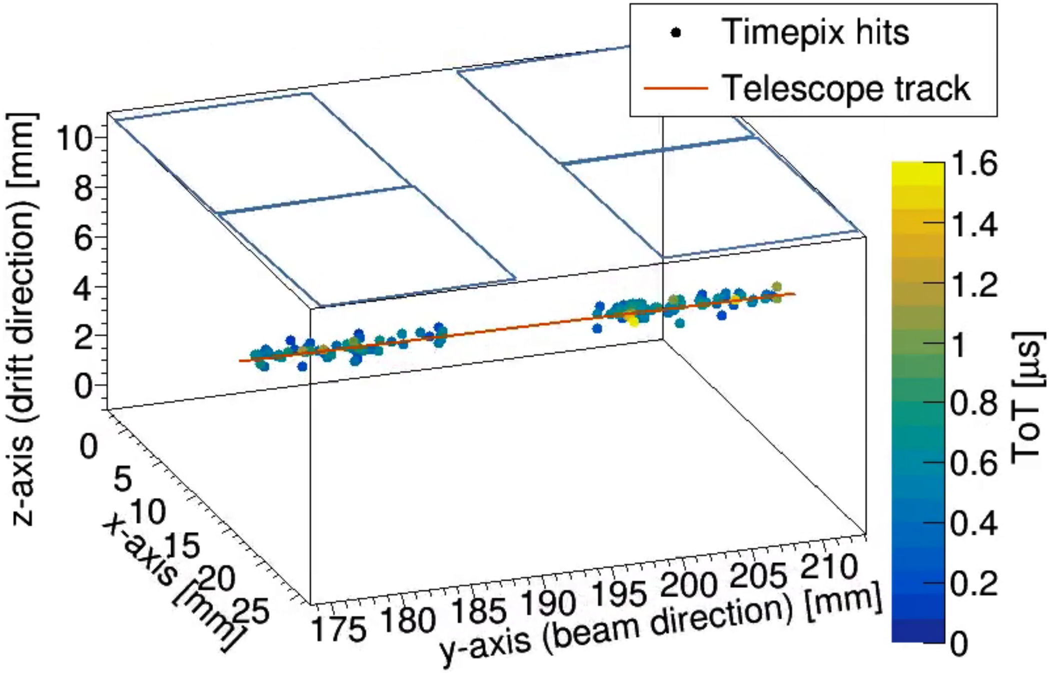


Performance of the GridPix quad TPC readout

Cornelis Ligtenberg, *Y. Bilevych, K. Desch, H. van der Graaf, M. Gruber, F. Hartjes, K. Heijhoff,*

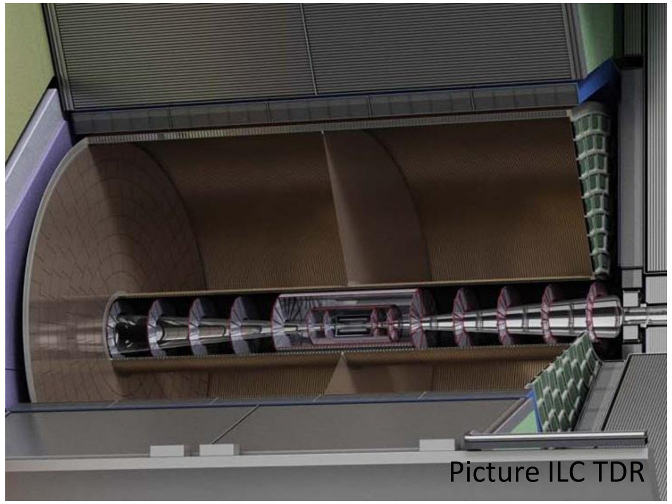
J. Kaminski, P.M. Kluit, N. van der Kolk, G. Raven, T. Schiffer, J. Timmermans

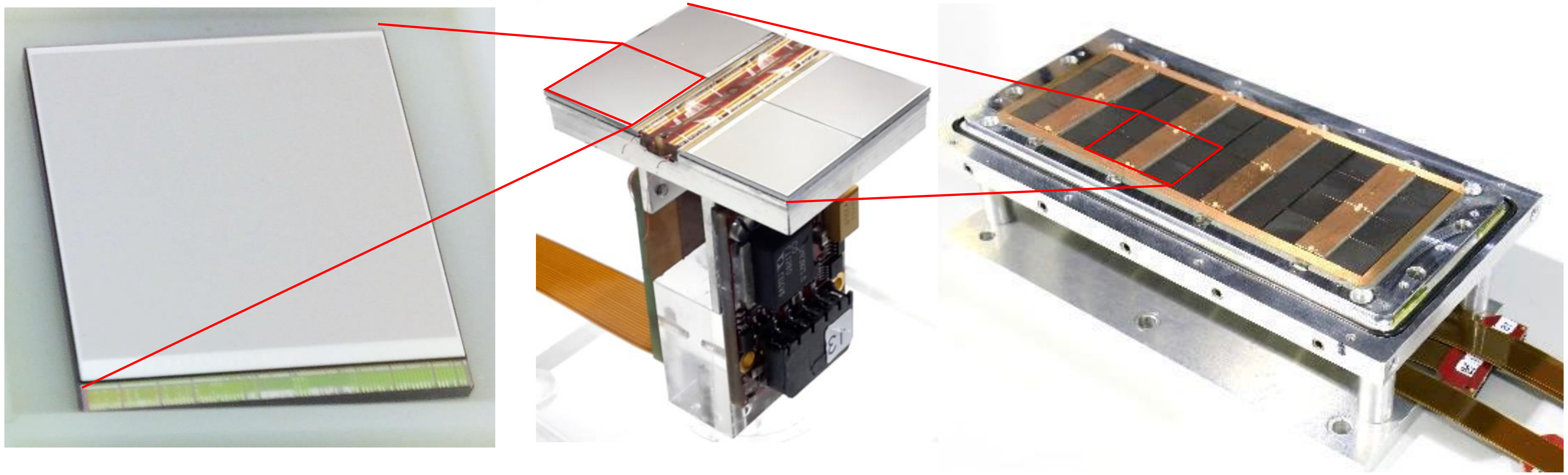
Nikhef · UNIVERSITÄT BONN · LC TPC

The 2019 International Workshop on the High Energy Circular Electron Positron Collider, November 18, Beijing

Introduction and outline

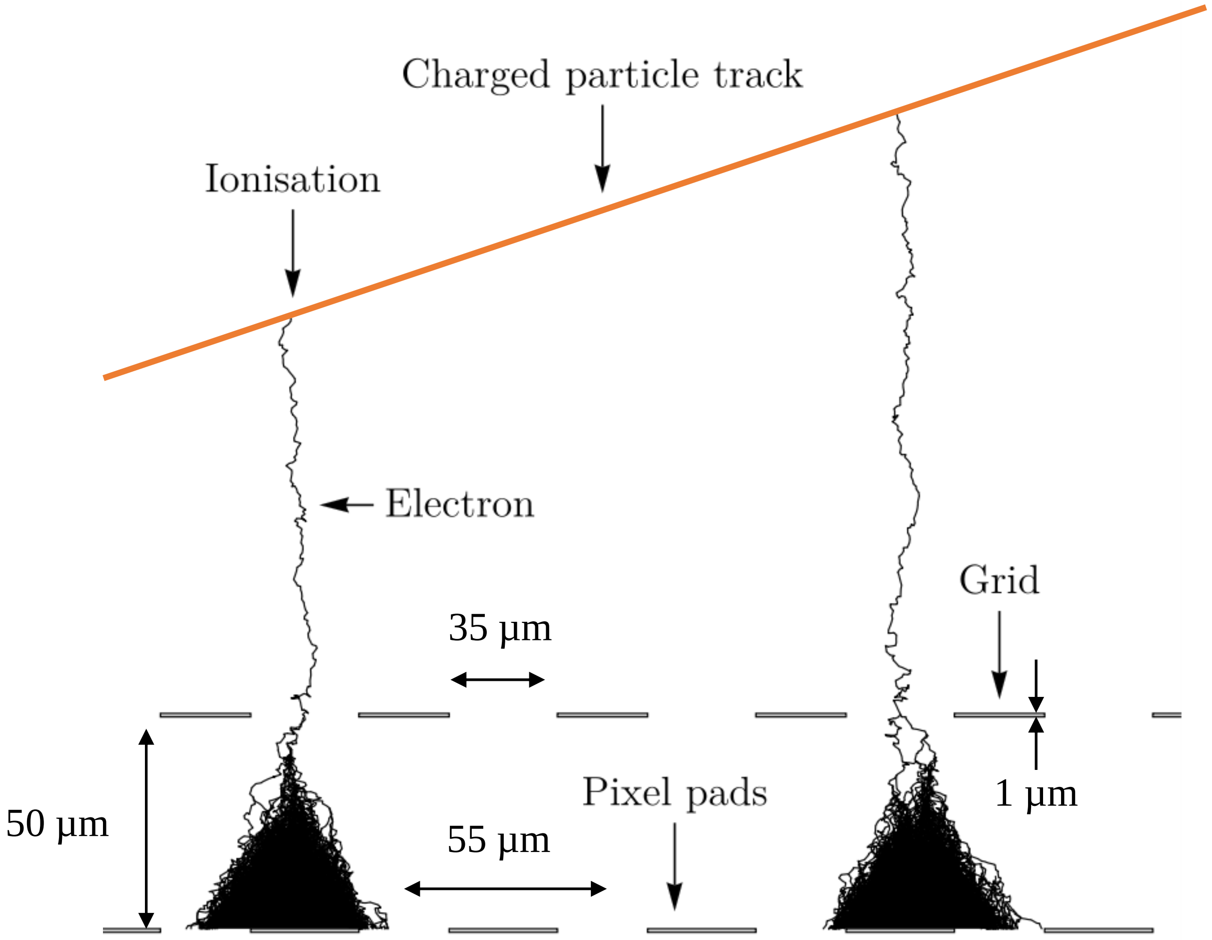
- <u>The goal is to develop a pixel readout for a large TPC</u>
- A large TPC with a 55 µm × 55 µm pixel readout
- First Timepix3 based GridPix test beam (2017)
- Quad module performance from test beam (2018)
- Development of 8 quad detector (2019-2020)

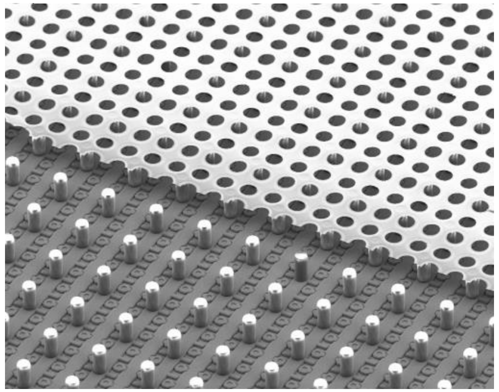

Picture ILC TDR

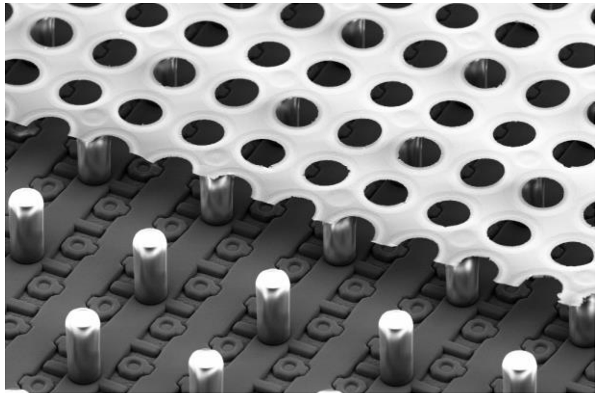


GridPix technology

- GridPix is a type of micro-pattern gaseous TPC readout
- The GridPix based on a Timepix3
  - 55 µm × 55 µm pixels
  - Digital simultaneous registration of Time of Arrival (1.56 ns) and Time over Threshold
  - An aligned Aluminium amplification grid is added by photolithographic postprocessing techniques
- Single ionization electrons are detected with high efficiency
  - The maximum possible information from a track is acquired
  - dE/dx by cluster counting

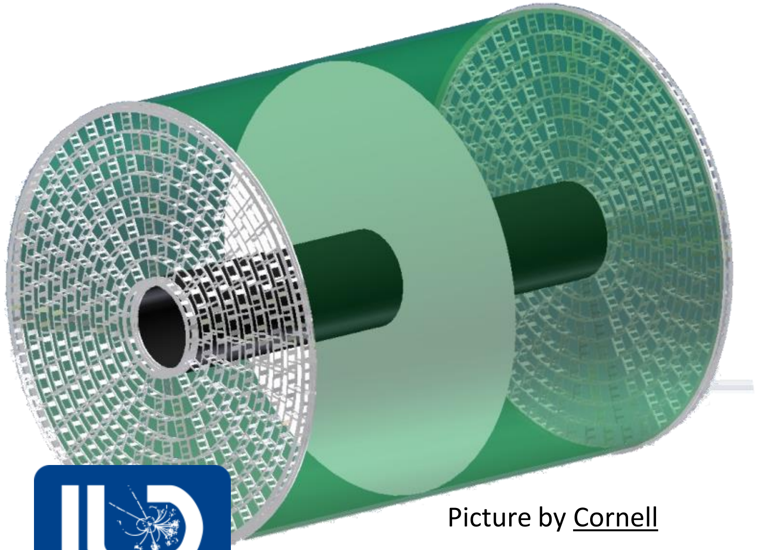






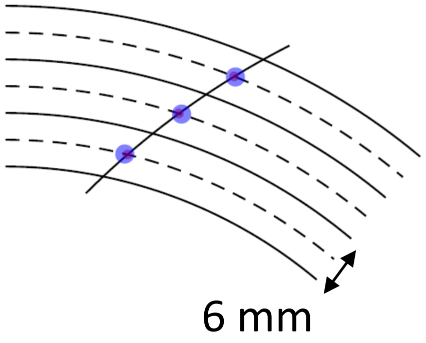
Simulation of ILD TPC with pixel readout

- To study the performance of a large pixelised 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



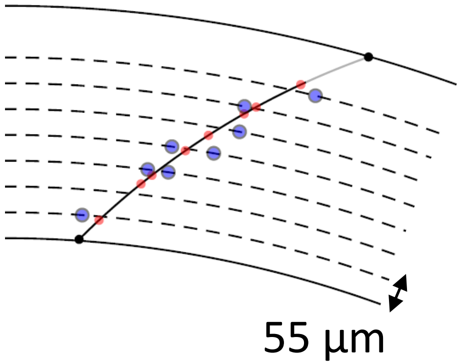
Picture by Cornell

Pads



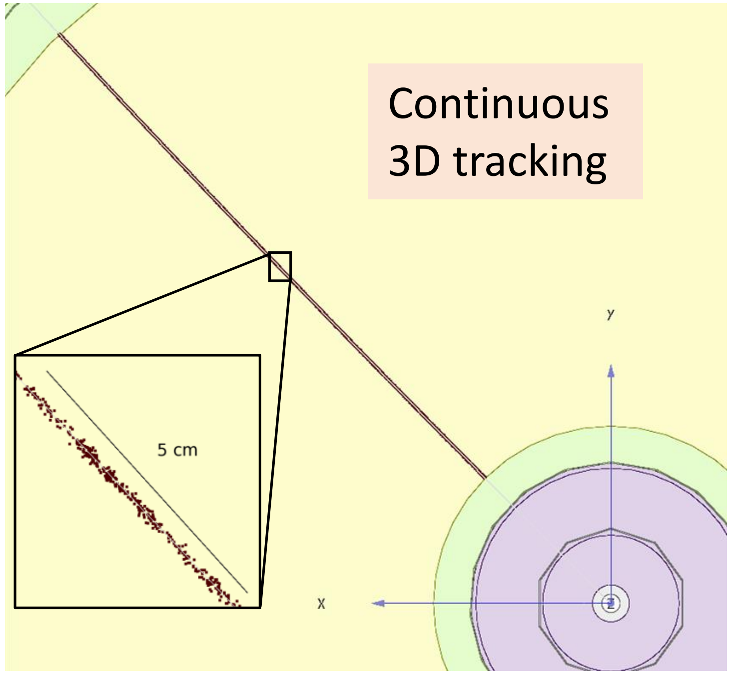
22 electrons / hit
~200 hits / track

Pixels



1 electron / hit
~10 000 hits / track

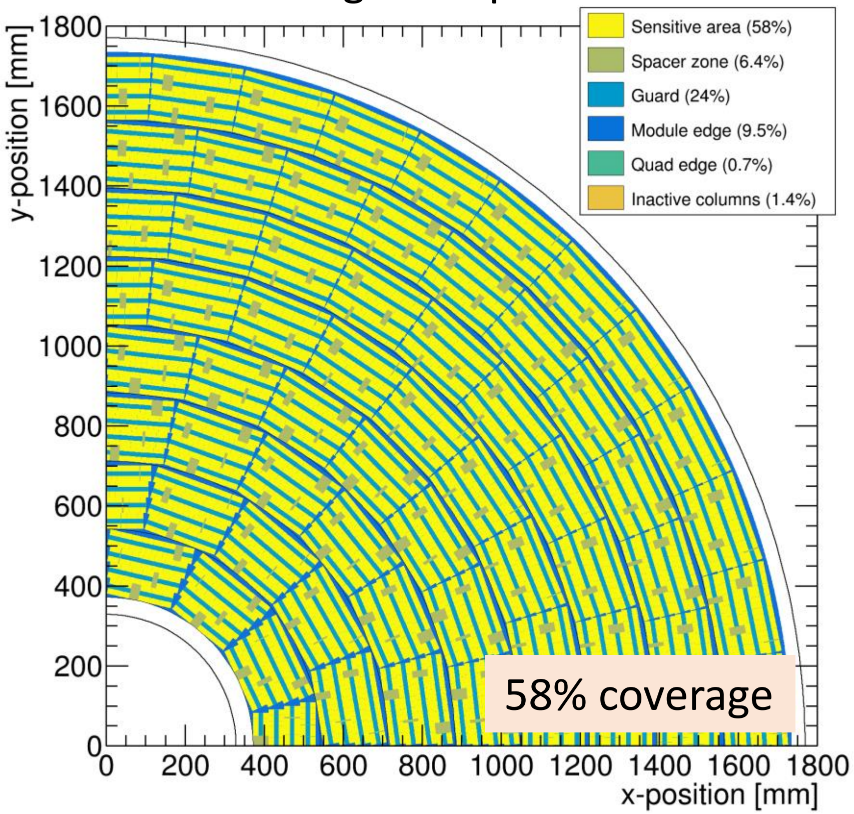
50 GeV muon track with pixel readout



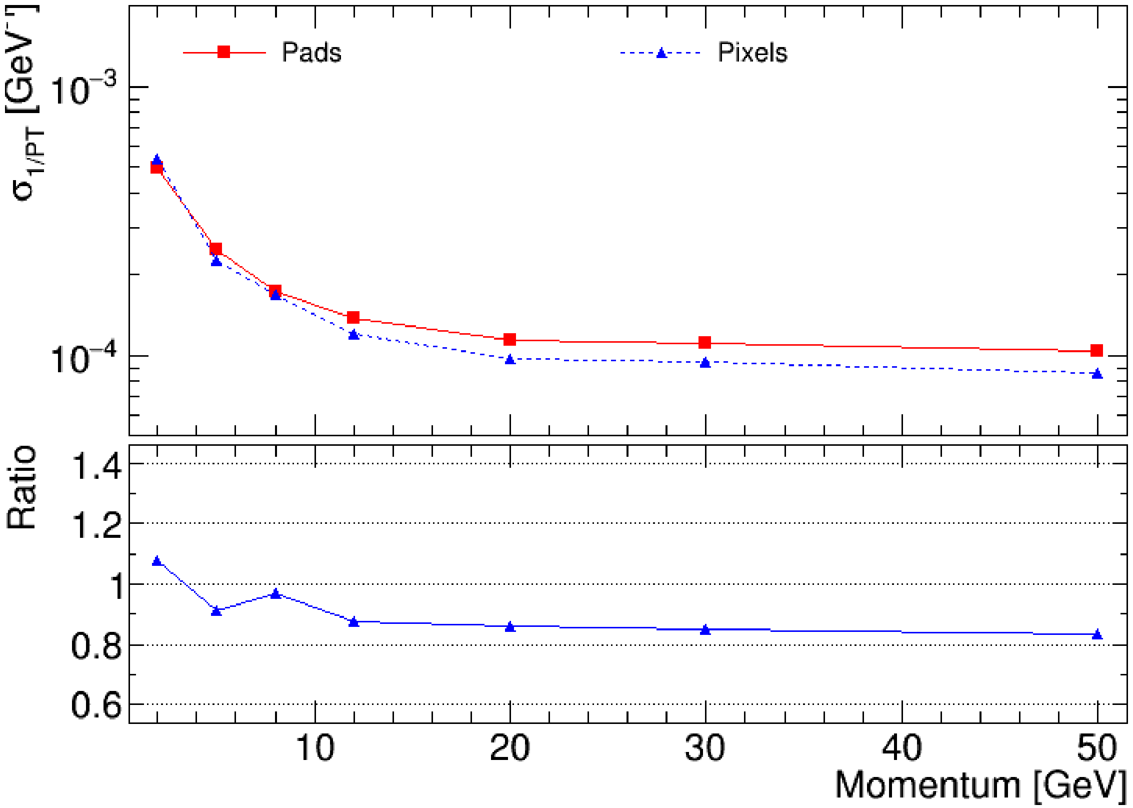
Performance of a GridPix TPC at ILC

- From full simulation, momentum resolution can be determined
- Momentum resolution is ~15% better (with realistic coverage and delta's)

Realistic tiling with quad module

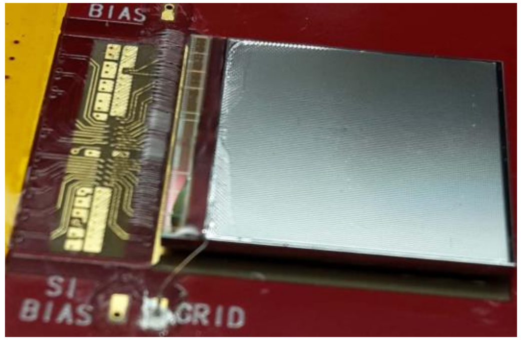


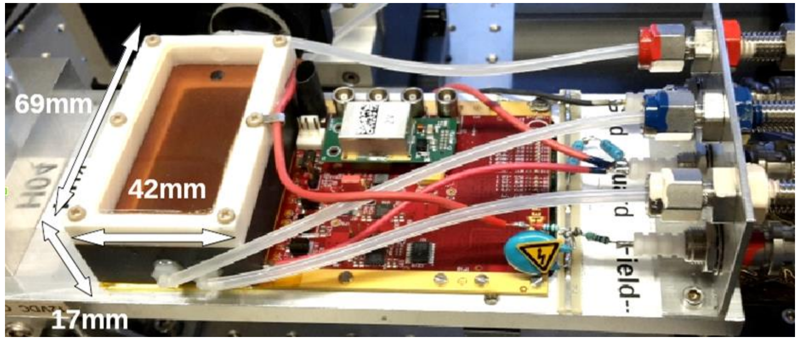
Momentum resolution of the TPC for a 50 GeV muon



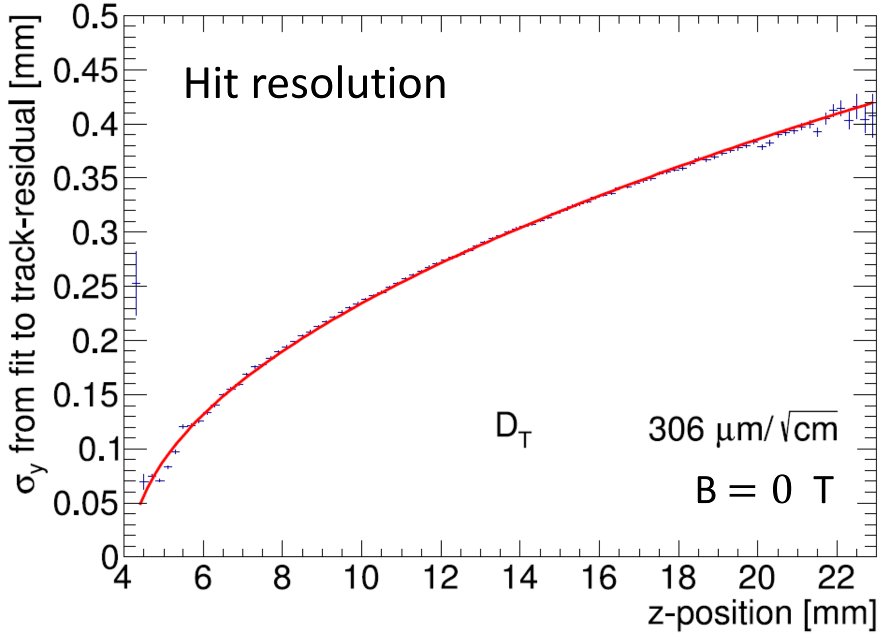
Single chip results (2017)

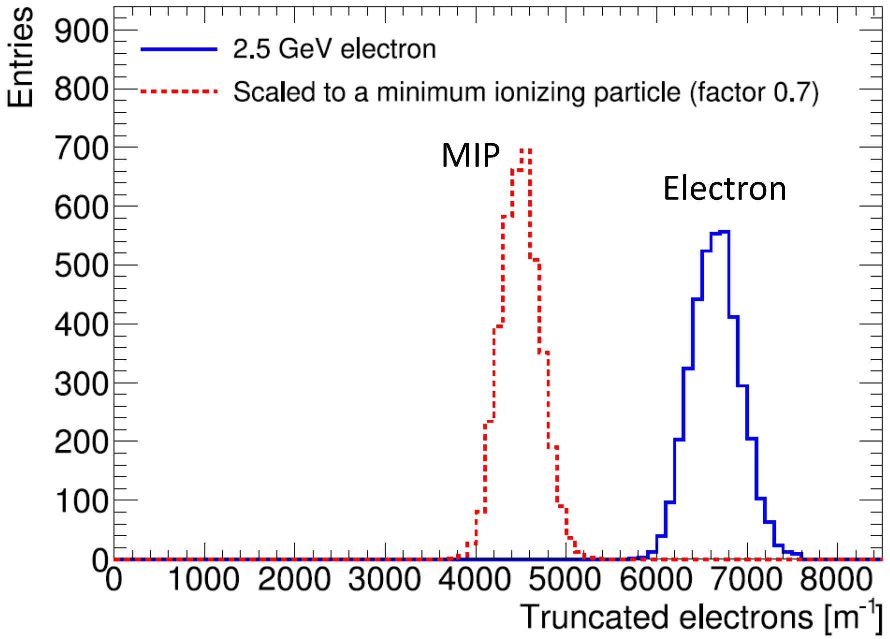
- A GridPix based on the Timepix3 chip was reliably operated in a test beam setup with 2.5 GeV electrons at ELSA (Bonn)
- T2K gas and E_{drift} = 280 V/cm, V_{grid} = -350 V
- The resolution is primarily limited by diffusion
- Systematic uncertainties are low: < 10 µm in plane
- Energy loss resolution (dE/dx) by electron counting is 4.1 % per meter





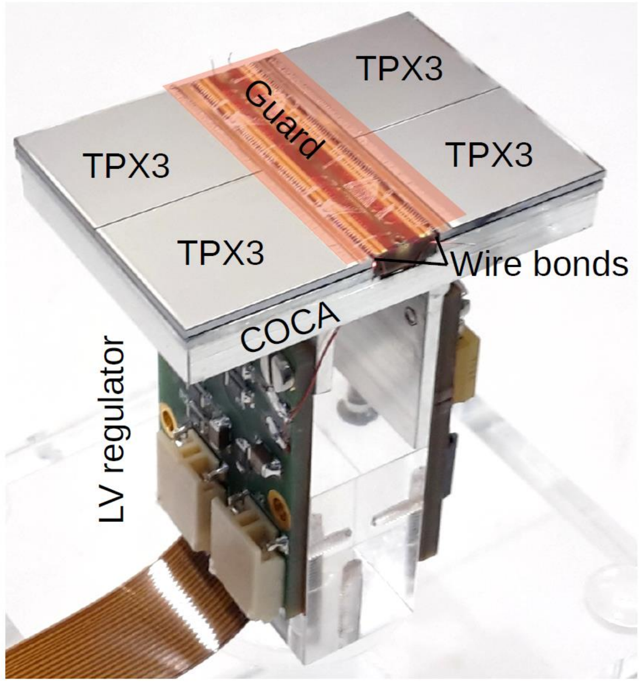
Published paper on this testbeam doi:10.1016/j.nima.2018.08.012

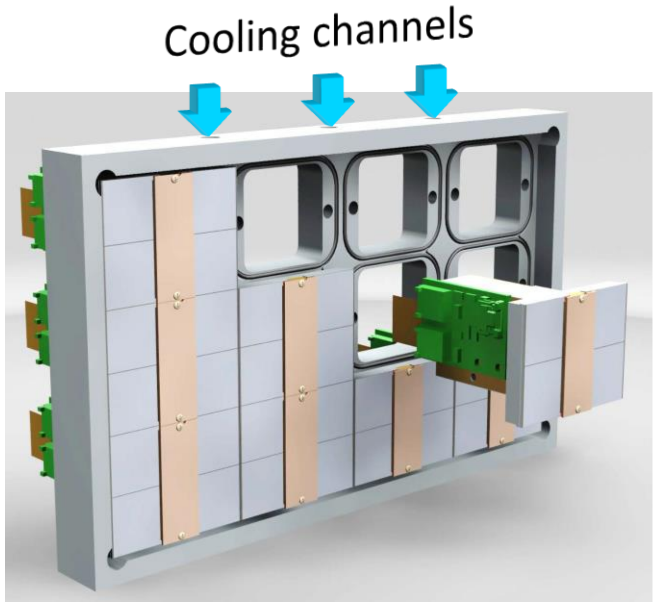




The quad module

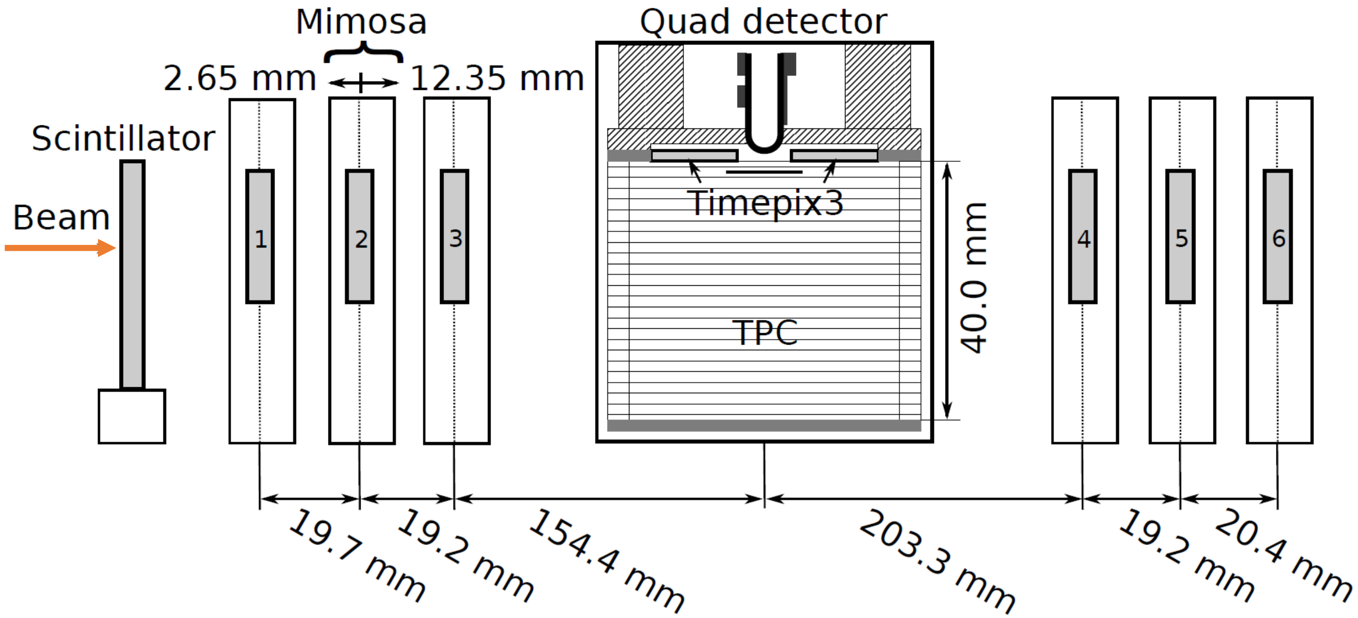
- A four chip module sized 39.6 mm × 28.38 mm
- The quad module has all services under the active area
    - Can be tiled to cover arbitrarily large areas.
- Area for connections IO was minimized
    - Maximises active area (68.9%)
- To maintain a homogenous electric field wire bonds are covered by a central guard
- High precision < 20 µm mounting of the chips and guard

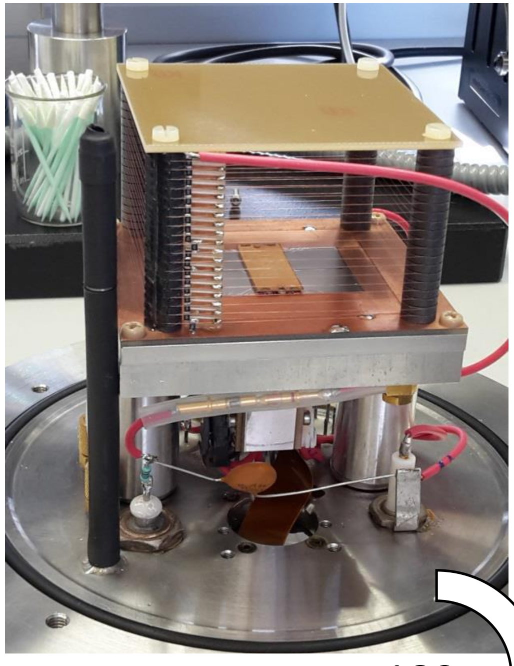




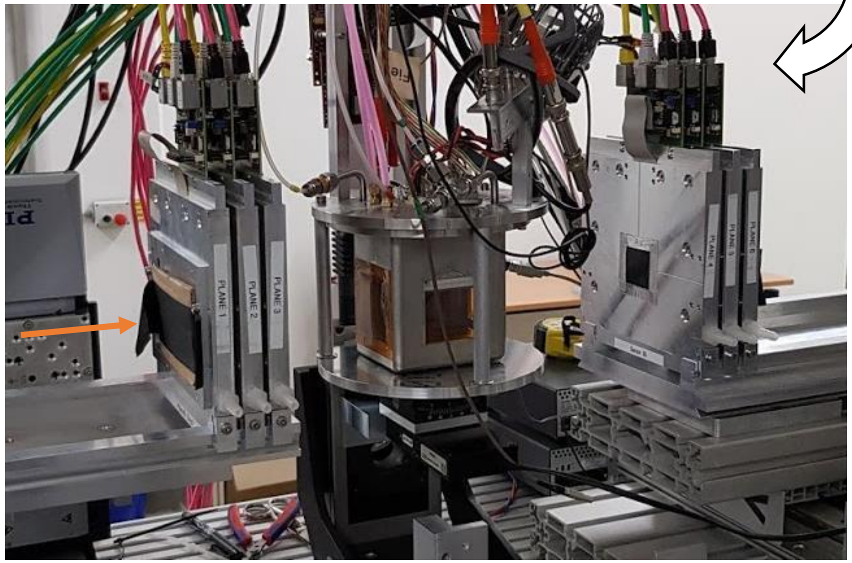
Test beam measurements (2018)

- 2.5 GeV electrons at the ELSA accelerator in Bonn, Germany
- T2K gas with E_{drift} = 280 V/cm, V_{grid} = -350 V
- Events are triggered by a scintillating plane
- 6 plane mimosa telescope with 18.4 µm × 18.4 µm sized pixels

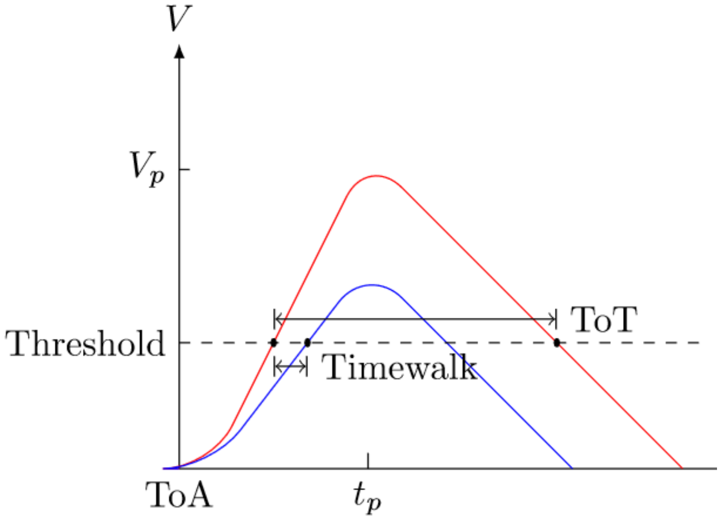


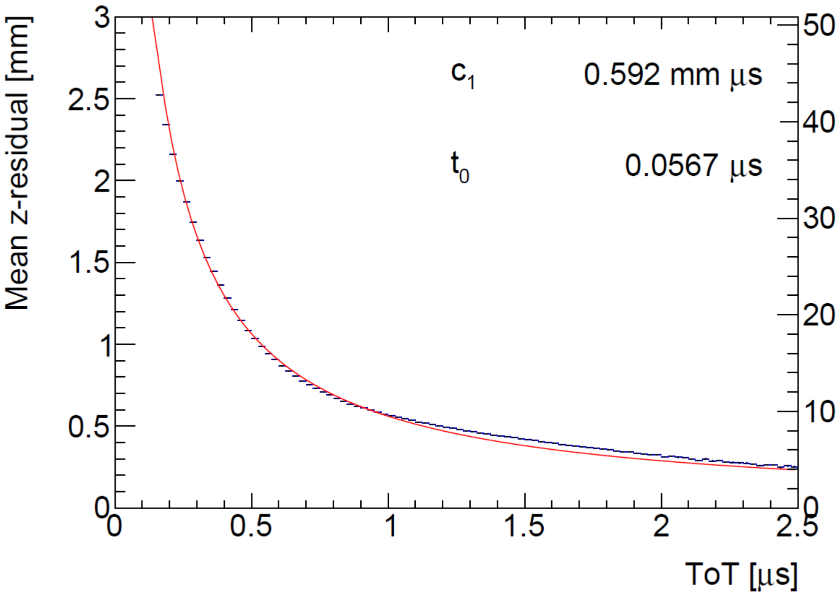


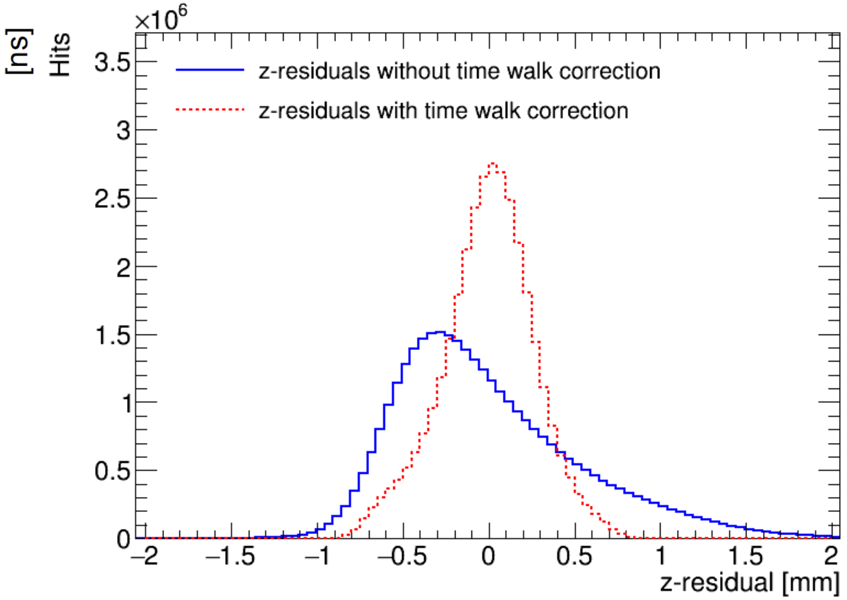
180 º



Time walk correction







Time walk error: time of arrival depends on signal amplitude

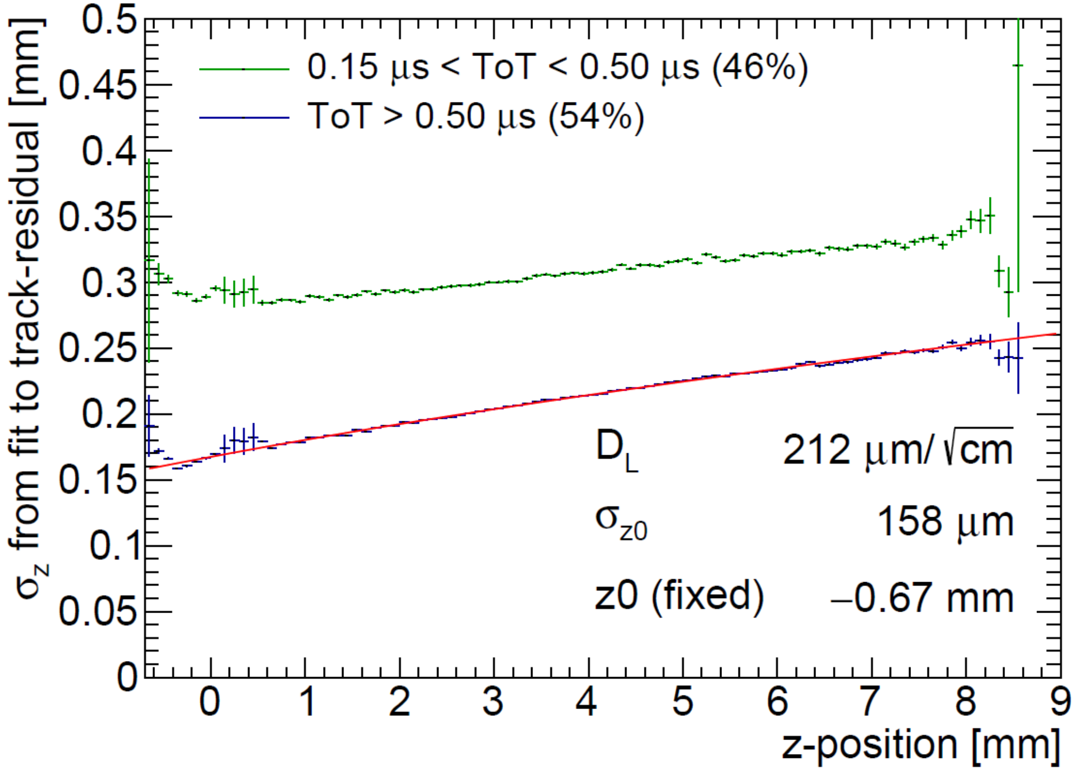
Time walk can be corrected using Time over Threshold (ToT) as a measure for signal strength

First order correction fitted and applied:

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

Distribution of residuals becomese more Gaussian after the time walk correction

Hit resolution in the drift direction



Single hit resolution in drift direction

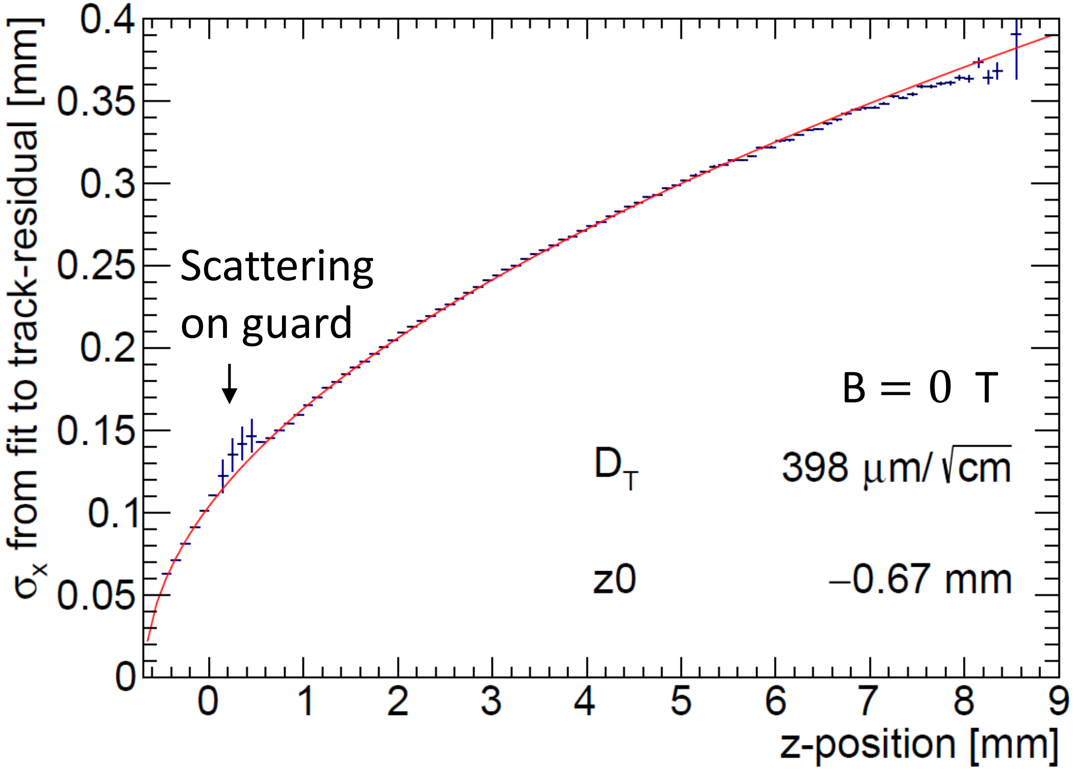
$$\sigma_z^2 = \sigma_{z0}^2 + D_L^2(z - z_0)$$

Depends on

- σ_{z0} from fit
- Diffusion D_L from fit

Because of a large time walk error in hits with a low signal strength, an additional ToT cut (> 0.60 µs) was imposed

Hit resolution in the pixel (precision) plane



Single hit resolution in pixel (precision) plane:

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

Depends on:

- σ_{y0} = pixel size 55 µm/$\sqrt{12}$
- Diffusion D_T from fit

Note that:

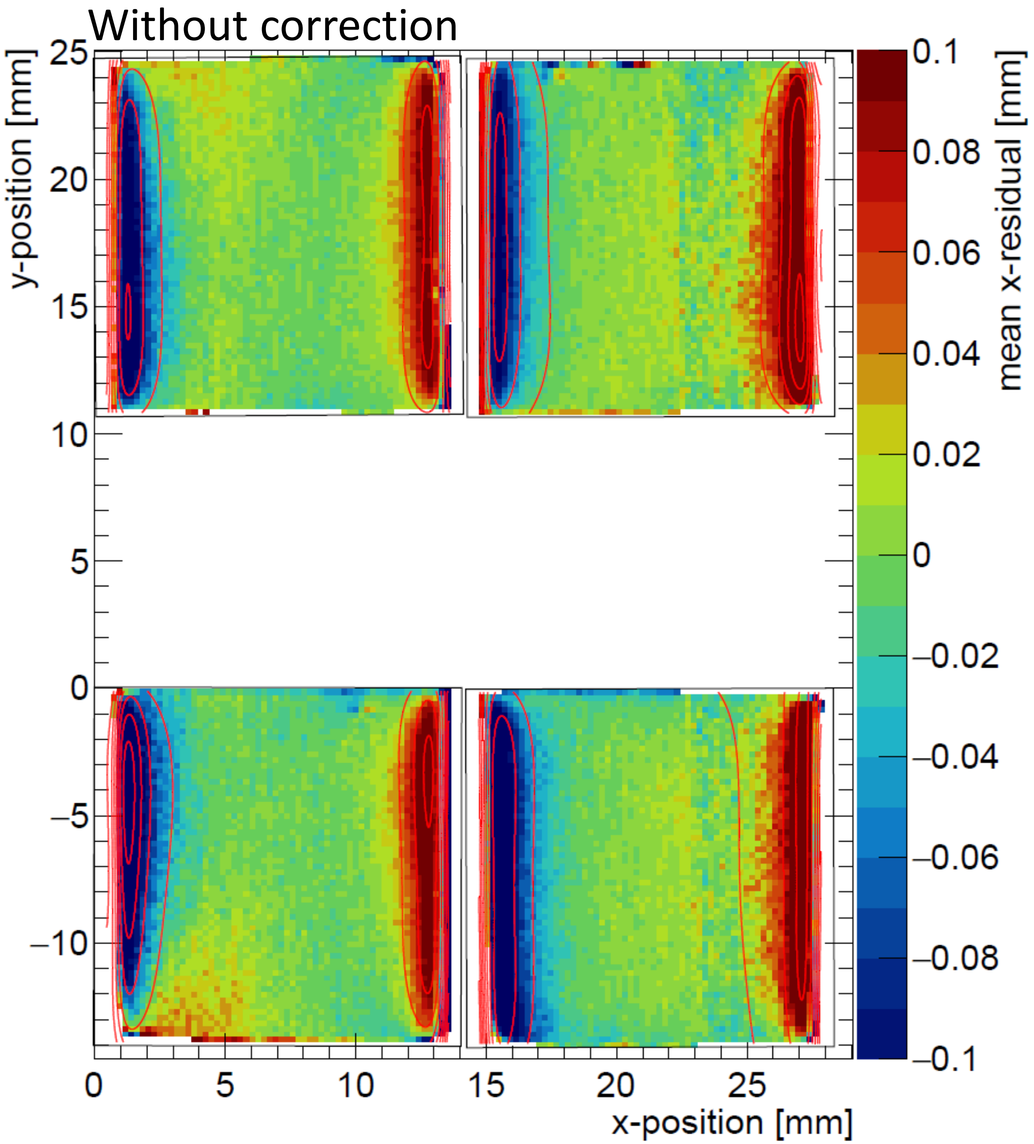
- A hit resolution of ~250 µm is ~25 µm for a 100-hit track (~ 1 cm track length)
- At $B = 4$ T , expected $D_T = 25\ \mu\text{m}/\sqrt{\text{cm}}$
- At $B = 2$ T , expected $D_T = {\sim}60\ \mu\text{m}/\sqrt{\text{cm}}$

Deformations in the pixel (precision) plane

- Investigation of systematic deviations over the pixel plane
- Each bin displays mean of residuals from 4×4 pixels
- Primarily due to electric field distortions

- Correction of deformations with 4 fitted Cauchy functions per chip:

$$\delta x = \sum_{j=0}^{4} \left(\frac{1}{\pi} \frac{\gamma_j}{\left(x - d_j\right)^2 + \gamma_j^2} \sum_{i=0}^{4} \left(c_{ij} y^i\right) \right)$$



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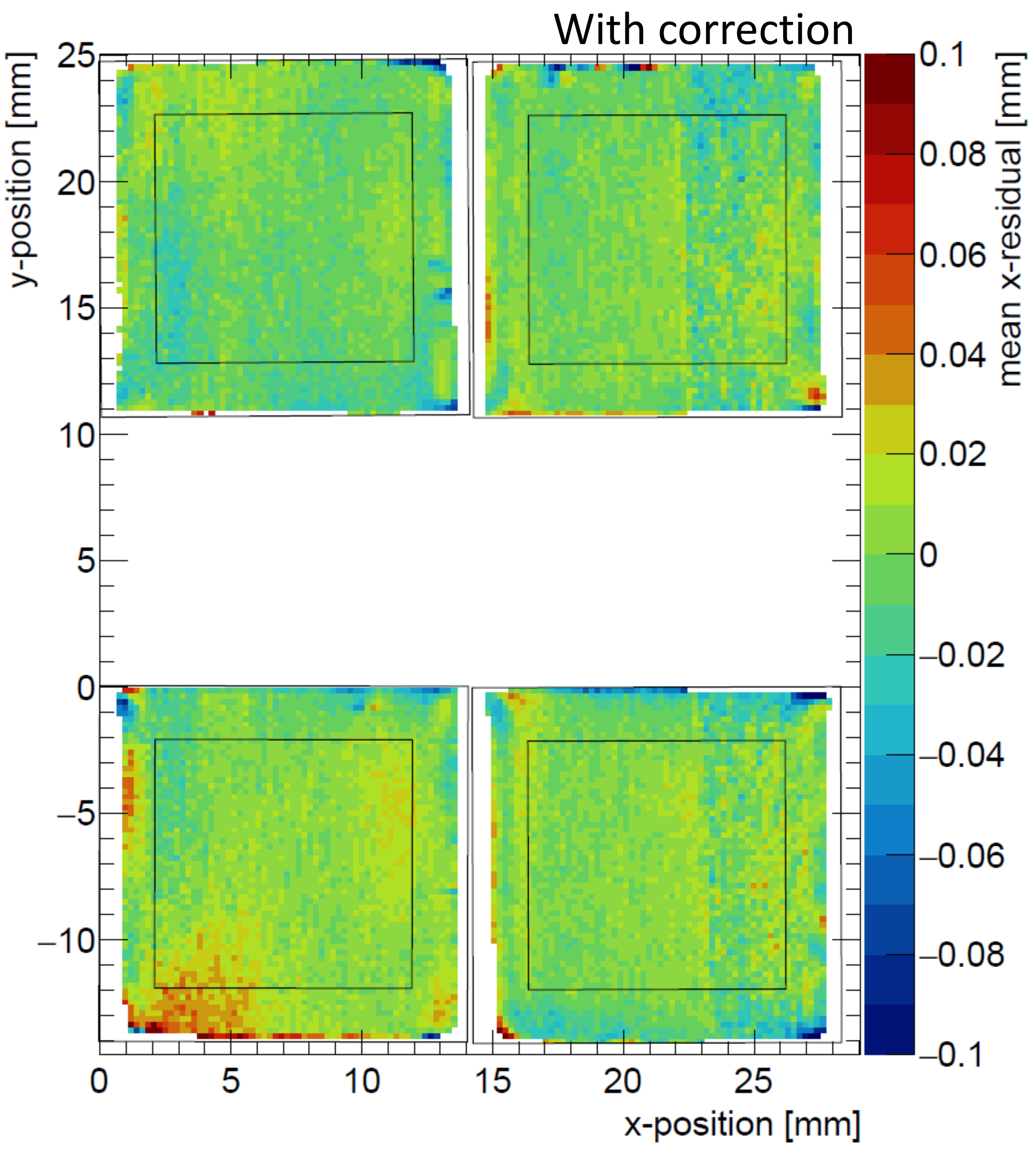
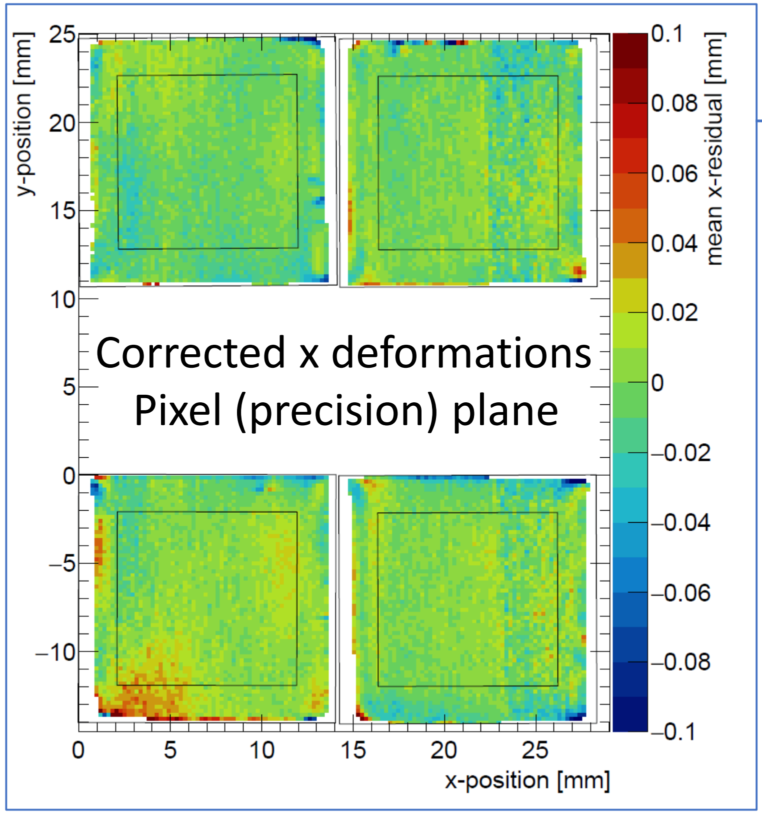
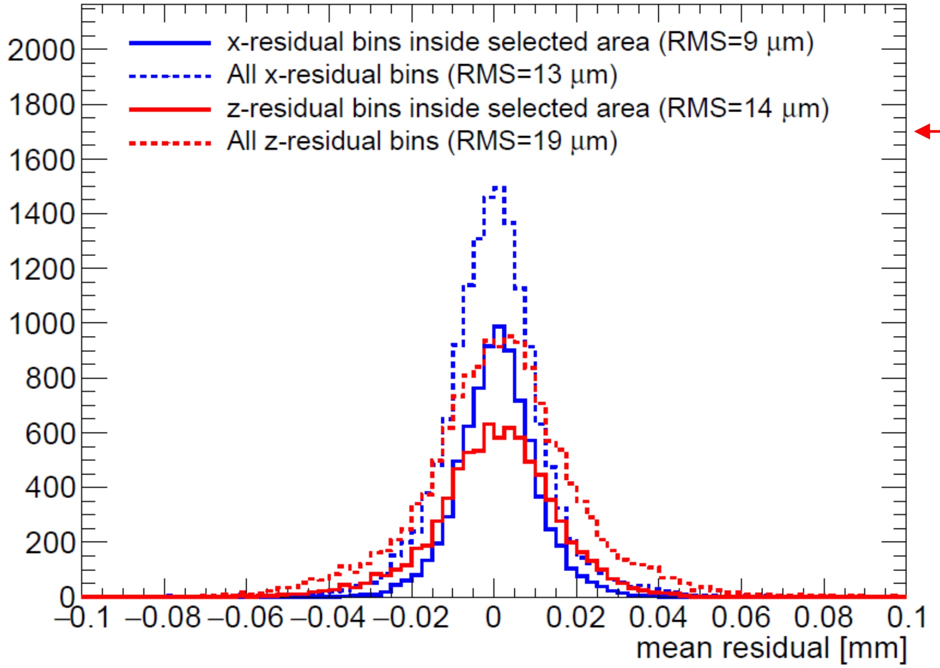
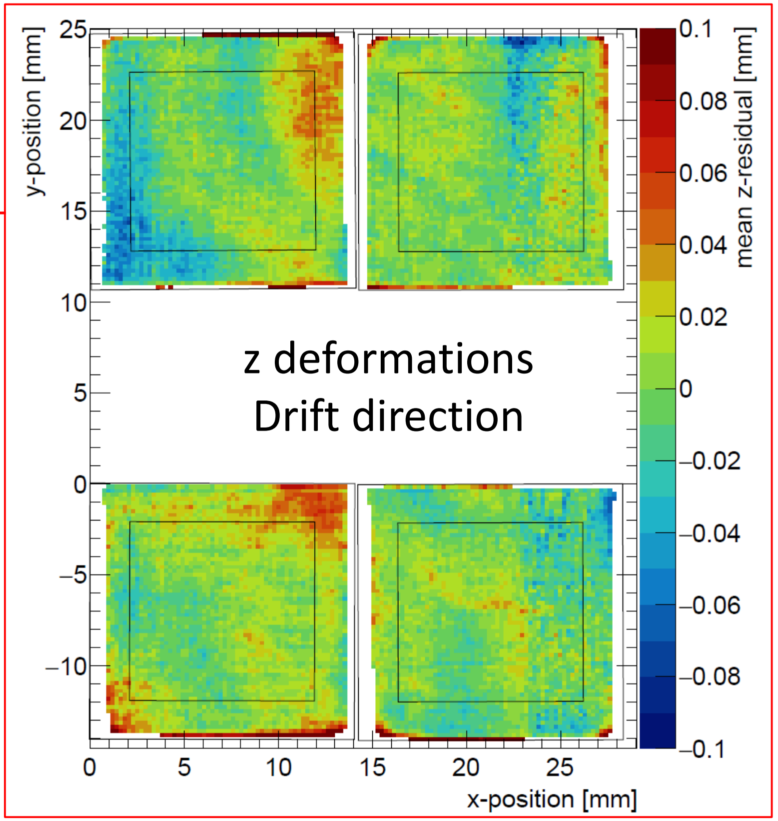


Deformations in pixel plane and drift direction

- Each bin displays mean of residuals from 4 × 4 pixels
- The RMS in the center of the chip is 9 μm (pixel plane after correction) and 14 μm (drift direction), which indicates small systematic errors

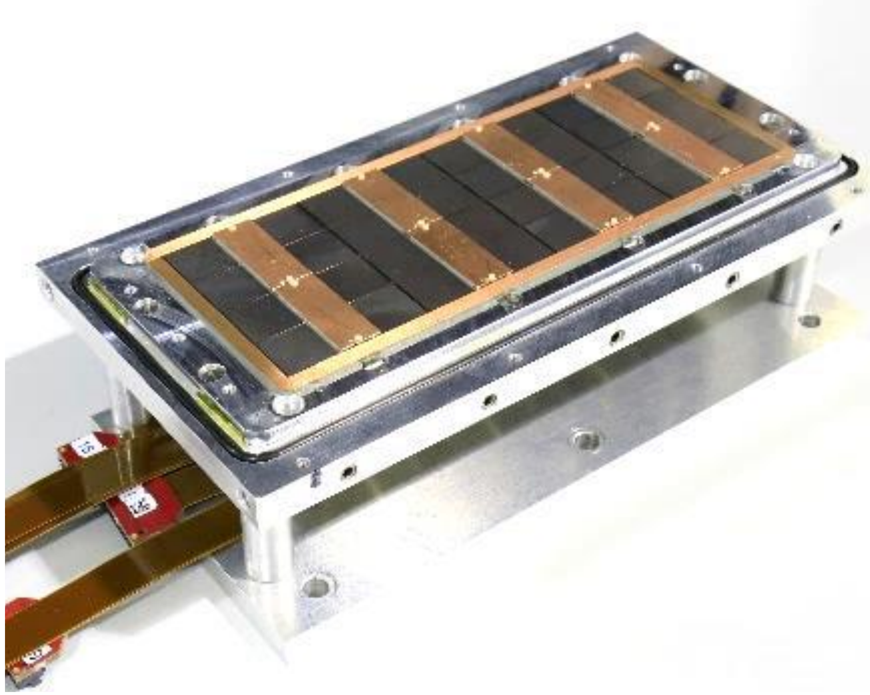


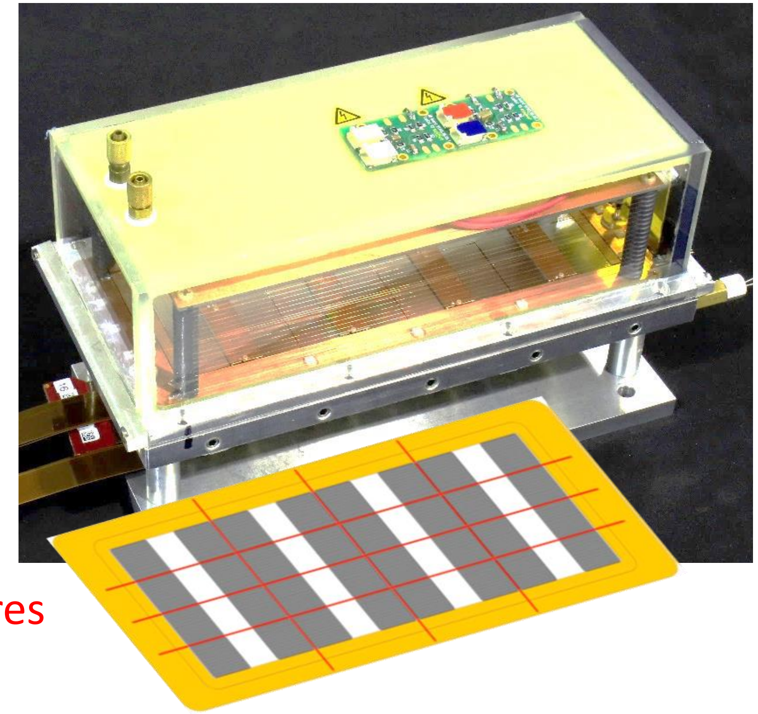




8 quad module development

- 8 quad test box with (32 chips)
- Simultaneous read out through one SPIDR board using a data concentrator
- Field wires added to improve electric field, and reduce deformations

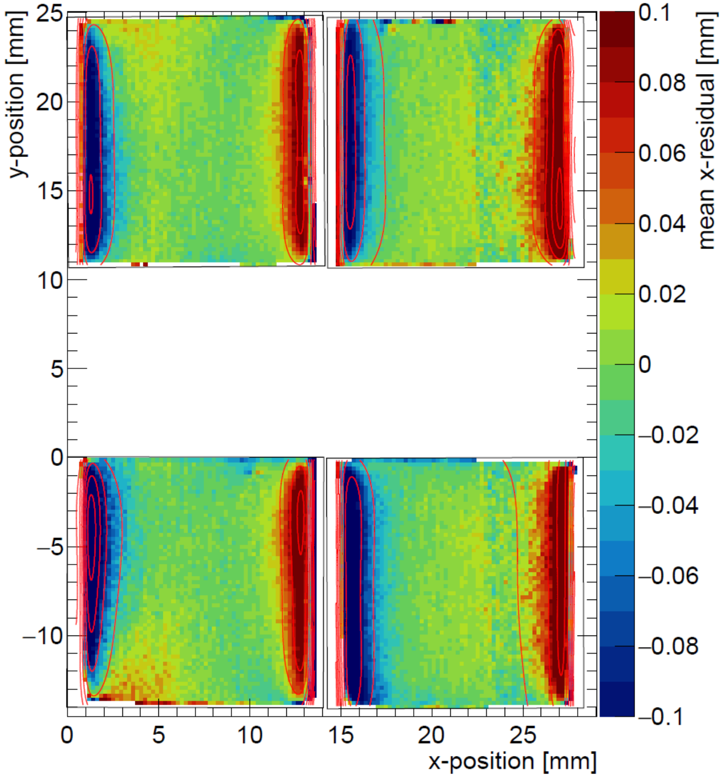




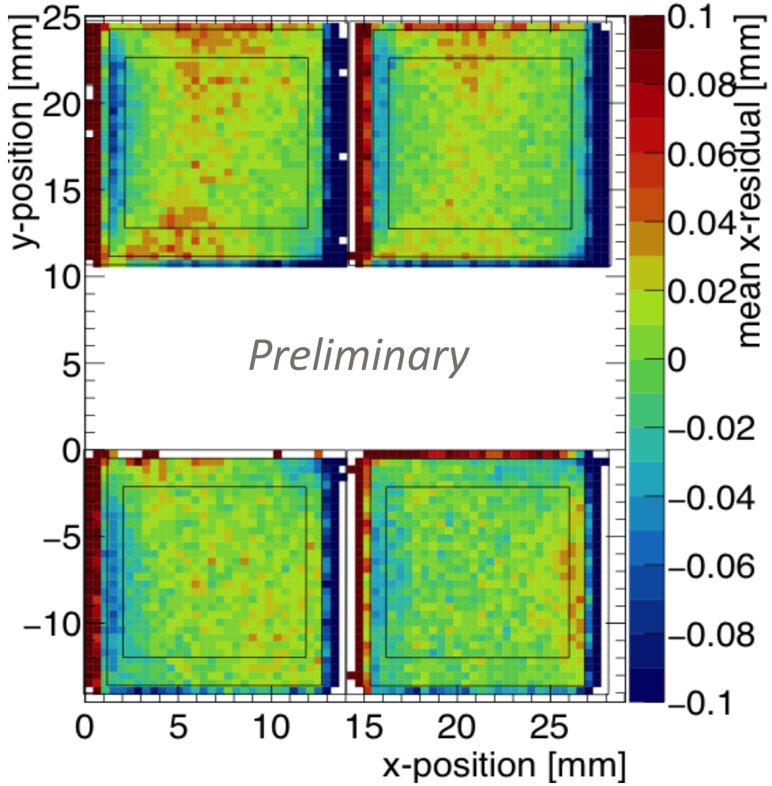
New field wires

8 quad module development

- Laser test indicate a reduction in electric field deformations with field wires
- Early 2020 test beam planned at DESY with 1 T magnetic field



Uncorrected residuals from quad test beam

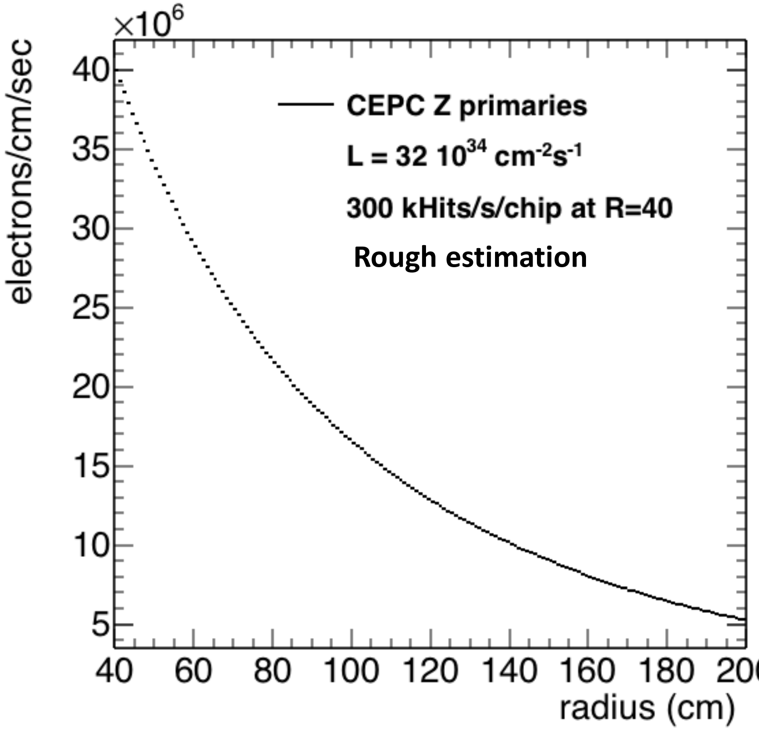


Uncorrected residuals from laser test with field wires

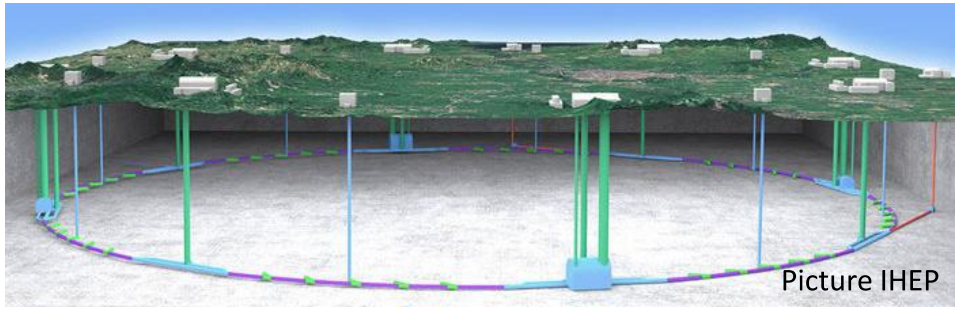
A GridPix TPC at the CEPC?

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

- The CEPC with L = 32 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 depending on hit rate
  - No power pulsing possible at the CEPC
  - Good cooling is important



A GridPix TPC at the CEPC?

Ions are not limiting performance in the 240 GeV (Higgs) runs

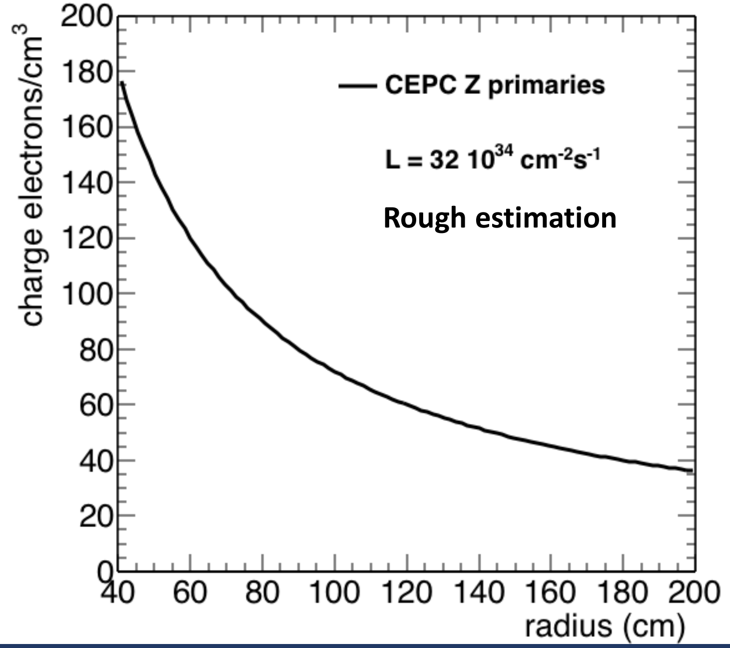
However, the number of Ions in the high luminosity 91 GeV run might be high

- Rough estimations at $L = 32 \cdot 10^{34}$ cm^{-2} s^{-1} indicate primary ionisation causes accumulated charge at an ILC250 level $\Rightarrow$ distortions < 5 μm (see backup slide)

Ion backflow (IBF) can give a lot of additional charge, so IBF must be controlled

- Measuring IBF for Gridpix is a priority, expected $\mathcal{O}(1‰)$
- Gating can greatly reduce IBF
    - At CEPC gating is possible because:

      max drift time of 30 μs < average Z interval 100 μs (10 kHz)
    - Will cause some leveling due to dead time



Conclusions

- A quad module with four Timepix3 based GridPixes has been designed and built
  - The resolution is limited by diffusion
  - Systematic uncertainties are small: 9 μm (pixel plane) and 14 μm (drift direction)
- A 8 quad detector with 32 chips is realized and is under investigation
- Simulations show an improvement in momentum resolution of a pixel TPC readout over a pad readout
- A GridPix pixel TPC is an interesting option for an experiment at the CEPC:
  - 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

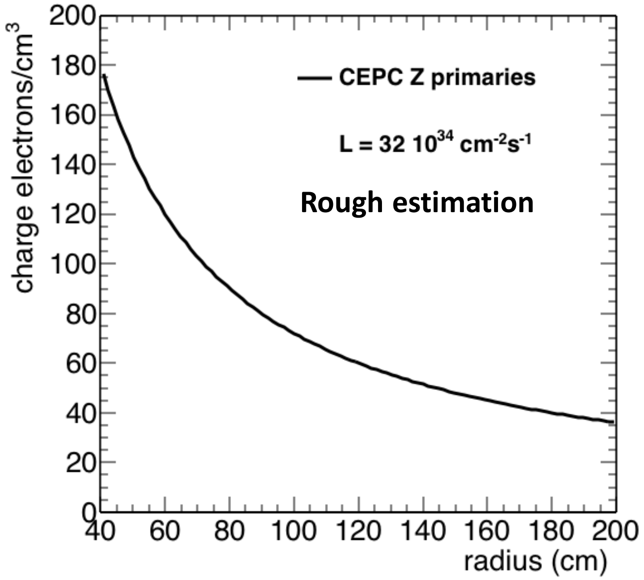
Backup

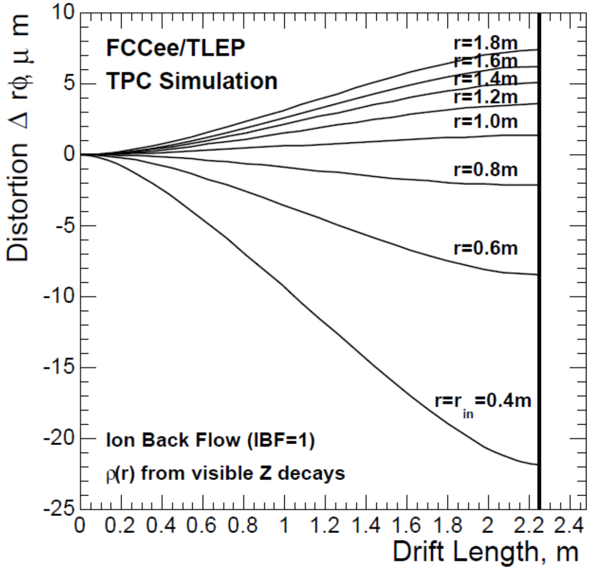
Ions in CEPC TPC

- Rough estimations at L = $35 \cdot 10^{35}$ cm^{-2} s^{-1} indicate primary ionisation at a ILC250 level
  ⇒ < 5 µm distortions (This equals 8 µm with IBF = 1?) See Arai Daisuke
- Simulation from CEPC CDR with Gain × IBF = 5 and L = $17 \cdot 10^{34}$ cm^{-2} s^{-1}
  ⇒ < 40 µm distortions (This equals 16 µm at Gain × IBF = 1 and L = $32 \cdot 10^{34}$ cm^{-2} s^{-1})
- FCCee/TLEP studies at Gain × IBF = 1 and 16.8 kHz hadronic Zs by Philippe Schwemling
  ⇒ < 22 µm distortions

Rough esitimation of primary ionisation

- 10 kHz Z event rate
- 500 ms will accumulate 5000 Z events
- 20 tracks / Z event and 10 000 e / track will make 10^8 ions in volume
- Volume is ~4 10^7 resulting in 25 e/cm^3
- Similar to ILC250 accumulated charge



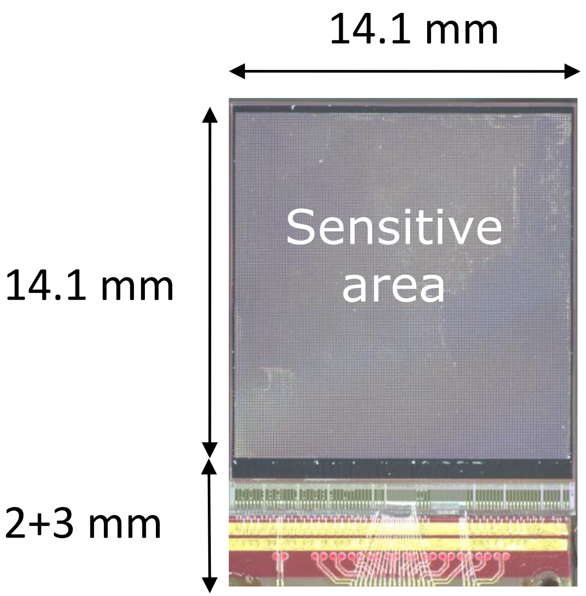


Ion backflow

- Ion backflow also needs to be controlled as this might lead to large distortions
- Old measurements from GridPix (thesis M. Chefdeville) indicate backflow can be reduced to per mil level
- New measurements are a priority

Timepix3 pixel chip

- 256 × 256 pixels with 55 µm × 55 µm pitch
- Sensitive area of 14.1 mm × 14.1 mm
- TDC with 640 MHz clock, resulting in a 1.56 ns time resolution
- Per pixel simultaneous measurement of arrival time (ToA) and signal amplitude (ToT)
- Readout using SPIDR
- Power consumption of 2W depending on hit rate
  - good cooling is important
- Wafer post-processed at IZM Berlin



Timepix3

Header	4 bit
Pixel address	16 bit
Course ToA	14 bit
ToT	10 bit
Fine ToA	4 bit

SPIDR

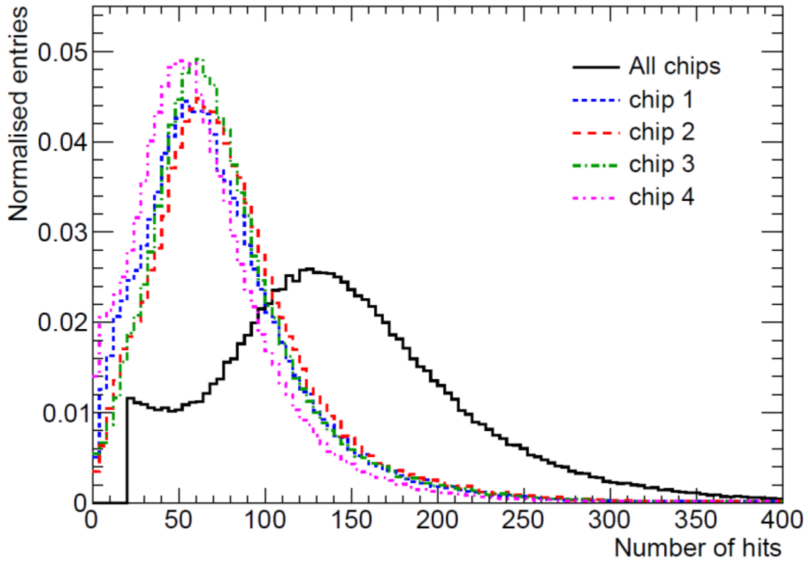
SPIDR timestamp	12 bit

64 bit data packets

Run parameters and selections

- Used T2K ($Ar:CF_4:iC_4H_{10}$ 95:3:2) gas with a water vapor contamination
  - Drift speed 54.6 µm/ns (59.0 µm/ns expected by magboltz)
- Most probable number of hits per 27.5 mm was 146 (225 expected)
  - This is due to the low effective grid voltage and possibly read out problems
- Use a stringent selection to get clean tracks

Runs duration	10 minutes
Triggers per run	2.2×10^6 triggers
V_{grid}	330 V
E_{drift}	400 V/cm
Threshold	550 e^-
Temperature	(300.5 ± 0.13) K
Pressure	(1011 ± 0.16) mbar
Oxygen concentration	814 ppm
Water vapor concentration	6000 ppm



Telescope
Number of planes hits ≥ 5
Reject outliers ($r_{x,z} < 50$ µm)
Slope difference between sets of planes < 1 mrad
GridPix hit selection
$-500\,\text{ns} < t_{\text{hit}} - t_{\text{trigger}} < 500\,\text{ns}$
Hit ToT > 0.15 µs
Reject outliers ($r_x < 1.5\,\text{mm}, r_z < 2\,\text{mm}$)
Reject outliers ($r_x < 2\sigma_x, r_z < 3\sigma_z$)
Event Selection
$N_{\text{hits}} \geq 20$
$(N_{r_x<1.5\text{mm}} \,/\, N_{r_x<5\text{mm}}) > 0.8$
$\lvert x_{\text{Timepix}} - x_{\text{telescope}} \rvert < 0.3\,\text{mm}$
$\lvert z_{\text{Timepix}} - z_{\text{telescope}} \rvert < 0.3\,\text{mm}$

Resolution of quad module

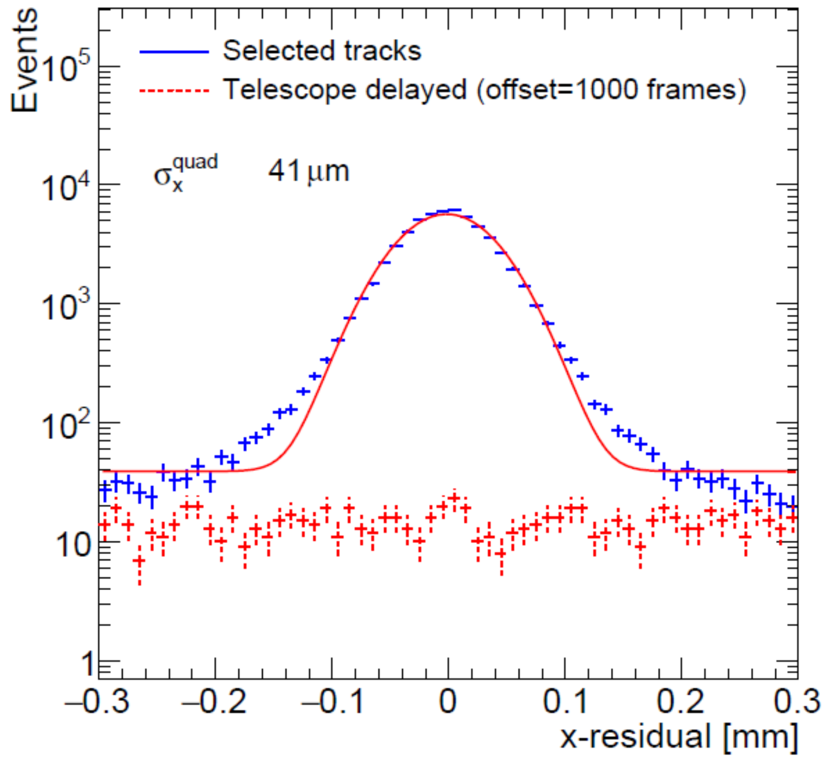
Determine overall accuracy of a track position measurement by comparing the quad track with the telescope track

- Subtract a background of unrelated tracks

Error contributions:

- Statistical error using hit resolution
- Systematic errors from RMS in pixel plane and drift direction
- Multiple scattering contribution from simple Monte Carlo simulation

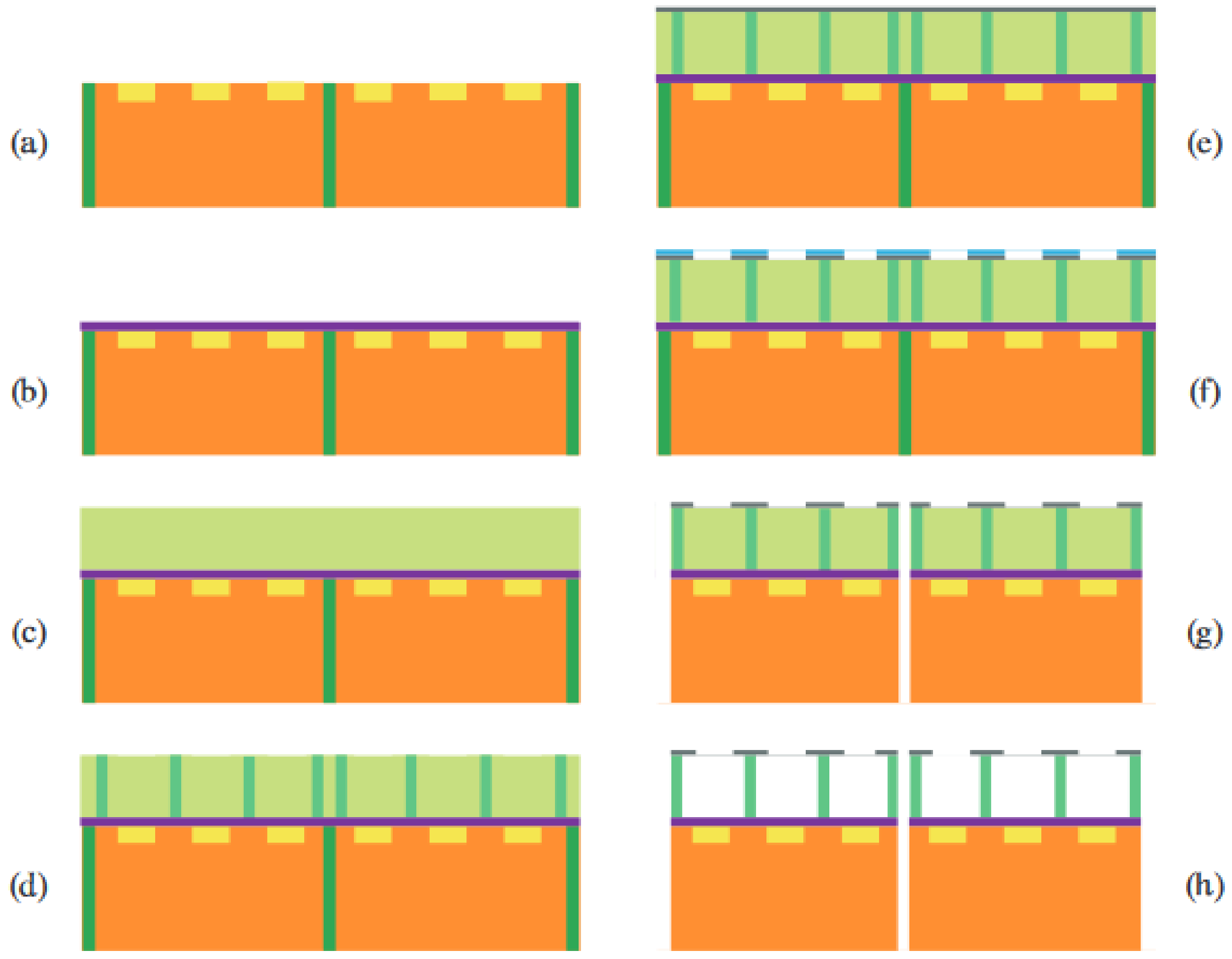
In the end, an unidentified contribution remains



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

Production of GridPixes

a) Cleaning
b) Deposition of Protection layer
c) SU-8 covering
d) Exposure with mask
e) Aluminium layer is deposited
f) Another layer of photoresist is applied, exposer with a mask creates a hole pattern, and the holes are chemically etched
g) The wafer is diced
h) The unexposed SU-8 is resolved



Thesis Stergios Tsigaridas, *Next Generation GridPix*

Motivation for a pixelised TPC

- Improved dE/dx by cluster counting
- Improved measurement of low angle tracks
- Improved double track seperation
- Much reduced hodoscope effect
- Lower occupancy in high rate environments
- Fully digital read out