Pixel TPC testbeam results

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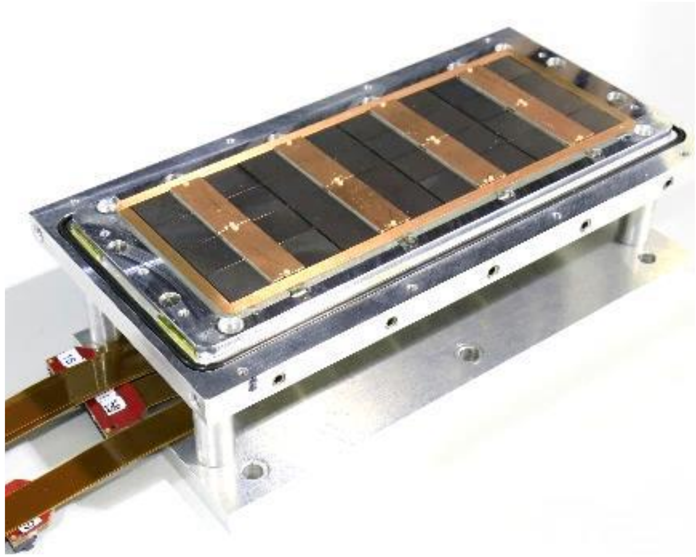
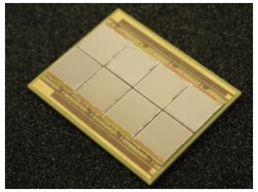
Technical support Henk Boterenbrood, Sander van Doesburg, Bas van de Heijden, Auke Korporaal

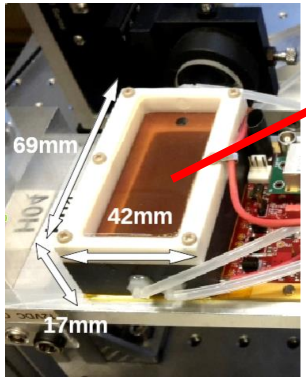


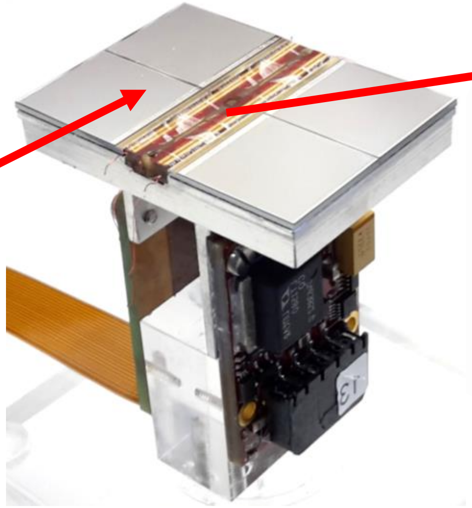
8 Quad Module

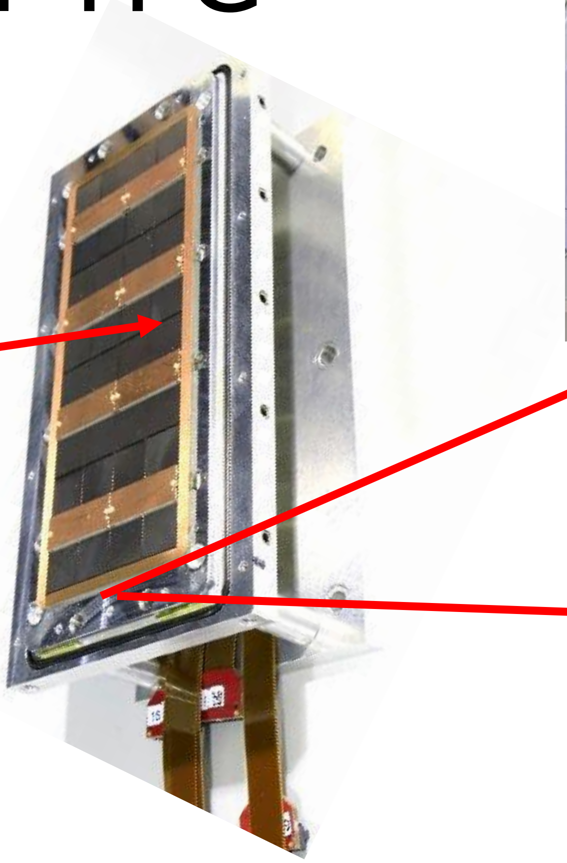
Pixel TPC

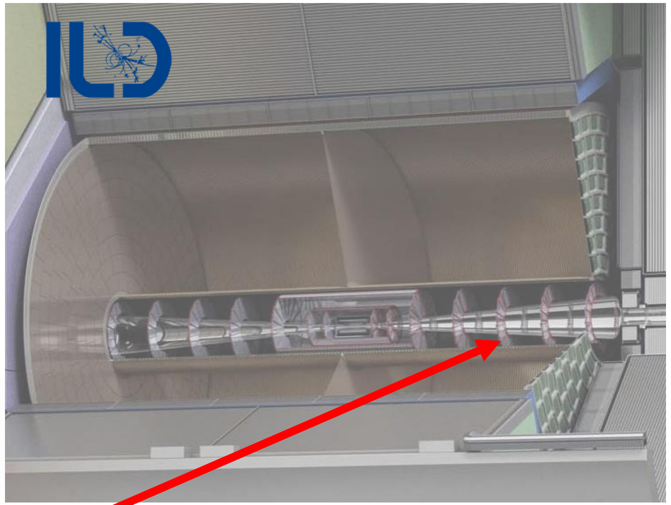


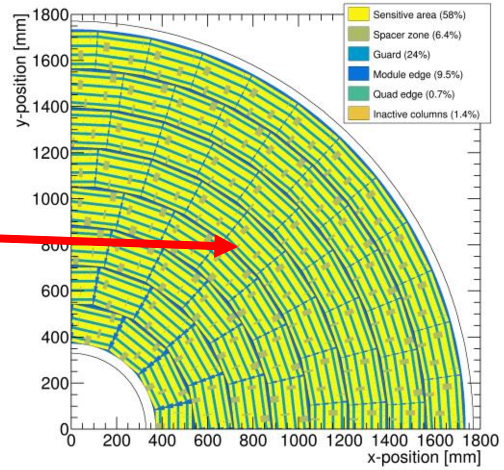
(Octopuce)





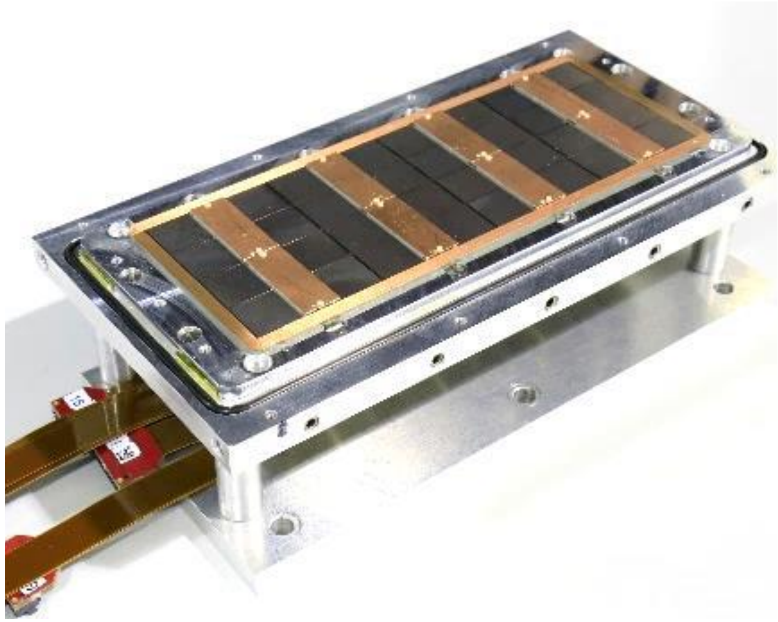


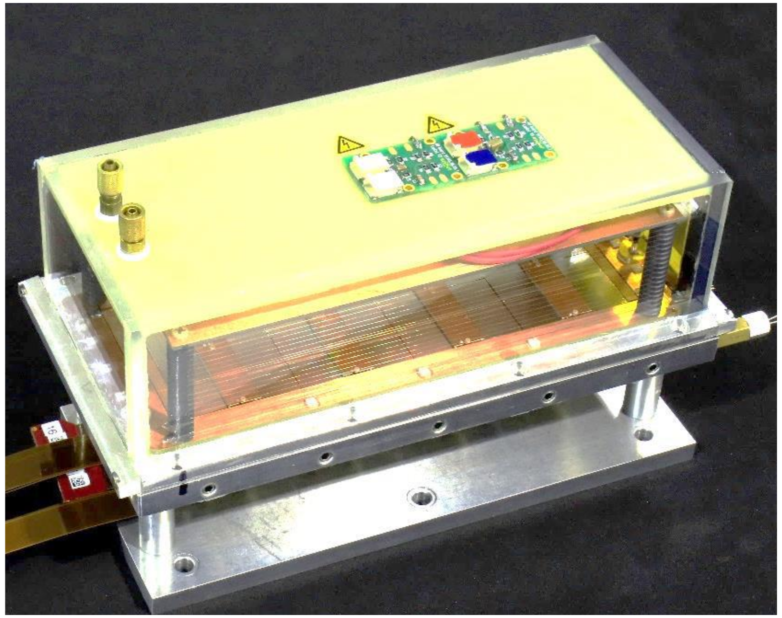


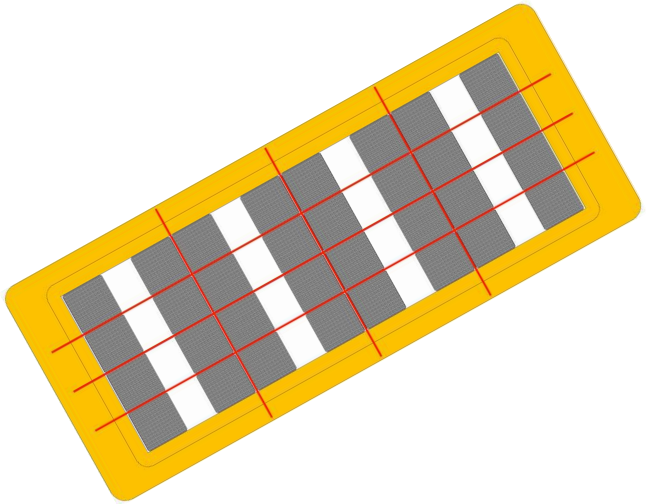


(TimePix1)	TPX3 chip	Quad	Module	TPC plane
(2007-14)	2017	2018	2019	

8-QUAD module with field cage

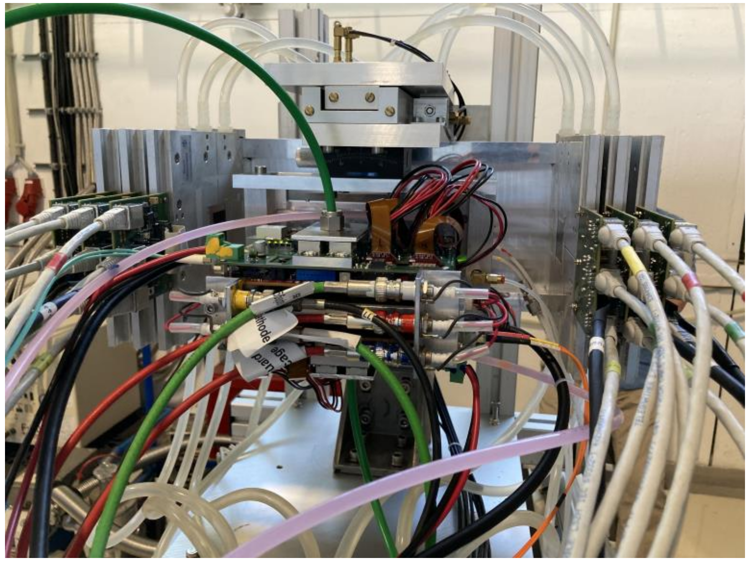


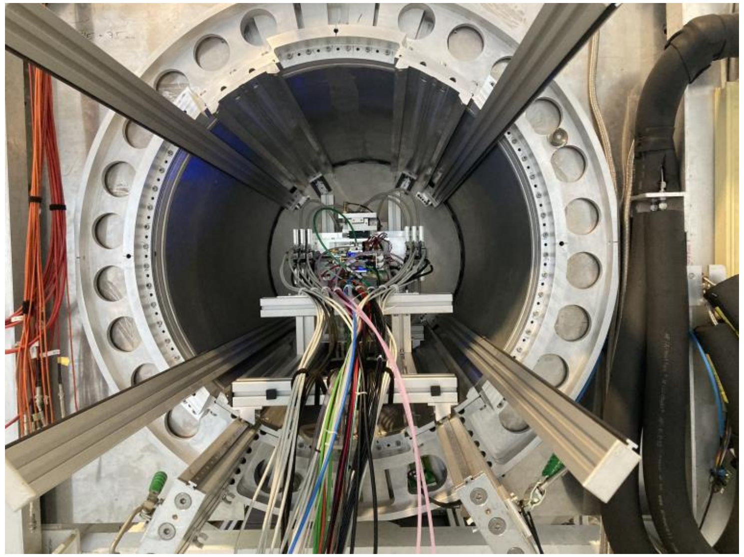




in red guard wires

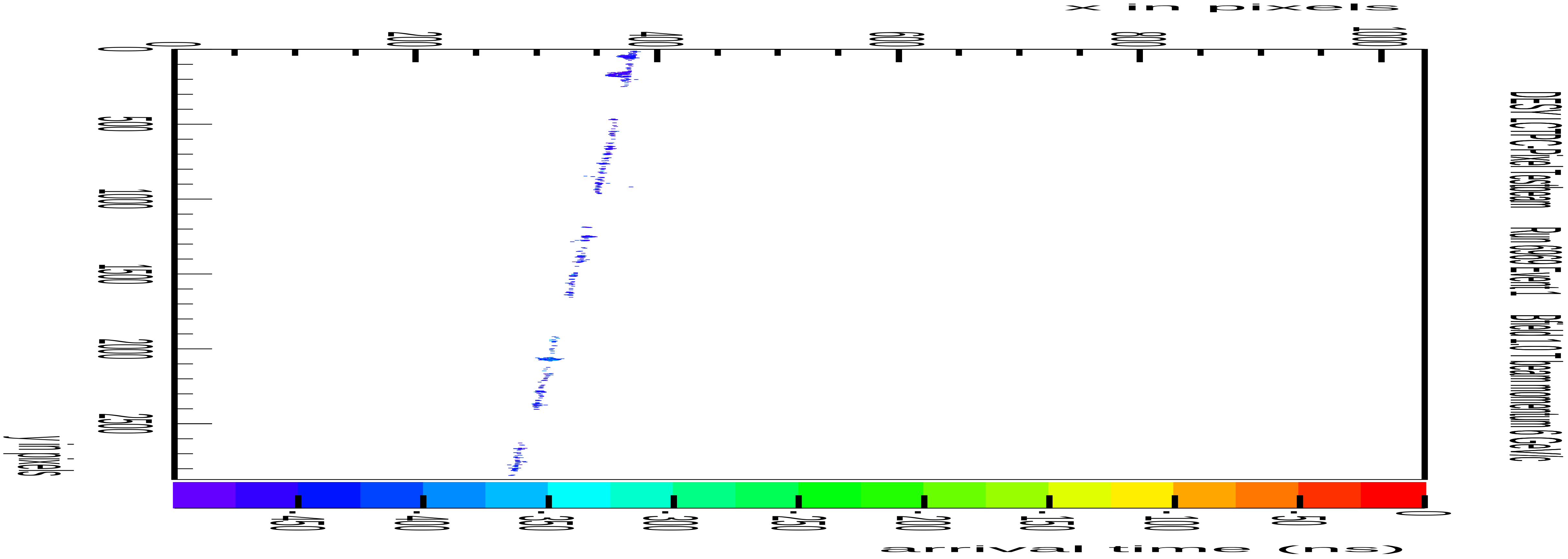
DESY testbeam June 2021



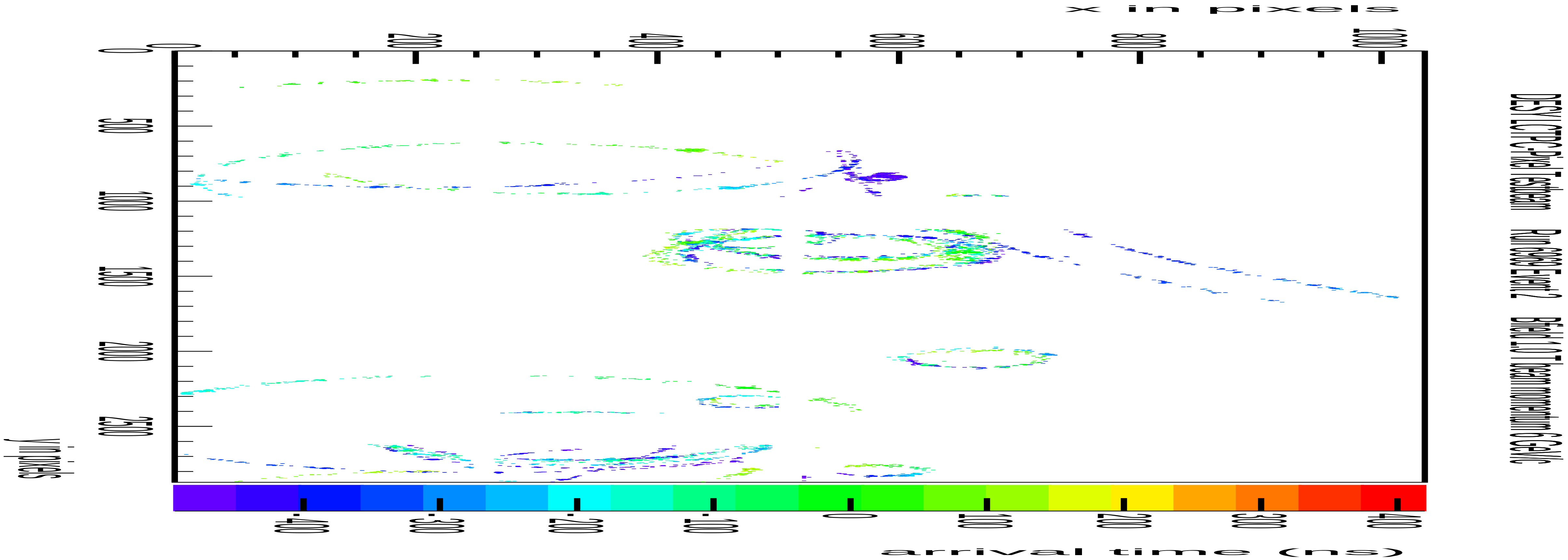


Mounting the 8 quad module between the silicon planes
sliding it into the 1 T PCMAG solenoid

DESY testbeam June 2021



DESY testbeam June 2021



DESY testbeam Analysis

- High statistics data taken with B=0, 0.5 and 1 T fields
- Electron Beam momenta of 6, 5 and smaller sets with 4,3,1 GeV
- The stager allowed to move the 8 Quad Module
  - 3 positions in x and 4 in z (drift)
- Some data was taken with a rotated Module to allow studies of e.g. ExB deformations

- The Mimosa Silicon telescope was described and aligned using the corryvreckan software with the General Broken Lines (GBL) track model. The ‘corryv’ software was updated to allow for a curved track fit

Setup with Telescope planes

5 4 3 2 1 0

beam exit

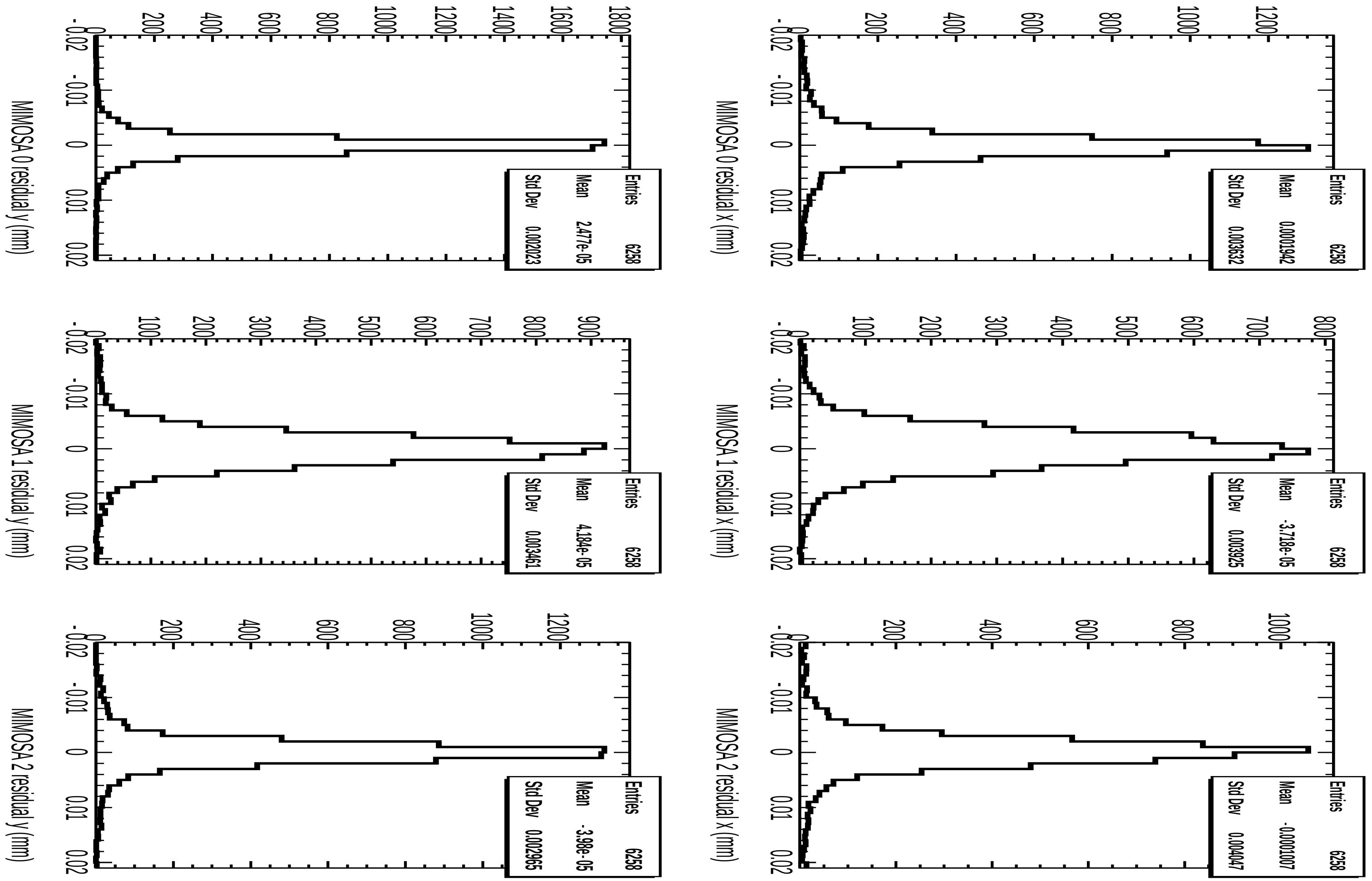
beam entry
z=0

← z axis

DESY Telescope Alignment

B=0 T run 6905

Preliminary



Six Mimosa planes

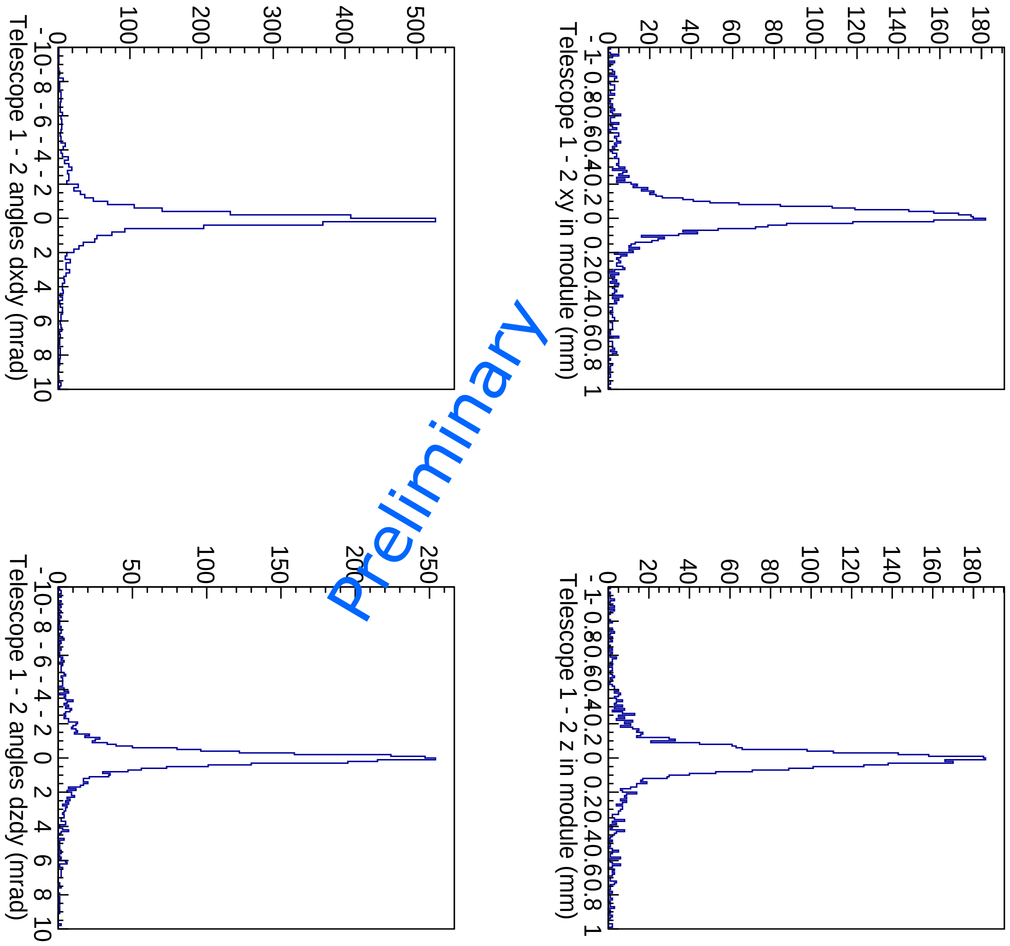
Resolution x, y
4 and 6 μm

Example plots: residuals in three Mimosa planes after alignment

DESY Telescope Alignment

B=0 T run 6916

Two extrapolations of straightline track fit in the two arms are compared in the middle of the module

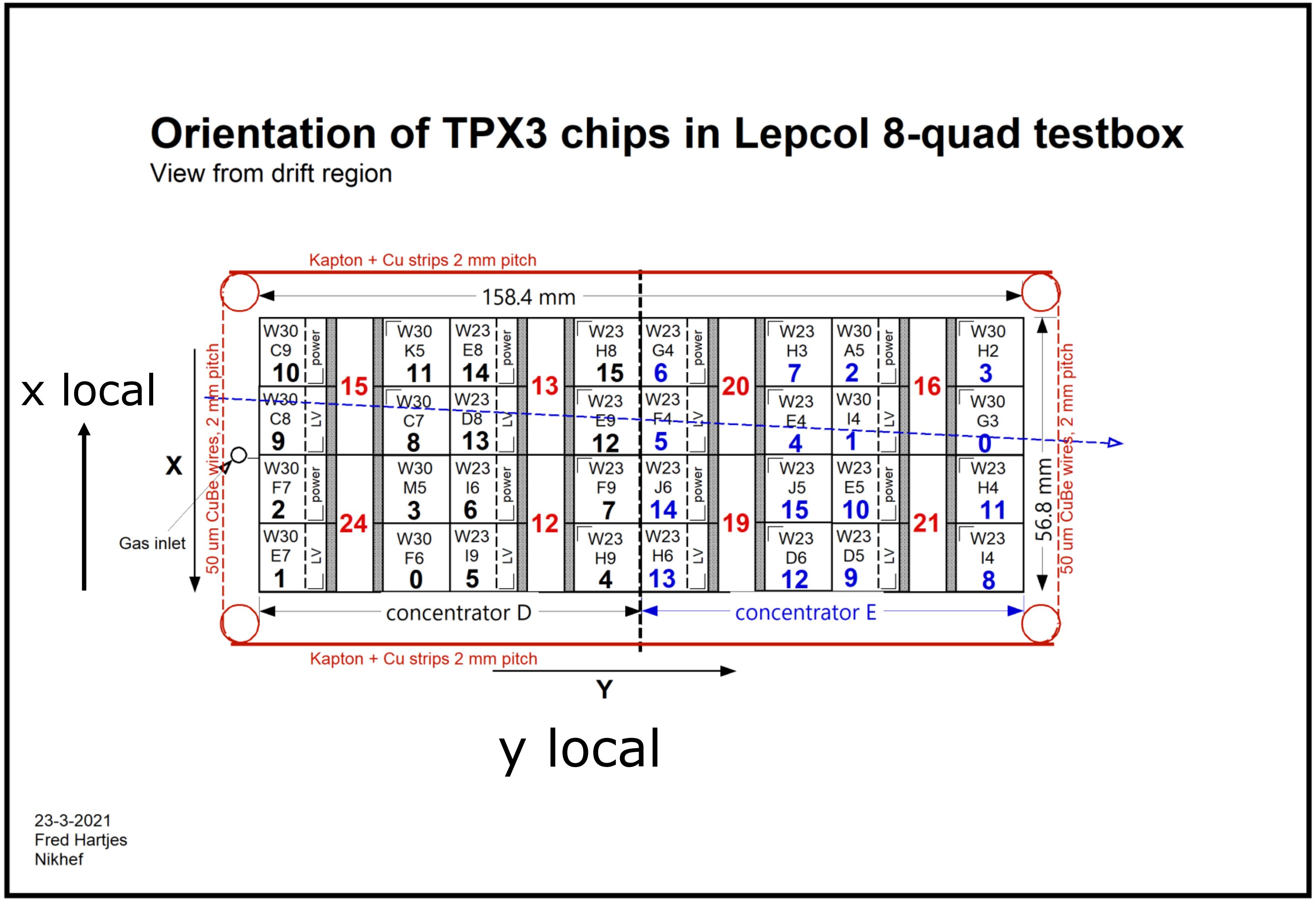


	fitted σ	mean
xy [μm]	52	-13
z [μm]	50	7
dxdy [μrad]	410	45
dxdz [μrad]	405	10

The (core) uncertainty on a 6 plane fit in the middle of the module is therefore:

σ_{xy} = 26 μm and σ_z = 25 μm

Geometry of the 8 quad module



The offline geometry follows this picture and has 0,0 in the lower bottom corner and x runs upwards

x local = off line x

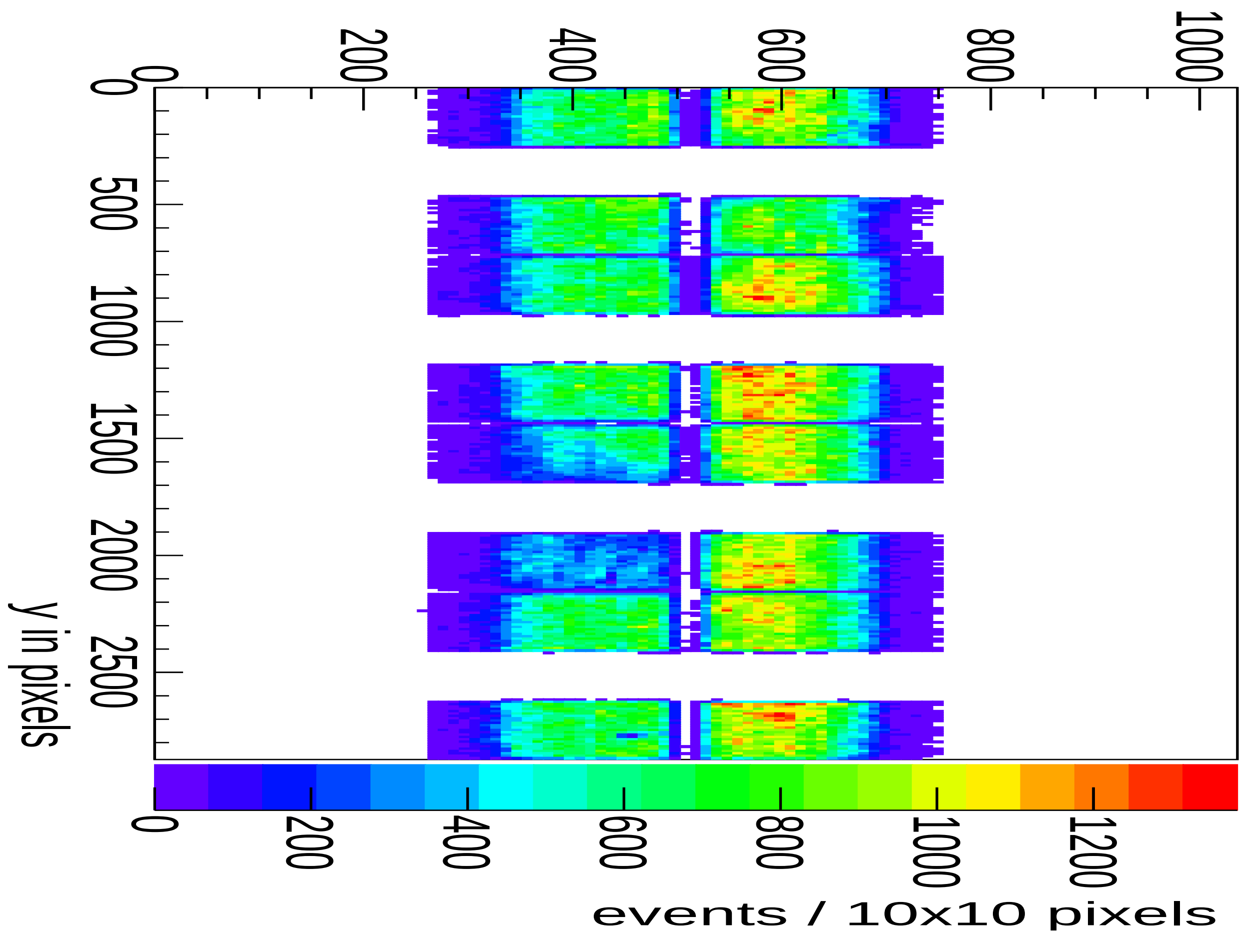
DESY testbeam Module Analysis

- Firstly results for Run 6916 B=0 T p =6 GeV will be presented
- Secondly runs 6916-18 B=0 T will be used to measure the single electron resolution and diffusion constants
- Thirdly a larger B=0 data set will be analysed to study the performance of the whole module and systematics in the module plane
  - Tracks are preselected using the Mimosa Telescope
  - Preselection of TPX3 hits and Telescope track (local x 2 mm and z 5 mm)
  - Performed a global alignment of the 8 quad module:
  - local frame xy and z (drift) positions; angles dx/dy and dz/dy
  - Time slewing correction applied using measured ToT
  - Drift velocity (E_d=280 V/cm) fixed to 62 μm/ns
  - A local fit is performed to the track hits using the expected error
  - σ_{xy} (z) and σ_z (z,ToT) (slight dependence on ToT)

DESY testbeam Module Analysis

Run 6916 B=0 T p =6 GeV

Hit map after preselection in module plane



Beam profile can be observed

Vertical white bands are the guards

Horizontal white line in the middle is between the quads

DESY testbeam Module Analysis

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Concerning the time measurement

A puzzle solved

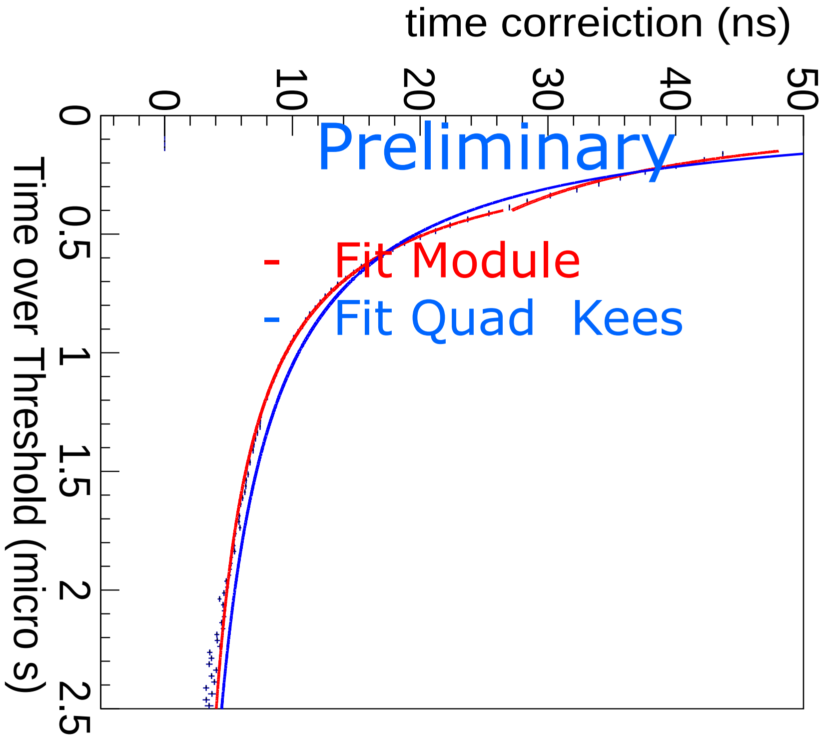
The clocks of the Telescope and the TPX3 were not synchronized. The scintillator trigger signal was input to the TLU and written in the Telescope bytestream. Unfortunately, we connected the wrong output of the TLU to the TPX3 Timestamp SPIDR (where the TPX3 time was recorded). This gave a jitter on the trigger time of 25 nsec.

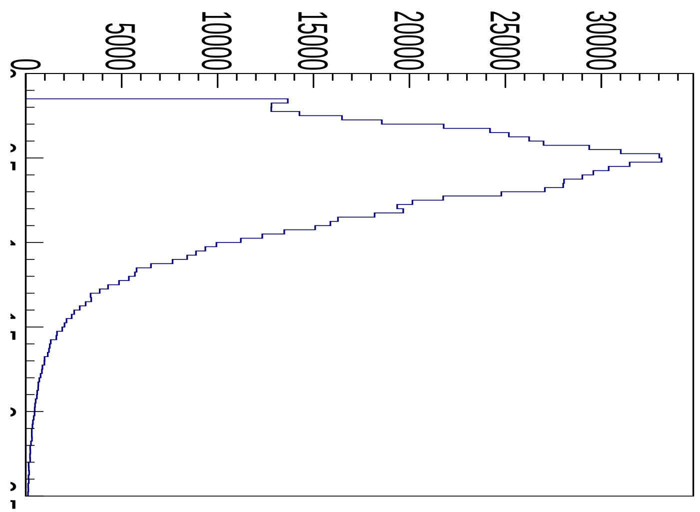
- This means that for the drift distance measurement we must use the Telescope z measurement.
- The drift residuals can be best determined by a TPX3 track fit where the z is free in the fit. In order to ensure a proper t0 estimation over the whole detector the telescope track is used for reference.

The fact that the Telescope stream and TPX3 stream were not synchronous made it more difficult to match the streams at high trigger rates. By looking at the relative timing difference this was solved.

DESY testbeam Module Analysis

Run 6916 B=0 T p=6 GeV





As for the single chip and quad analysis we use the Time over Threshold to correct for the time slewing[1].
In this way the drift residuals uncertainty is reduced.

Generic time slewing correction applied using ToT:

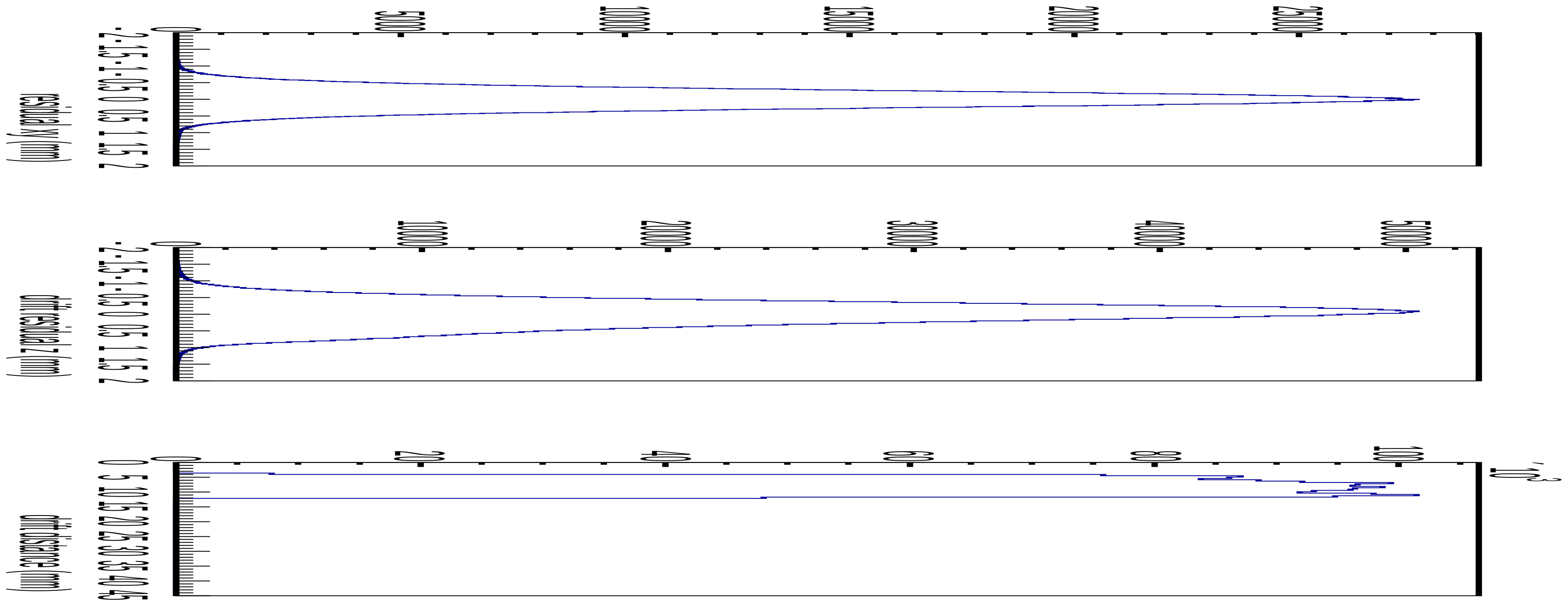
$$\delta t\ (\text{ns}) = 18.6 / (0.1577 + \text{ToT}(\mu s))$$

[1] Also systematic patterns in the t0 per row and column (odd/even and modulo 16 pattern) were corrected for.

DESY testbeam Module Analysis

Run 6916 B=0 T p=6 GeV

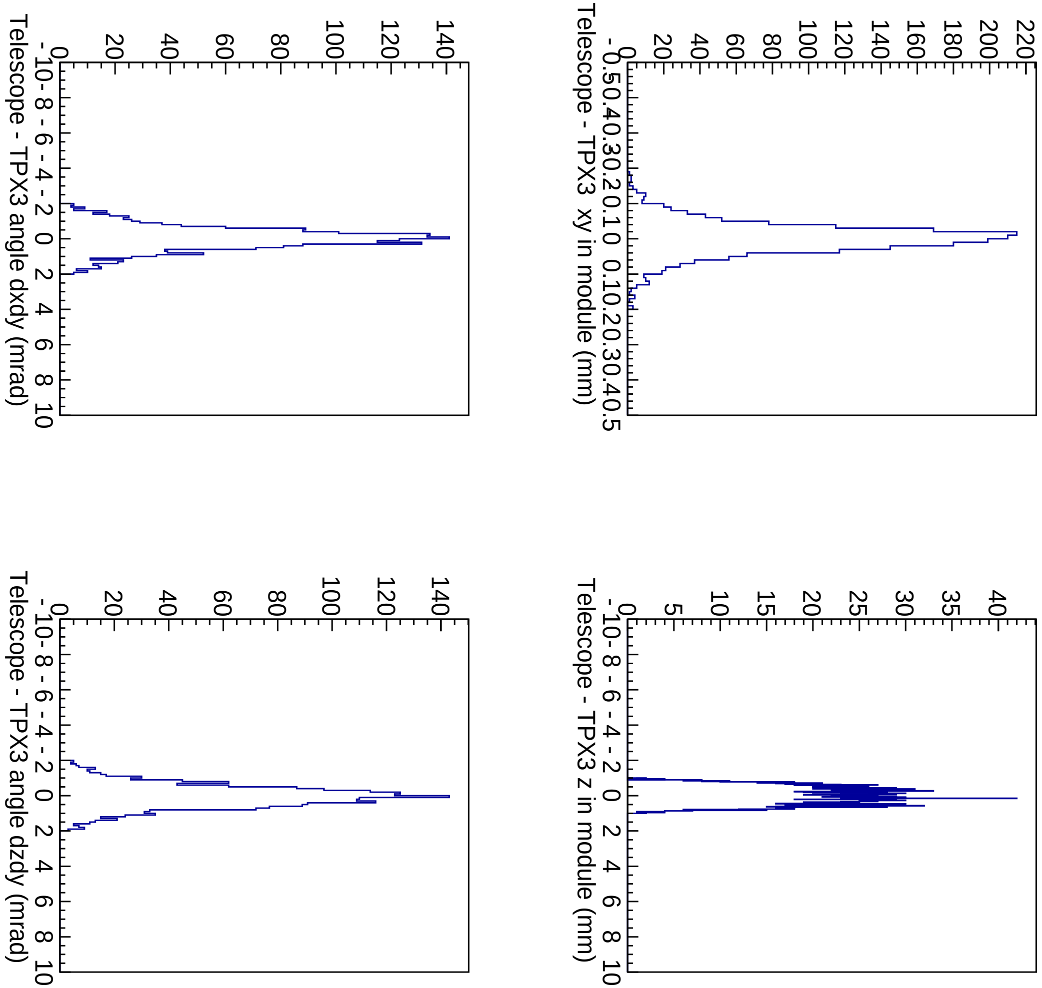
rms xy 270 μm and rms z (drift) =355 μm   1.7M hits



Limited z acceptance due to Telescope

DESY testbeam Module Analysis

Run 6916 B=0 T p=6 GeV



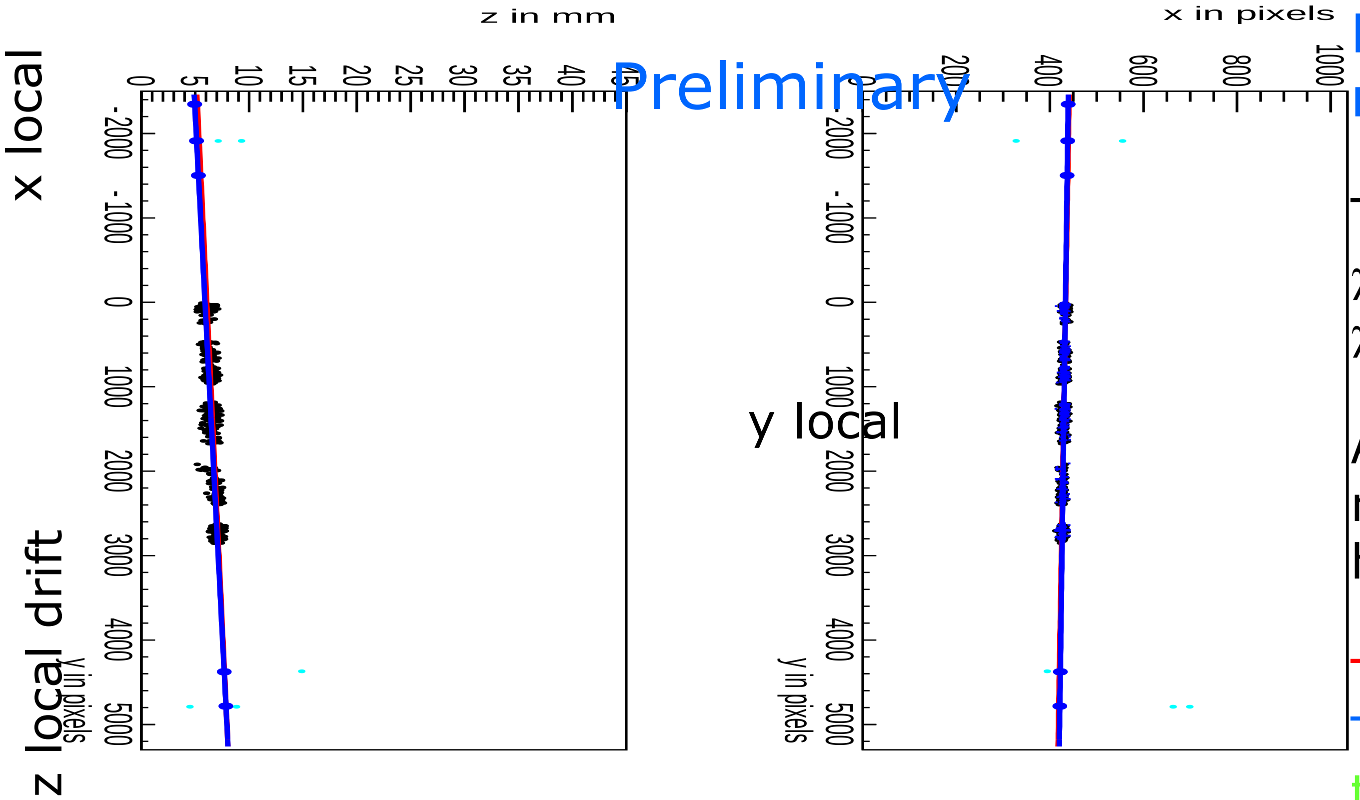
Track matching between Telescope and TPX3

position|xy| < 0.2 mm
Postion |z| < 2 mm (25 nsec)
angle |dx/dy|< 2 mrad
angle |dz/dy|< 2 mrad

Fit a gaussian to core gives

σ_{xy} = 37 μm
σ_{dxdy} = 0.52 mrad
σ_{dzdy} = 0.55 mrad

DESY testbeam Module Analysis



Event display with module and telescope

TPX3 track 1130 hits
$\chi^2_{xy} = 677.5/1128$
$\chi^2_{z} = 775.9/1069$

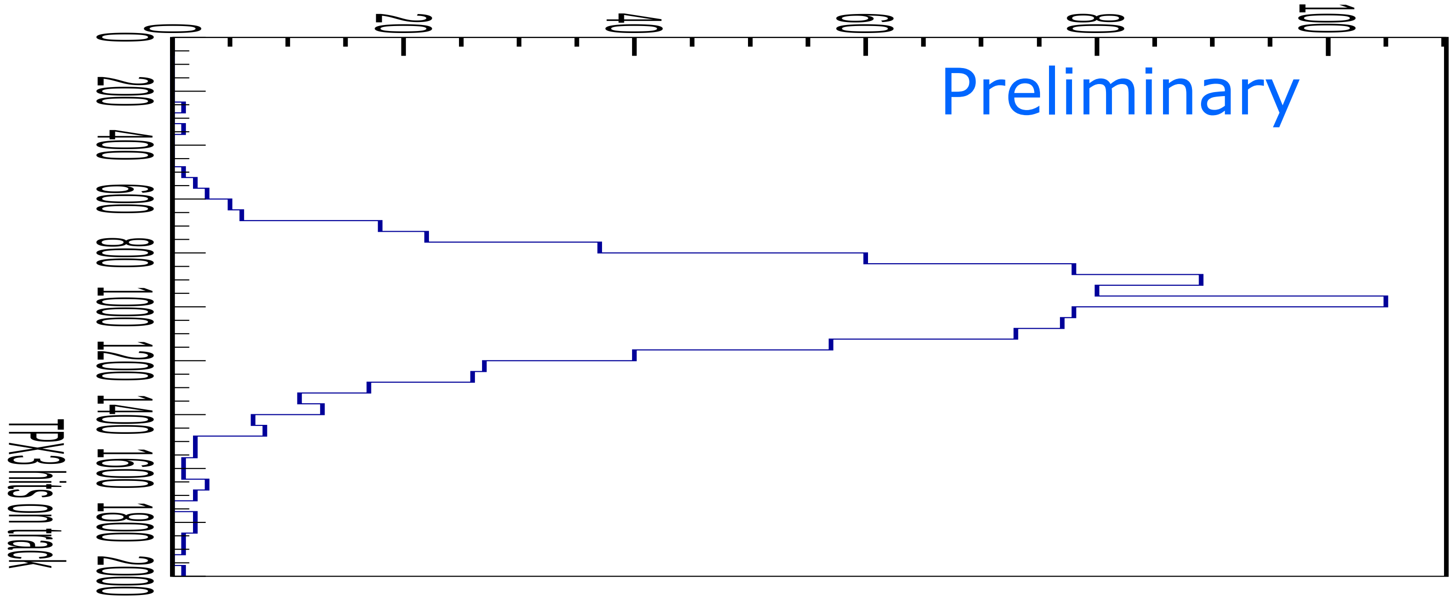
Asymmetric tail outlier removal applied 1071 hits in z kept.

TPX3 track hits
Telescope track hits (off track green)

DESY testbeam Module Analysis

Run 6916 B=0 T p=6 GeV

For chips in upper row (with x > 500 see hitmap)
TPX3 hits per track



964 selected tracks

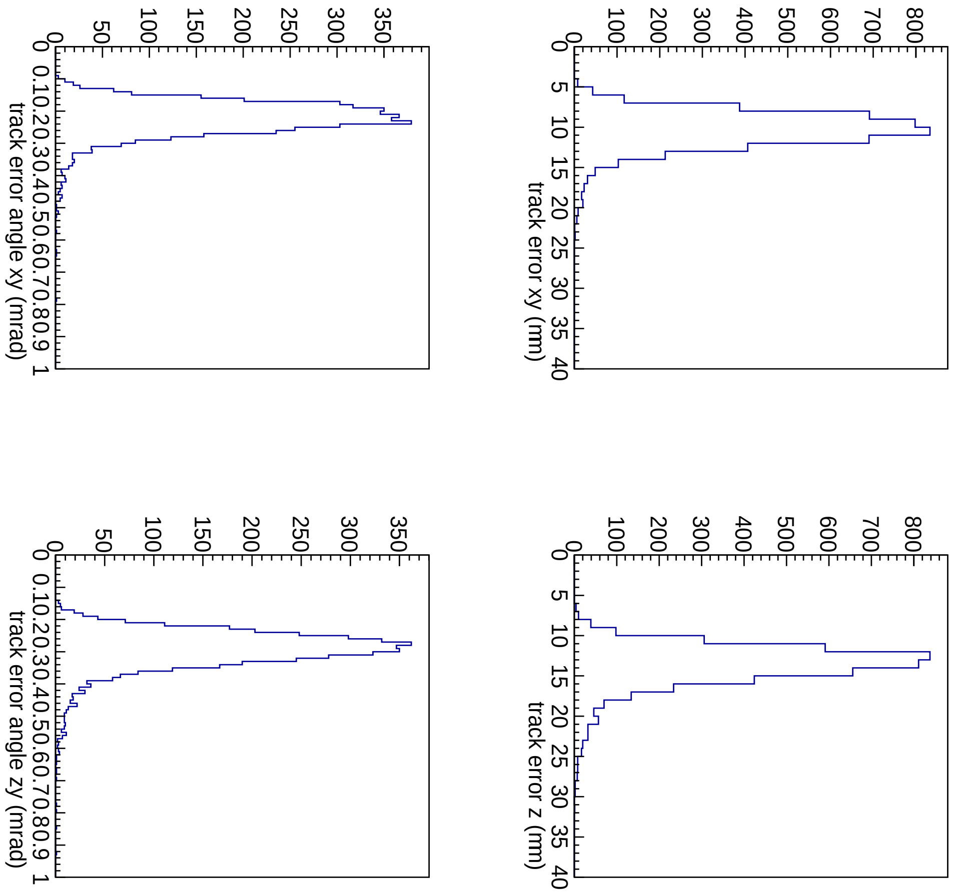
Impressive 1009 hits / track

module or tracklength 157.96 mm

DESY testbeam Module Analysis

Run 6916 B=0 T p=6 GeV

Preliminary



module tracklength = 157.96 mm

Expected TPX3 tracking precision using a straightline fit see plots:

position 9 (xy) 13 (z) μm
angle 0.19 (dx/dy) 0.25 (dz/dy) mrad

In a B field because of the reduced diffusion the tracking precision will improve substantially

This means that the position uncertainty in xy and z comparing the telescope and TPX3 is dominated by the telescope extrapolation uncertainties (lever arm and multiple scattering)

DESY testbeam Module Analysis

The TPX3 alignment procedure

Procedure for the xy and z coordinate:

- Determine constants per run [1]
- Per chip fit two 1D fits 256 bins
- One linear fit $\delta xy(z)/\delta row$ and a second linear fit for mean <xy(z)> $\delta xy(z)/\delta$expected column
- This gives three parameters per fit
  - using the column is not a good idea because it is correlated to x
  - The fit is performed in a fiducial area (staying away 10 rows and 10 expected columns) requiring > 1000 events per bin

- For xy the residuals with respect to the Telescope track are used
- For z the first alignment iteration used the Telescope track residuals. The next iteration(s) use the TPX3 track residuals that have a much better resolution.

The mean and $\delta xy(z)/\delta row$ correspond to a shift and a rotation of the chip.
The $\delta xy(z)/\delta$expected column corresponds to e.g. a tilt of the chip dz/dx.

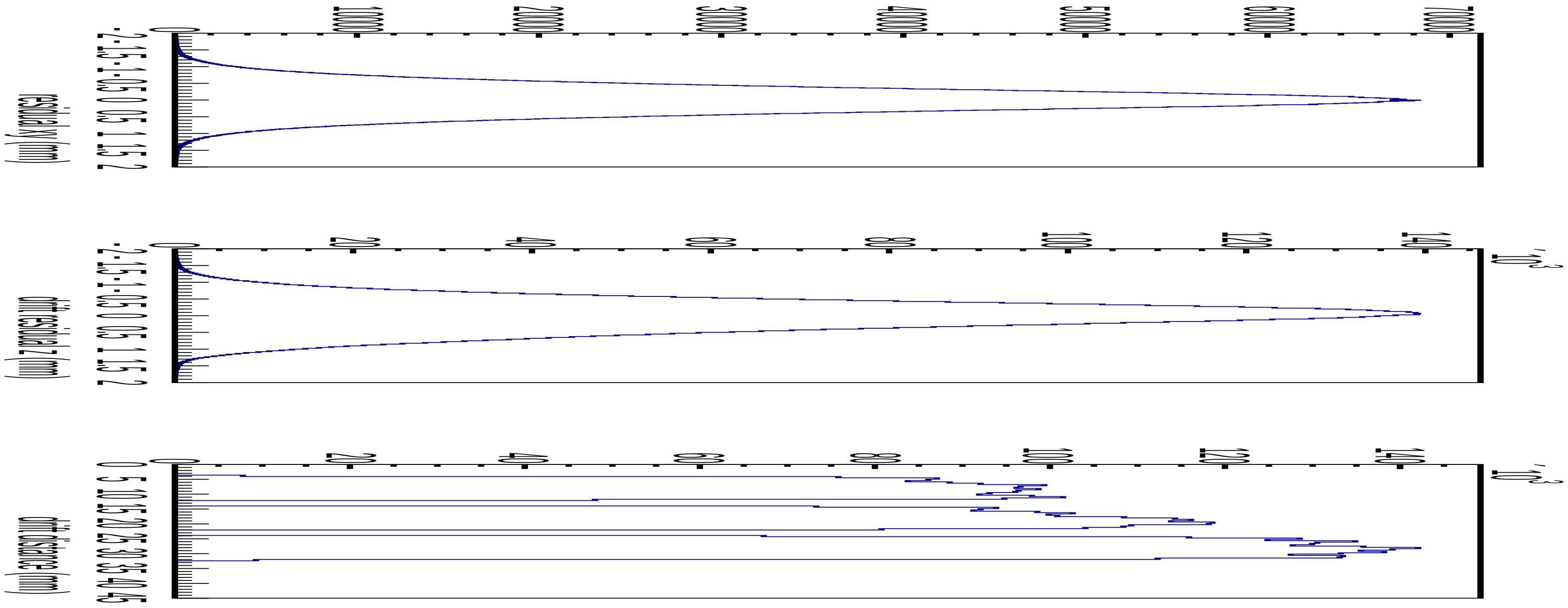
[1] the drift velocity is now taken constant but should be adjusted per run

DESY testbeam Module Analysis

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

Three runs at different drift distances and same x coverage as 6916

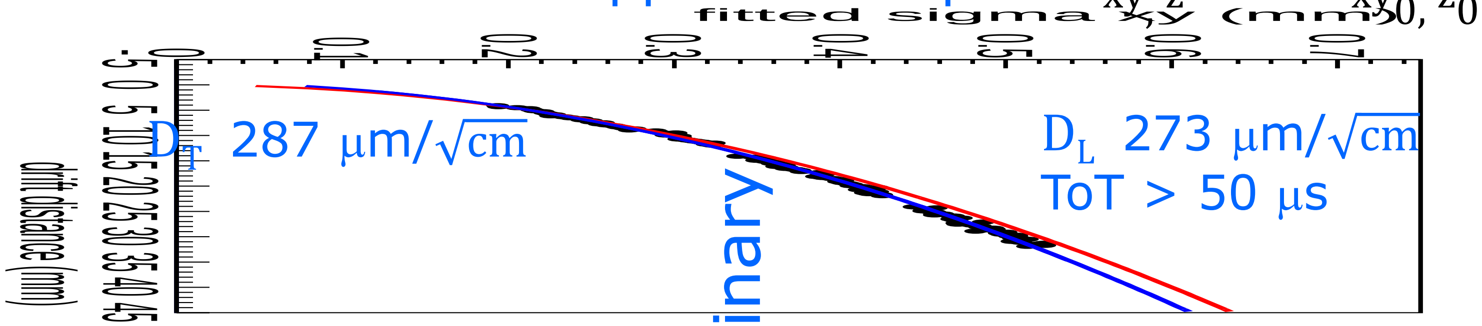
Preliminary

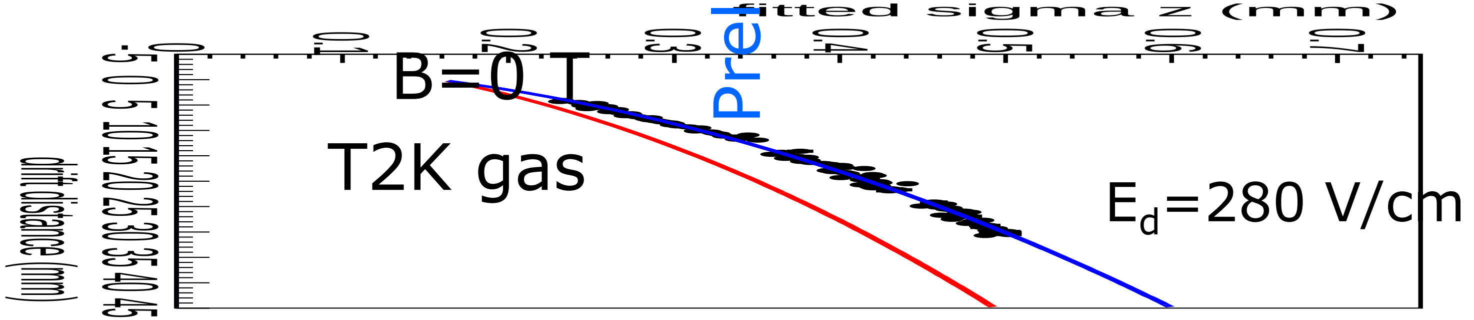


DESY testbeam Module Analysis

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

Fitted resolution for 8 upper row chips $\sigma_{xy,z}{}^2 = \sigma^2_{xy_0, z_0} + D^2_{xy,z}\,(z - z_0)$





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

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

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

In red the published single chip results

Magboltz:

D_T 318 $\mu m/\sqrt{cm}$

D_L 220 $\mu m/\sqrt{cm}$

σ_{xy_0} = 38 µm (fixed)

D_{xy} = 287 (306) $\mu m/\sqrt{cm}$

Z_0 = -330 µm

χ^2/dof = 97.3/118 σ_{sys}=4 µm

σ_{z_0} = 150 (135) µm

D_z = 273 (226) $\mu m/\sqrt{cm}$

Z_0 = -330 µm (fixed)

χ^2/dof = 129.8/112 σ_{sys}=5 µm

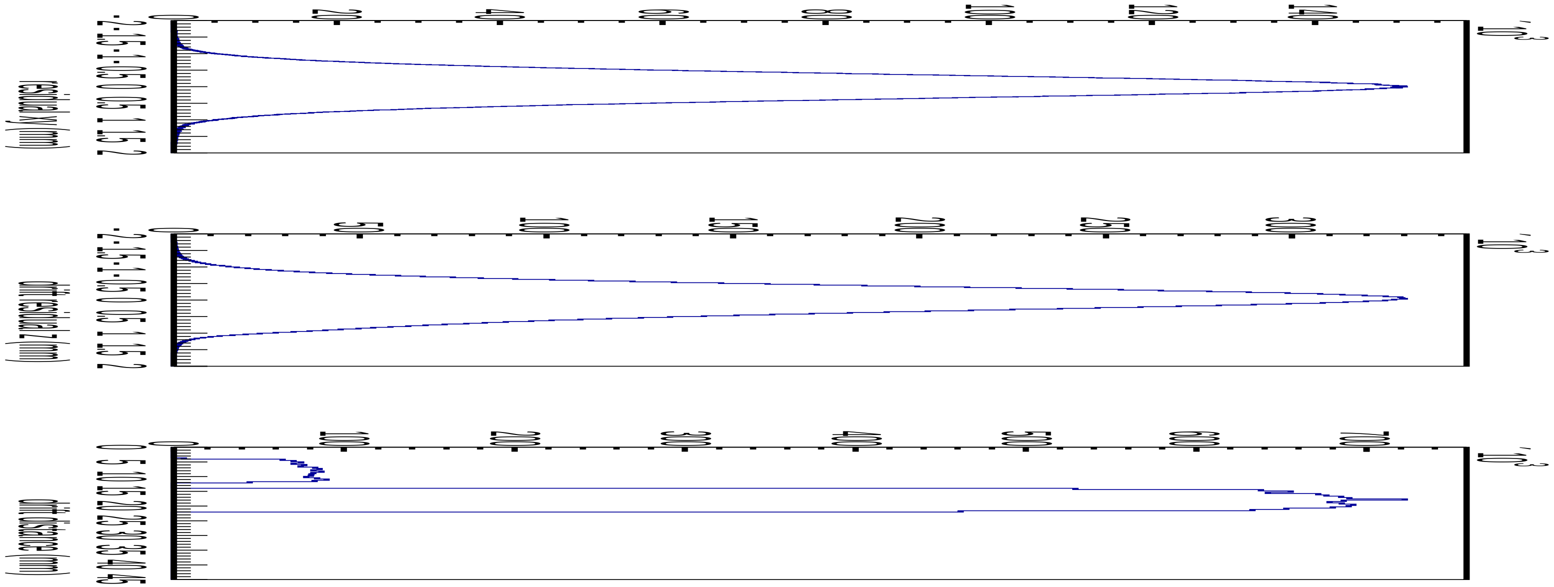
DESY testbeam Module Analysis

Full 8 quad Module

- Results for Run 6909, 6916, 6917 B=0 T p=6 GeV (stager at x=1 z=2,1,2)
- And runs 6934, 6935 B=0 T p=5 GeV (stager at x=0,2 z=2)
- Note that the 5 GeV data has a much higher trigger and data rate
- Same procedure for the analysis as described on slide 15

hit residuals and drift distance 18M TPX3 hits

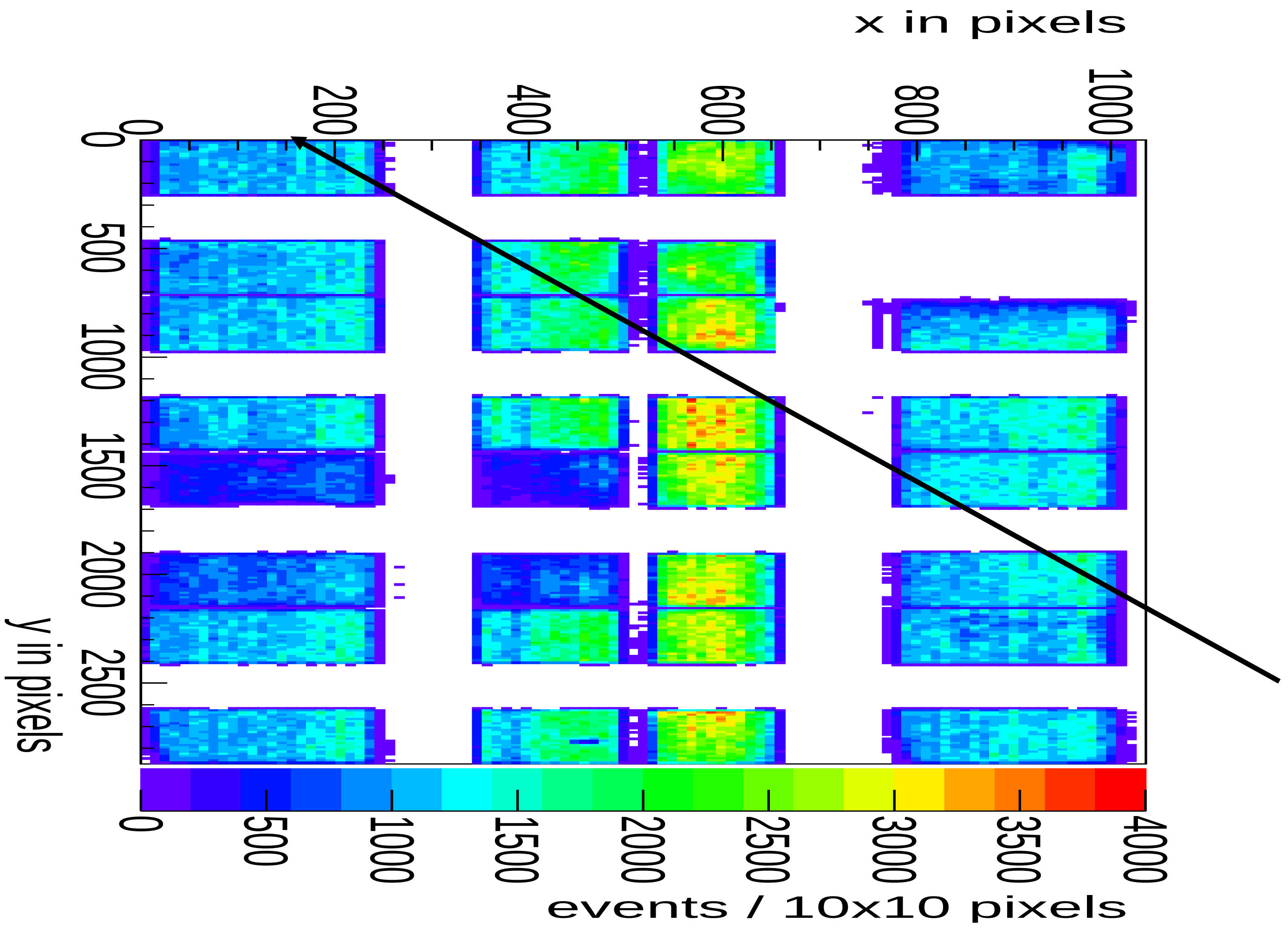
Preliminary



DESY testbeam Module Analysis

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

Hit map after preselection in module plane



Preliminary

Several beam profiles can be seen

Vertical white bands are the guards

Horizontal line in the middle is between the quads

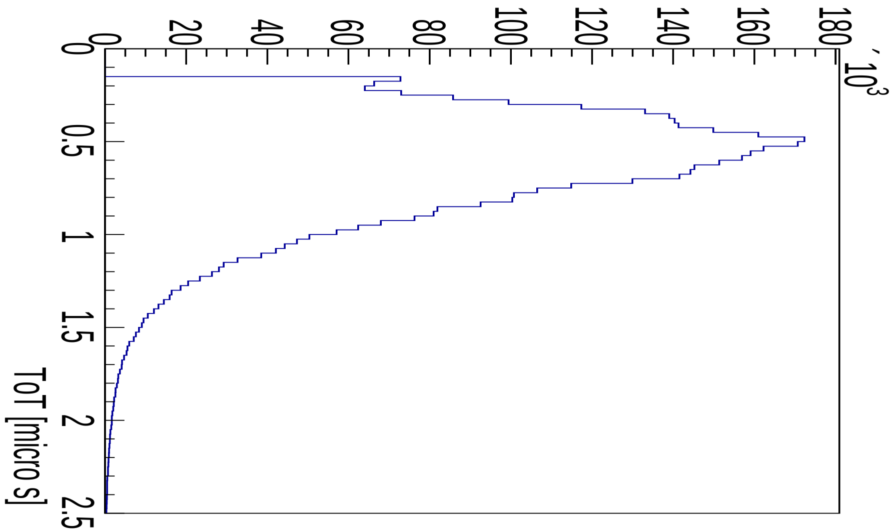
Chip 11 had a short and was disconnected

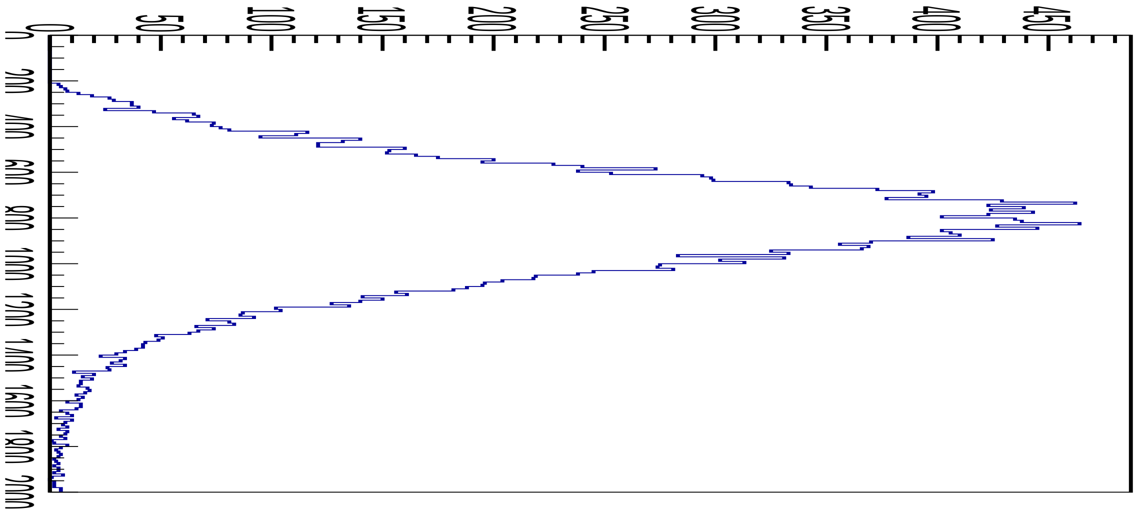
DESY testbeam Module Analysis

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

Time over Threshold and TPX3 hits on track 25k tracks

Preliminary





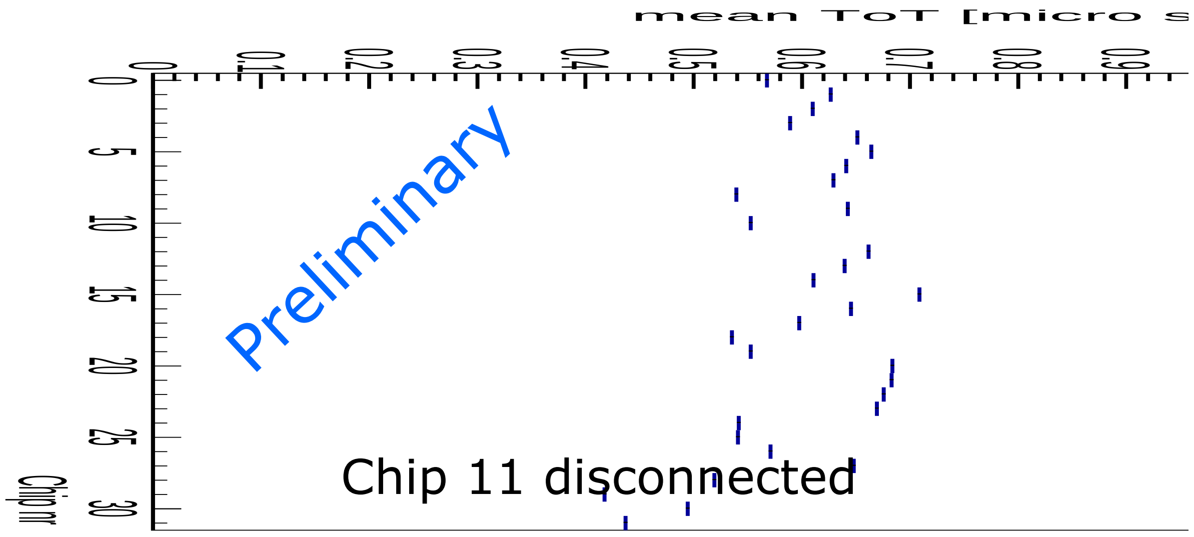
Mean 838 TPX3 hits/track

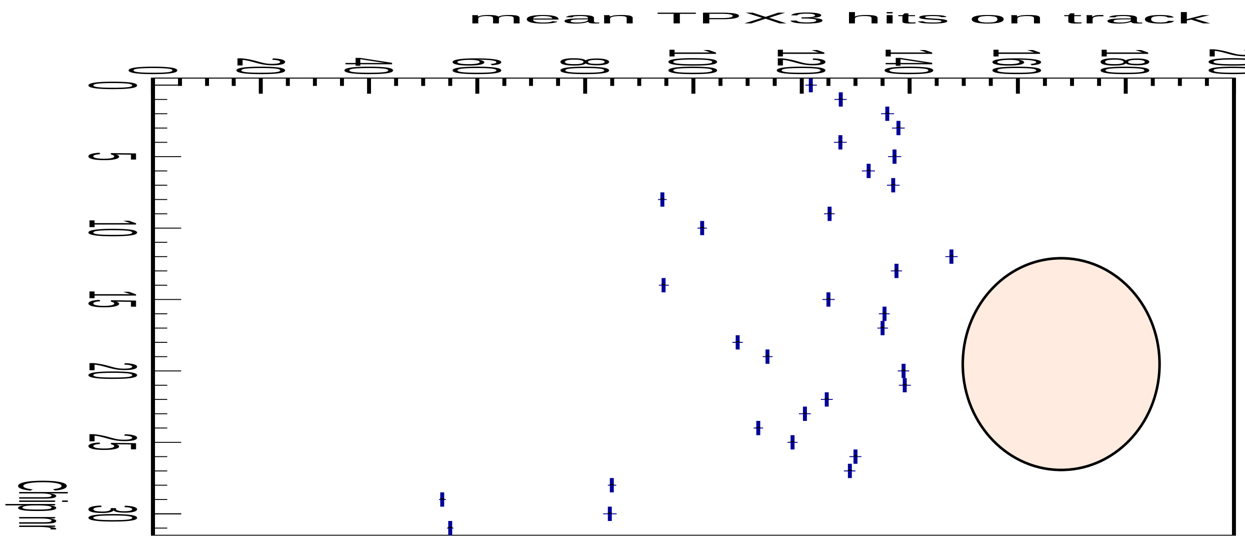
This includes less efficient chips (see next slide)

DESY testbeam Module Analysis

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

Per chip: Time over Threshold and TPX3 hits on track





Chips 28-31 (one quad) lower ToT and less hits
Clear correlation gain – ToT – efficiency
Need to design a possibility to adjust the HV of individual chips

DESY testbeam Module Analysis

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

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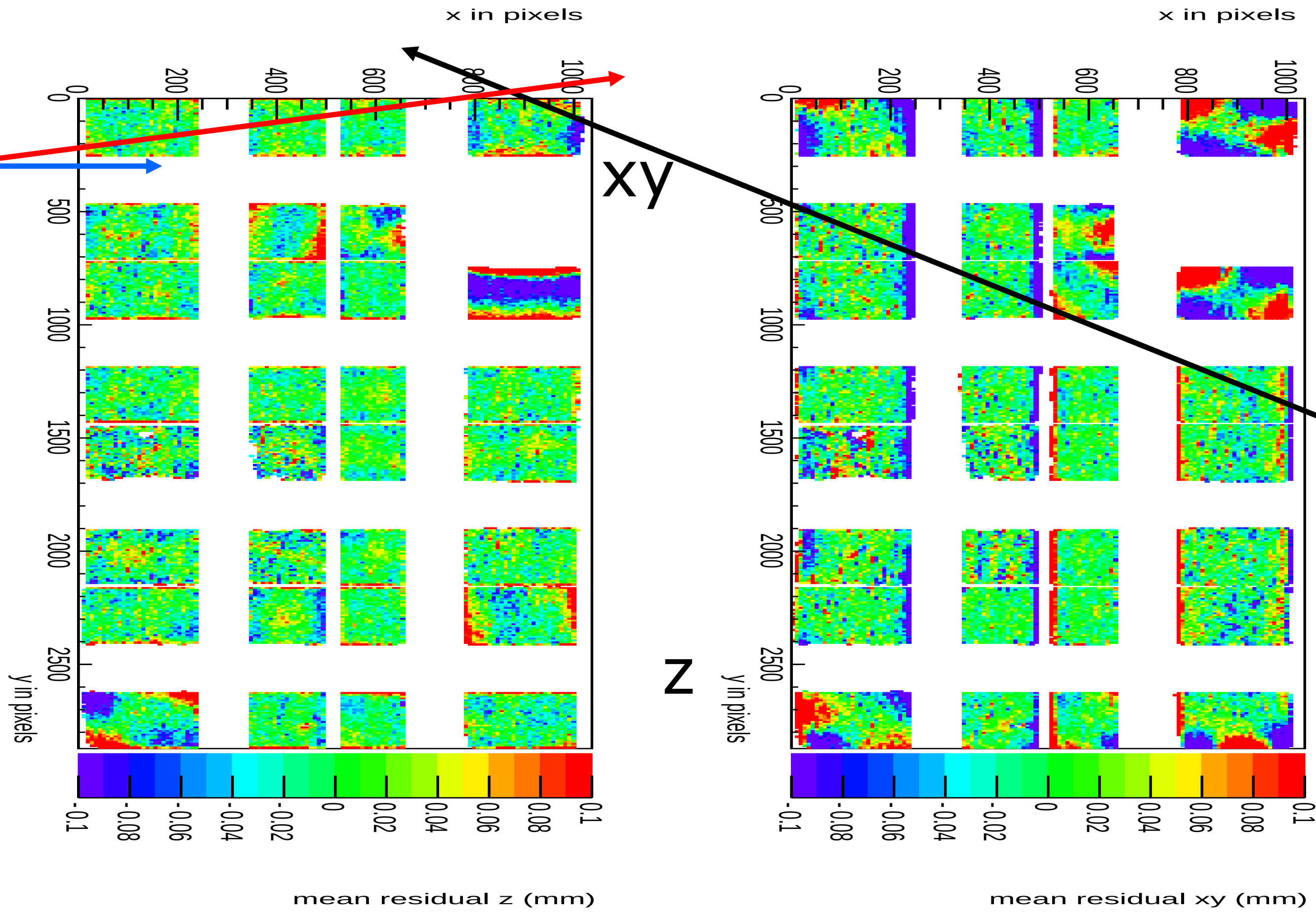
Mean residuals in the module plane no acceptance cuts

Preliminary

The blue/red horizontal lines are due to the absence of a chip acceptance cut



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

The field around chip 11 (no grid HV) in particular chip 8 is affected.

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

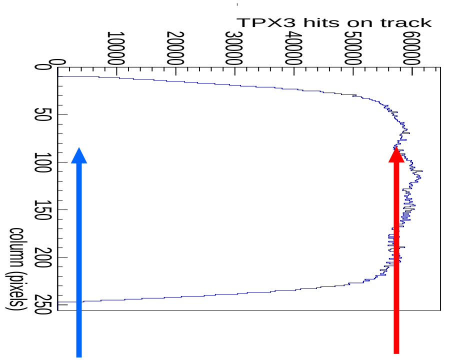
LCTPC 2023

DESY testbeam Module Analysis

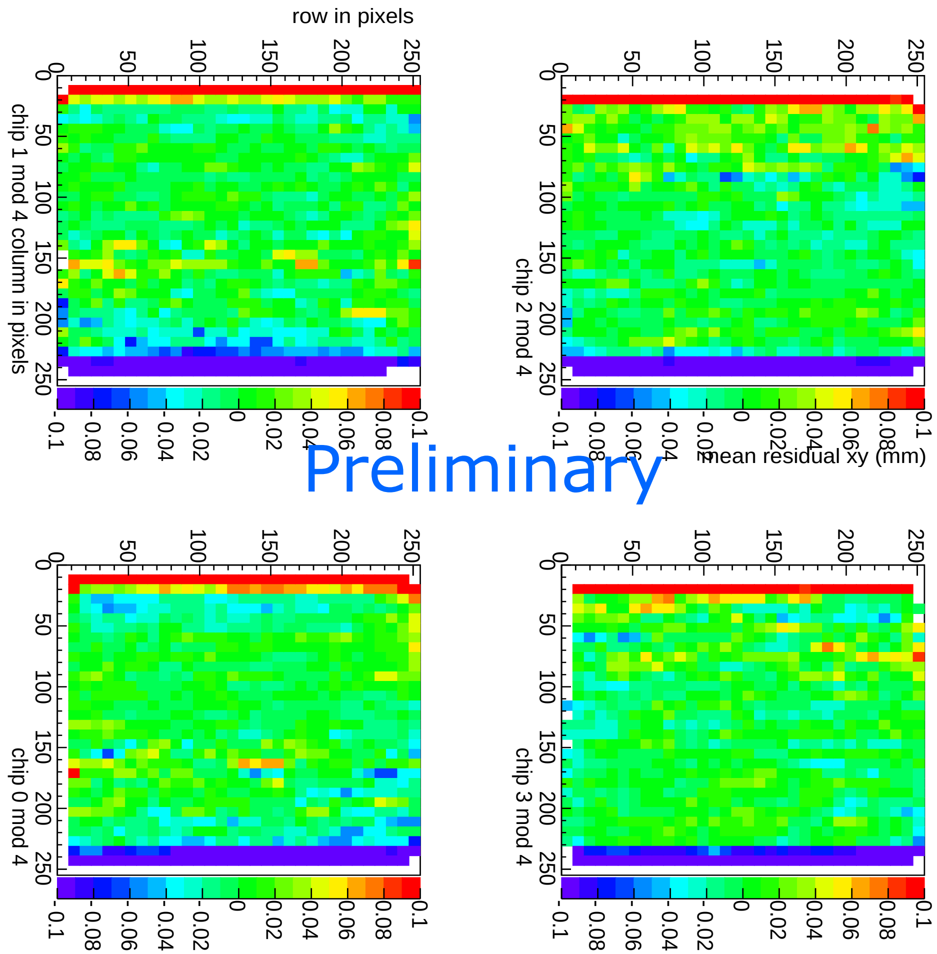
Runs 6909, 6916-17, 6934-35 B=0 T p =6,5 GeV

Mean residuals xy in the quad plane 24 chips

Columns horizontal



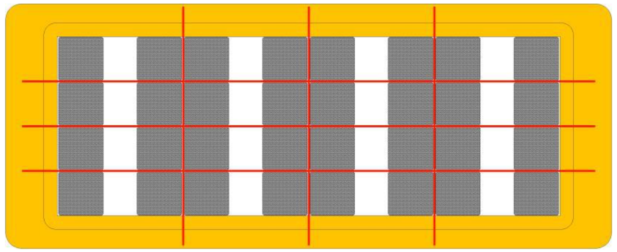
At the column edges the efficiency drops and introduces a bias (in local x).



In total 24 chips projected in the quad plane

Granularity 8x8 pixels

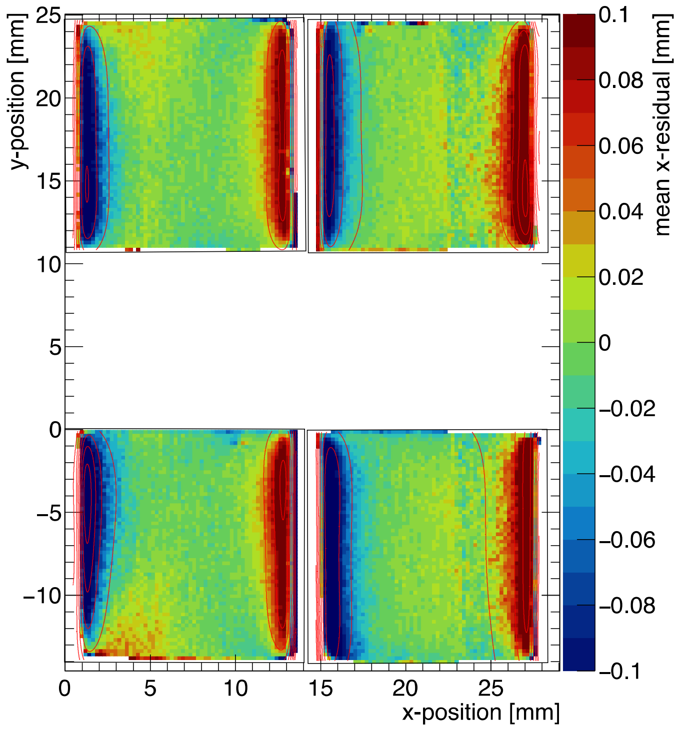
Only small deformations at the chip column edges.
This means that the guard and guard wires are reasonably well tuned.

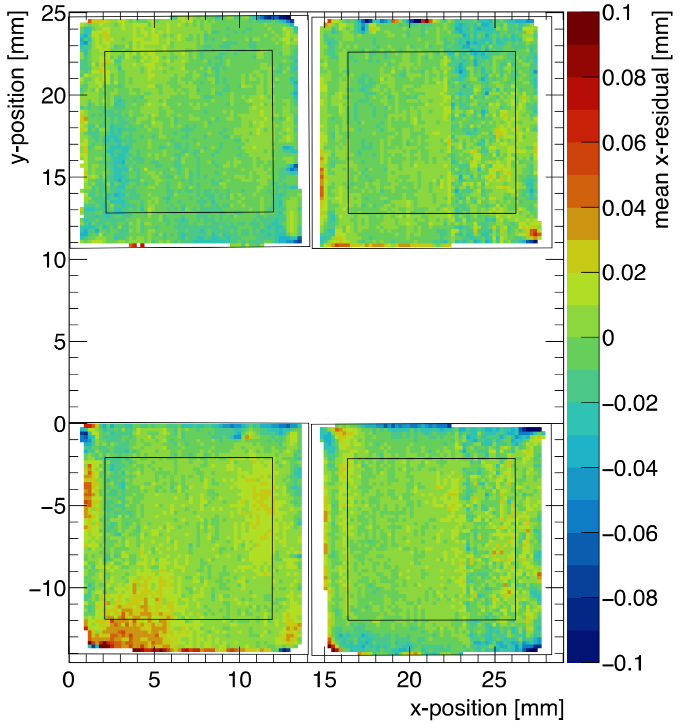


DESY testbeam Module Analysis

Thesis Kees Ligtenberg

Mean residuals xy after fitted correction in the quad





The lefts plot shows the deformations before corrections. The right plot after corrections

This can be compared to the quad plot for module

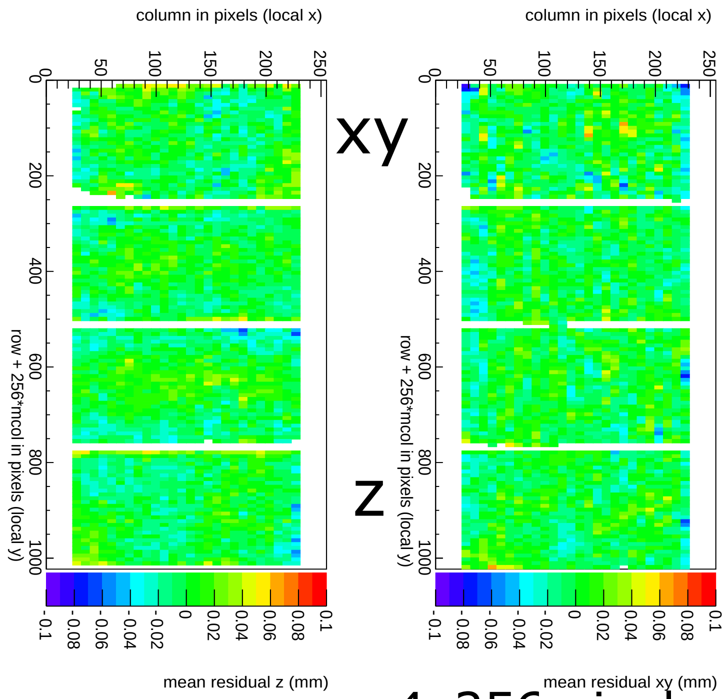
The plots for the module should be compared to the left plot.

DESY testbeam Module Analysis

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

Mean residuals (module) row (module) column

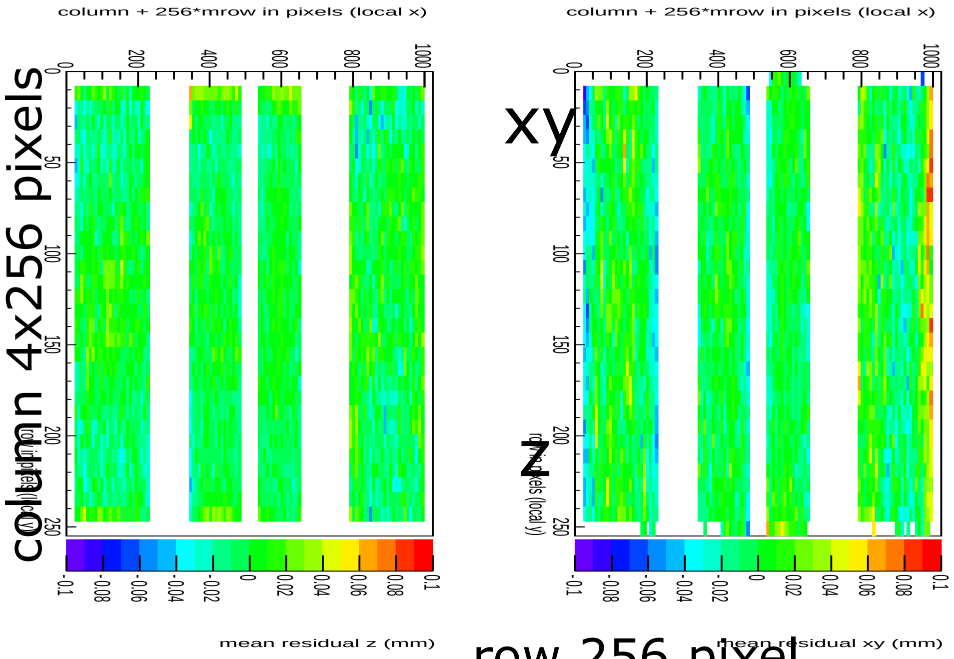
column 256 pixels



row 4x256 pixels

Preliminary

column 4x256 pixels



row 256 pixel

Regrouping the module plane to increase stats

Granularity 8x8 pixels

After cuts
entries > 1500
25 < col < 230
10 <row < 245

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

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

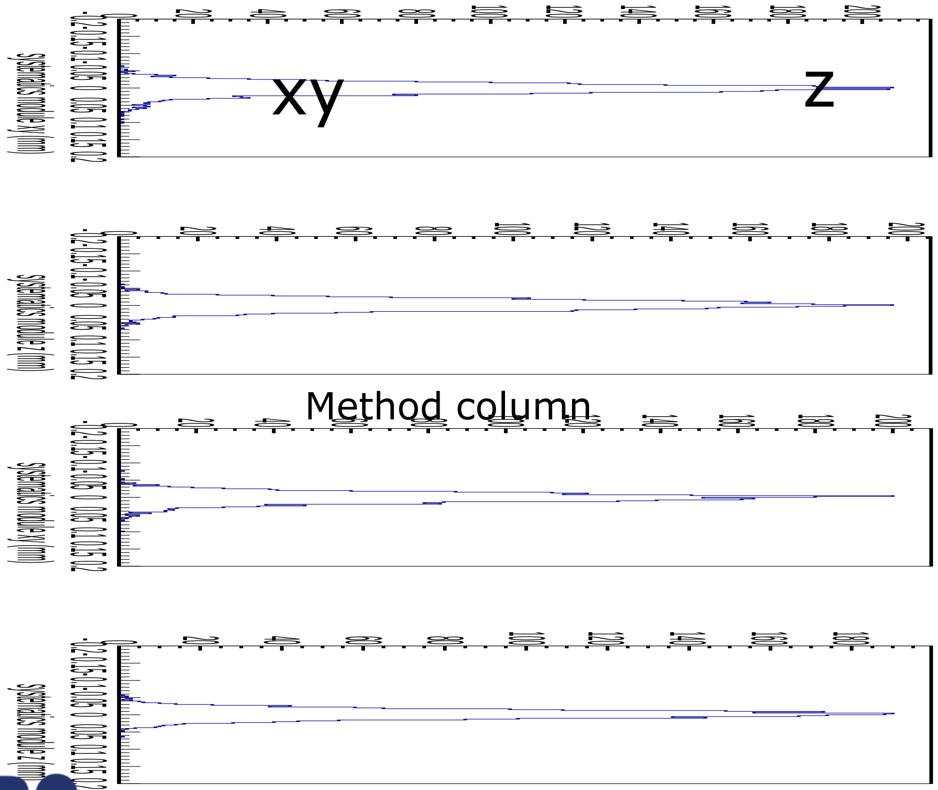
DESY testbeam Module Analysis

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

Distribution of mean residuals in the plane with E field correction

Method row

Method column



Preliminary

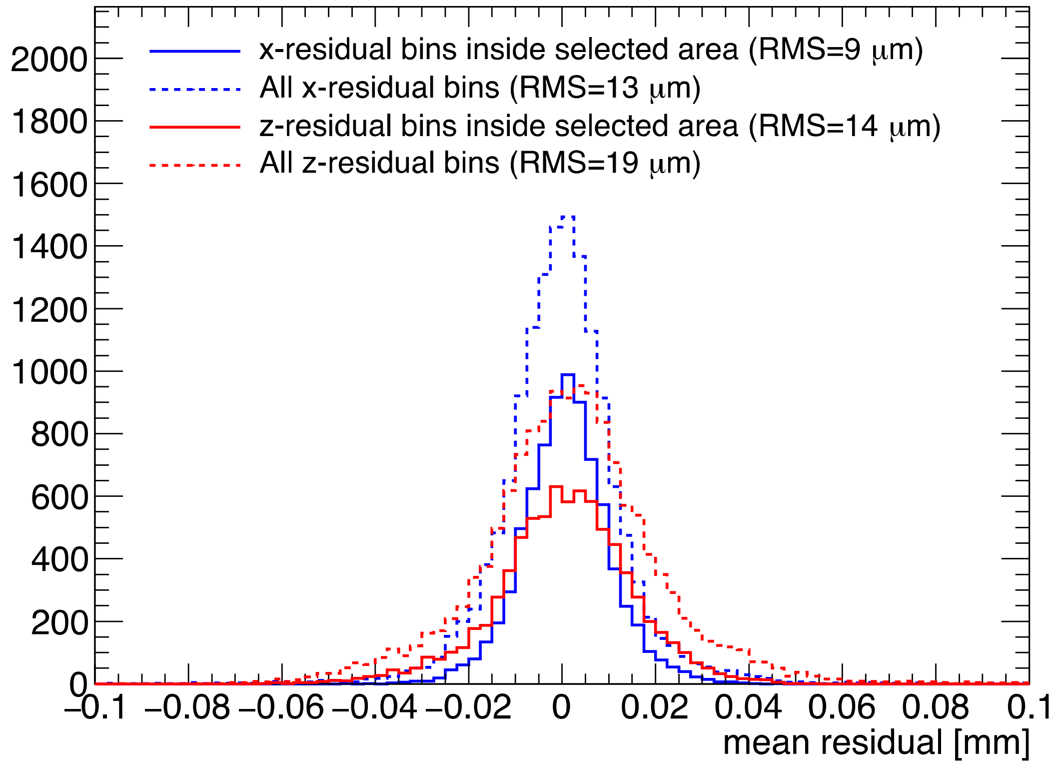
- Removing top edge box colums > 215
- Fit the small E field corrections xy and z per chip in the column plane per chip (two parameters edge 0 and edge 255) improves the xy column result and a bit the other results

method	rms (stat) xy	bins xy	rms (stat) z	bins z
row	15 (7) μm	2914	15 (8) μm	2864
column	14 (6) μm	2417	13 (8) μm	2370

We did not include the 4 corner chips and (11), 14, 8 and 13.

DESY testbeam Module Analysis

Mean residuals after correction in the quad



Thesis Kees Ligtenberg

The z results for the module are 15 (13) μm. The module results are a bit better than the quad results of 19 (14) μm,

The xy results for the module are 15 (16) μm. This is a bit worse than the quad results (13 and 9 μm).

However ….
Statistics per chip is about a factor 100 higher for the quad.
For the module the stats error is 7 μm and limiting to reach e.g. 10 μm.

Nikhef

DESY testbeam Module Analysis

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Some remarks on the required E field precision

The electric field defined by the field cage is not homogeneous at the level of 10 μm and distorts the drift process.

- The electric field is distorted around the 4 corner chips
- At the edge of the drift box (in x) distortions are observed
- If the drift volume is sliced in z (drift) shifts are observed of typically 40 μm for 1 cm drift distance
- Because of the disconnected chip 11 field distortions were introduced

The obvious lesson is that module merits a very precise field cage ..

The 24 other chips (not at the 4 corners and not around chip 11) are less affected by the inhomogeneities in the E field as the results show.

Conclusions of Module Analysis

- First preliminary results of the 8 Quad Module in the DESY test beam in June 2021 have been presented
- High statistics runs at B=0 T with p=5 and 6 GeV have 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 telescope tracks
- 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
- Using runs 6916-6918 the single electron resolution and diffusion coefficients are measured for drift distances 4-30 mm:
  - D_{xy} = 287 (318) $\mu m/\sqrt{cm}$ and D_z = 273 (220) $\mu m/\sqrt{cm}$ (Magboltz)

Conclusions of Module Analysis

- A large data set was analysed to extract results for the module. One chip (nr 11) out of 32 was disconnected due to a short.
- After careful calibration of the chips the residuals were studied in the full module plane using 25k tracks (25M hits). This showed that the E field of three neighbour chips of chip 11 was distorted up to 100 μm. In the corners of the drift box the E field had deformations up to 200 μm.
- This underlines the importance of a precise field cage for precision tracking.
- Results for the 16 chips with minimal E field distortions showed that:
  - rms residuals xy 15 (16) μm and z 15 (13) μm
  - The results confirm that the HV of the guard wires was well tuned.
  - The results are compatible with high stats the quad measurement taking into account the stat errors.

Analysis plans for the module

- What remains is the analysis of the B=0.5 and 1 T data set
- First priority are resolutions and diffusion constants for the 1 T data set
- Second priority is to extract the dE/dx resolution using single electron and cluster counting for B=0 and 1 T fields.
- It would be interesting to study the residuals over the module plane for the B=1 T data set (and compare to the B=0 data)
- We have also data with a rotated module; data at a different drift field; and data with the B field not parallel to the E field
- Ultimate aim is a NIM paper with the module results including the B=1 T and dEdx results

What can be improved on the module?

- Understand and fix the short in chip 11 -> We (Fred, Peter) will go to Bonn
- Understand (and fix?) the lower ToT and efficiency of quad 7 (chips 28-31)
- The multiplexer DAQ system is not very stable; several tries are needed to connect all chips. In a run sometimes one chip falls out and we have to stop the run
  - A re-optimization of the multiplexer (with a larger memory) is needed for the use in larger systems
  - Cooling of the multiplexer helps to reach a more stable DAQ situation (in the test beam we used and elephant tube with a ventilator)
- The field cage should be more precise and placed further from the chips. The field of grid and field cage should be more continuous to minimize E field distortions
- Design a HV distribution system where the HV grid voltage can be adjusted per chip to achieve a same mean ToT and efficiency per chip
- Concerning timing in the test beam: use the proper TLU output for the trigger signal and avoid the 25 nsec jitter

Towards a Pixel TPC

- As discussed in ILD it is important for high Luminosity Z running that the Ion Back Flow is significantly reduced to a level of IBF x Gain < 1
- This is possible to achieve by a double grid structure. It is possible to perform and test this idea in the new detector laboratory in Bonn
- A next step is the test of the module in a test beam in the US in the context of the Electron Ion Collider. The module will be placed in a TPC and the particle identification capabilities of the module can be studied in detail (see also the talk by Klaus Dehmelt The MiniTPC Project at the EIC)
- A next step would involve the production of a new set of GridPixes TPX3 for an endcap; In that case a different layout of the module (without quads) and improved multiplexer electronics and DAQ software could also be developed and tested
- A further improvement would be the use of the TPX4 chip to build a module. The larger surface of the TPX4, the possibility chips to daisy chained chips (no multiplexer) and the use of TSV’s gives a higher detector coverage with less edges

General Pixel TPC conclusions

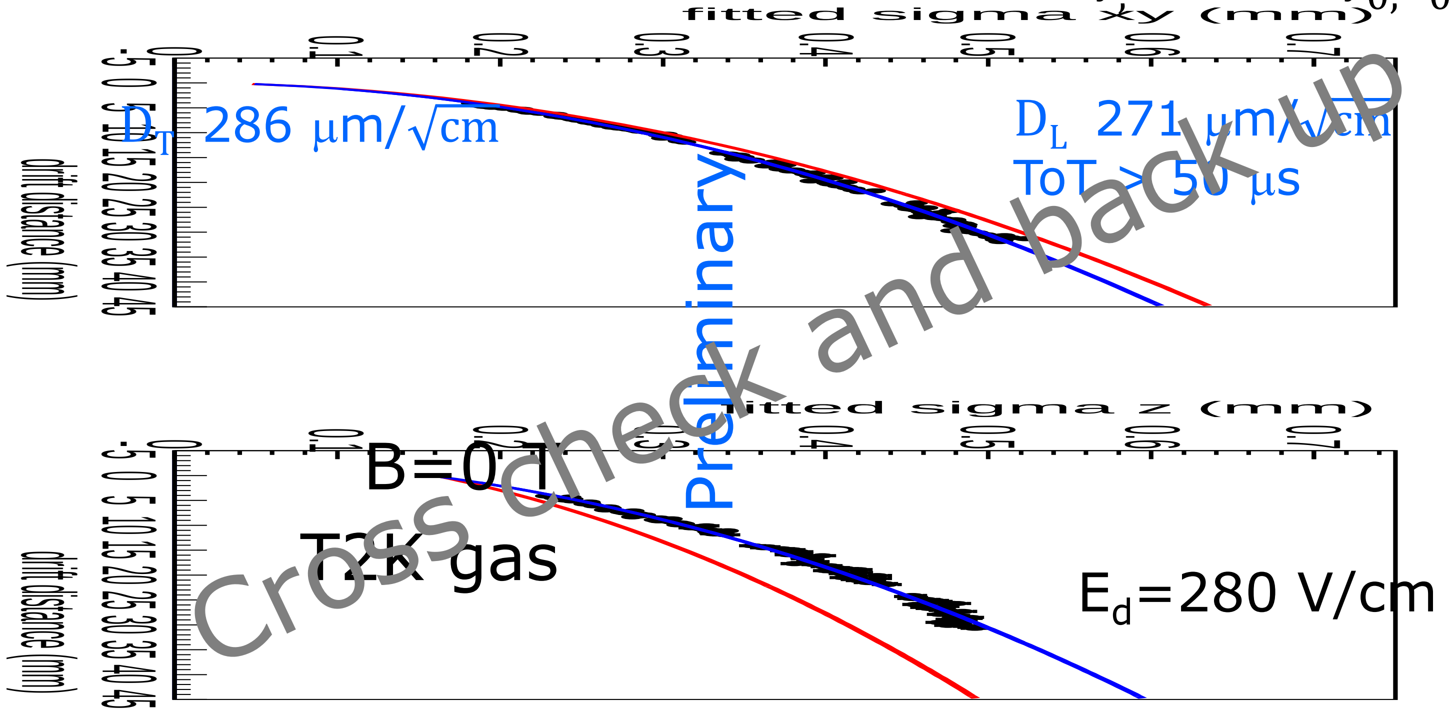
Backup

- 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 homogeneous field
  - After correcting the edges, deformations in the transverse plane shown to be < 15 μm
- An 8-Quad module has been designed with guard wires
- Test beam data taken at DESY in 2021 were analysed
  - Deformations in the transverse plane for 16 chips were shown to be < 15 μm
- 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

DESY testbeam Module Analysis

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

Fitted resolution for 8 lower row chips $\sigma_{xy,z}^2 = \sigma^2_{xy_0, z_0} + D^2_{xy,z}(z - z_0)$



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

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

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

In red the published single chip results

Magboltz:

D_T 318 $\mu m/\sqrt{cm}$

D_L 220 $\mu m/\sqrt{cm}$

σ_{xy_0} = 38 μm (fixed)	σ_{z_0} = 154 (135) μm
D_{xy} = 286 (306) $\mu m/\sqrt{cm}$	D_z = 271 (226) $\mu m/\sqrt{cm}$
Z_0 = 109 μm	Z_0 = 109 μm (fixed)
χ^2/dof = 110.6/118 σ_{sys}=4 μm	χ^2/dof = 125.9/112 σ_{sys}=5 μm

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