Pixel TPC resolution and deformation results

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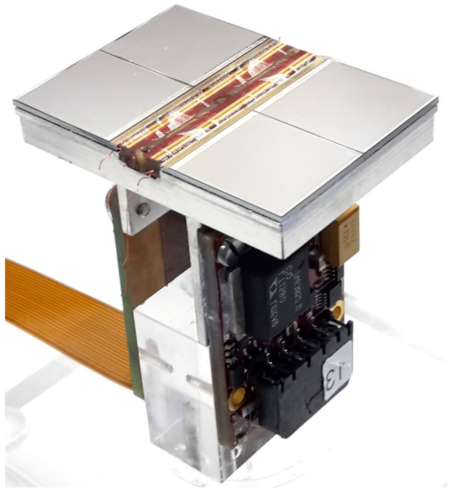
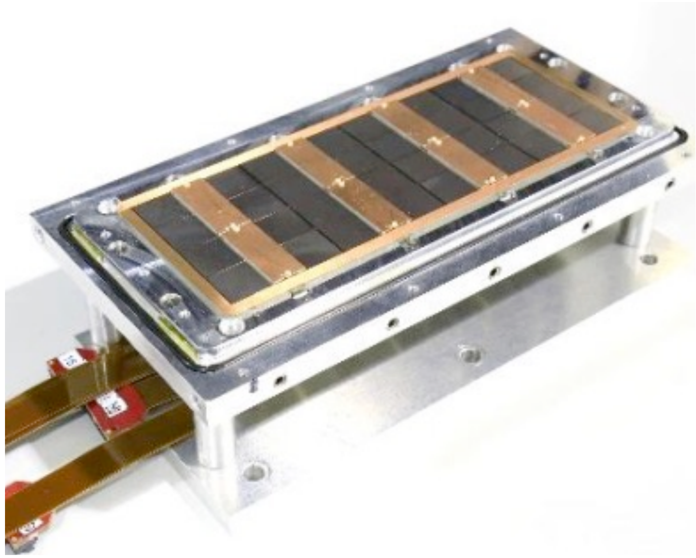
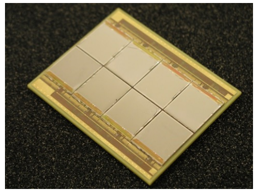


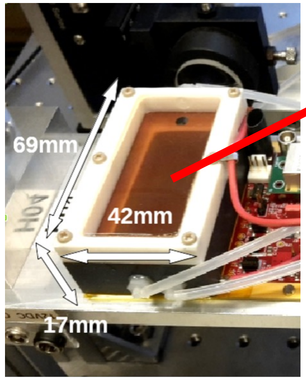


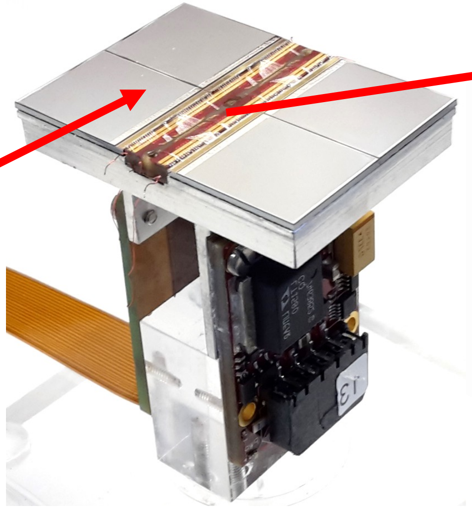
LCTPC Bonn meeting January 2025

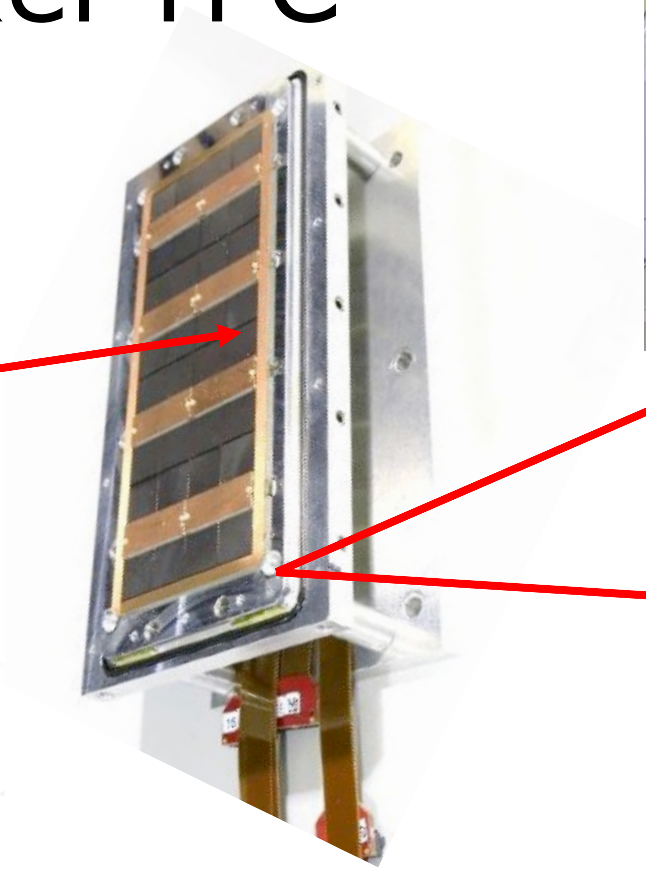
Pixel TPC

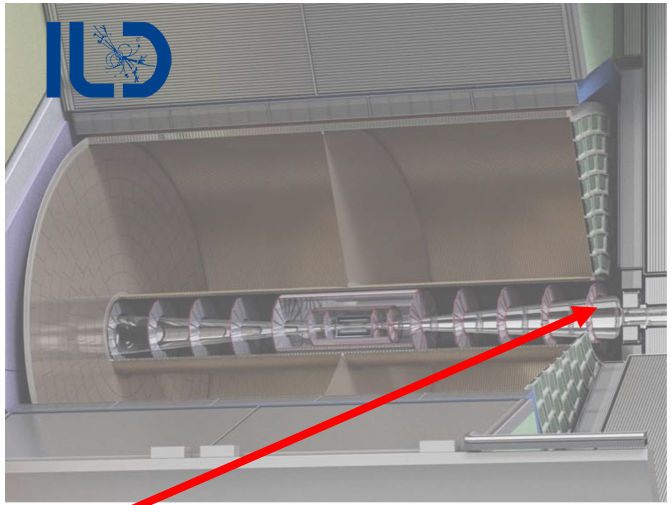


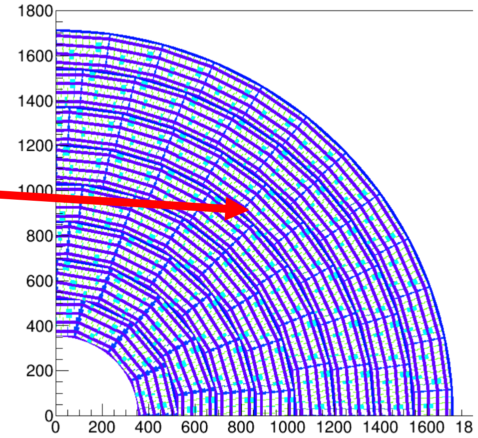
(Octopuce)





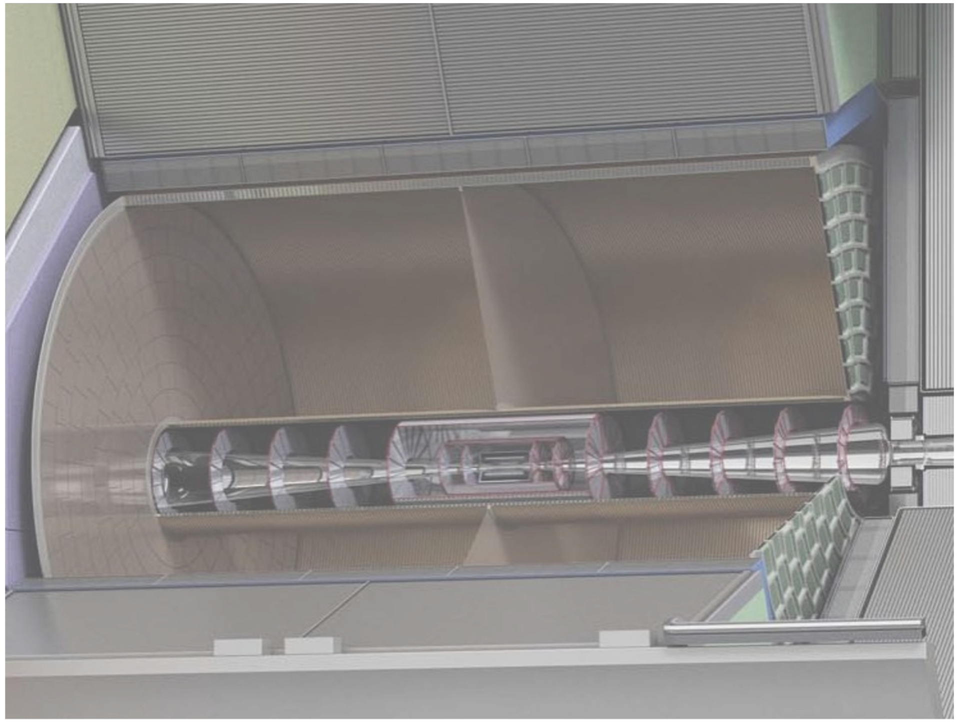




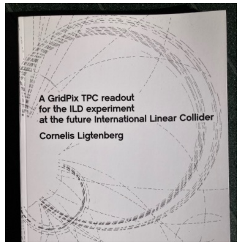


(TimePix1)	TPX3 chip	Quad	Module	TPC plane
(2007-14)	2017	2018	2019	

Pixel TPC



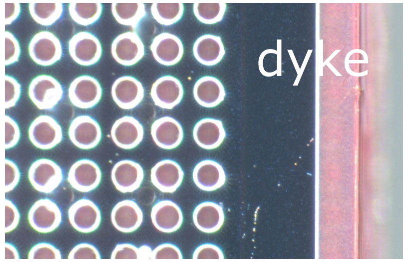
- Material budget is
  - 0.01 X_0 TPC gas
  - 0.01 X_0 inner cylinder
  - 0.03 X_0 outer cylinder
  - < 0.25 X_0 endplates (incl readout)
- Note the very low budget in the barrel region. Material budget can be respected by different technologies like GEM, MicroMegas and Pixels
- TPC is sliced between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



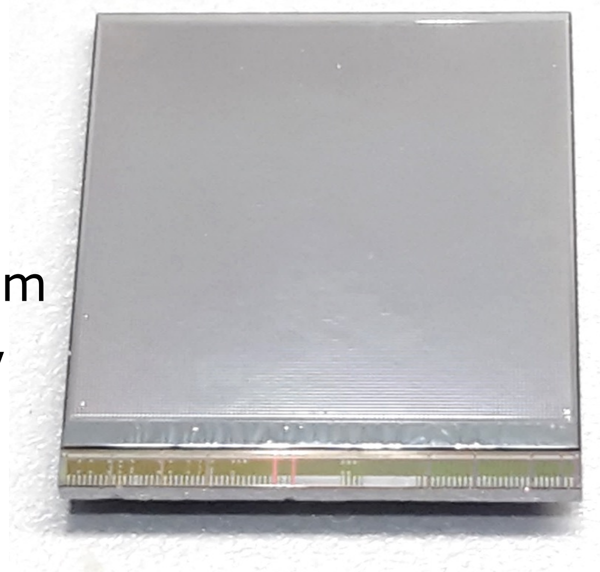
https://www.nikhef.nl/pub/services/biblio/theses_pdf/thesis_C_Ligtenberg.pdf

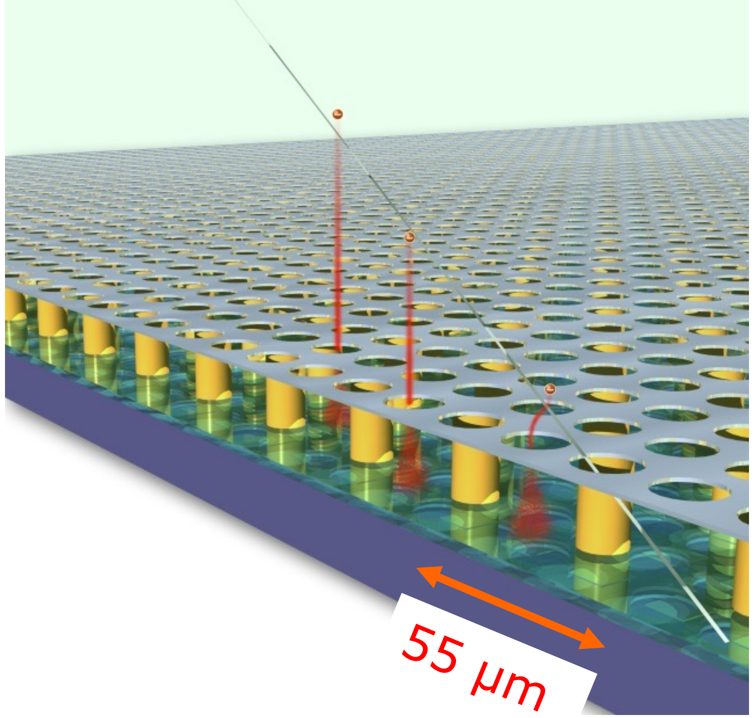
GridPix technology

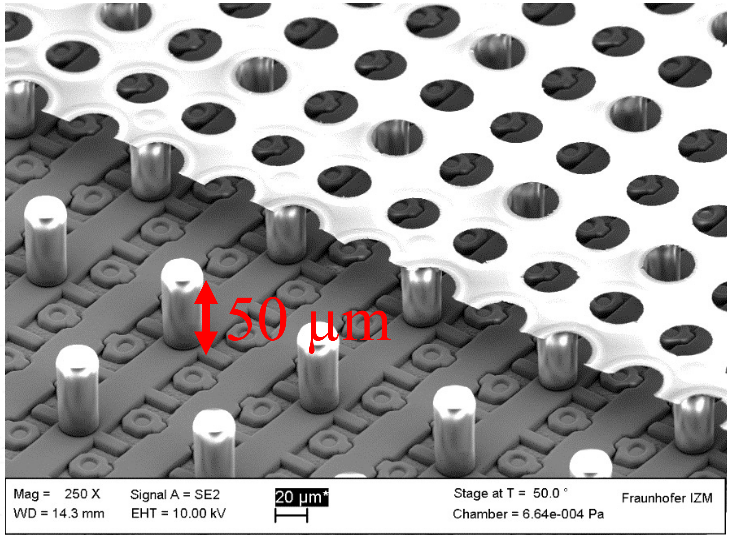
- Pixel chip with integrated Grid (Micromegas-like)
- InGrid post-processed @ IZM
- Grid set at negative voltage (300 – 600 V) to provide gas amplification
- Very small pixel size (55 µm)
- detecting individual electrons



- 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

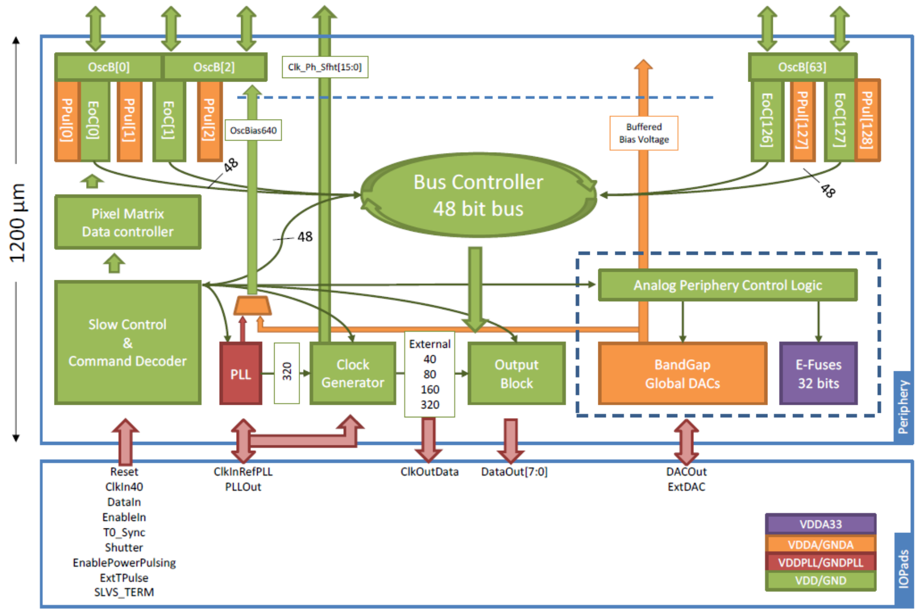


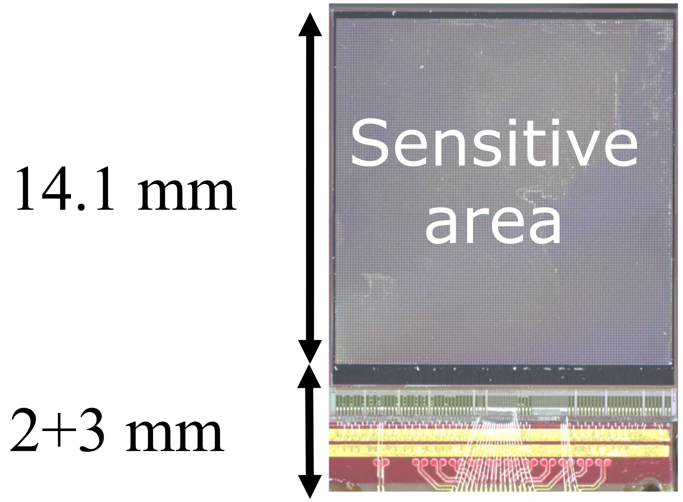




Pixel chip: TimePix3

- 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

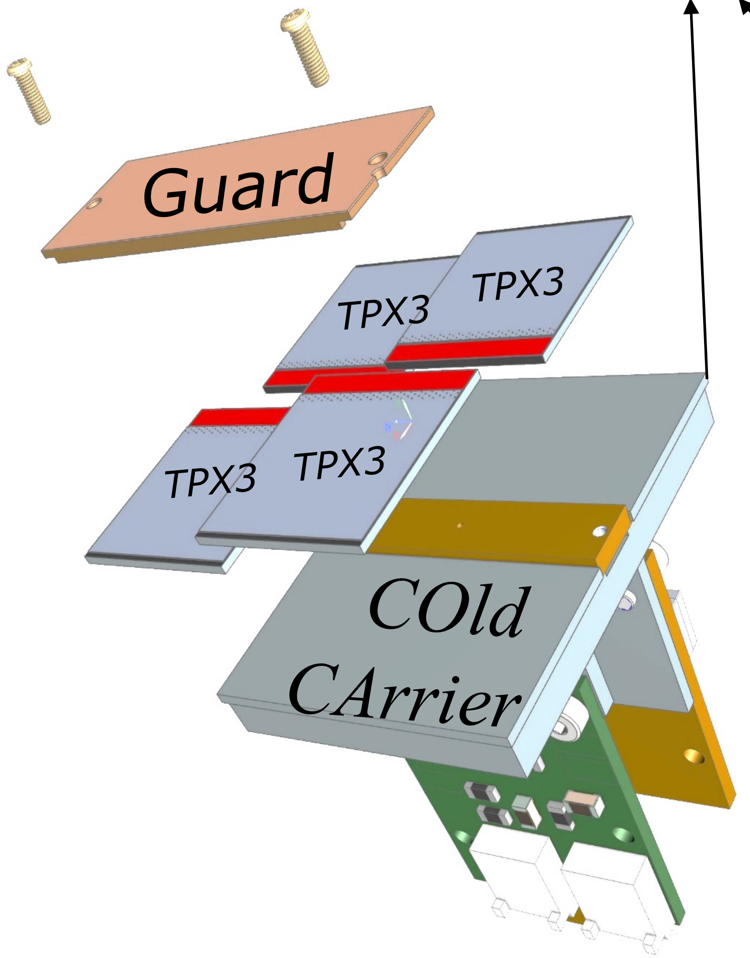




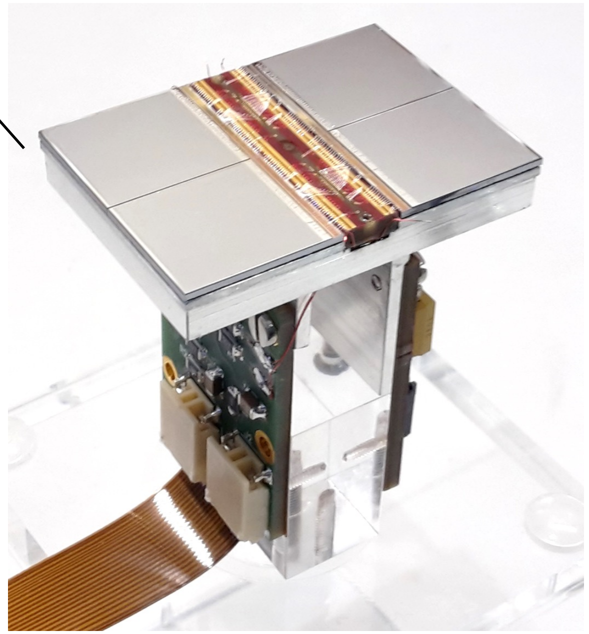
QUAD design and realization

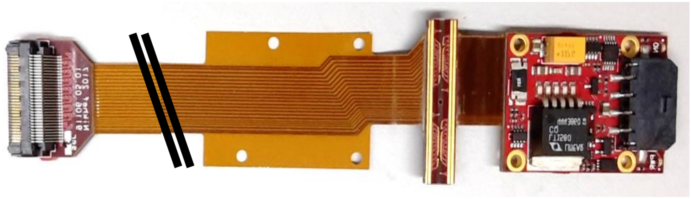
- Four-TimePix3 chips
- All services (signal IO, LV power) are located under the detection surface
- The area for connections was squeezed to the minimum
- Very high precision 10 µm mounting of the chips and guard
- QUAD has a sensitive area of 68.9%
- DAQ by SPIDR

39.6 x 28.38 mm



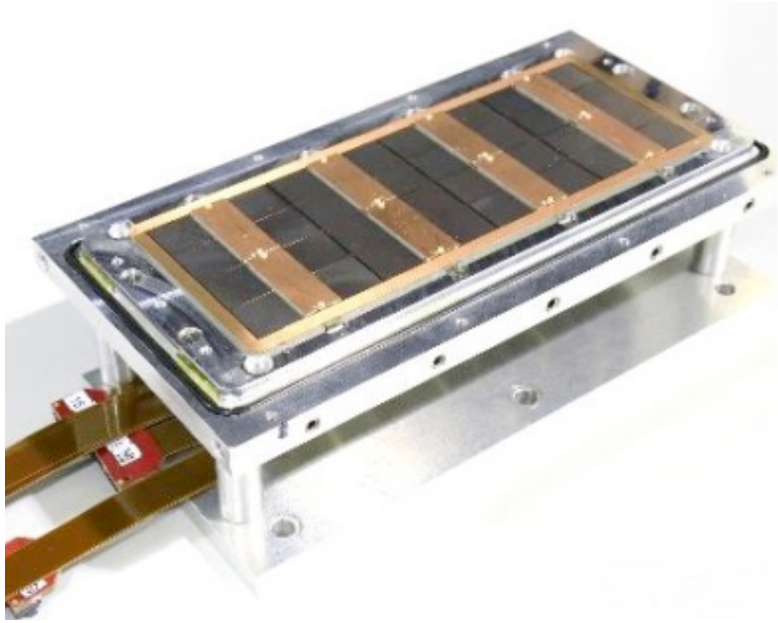
series of QUADs

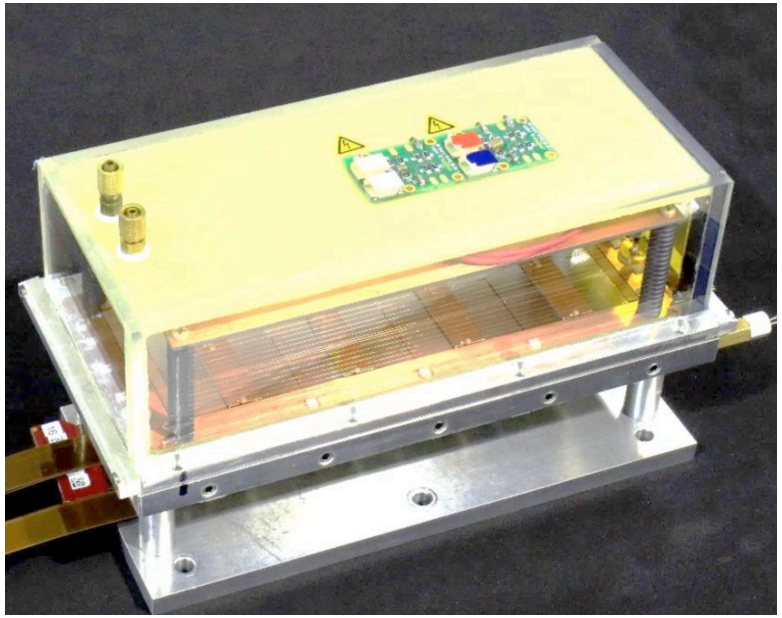


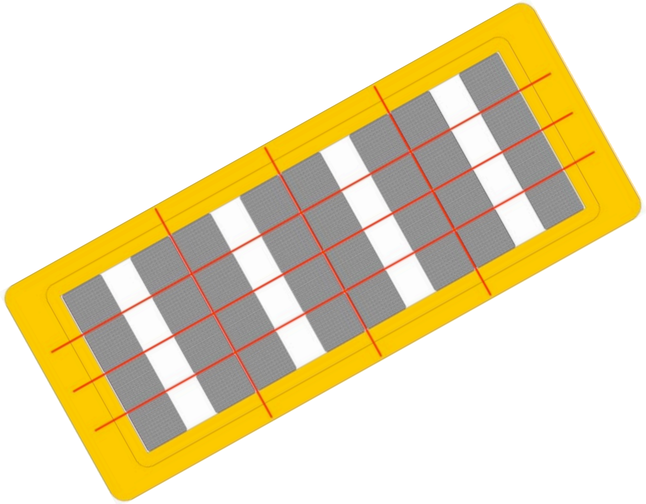


QUAD as a building block

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

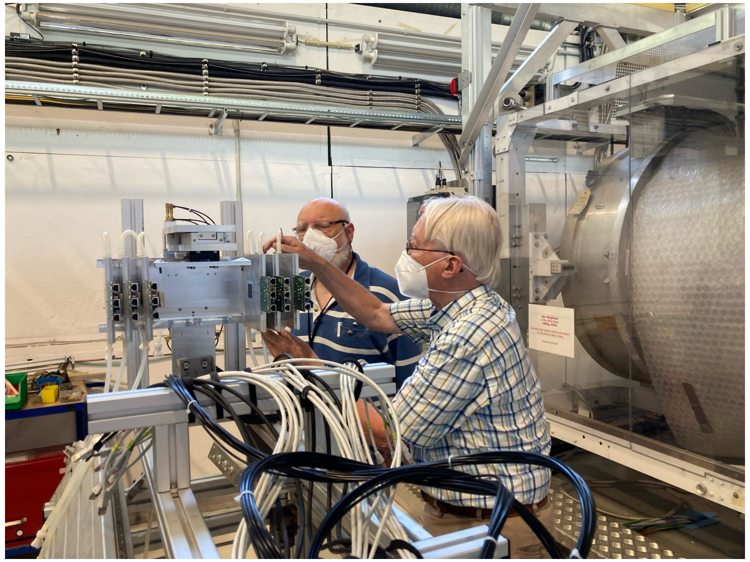


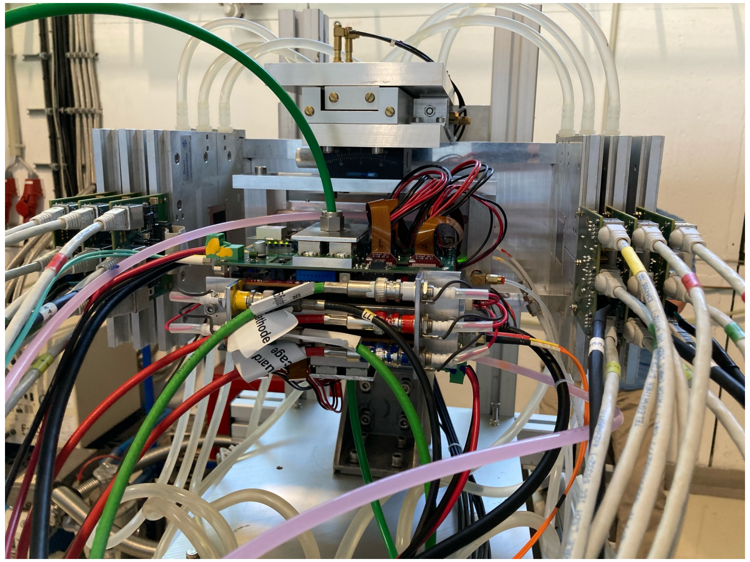


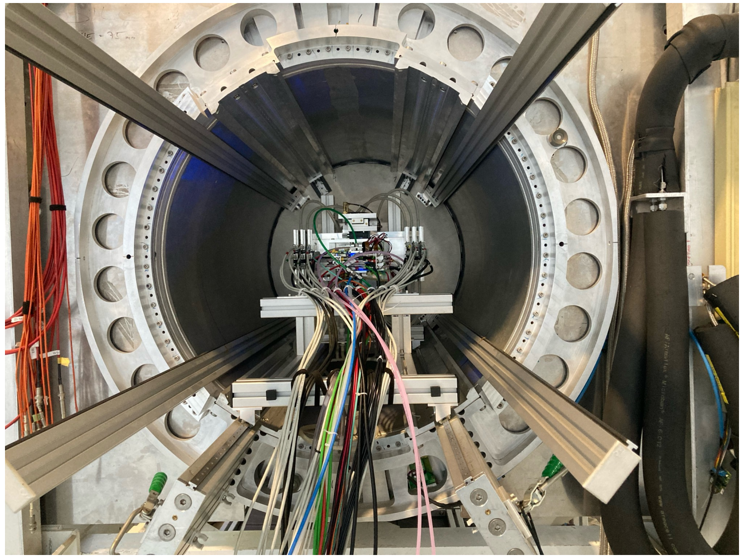


in red guard wires

DESY testbeam June 2021







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

Discuss of two NIM papers on module performance

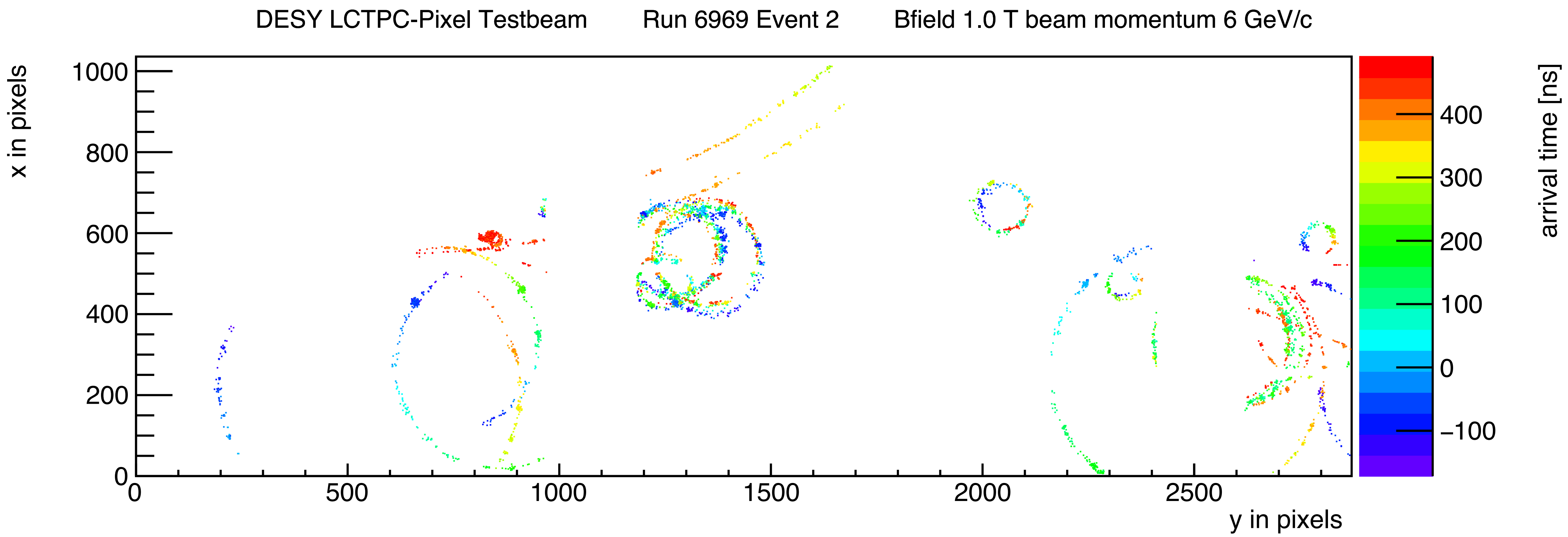
- First paper with emphasis on module construction and tracking performance (this talk)

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

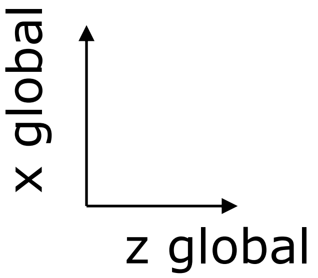
- Second paper with emphasis particle identification (second talk) and other analysis results (this talk)

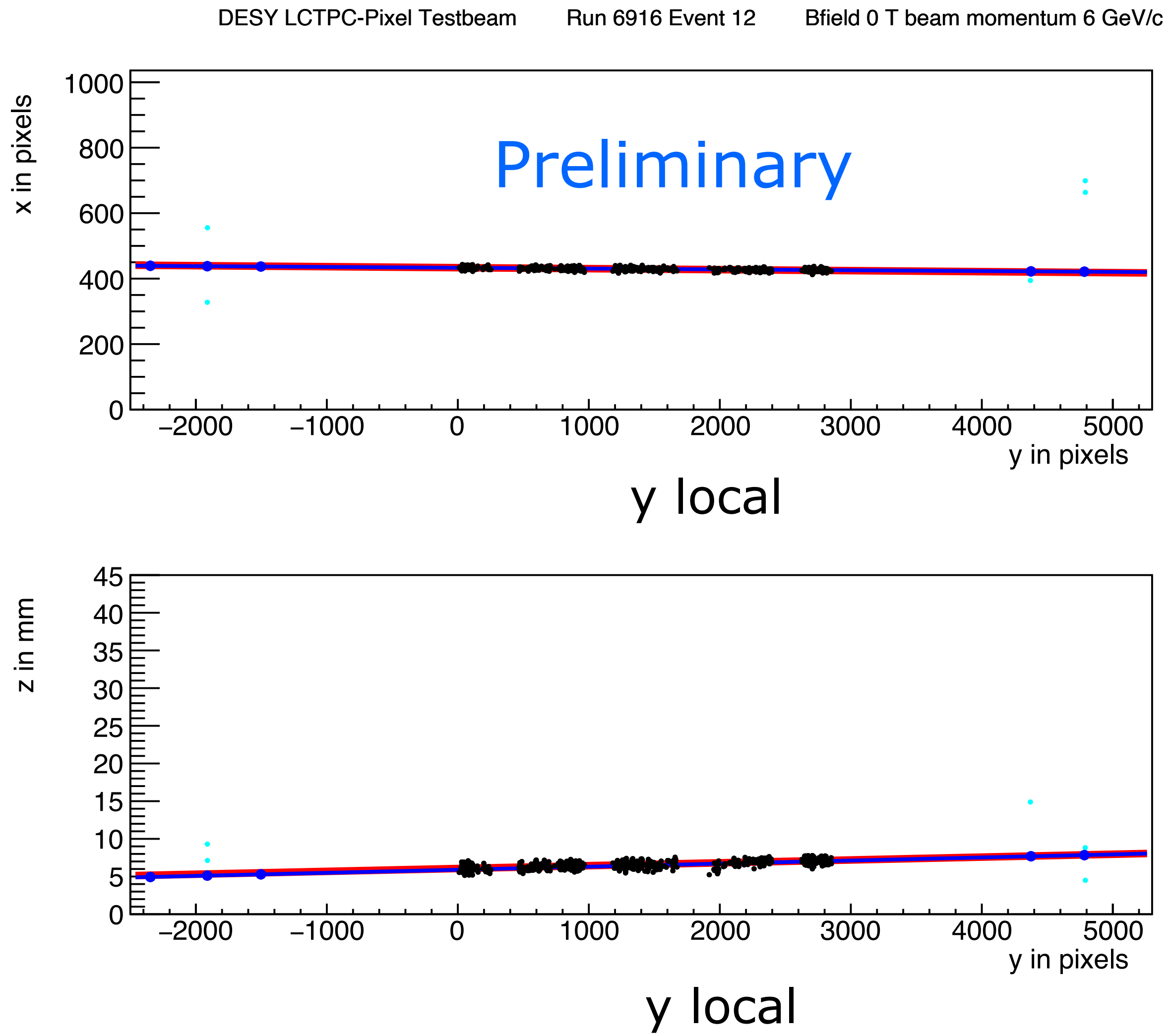
Towards a Pixel TPC part II: particle identification with a 32-chip GridPix detector

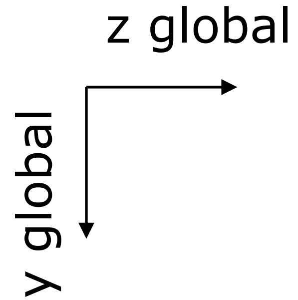
DESY testbeam June 2021



DESY testbeam Module Analysis







Event display with module and telescope

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

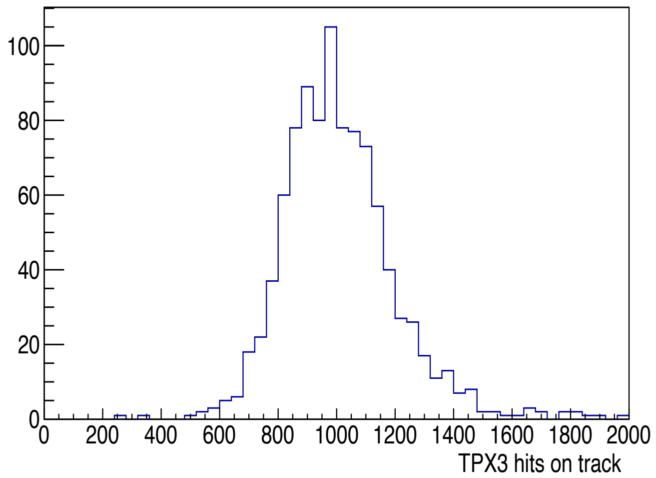
Asymmetric tail outlier removal applied 1071 hits in z kept.

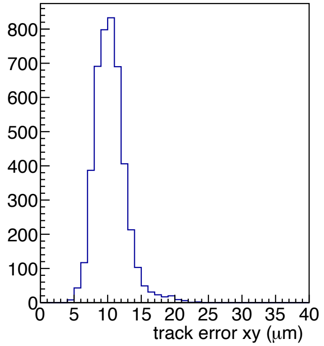
TPX3 track hits
Telescope track hits (off track green)

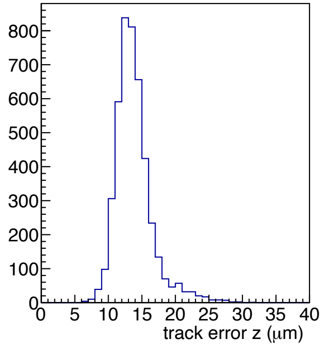
DESY testbeam Module Analysis

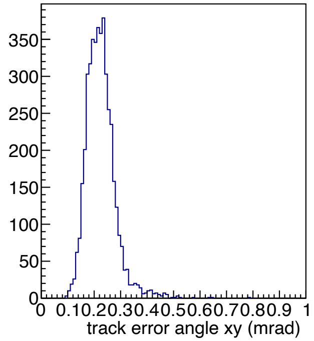
B=0 T and p =6 GeV

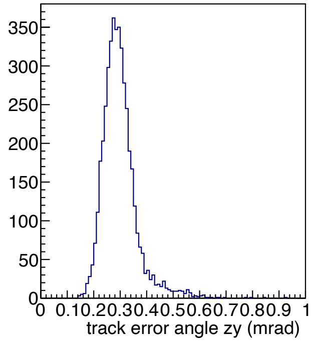
Preliminary











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 mrad (dz/dy)
module tracklength = 157.96 mm

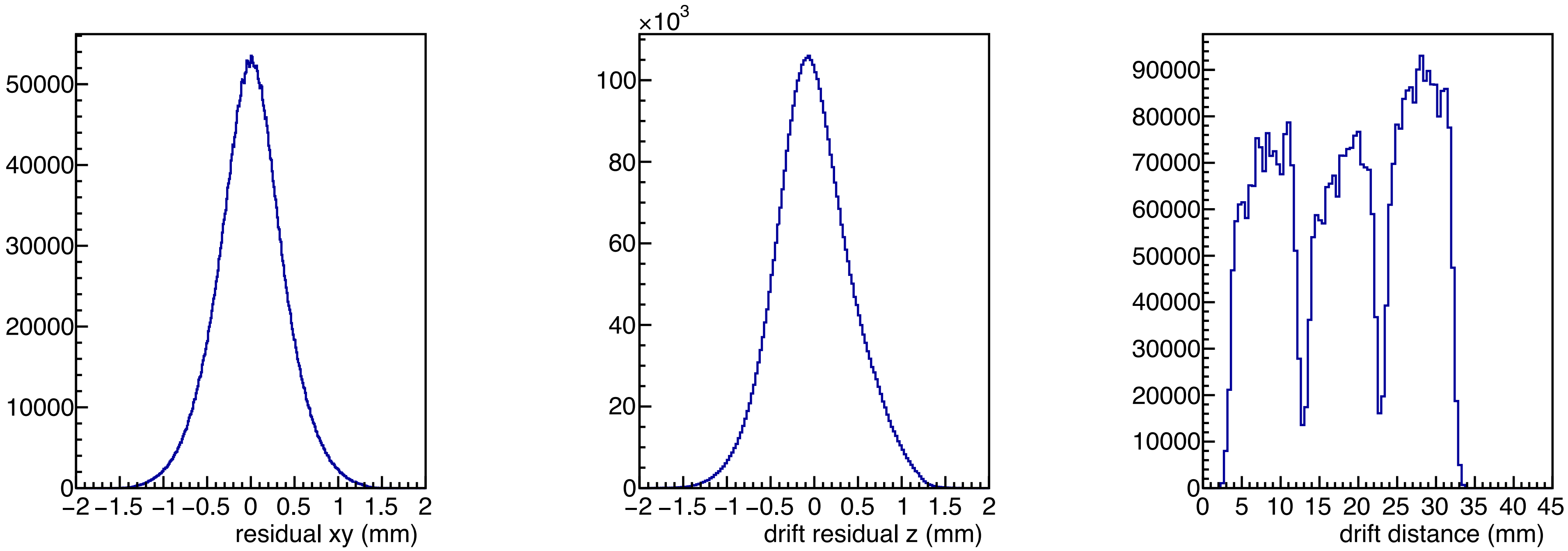
Note that in a B field because of the reduced diffusion the tracking precision will improve substantially

DESY testbeam Module Analysis

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

Three runs at different drift distances

Preliminary

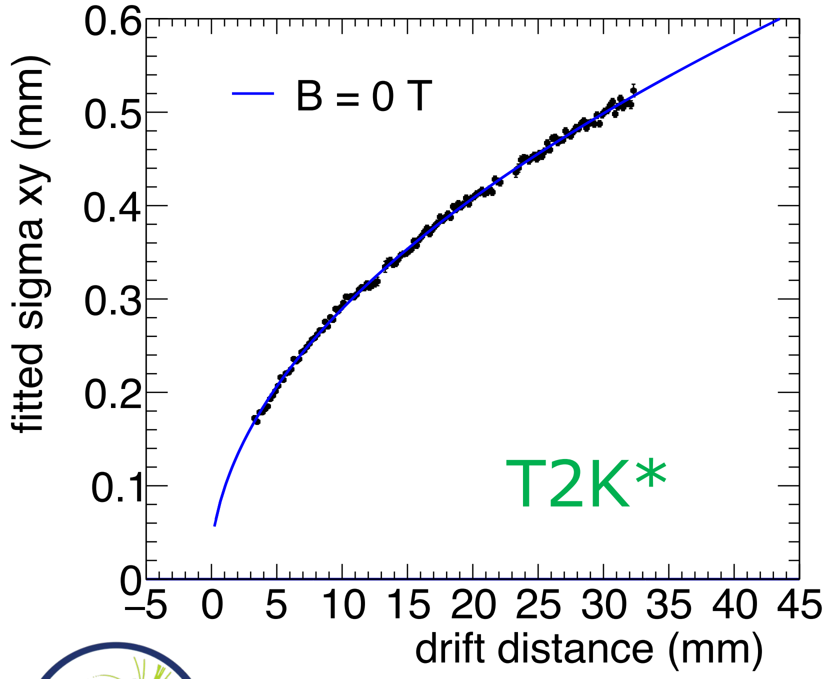


DESY testbeam Module Analysis

B=0, 1 T p=5, 6 GeV

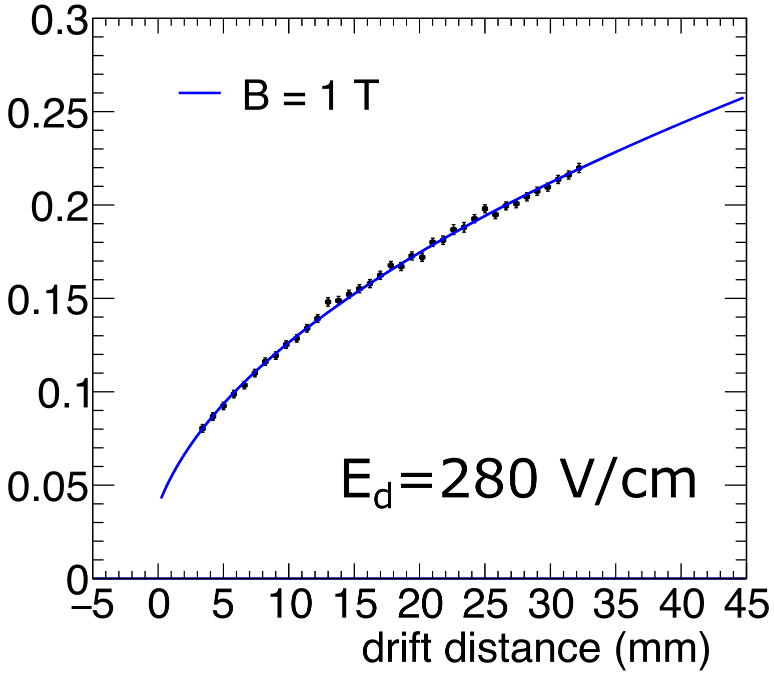
Fitted resolution $\sigma_{xy}{}^2 = \sigma^2_{xy_0} + D^2_T\,(z - z_0)$

D_T 287 ±0.5 $\mu m/\sqrt{cm}$



Preliminary

D_T 120 ±0.5 $\mu m/\sqrt{cm}$



$\sigma^2_{xy0} = \sigma^2_{pixel} + \sigma^2_{xy\ tele}$
$\sigma^2_{pixel} = 55^2/12\ \mu m^2$
$\sigma_{xy\ tele} = 35\ \mu m$

Predictions Magboltz

D_T (0) 287 $\mu m/\sqrt{cm}$ ±4%
D_T (1T) 119 $\mu m/\sqrt{cm}$ ±2%

T2K* = T2K gas with O_2 and H_2O

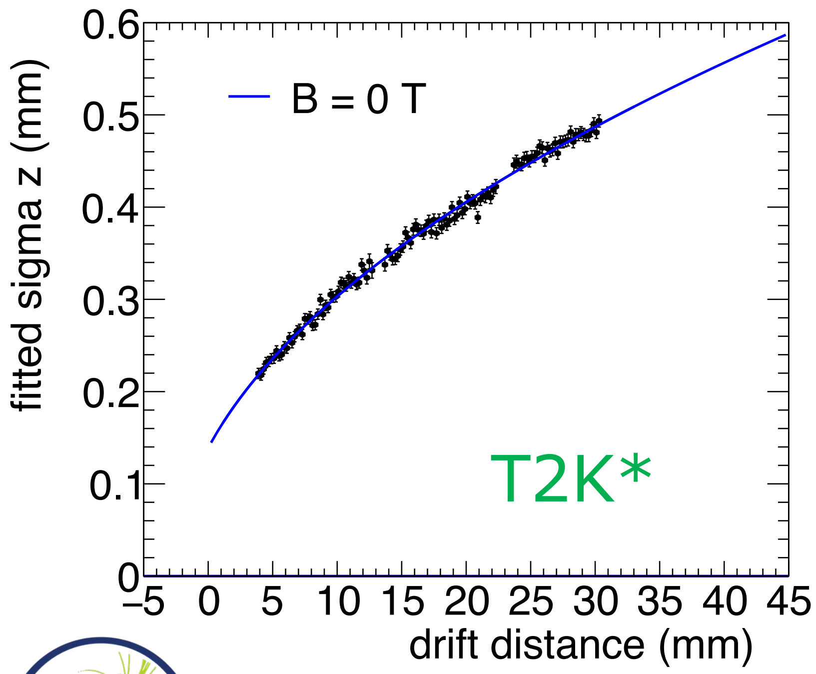
Ar/iC4H10/CO2 gas mixture 93.6/5.0/1.4

DESY testbeam Module Analysis

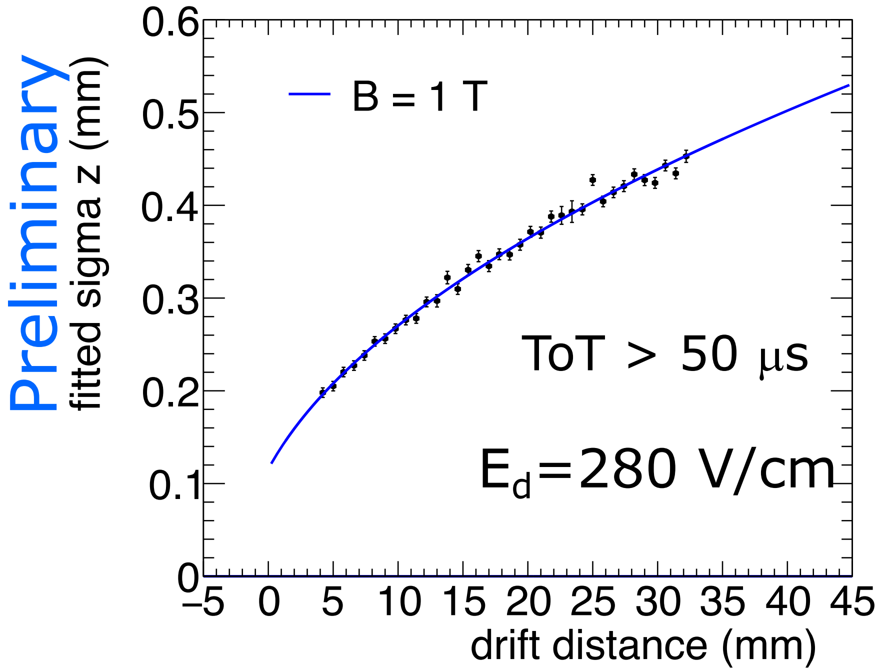
B=0, 1 T p=5, 6 GeV

Fitted resolution $\sigma_z^2 = \sigma^2_{z_0} + \sigma^2_{z\ track} + D^2_L\,(z - z_0)$

D_L 251 ± 14 $\mu m/\sqrt{cm}$



D_L 224 ± 14 $\mu m/\sqrt{cm}$



σ_{z0}= fit 129 (0 T)
114 (1 T) μm

$\sigma_{z\ track}$=50 ± 25 μm

Rather large experimental uncertainty coming from syst uncertainty on $\sigma_{z\ track}$

Predictions Magboltz

D_T (0) 236 ±3 $\mu m/\sqrt{cm}$

D_T (1T) 245 ±4 $\mu m/\sqrt{cm}$

T2K* = T2K gas with O_2 and H_2O

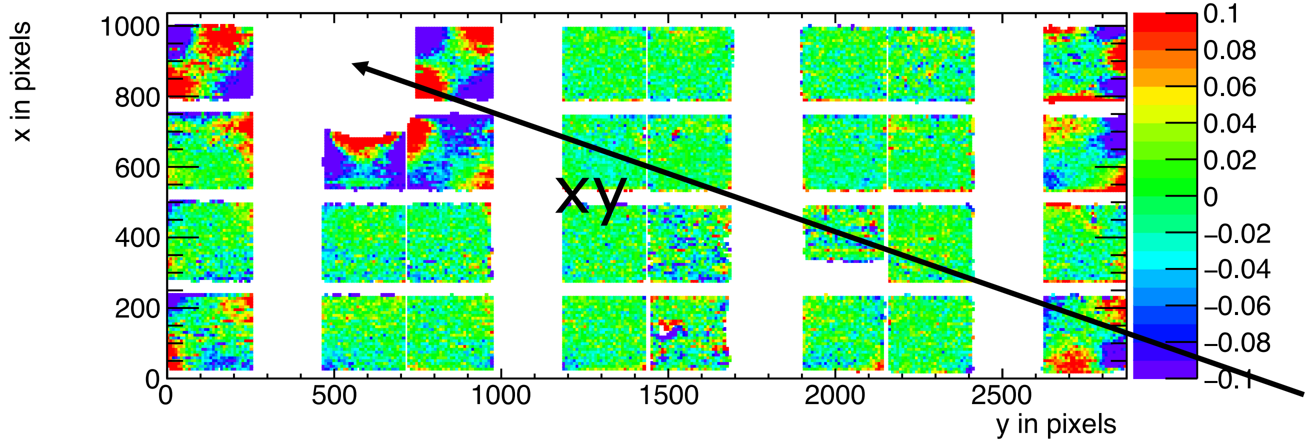
Ar/iC4H10/CO2 gas mixture 93.6/5.0/1.4

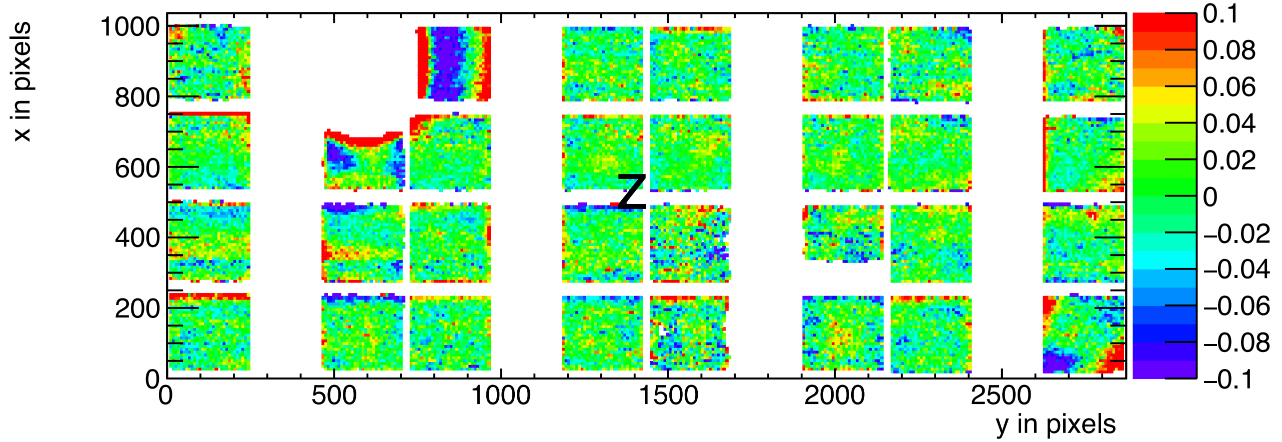
DESY testbeam Module Analysis

B=0 T situation

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

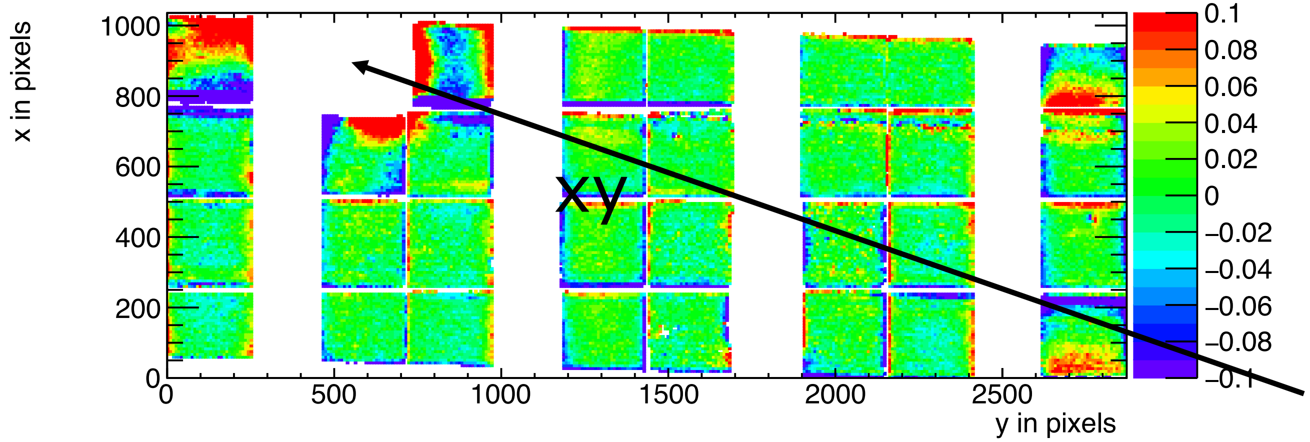
The Efield defined by the field cage is in these areas not homogenous enough

DESY testbeam Module Analysis

B=1 T situation

Mean residuals in the module plane with acceptance cuts

Preliminary



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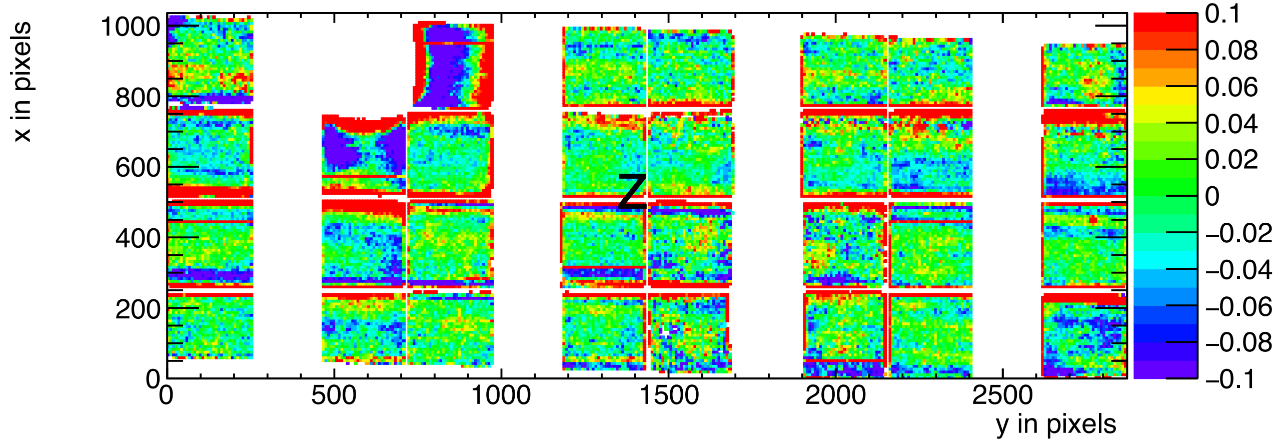


The Efield defined by the field cage is in these areas not homogenous enough

DESY testbeam Module Analysis

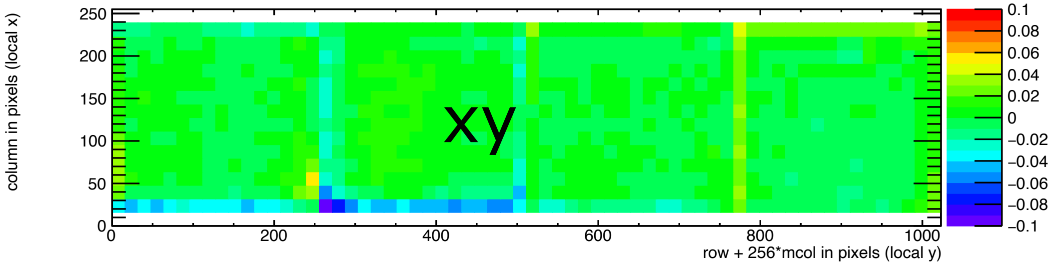
Regrouping the module plane to increase stats

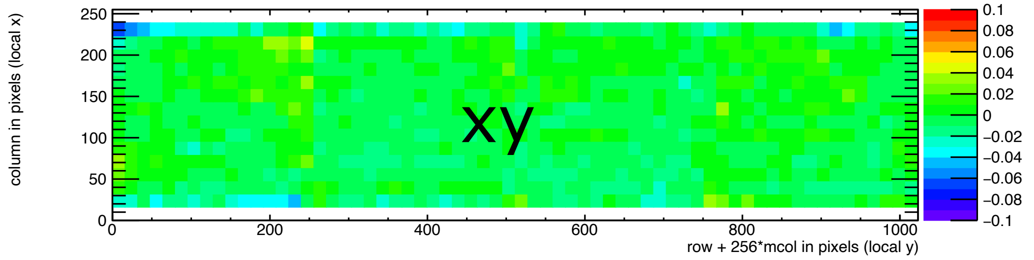
Mean residuals (module) ‘row’ regrouping

B=0 T

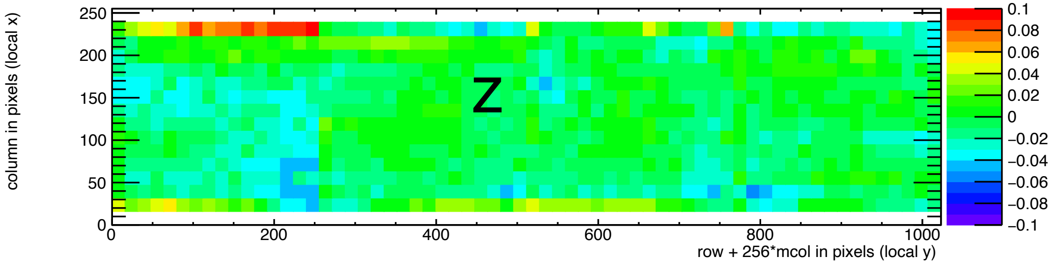
B=1 T

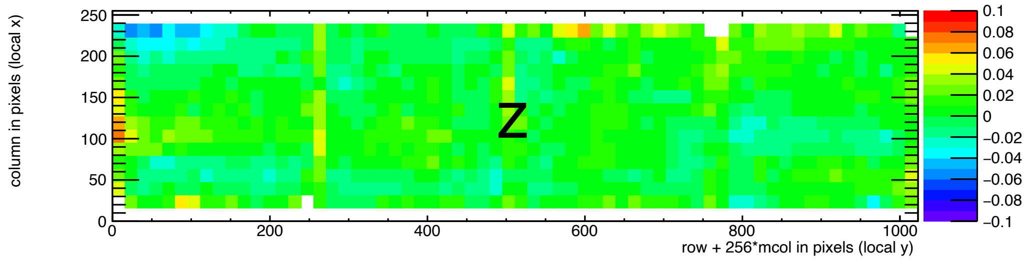
column 256 pixels





Preliminary





row 4x256 pixels

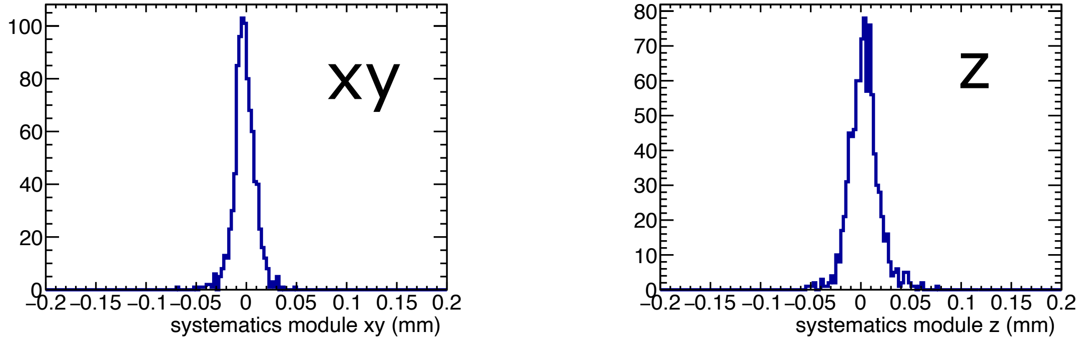
DESY testbeam Module Analysis

B=0 T

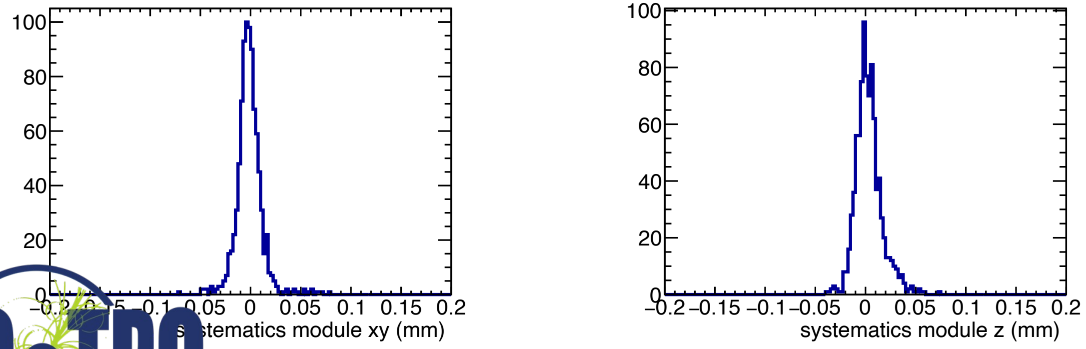
Distribution of mean residuals in the plane

Preliminary

Method row



Method column



B=0 T situation

method	rms (stat) xy	bins xy	rms (stat) z	bins z
row	11 (4) μm	896	15 (5) μm	891
column	13 (4) 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.

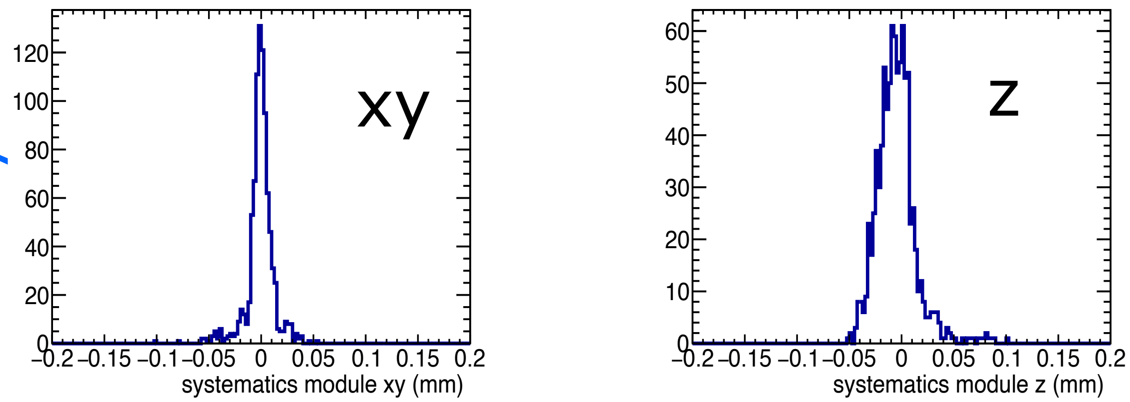
DESY testbeam Module Analysis

B=1 T

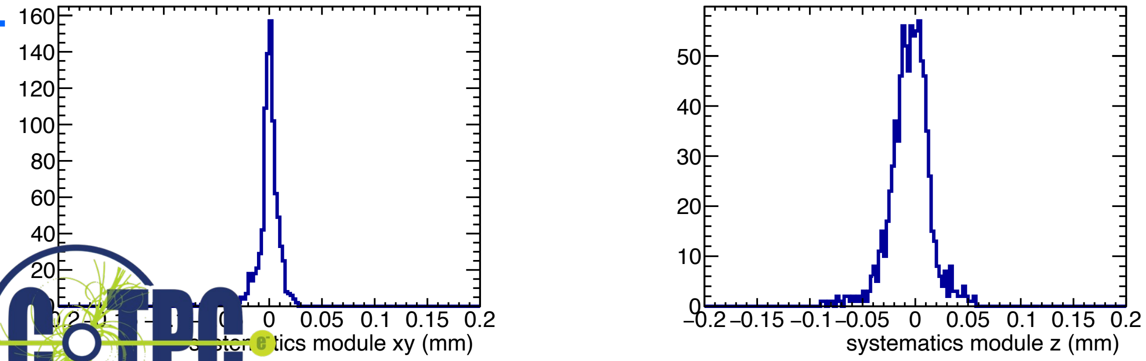
Distribution of mean residuals in the plane

Preliminary

Method row



Method column



B=1 T situation

method	rms (stat) xy	bins xy	rms (stat) z	bins z
row	13 (2) μm	896	19 (3) μm	896
column	11 (2) μm	880	20 (3) μm	880

Conclusions on module performance resolution and precision

- 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 is D_T = 287 ±0.5 D_L = 251 ± 14 μm/$\sqrt{cm}$
- The diffusion coefficients at B=1 T is D_T = 120 ±0.5 D_L = 224 ± 14 μm/$\sqrt{cm}$
  - In agreement with Magboltz D_T = 119 μm/$\sqrt{cm}$ ±2%

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

Conclusions on module performance resolution and systematics

- 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 in the bending plane:
  - deformations in xy stay below 13 μm

DESY testbeam Module Analysis

Analysis topics part of the second paper

Towards a Pixel TPC part II: particle identification
with a 32-chip GridPix detector

A. Measured efficiency at high hit rates

B. Study and characterization of bursts i.e. large numbers of hits due to highly energizing particles (e.g. delta's)

C. Extraction of the resolution as a function of the incident angle using circles (helixes)

DESY testbeam Module Analysis

Efficiency at high hit rates

- The efficiency of the device to detect a hit in a high (low) rate environment is measured comparing the mean time over threshold for low and high rate runs at B fields of 0 and 1T.
- A succesfull approach is based on hits associated to TPX3 tracks using the two central rows of six chips. The mean ToT was calculated for ToT values between 0.15 and 1.4 μs to remove the tail.
- The change in ToT in low and high rate runs is then related to a (maximum) the efficiency change.

DESY testbeam Module Analysis

Efficiency at high hit rates

Table 2: Measured mean ToT and rates for different runs

run	B [T]	ToT1 [μs]	ToT2 [μs]	triggers 10^3	run time [10^3s]	Hits1 10^6	Hits2 10^6	trig rate [Hz]	Rate1 [10^3hits/s]	Rate2 [10^3hits/s]
6916	0	0.628	0.653	16.8	5.81	6.25	13.1	2.9	1.08	2.26
6934	0	-	0.651	73.4	0.60	-	20.5	121.7	-	33.92
6935	0	0.620	-	73.9	0.60	6.95	-	122.5	11.51	-
6969	1	0.650	0.666	7.94	3.45	1.93	2.16	2.3	0.56	0.62
6983	1	0.657	0.678	67.9	0.70	11.6	14.1	96.2	16.44	19.94

- Tot 1 (2) = mean ToT for upper/lower part (each 6 chips) stat errors are neglible
- Hits 1 (2) are raw hits with ToT> 0.15 μs
- Trigger rate is not corrected for efficiency off scintillators and duty cycle of machine
- The raw hit rates are not affected by the trigger efficiency

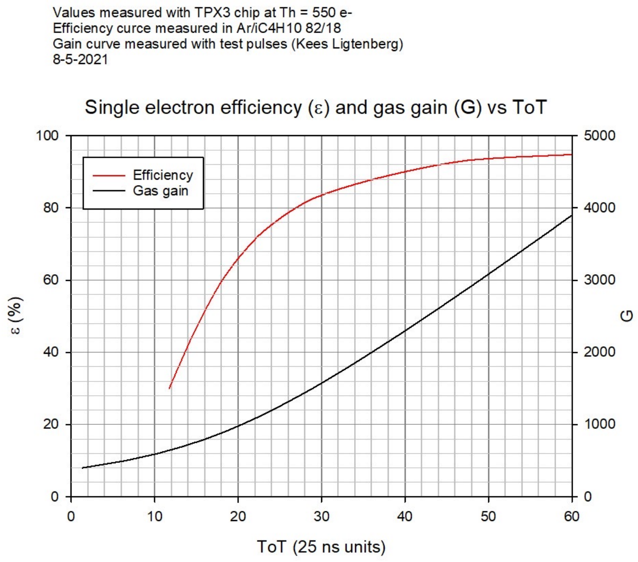
DESY testbeam Module Analysis

Efficiency at a high hit rates

- The relative change in mean ToT is related to the relative change in the efficiency ε - at the working point around 0.6 μs - as:

$$\delta\varepsilon/\varepsilon \sim 0.5\ \delta ToT/ToT$$

- This means that the efficiency δε/ε is stable at the level of +0.9% (B=1T) and -0.6% (B=0T) for hit rates up to 3.3 (5.7) kHz per chip.



Conclusion

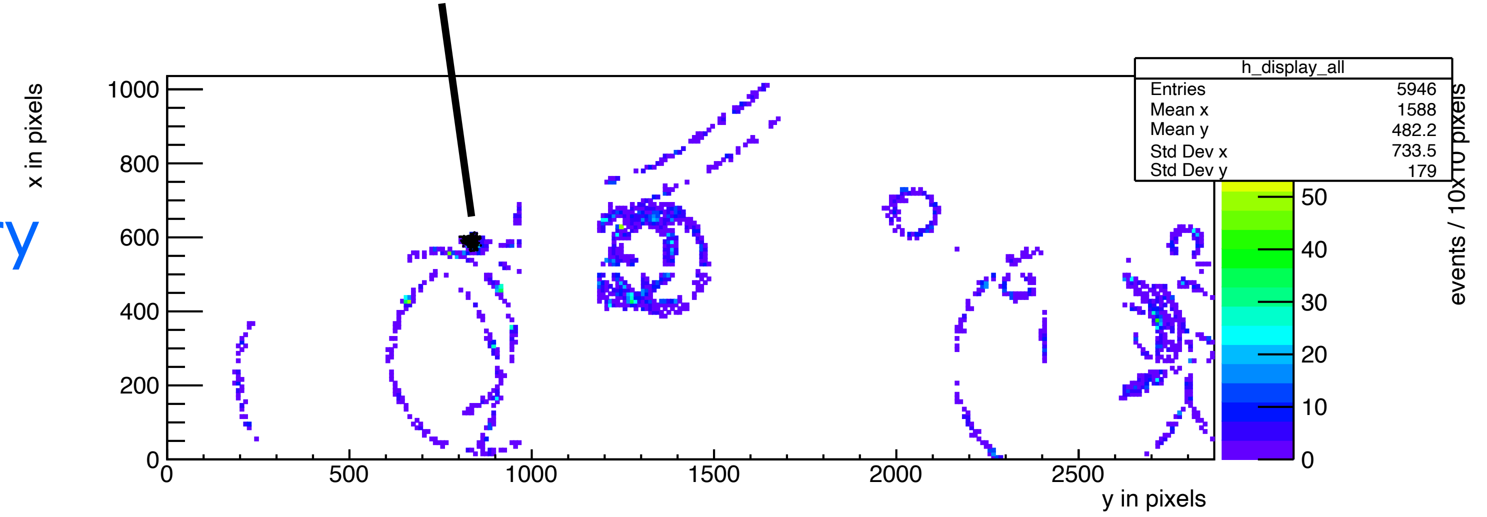
It is demonstrated that running at hit rates up 5.7 kHz per chip or 2.9 kHz/cm^2 (a quite high rate) gives at most a reduction of 0.6% in the relative efficiency.

DESY testbeam Module Analysis

Characterisation of large hit bursts

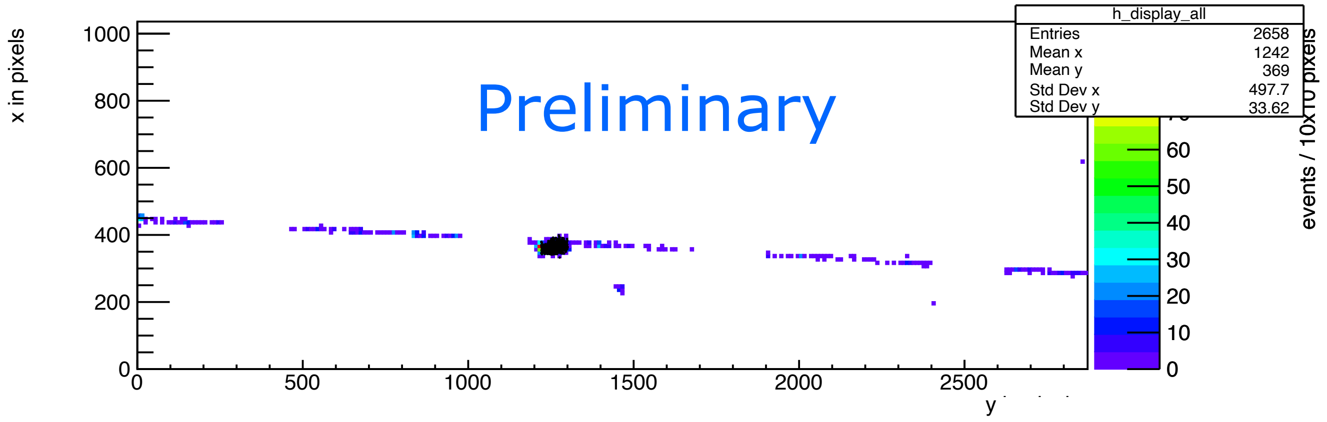
- It is interesting to study the large hit bursts, where in a location many hits are detected.
- For this pattern recognition was written: looking in a radius of 25 pixels for burtst of hits. For large bursts this radius is increased by a factor √(N/400) and maximally 2. For the largest burst 3180 hits the radius is 50 pixels.
- Here a large burst 463 hits for the many circles event 2:

Preliminary

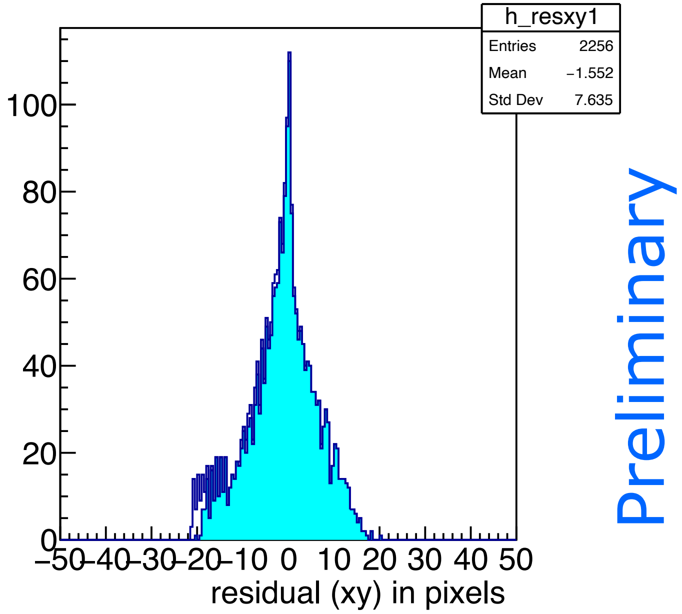


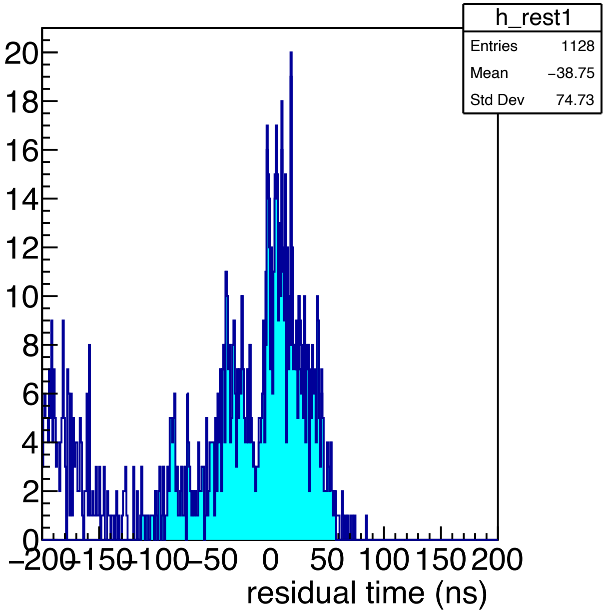
DESY testbeam Module Analysis

Large hit bursts



Event 42 with a burst of 1066 hits





Note that the TPX3 deadtime of a pixel is 475 ns and therefore not all the hits in the core of the burst will be detected

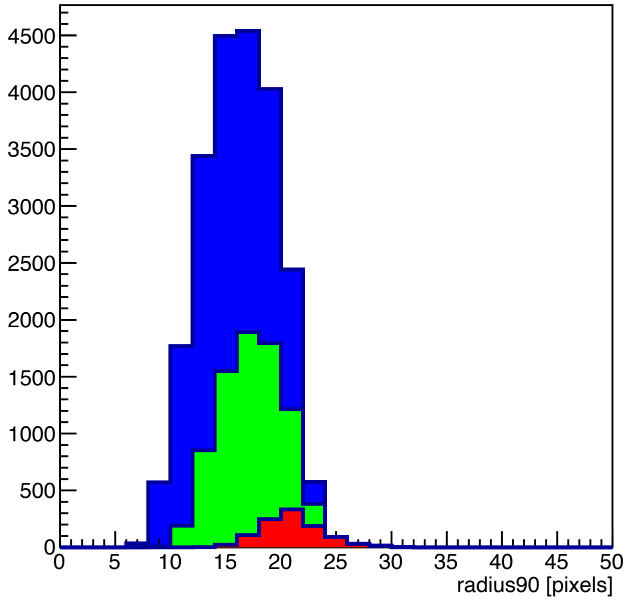
DESY testbeam Module Analysis

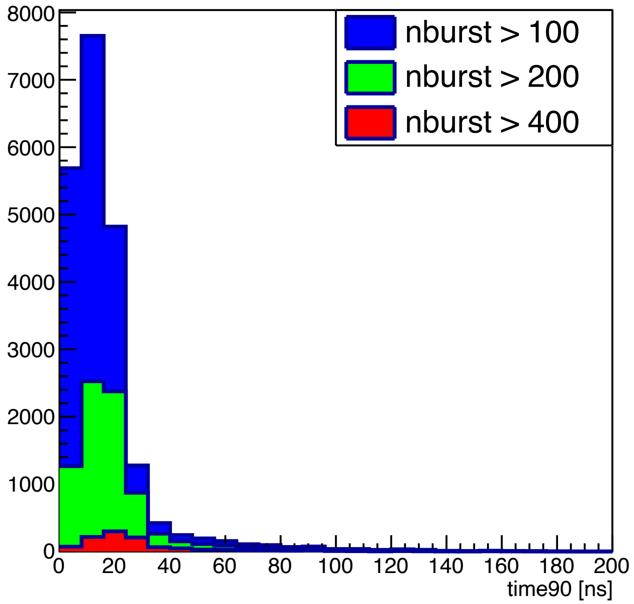
Characterisation of large hit bursts B = 0

Preliminary

Radius90 (time90) is radius (time) where 90% of the hits are contained

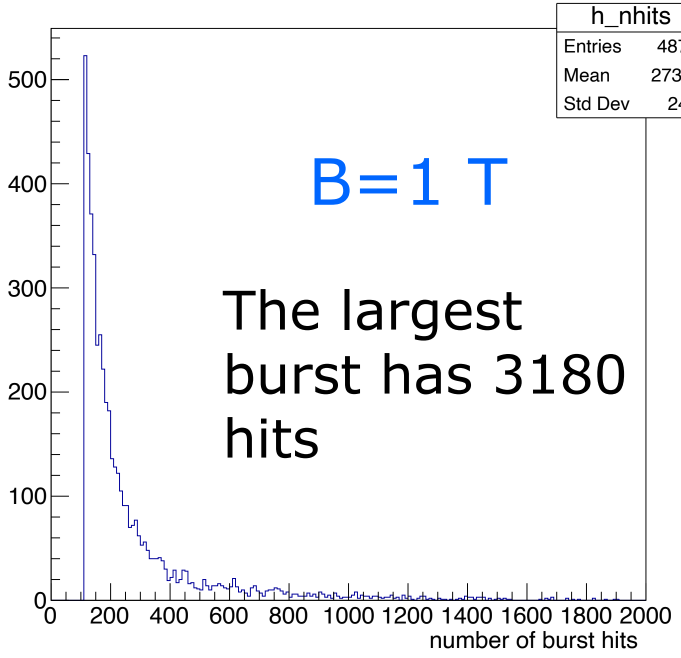
For the B=0 radius90 and time90 distributions are pretty similar for large hit bursts.





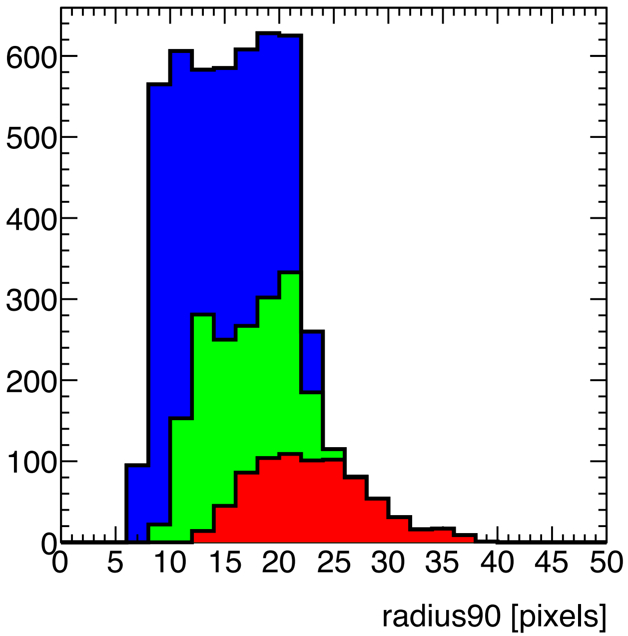
DESY testbeam Module Analysis

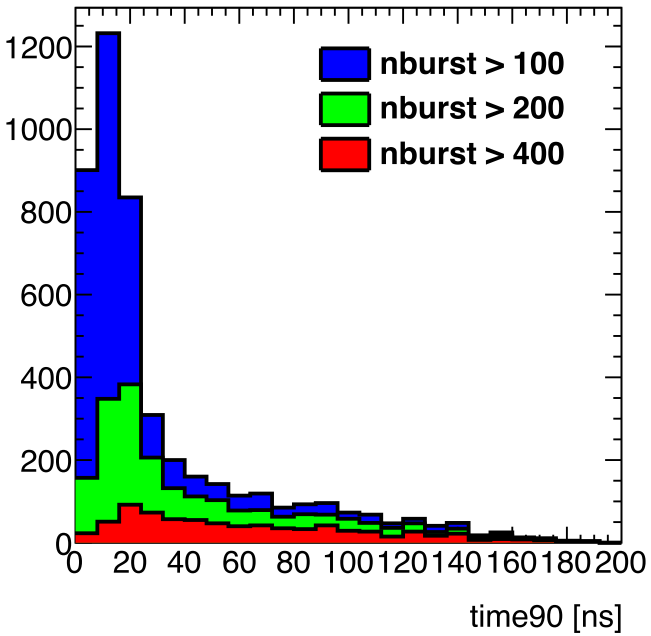
Characterisation of large hit bursts B = 1 T



Radius90 and time90 are pretty different for large bursts!

Preliminary





data B=1 T p= 6 GeV run 6969 ~ 8000 triggers (events)

DESY testbeam Module Analysis

Track fitting and large hit bursts

For tracking this means that it is important to cut tightly around the residuals in xy and z. In particular the cut in z (time) reduces the impact of bursts in the B=1 T data – as shown in the time90 distribution. In the B=0 T data the reduction is much smaller.

Still after say 3 σ cuts in xy and z the burst will contribute locally to the resolution: 6 $\sigma_{d0,z}/\sqrt{(12)} = 1.73\ \sigma_{d0,z}$ in stead of with 1 $\sigma_{d0,z}$
This means that a better track fit can be performed by down weighting the burst events with 0.58.

DESY testbeam Module Analysis

Does a Pixel TPC have a hit resolution independent of the local track angle?

- In a pixel TPC one expects that the resolution is independent of the local track angle ϕ. For pads one expects and has measured a rather strong dependence.

- In order to study this topic we use circular tracks (curlers)*. Each hit on the circle will have a different local track angle ϕ
- To get a part of a circle and a large ϕ phi range, we analysed the B=1 data for run 6969 p = 6 GeV beam.
- a Hough transform for a circle was coded; also a straight line hough transform was used to reject high momentum tracks.

- We took data with small incident beam angles plus min 10 degrees; in a circle one will have 360 degrees incident angles.

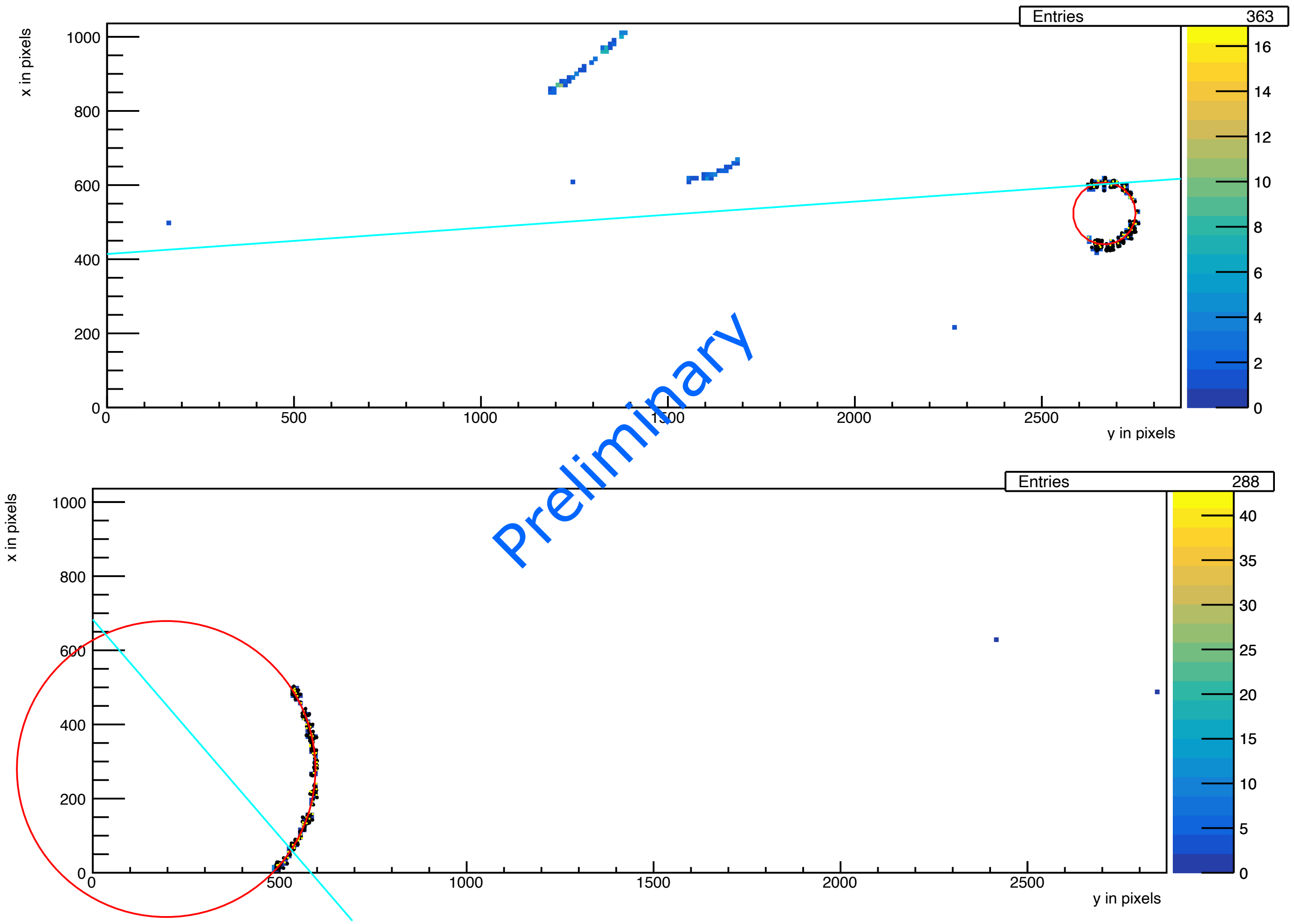
DESY testbeam Module Analysis

Circle finding

The center should lie in the plane

Pattern finding can get disturbed by large hit bursts and "straight" line beam particles

The solutions in red are selected



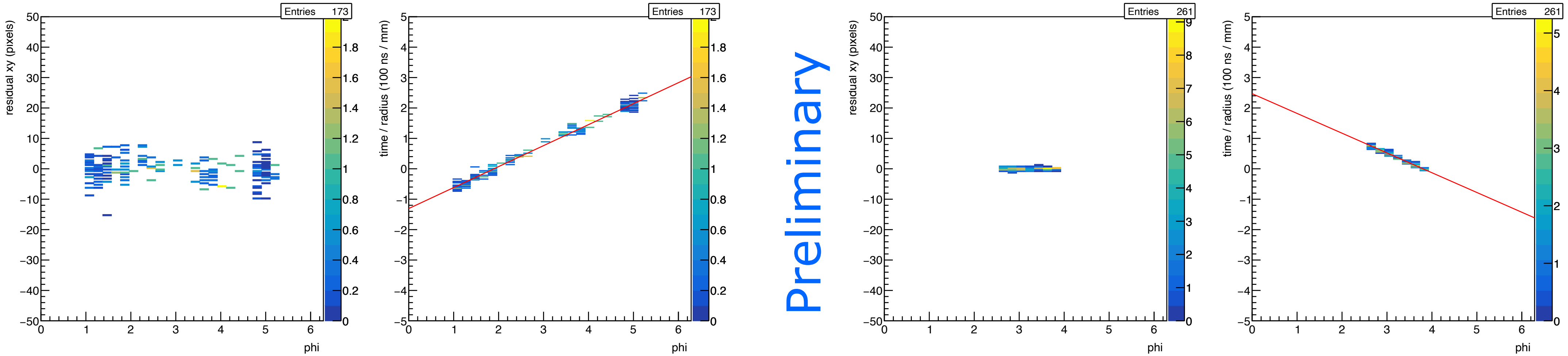
Events 14 and 41

R = 1024 pixels
p = 16.9 MeV/c
R = 121 pixels
p = 1 MeV/c
R = 25 pixels
p = 412 keV/c

DESY testbeam Module Analysis

Circle finding

For the events 14 and 41. Calculate phi around the circle (phi = 0 is pointing opposite the local y axis = right to left in the event display).The drift time (z) can be fitted vs phi. It has a linear dependence (for a helix). The residuals in z are calculated after the fit.



phi hit on circle

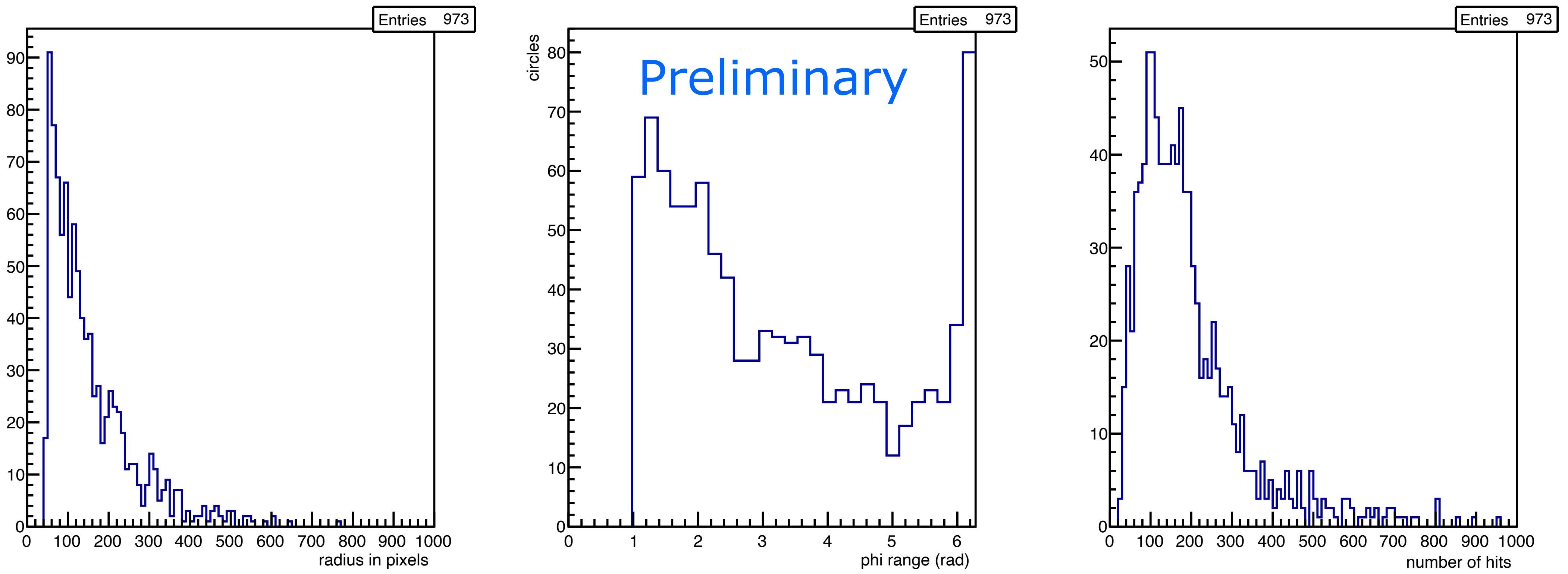
DESY testbeam Module Analysis

Event selection for circles

- Radius > 50 pixels with at least 20 selected hits
- Reject circles with a better SL line fit by applying cuts on the χ^2 and number of hits for the circle and line hypothesis.
- Resolution σ_{xy} = 4 pixels and σ_z = 1 mm
- Track χ^2_{xy}/dof < 5 χ^2_z/dof < 5
- Phi range (phi max – phi min) > 1 rad
- phi> 8 π/32 and phi < 2 π – 8 π/32
- Remove hits near edge of chip (15 pixels columns and rows)
- Residual cuts at 2.5 σ (xy and z)
- Down weighting of large clusters (counting hits N in bins Rϕ 1 pixels) where w = 1/ (N(bin-1)+N(bin)+N(bin+1))

DESY testbeam Module Analysis

Selected circles plots



DESY testbeam Module Analysis

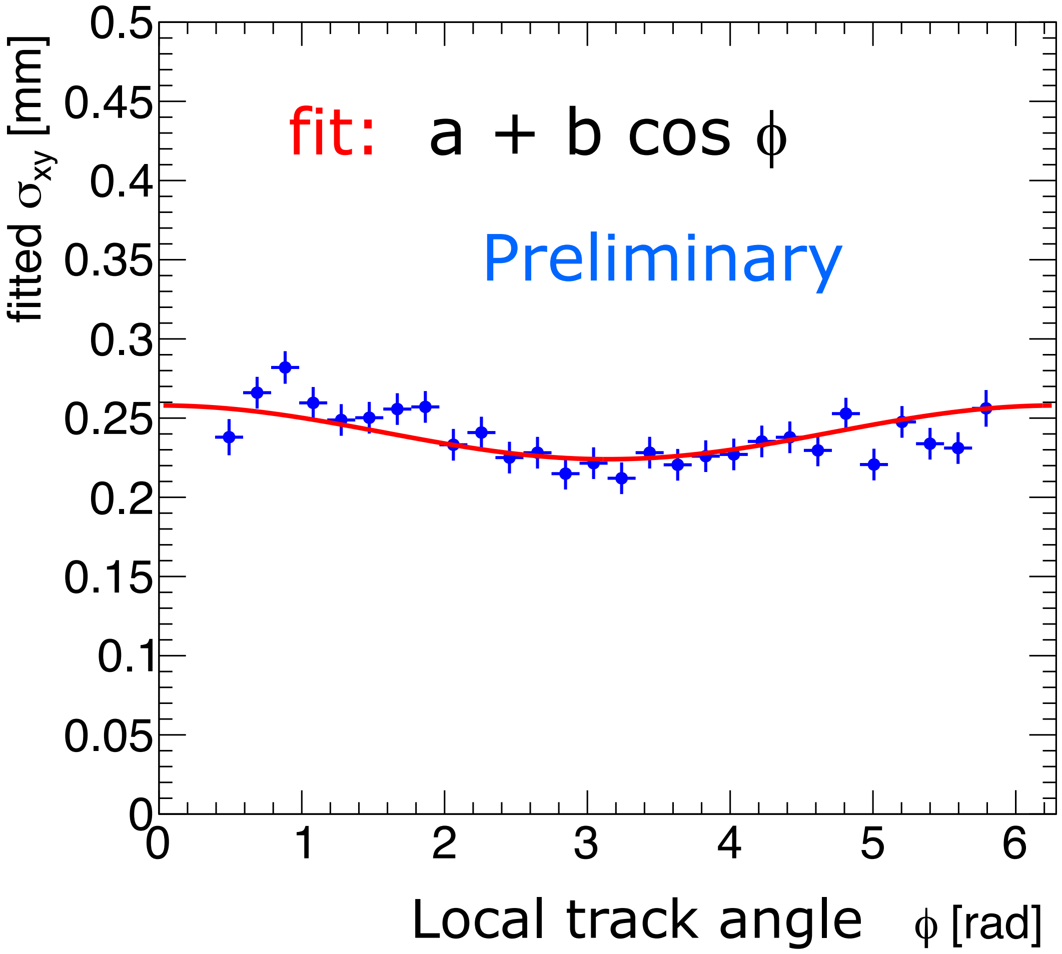
Fitted resolution in xy

More details in backup

Fit result resolution flat in phi
0.241 ± 0.016 mm

Conclusion

the Pixel TPC single electron resolution is – as expected - independent of the local track angle within an uncertainty of 16 μm.



Conclusions Pixel TPC analysis topics

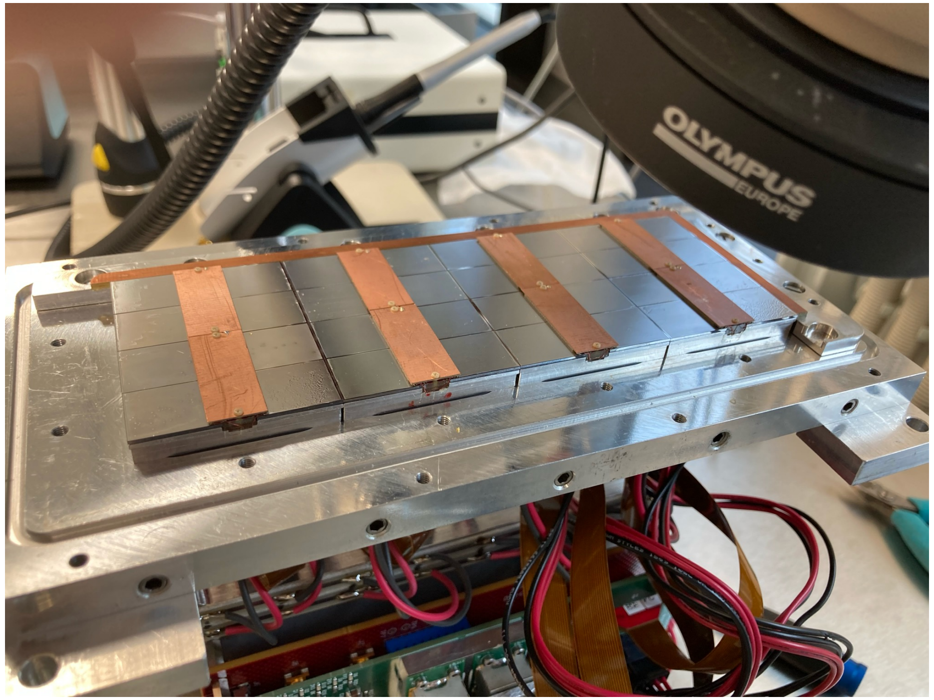
A. Measured efficiency at high hit rates
It is demonstrated that running at hit rates up 5.7 kHz per chip or 2.9 kHz/cm^2 at most a reduction of 0.6% in the relative efficiency.

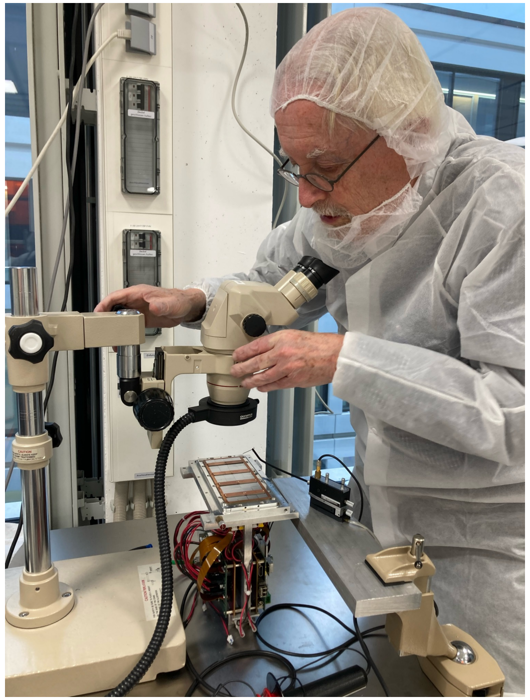
B. Characterization of bursts
The time distribution in the B=1 T data is most sensitive to reject burts. In the track fit an improvement can be obtained by identifying and downweighting burst.

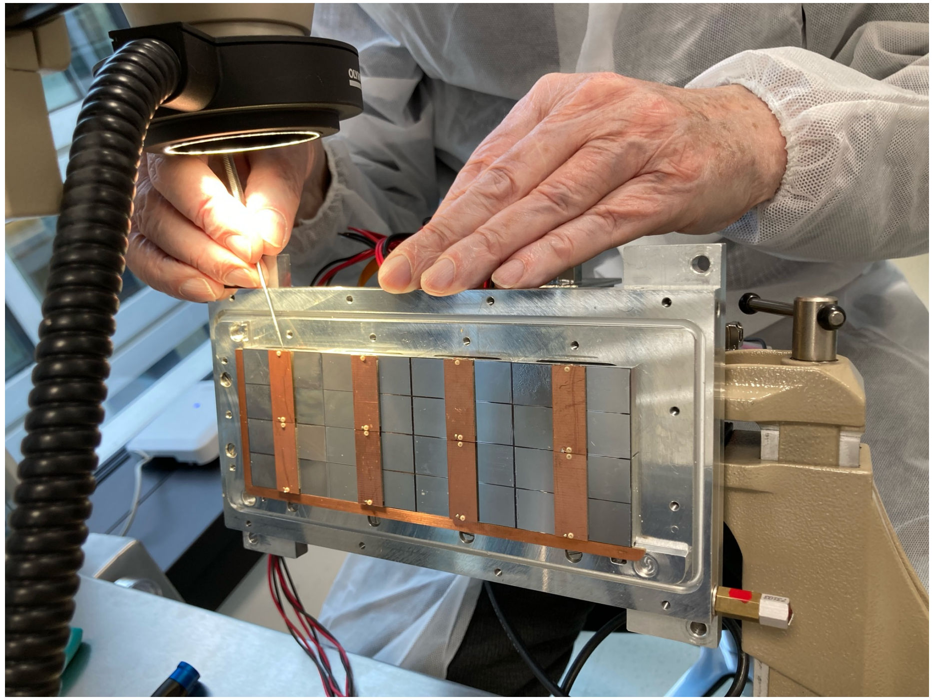
C. The Pixel TPC single electron resolution is – as expected - independent of the local track angle within an uncertainty of 16 μm.

Backup

Pictures of repair work in Bonn







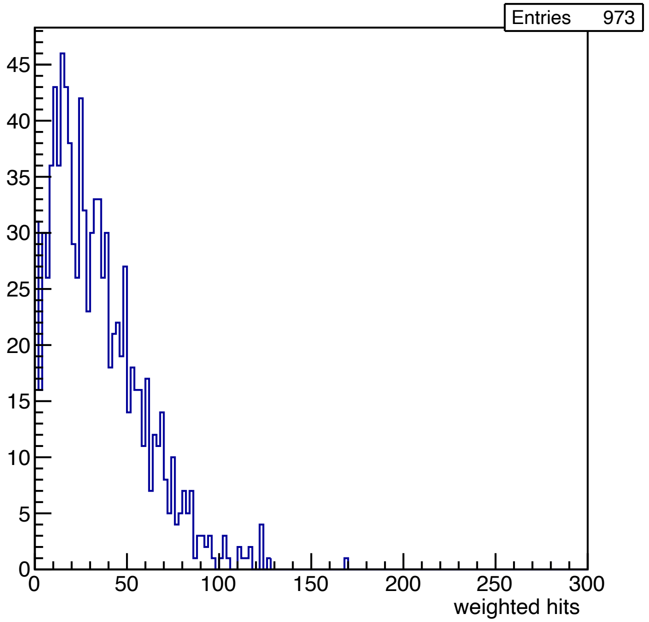
The short in chip 11 was succesully repaired by Fred Hartjes

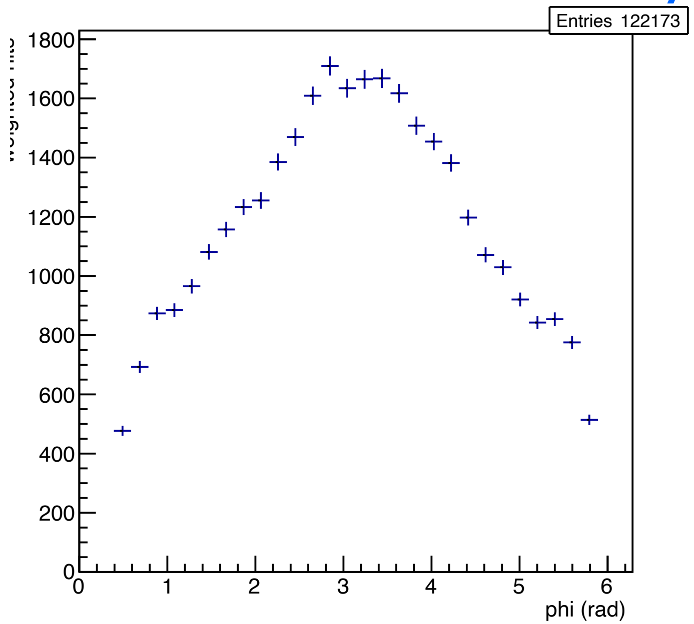
DESY testbeam Module Analysis

Backup

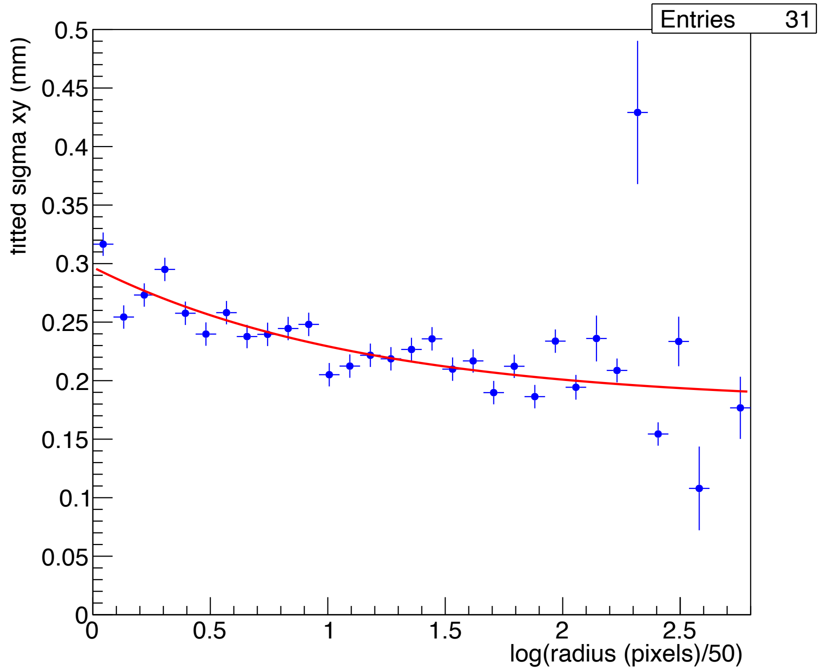
Selected circles plots weighted

Preliminary





local phi angle



There is a dependency of the resolution of phi and the radius
Small radii correlated to large phi range