Pixel TPC resolution and deformation results

Yevgen Bilevych, Klaus Desch, Sander van Doesburg, Harry van der Graaf, Fred Hartjes, Jochen Kaminski, Peter Kluit, Naomi van der Kolk,
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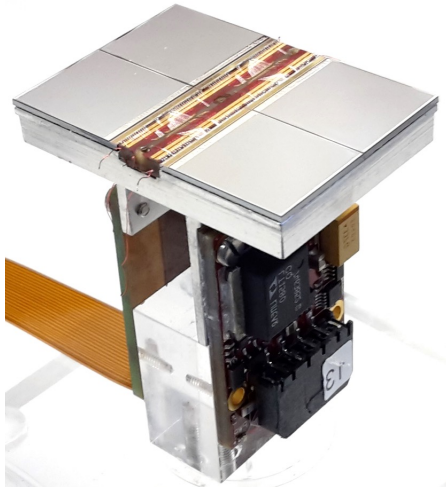
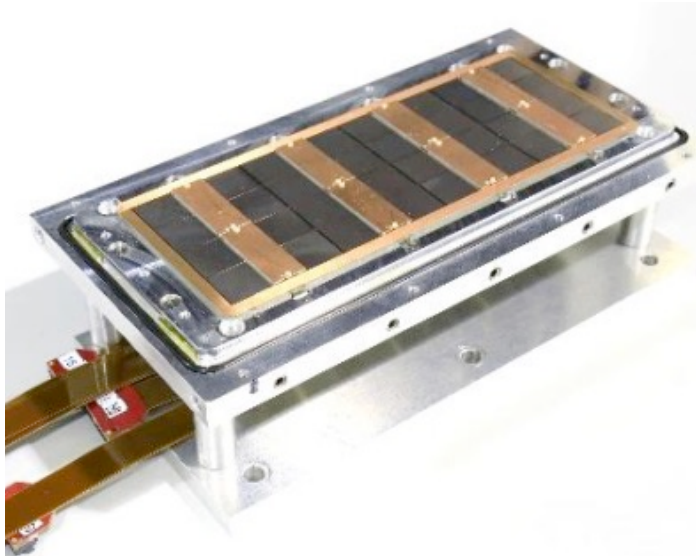
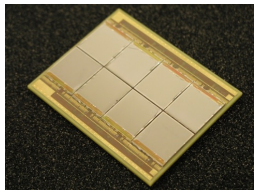


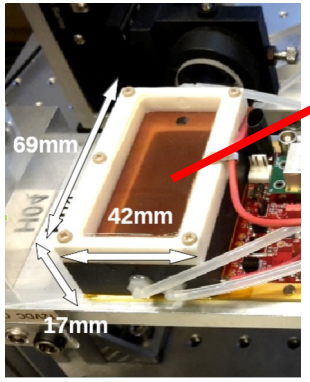


LCTPC DESY meeting March 2024

Pixel TPC



(Octopuce)

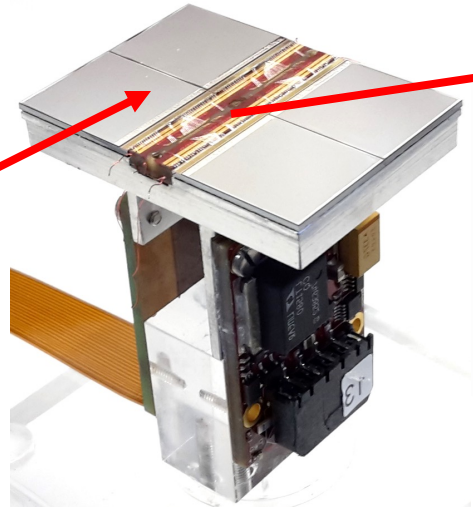


(TimePix1)

TPX3 chip

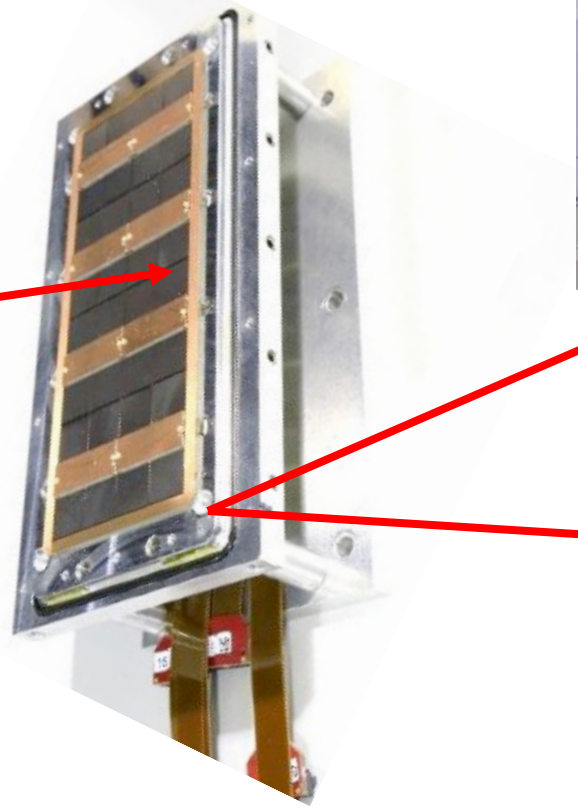
(2007-14)

2017



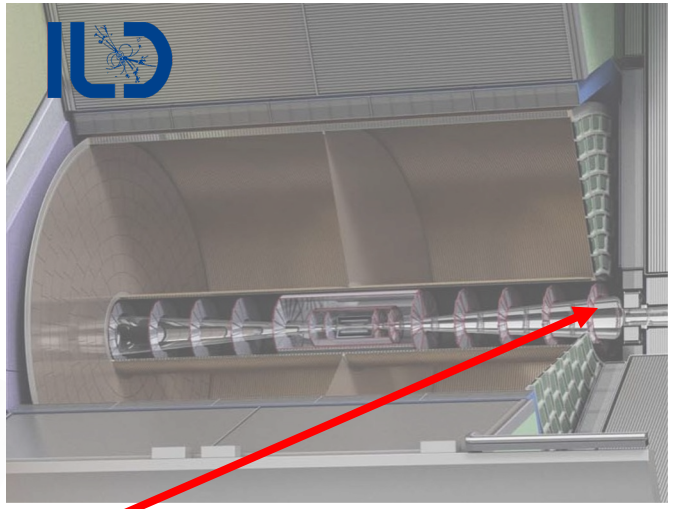
Quad

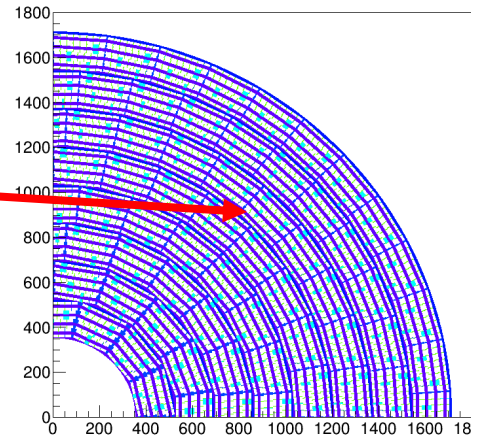
2018



Module

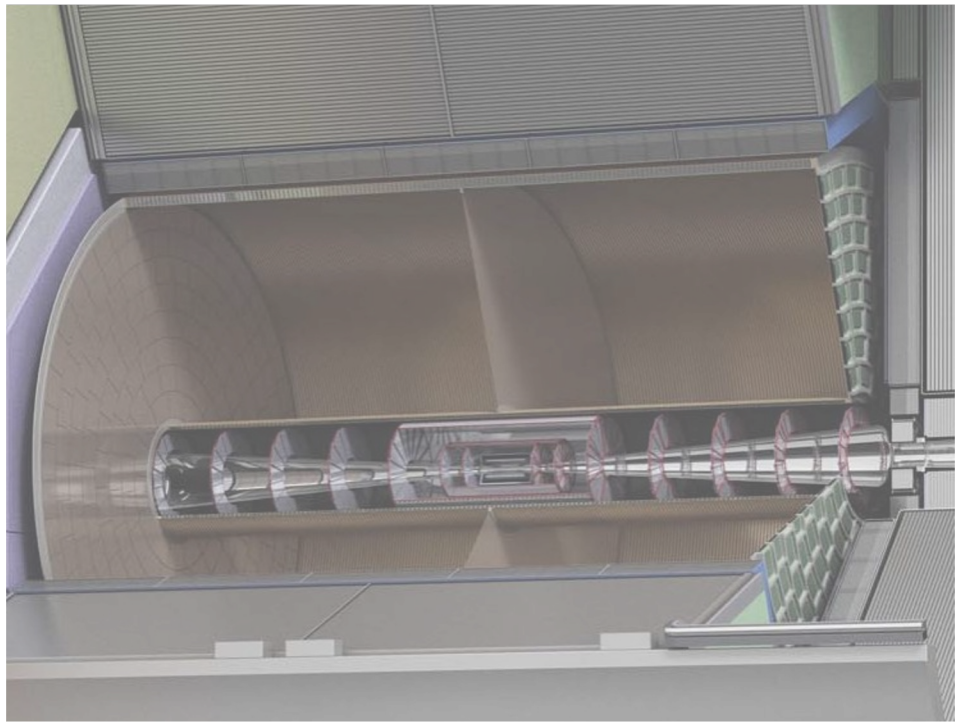
2019

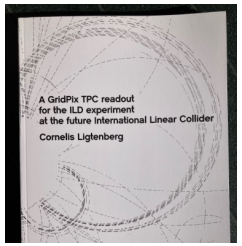




TPC plane

Pixel TPC



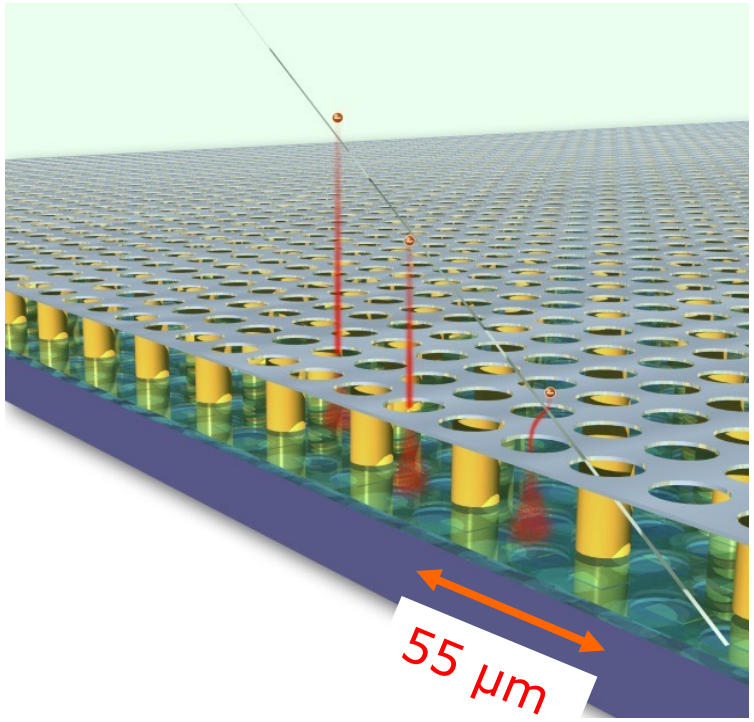


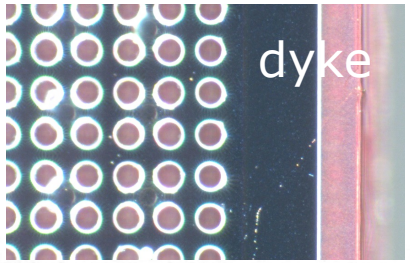
- Material budget is
  - 0.01 X_0 TPC gas
  - 0.01 X_0 inner cylinder
  - 0.03 X_0 outer cylinder
  - < 0.25 X_0 endplates (incl readout)
- Note the very low budget in the barrel region. Material budget can be respected by different technologies like GEM, MicroMegas and Pixels
- TPC is sliced between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

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

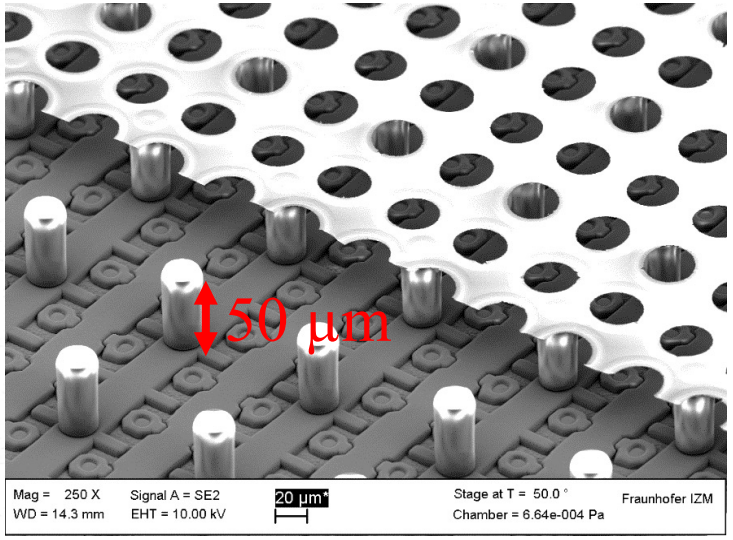
GridPix technology

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



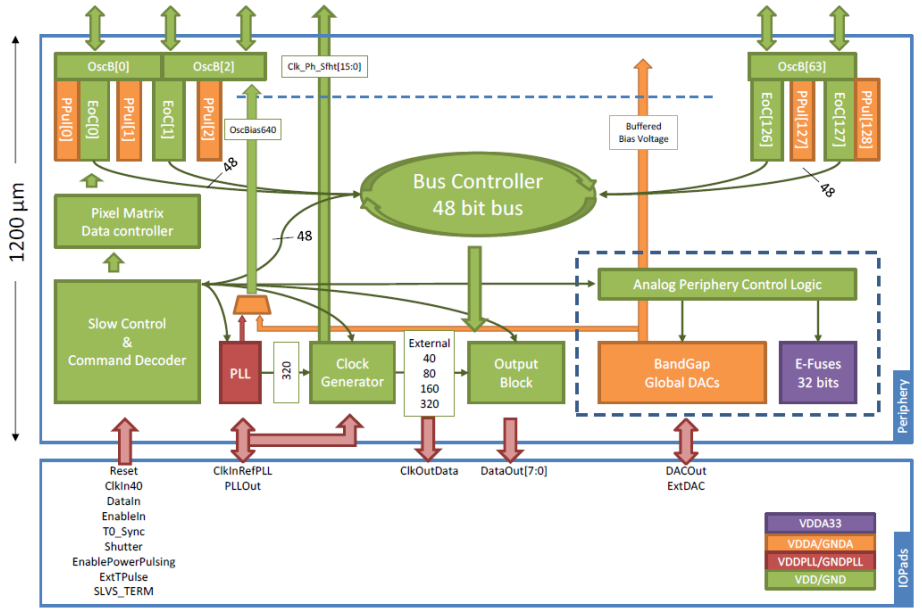


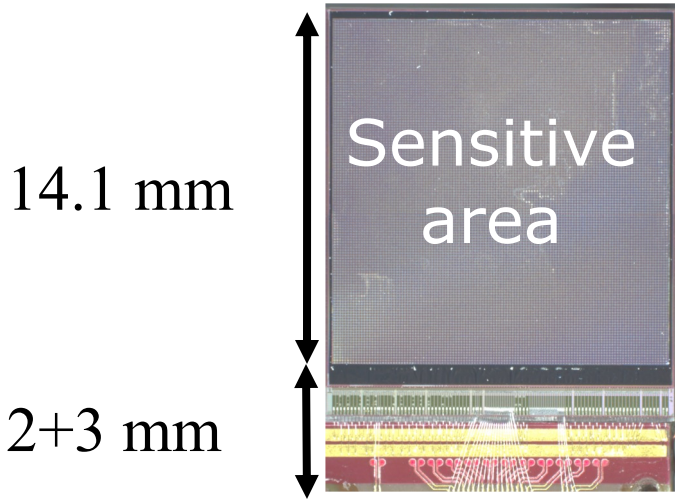
- Aluminium grid (1 µm thick)
- 35 µm wide holes, 55 µm pitch
- Supported by SU8 pillars 50 µm high
- Grid surrounded by SU8 dyke (150 µm wide solid strip) for mechanical and HV stability



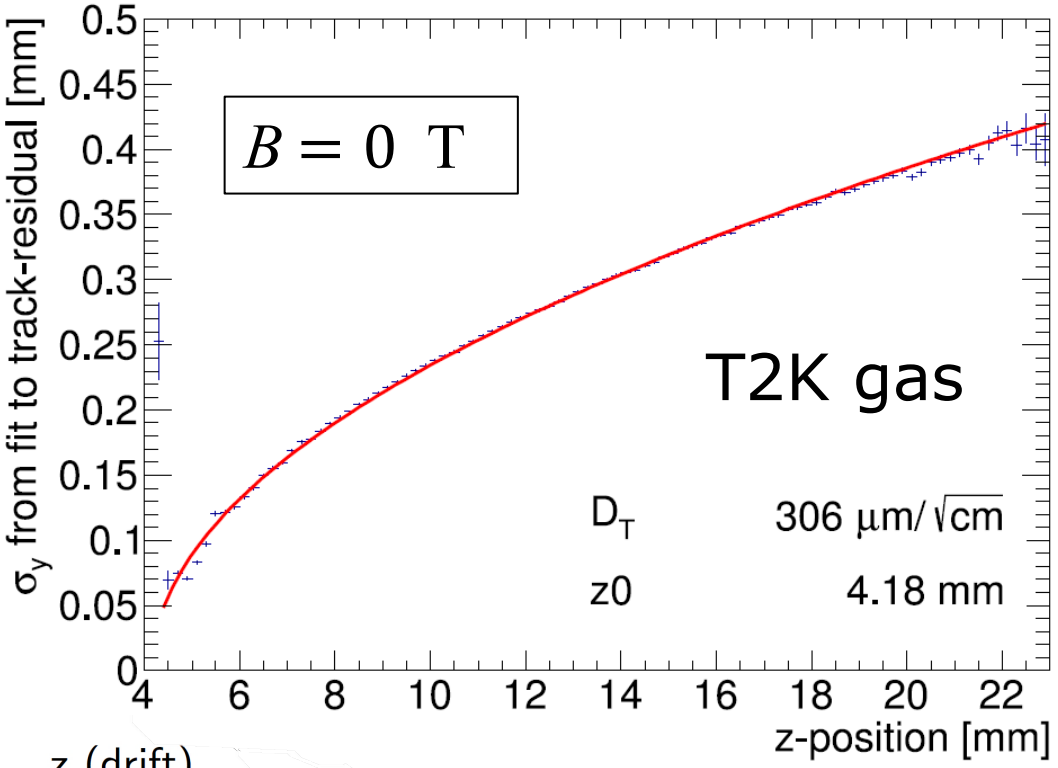
Pixel chip: TimePix3

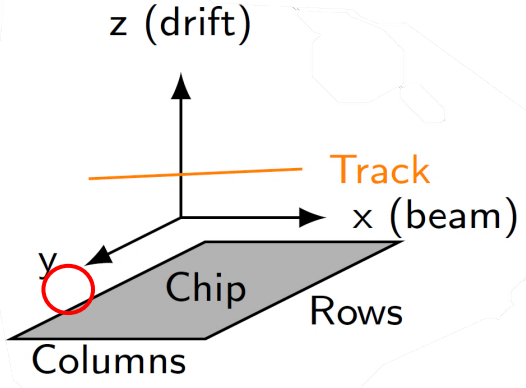
- 256 x 256 pixels
- 55 x 55 µm pitch
- 14.1 x 14.1 mm sensitive area
- TDC with **640 MHz clock** (1.56 ns)
- Used in the data driven mode
  - Each hit consists of the **pixel address** and **time stamp** of arrival time (ToA)
  - Time over threshold (ToT) is added to register the signal amplitude
  - compensation for time walk
  - **Trigger** (for t_0) added to the data stream as an additional time stamp
- Power consumption
  - ~1 A @ 2 V (2W) depending on hit rate
  - good cooling is important





Single hit resolution in transverse direction





$D_T = 306\ \mu m/\sqrt{cm}$

$(318 \pm 7\ \mu m/\sqrt{cm}$ expected)

Results from Bonn-Elsa testbeam in 2017
https://doi.org/10.1016/j.nima.2018.08.012

Single hit resolution in pixel plane:

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

Depends on:

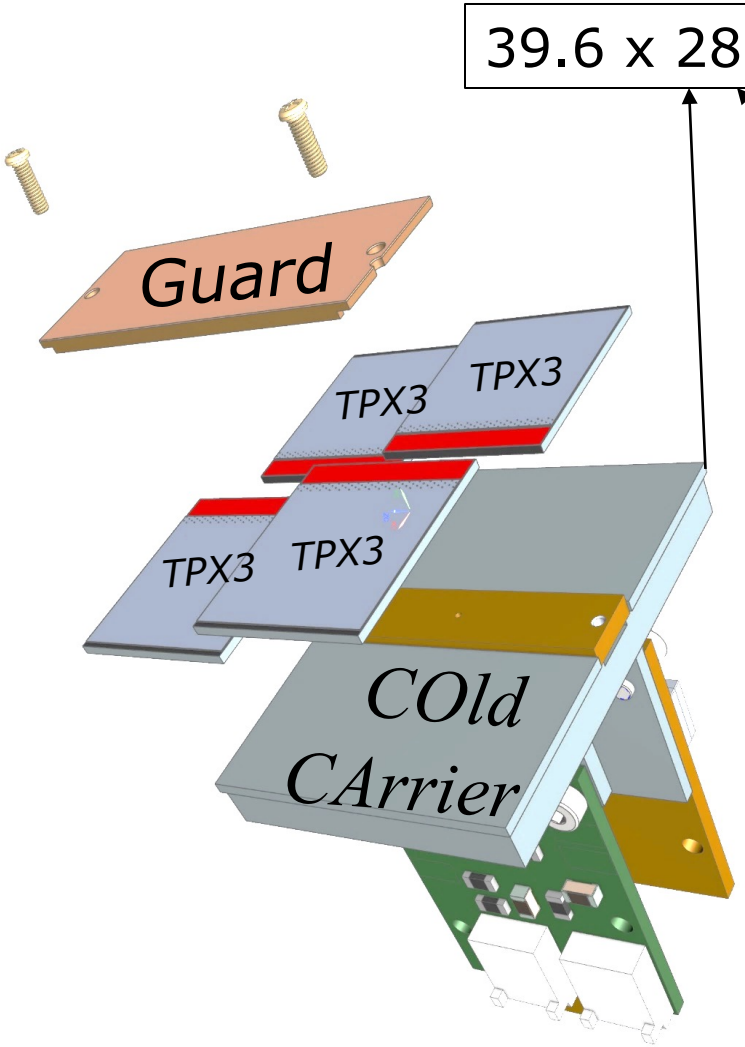
- σ_{y0} = pixel size $/\sqrt{12}$
- Diffusion D_T from fit

Note that:

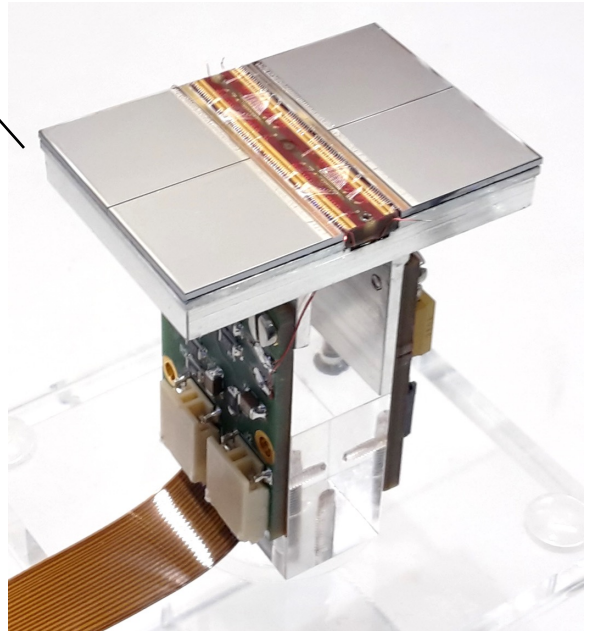
- A hit resolution of ~250 µm is ~25 µm for a 100-hit track (~ 1 cm track length)
- At $B = 4$ T , $D_T = 25\ \mu m/\sqrt{cm}$

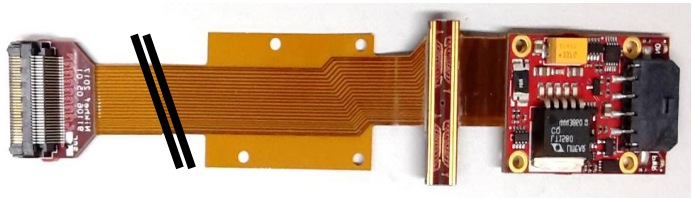
QUAD design and realization

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



series of QUADs

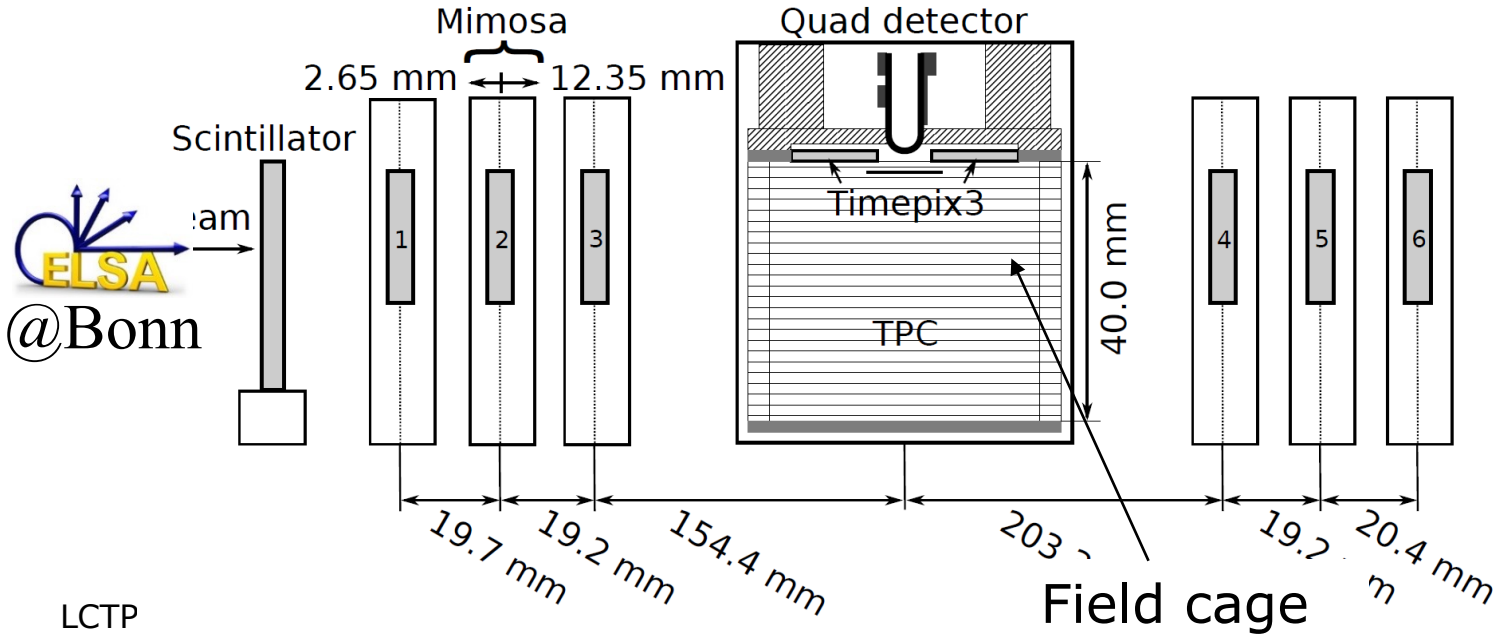


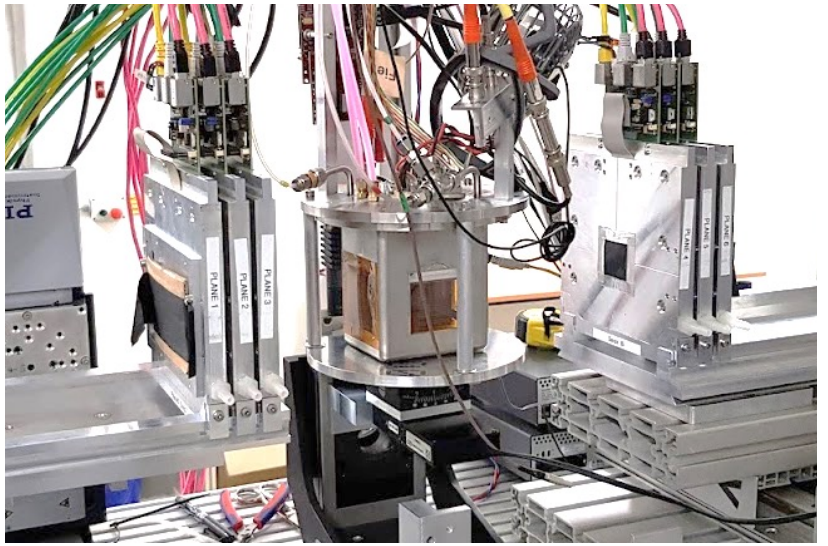


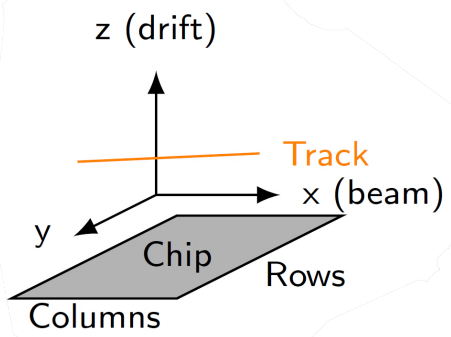
QUAD test beam in Bonn (October 2018)

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

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

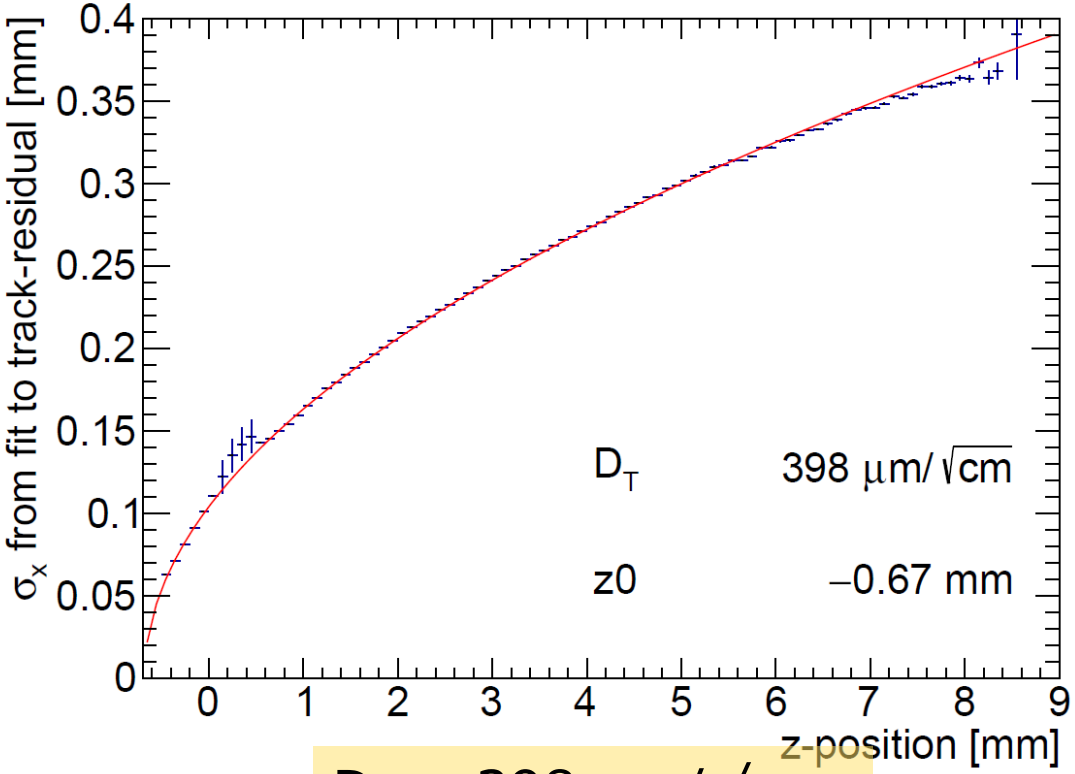






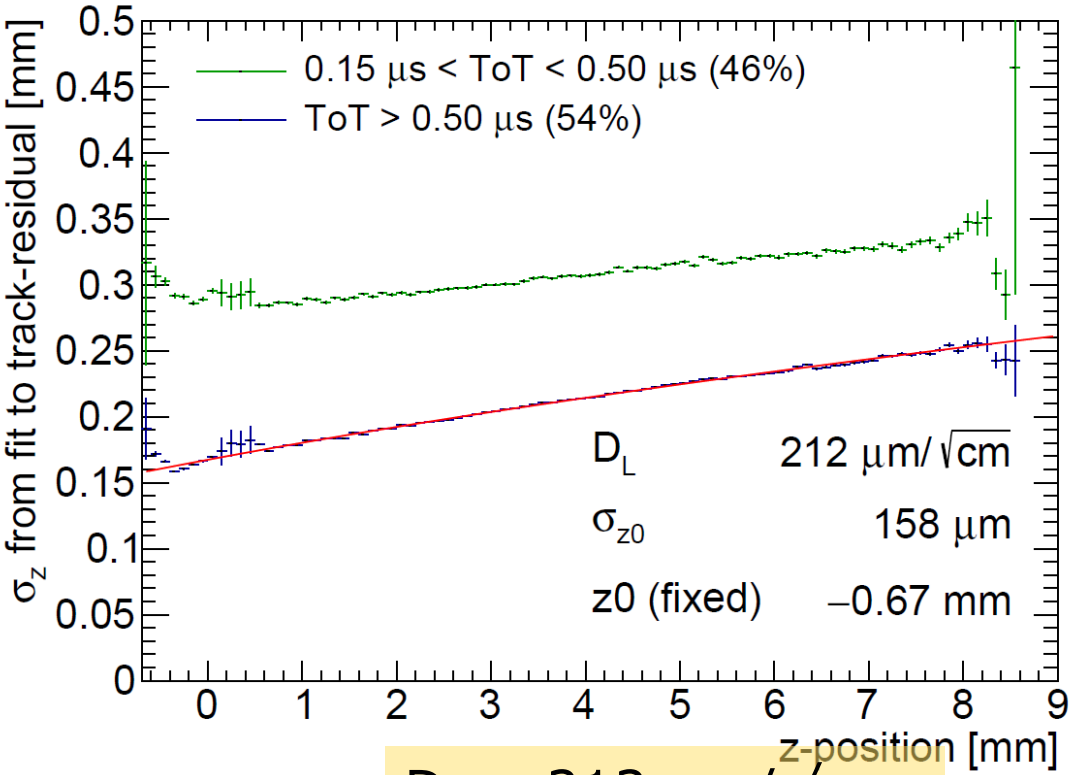
QUAD single hit resolution

Transverse



D_T = 398 µm/√cm

Longitudinal

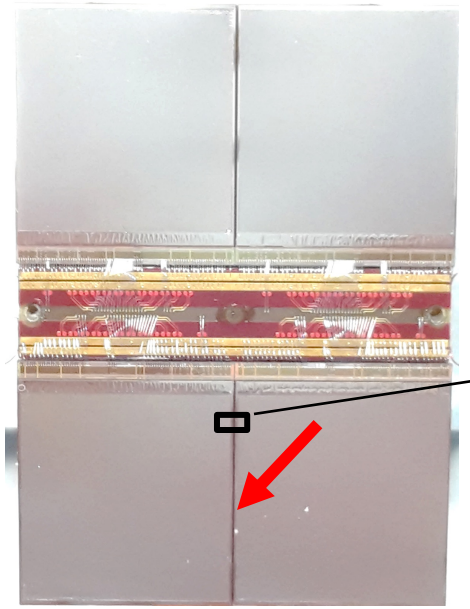


D_L = 212 µm/√cm

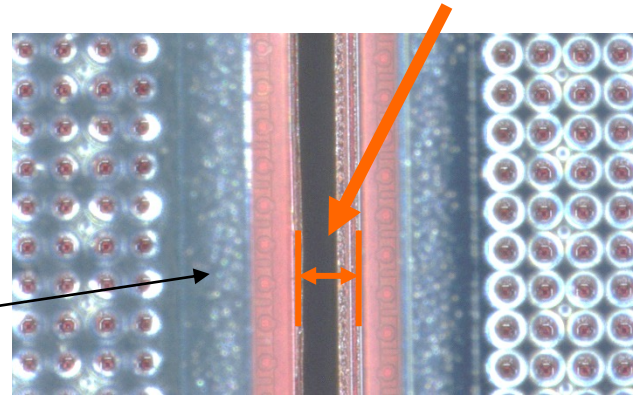
The D_T value is rather high due to an error in the gas mixing (too low CF4)

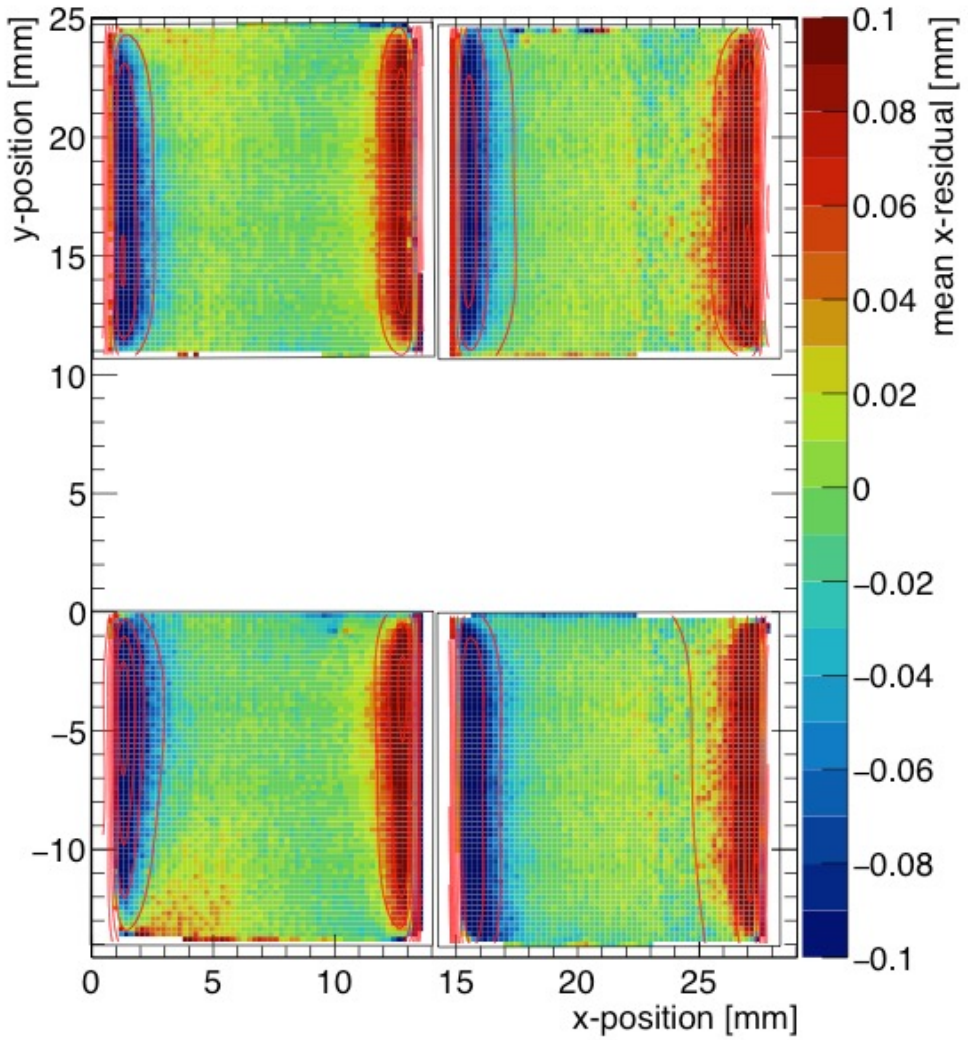
QUAD edge deformations (XY)

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



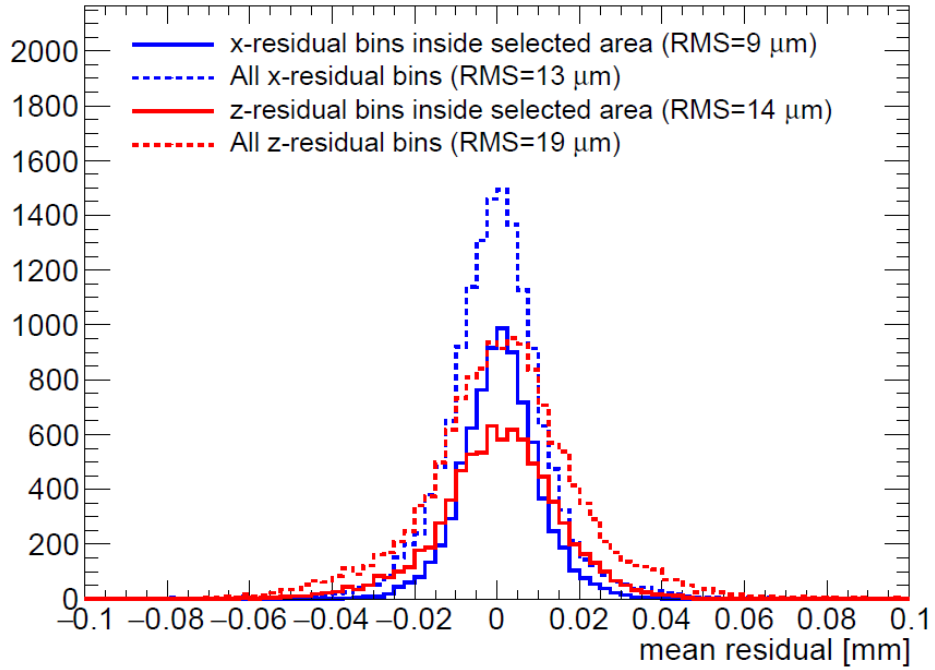
Grounded region

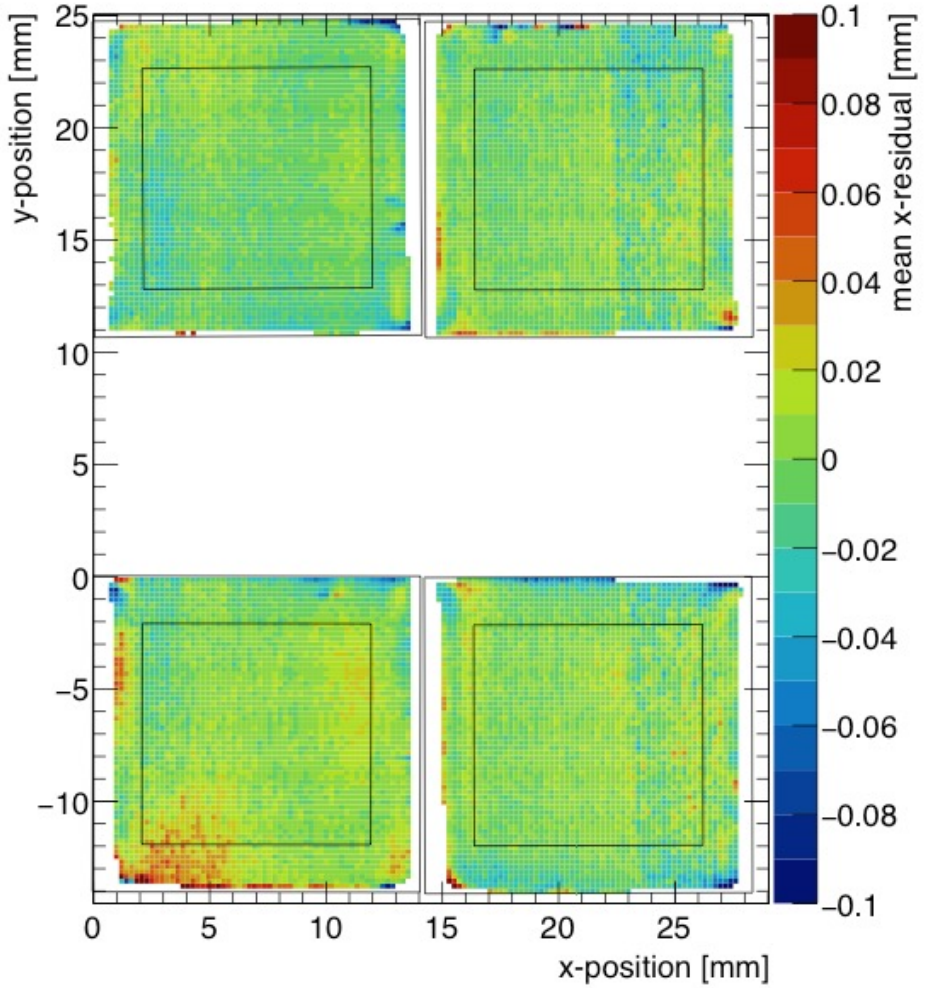




QUAD deformations in transverse plane (XY)

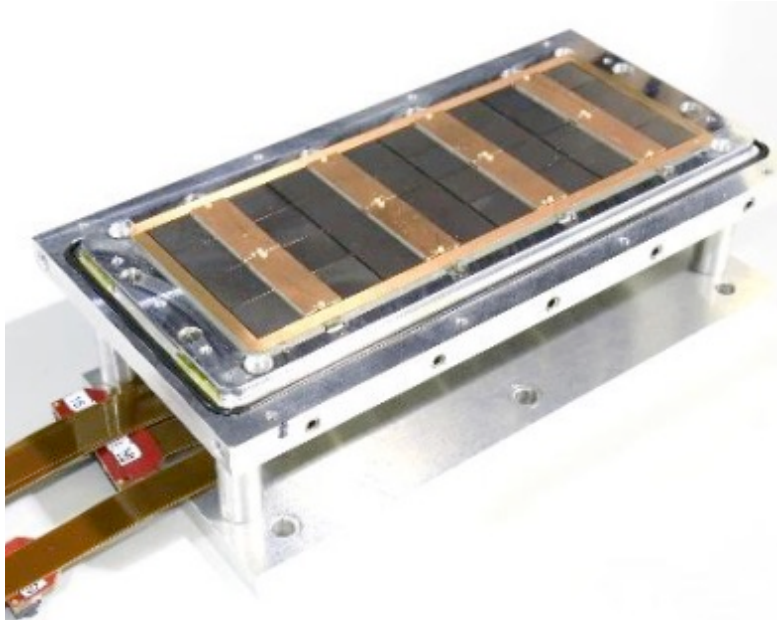
- After applying fitted edge corrections
- RMS of the mean residuals are 13 µm over the whole QUAD

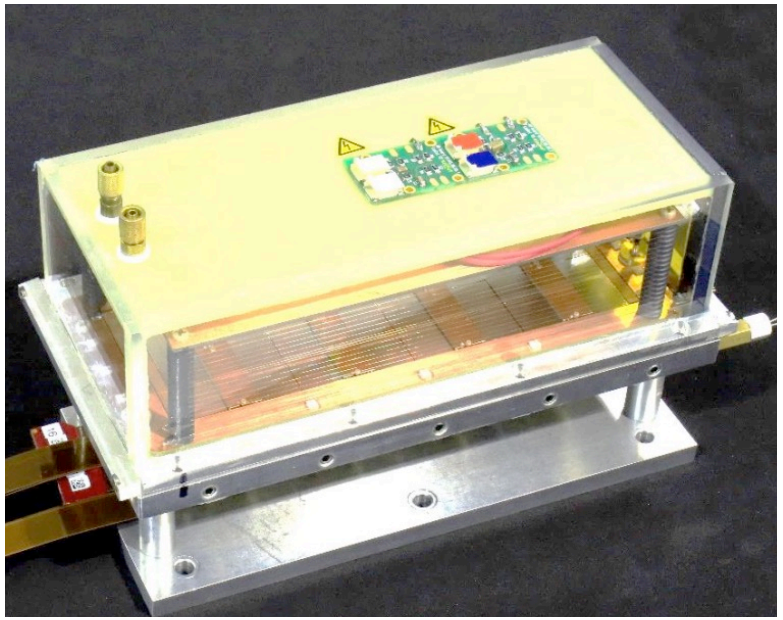


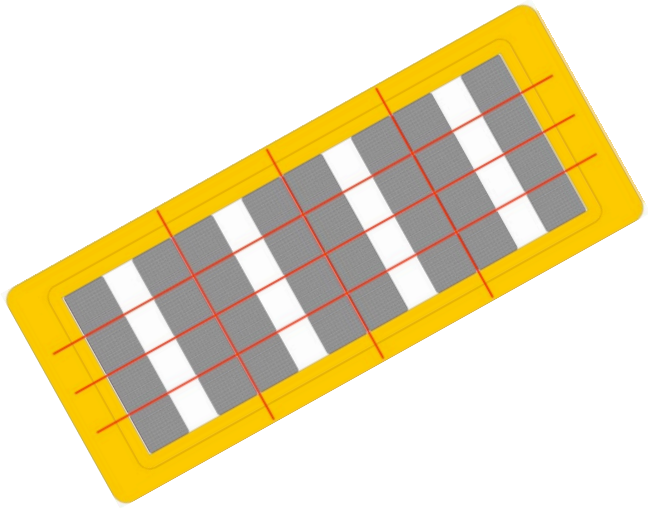


QUAD as a building block

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

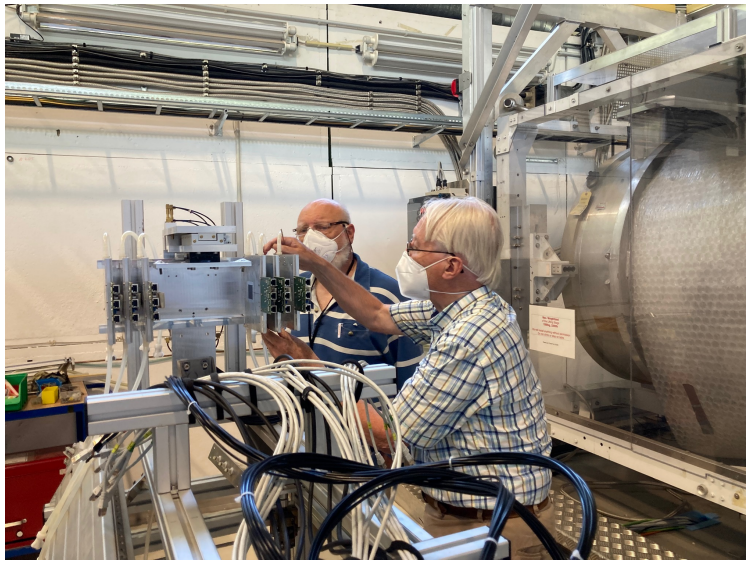


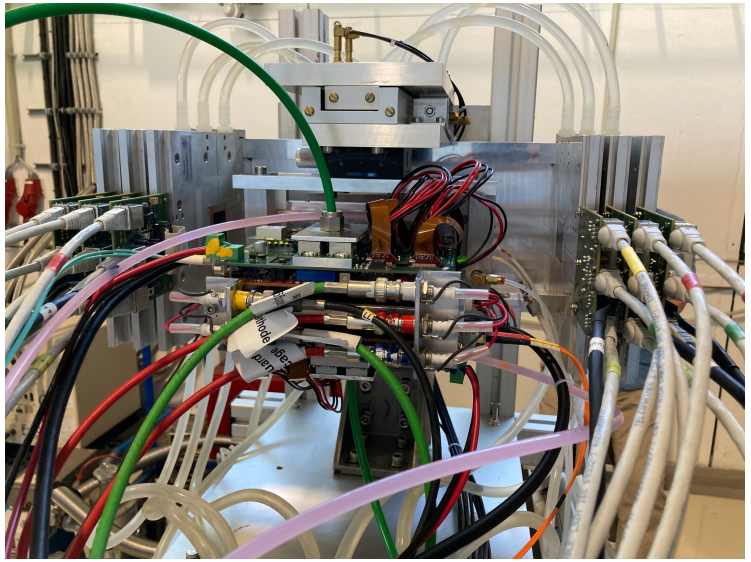


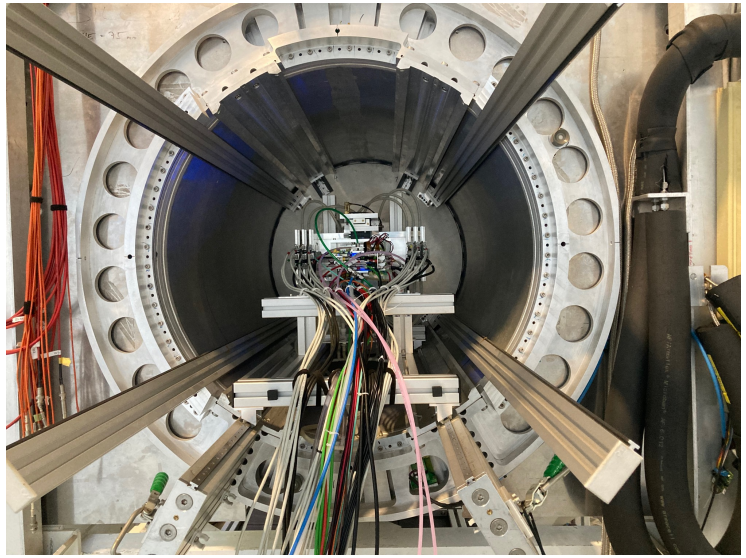


in red guard wires

DESY testbeam June 2021

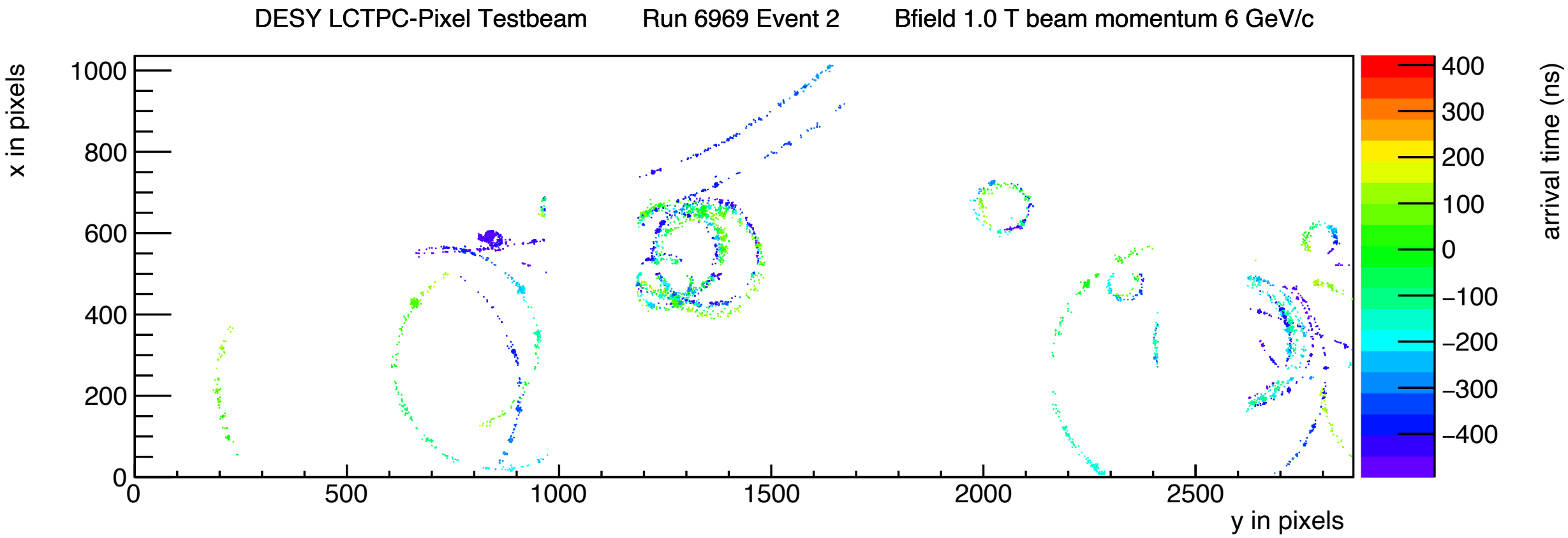




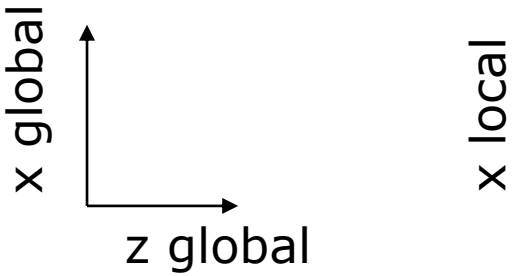


Mounting the 8 quad module between the silicon planes
sliding it into the 1 T PCMAG solenoid

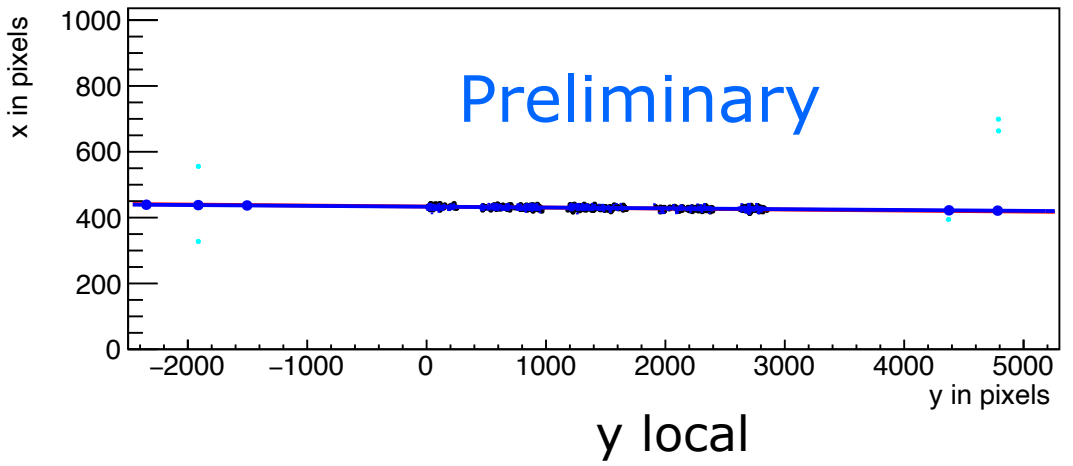
DESY testbeam June 2021

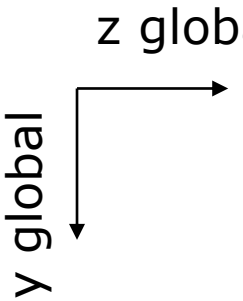


DESY testbeam Module Analysis

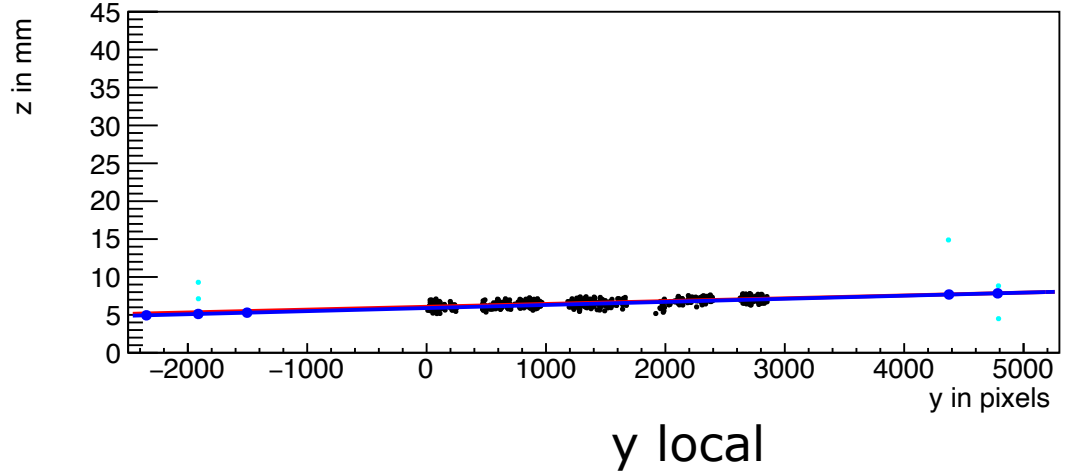


x local





z local drift



Event display with module and telescope

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

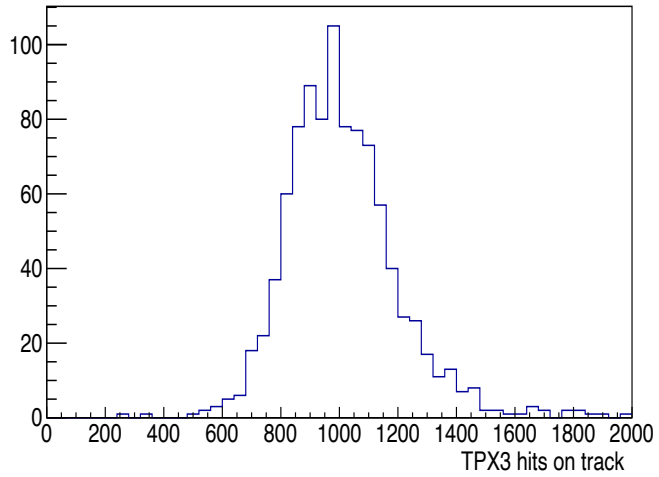
Asymmetric tail outlier removal applied 1071 hits in z kept.

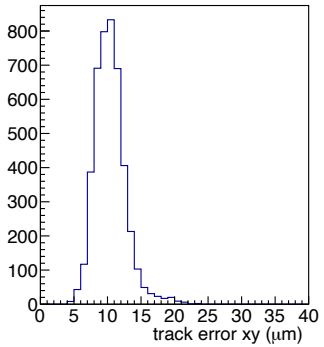
TPX3 track hits
Telescope track hits (off track green)

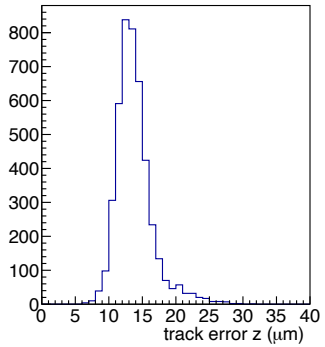
DESY testbeam Module Analysis

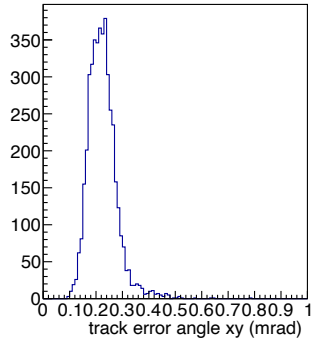
Run 6916 B=0 T p =6 GeV

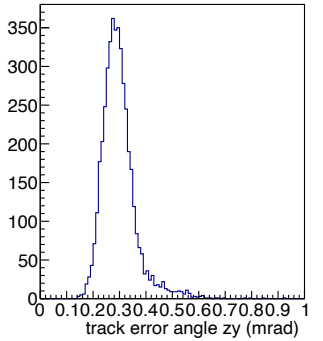
Preliminary











964 selected tracks
Impressive 1009 hits / track

8-quad module Tracking precision:

position 9 μm (xy) 13 μm (z)
angle 0.19 mrad (dx/dy) 0.25 (dz/dy) mrad
module tracklength = 157.96 mm

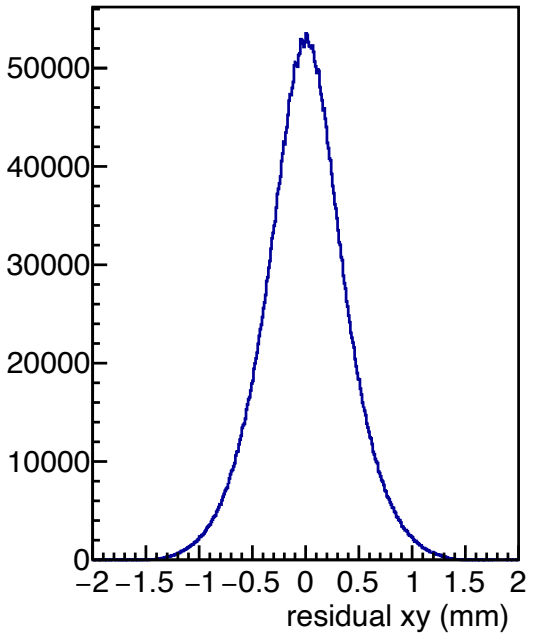
Note that in a B field because of the reduced diffusion the tracking precision will improve substantially

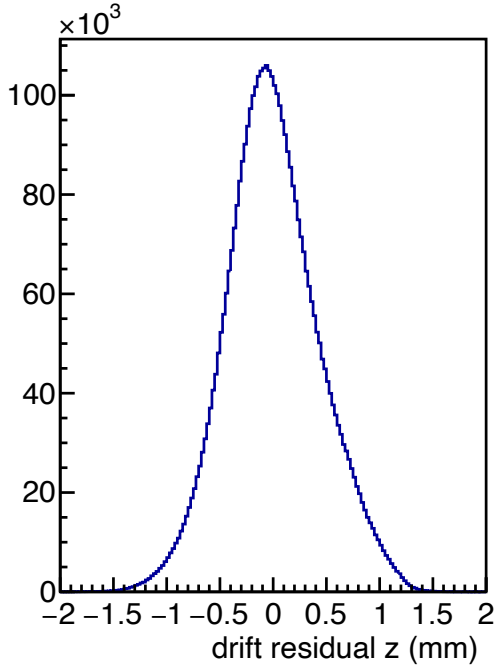
DESY testbeam Module Analysis

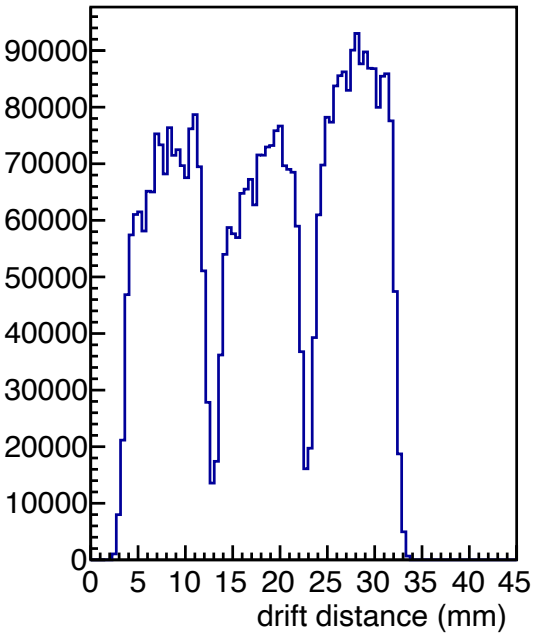
Run 6916-6918 B=0 T p=6 GeV

Three runs at different drift distances

Preliminary





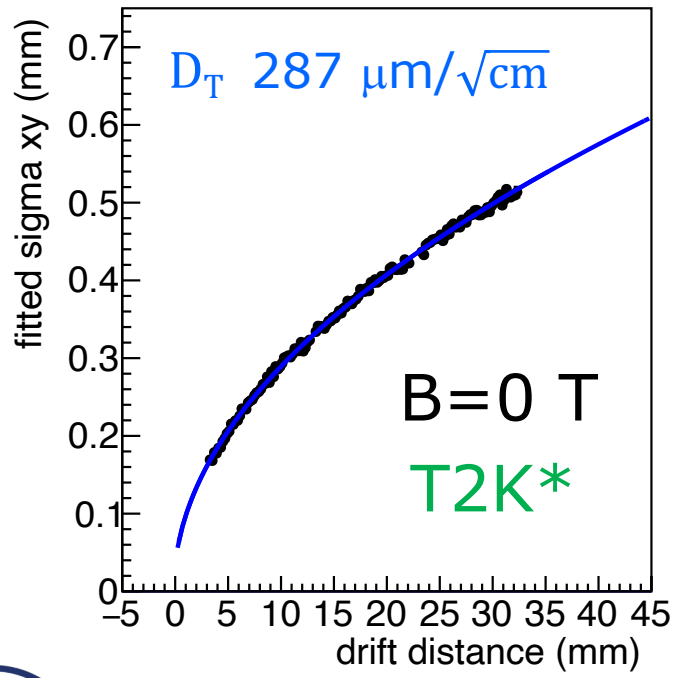


DESY testbeam Module Analysis

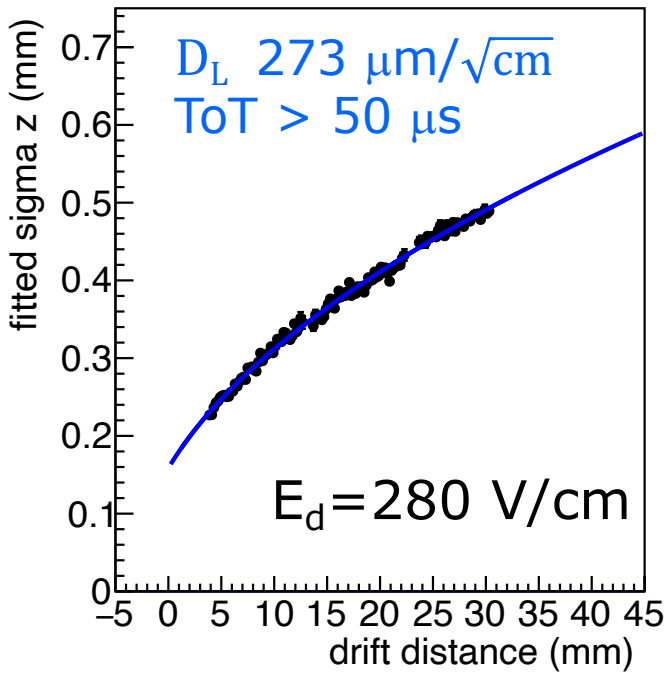
Run 6916-6918 B=0 T p=6 GeV

Fitted resolution

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



Preliminary



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

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

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

Magboltz gives D_T 287 μm/√cm

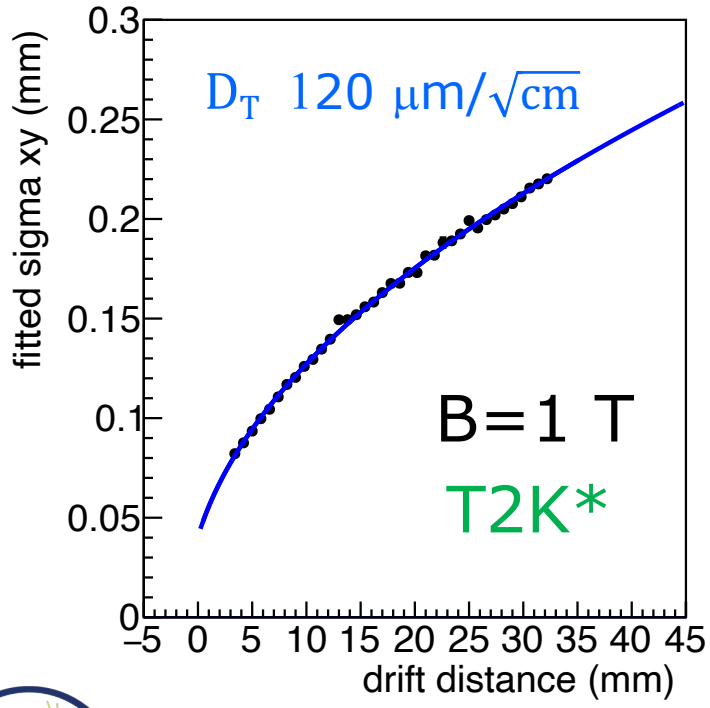
T2K* = T2K gas with O_2 and H_2O

DESY testbeam Module Analysis

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

Fitted resolution

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



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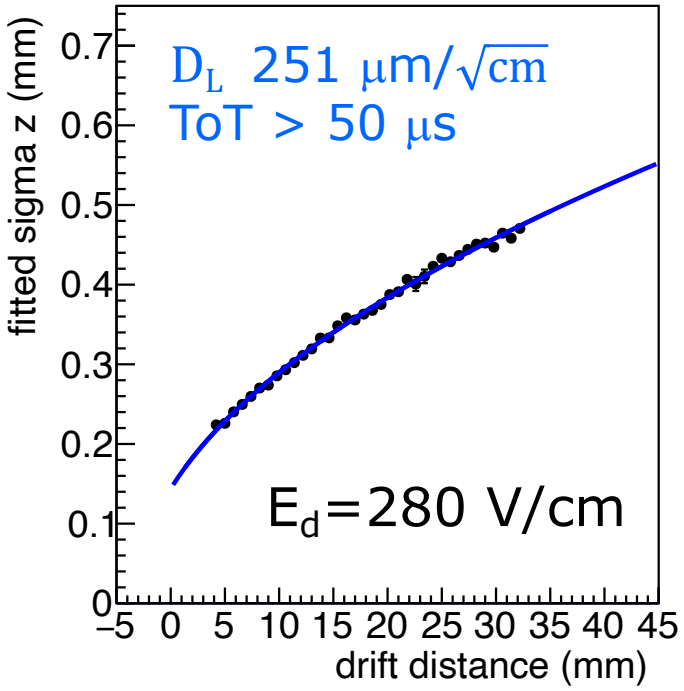


$\sigma^2_{xy0} = \sigma^2_{pixel} + \sigma^2_{xy\ tele}$

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

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

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

T2K* = T2K gas with O_2 and H_2O

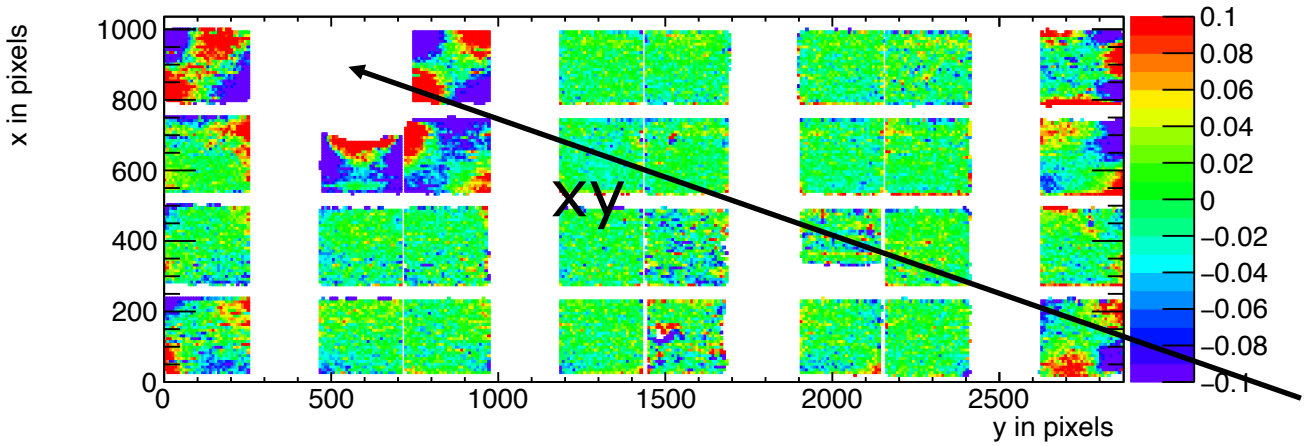
DESY testbeam Module Analysis

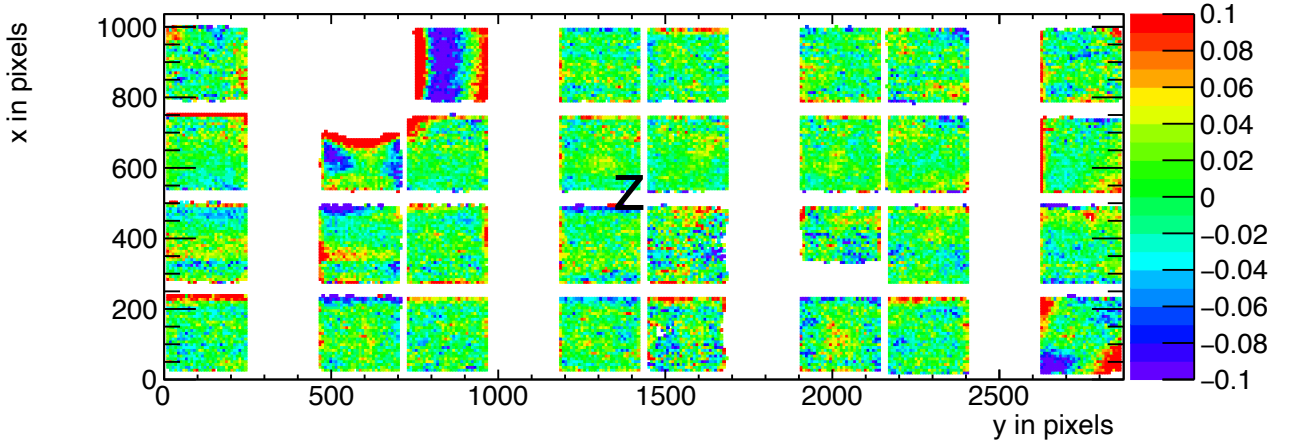
Runs 6909, 6916-17, 6934-35 B=0 T p =6 & 5 GeV

Mean residuals in the module plane with acceptance cuts

B=0 T situation

Preliminary





Vertical white bands guards

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

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

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

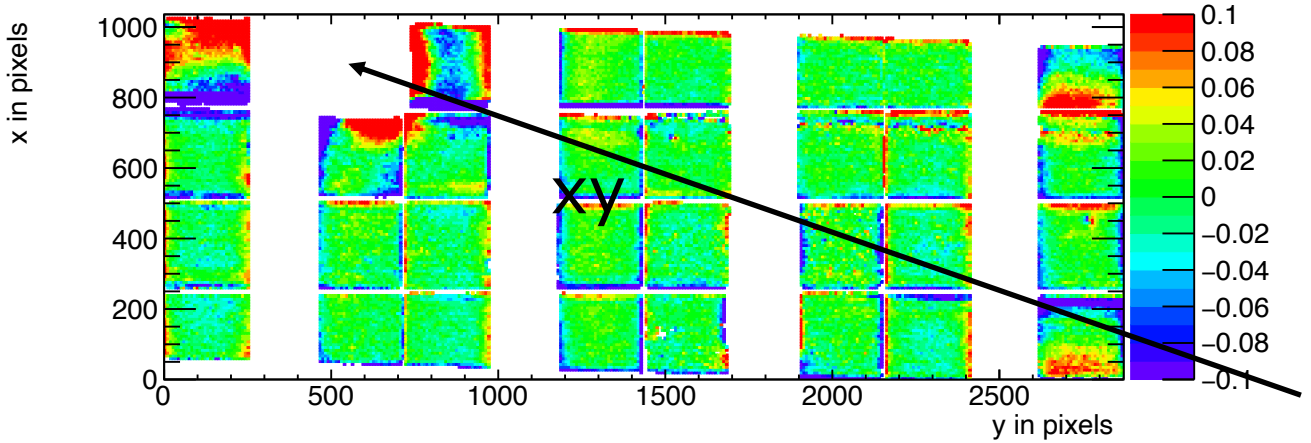
DESY testbeam Module Analysis

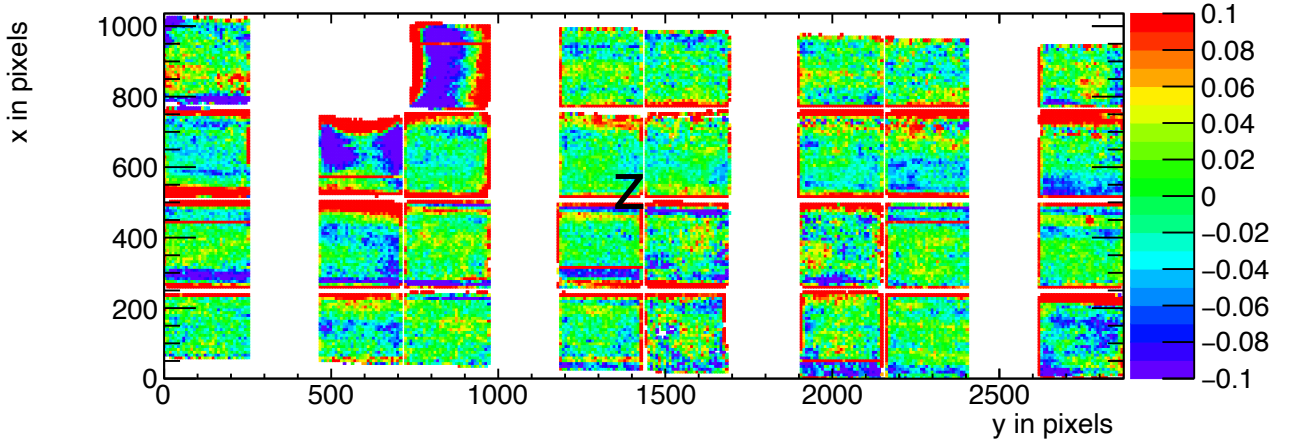
Runs 6981-6988 B=1 T p=5 GeV

Mean residuals in the module plane with acceptance cuts

B=1 T situation

Preliminary





Vertical white bands guards

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

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

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

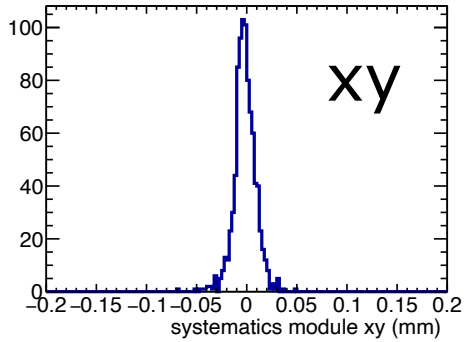
DESY testbeam Module Analysis

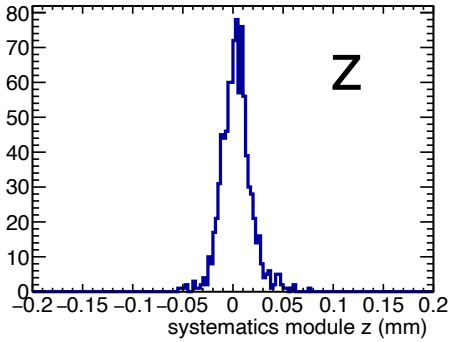
Runs 6909, 6916-17, 6934-35 B=0 T p =6 & 5 GeV

Distribution of mean residuals in the plane

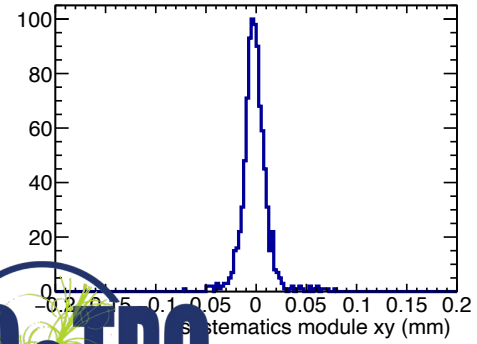
Preliminary

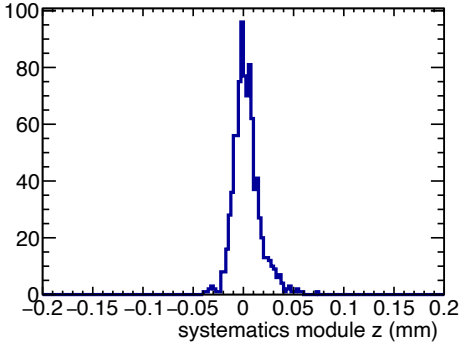
Method row





Method column





See back up slide for the two methods that group the module plane

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

We did not include the 4 corner chips and (11), 14, 8, 13 and 19. These are affected by the field cage and the short in chip 11.

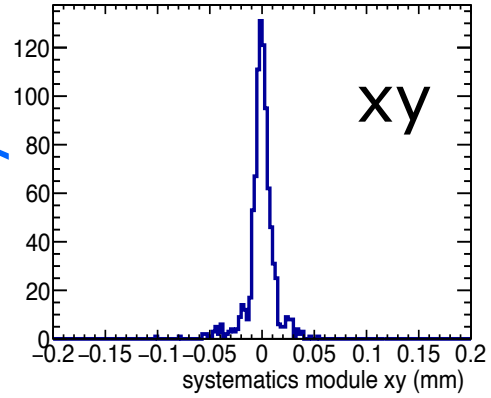
DESY testbeam Module Analysis

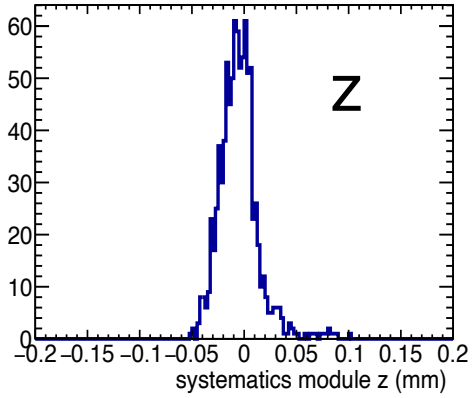
Runs 6983-6988 B=1T p=5 GeV

Distribution of mean residuals in the plane

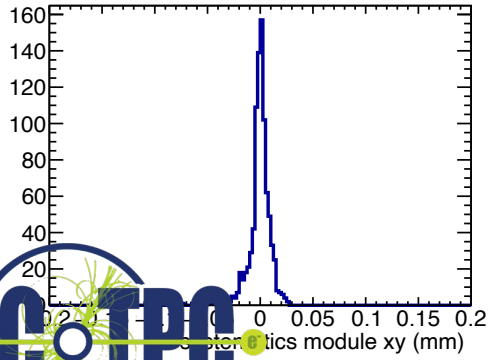
Preliminary

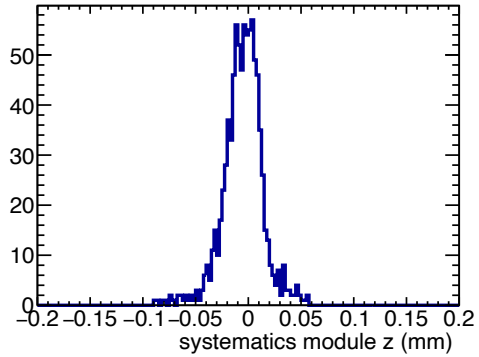
Method row





Method column





B=1 T situation

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

We did not include the 4 corner chips and (11), 14, 8, 13 and 19. These are affected by the field cage and the short in chip 11.

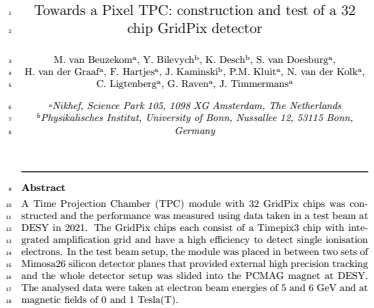
Conclusions on module performance Resolution and precision

- 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 $D_{xy} = 287\ \mu m/\sqrt{cm}$ $D_z = 273\ \mu m/\sqrt{cm}$
- The diffusion coefficients at B=1 T is $D_{xy} = 120\ \mu m/\sqrt{cm}$ $D_z = 251\ \mu m/\sqrt{cm}$
  - In agreement with Magboltz $D_{xy} = 121\ \mu m/\sqrt{cm}$

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

Conclusions on module performance
Resolution and precision

- Results for the module showed that:
  - the HV of the guard wires was well tuned
  - B=0 T rms residuals in the module plane xy 13 μm and z 15 μm
  - The results are compatible with (very) high stats quad measurement
  - B= 1 T rms residuals in the plane xy 13 μm and z 20 μm;
- High tracking precision is demonstrated with small systematics
  - deformations xy stay below 13 μm
- Writing a NIM paper (including more results)



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

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Abstract

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

DESY testbeam Module Analysis

Analysis topics discussed in the following:

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 – see next slides - 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 for B=0T

run	ToT 1	ToT 2	triggers	time	Hits 1	Hits 2	trigger	Rate 1	Rate 2
	µs	µs	nr	(s)			Hz	Hits/s	Hits/s
6916	0.6280	0.6527	16837	23221	6.252e+06	1.312e+07	0.72	269	565
6909	0.6220	0.6482	89250	134254	2.226e+07	5.040e+07	0.66		
6934		0.6510	73414	2413		2.046e+07	30.4		8479
6935	0.6204		73902	2414	6.948e+06		30.6	2878	

- Tot 1 (2) = mean ToT for mcol =1 (2) (each 6 chips) stat errors are neglible
- Hits 1 (2) are raw hits with ToT> 0.15 µs
- Runs 6916 and 6909 are consistent within 1%
- Relative change wrt 6916 in mean ToT -1.2% (mcol=1) -0.3% (mcol=2) up to 8.5 kHz for 6 chips or 1.4 kHz per chip.
- The black numbers could go in the paper

DESY testbeam Module Analysis

Efficiency at high hit rates for B=1T

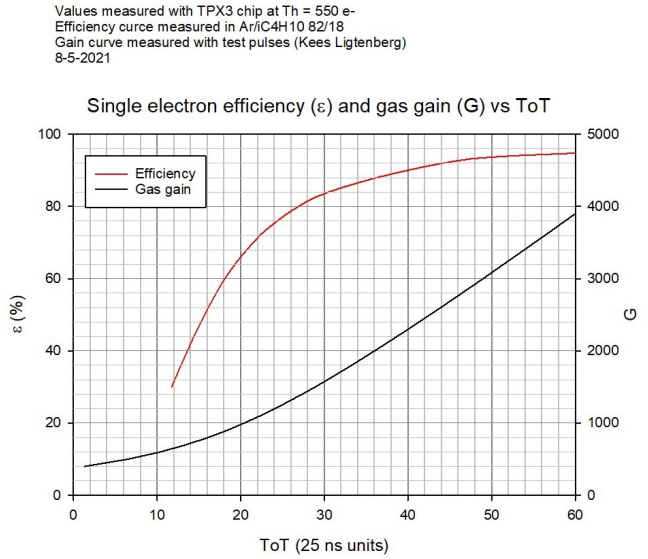
run	ToT 1	ToT 2	triggers	time	Hits 1	Hits 2	trigger	Rate 1	Rate 2
	µs	µs	nr	(s)			Hz	Hits/s	Hits/s
6969	0.6499	0.6658	7947	13816	1.929e+06	2.164e+06	0.57	139	156
6983	0.6568	0.6775	67968	2825	1.162e+07	1.409e+07	24.1	4110	4986
6985		0.6783	102488	4373		2.925e+07			
6988	0.6653		95785	4251	6.148e+06				

- Runs 6985 and 6988 are consistent with 6983 within 0.5%
- Relative change wrt 6983 in mean ToT +1% (mcol=1) +1.7% (mcol=2) up to 5 kHz for 6 chips or 1.2 kHz per chip.
- The black numbers could go in the paper

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:
  - See efficiency vs ToT curve $\delta\varepsilon/\varepsilon \sim 0.5\ \delta ToT/ToT$
- This means that the efficiency $\delta\varepsilon/\varepsilon$ is stable at the level of +0.8% (B=1T) and -0.6% (B=0T) for hit rates up to 1.2 kHz per chip.



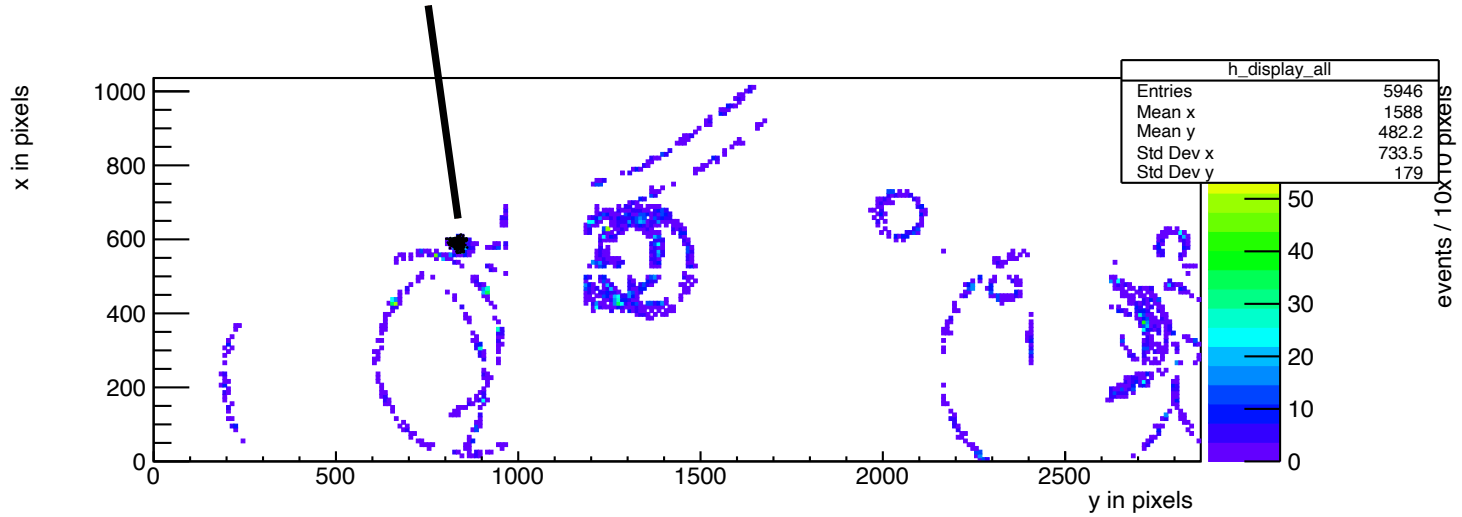
Conclusion

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

DESY testbeam Module Analysis

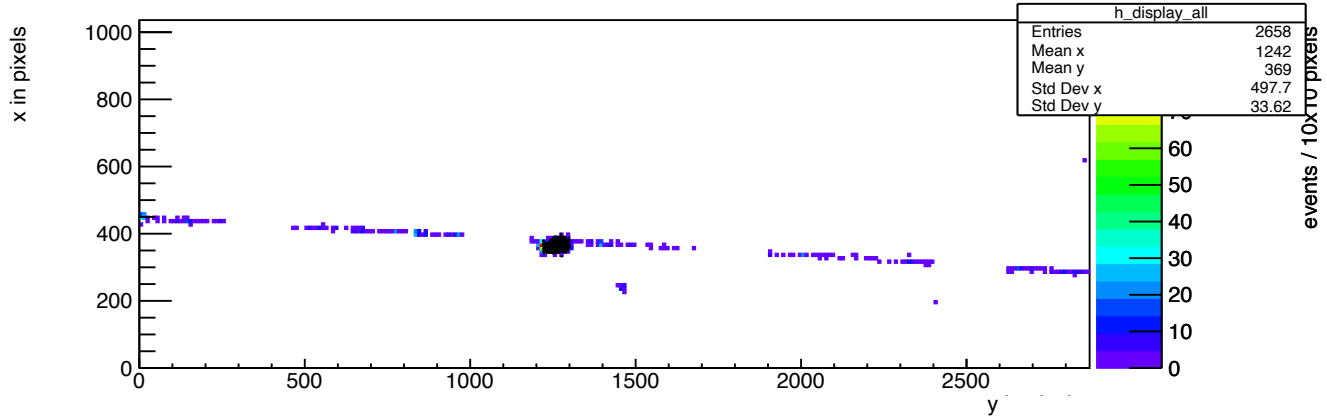
Large hit bursts

- 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:

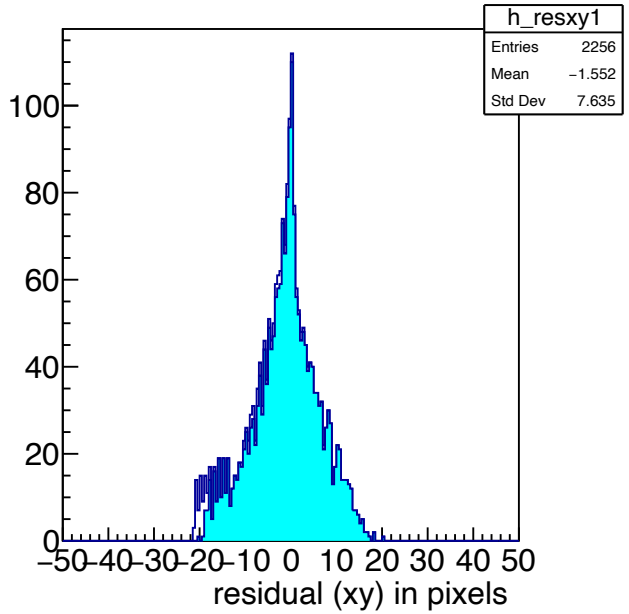


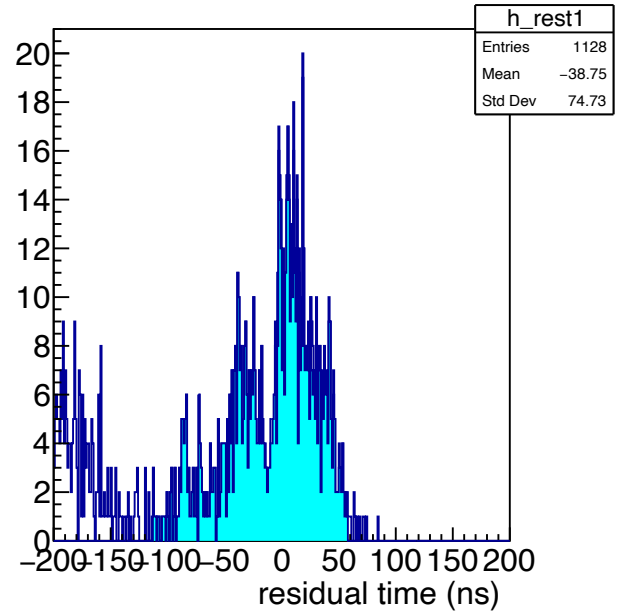
DESY testbeam Module Analysis

Large hit bursts



Event 42 with a burst of 1066 hits

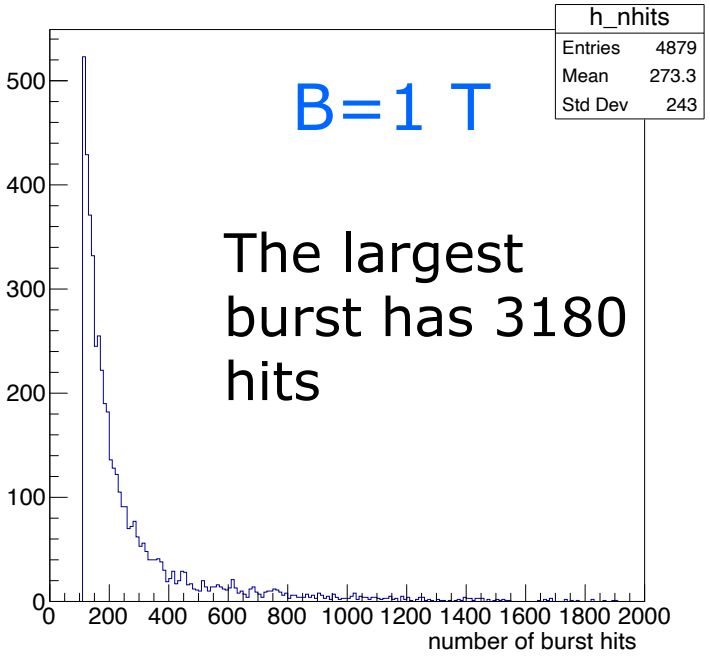




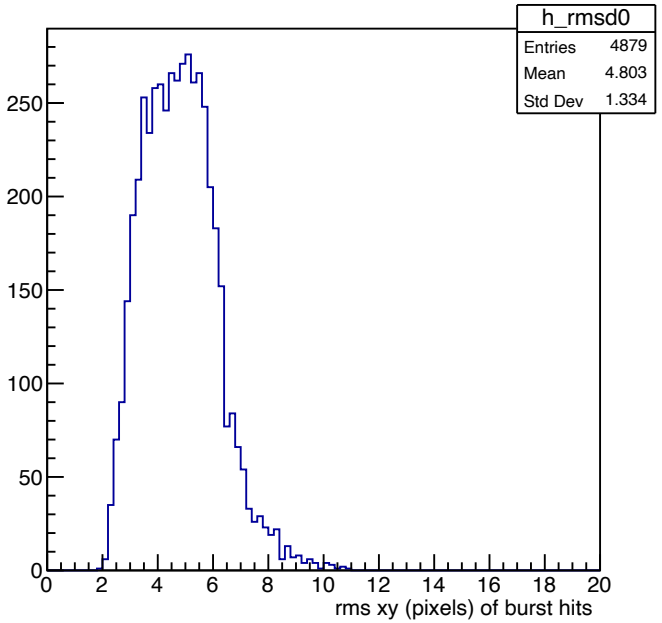
DESY testbeam Module Analysis

Large hit bursts

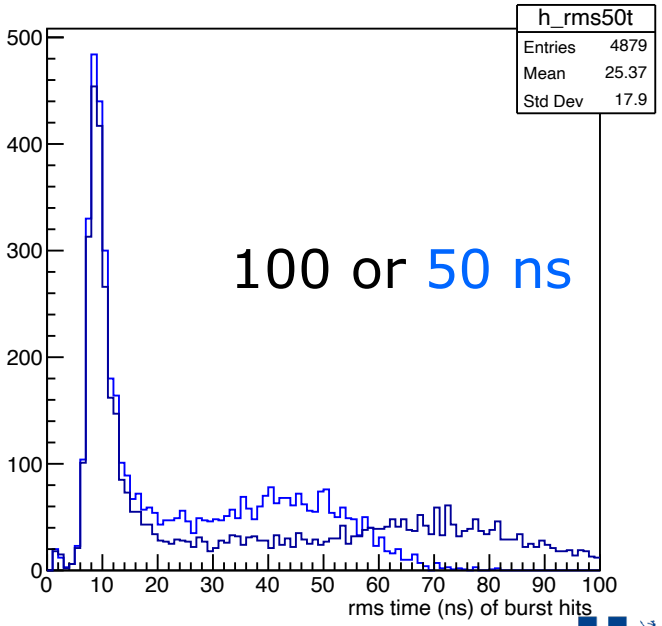
- For B=1 T p= 6GeV run 6969 ~ 8000 triggers (events)



rms d0



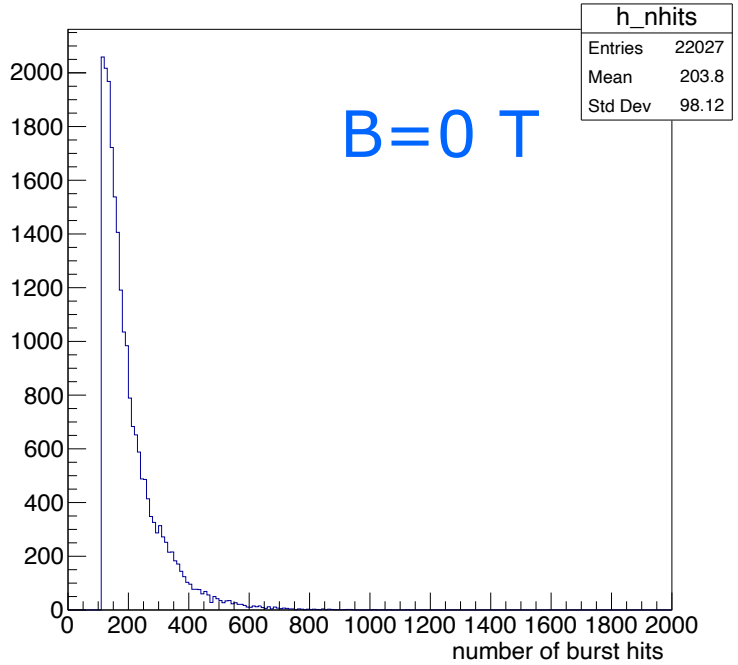
rms t



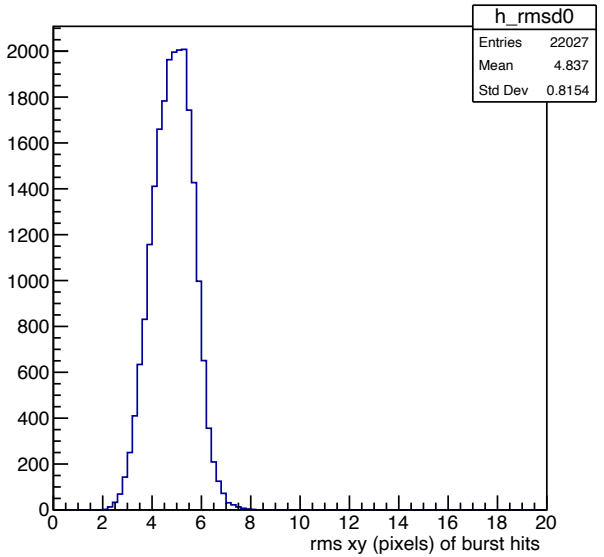
DESY testbeam Module Analysis

Large hit bursts

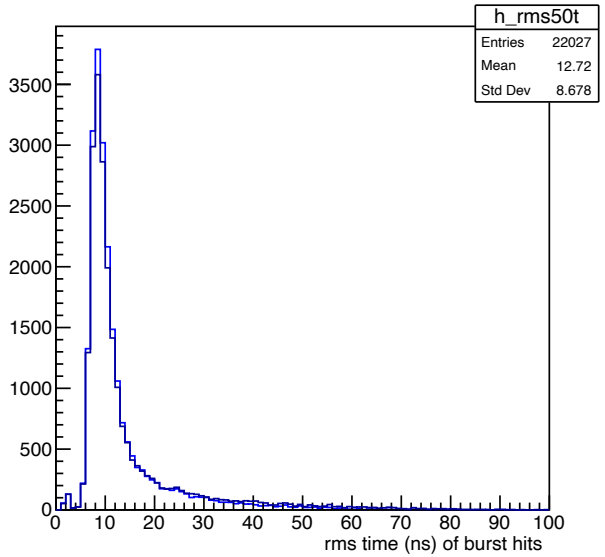
- For B=0 T p= 6 GeV run 6916 ~ 20k triggers (events)



rms d0



rms t



Much reduced time tails wrt B=1 T

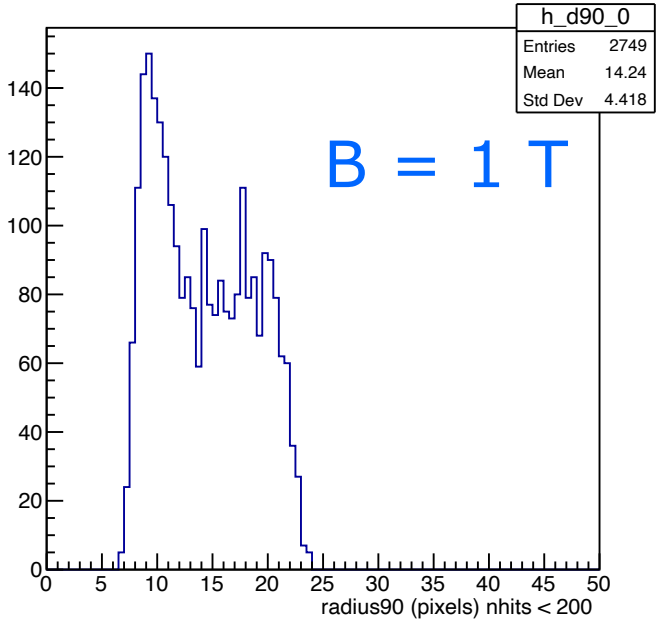
DESY testbeam Module Analysis

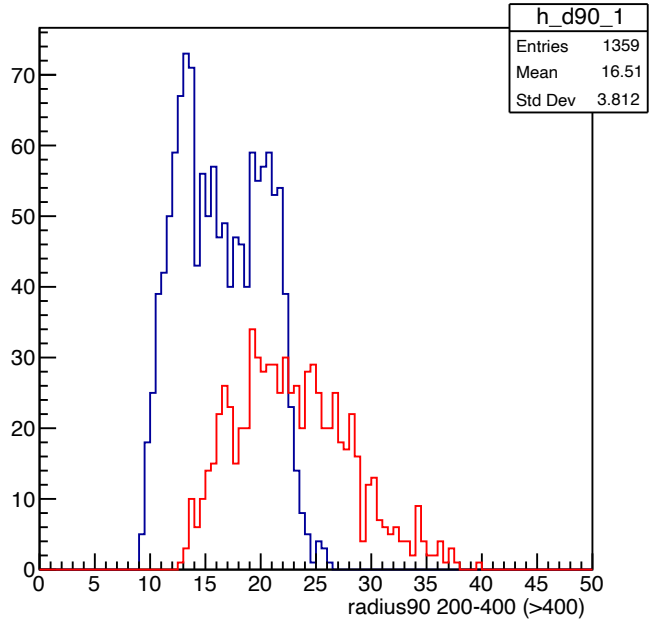
Large hit bursts run 6969

radius90: radius in which 90% of hits are found

Average Hit density in a burst is 3180 hits /3.14*50*50 pixels = 0.4 per pixel.

Max hit density is 1, because after one hit the pixel is dead for 475 ns.





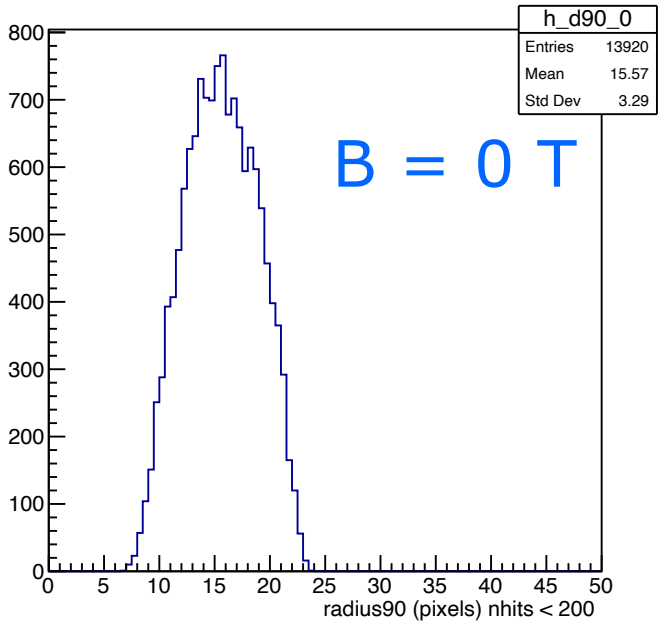
DESY testbeam Module Analysis

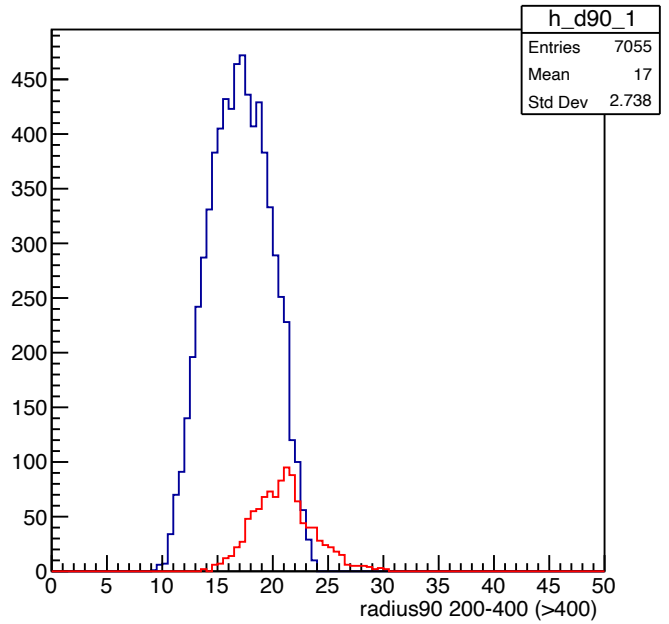
Large hit bursts run 6916

radius90: radius in which 90% of hits are found

Conclusion

- B=0 and 1 T radius distribution similar
- More often hits > 400 in B =1 T





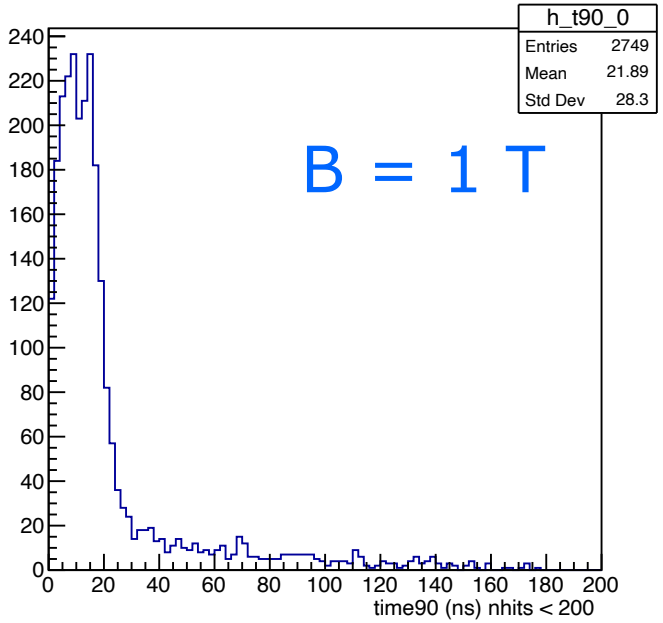
DESY testbeam Module Analysis

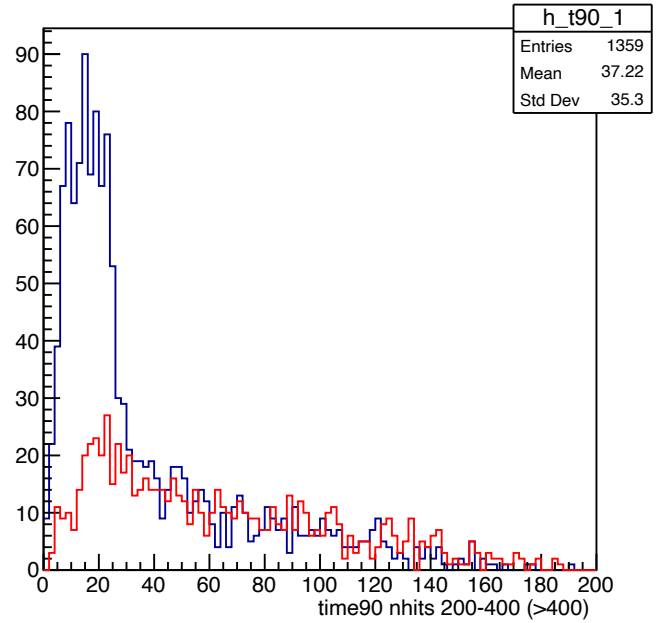
Large hit bursts run 6969

time90 time in which 90% of hits are found

Time varies
goes from 0-200 nsec
(0 μm to 12 mm)

At low multiplicities
shorter "tracks"
Diffusion peak
time90<20 ns





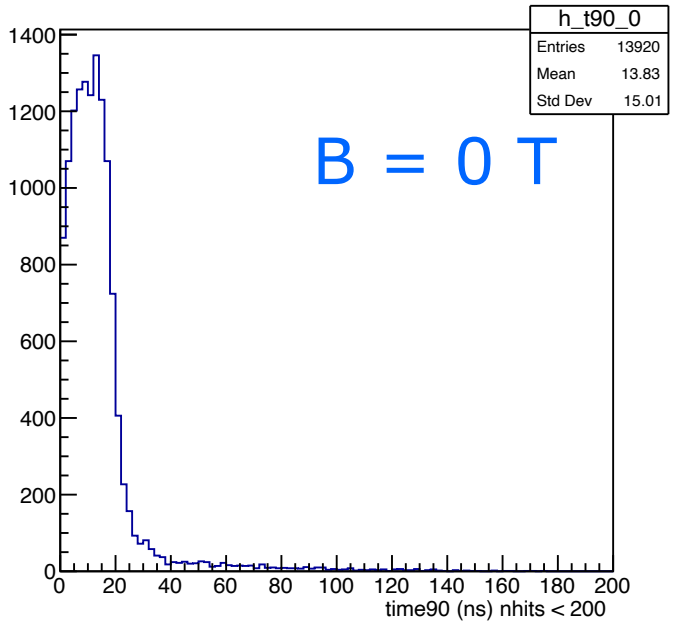
DESY testbeam Module Analysis

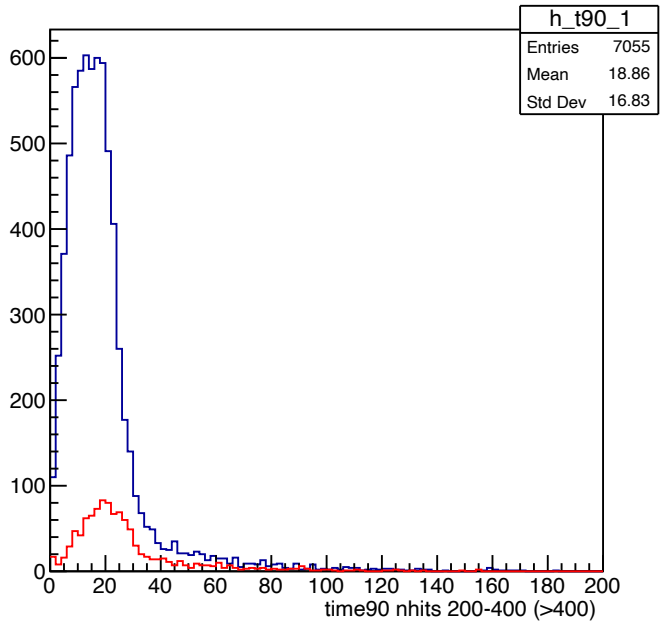
Large hit bursts run 6916

time90 time in which 90% of hits are found

Conclusion

- Much more tail in B=1 T time distribution (previous slide)





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 reduces the impact of bursts in the B=1 T data. 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 incident angle of the track?

- In order to study this topic we use circular tracks (curlers).
- We took data with small incident angles plus min 10 degrees; in a circle one will have 360 degrees incident angles.
- To get a (part of a) circle the one needs a B field. Not that the electrons from the beam go “straight” and we need to look for lower momentum electrons in the event.
- Here 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.

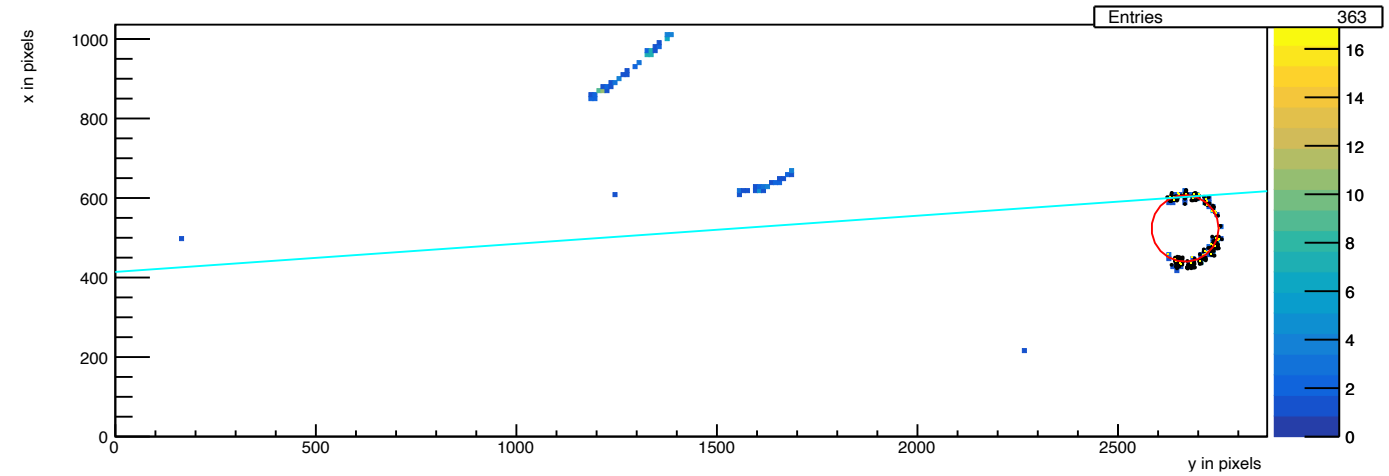
DESY testbeam Module Analysis

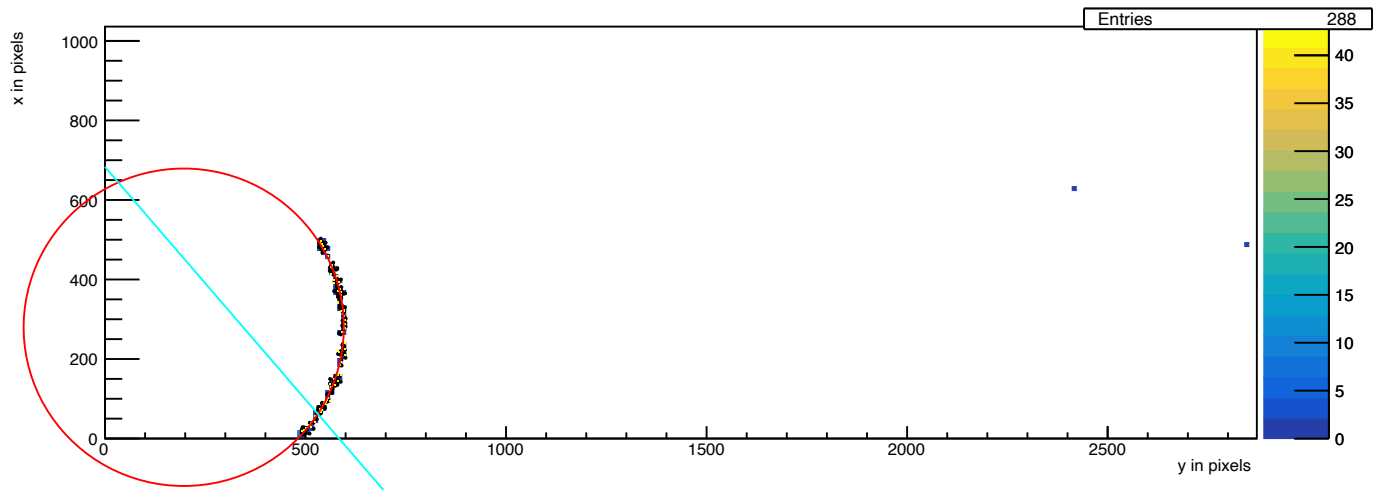
Circle finding

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





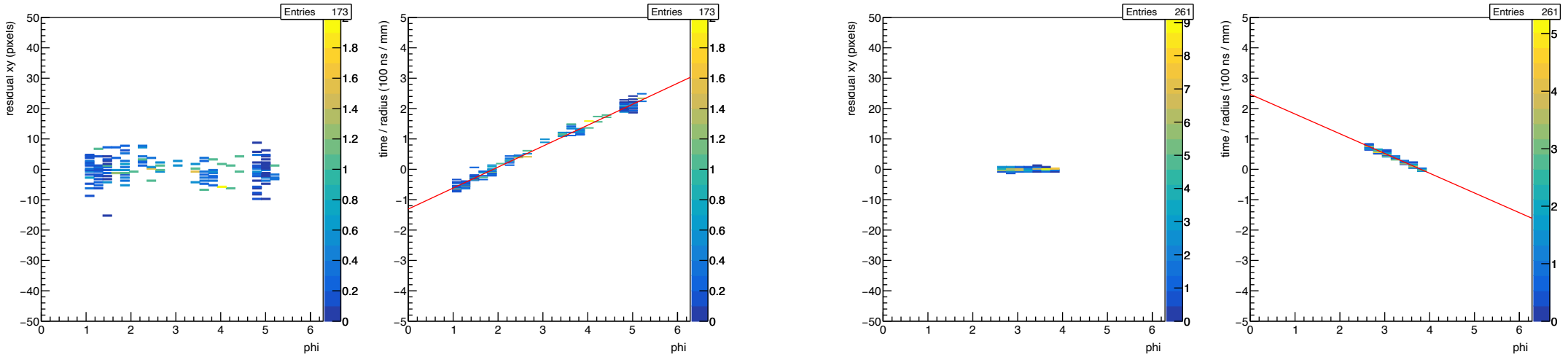
Events 14 and 41

R = 1024 pixels
p = 8.45 MeV/c
R = 121 pixels
p = 1 MeV/c
R = 25 pixels
p = 206 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

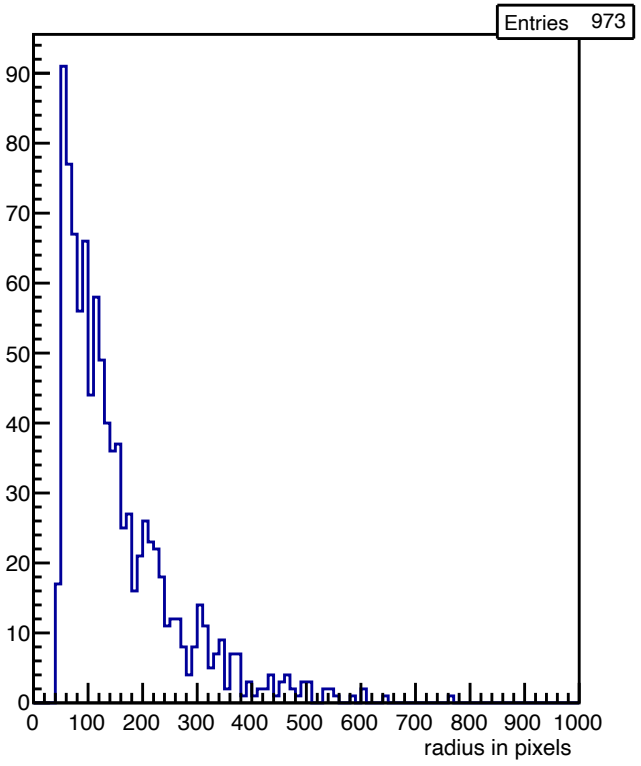
DESY testbeam Module Analysis

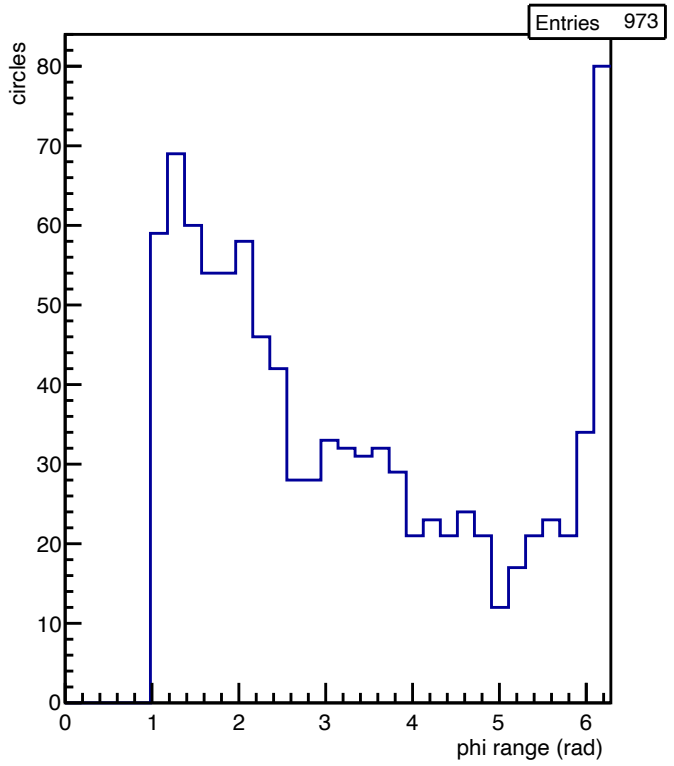
Event selection for circles

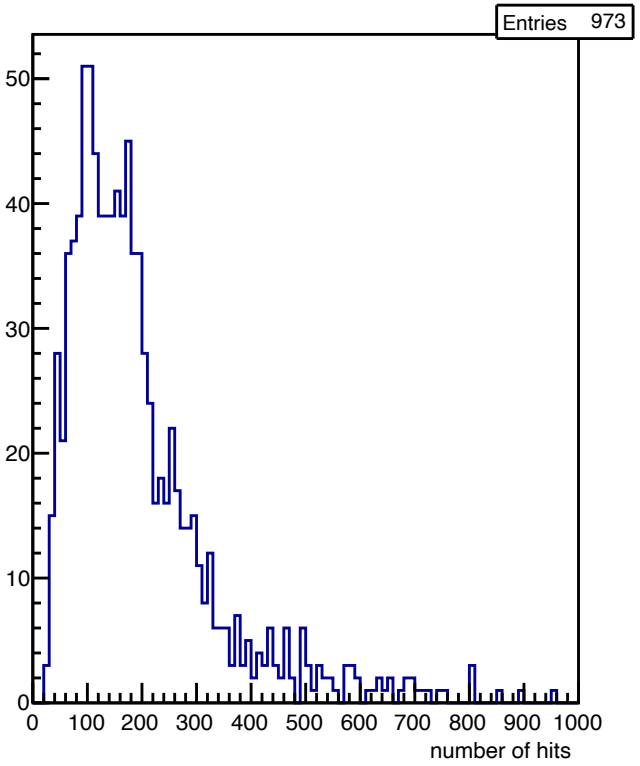
- Radius > 50 pixels with at least 20 selected hits
- Reject circles with a better SL line fit by applying cuts on the χ^2 and number of hits for the circle and line hypothesis.
- Resolution σ_{xy} = 4 pixels and σ_z = 1 mm
- Track χ^2_{xy}/dof < 5 χ^2_z/dof < 5
- Phi range (phi max – phi min) > 1 rad
- 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

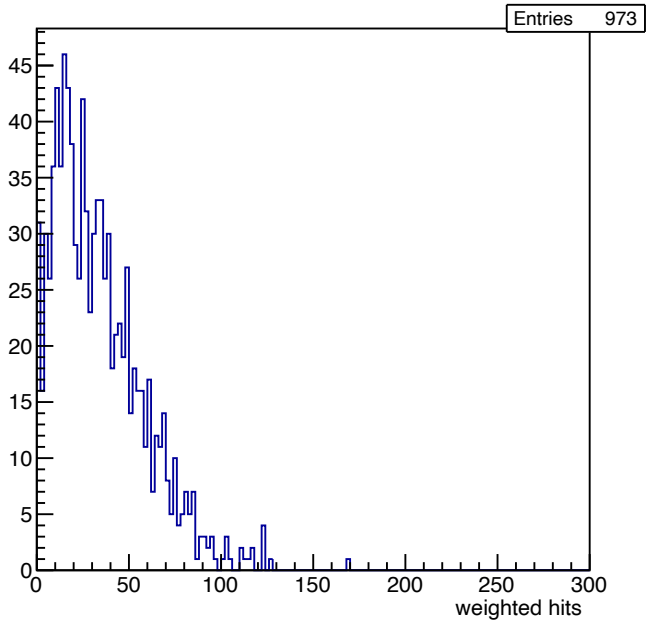


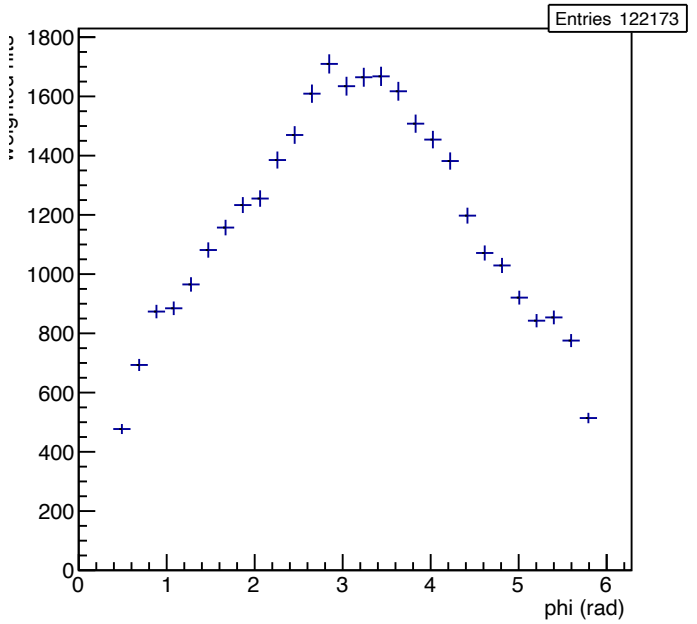




DESY testbeam Module Analysis

Selected circles plots weighted

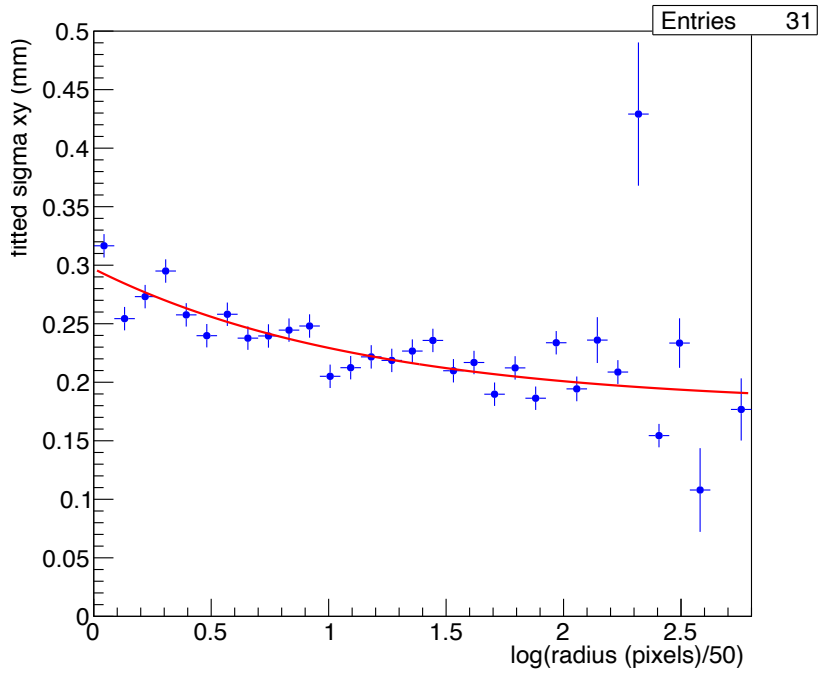




phi hit on circle

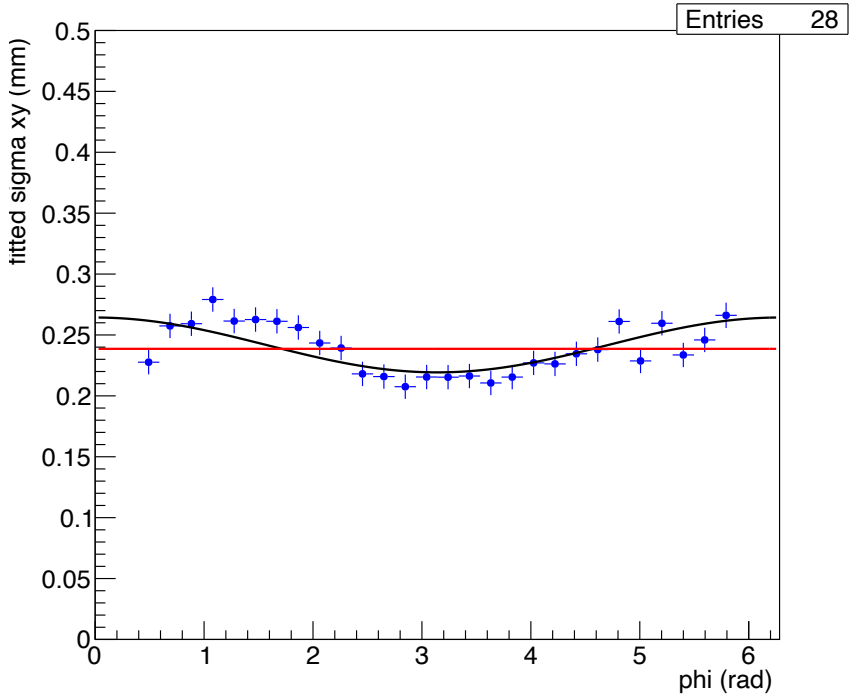
DESY testbeam Module Analysis

Selected circles plots resolution xy



There is a dependency of the resolution of phi and the radius

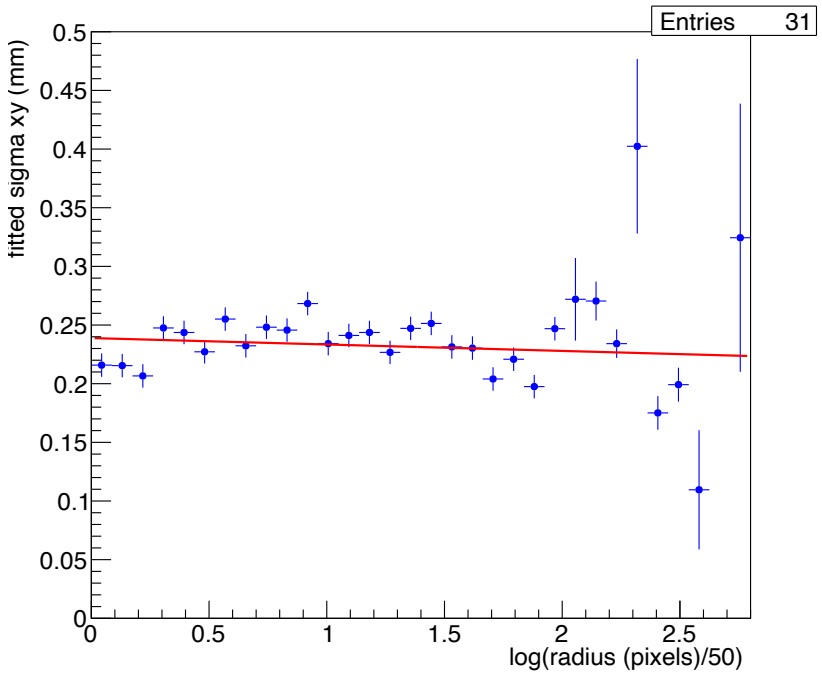
Small radii correlated to large phi range



phi hit on circle

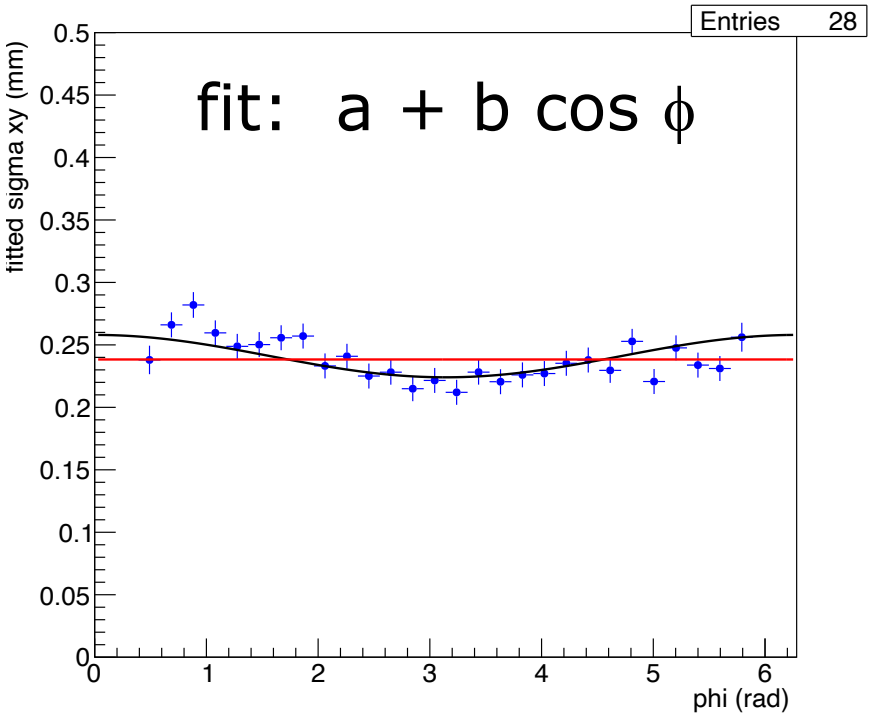
DESY testbeam Module Analysis

Selected circles plots resolution xy



Taking out these dependencies

Fit result
resolution flat in phi
0.241 ± 0.016 mm



phi hit on circle

DESY testbeam Module Analysis

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

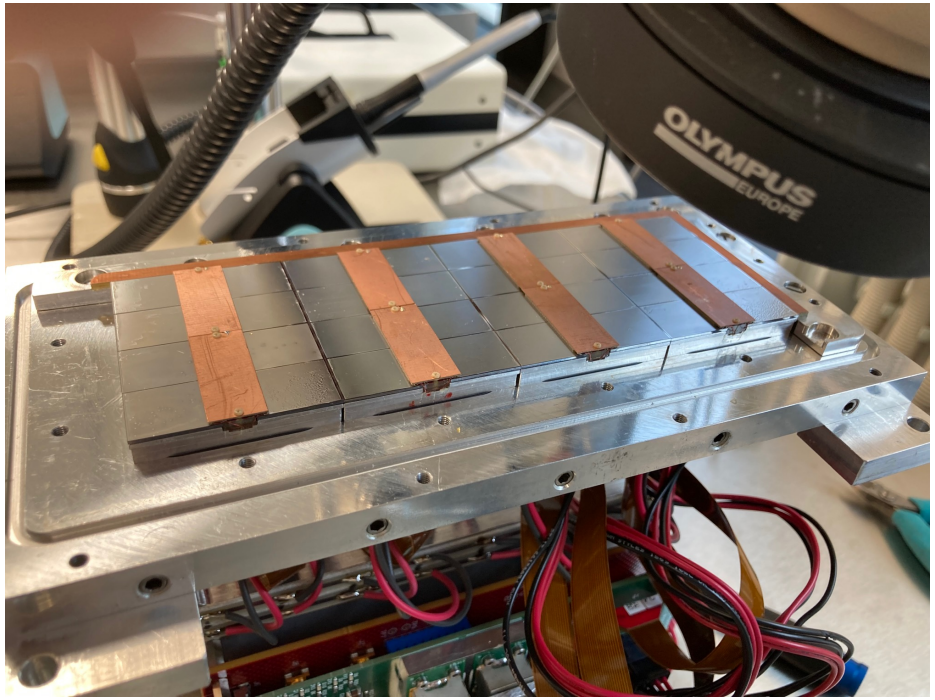
Using circles in the 1 T data set, it can be concluded that the Pixel TPC single electron resolution is – as expected - independent of the incident track angle within an uncertainty of 16 μm.

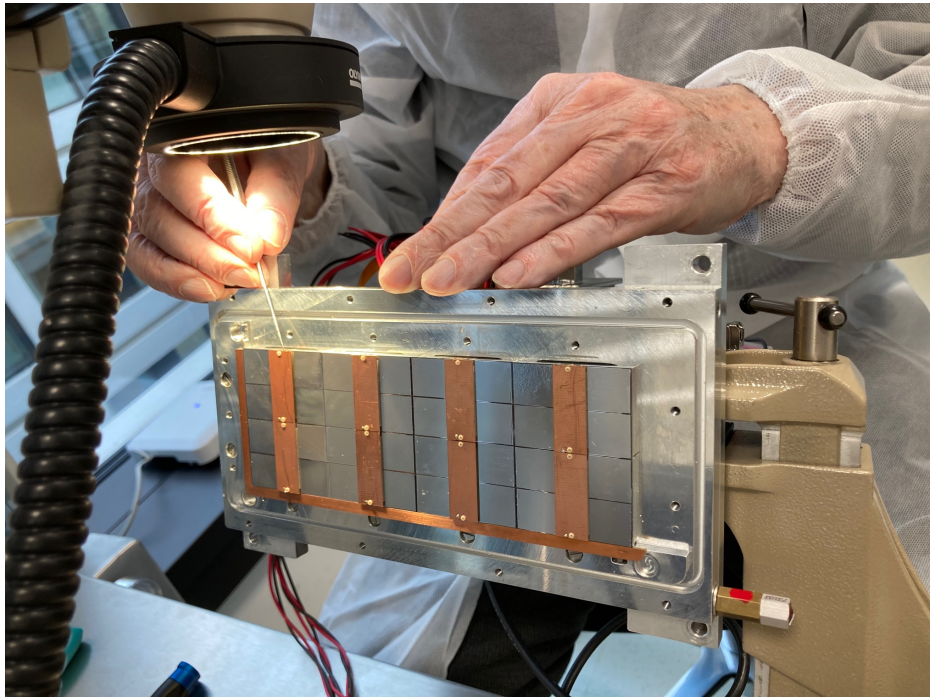
DESY testbeam Module Analysis

Conclusions

A. Measured efficiency at high hit rates
   It is demonstrated that running at hit rates up 1.2 kHz gives at most a reduction of 0.6% in the relative efficiency.
B. Study and 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 independent of incident track angle within an uncertainty of 16 μm.

Pictures of repair work in Bonn



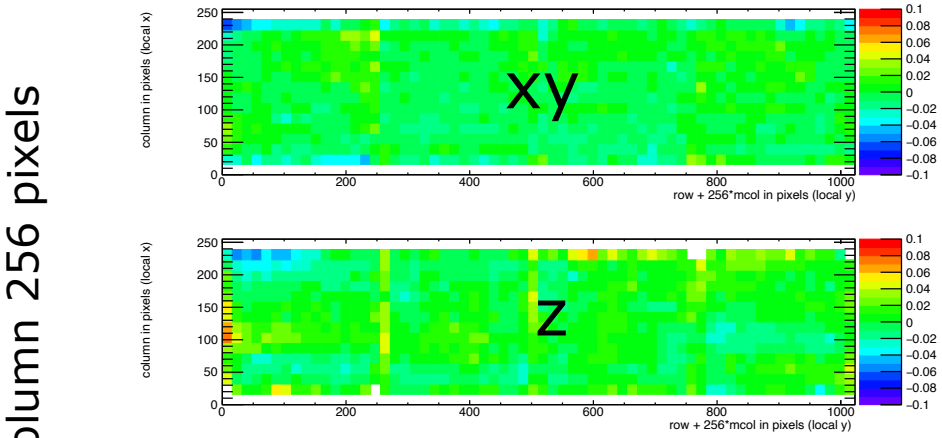


The short in chip 11 was succesully repaired by Fred Hartjes

DESY testbeam Module Analysis

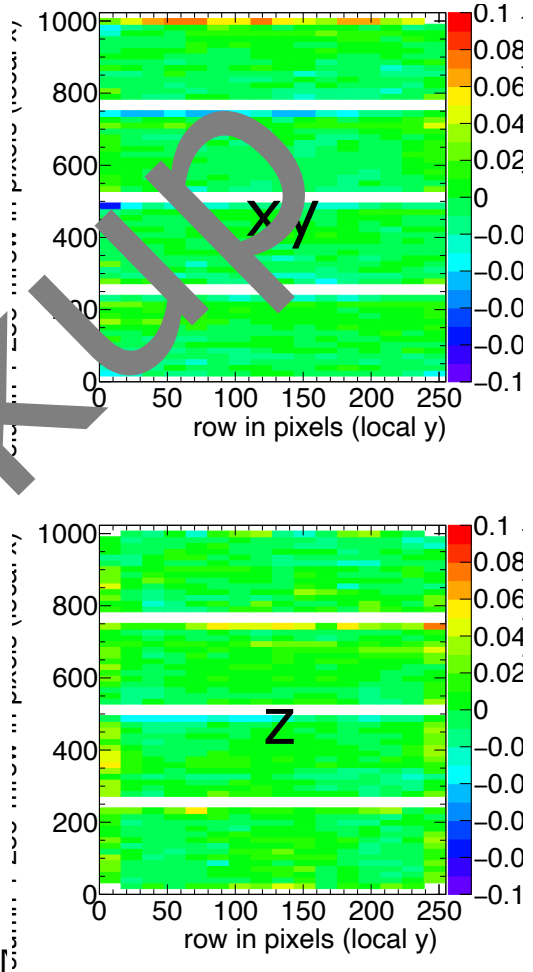
Runs 6909, 6916-17, 6934-35 B=0 T p =6,5 GeV

Mean residuals (module) row



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

(module) column



Regrouping the module plane to increase stats

Granularity 8x8 pixels

acceptance cut
entries > 1500

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

Preliminary

Backup