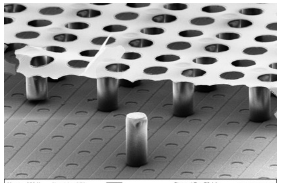

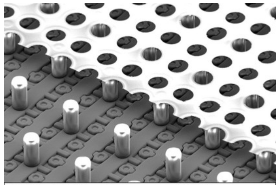

# GridPix TPC


Jochen Kaminski

University of Bonn


ILD – TPC meeting
zoom, 7.9.2026

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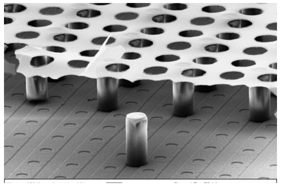
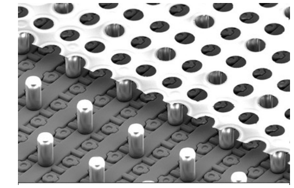


# Time Projection Chambers

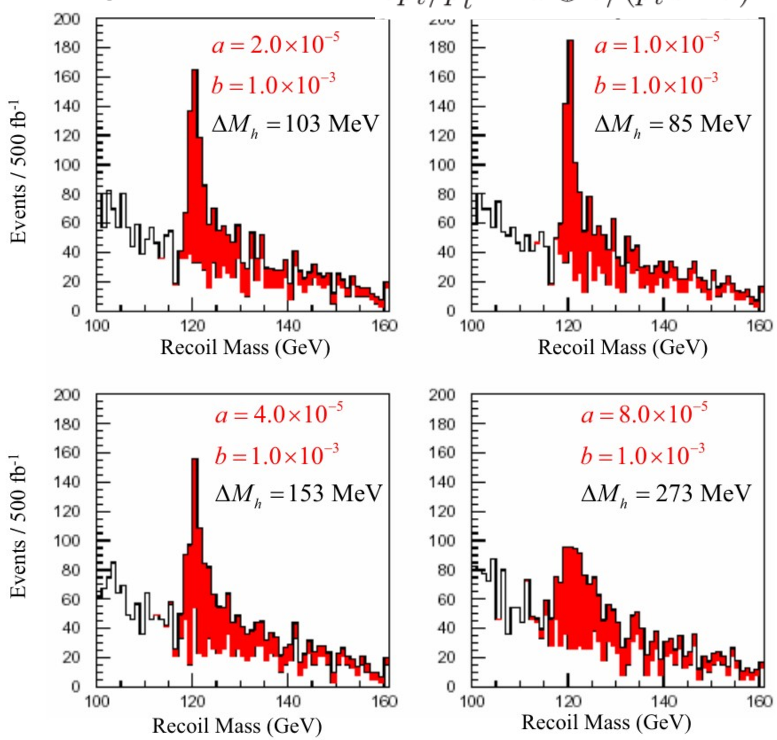


Why are TPC interesting as central tracking detectors at modern colliders?

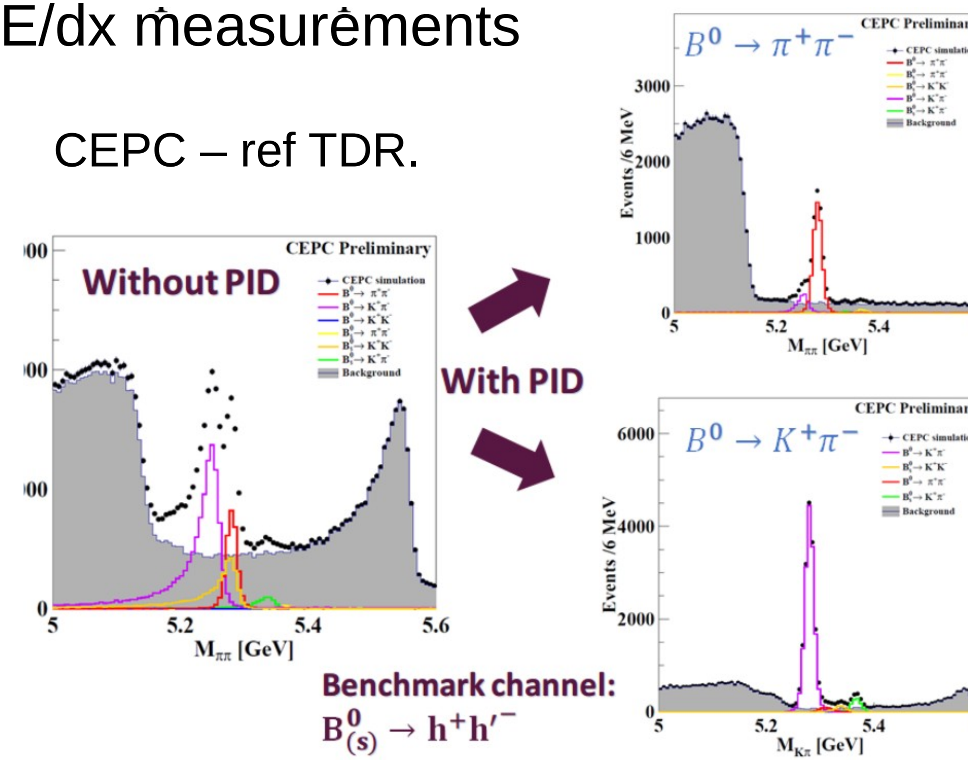
- large number of track points (pixels: 10,000) allows continuous tracking
- low material budget (inner field cage: $X_0$ ~ 2%, gas: $X_0$ ~ 1%)
- material is very homogeneously distributed
- high detection efficiency (>99%) for low momentum tracks (p>= 500 MeV/c)
- high detection efficiency for long lived neutral particles (e.g. $K_{long}$)
- excellent PID for charged tracks by dE/dx measurements

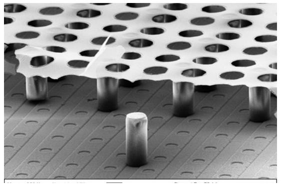
ILC RDR

$$\delta p_t / p_t^2 = a \oplus b/(p_t \sin\theta)$$

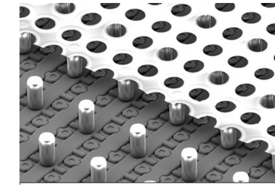



CEPC – ref TDR.

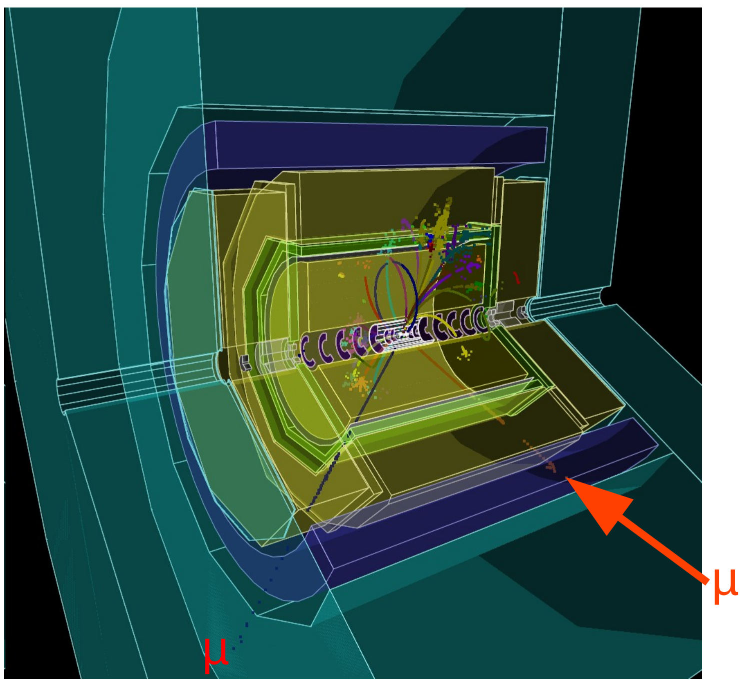




# ILD-TPC Requirements



Requirements are driven by benchmark processes, in the case of ILD – TPC the most stringent measurement is the Higgs-recoil measurement:




## Requirements of TPC from ILC TDR vol. 4

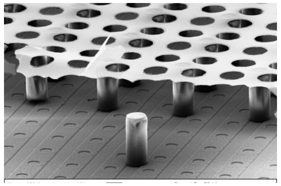
| Parameter | |
|---|---|
| Geometrical parameters | $r_{in}$ 329 mm, $r_{out}$ 1808 mm, z $\pm$ 2350 mm |
| Solid angle coverage | up to $\cos\theta \simeq 0.98$ (10 pad rows) |
| TPC material budget | $\simeq 0.05\ X_0$ including outer fieldcage in $r$ |
| | $< 0.25\ X_0$ for readout endcaps in $z$ |
| Number of pads/timebuckets | $\simeq$ 1-2 $\times\ 10^6/1000$ per endcap |
| Pad pitch/ no.padrows | $\simeq 1\times 6\ \text{mm}^2$ for 220 padrows |
| $\sigma_{\text{point}}$ in $r\phi$ | $\simeq 60\ \mu$m for zero drift, $< 100\ \mu$m overall |
| $\sigma_{\text{point}}$ in $rz$ | $\simeq 0.4 - 1.4$ mm (for zero – full drift) |
| 2-hit resolution in $r\phi$ | $\simeq 2$ mm |
| 2-hit resolution in $rz$ | $\simeq 6$ mm |
| dE/dx resolution | $\simeq 5$ % |
| Momentum resolution at B=3.5 T | $\delta(1/p_t) \simeq 10^{-4}$/GeV/c (TPC only) |

Momentum resolution at B = 3.5 T  $\delta(1/p_t) \approx 2\cdot 10^{-5}$ /GeV/c (full tracking)
In addition: very high efficiency for particle of more than 500 MeV.

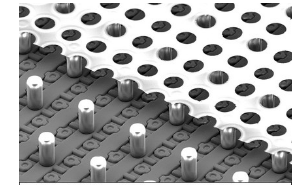
LCTPC community is studying MPGD-TPCs for Lepton Colliders for the last 20 years.



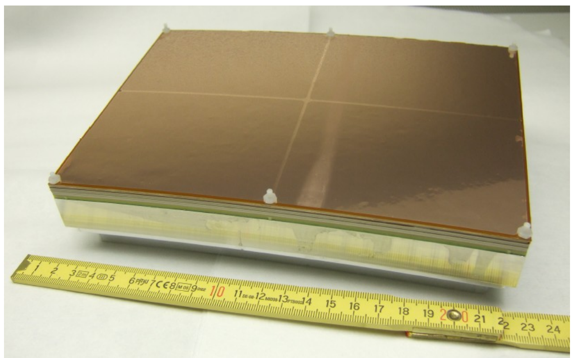
arXiv: 1306.6329



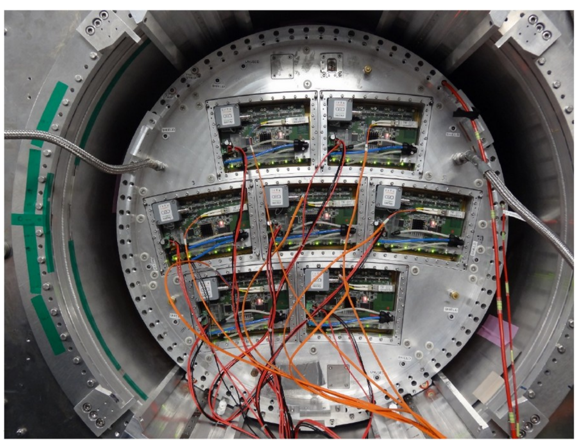
# Test setup at DESY



A test facility has been built to compare different detector readouts under identical conditions and to address integration issues.
Various gaseous amplification stages have been tested:
GEMs and Micromegas with mm-size pads show similar performance fulfilling the ILD requirements.



Module with 3 standard GEMs

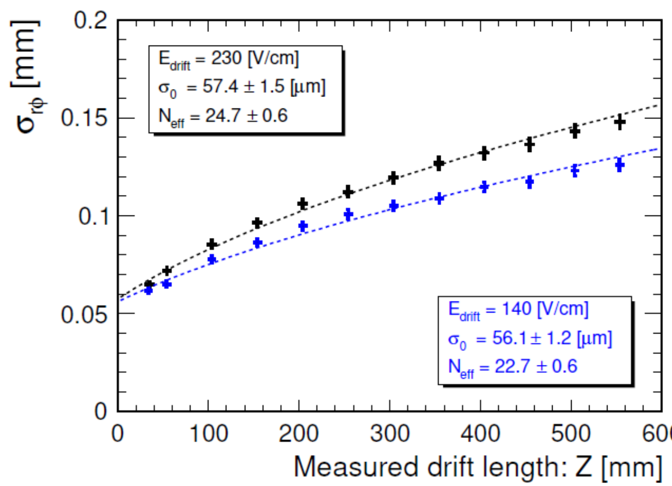


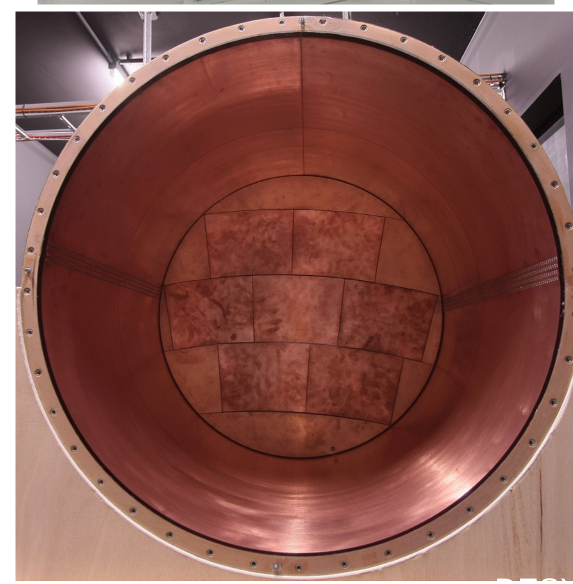
7 Micromegas modules

PCMAG: B <= 1.0 T
Electron test beam: E = 1- 6 GeV

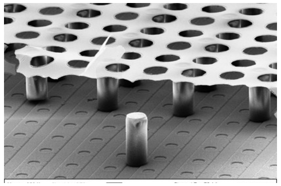
LP Field Cage & modular end plate

External Silicon Tracker (LYCORIS) to identify track distortions.

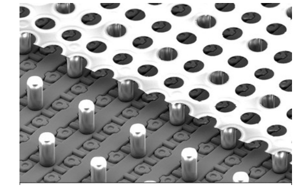


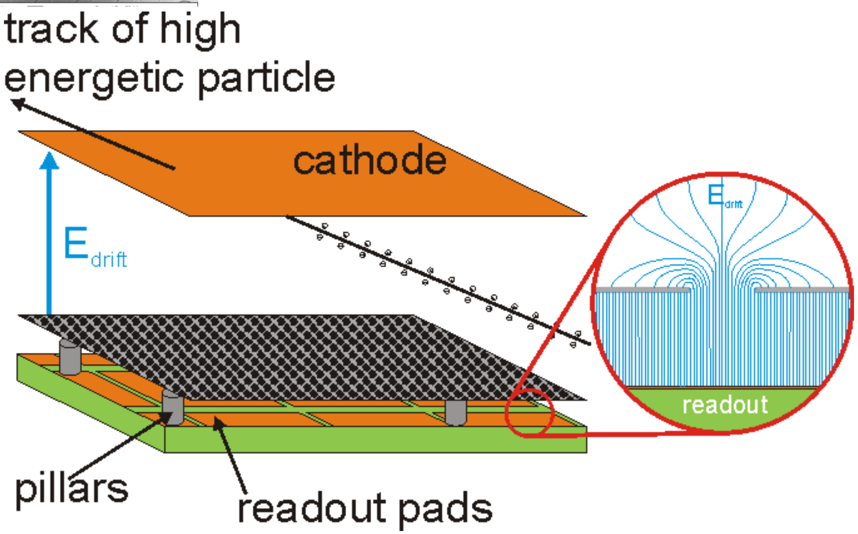



JINST 5:P10011,2010



# From Micromegas to GridPix






Could the spatial resolution of single electrons be improved?

Diffusion in amplification region:

$Ar:CO_2$ 80:20 → $\sigma$ = 11 µm

$Ar:iC_4H_{10}$ 95:5 → $\sigma$ = 11 µm

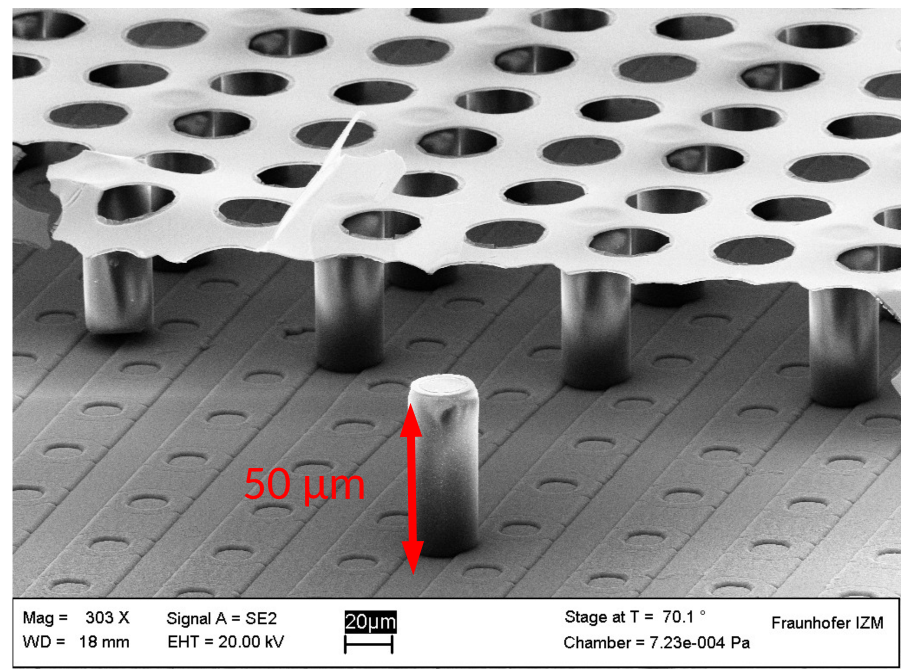
$Ar:CF_4:iC_4H_{10}$ 95:3:2 → $\sigma$ = 11 µm

Smaller pads/pixels could result in better resolution!

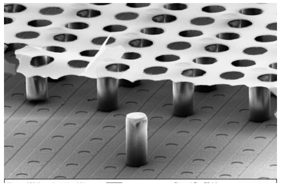
At NIKHEF the GridPix was invented.

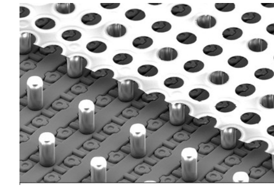
Standard charge collection:
Pads / long strips

Instead: Bump bond pads are used as charge collection pads.




Charge avalanche is collected by one pixel
→ one hit corresponds to one primary electron





# Forschungs- und Technologiezentrum Detektorphysik

First stone laying ceremony 2.11.2016
Inauguration ceremony 8.11.2021

Office space:
- 880 m$^2$
- 4 Floors

Lab space
- 2010 m$^2$
- 4 Levels + Underground Laboratory
- 360 m$^2$ clean rooms (ISO 5, 6, 7)



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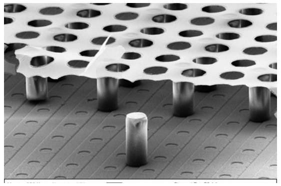
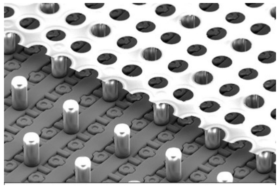
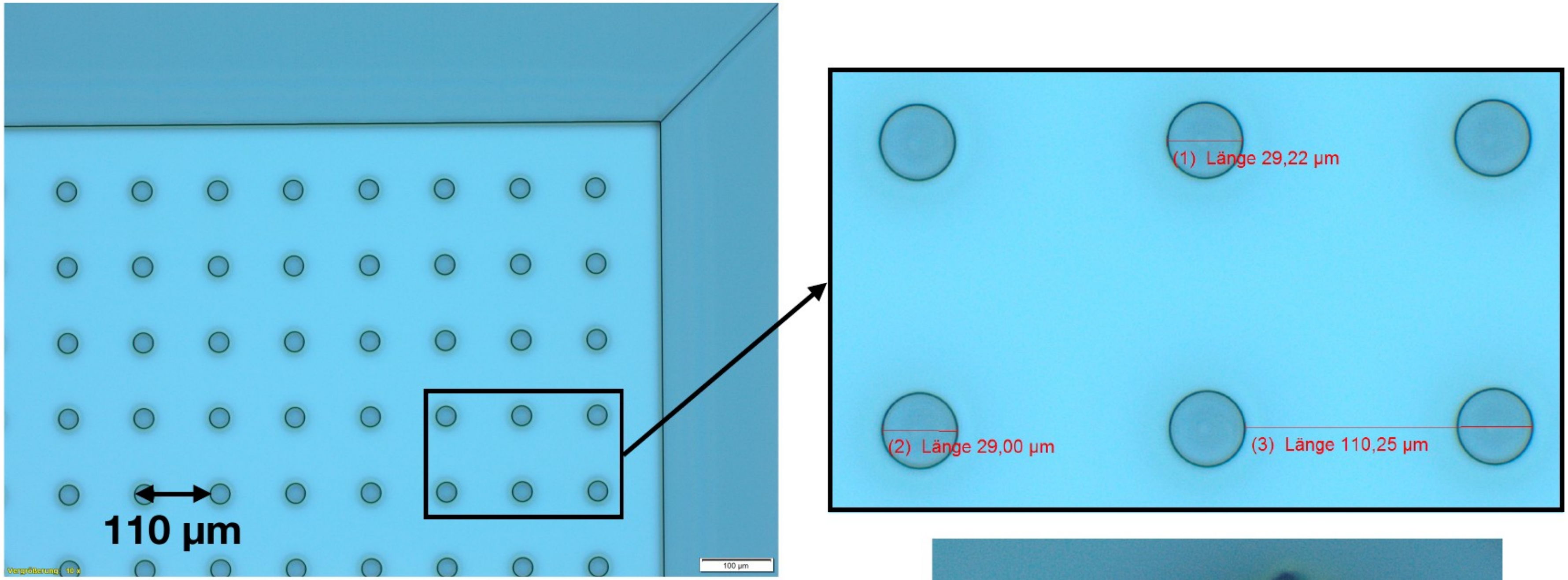


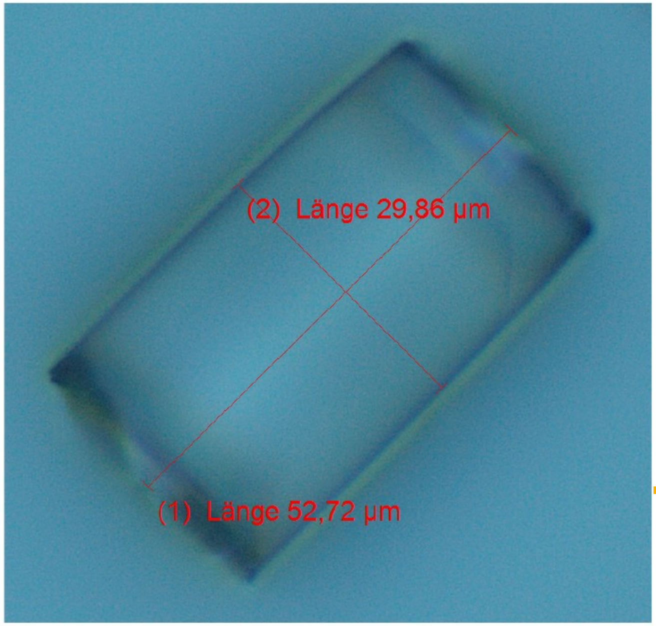


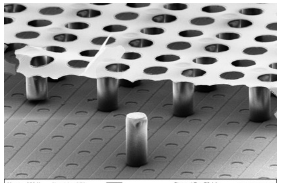
# First Steps Towards “GridPixes made in Bonn” - SU8-Pillars

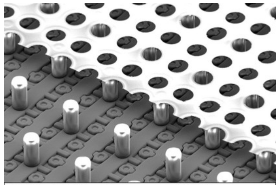
What we want: 50 µm high pillars with 30 µm diameter and 110 µm pitch



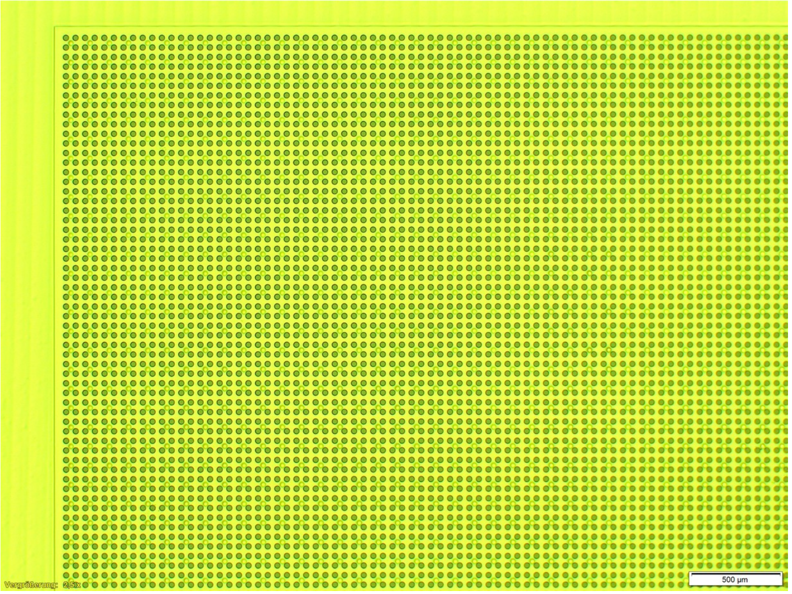

Lithographic Wetbench with Spinner and Hotplates

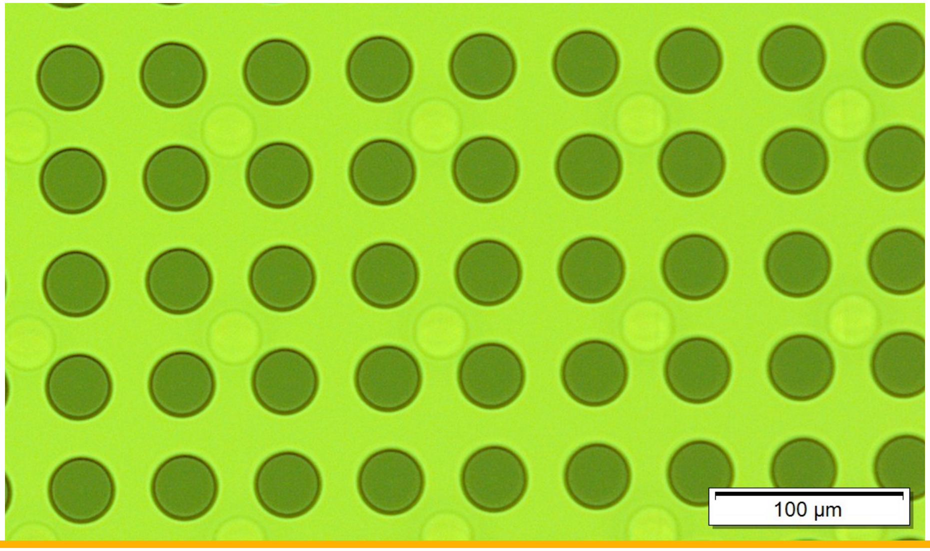






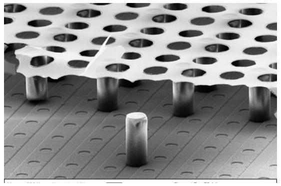
# Second Step Towards "GridPixes made in Bonn" - Metallic Grid

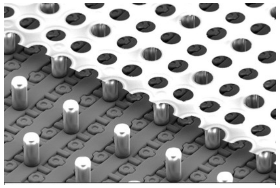



First sample with grid on pillars:
- Not yet reproducible at the moment,
- Only 10µm high pillars in this sample

Nevertheless → first freestanding pillars with grid



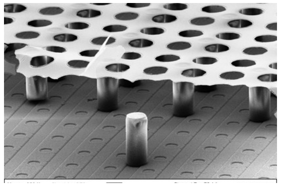
# Commissioning of last machines



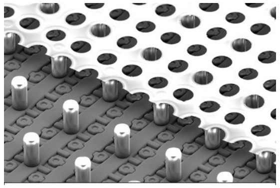
For production of GridPixes, still 2 machines are missing: RIE and PECVD to clean the chips and to produce the protection layer

These machines need nasty gases.
Work has started to install the necessary high class piping and instrumentation.

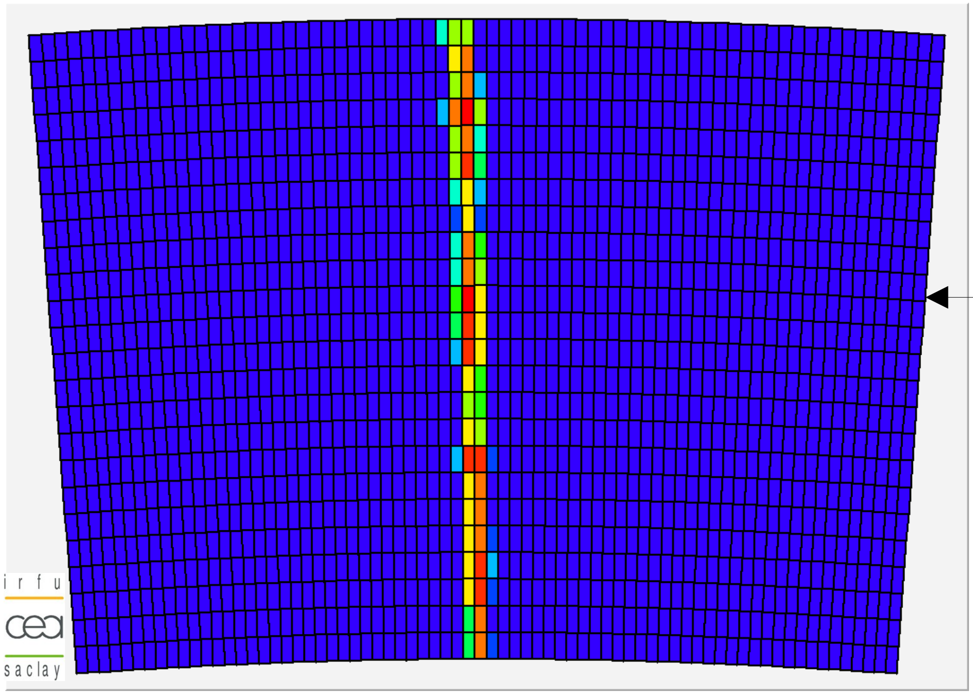
Hopefully, machines can be serviced and commissioned in November and work on protection layer can start early next year.

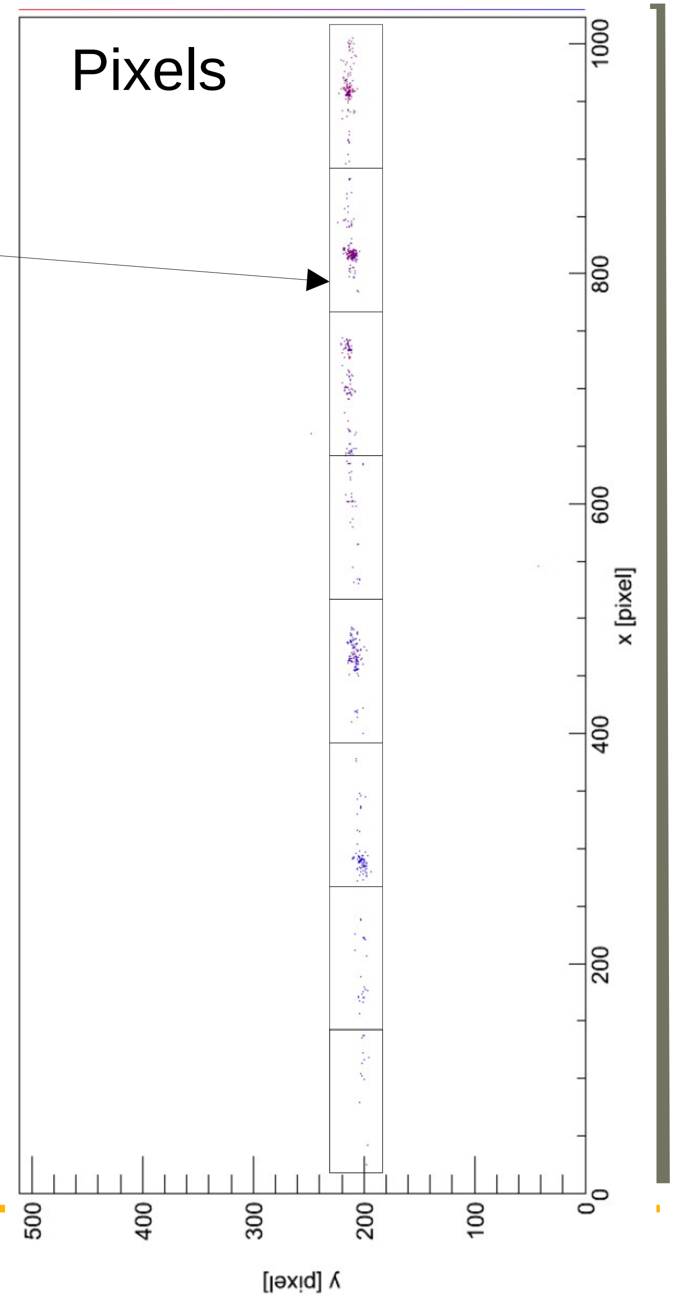
# Comparison Pads vs. Pixels (I)



## Standard charge collection: Pads of 3x7 mm²

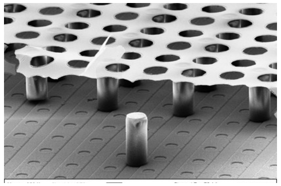



Rectangles correspond to pads

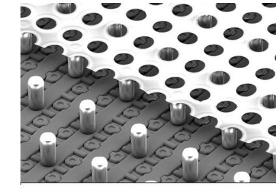



## Advantage of small pixels (55x55 µm²)

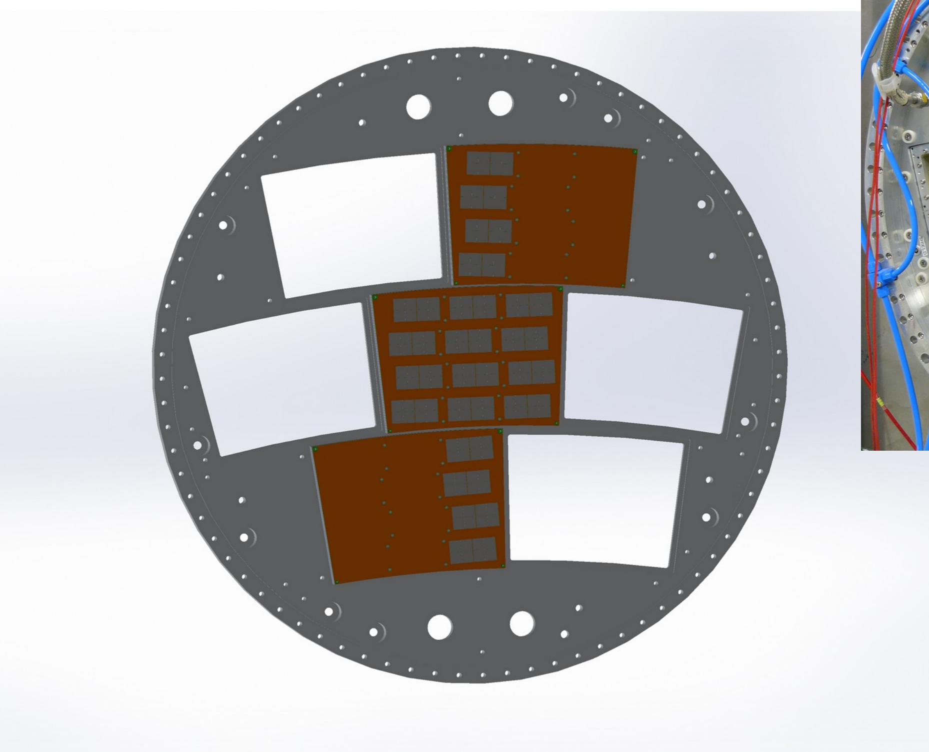
- Lower occupancy
  → better track finding
- Identification and removal of δ-rays and kink removal
- Improved dE/dx, because of primary electron counting
- Pad plane and readout electronics fully integrated

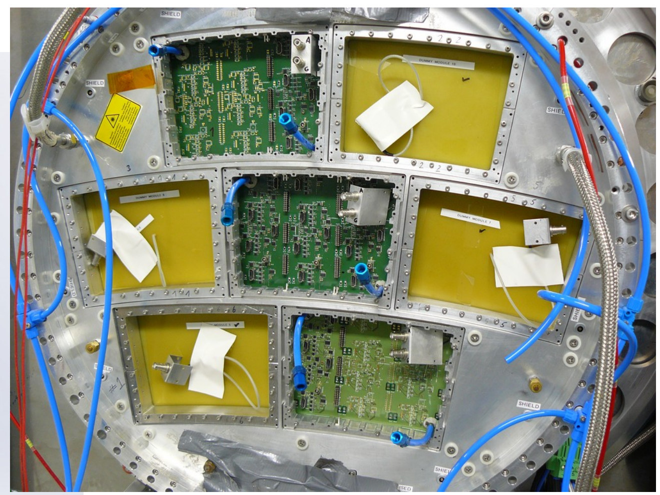


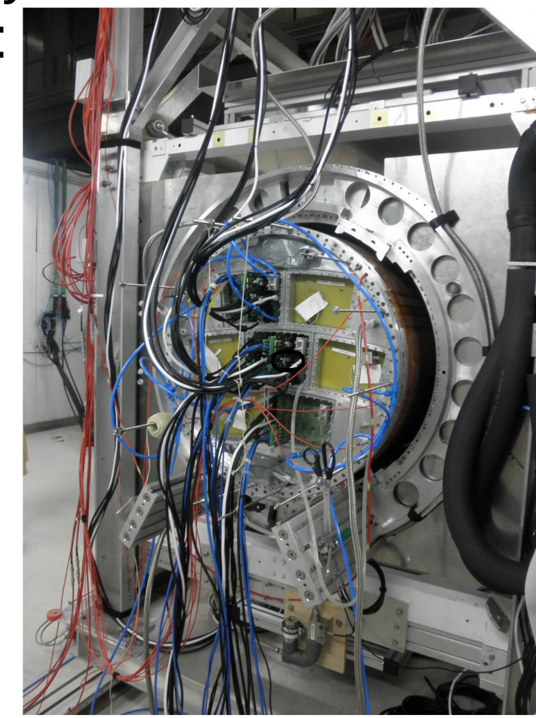
# Test with 160 GridPix Detectors



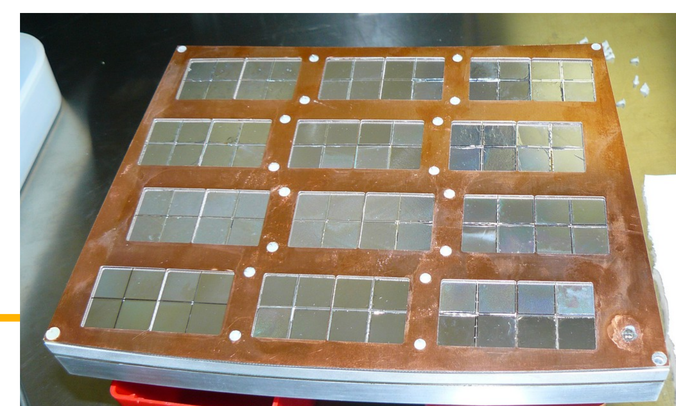
The final goal foresaw a LP-module covered completely with GridPixes (~100).
This goal could even be surpassed by adding two partially covered modules.
In total 160 GridPixes covered an active area of 320 cm²:
- central module with 96 chips (coverage 50 %)
- 2 outer modules with 32 chips each

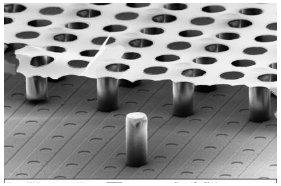




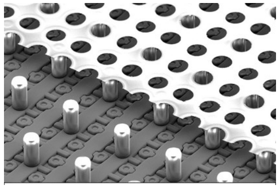


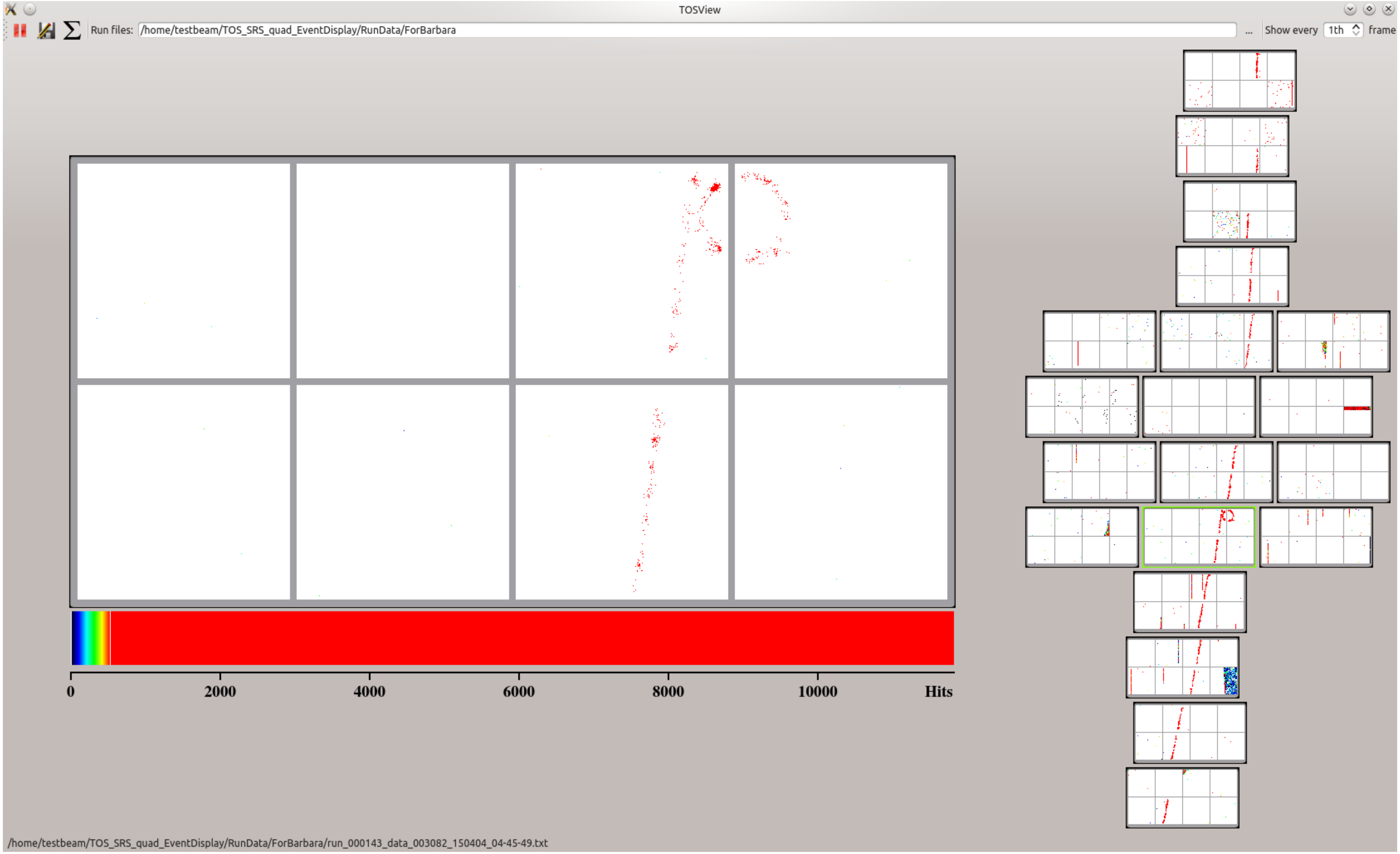
IEEE TNS,
VOL. 64, 2017,
1159

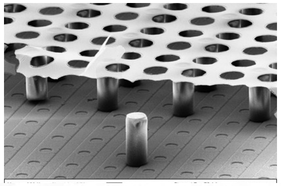




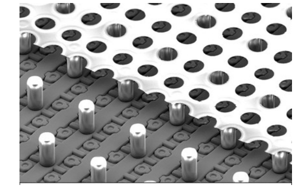
# Event Picture

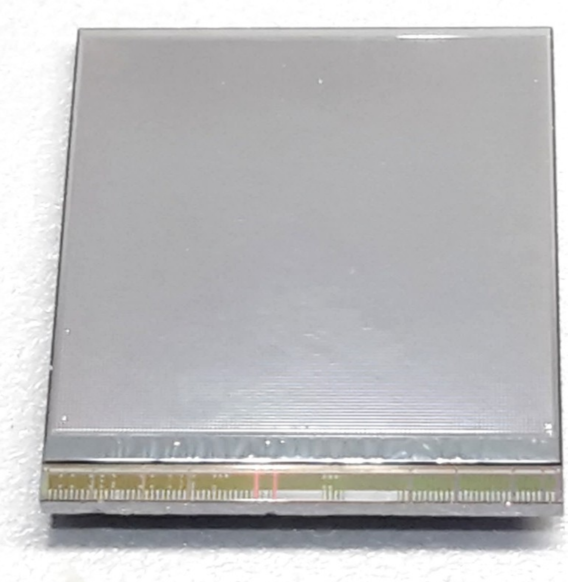


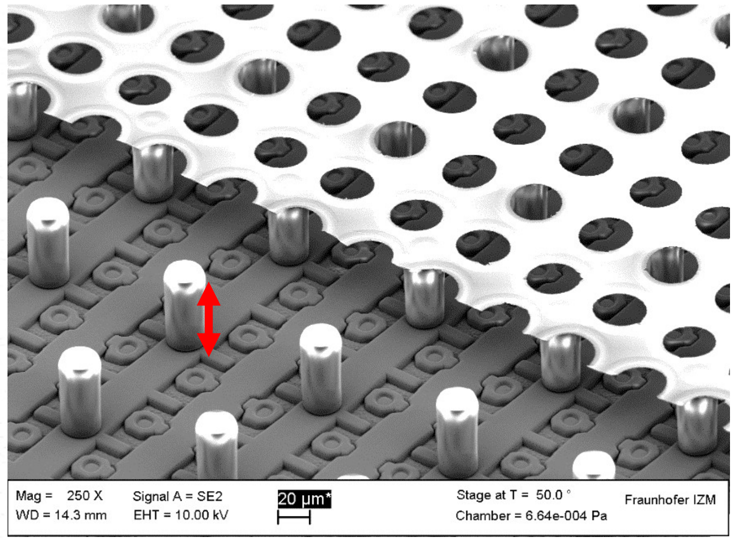


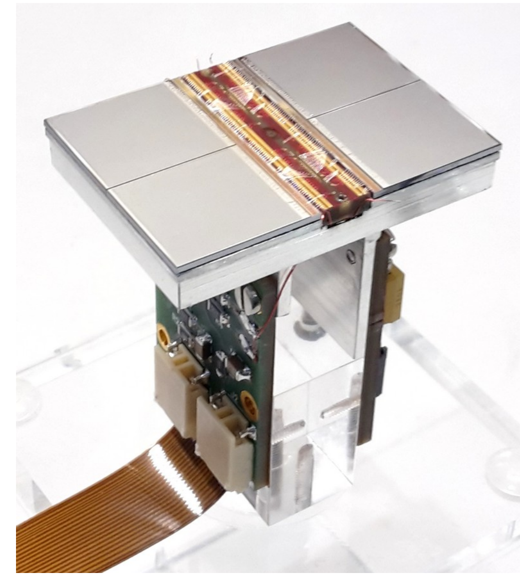


# GridPix based on Timepix3

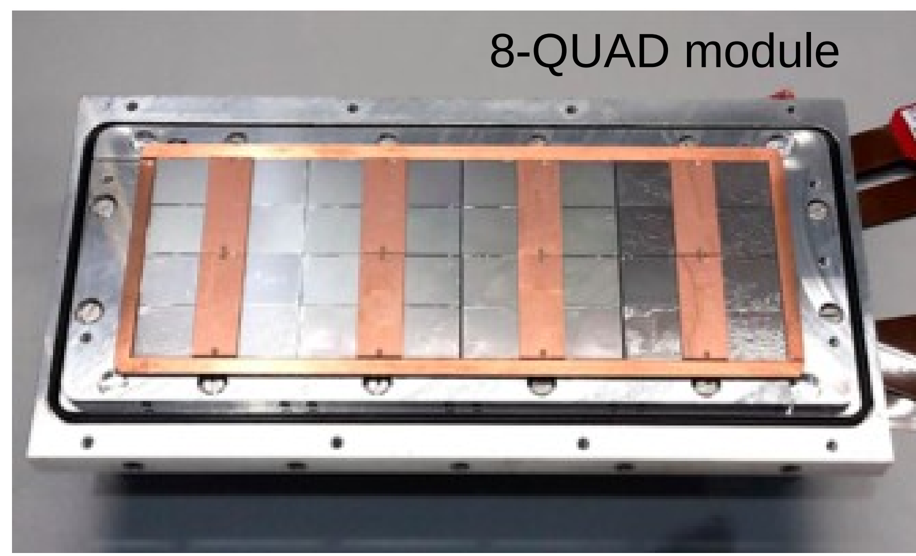






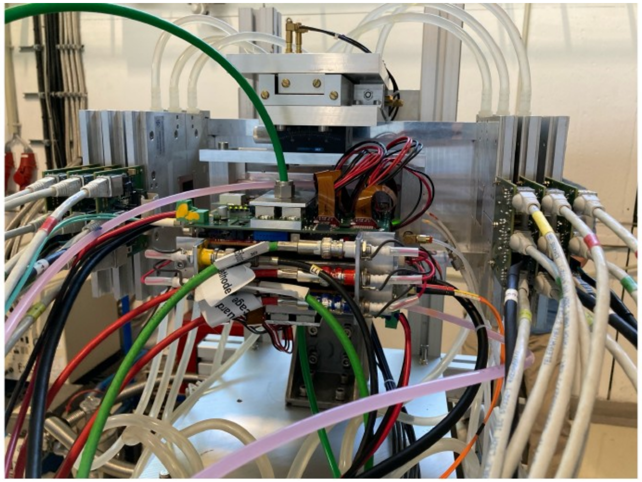



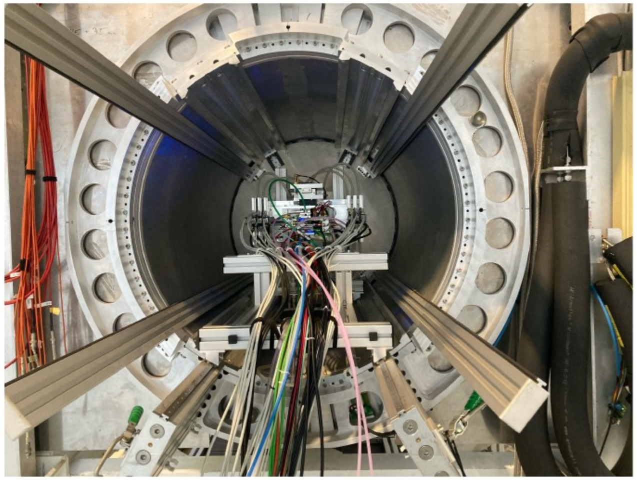
- Number of pixels: 256 × 256 pixels
- Pixel pitch: 55 × 55 µm²
- ENC: ~ 60 $e^-$
- Charge and time available for each hit
- Timing resolution: 1.56 ns
- Zero suppression on chip (sparse readout)
- Multi-hit capable: Super-pixels store hits for some time
- Output rate up to 5.12 Gbps



# Test Beam at DESY

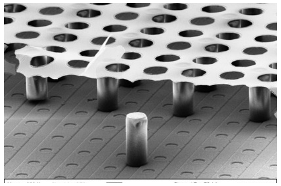
June 2021: Mounting detector in PCMAG (B = 0-1 T) at T24/1.
6 Mimosa planes used as external tracker.



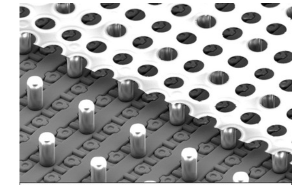


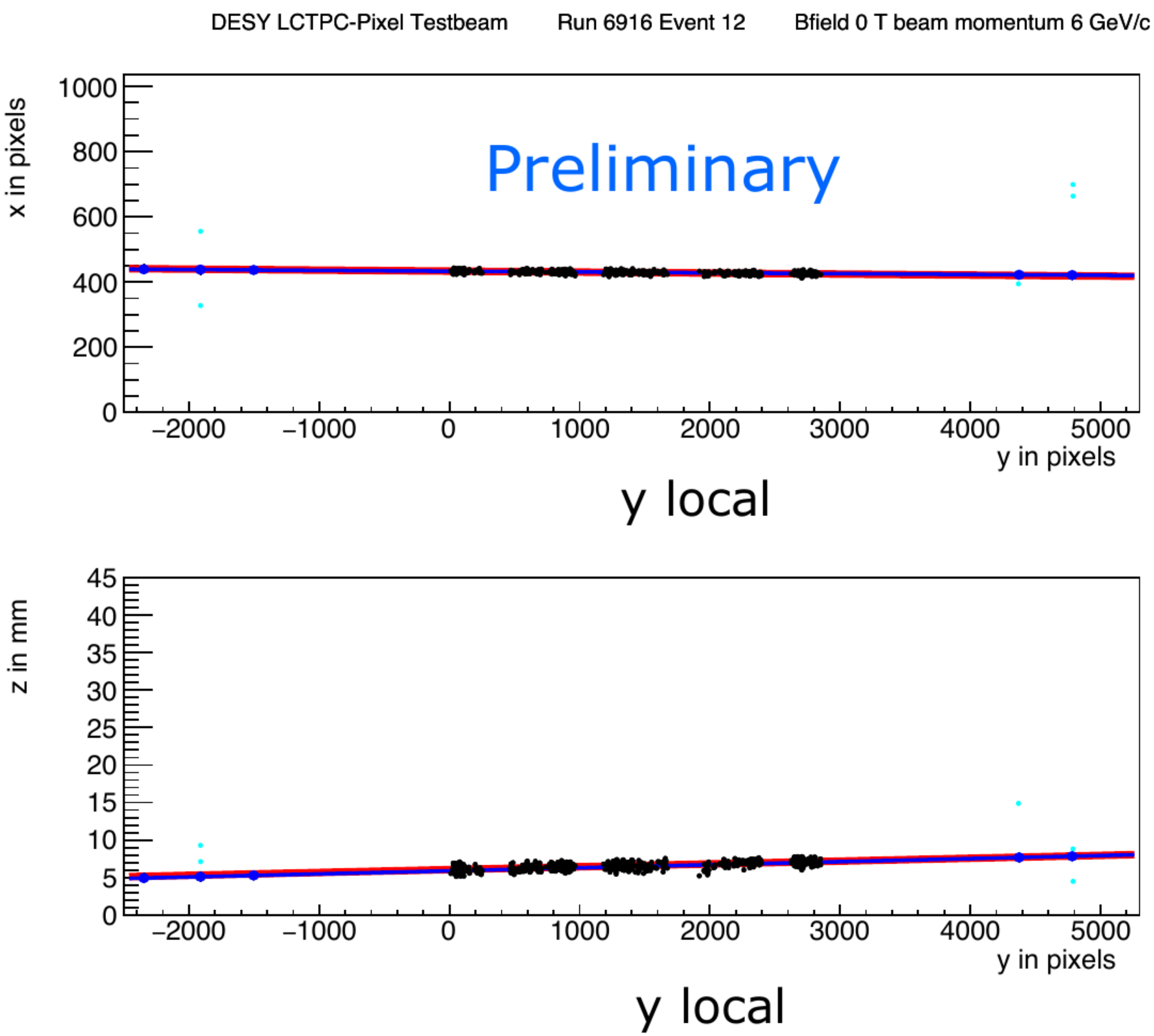
First paper with emphasis on module construction and tracking performance :
“Towards a Pixel TPC part I: construction and test of a 32-chip GridPix detector”

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



# Event Display with Module and Telescope






Example track:
32 GridPix-module track contains 1170 hits

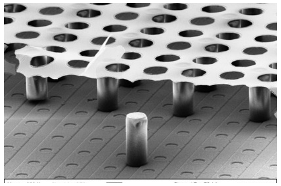
$\chi^2_{xy}$ = 677.5/1128

Asymmetric tail outliers removal applied → 1071 hits kept for z track fitting

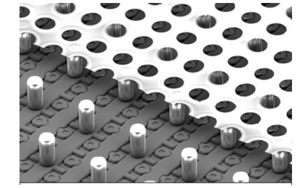
$\chi^2_{z}$ = 775.9/1069

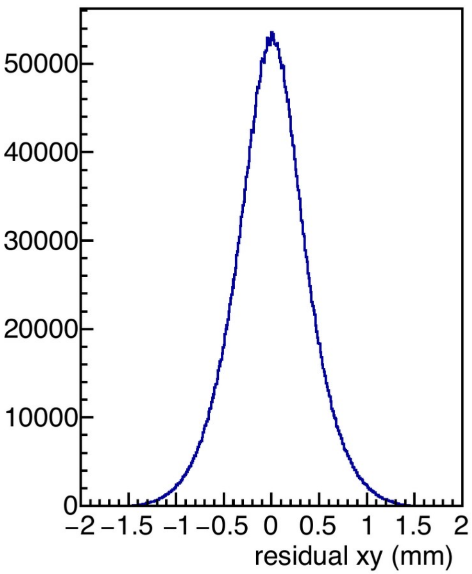
GridPix track
Telescope track

→ On average 1000 hits per 16cm track



# Spatial Resolution






Determine the distributions of residuals perpendicular to the track

Combining several consecutive runs with different drift distances

Use fit function: $\sigma^2_{xy} = \sigma^2_{pixel} + \sigma^2_{tele} + D^2_T(z - z_0)$ to determine $D_T$

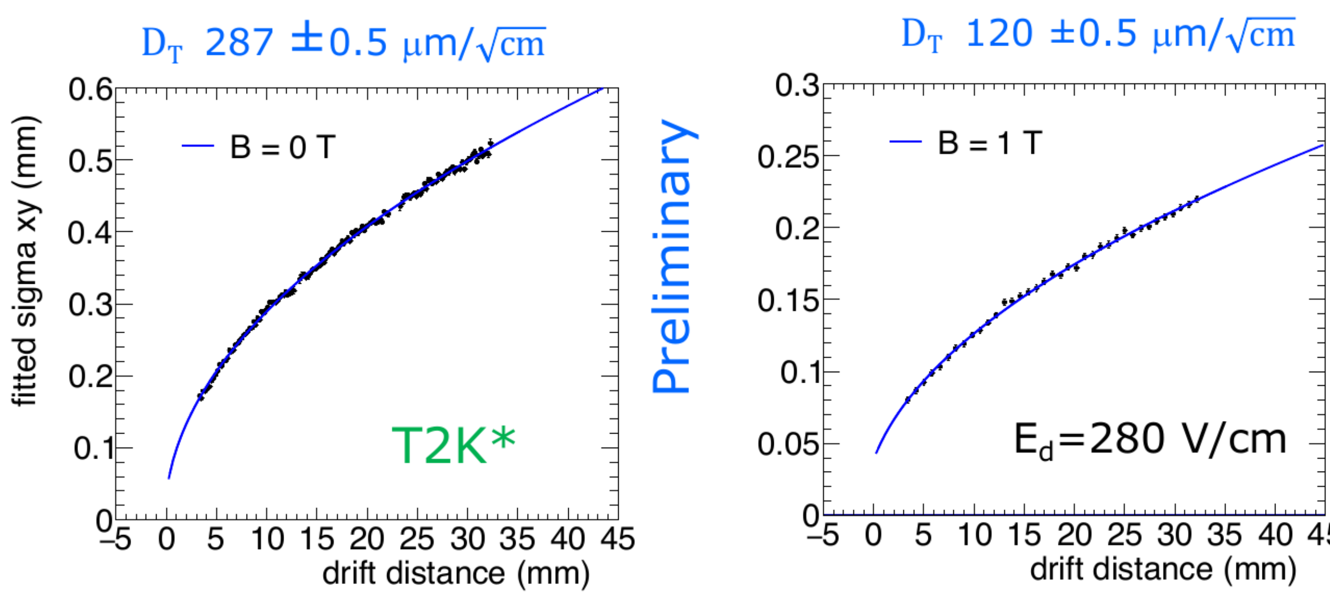
Given: $\sigma^2_{pixel} = (55\ \mu m/\sqrt{12})^2$, $\sigma^2_{tele} = (30\ \mu m)^2$ (measured)

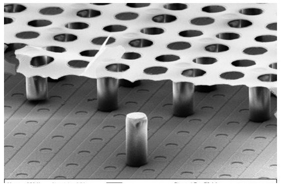
Gas: T2K mixture:
Ar: $CF_4$: $iC_4H_{10}$ 95:3:2
with $O_2$ and $H_2O$ contamination

Predictions by Magboltz:

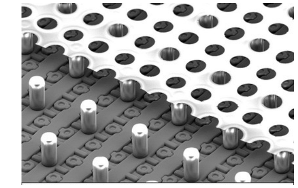
$D_T(0T) = (287 \pm 12)\ \mu m/\sqrt{cm}$

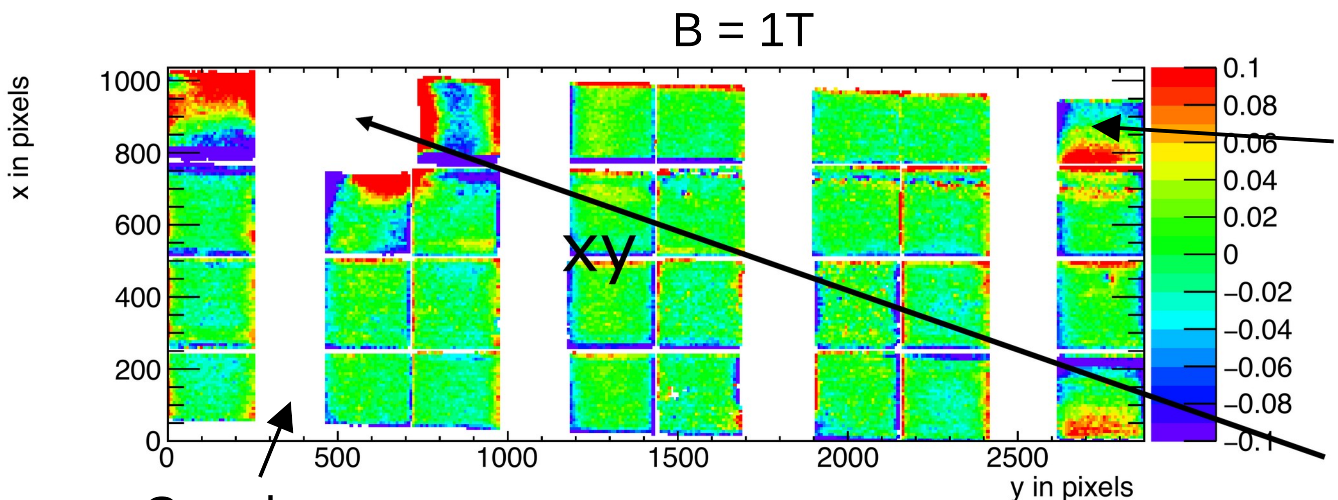
$D_T(1T) = (119 \pm 3)\ \mu m/\sqrt{cm}$





# Systematics: Mean of Residuals



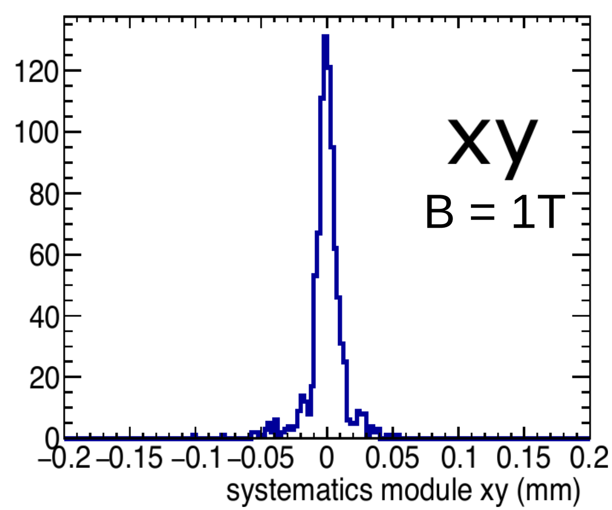



Guards

Clear deformations for GridPixes in the corners

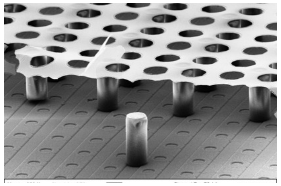
One GridPix with a HV problem
→ disconnected.

To increase statistics, either 4 columns or 4 rows were combined in residual histograms

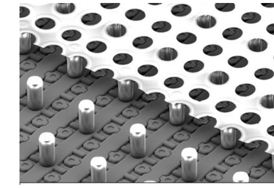



Distribution of mean of residuals

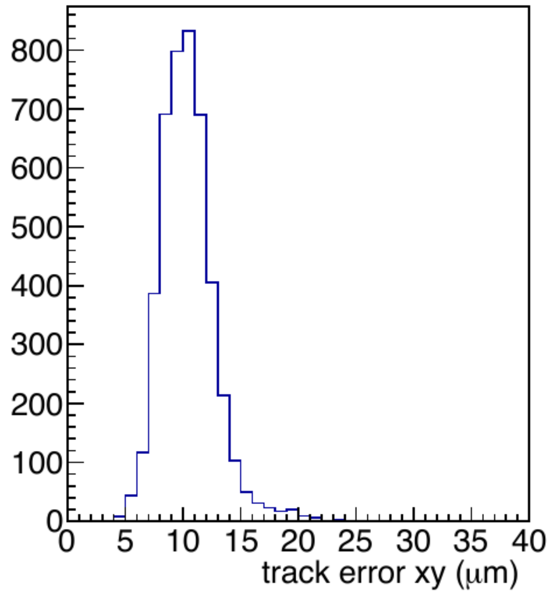
| method | RMSxy | RMSz |
|---|---|---|
| B = 0T, row | 11±4 µm | 15±5 µm |
| B = 0T, column | 13±4 µm | 13±5 µm |
| B = 1 T, row | 13±2 µm | 19±3 µm |
| B = 1 T column | 11±2 µm | 20±3 µm |

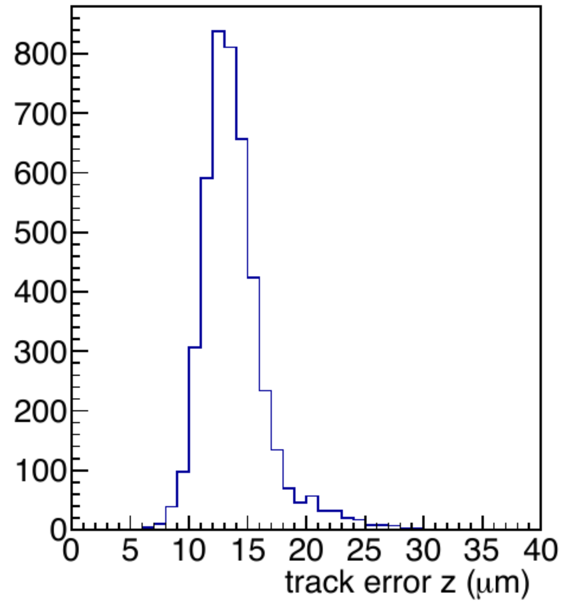


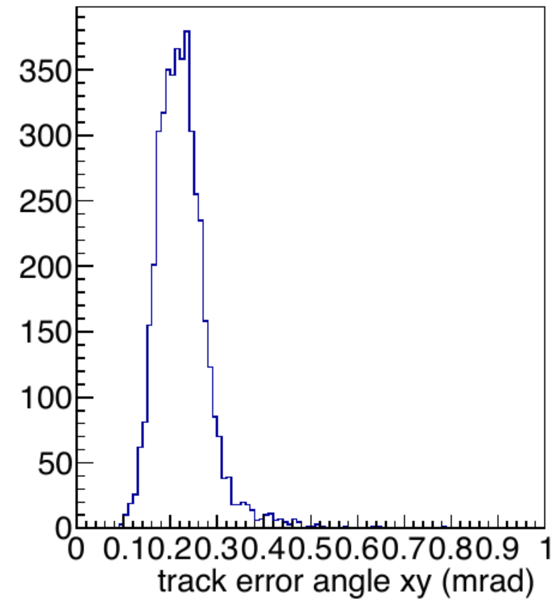
# Tracking Precision

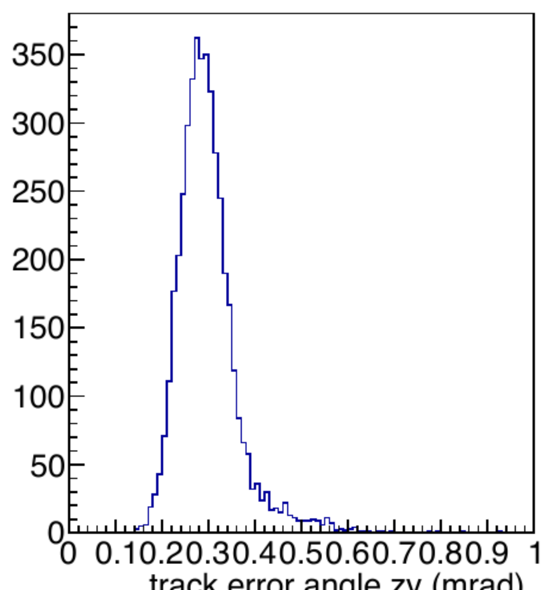


Comparing piercing points of telescope tracks and 32-GridPix module tracks.

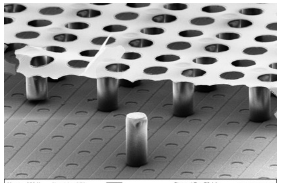


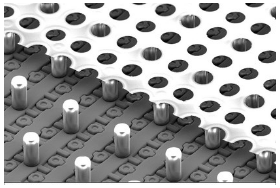



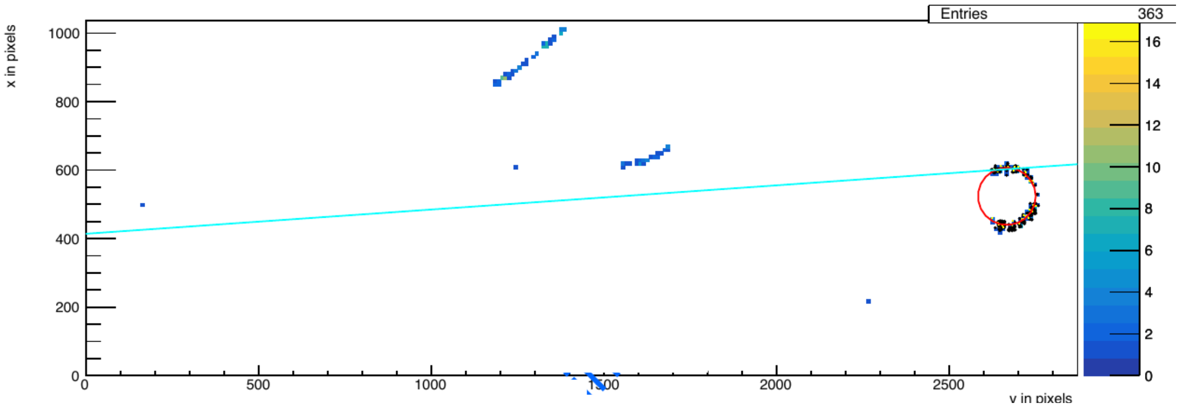



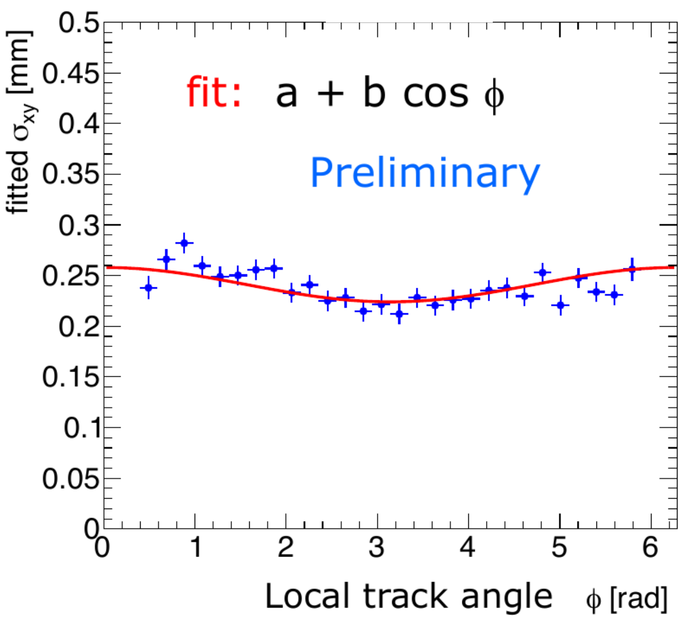

8-quad module
Tracking precision:
position 9 μm (xy) 13 μm (z)
angle 0.19 mrad (dx/dy) 0.25 mrad (dz/dy)
module track length = 157.96 mm



# Spatial Resolution in Dependence on Track Angle





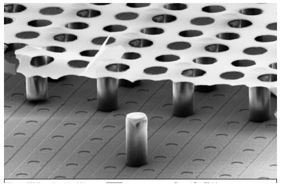

Using curlers as tracks, fitting circle

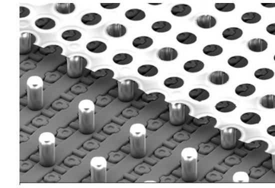
- Radius > 50 pixels with at least 20 selected hits
- Reject circles with a better SL line fit by applying cuts on the $\chi^2$ and number of hits for the circle and line hypothesis.
- Resolution $\sigma_{xy}$ = 4 pixels and $\sigma_z$ = 1 mm
- Track $\chi^2_{xy}$/dof < 5 and $\chi^2_z$/dof < 5
- Phi 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 2.5σ (xy and z)
- Down weighting of large clusters

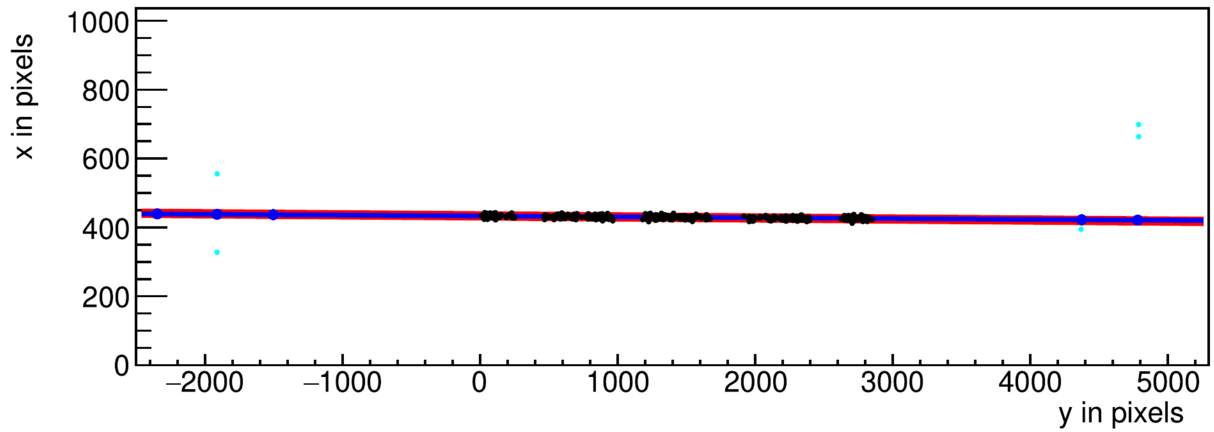
=> Fit results:

Average spatial resolution: a = 0.241µm (all drift d.)
Variation in dep. of angle: b = 16µm

# Extrapolation of test beam results to ILD

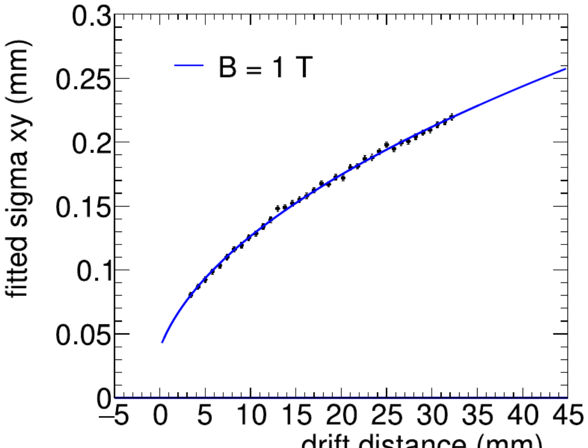




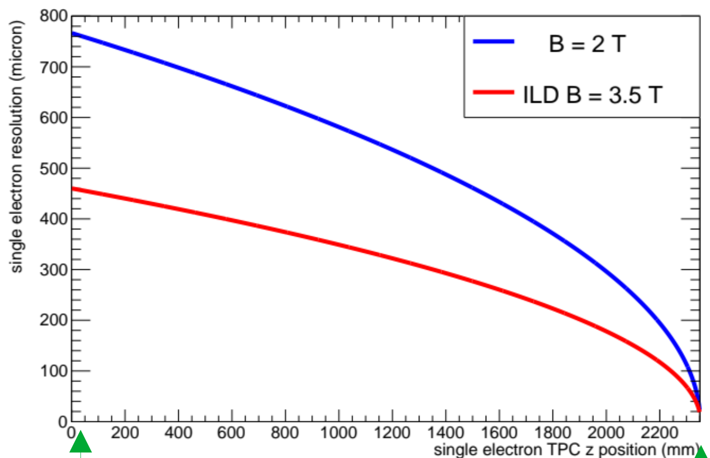



Extrapolation for ILD conditions (B = 3.5 T)

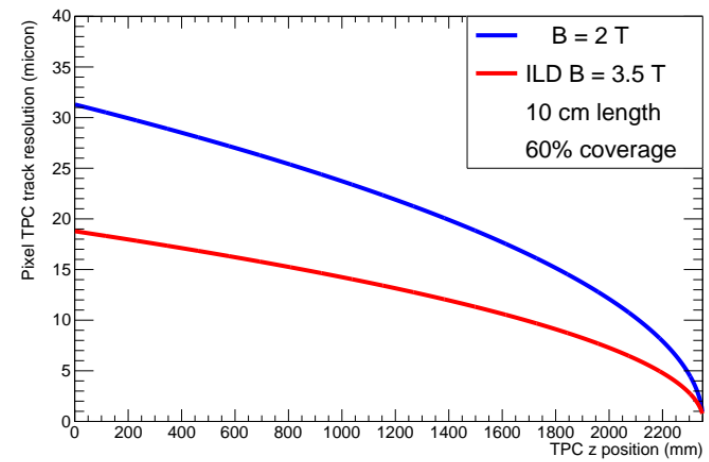
Test beam results




Single electron resolution



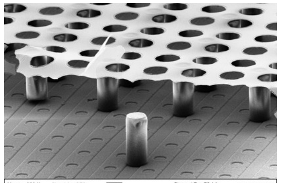

10 cm track resolution



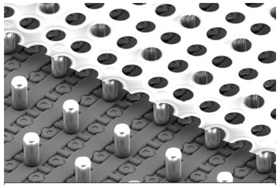

Central cathode

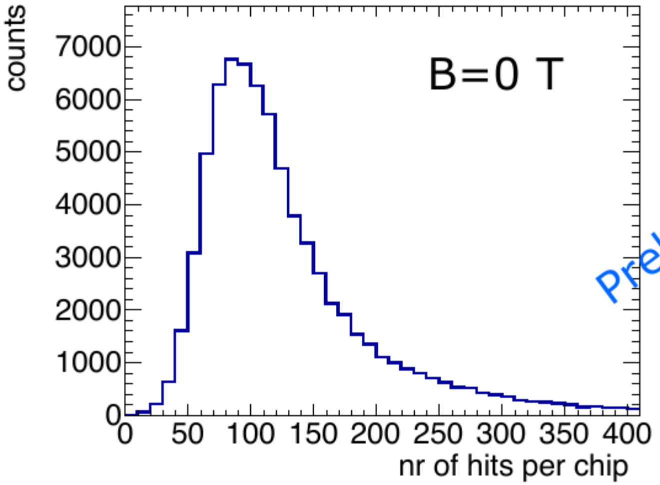
Endcap

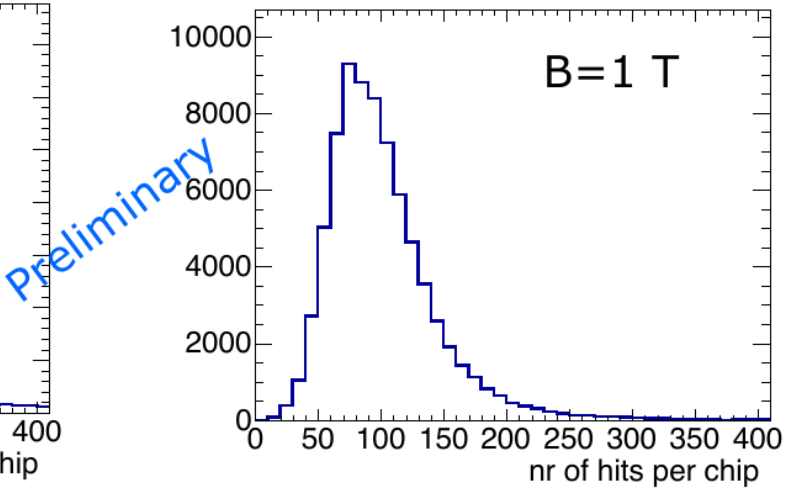
NIM A 1075 (2025) 170397



# PID – Truncation Methode

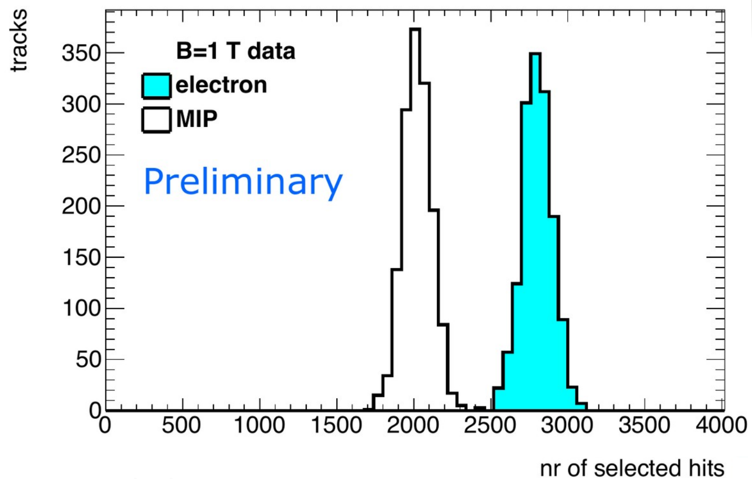


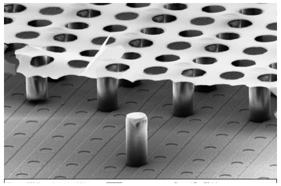


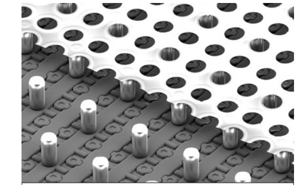

**Extrapolation:**
- Event stitching to get 1m long tracks with 60% coverage
- Electrons (blue) are measurement, mips are scaled (1 : 0.7)
- Z-drift: 5-15 mm
- B = 1 T

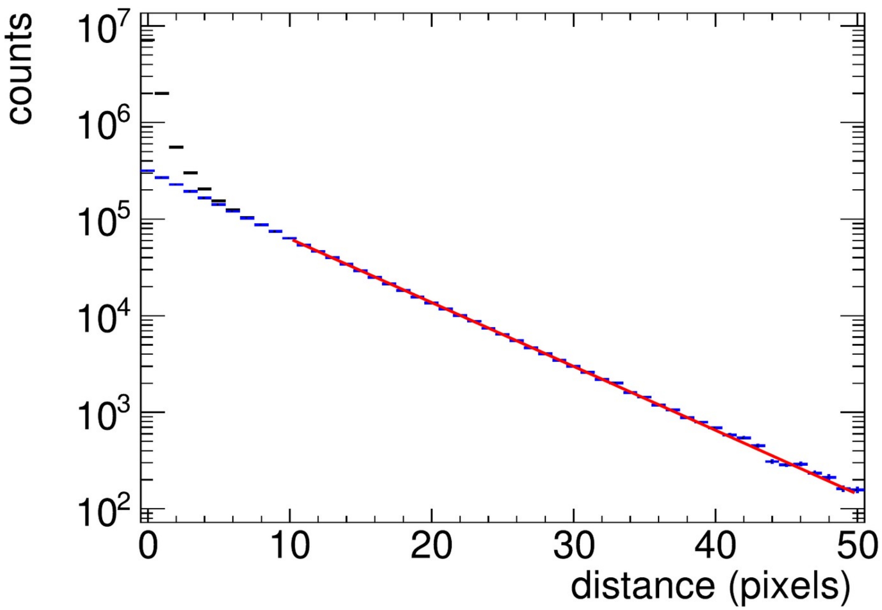
**Truncation method**
- Number of hits per track are about 1000
- Split track into equidistant parts and count electrons
- Reject large clusters with more than 6 hits in 5 consecutive pixels
- dEdx @ 90% with slices of 20 pixels along track (xy) (gives nr of selected hits)





# PID – Template Method

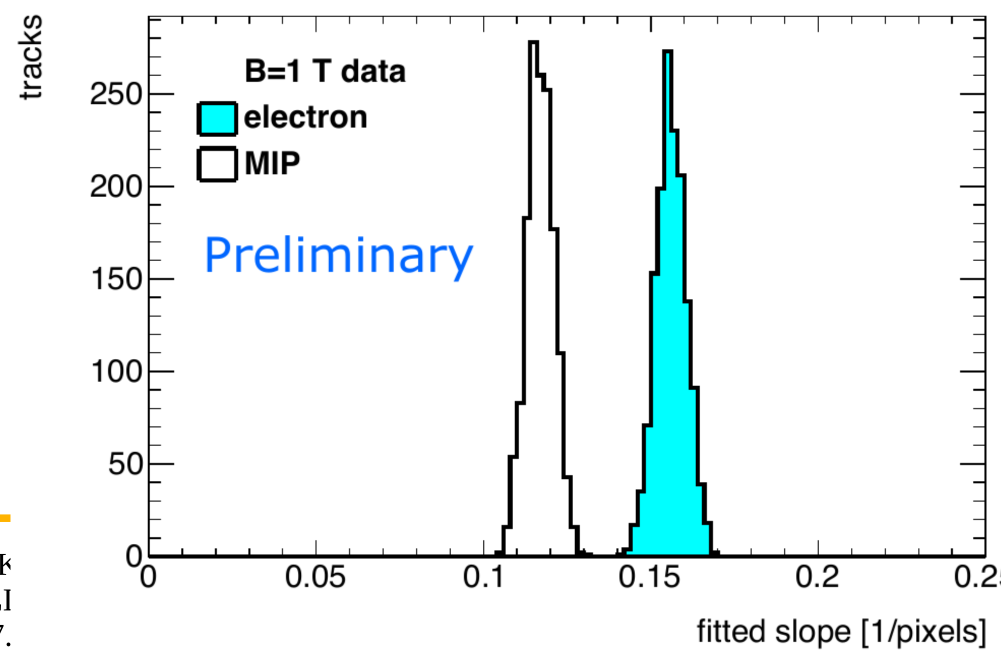


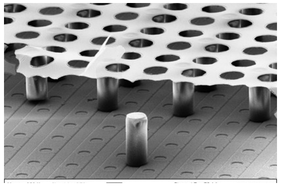



**Template method**

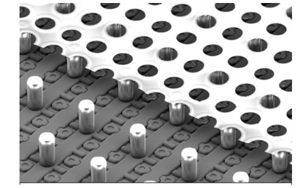
- Measure shortest distance between consecutive hits
- Clusters/primary interactions give exponential distribution
- First 10 bins show significant increase
  → clusters with more than 1 electron
  → rescaling
- Fit linear slope

Template method is an interesting algorithm to exploit dN/dx in space





# PID – Comparison and Extrapolation

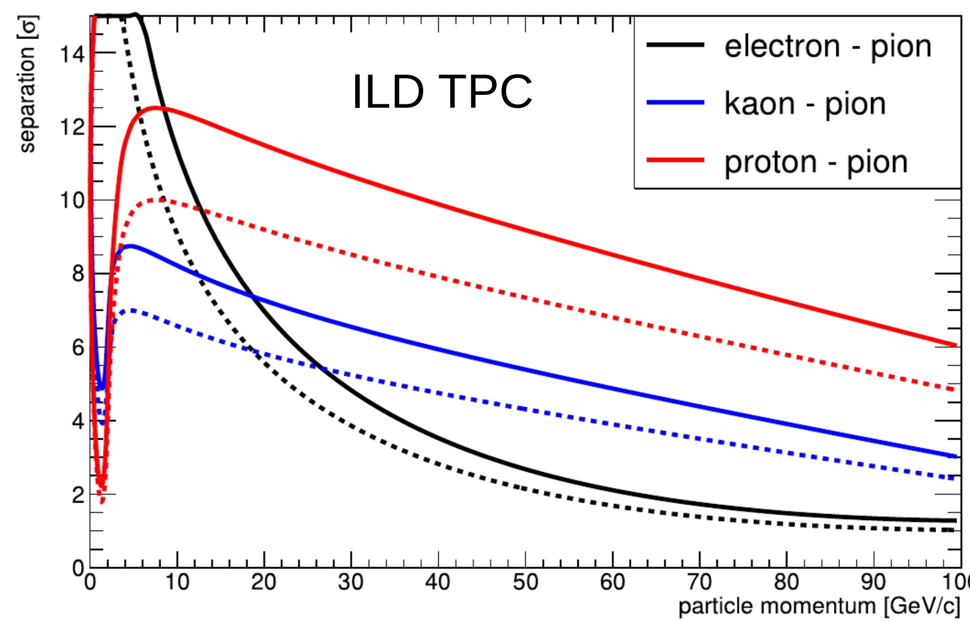


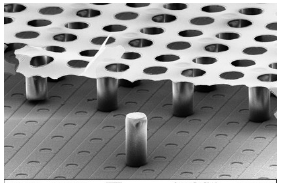
For 1m long tracks with 60 percent coverage,
we get for 5 GeV electrons the dE/dx-, dN/dx-resolution:

| Method | Energy resolution B = 0 T | Energy resolution B = 1 T |
|---|---|---|
| Truncation | 6.0 % | 3.6 % |
| Template fit | 5.4 % | 2.9 % |

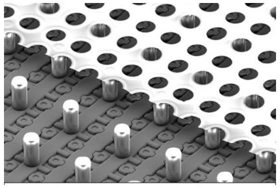
**Extrapolation to ILD detector:**

- $r_{min}$= 329mm, $r_{max}$ = 1770mm
- Tracks at $\theta = \pi/2$
- Still B = 1 T
- Electron “dE/dx”: 2.5 %
- ILD PID Performance for the two methods: template fit (solid), truncation (dashed)





# Outlook



Quite a lot of things remain to be studied. Here is an incomplete list of the next steps in the hardware development:

1.) Resurrect GridPix production at Bonn
2.) Optimization of GridPixes (e.g. low IBF, reduce resistivity of protection layer)
3.) Switch to Timepix4 (4 sides-buttable, lower energy consumption, …)
4.) Build readout for Timepix4 detectors
5.) Equip LP module with GridPixes
6.) dN/dx for different particle species (CERN PS,….)
7.) IBF measurements
8.) Low power readout modes of ASICs