

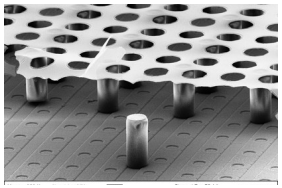
PixelTPC – A GridPix readout of a Time Projection Chamber

Jochen Kaminski

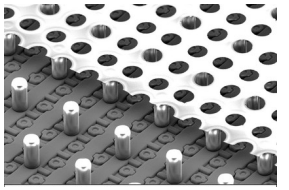
University of Bonn

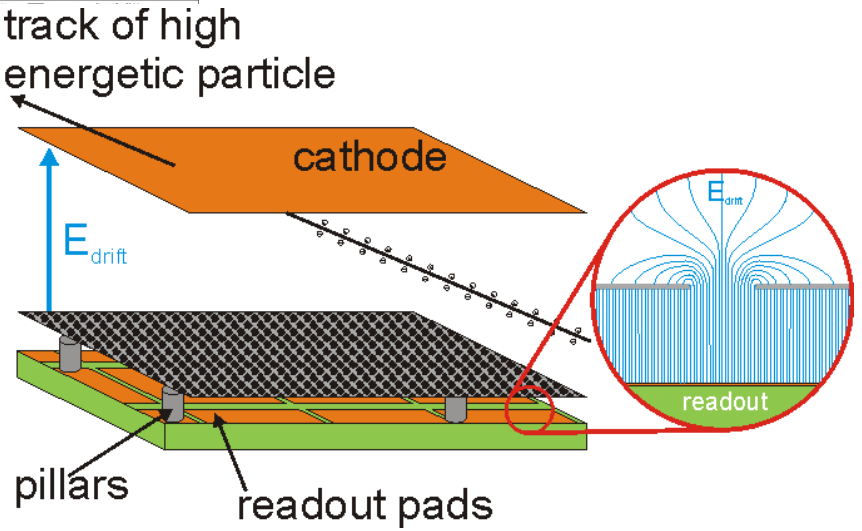
International Workshop on the High Energy Circular Electron Positron Collider 2026
Shanghai

UNIVERSITÄT BONN



From Micromegas to GridPix





Could the spatial resolution of single electrons be improved?

Diffusion in amplification region:

$Ar:CO_2$ 80:20 → σ = 11 µm

$Ar:iC_4H_{10}$ 95:5 → σ = 11 µm

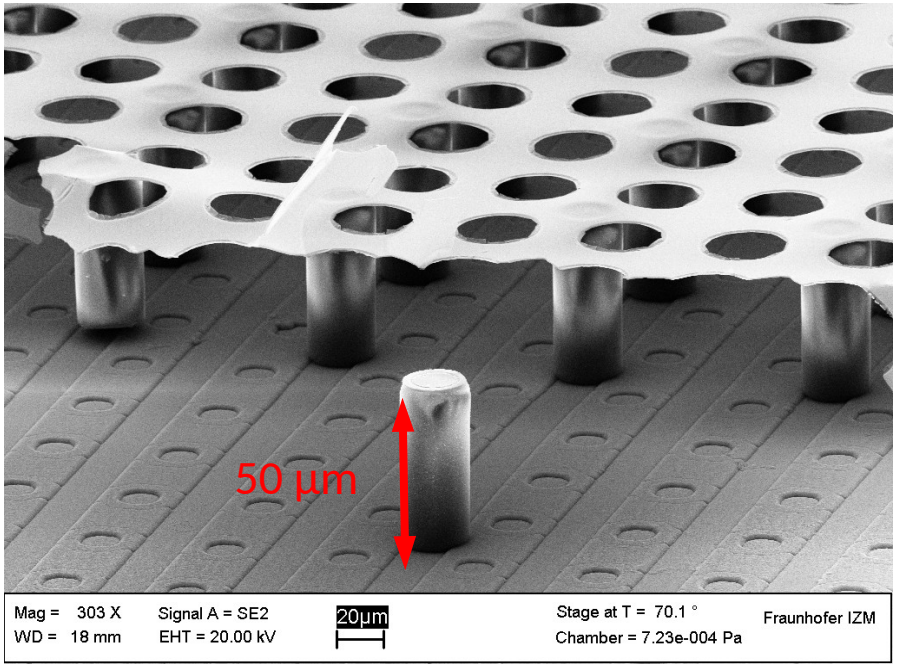
$Ar:CF_4:iC_4H_{10}$ 95:3:2 → σ = 11 µm

Smaller pads/pixels could result in better resolution!

At NIKHEF the GridPix was invented.

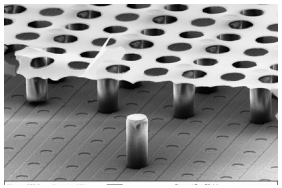
Standard charge collection:
Pads / long strips

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

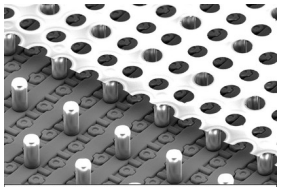


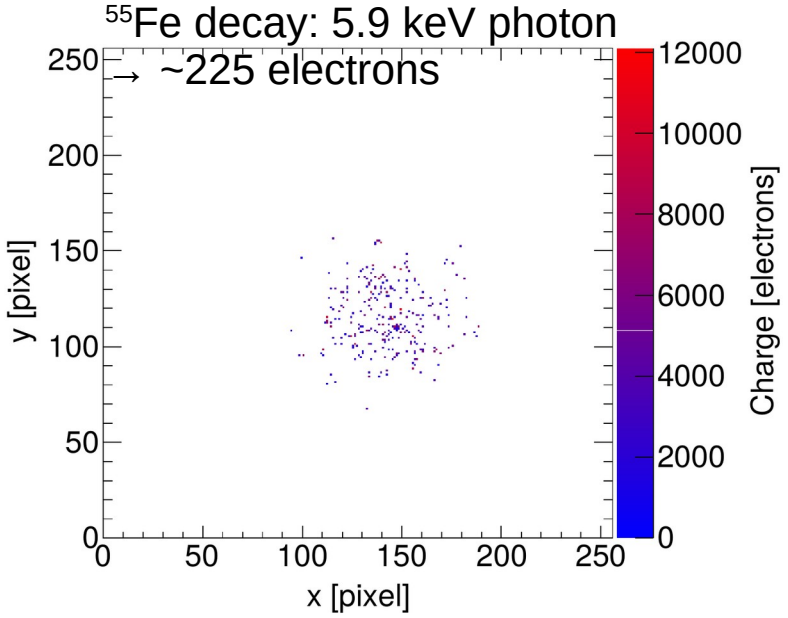
Charge avalanche is collected by one pixel

→ one hit corresponds to one primary electron



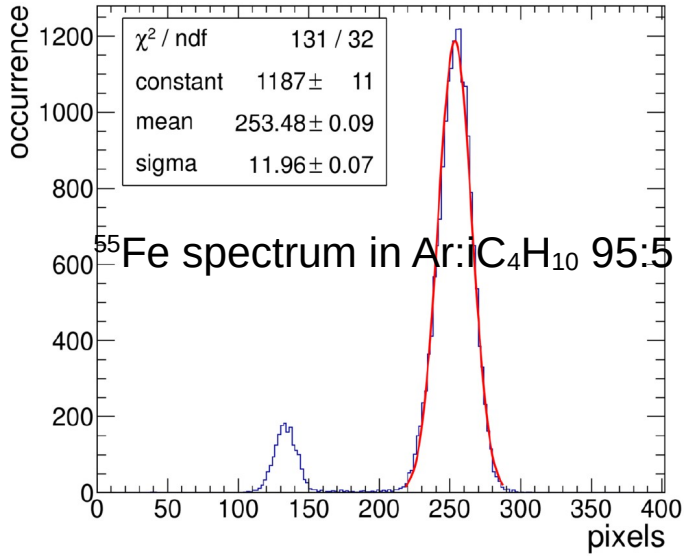
Single Electrons

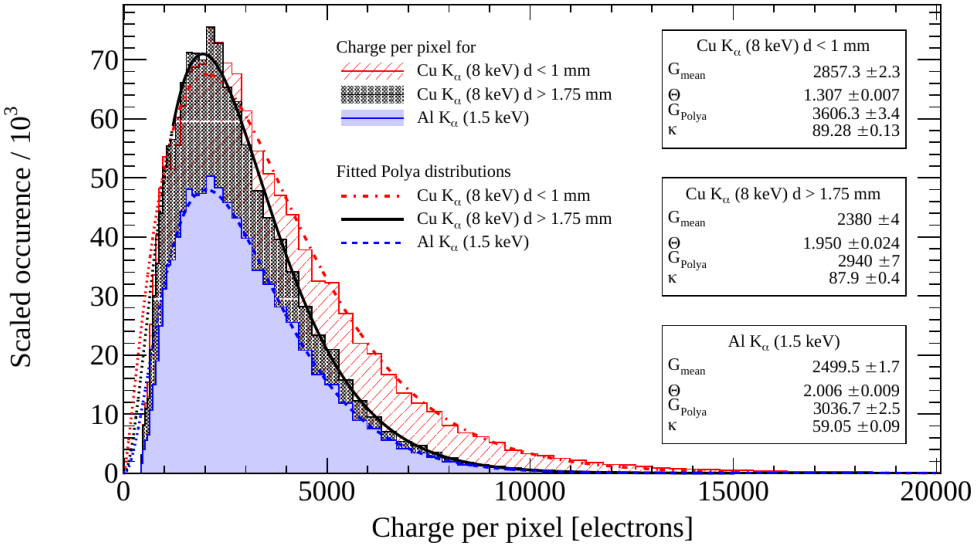


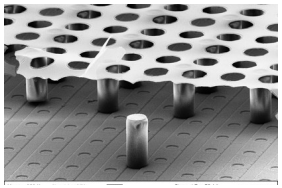


Detailed studies with X-rays.
electron counting = pixel counting
→ high diffusion necessary
Detailed study with variable X-ray source.

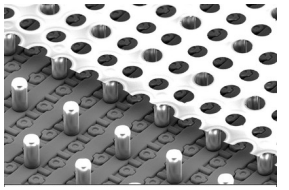
Single pixels show Polya distribution of gas gain

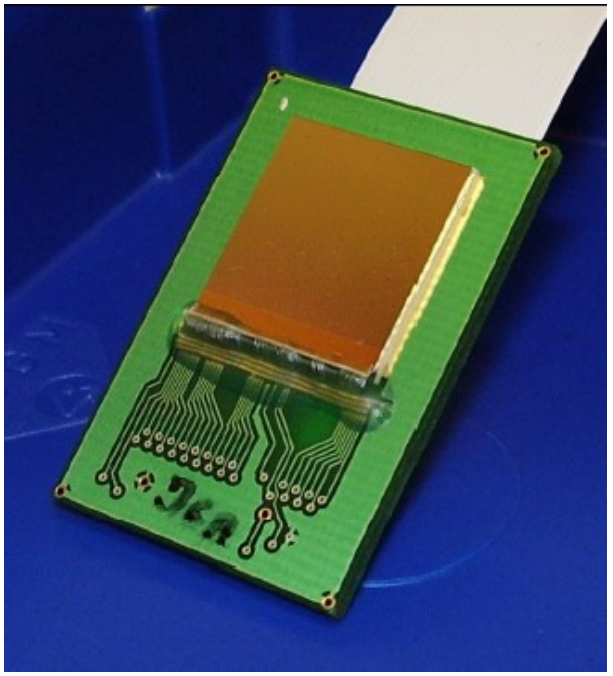






Timepix Family





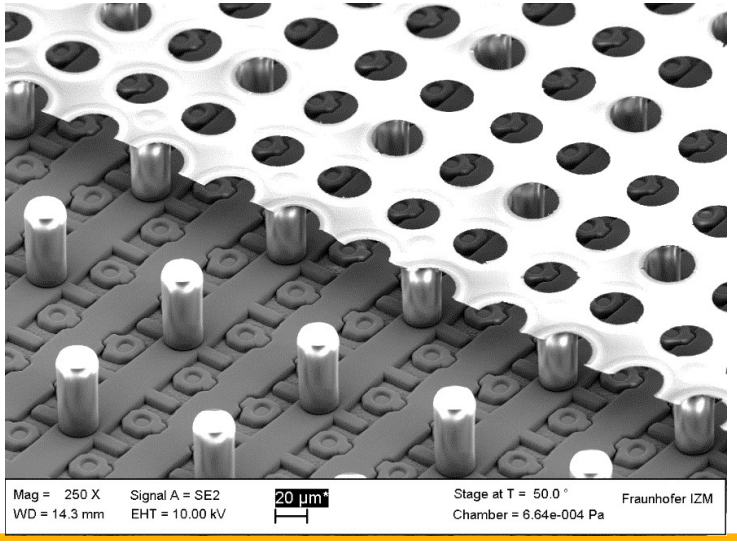
Timepix: Available for tests since Nov. 2006

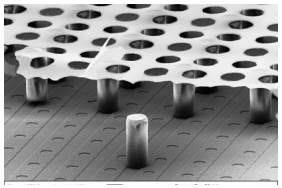
Number of pixels: 256 × 256 pixels
Pixel pitch: 55 × 55 µm²
Chip dimensions: 1.4 × 1.4 cm²
ENC: ~ 90 e^-

Limitations: no multi-hit capability.
Each pixel can be set to one of these modes: TOT = time over threshold (charge)
Time between hit and shutter end
Both not possible simultaneously.

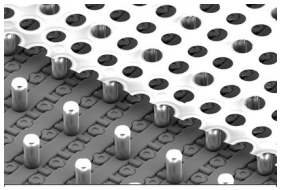
Timepix3: Available since 2018

- 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)
- Output rate up to 5.12 Gbps





Protection Layer

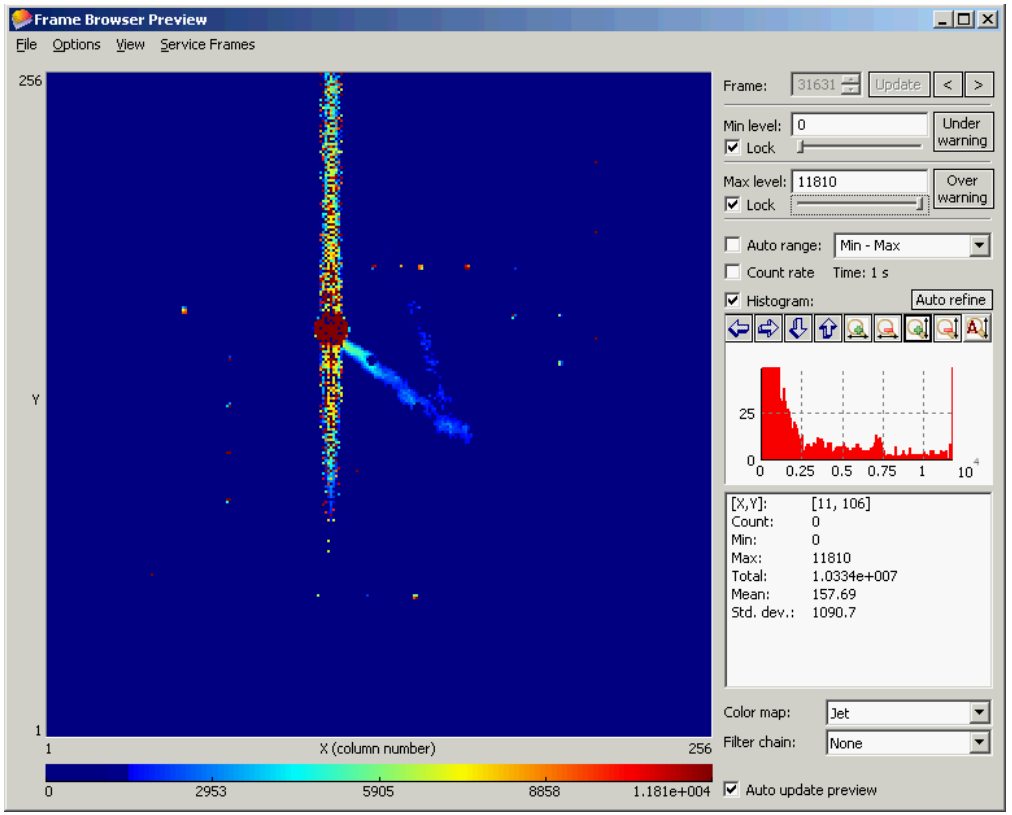


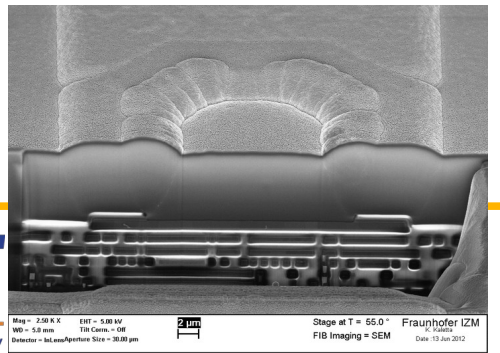
Discharges triggered for example by highly ionizing particles could easily destroy the chip. The charge collected by one pixel was too high.

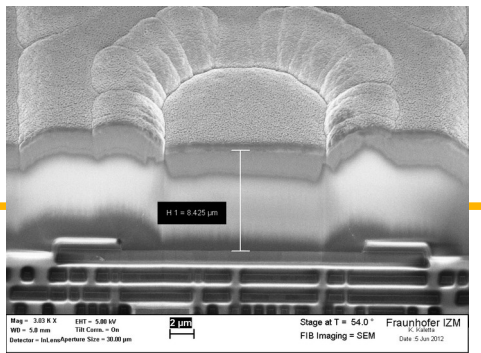
A protection layer is placed on the chip to disperse the charge on many pixels and thus lower the input current per pixel. Besides, the charge is removed slowly and thus quenches the discharge.

<u>high resistive material</u>
4 µm Si_XN_Y (~10^{12} Ω·cm)

Chips survive several million discharges.







UNIVERSITÄT BONN

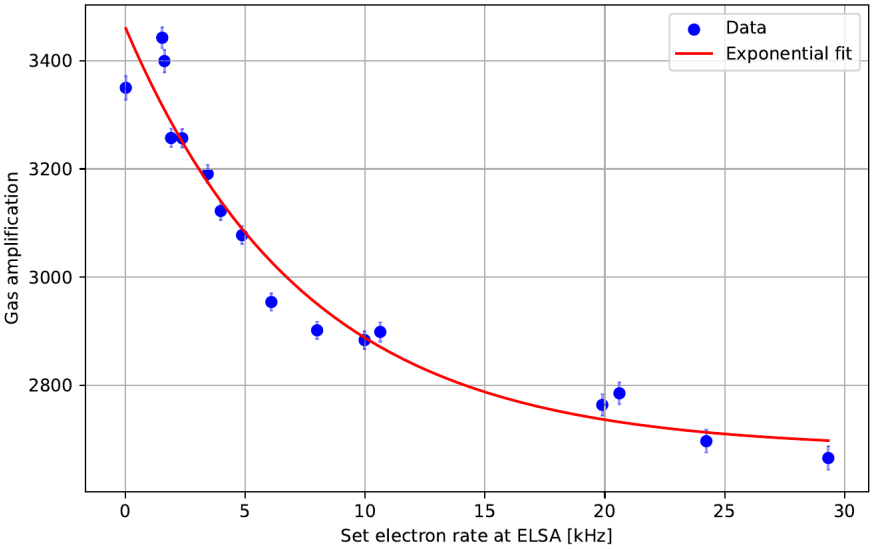
NikhefMESA+ Institute for Nanotechnology

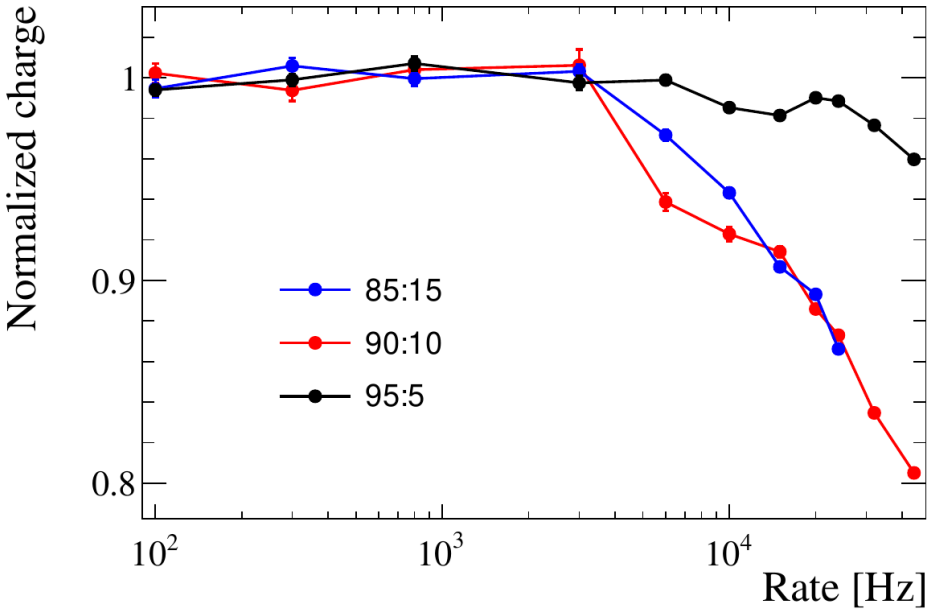
Charge Up

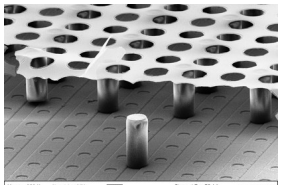
During test beam studies a reduction of the gas gain at high rates (O(kHz)) was observed.

A more detailed study is ongoing to measure the resistivity.

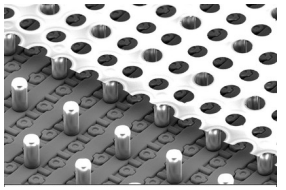
Once the production of GridPixes at Bonn is running, it will be investigated how to reduce the resistivity.



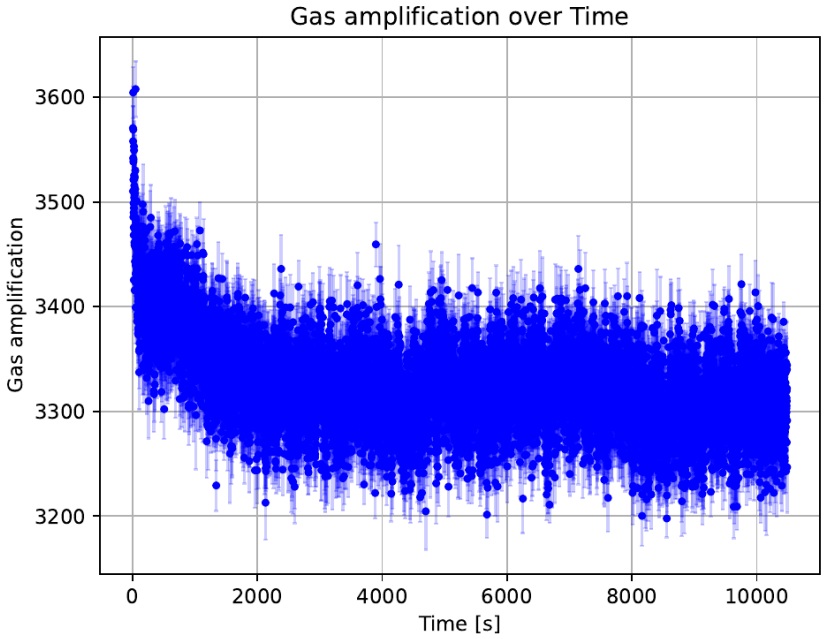


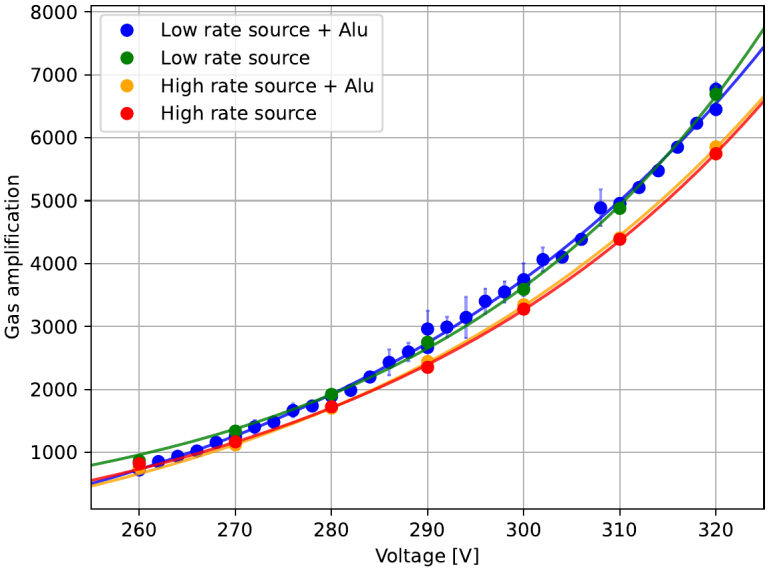


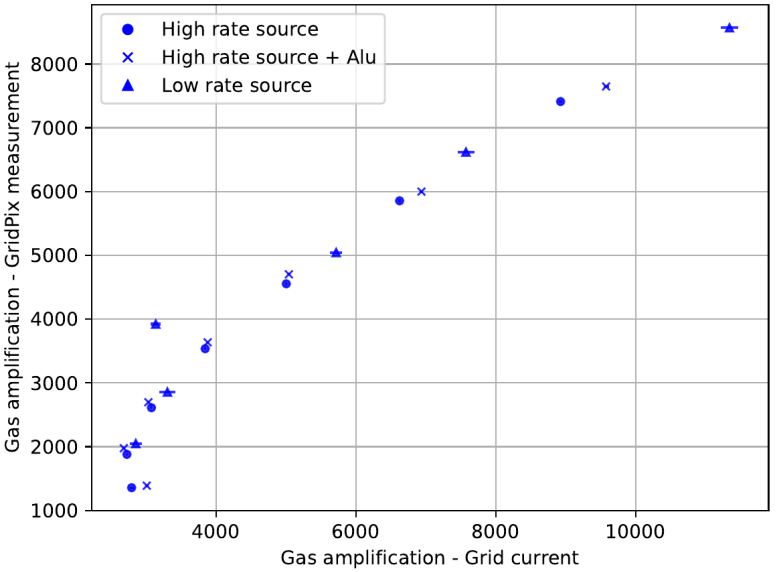
Measurement of Resistivity (I)



1. Charge up with ^{55}Fe - Source







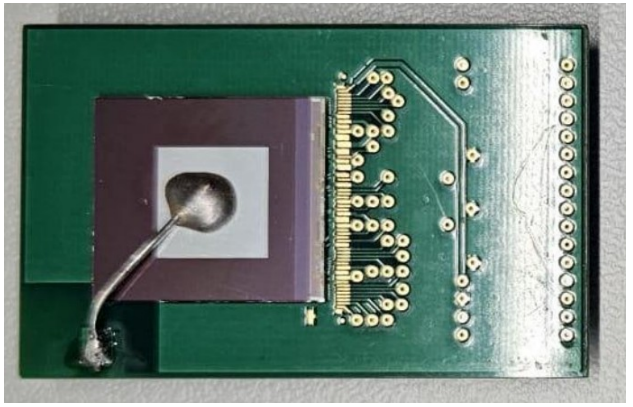
- Fit the stable plateau of charge up
- Use various source strengths
- Determine the voltage drop with respect to lowest rate
- Investigating the current measurement:
  - Hit counting
  - Photon conversions
  - Measure grid current

Measurement of Resistivity (II)

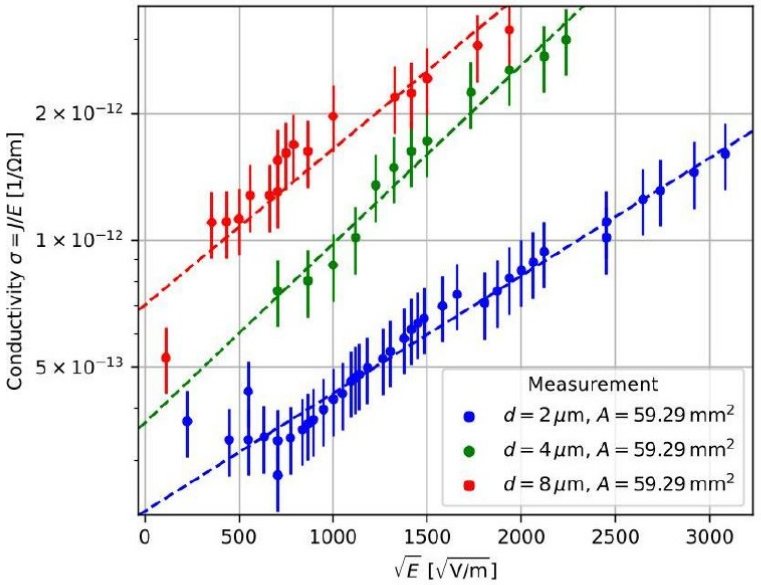
2. Metal pad on the protection layer

Deposit metallic layer on protection layer

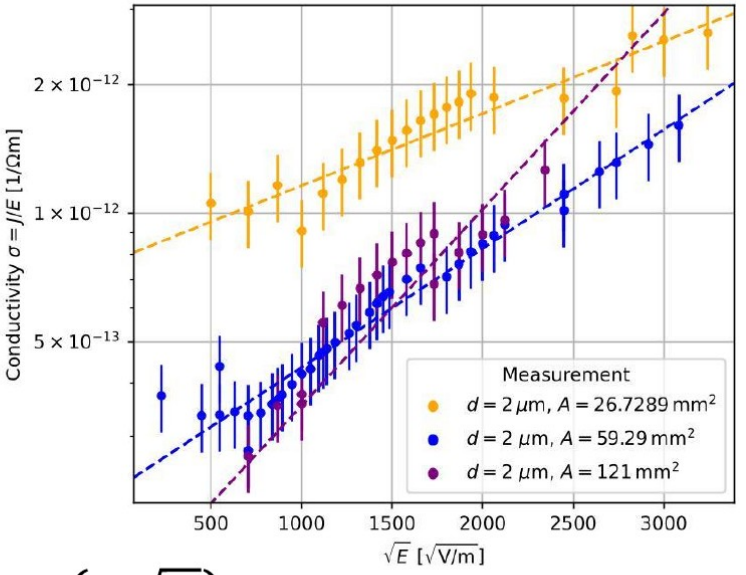
=> Best method to determine resistivity



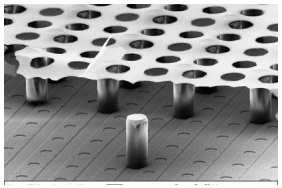
Different protection layer thicknesses



Changing the pad sizes

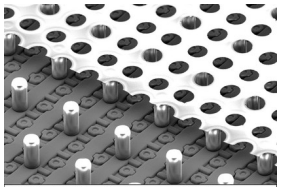


$$\sigma = \sigma_0 * exp\left(P\sqrt{E}\right)$$

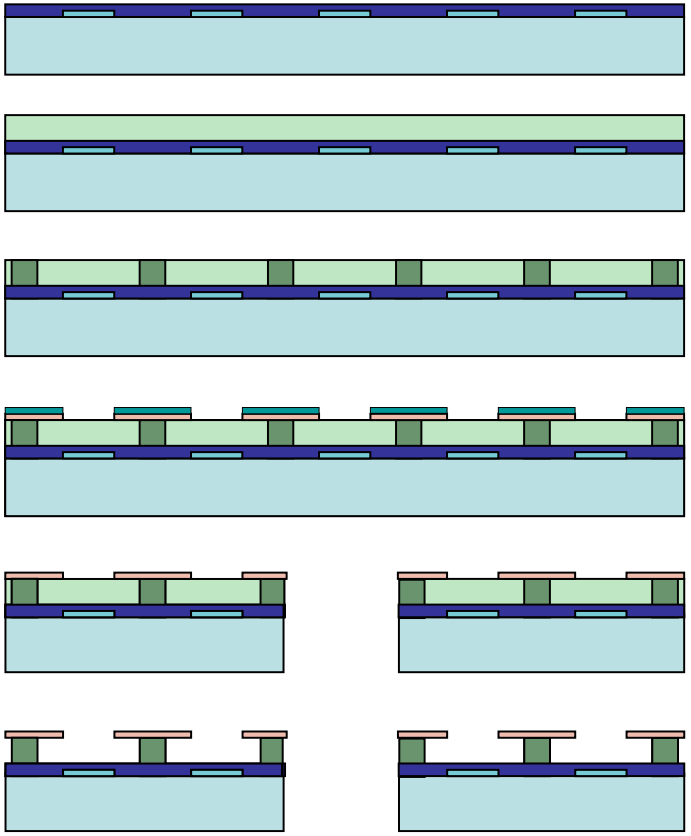


Wafer-based Production

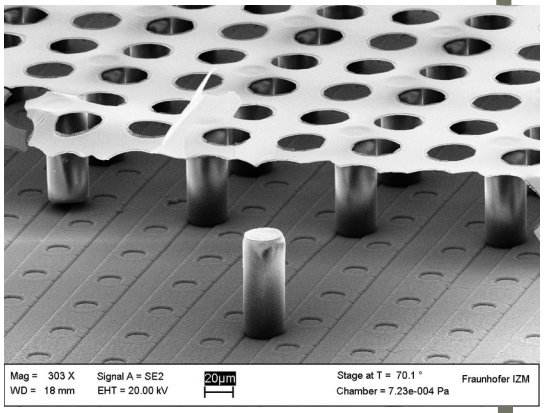
Fraunhofer IZM



Production at Twente was based on a 1 to 9 chips process.
This could not satisfy the increasing demands of R&D projects.
A new production was set up at the Fraunhofer Institut IZM at Berlin.
This process is wafer-based → 1 wafer (107 chips) is processed at a time.



1. Formation of Si_xN_y protection layer
2. Deposition of SU-8
3. Pillar structure formation
4. Formation of Al grid
5. Dicing of wafer
6. Development of SU-8



Forschungs- und Technologiezentrum Detektorphysik

First stone laying ceremony 2.11.2016
Inauguration ceremony 8.11.2021

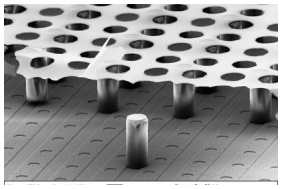


Office space:
- 880 m^2
- 4 Floors

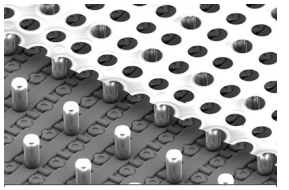
Lab space
- 2010 m^2
- 4 Levels + Underground Laboratory
- 360 m^2 clean rooms (ISO 5, 6, 7)



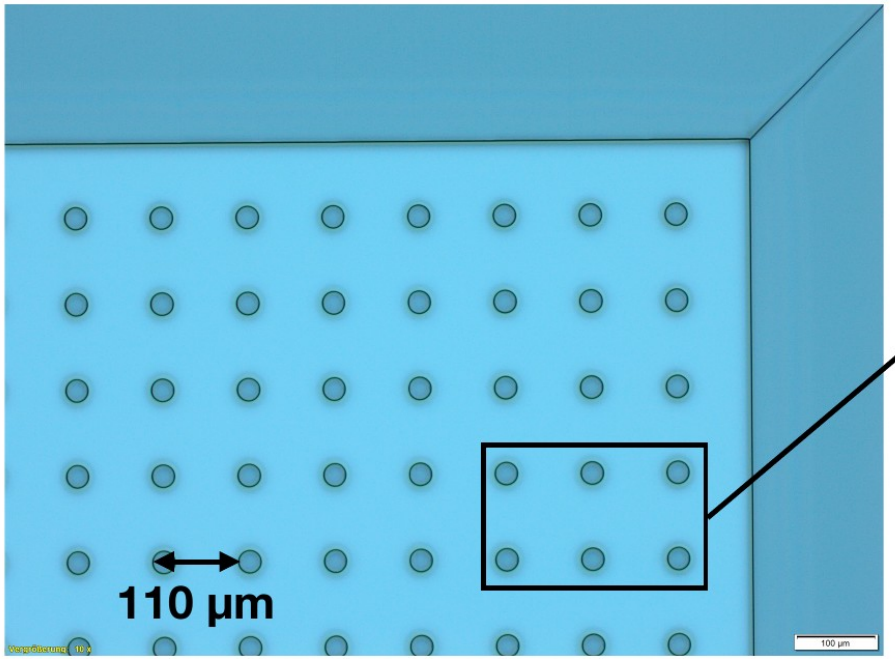


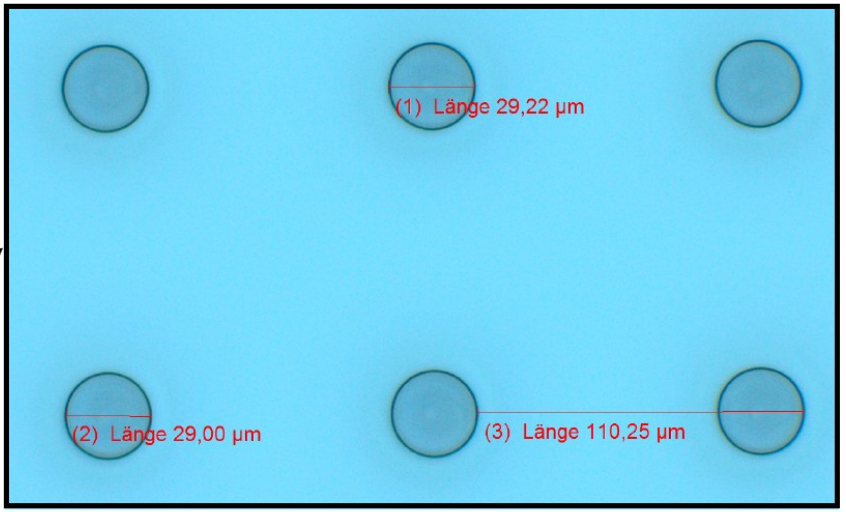


First Steps Towards “GridPixes made in Bonn” - SU8-Pillars



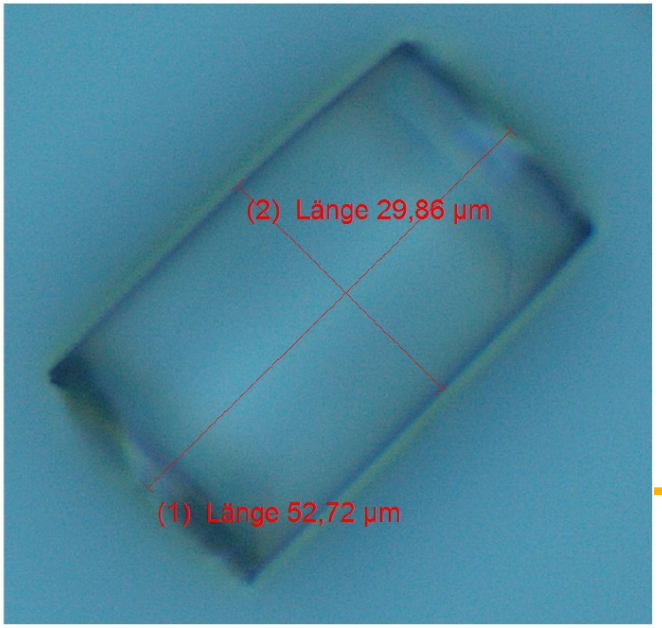
What we want: 50 µm high pillars with 30 µm diameter and 110 µm pitch

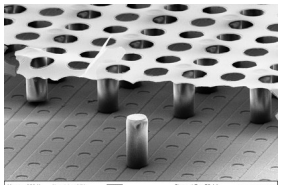




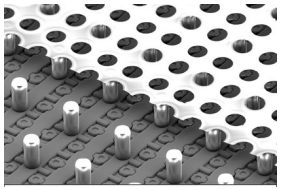
Lithographic Wetbench with Spinner and Hotplates



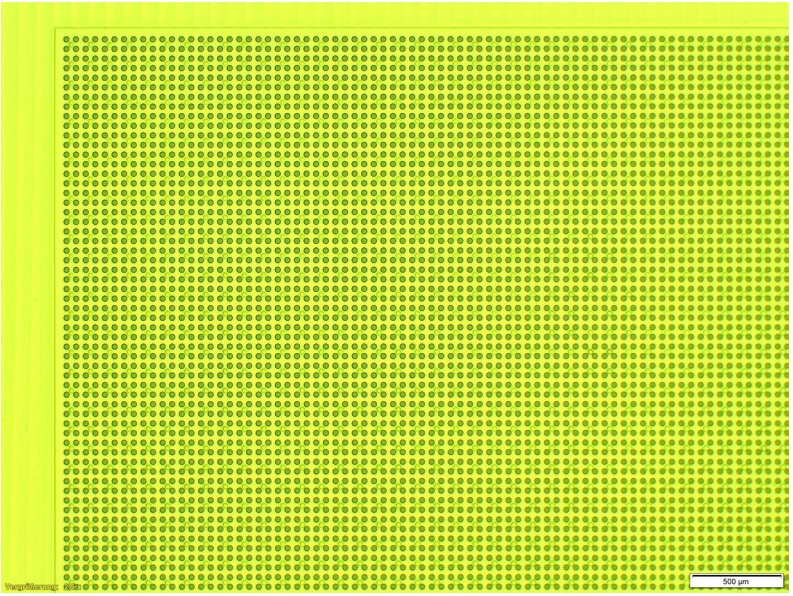


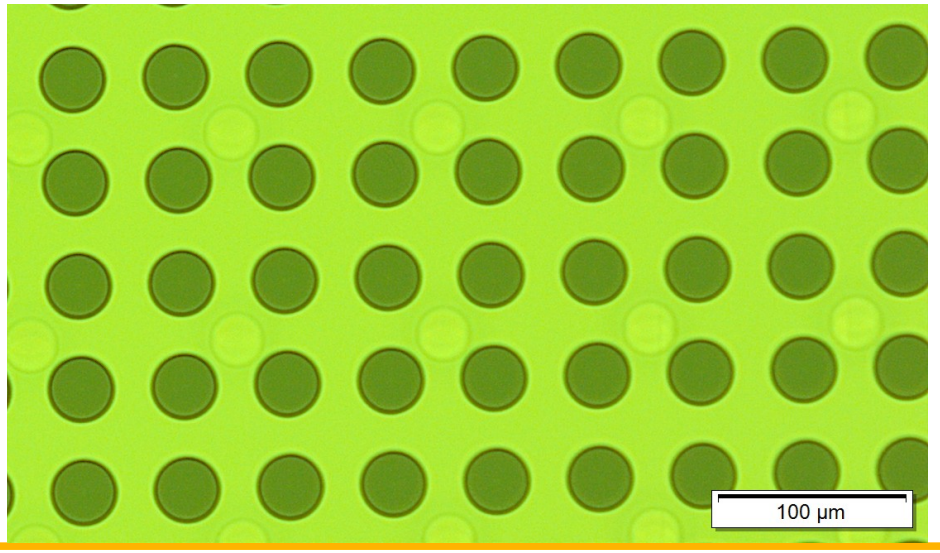


Second Step Towards “GridPixes made in Bonn” - Metallic Grid









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.

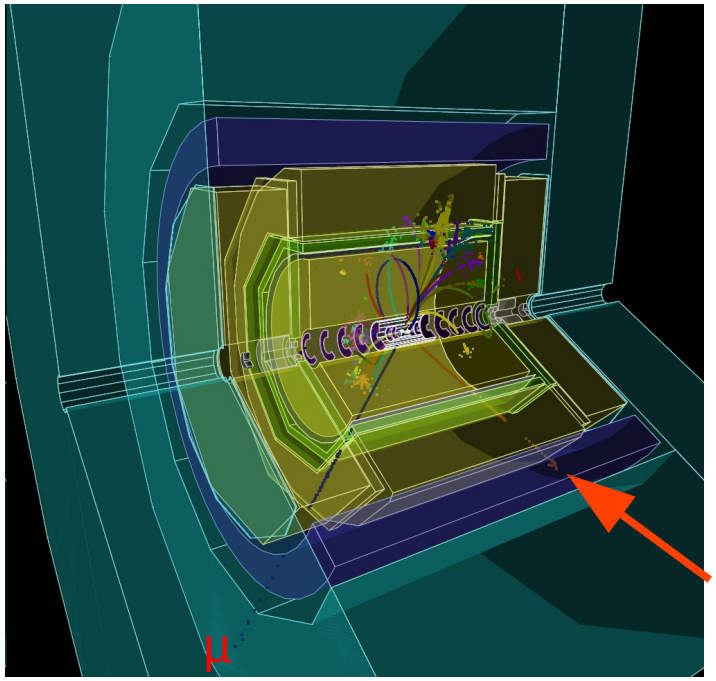
Hopefully, machines can be serviced and commissioned in December and work on protection layer can start early next year.





ILD-TPC Requirements

Both linear (ILC) and circular (FCCee/CEPC) have similar physics requirements driven by benchmark processes, in the case of ILD – TPC the most stringent measurement is the Higgs-recoil measurement:



Backgrounds vary significantly!

Requirements of TPC from ILC TDR vol. 4

Parameter			
Geometrical parameters	r_{in}	r_{out}	z
	329 mm	1808 mm	$\pm$ 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 mm^2 for 220 padrows		
σ_{point} in $r\phi$	$\simeq$ 60 μm for zero drift, $<$ 100 μm overall		
σ_{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 $\delta(1/p_t) \approx 2\cdot10^{-5}$ /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.

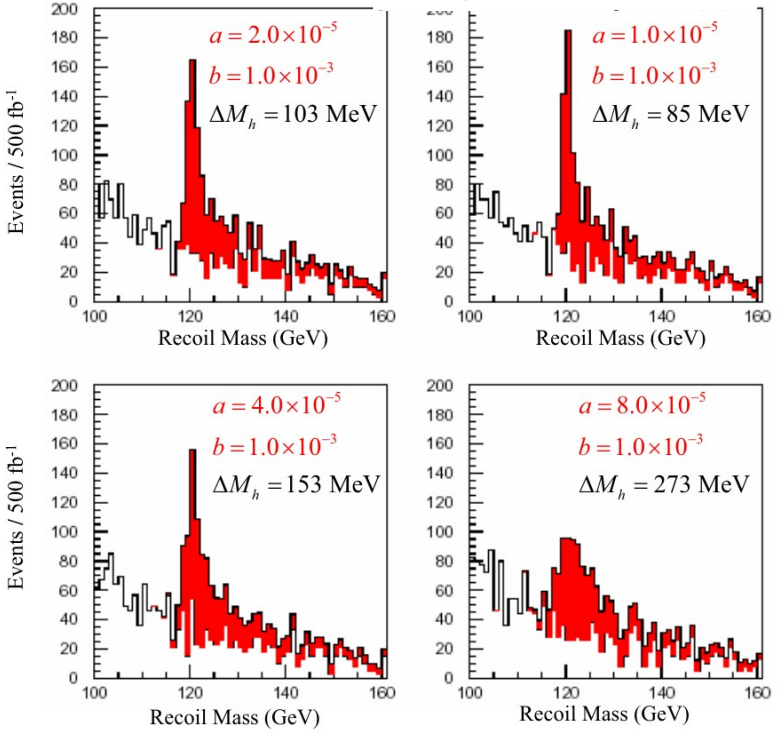
Time Projection Chambers

Why is a pixelTPC interesting as central tracking detectors at modern colliders?

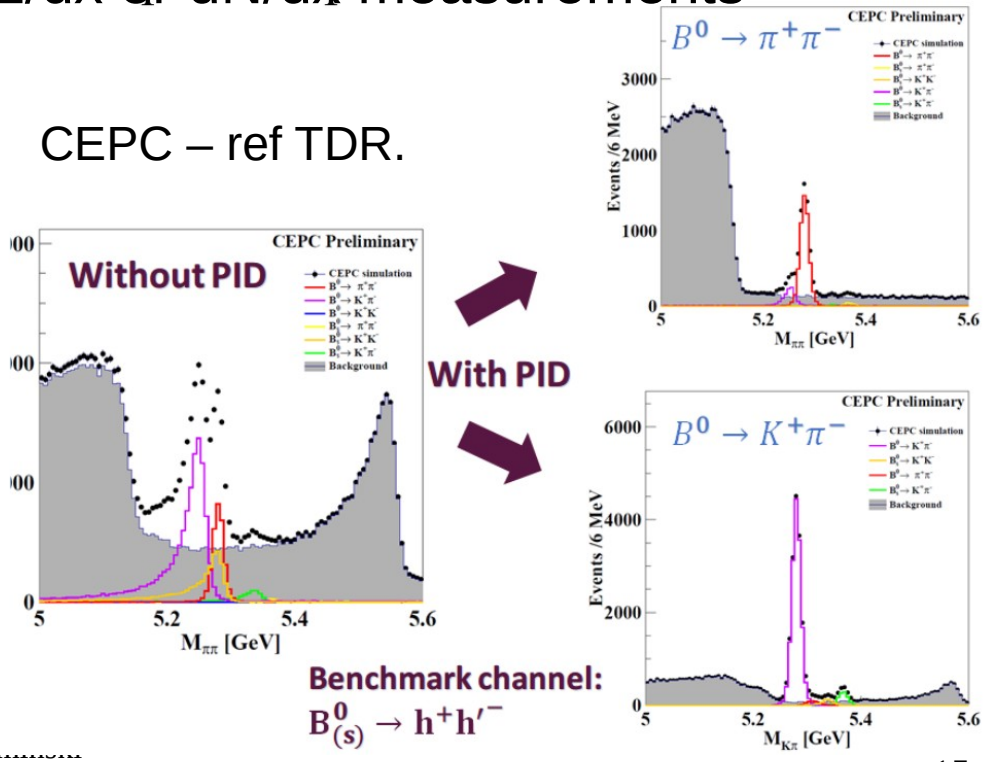
- large number of track points (pixels: 10,000) allows continuous tracking
- low material budget (inner field cage: X_0 ~ 2%, gas: X_0 ~ 1%)
- material is very homogeneously distributed
- high detection efficiency (>99%) for low momentum tracks (p>= 500 MeV/c)
- high detection efficiency for long lived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

ILC RDR

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



CEPC – ref TDR.

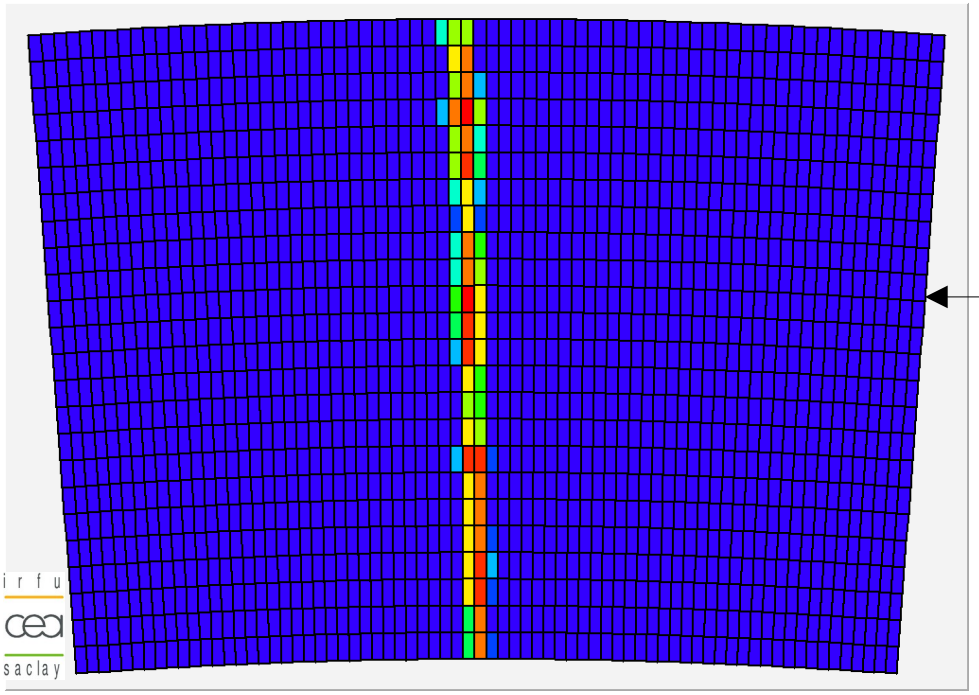


Benchmark channel:

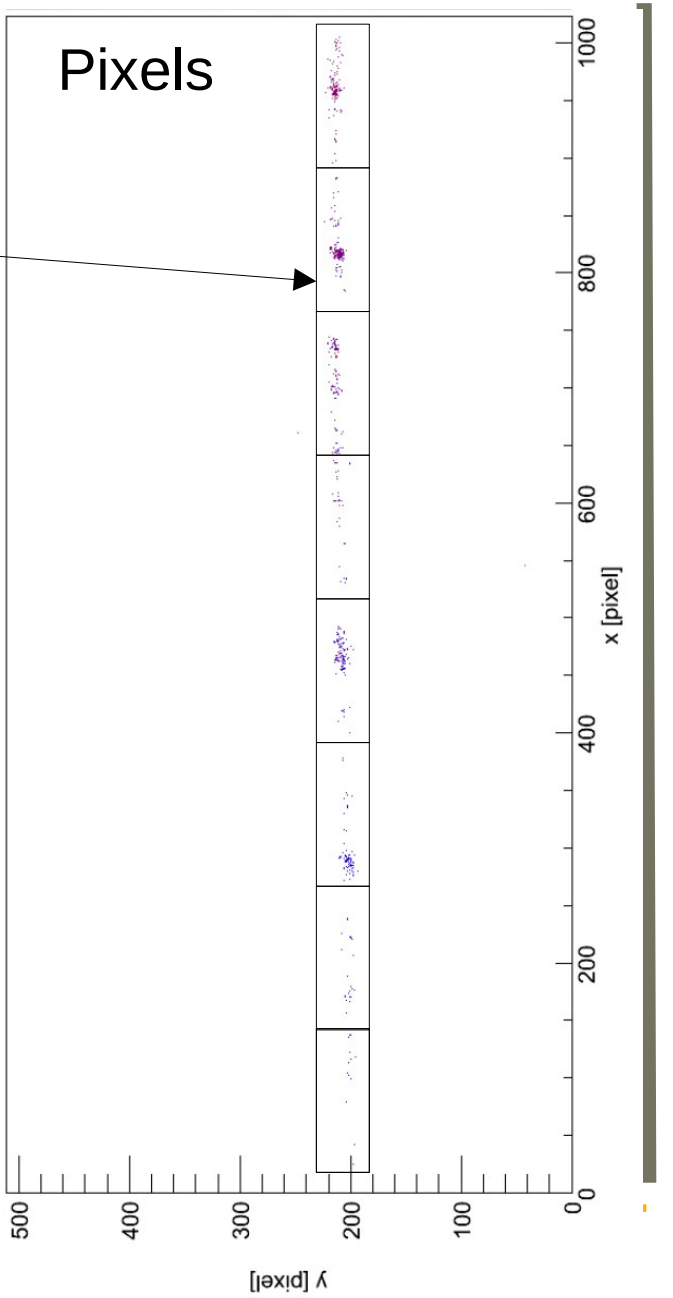
$B^0_{(s)} \to h^+h'^-$

Comparison Pads vs. Pixels

Standard charge collection: Pads of 3x7 mm²

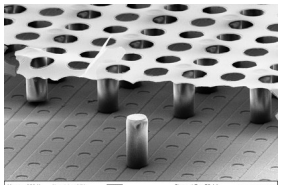


Rectangles correspond to pads

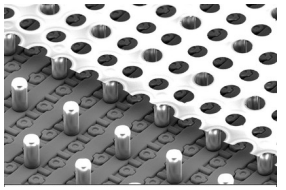


Advantage of small pixels (55x55 µm²)

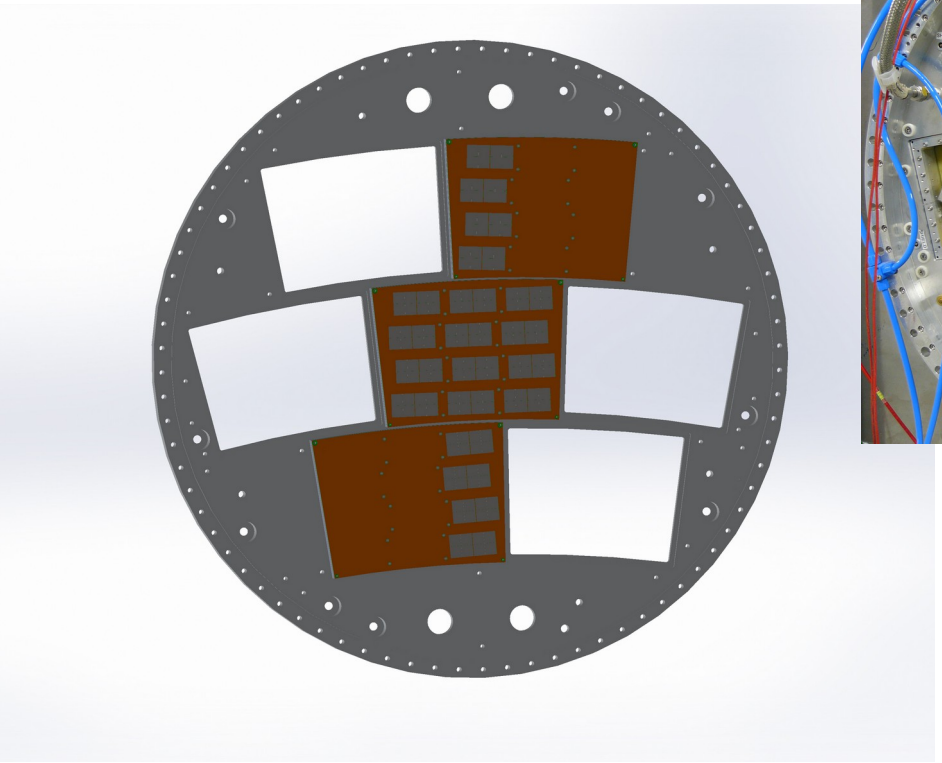
- Lower occupancy
  - → better track finding
- Identification and removal of δ-rays and kink removal
- Improved dE/dx, because of primary electron counting
- Pad plane and readout electronics fully integrated

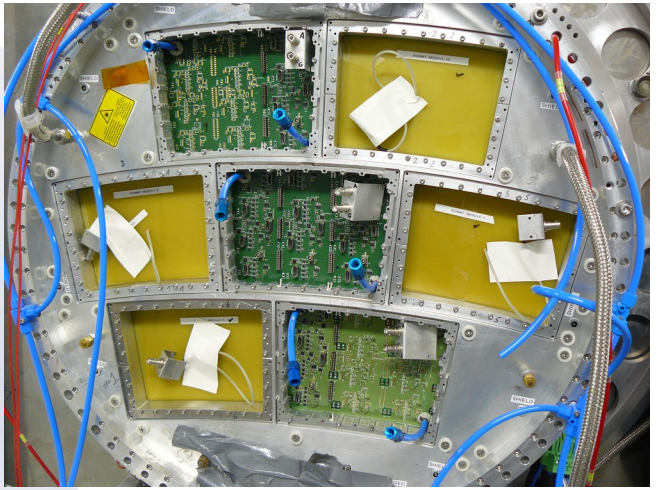


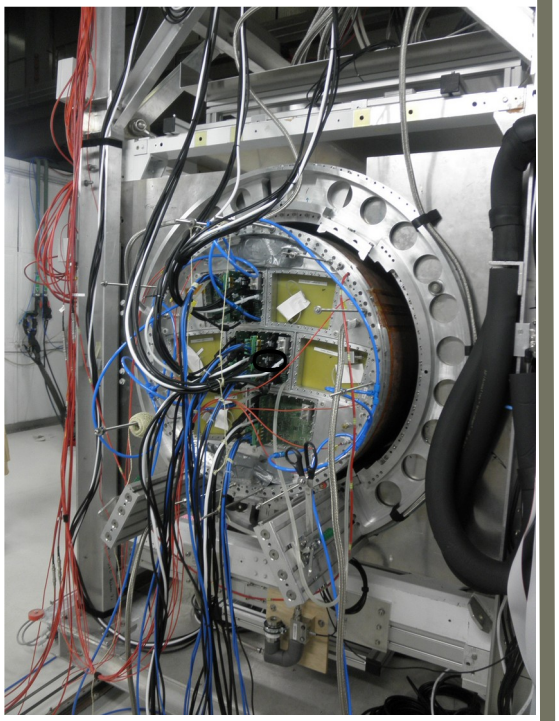
Test with 160 GridPix Detectors

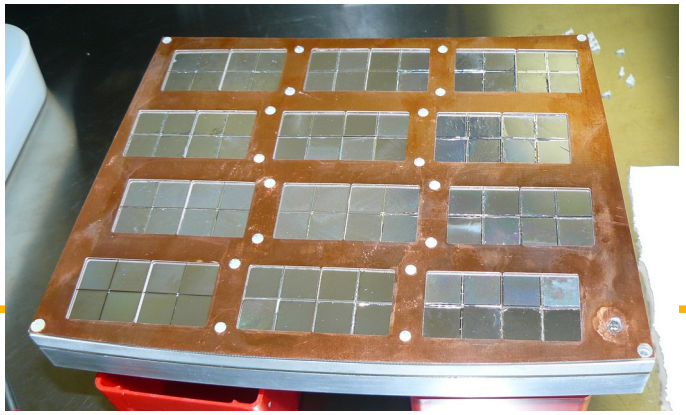


The final goal foresaw a LP-module covered completely with GridPixes (~100).
This goal could even be surpassed by adding two partially covered modules.
In total 160 GridPixes covered an active area of 320 cm²:
- central module with 96 chips (coverage 50 %)
- 2 outer modules with 32 chips each



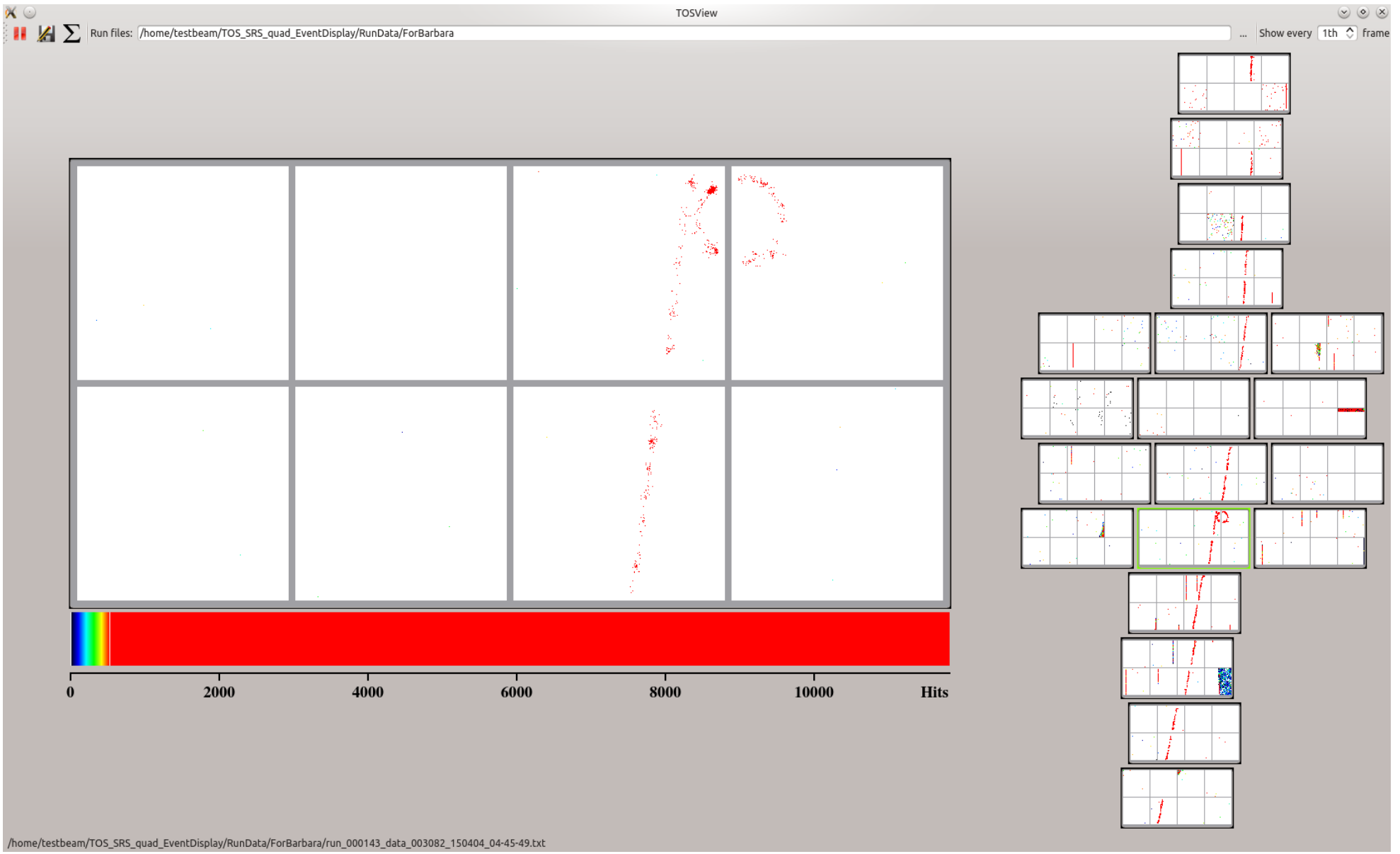




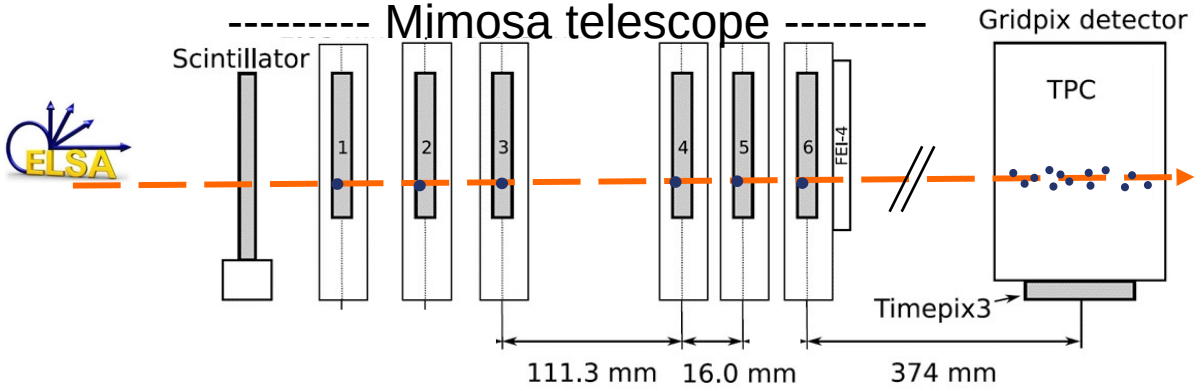


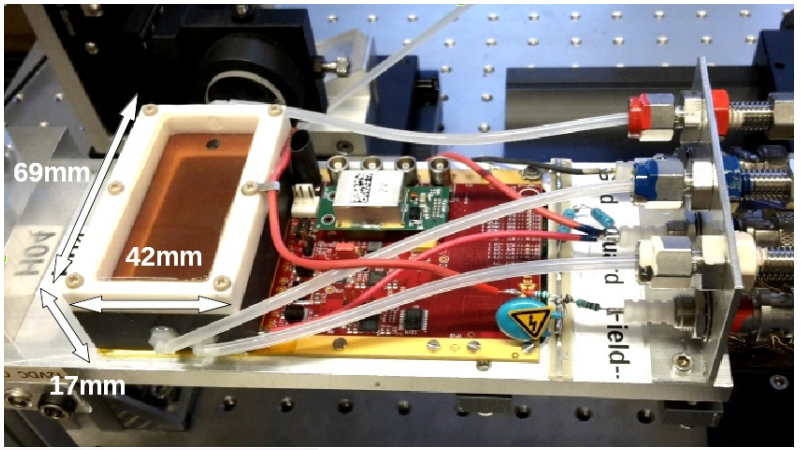
IEEE TNS,
VOL. 64, 2017,
1159

Event Picture

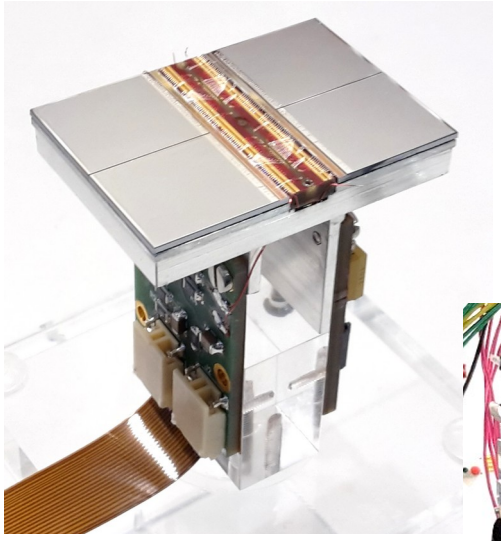


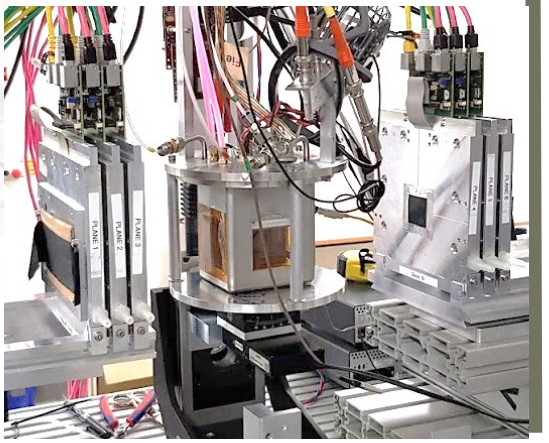
Test Beams at Bonn





- Test beam in July 2017 and October 2018 at ELSA, Bonn
- 2.5 GeV electrons at up to 10 kHz
- Tracks referenced by 6 layers of Mimosa telescope in front of detector
- Gas: $Ar/CF_4/iC_4H_{10}$ 95/3/2 (T2K)
- E_d = 280 V/cm, V_{grid} = -350 V

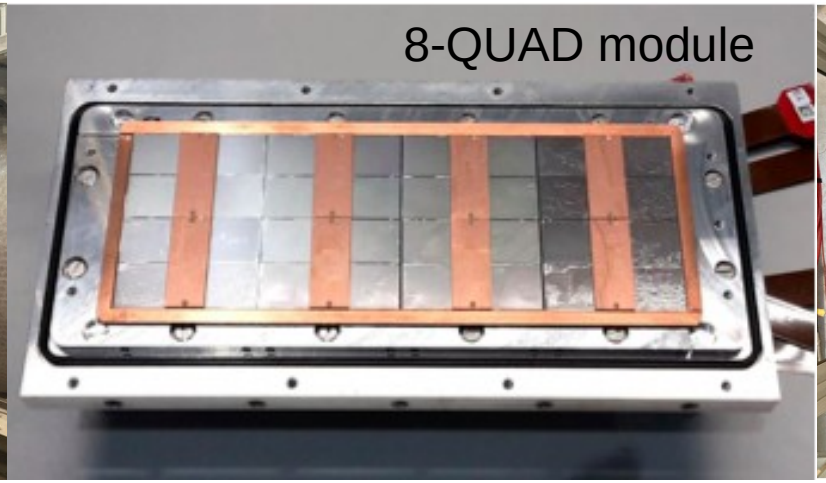


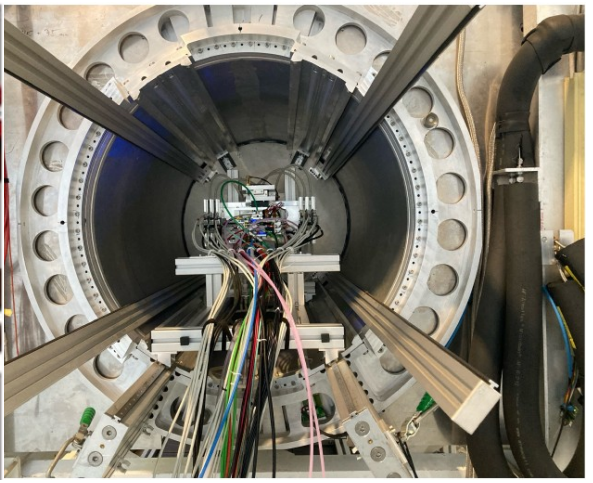


Test Beam at DESY

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

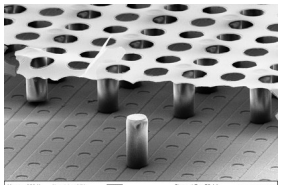




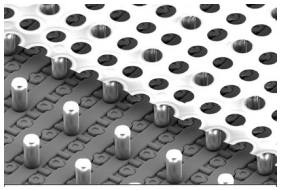


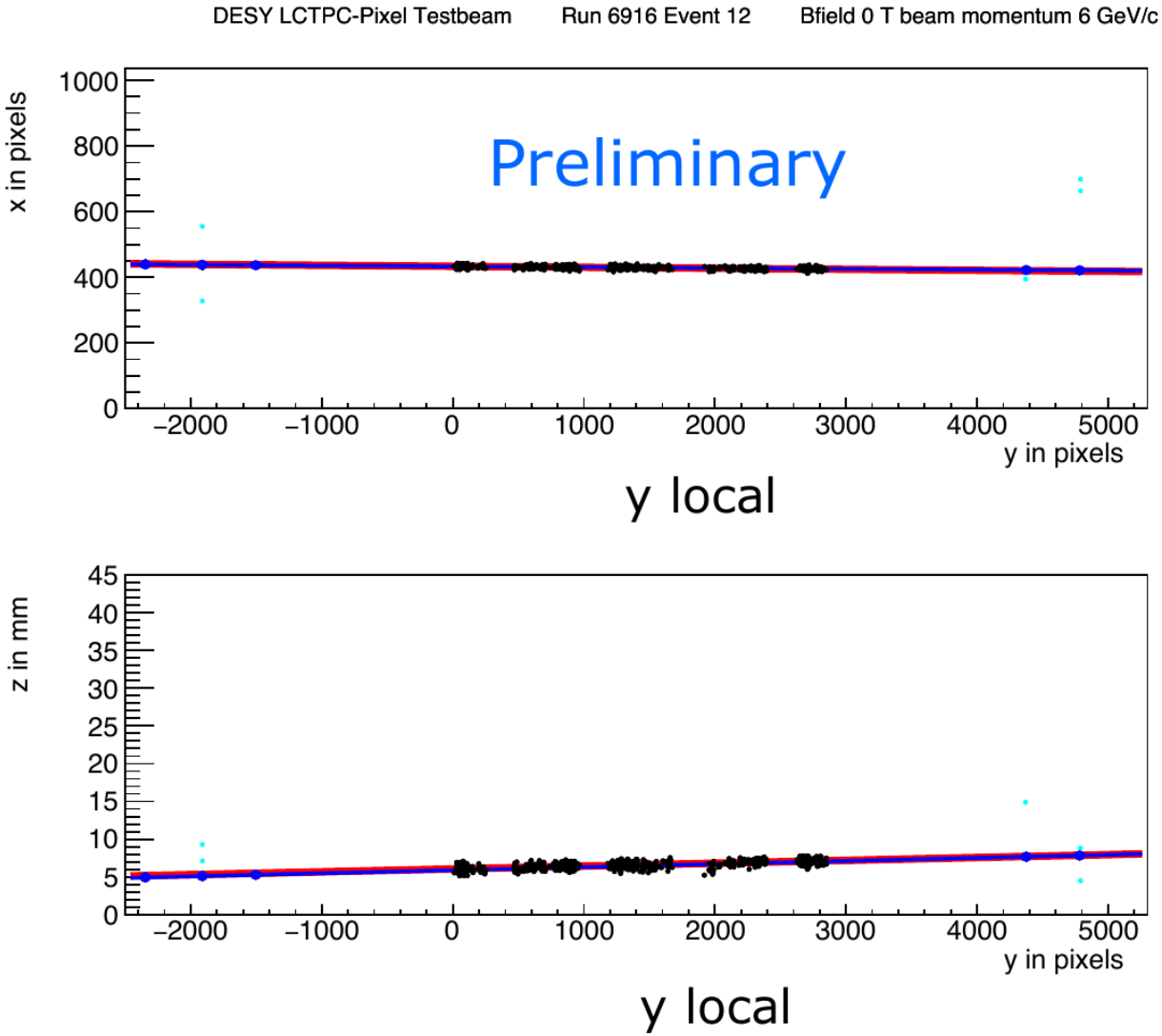
First paper with emphasis on module construction and tracking performance:
"Towards a Pixel TPC part I: construction and test of a 32-chip GridPix detector"

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

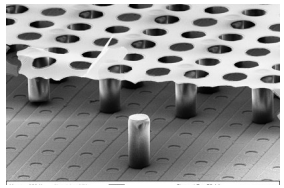
χ^2_{xy} = 677.5/1128

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

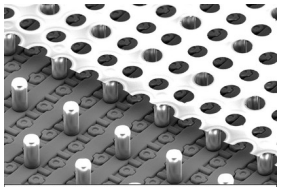
χ^2_z = 775.9/1069

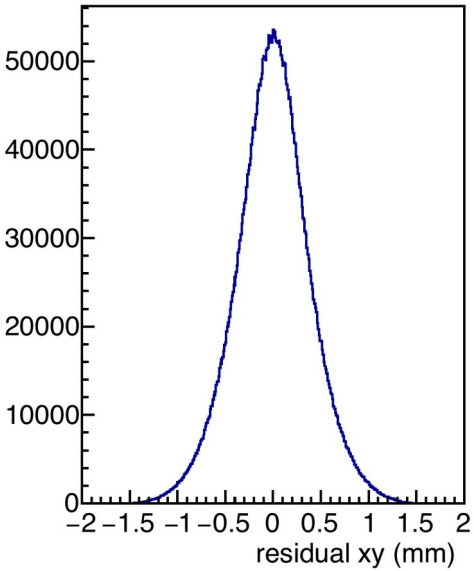
GridPix track
Telescope track

→ 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

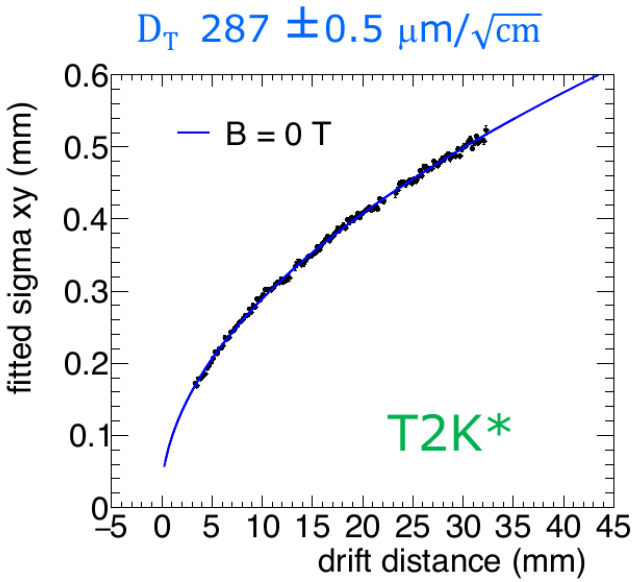
Given: $\sigma^2_{pixel} = (55\ \mu m/\sqrt{12})^2$, $\sigma^2_{tele} = (30\ \mu m)^2$ (measured)

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

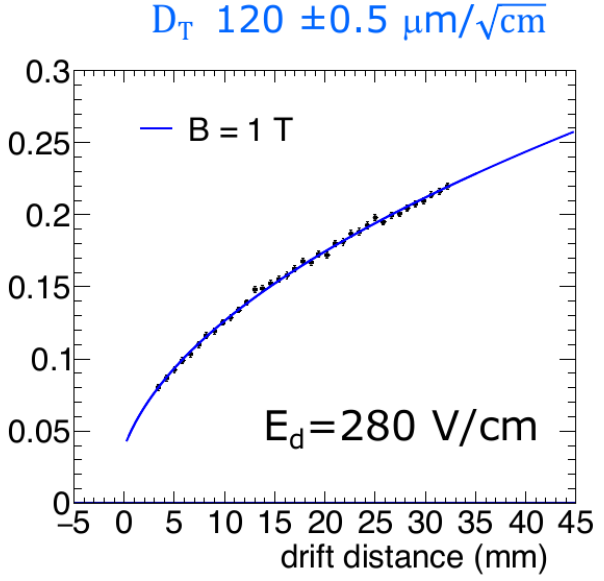
Predictions by Magboltz:

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

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

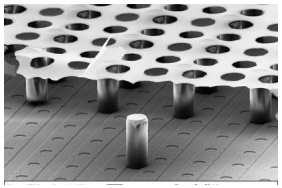


Preliminary

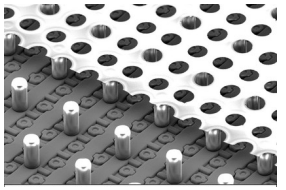


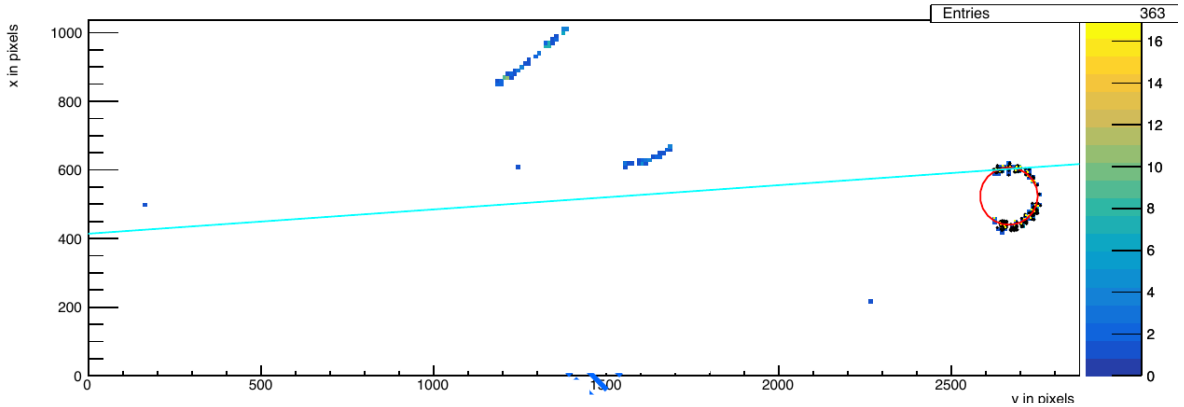
8-quad module (track length = 157.96 mm)
Spatial precision: 9 µm (xy) 13 µm (z)
Angular precision: 0.19 mrad (dx/dy) 0.25 mrad (dz/dy)

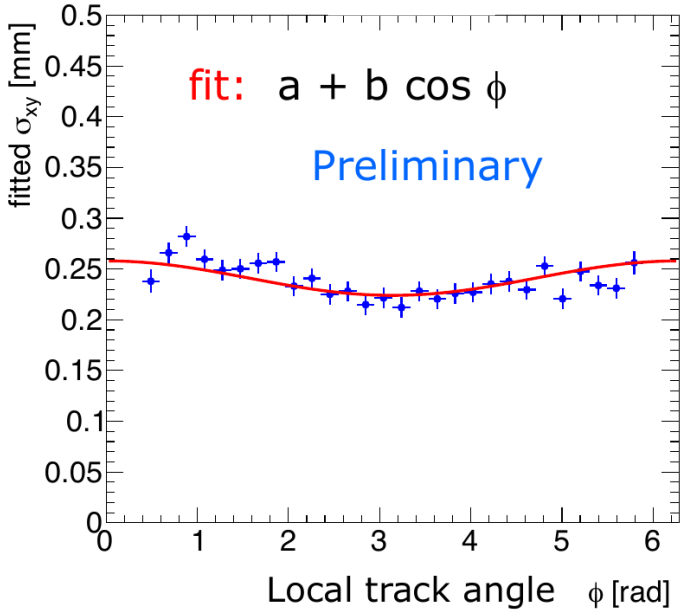
UNIVERSITÄT BONN



Spatial Resolution in Dependence on Track Angle







Using curlers as tracks, fitting circle

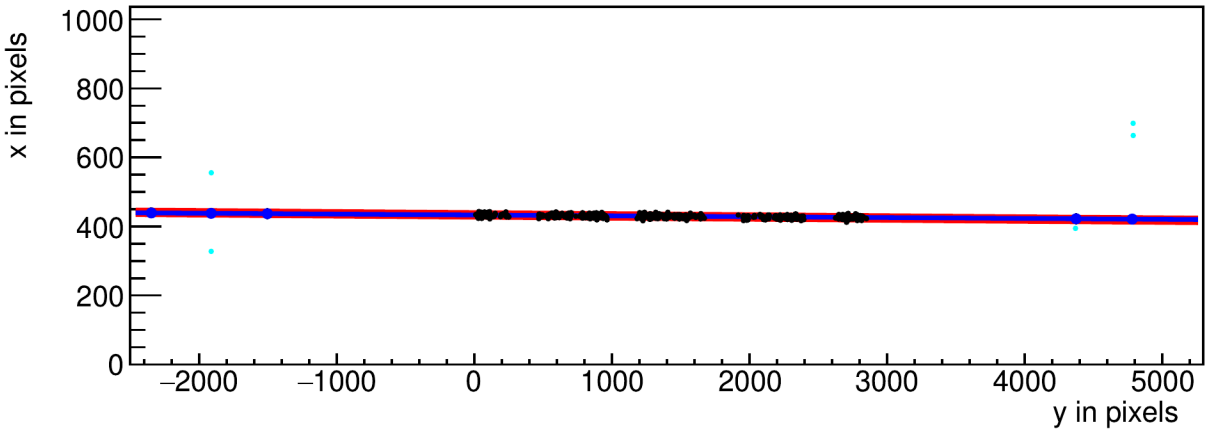
- Radius > 50 pixels with at least 20 selected hits
- Reject circles with a better SL line fit by applying cuts on the χ^2 and number of hits for the circle and line hypothesis.
- Resolution σ_{xy} = 4 pixels and σ_z = 1 mm
- Track χ^2_{xy}/dof < 5 and χ^2_z/dof < 5
- Phi range (phi_{max} – phi_{min})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

<u>=> Fit results:</u>

Average spatial resolution: a = 0.241µm (all drift d.)

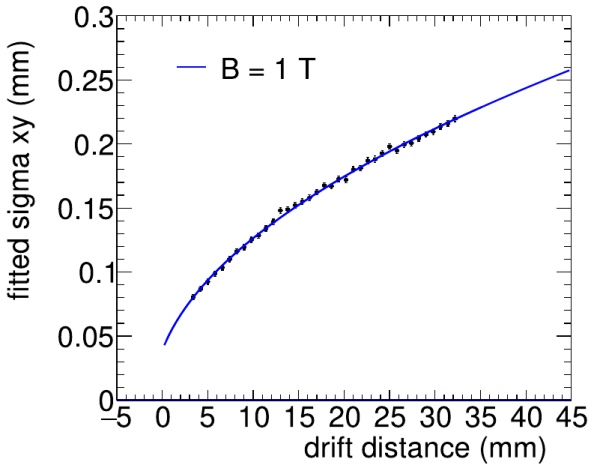
Variation in dep. of angle: b = 16µm

Extrapolation of test beam results to ILD

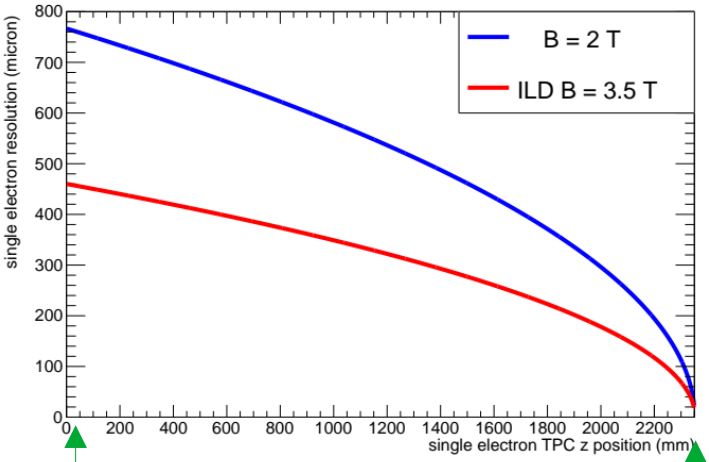


Extrapolation for ILD conditions (B = 3.5 T)

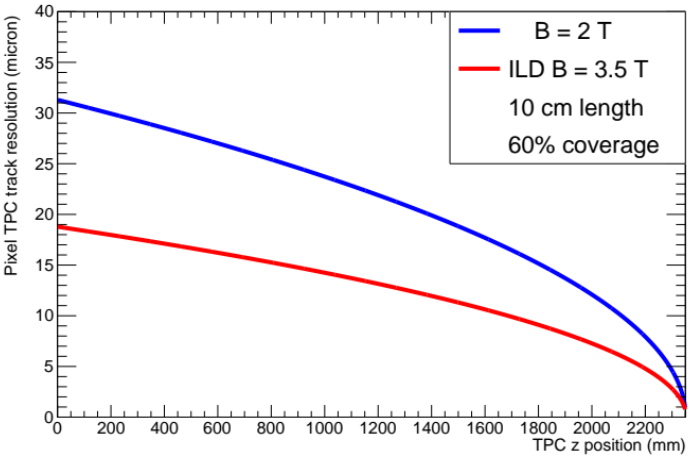
Test beam results



Single electron resolution



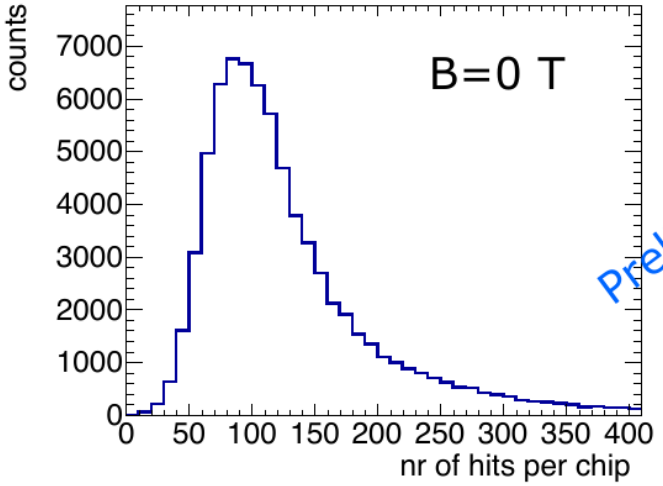
10 cm track resolution

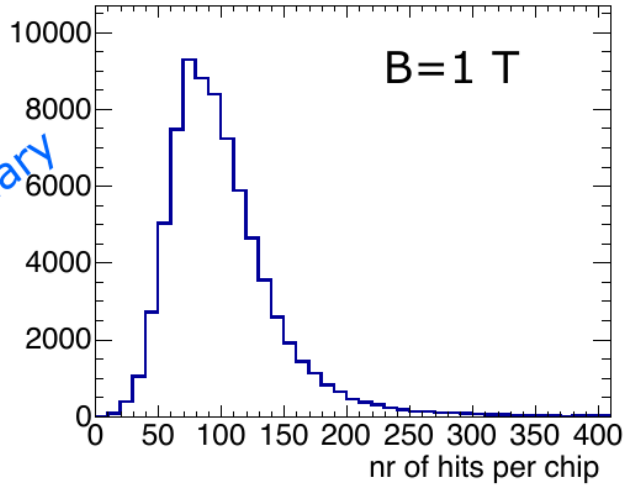


Central cathode

Endcap

PID – Truncation Method



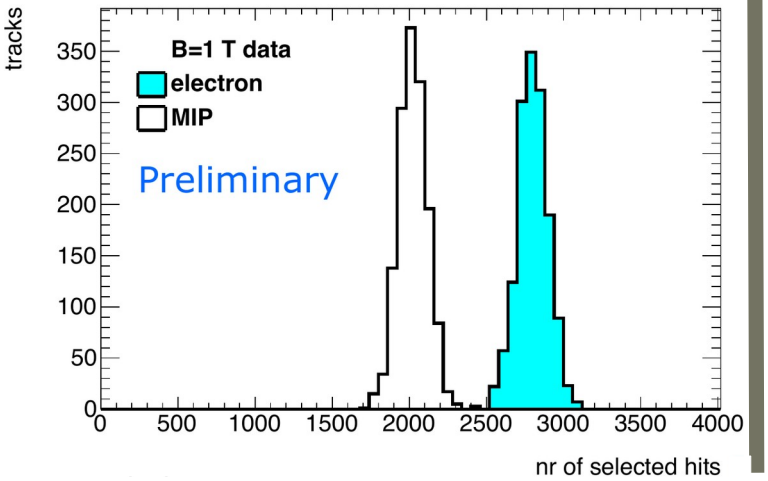


Extrapolation:

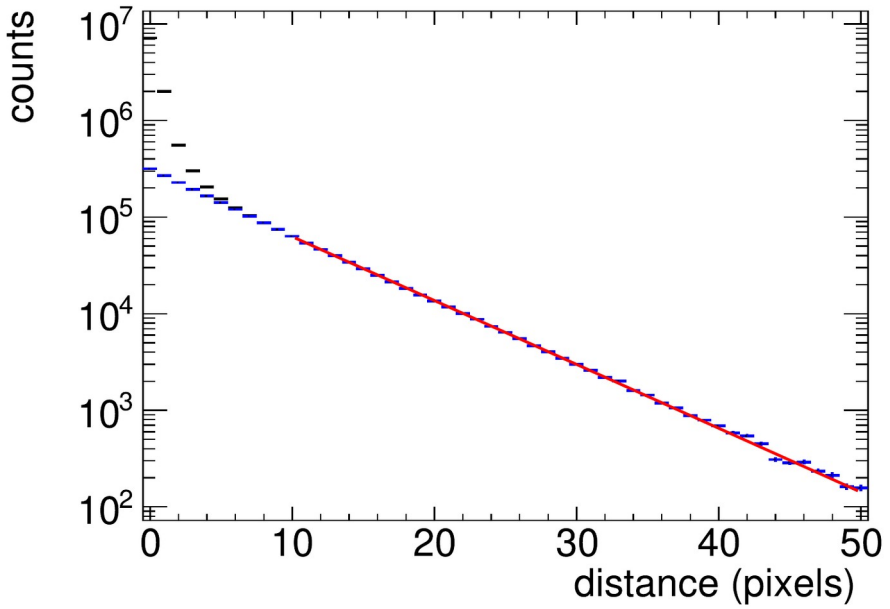
- Event stitching to get 1m long tracks with 60% coverage
- Electrons (blue) are measurement, mips are scaled (1 : 0.7)
- Z-drift: 5-15 mm
- B = 1 T

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)



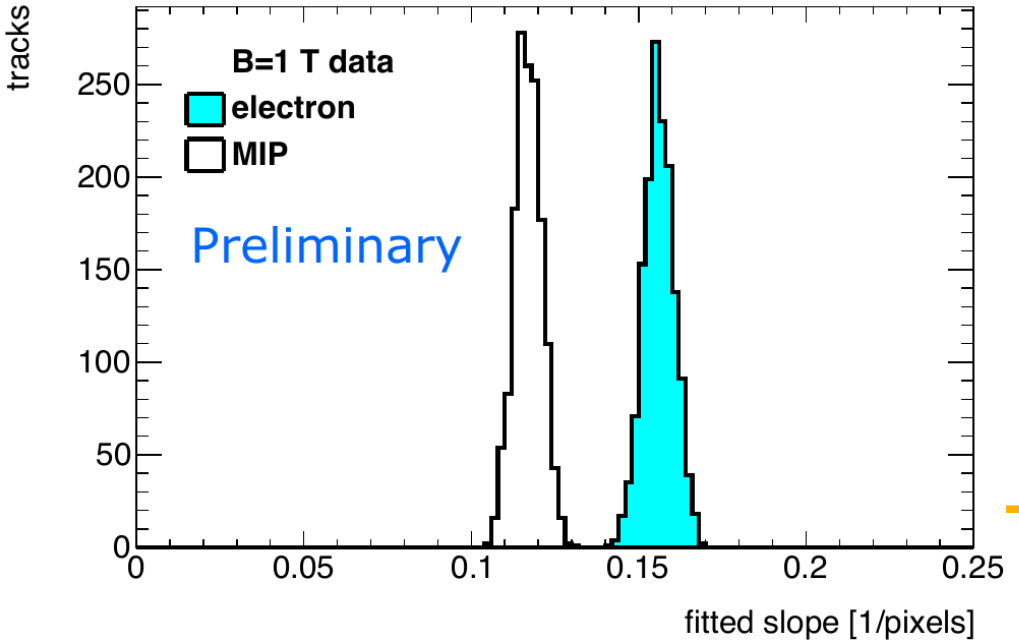
PID – Template Method



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



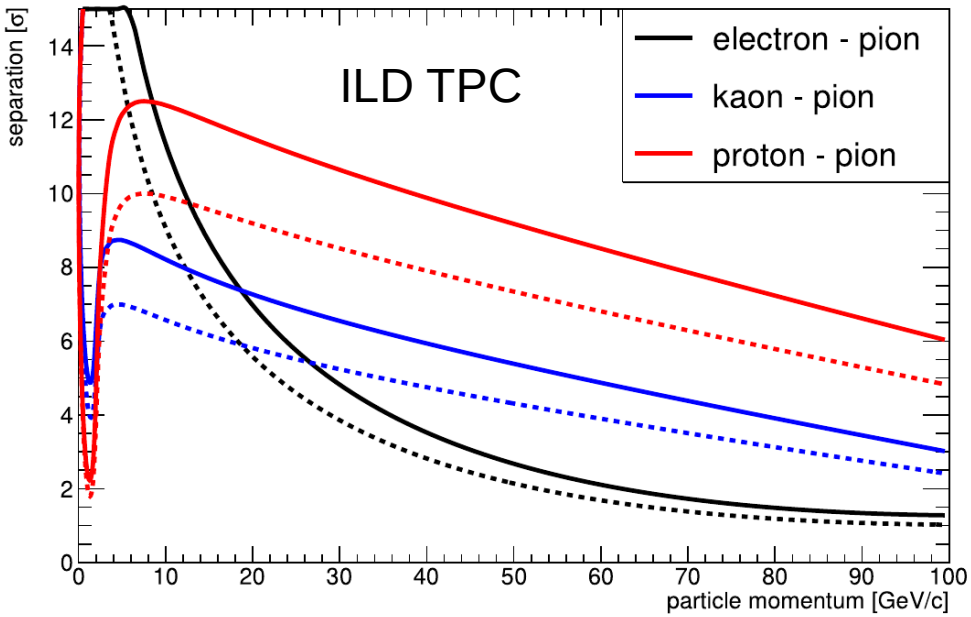
PID – Comparison and Extrapolation

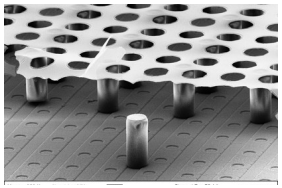
For 1m long tracks with 60 percent coverage,
we get for 5 GeV electrons the dE/dx-, dN/dx-resolution:

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

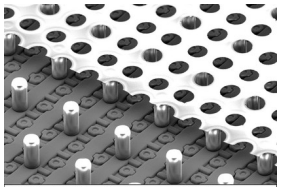
Extrapolation to ILD detector:

- 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)

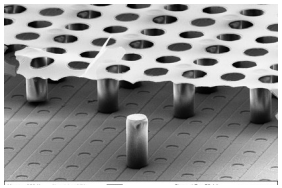




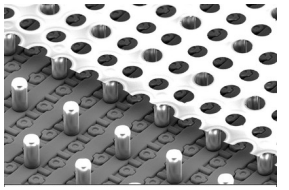
Outlook



- GridPix production will be reestablish in 2027 (hopefully)
- GridPixes will be optimized.
  e.g lower resistivity of protection layer, revisit hole and pillar heights
- And yes, of course – we will also do GridPixes with Timepix4 – once we …



Acknowledgment



This is of course the work of many people. Some of them are named here.

In Bonn:
Yevgen Bilevych, S. Hartung (who build the InGrids)
M. Lupberger (LCTPC).
+ many BSc. and MSc. students.
and of course Klaus Desch.
Special thanks goes to our technical team
H. Blank, D. Leintz, W. Ockenfels, R. Rosenthal, S. Zigann-Wack, as well as the electronics and mechanical workshops and FTD staff.

At Nikhef:
H. van der Graaf, F. Hartjes, P. Kluit, C. Ligtenberg, G. Raven, J. Timmermans.