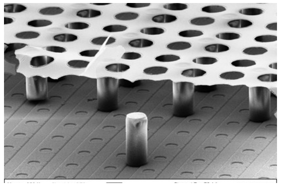

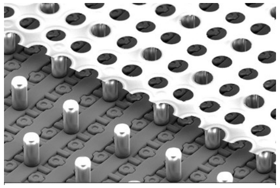

GridPixes and their Application

Jochen Kaminski

University of Bonn

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

GSI strategic Meeting
Darmstadt
1.12.2023

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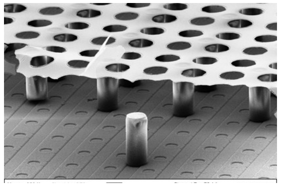
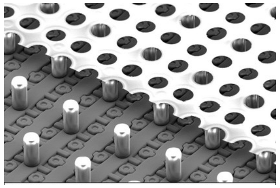
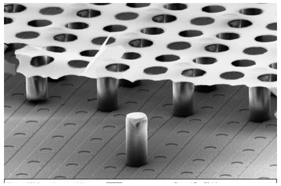


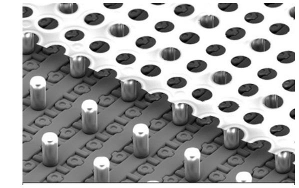
Content

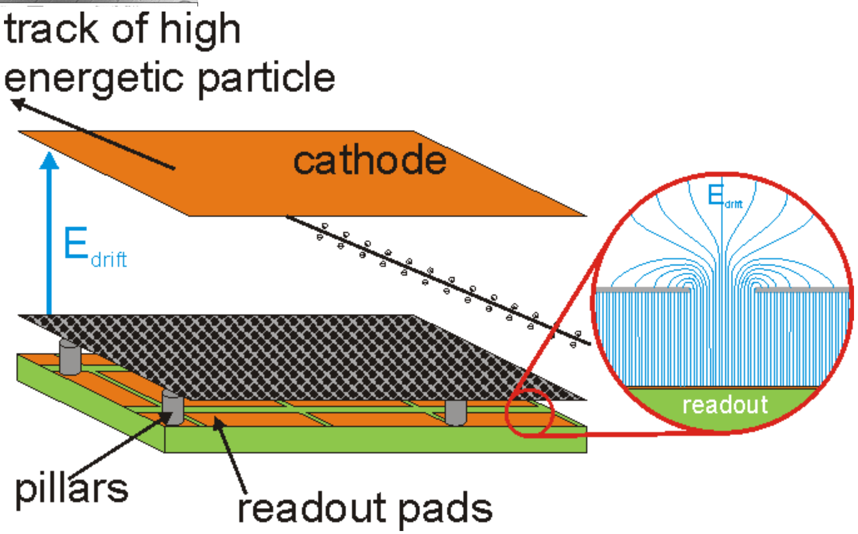


- GridPix Detectors
- X-ray Photon Detector for Axion Searches
- TPC Readout at future Higgs factories
- GridPix for X-ray Polarimetry
- GridPix in Neutron Detectors
- GridPix in a Negative Ion TPC
- GridPix in educational detectors



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

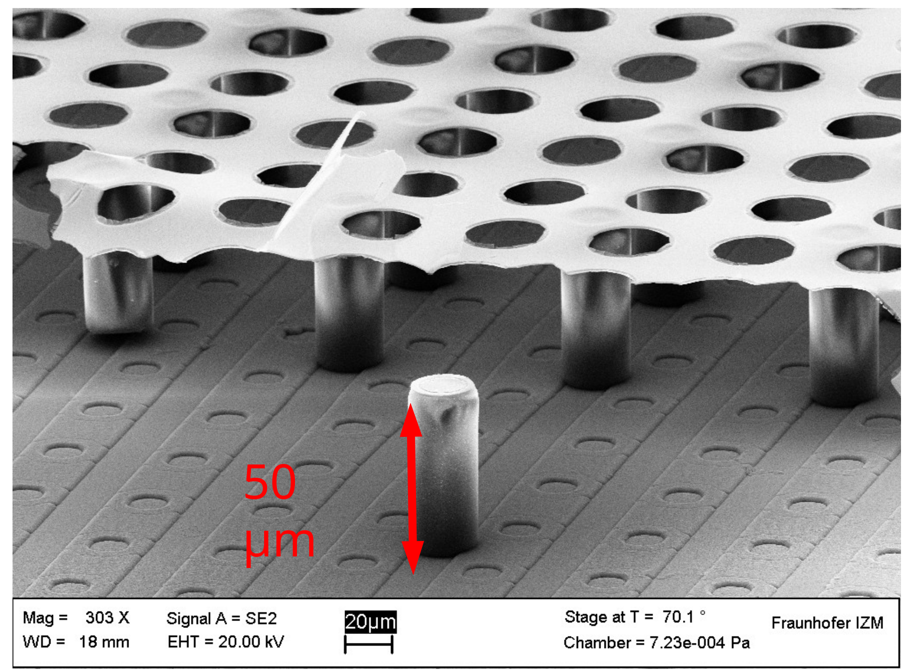
$Ar:CF_4:iC_4H_{10}$ 95:3:2 → σ = 11 µm

Smaller pads/pixels could result in better resolution!

At NIKHEF the GridPix was invented.

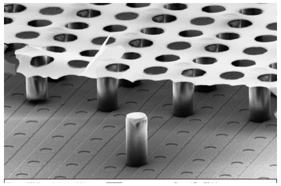
Standard charge collection:
Pads / long strips

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

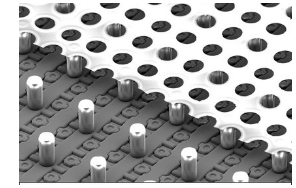


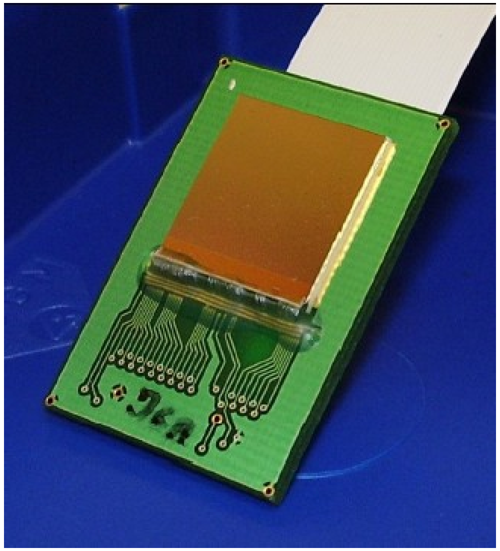
Charge avalanche is collected by one pixel
→ one hit corresponds to one primary electron

NIM A535 (2004) 506-510
NIM A845 (2017) 233-235



The ASICs - Timepix(3)





Timepix: Available for tests since Nov. 2006

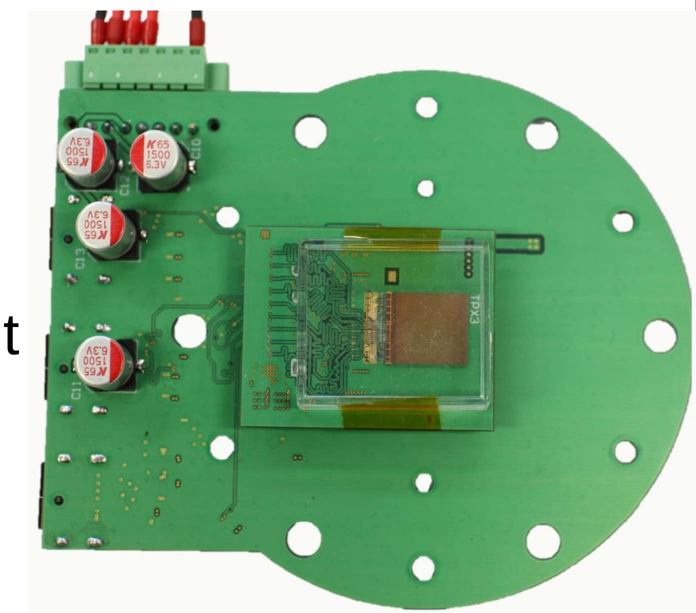
Number of pixels: 256 × 256 pixels
Pixel pitch: 55 × 55 µm²
Chip dimensions: 1.4 × 1.4 cm²
ENC: ~ 90 e$^-$

Limitations: no multi-hit capability.
Each pixel can measure either charge or time.

Timepix3: Available for tests since 2012

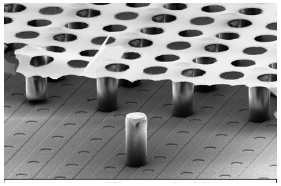
Number of pixels: 256 × 256 pixels
Pixel pitch: 55 × 55 µm²
ENC: ~ 70 e$^-$

- Charge (ToT) and time (ToA) available for each hit
- Timing resolution: 1.56 ns for duration of ~410 µs
- Zero suppression on chip (sparse readout)
- Multi-hit capable
- Output rate up to 5.12 Gbps

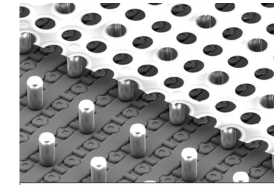


Timepix(3) in the SRS:
NIM A830 (2016) 75-81
JINST 17 (2022) C04015

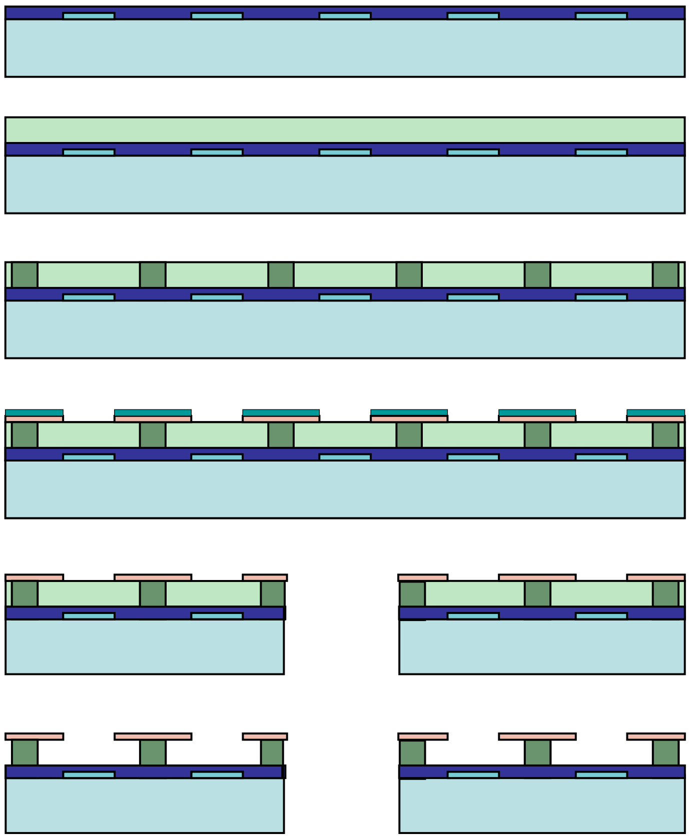
Medipix collaboration:
NIM A581 (2007) 485-494
JINST 9 (2014) C05013



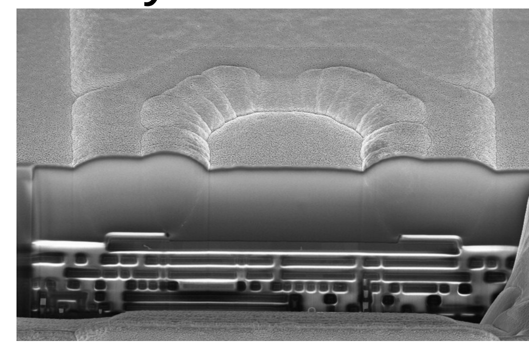
GridPix - Production

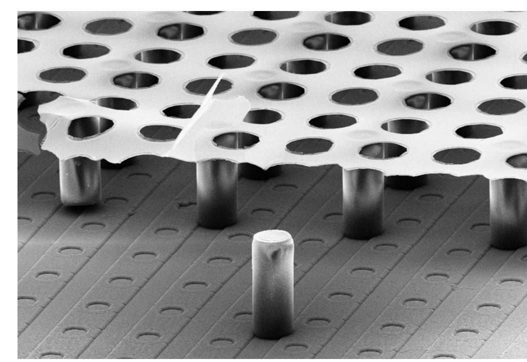


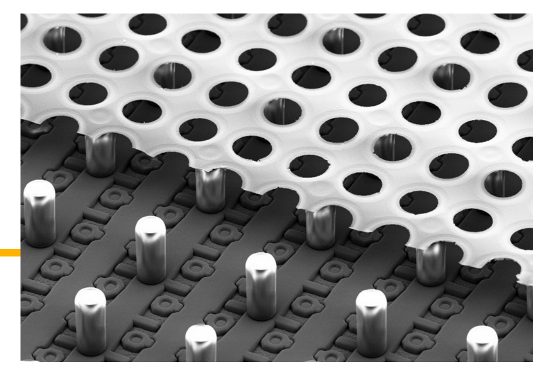
A wafer-based production was set up at the Fraunhofer Institut IZM at Berlin.
One wafer (107 chips) is processed at a time.



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







We have started to transfer the process to the FTD at Bonn in 2023/24.

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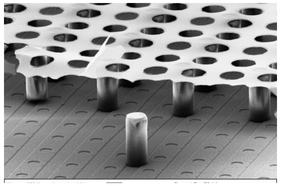
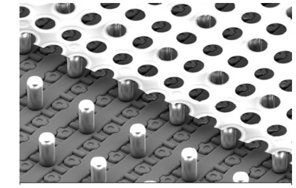
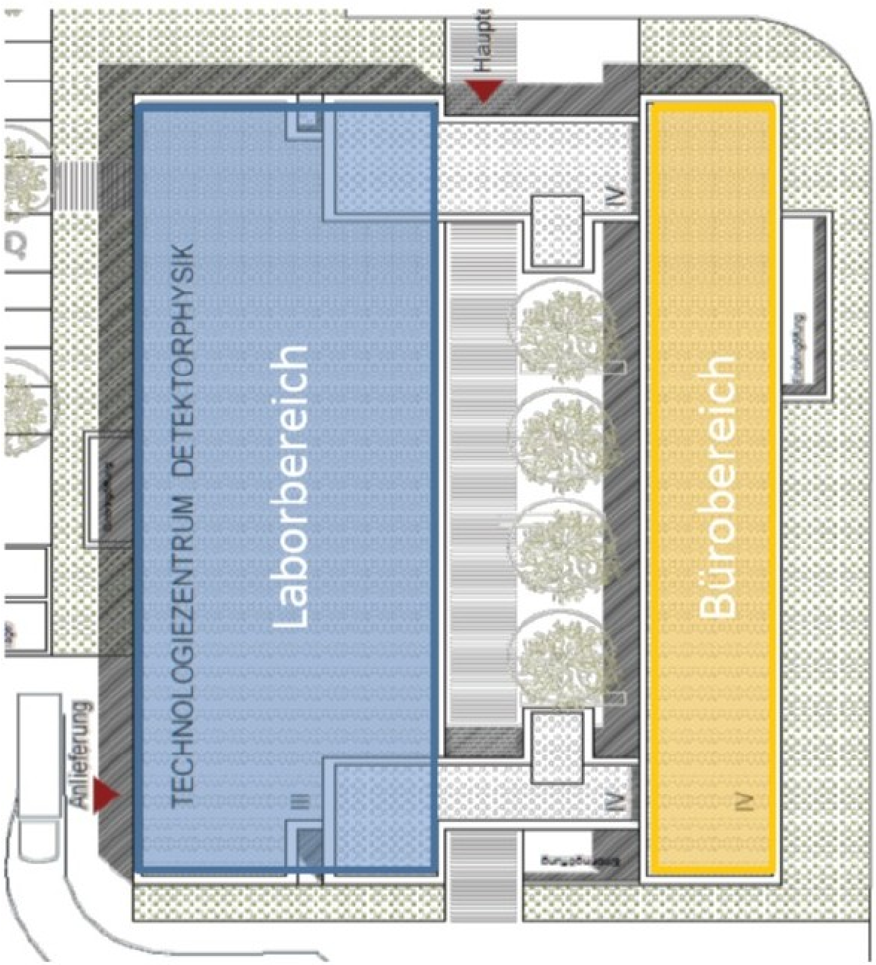
Fraunhofer IZM

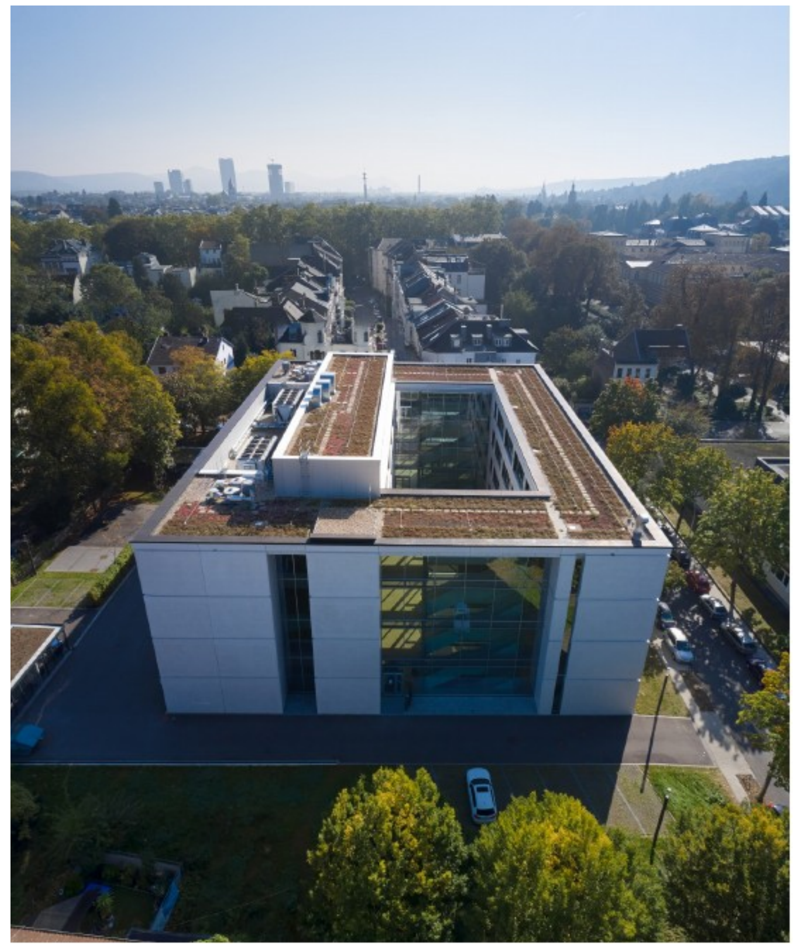




Forschungs- und Technologiezentrum Detektorphysik

First stone laying ceremony 2.11.2016
Inauguration ceremony 8.11.2021





Office space:
- 880 m²
- 4 Floors

Lab space
- 2010 m²
- 4 Levels + Underground Laboratory
- 360 m² clean rooms (ISO 5, 6, 7)

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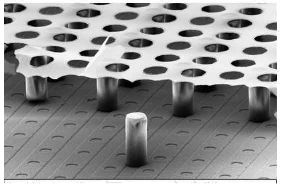
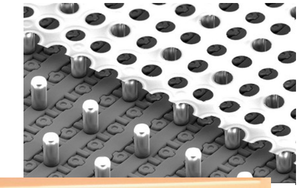


Cleanroom

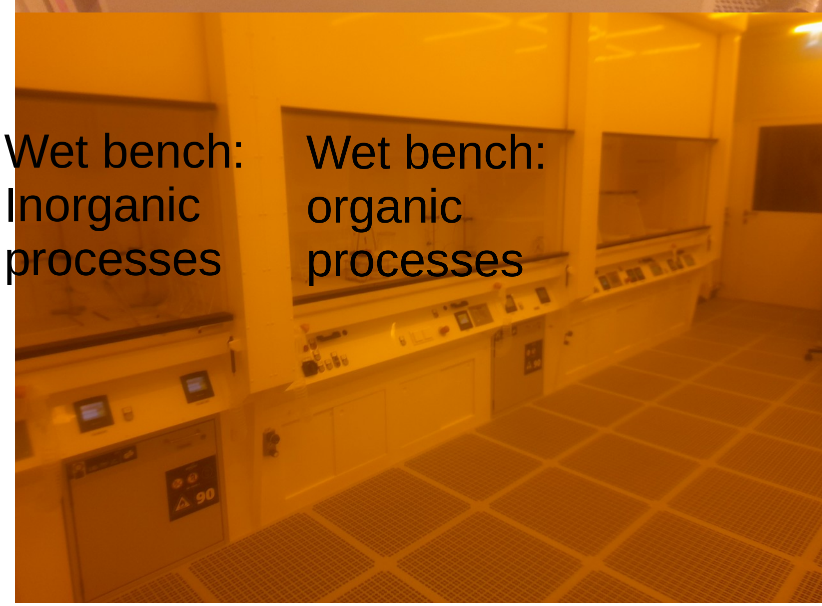


ISO 7

ISO 6

Maskless
Aligner

ISO 5



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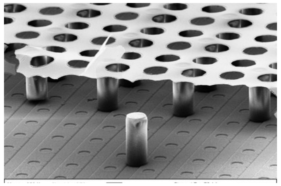
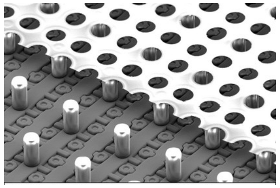
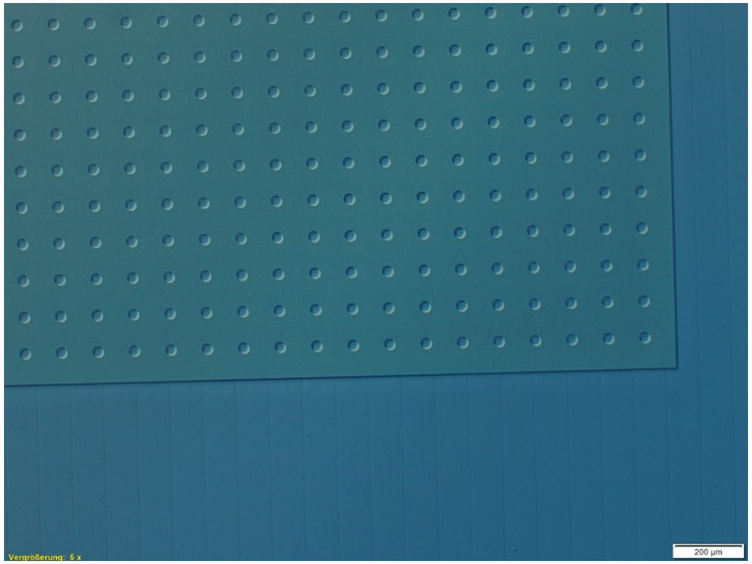
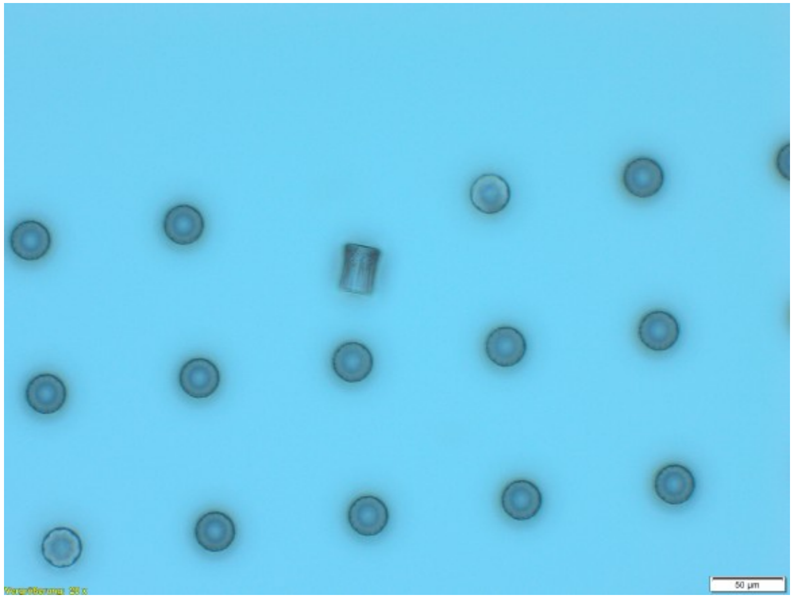


First Steps Towards “GridPixes made in Bonn”

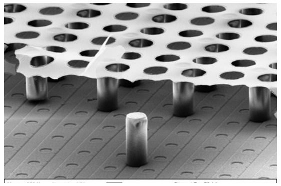


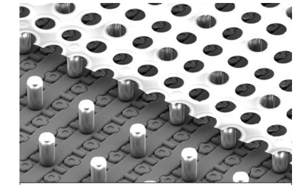
First structures made of SU8: 30µm high pillars and dykes



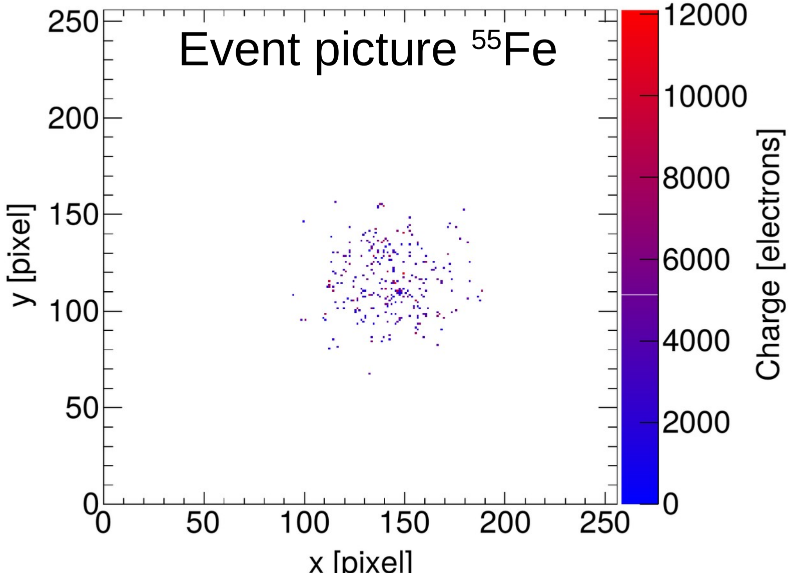


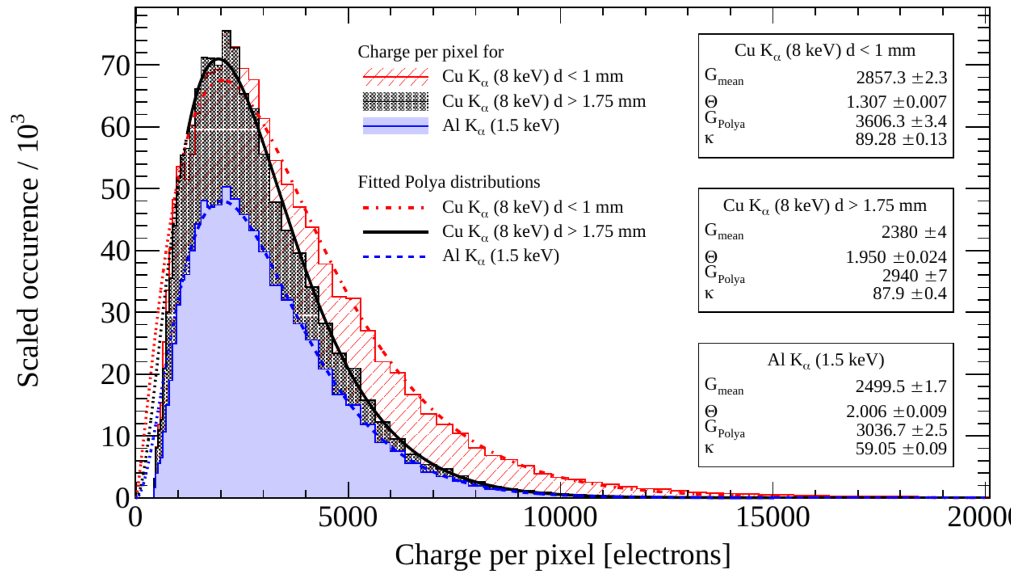
GridPix – Single Primary Electrons

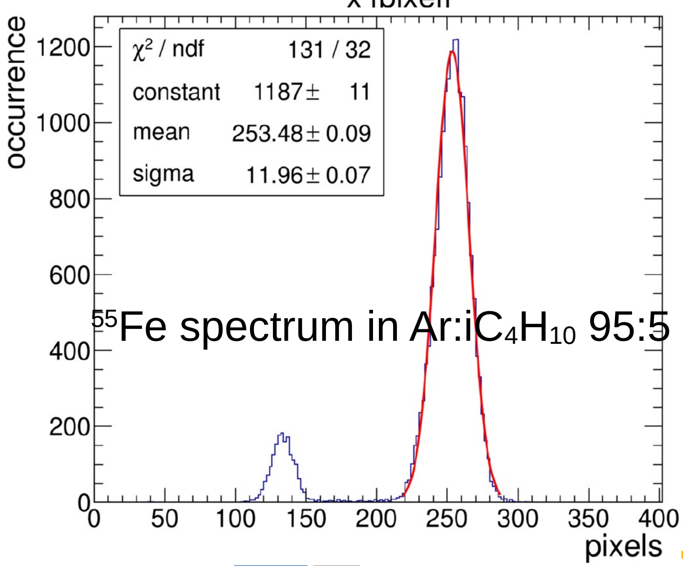




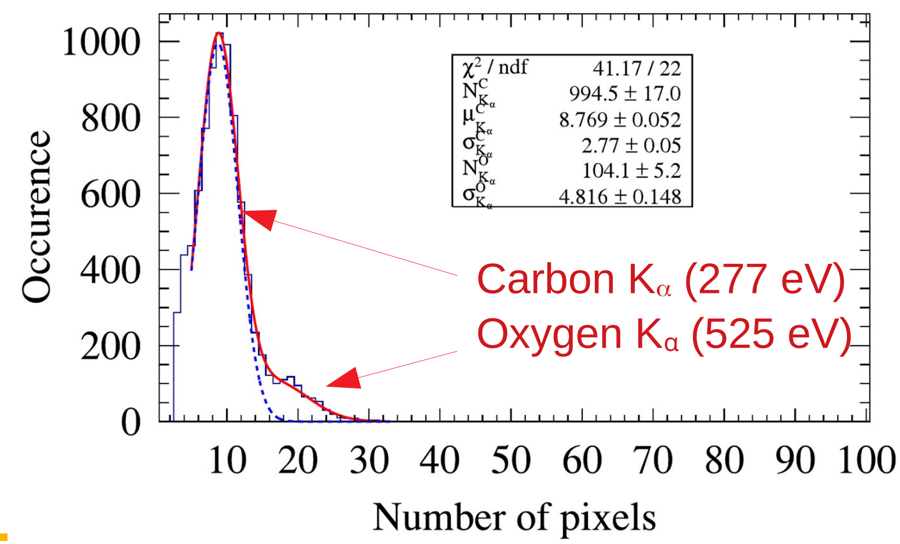
Single primary electrons can be counted leading to excellent energy resolution.



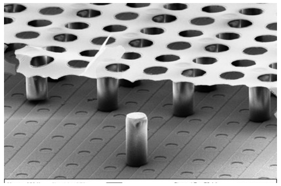


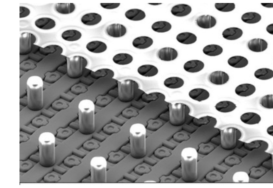


Energy resol. σ_E/E of down to 3.85 % was reached in $Ar{:}iC_4H_{10}$ 90:10 at 5.9 keV.

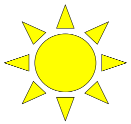


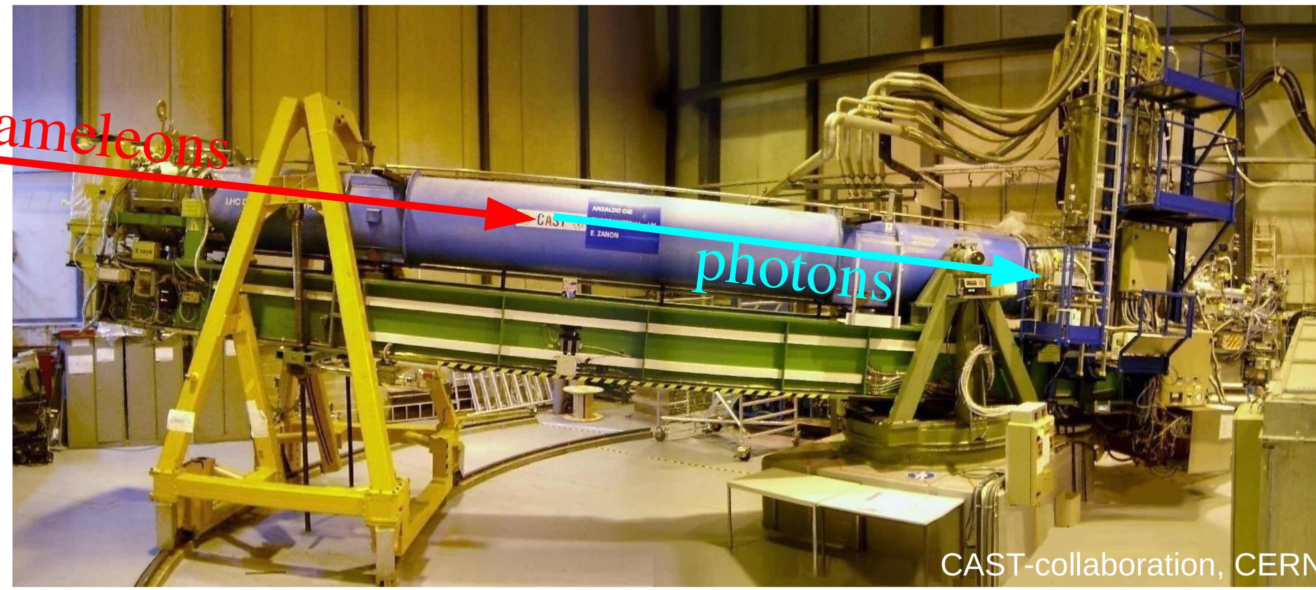
NIMA 893 (2018) 26-34



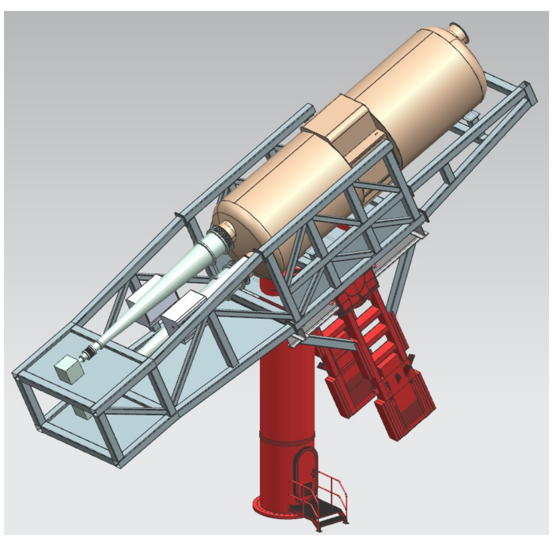


CAST/IAXO – Search for Solar Axions

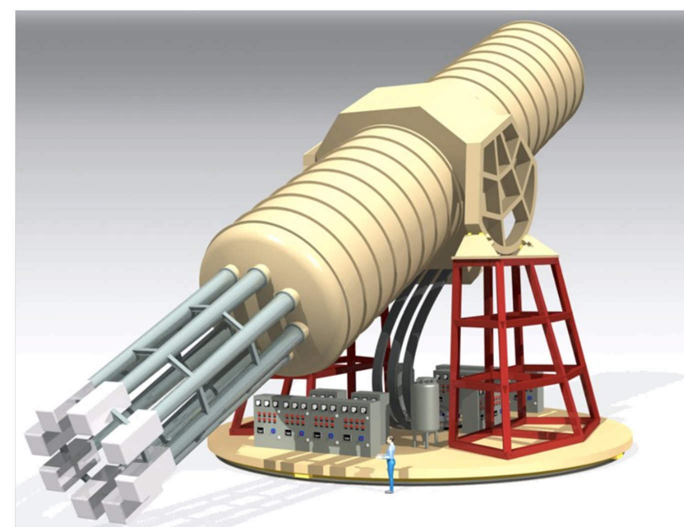


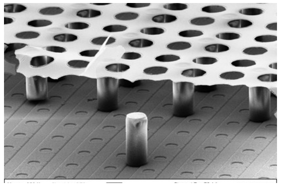


CAST: Decommissioned LHC-magnet is pointed to the Sun. Axions and Chameleons produced in the Sun convert into X-ray photons.

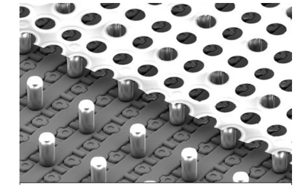


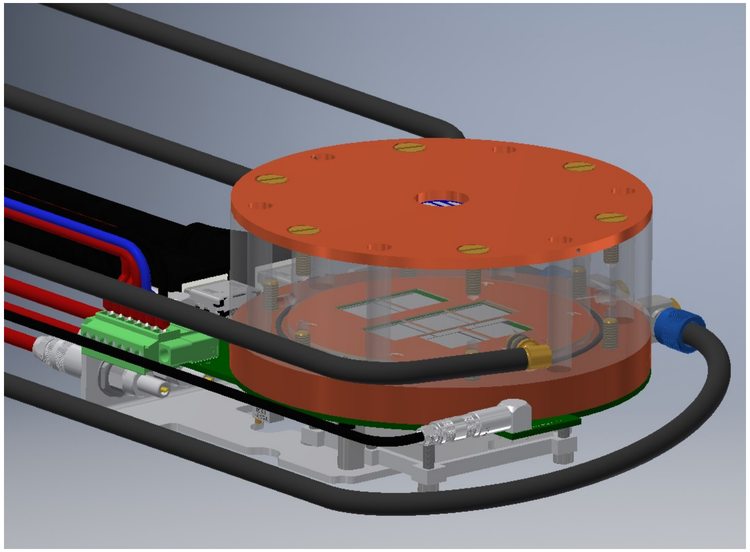
Successor experiment (Baby-)IAXO is planned to be built at DESY.
→ X-ray detectors with
- Low energy threshold
- High spatial resolution
- High radiopurity
- Shielded by lead





CAST

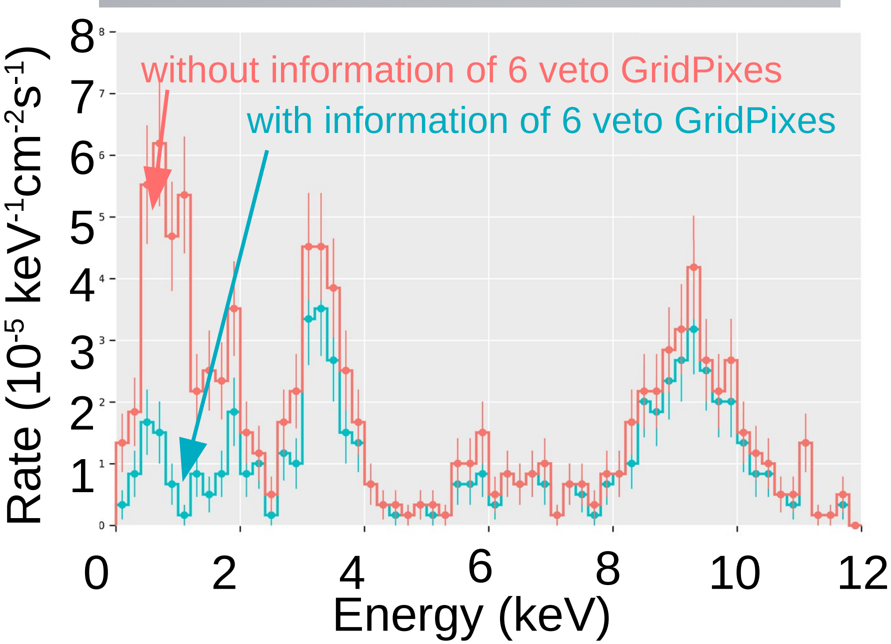


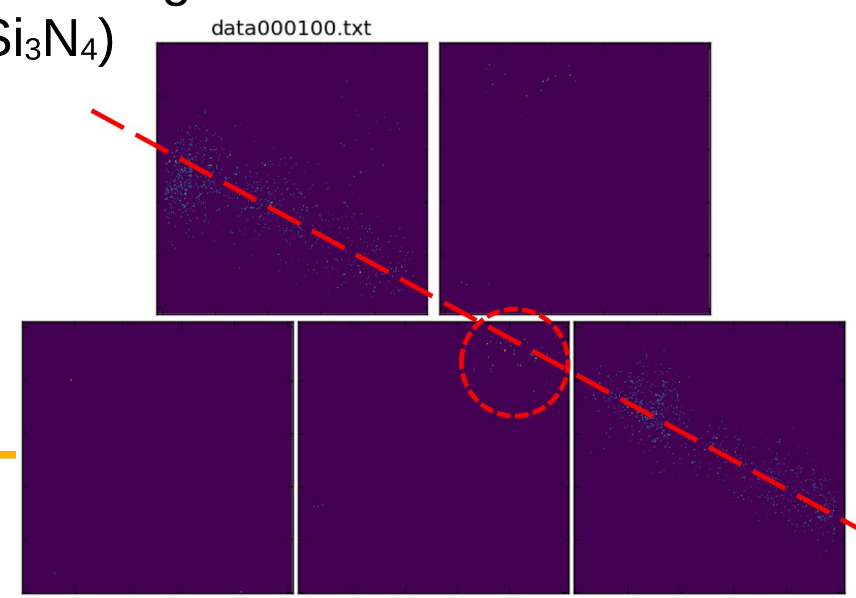


1. data run 2014/15 → Data published
2. data run 2017/18 → Analysis is finalized

Data Run 2 had several improvements in the detector:

- 7 GridPix arrangement (central main detector + 6 veto detectors)
- Signal decouple from grid and digitized by FADC
- 2 veto scintillators (behind GridPix and on top of lead shielding)
- Low material budget entrance window (300 nm Si_3N_4)





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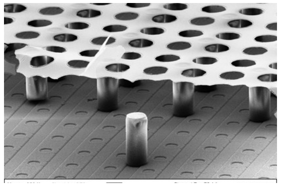
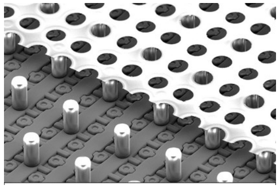
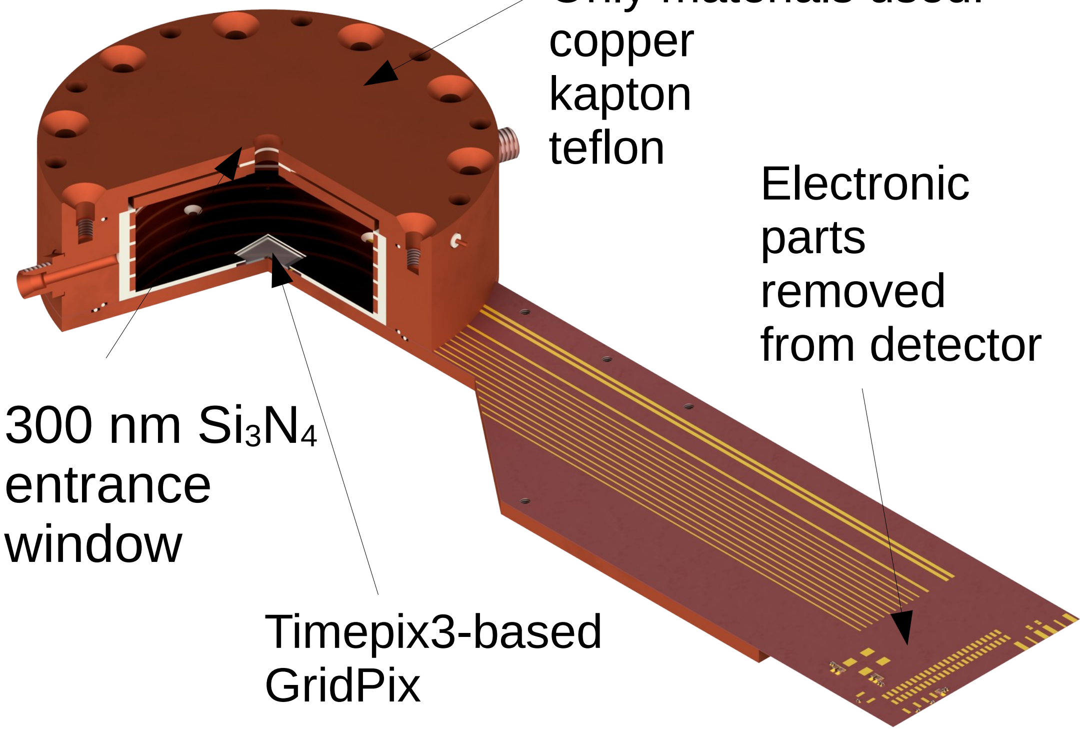
NIM A867 (2017) 101-107
JCAP 01 (2019) 032



BabyIAXO Prototype Detector

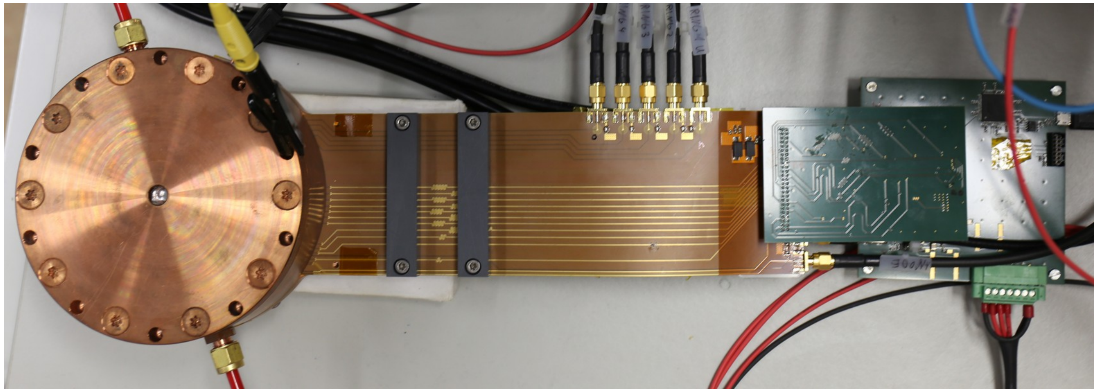


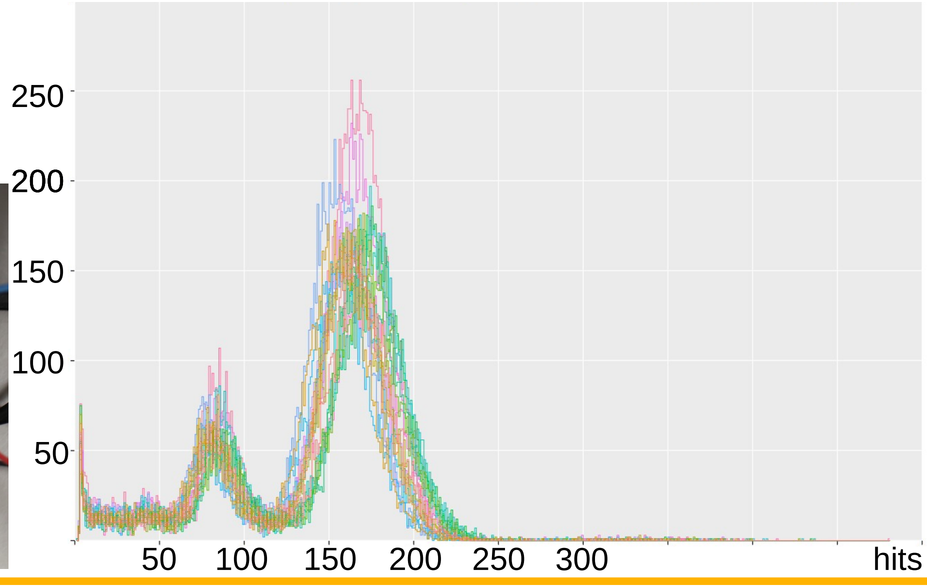


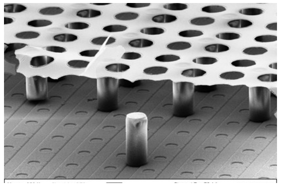
Further improvements of the CAST detector:

- Timepix3 (currently only one)
- Use of radiopure materials only (copper, teflon, kapton)
- Move non-essential parts further away

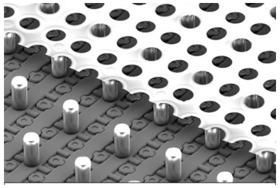
Currently first prototype without radiopure copper/cleaning.



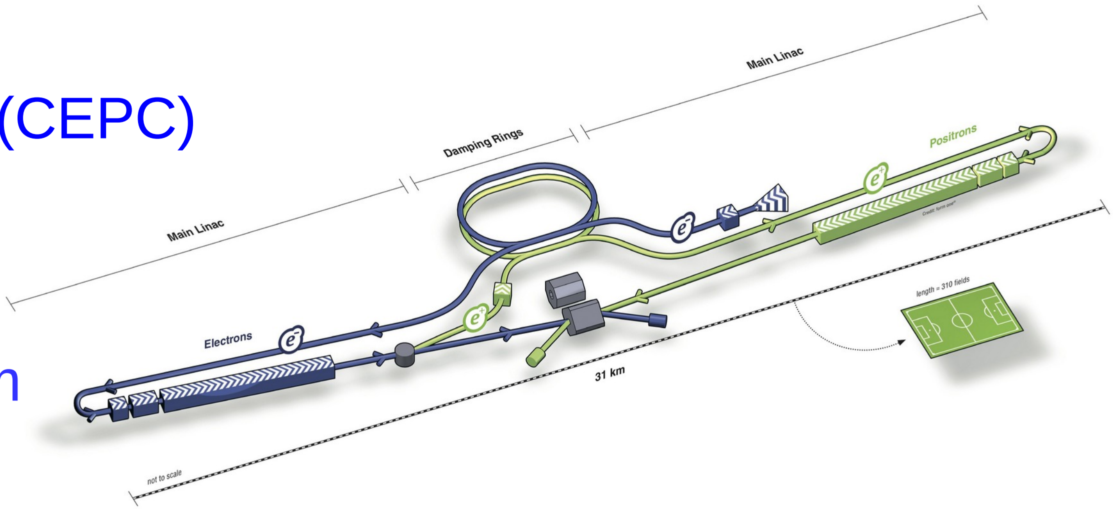




Tracker for Future Higgs Factories



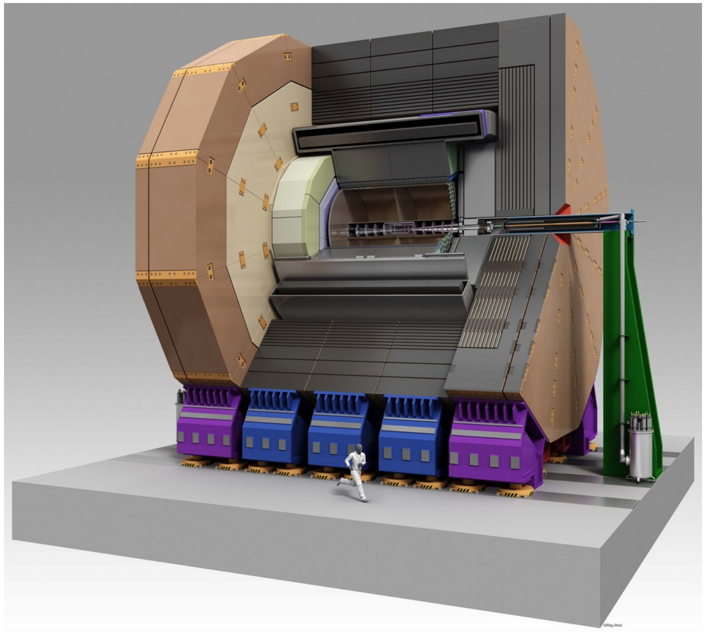
International Linear Collider (ILC) /
Chinese Electron Position Collider (CEPC)
Future Circular Collider (FCCee)
are e^+e^- colliders with:
$\sqrt{s}$ = 90 GeV – 1 TeV / 90-240 GeV
Overall length of 21-50 km / 100 km



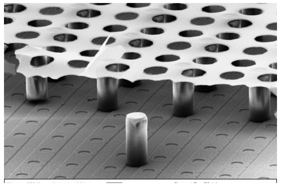
Requirements of TPC from
ILC TDR vol. 4

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 $r\phi$	$\simeq 60\ \mu$m for zero drift, $< 100\ \mu$m 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)		

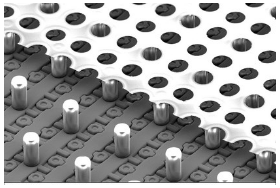
In addition: very high efficiency for particle of more than 1 GeV.



International Large Detector
- Standard layout HEP detector with improved performance
- TPC as main tracker



PixelTPC for tracking at Colliders



A pixelTPC has some advantages compared to a conventional pad TPC

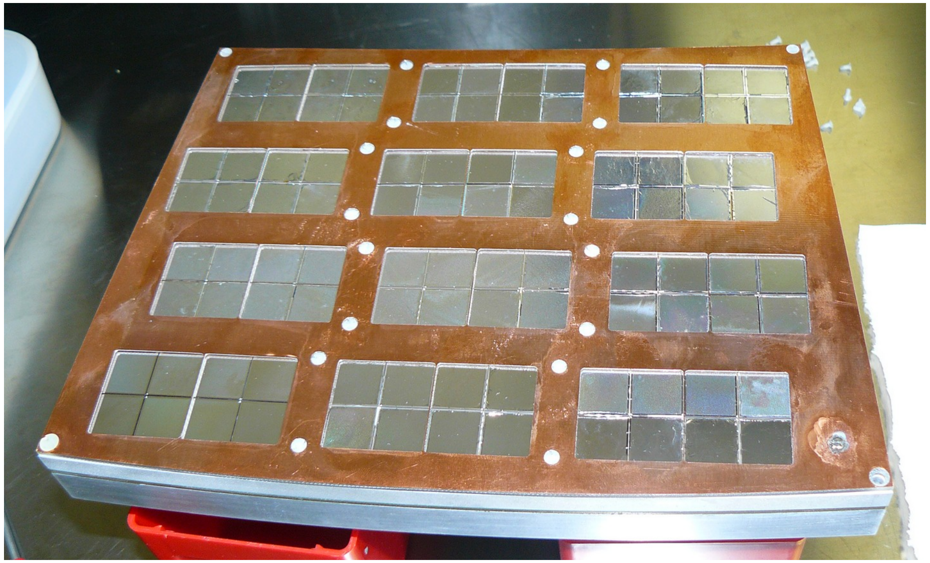
- Lower occupancy → easier track reconstruction at higher backgrounds
- Improved dE/dx: <4% seems possible with electron or even cluster counting
- Removal of δ-rays and kink removal
- No angular pad effect

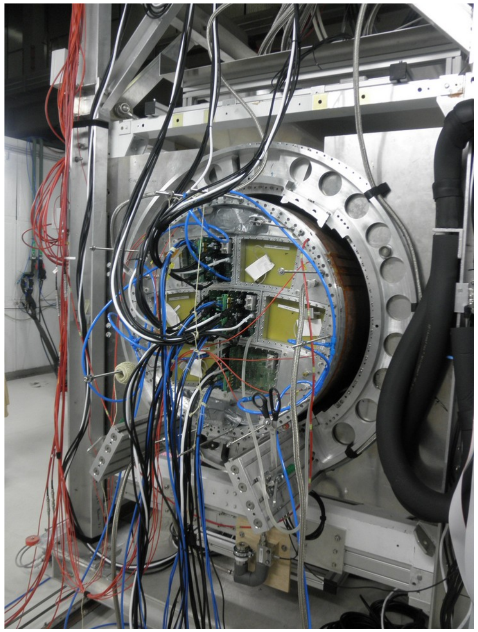
To readout a large TPC:~50000 GridPixes needed

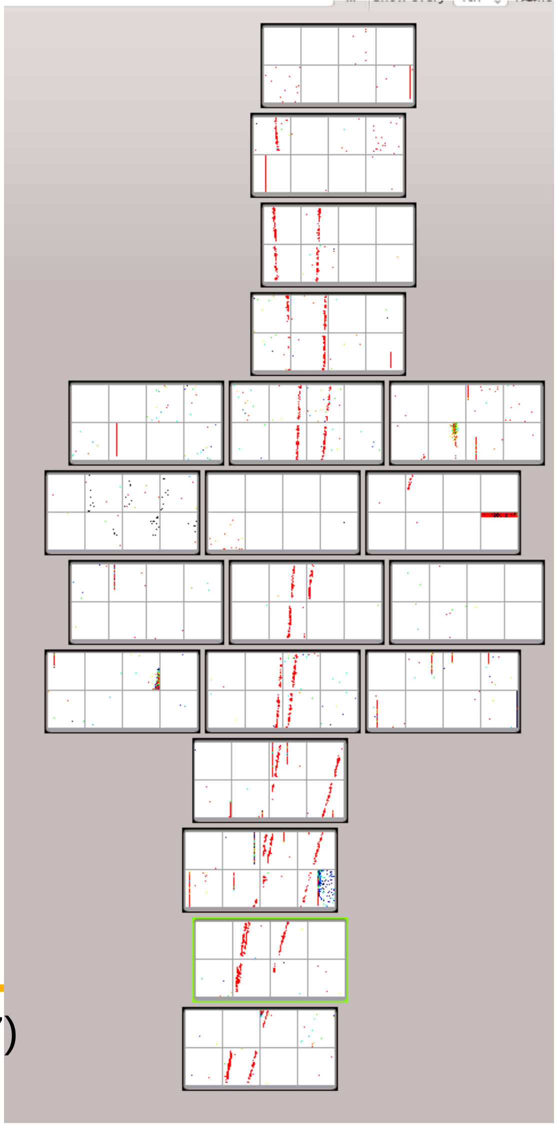
→ Demonstrator with 160 GridPixes (Timepix) in 2015

Central module with 96 GridPixes (coverage 50%)

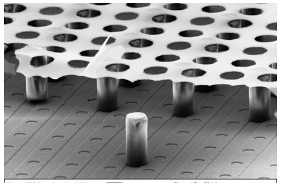
2 weeks of successful test beam.



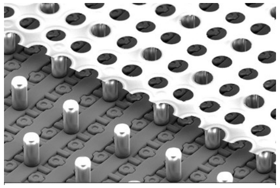




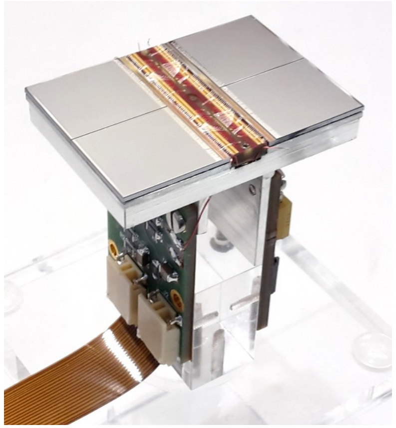
IEEE TNS 64 (2017) 1159-1167

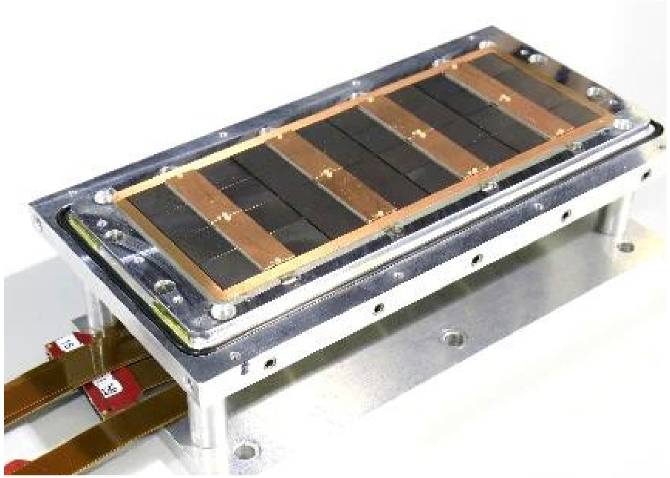


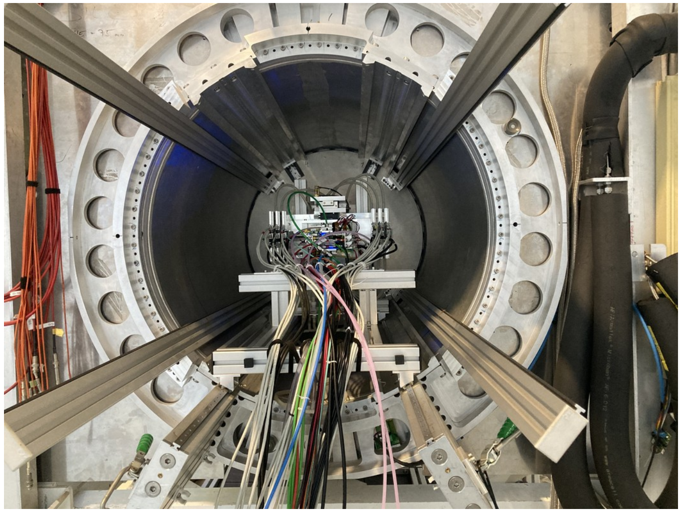
Tracking with Timepix3



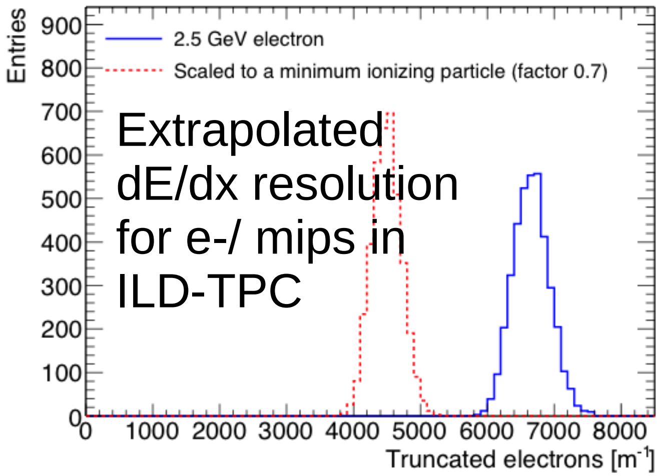
New effort to build larger modules with Timepix3 based GridPixes:
First single chip (2017), then quads (2018), finally 8 quads (June 2021).



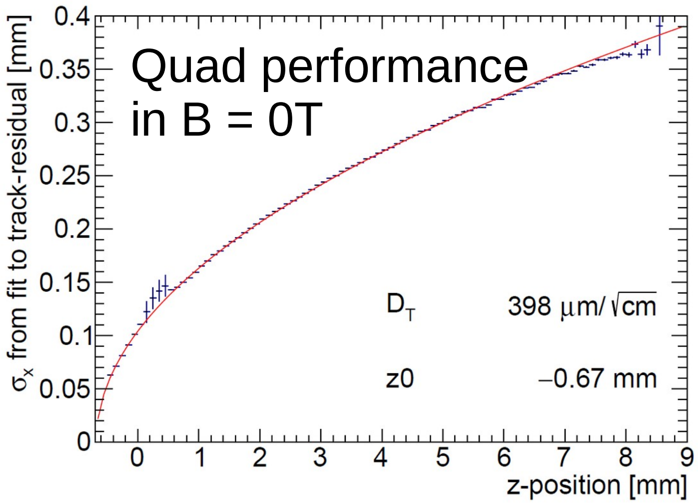




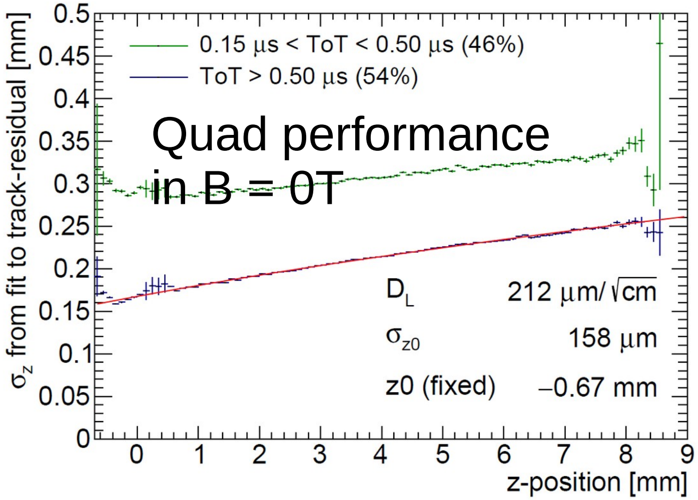
Quad coverage: 68.9 %



Extrapolated dE/dx resolution for e-/ mips in ILD-TPC

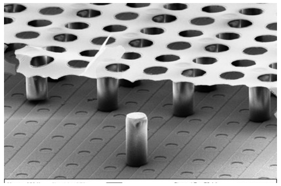


Quad performance in B = 0T

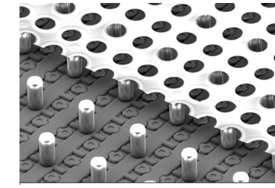


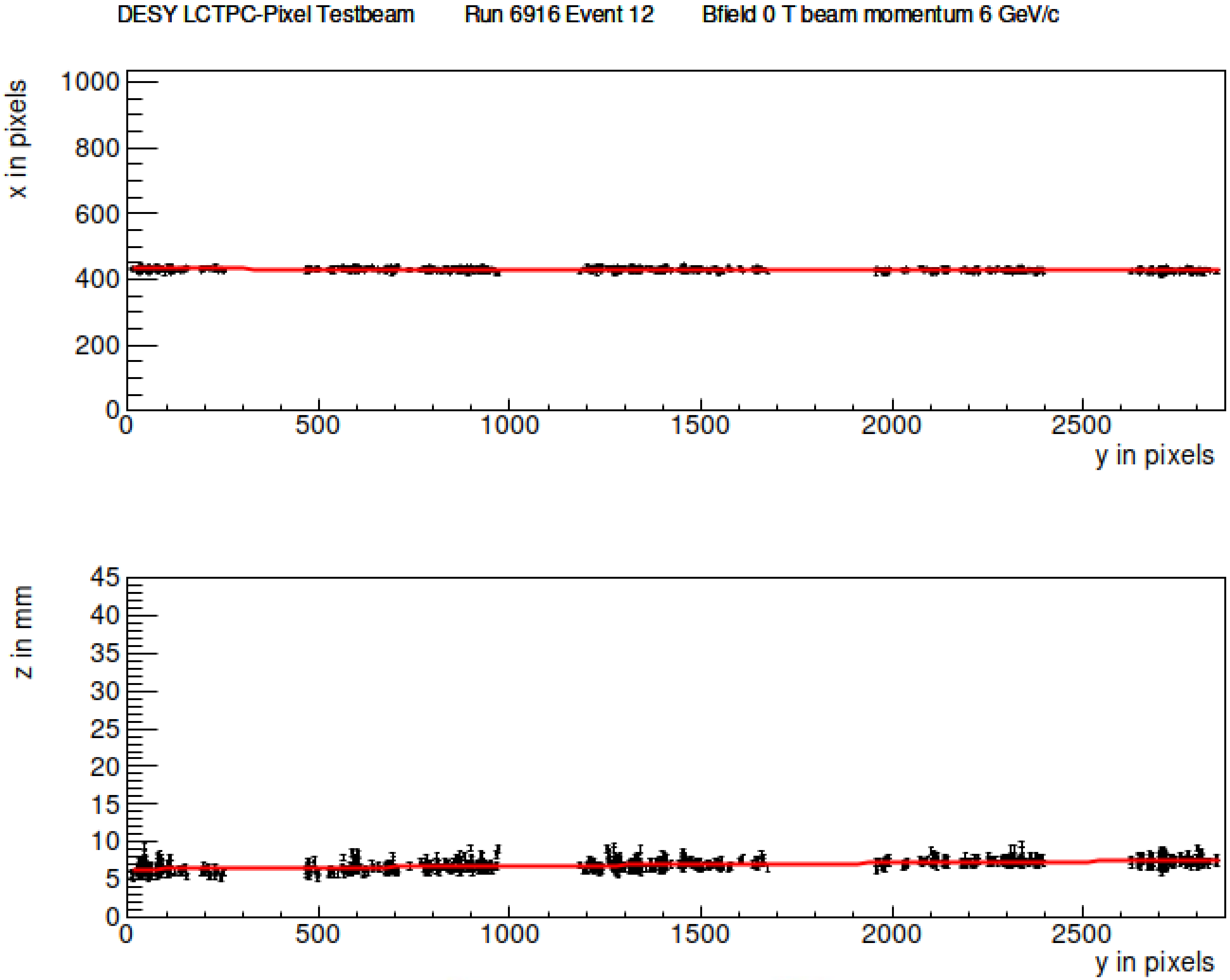
Quad performance in B = 0T

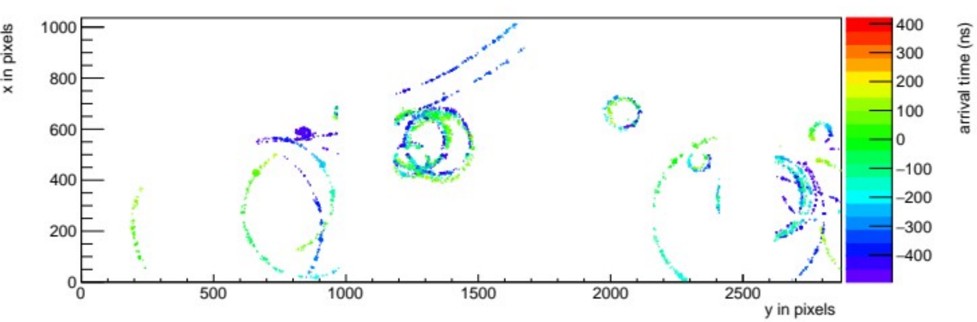
NIM A908 (2018) 18-23
NIM A956 (2020) 163331



Tracking with Timepix3



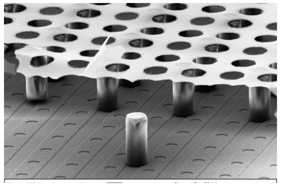




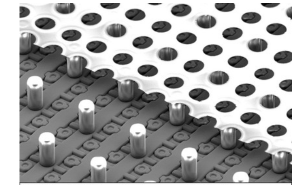
Track with 1050 hits:
χ^2_{xy} = 912/1048
χ^2_{z} = 1740/1048

No asymmetric tail (z time slewing) or outlier removal applied yet.

Many tests performed
in B = 0/1 T
with various beam energies
with various rates
with various angles
For the complete data taking a high precision external tracker was available



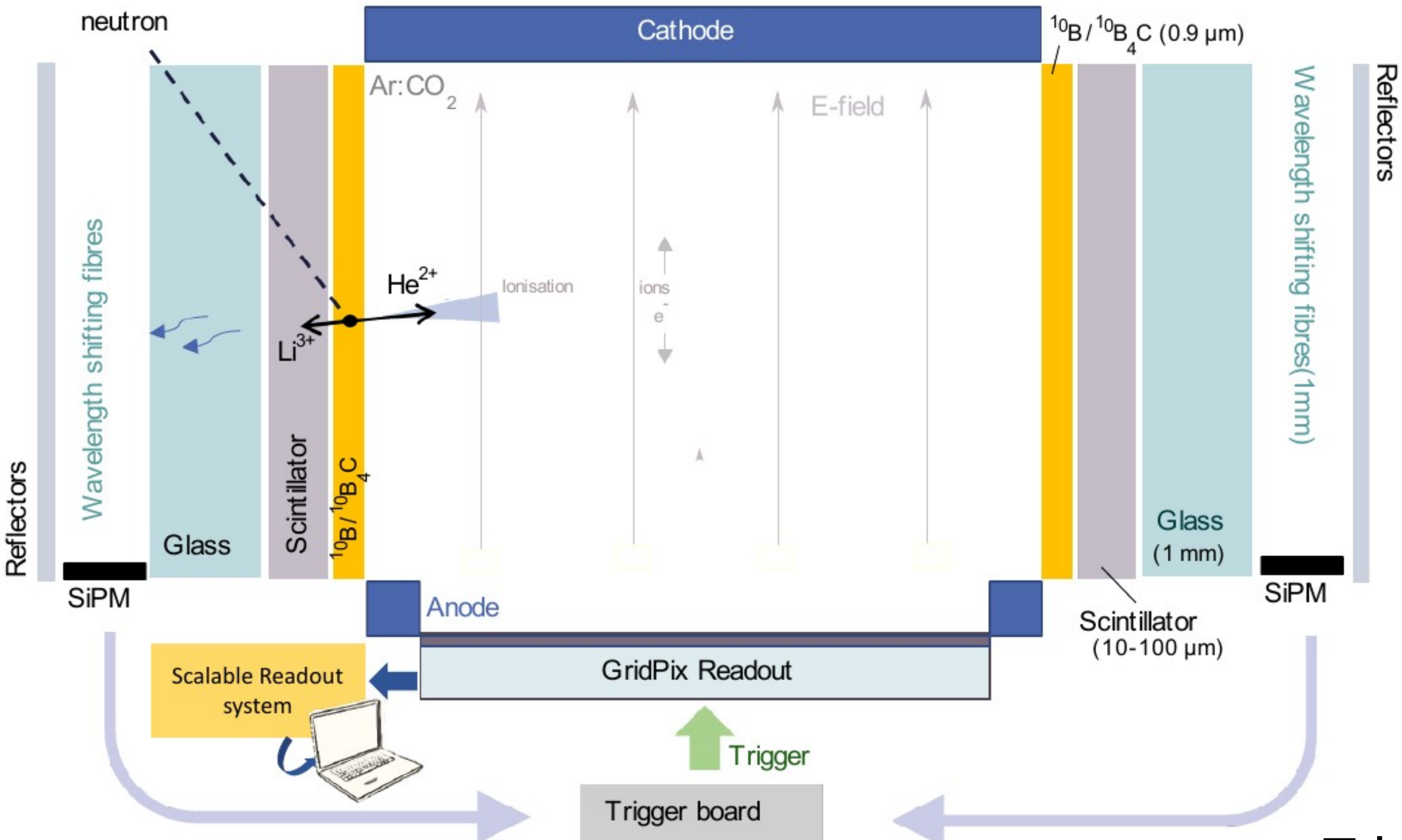
Neutron TPC

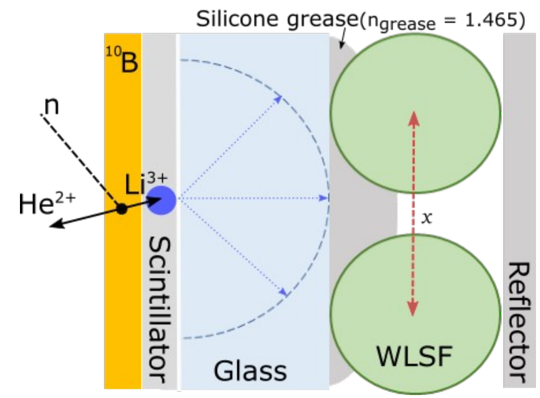


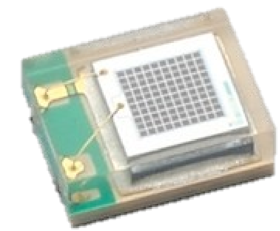
TPC with solid state converter on side walls

$^{10}B + n \rightarrow {}^{7}Li + \alpha$ => two fragments: trigger + tracking

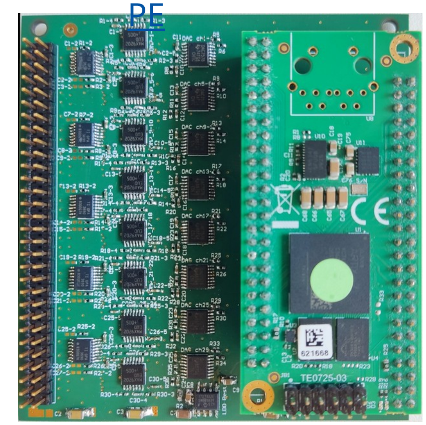
Side walls: ^{10}B, scintillator, glas, WLSF



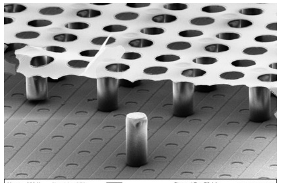


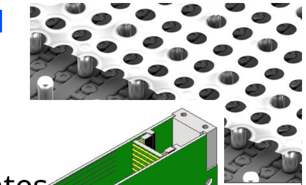


MPPC S13360-1375 PE

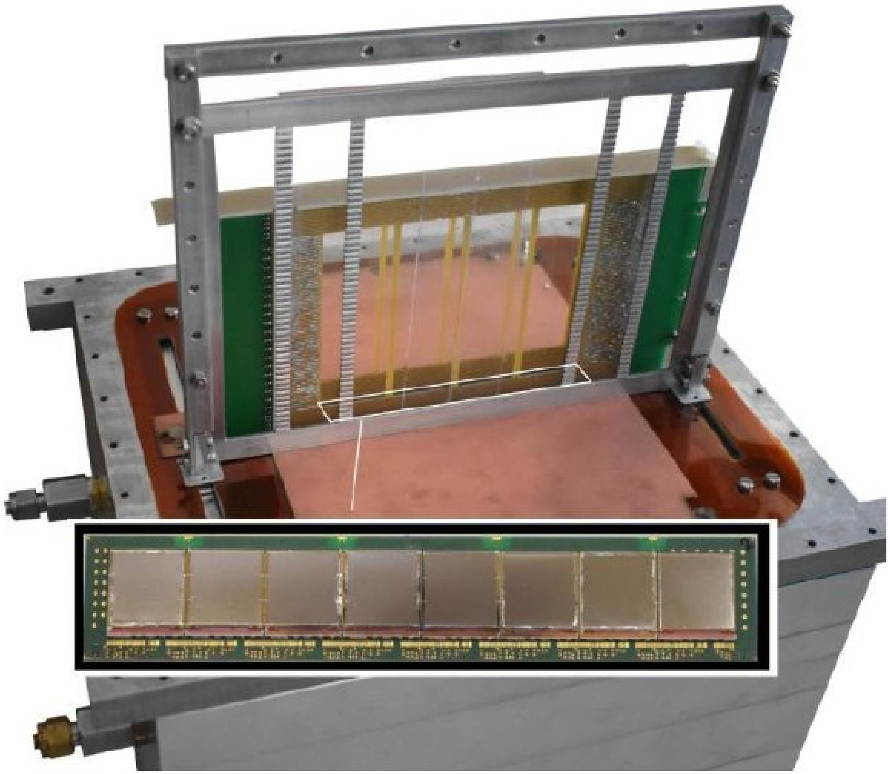


Trigger board for 30 SiPMs

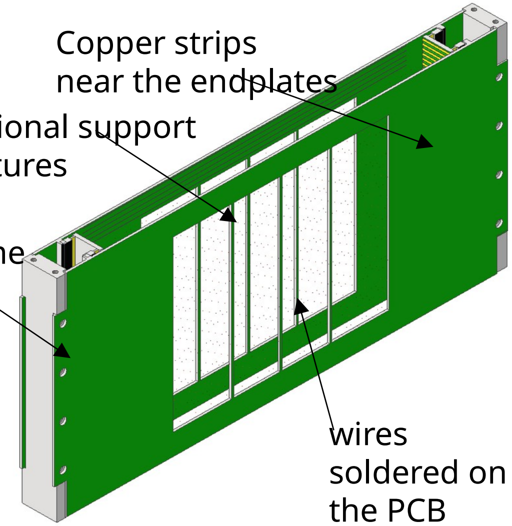




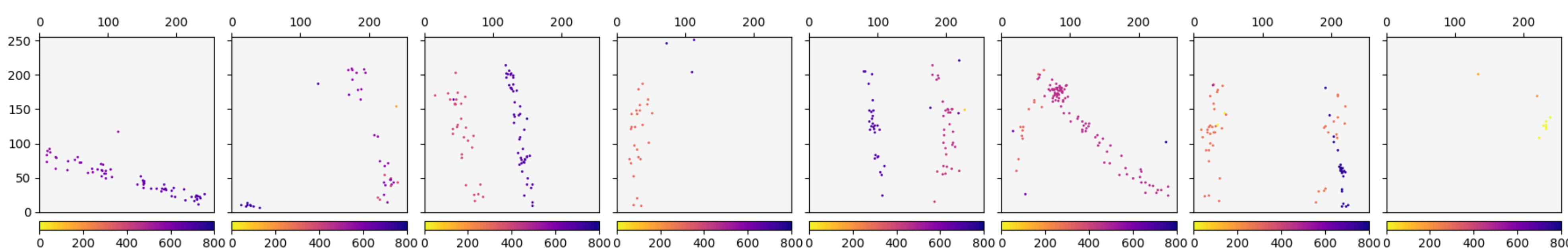
Neutron TPC

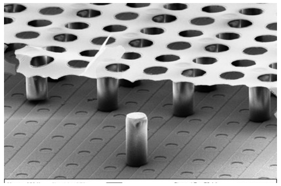


Current field cage: 30 µm thick wires with a spacing of 2 mm soldered on PCB.

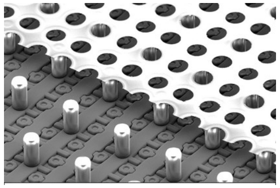


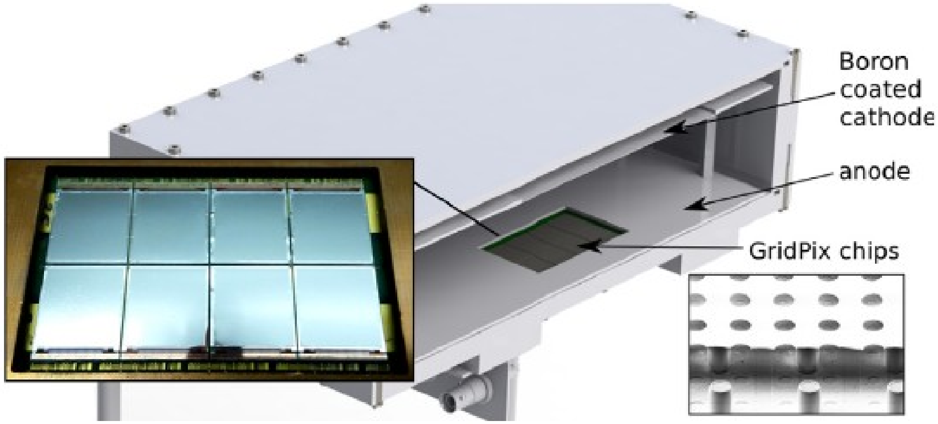
First tracks of cosmic muons recorded with the TPC and external trigger. Analysis shows, that there are no track distortion in the xy-plane seen. Some distortions in the drift direction are seen close to the wires.

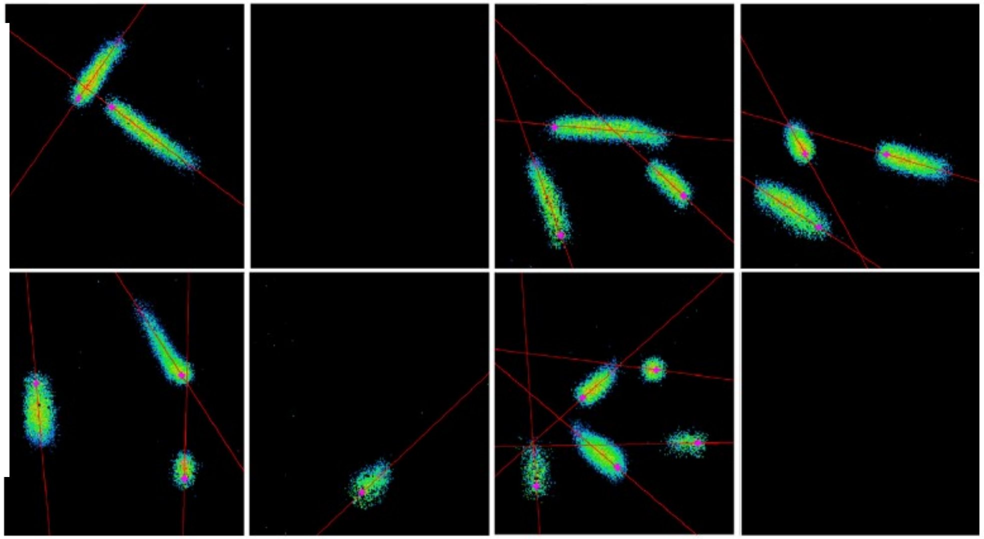


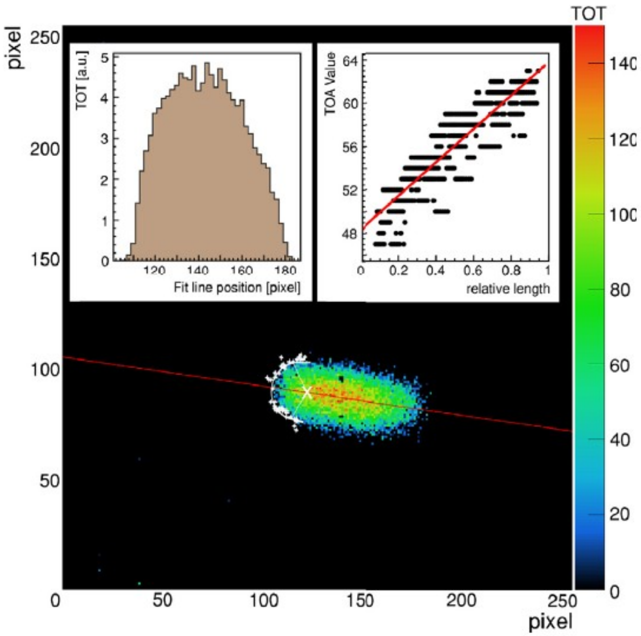


Prestudies – alphas with GridPixes

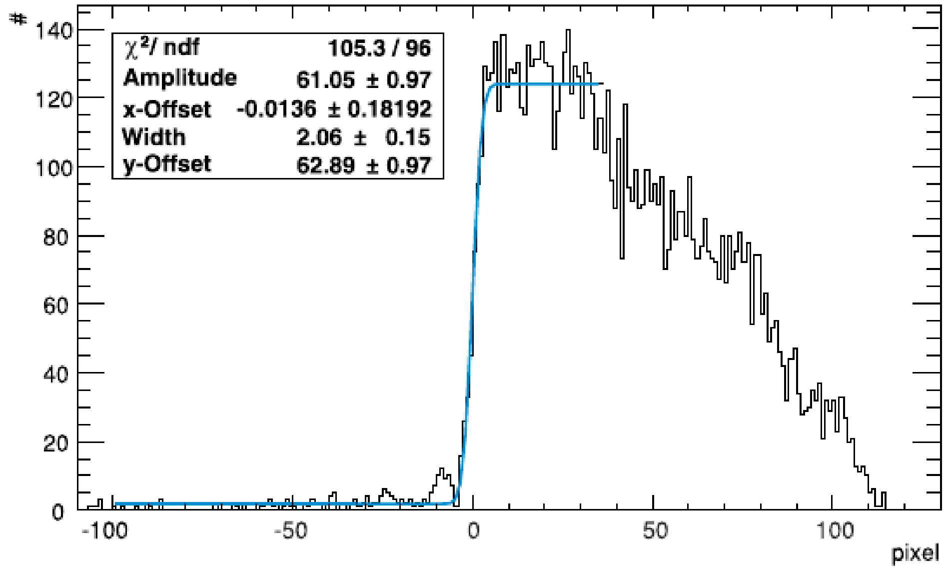




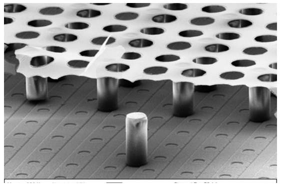




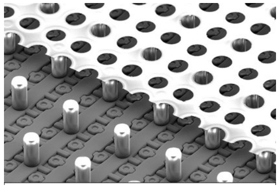
Strip with BC_4 on cathode



Physica B: Condensed Matter 551 (2018) 517–522



X-ray Polarimetry

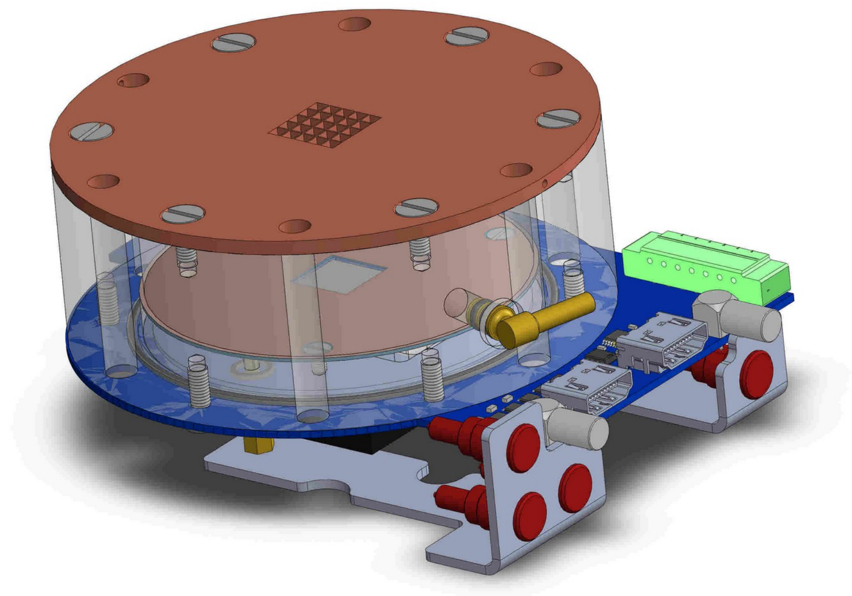


Polarization is interesting to measure, since it gives information about materials or physical processes.

→ Difficult to measure at low X-ray energies with standard techniques

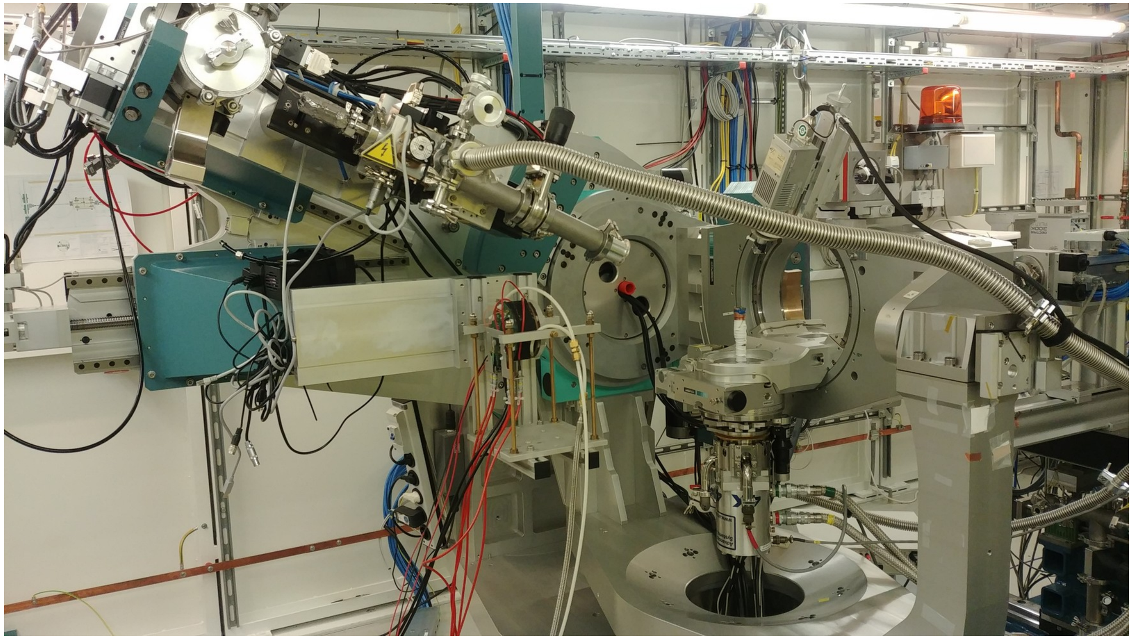
Photoelectrons follow E-field of polarization

=> need gaseous detectors with high resolutions (GridPixes 🙂)



- CAST type detector with 3 cm drift
- Different He-based gas mixtures with CO_2 or DME
- Test beam at PETRA III (DESY) and KARA (KIT)
- Beam energies 4-11 keV
- Beam is >95 % linearly polarized

→ reconstructed polarization 76% (sofar)



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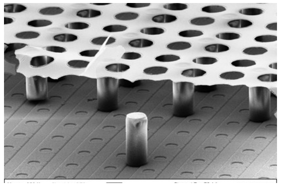
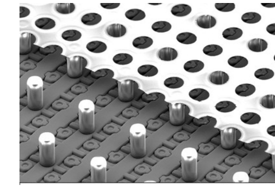
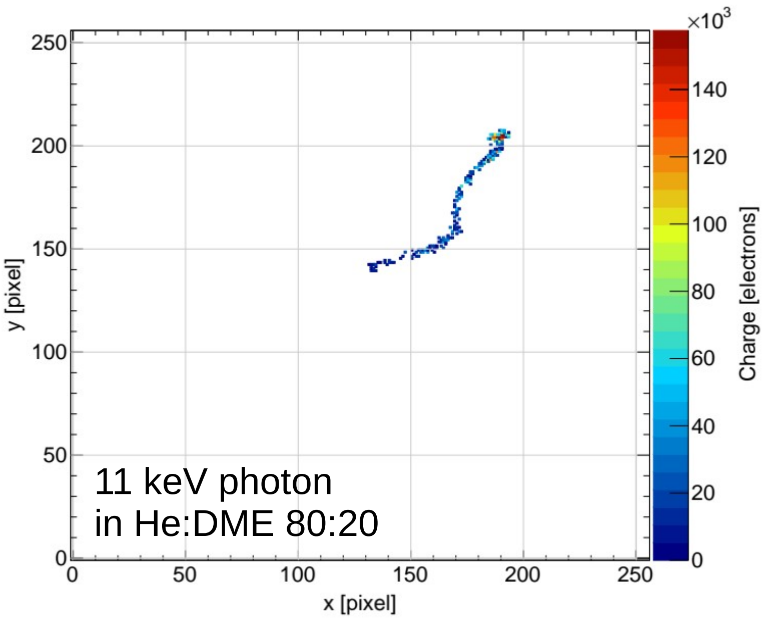


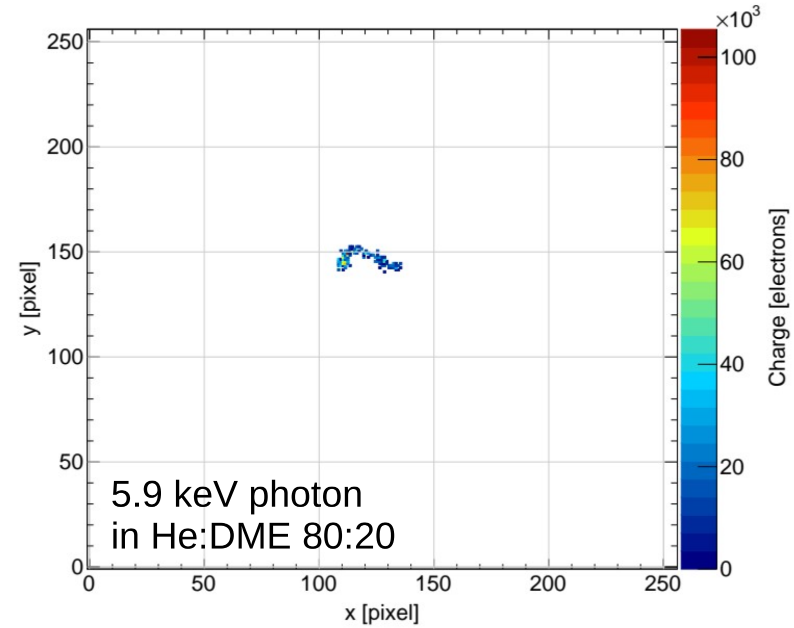
X-ray Polarimetry

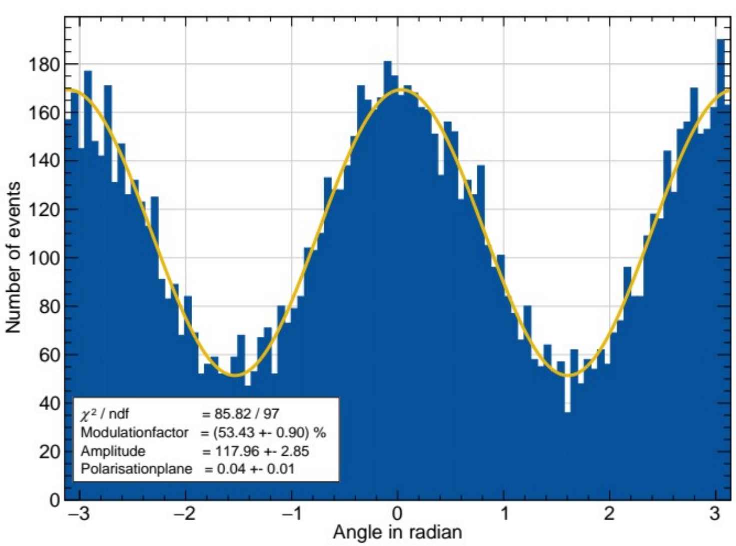


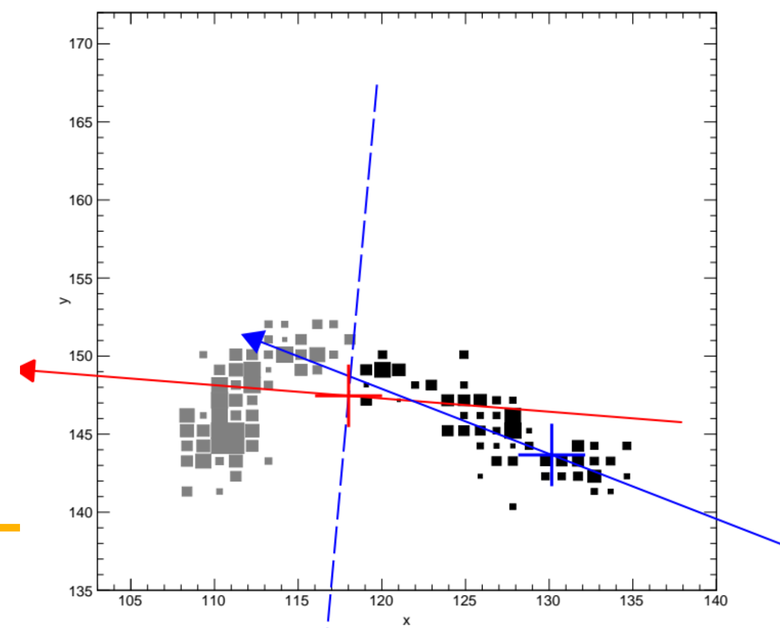


Reconstruction:

- Find center of event
- Split track
- Find end with higher ioniz.
- Reconstruct the other end
- Determine direction







GSI 2023
J. Kaminski

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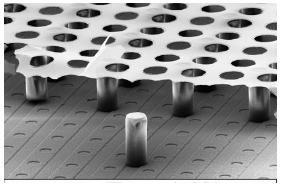
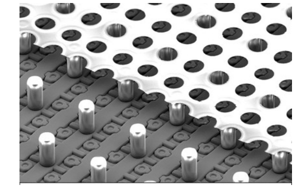
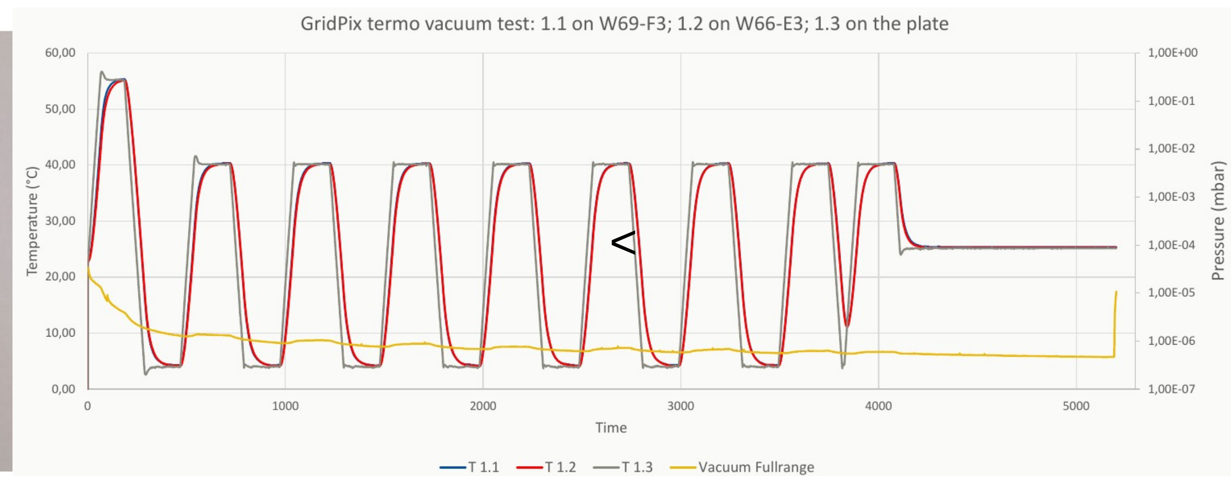


X-ray Polarimetry in Astrophysics



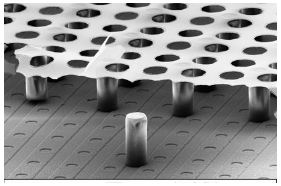
Project by the X-ray polarimetry group at INAF-IAPS (lead by Paolo Soffitta). Idea is to prepare and propose a follow-up mission of the IXPE satellite, potentially using a GridPix instead of a Gas Pixel Detector.
Important first tests have been performed with 2 standard GridPixes:

1.) Thermo vacuum tests

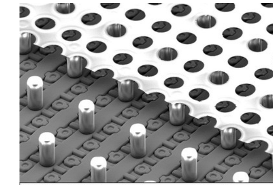


2.) random vibration test → no resonances found up to 2 kHz

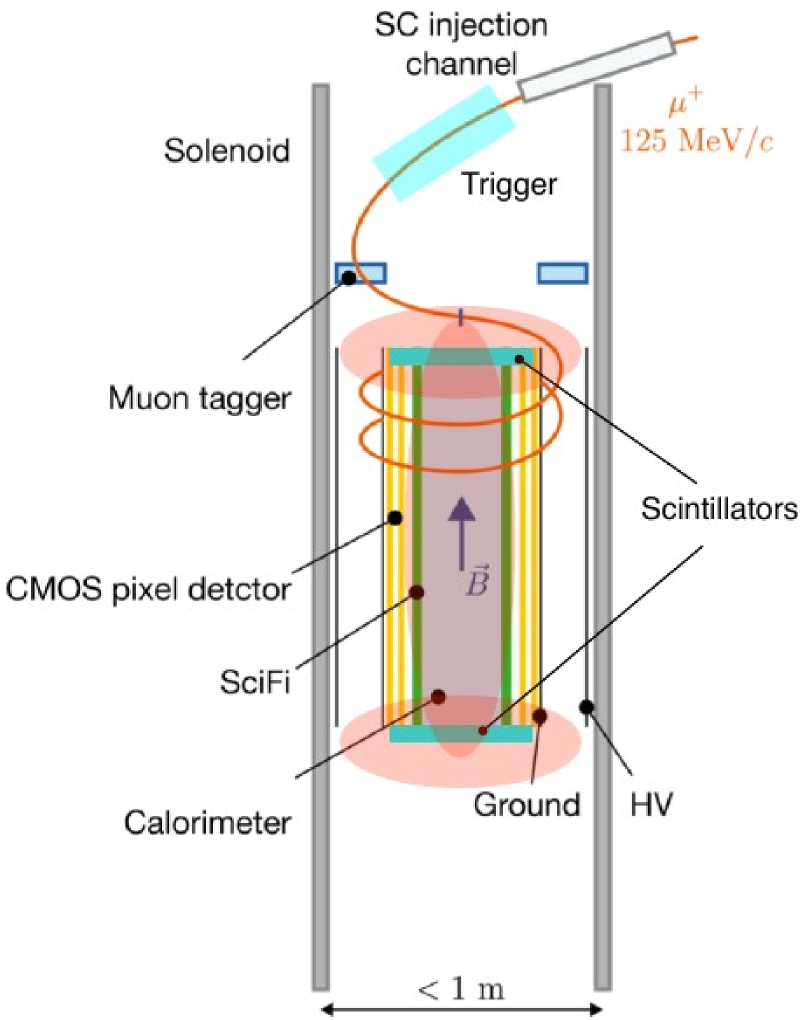
Before and after the two environmental tests high resolution pictures of the grid were taken and the ASICs were tested electronically → no differences were found



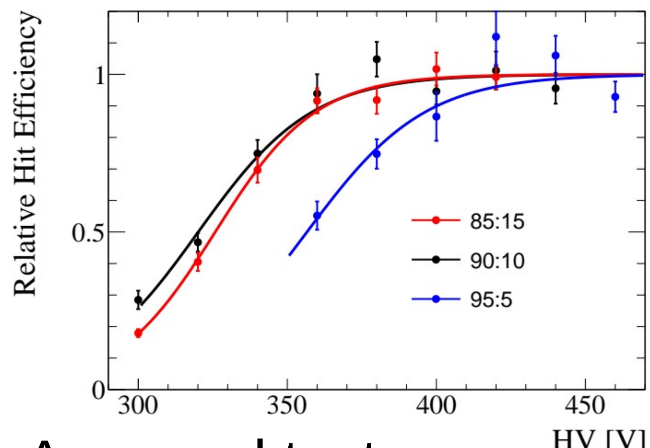
Muon EDM at PSI



A new project for a dedicated measurement of the muon EDM

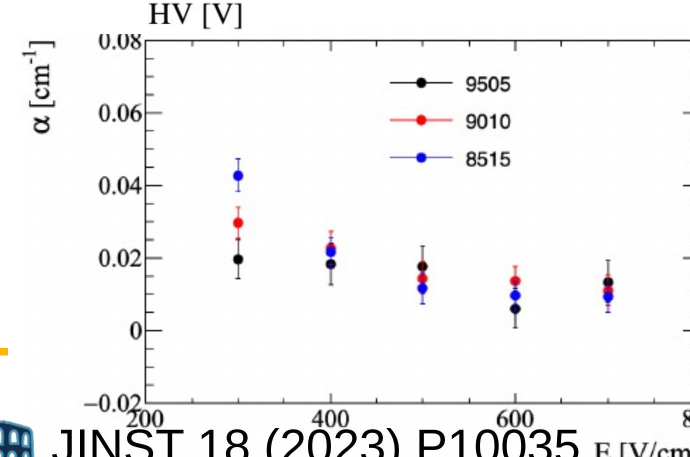


First tests to evaluate GridPix-TPC (F. Renga, INFN Roma) to characterize the muon beam during the commissioning of the phase-I experiment (2025-2026).
Test beam with different mixtures of $He:iC_4H_{10}$ (95:5, 90:10, 85:15)



Rich study of gas parameters: V_{drift}, D_T, D_L, attachment α

A second test beam with $He:CO_2$ mixtures just took place.



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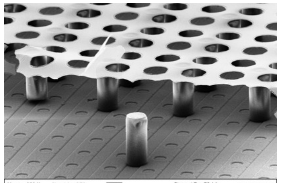
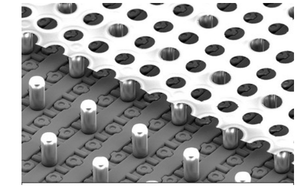
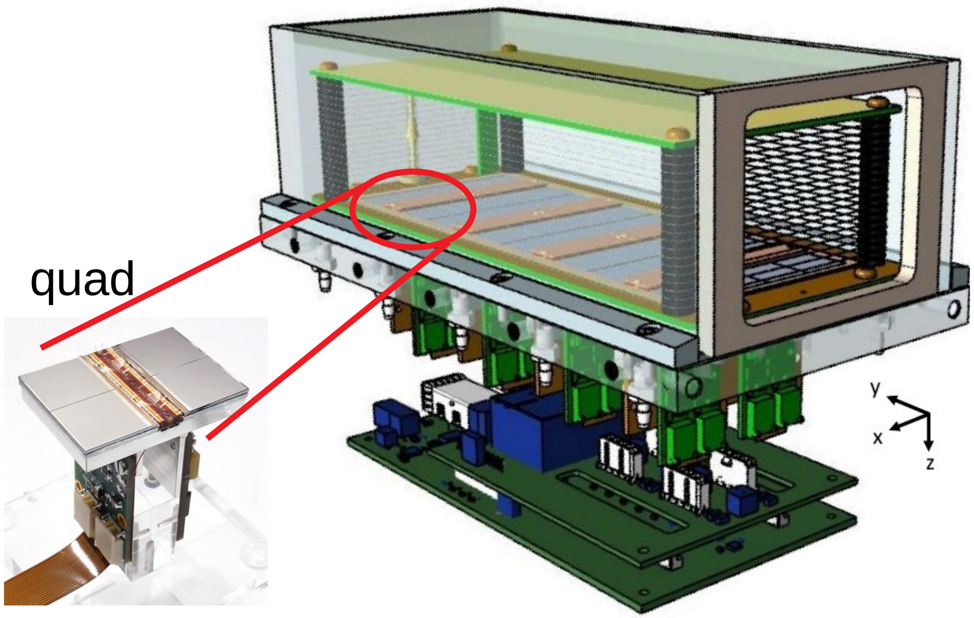
INFN Istituto Nazionale di Fisica Nucleare Sezione di Roma

JINST 18 (2023) P10035



Negative Ion TPC





Detector with 32 GridPixes based on Timepix3

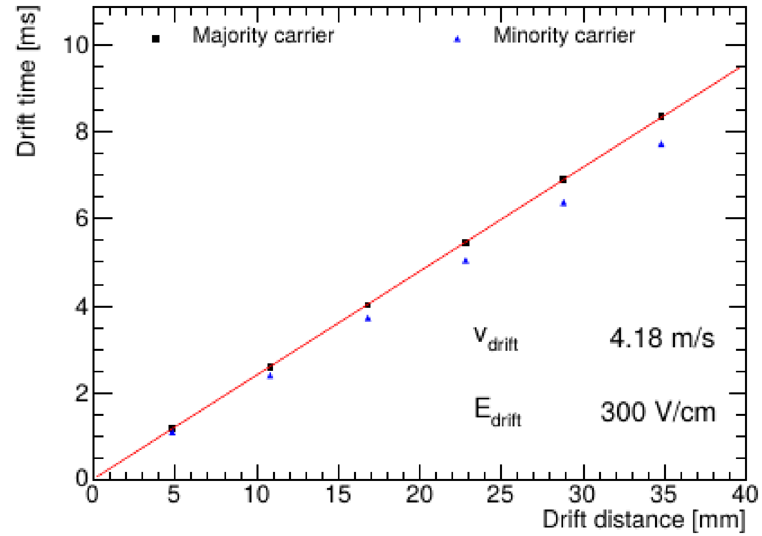
UV laser (337nm) used to generate tracks.

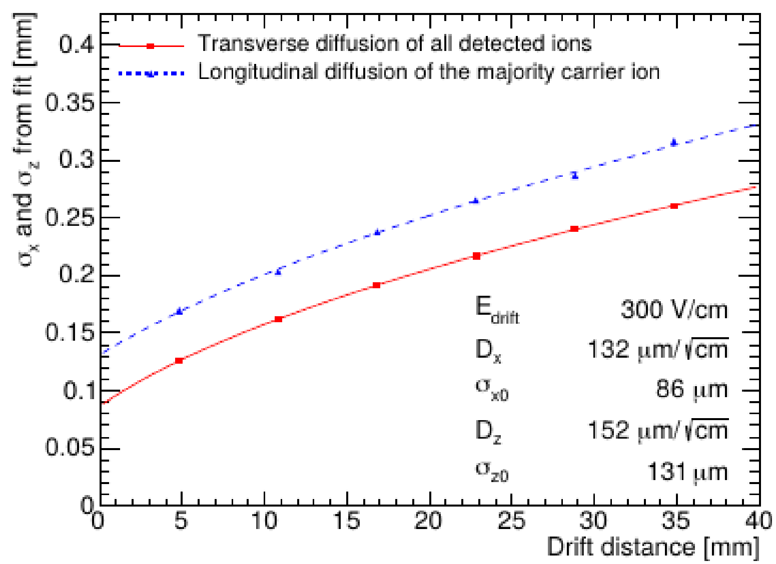
<u>Gas mixtures:</u>

$Ar:iC_4H_{10}:CS_2$ 93.6:5.0:1.4

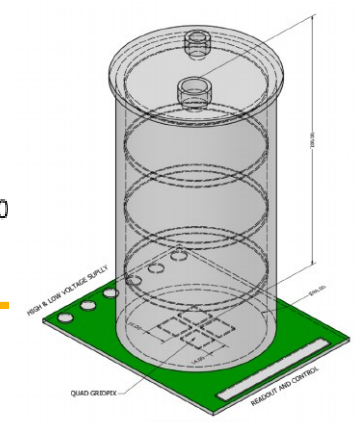
+ O_2 (650-1150 ppm) -minority carrier

+ TMPD (to enhance sensitivity to laser)

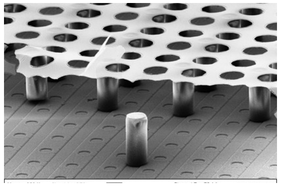




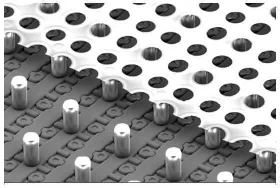
- Gas at atmospheric pressure
- Both majority (CS_2) and minority (O_2) carriers observed
- Transverse diffusion at thermal limit
- Have to optimize gas

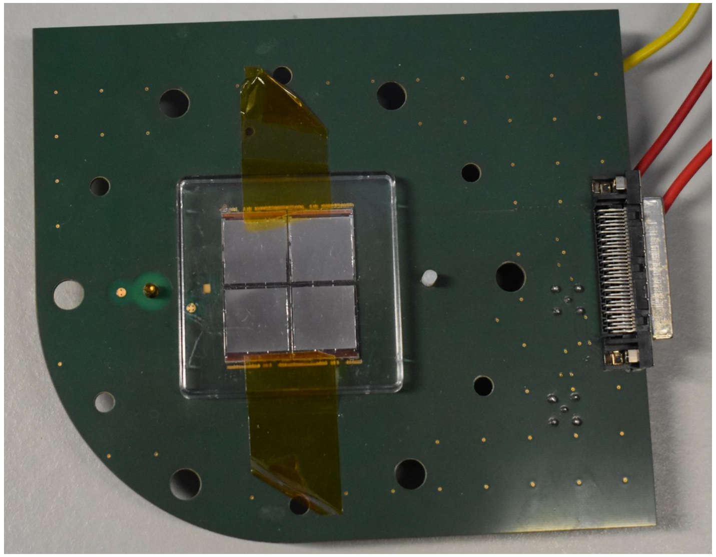


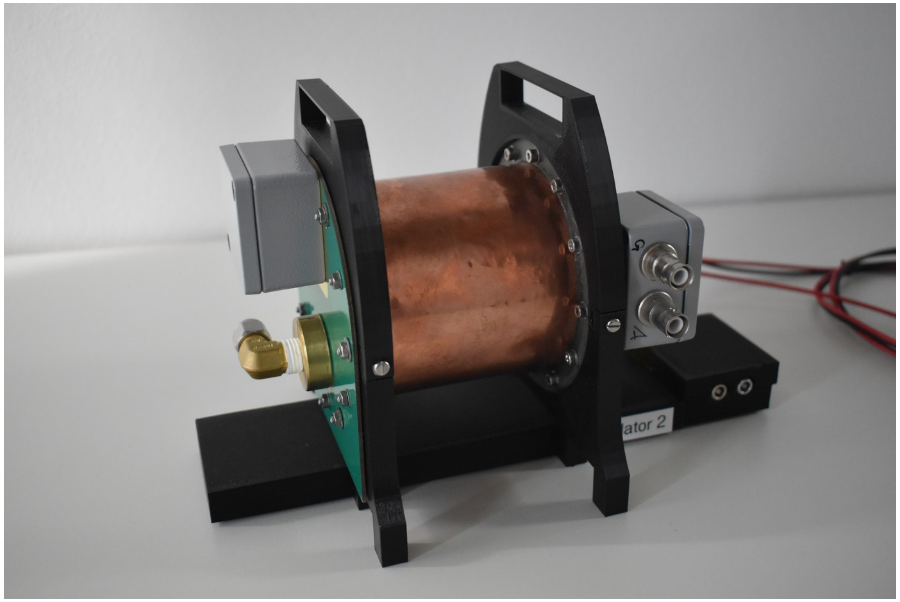
NIM A1014 (2021) 165706



SchulTPC

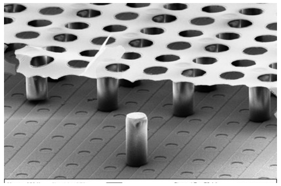




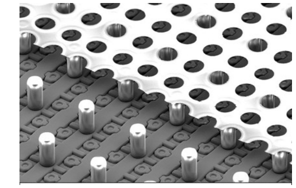


Compact, flexible and mobile detector for educational purposes such as: exhibitions, school projects, workshops at schools

Setup consists of (partially planned)
- TPC: 10 cm length, 8 cm inner diameter
- 4 GridPixes
- Compact readout system (FitPix)
- 2 trigger scintillators
- Possibly small, compact HV supply
- Operated with welding gas (cheap)
- Currently developing an educational concept for schools
- Thinking about a small magnet



GridPix Production in the Future



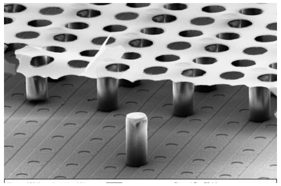
Once the GridPix production is reestablished we have several ideas
- study if larger pads improve the signal size
- revisit hole size/amplification study
  → interesting for higher / lower gas pressures
- reduce resistivity of protective layer
- Study the 'pillar density'   => GEMgrids to absorb UV photons
- double / triple grid structure (see next slide)

(-investigate low power mode of Timepix3 – 1/10 of regular power are claimed)

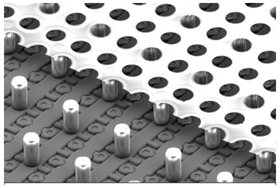
Other ASICs:

With the flexible setup in Bonn, other design of the grid can be easily implemented → Any chips are welcome

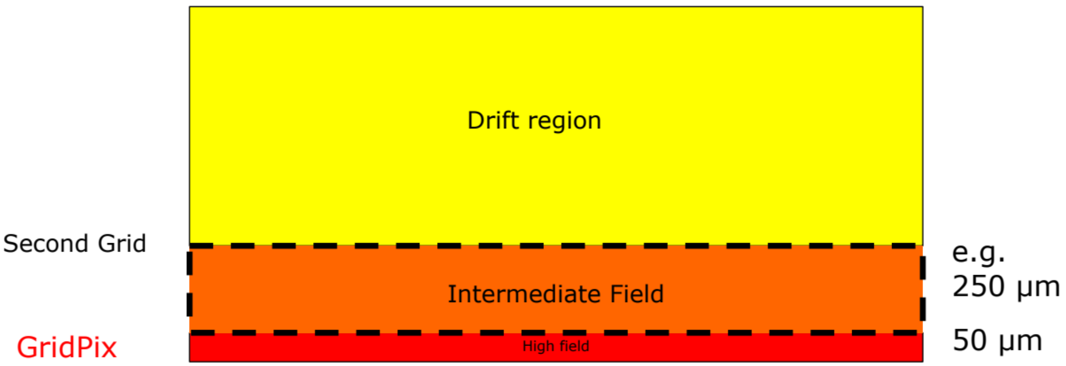
Timepix4:
- larger area (4x Timepix3), 4-sided butteble, slightly better time resolution, slightly lower power consumption
- we can certainly do grids on Timepix4, if someone needs it, but we will not switch as a standard because
  * machines are layer out for 20cm not 30 cm diameter
  * can't afford to implement in readout system
  * large radical size reduces yield too much
  * large R&D program needed to study how to handle thinned GridPixes.



Reducing the IBF in a Pixel TPC



The Ion back flow can be reduced by adding a second grid to the device. It is important that the holes of the grids are aligned. The Ion back flow is a function of the geometry and electric fields. Detailed simulations – validated by data.



Ion backflow	Hole 30 μm	Hole 25 μm	Hole 20 μm
Top grid	2.2%	1.2%	0.7%
GridPix	5.5%	2.8%	1.7%
Total	$12\ 10^{-4}$	$3\ 10^{-4}$	$1\ 10^{-4}$
transparancy	100%	99.4%	91.7%

With a hole size of 25 μm an IBF of $3\ 10^{-4}$ can be achieved and the value for IBF*Gain (2000) would be 0.6.

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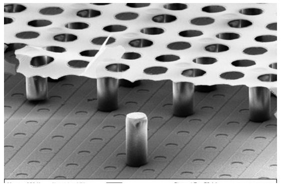
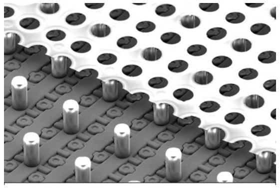


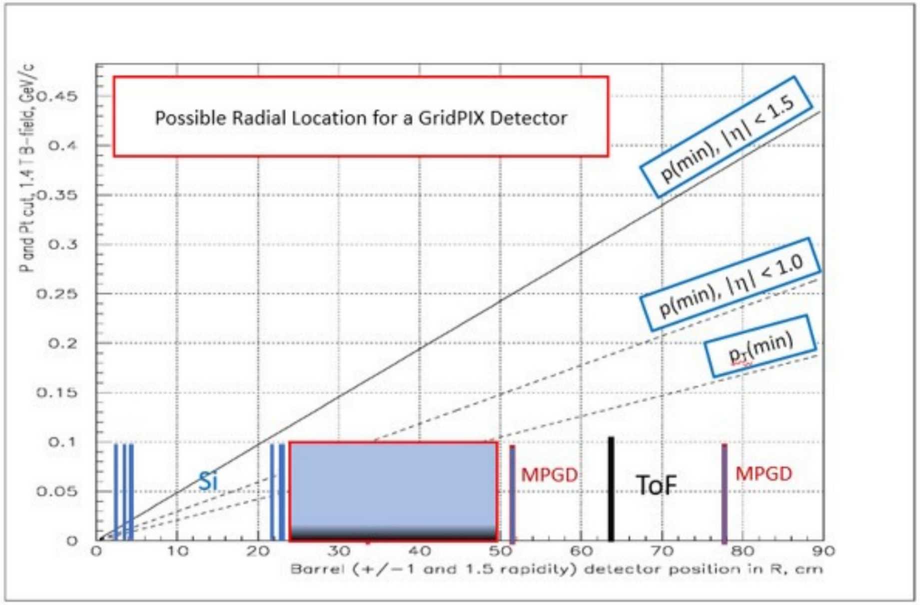
EIC – exploiting PID



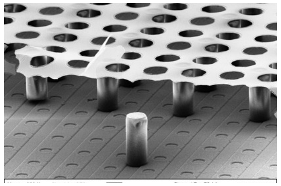
Originally proposed for ATHENA – no a possibility for 2nd detector

Small TPC mostly for PID:

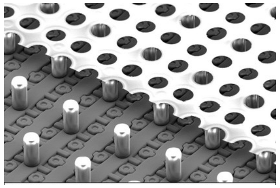
Minimal Low momentum
Radii:
Inside of Silicon layer 5
Outside of Silicon layer 4
Zed:
Look at Zed of 1st large disk
Go inside of this.
No side effect



Funding by GENERIC EIC-RELATED DETECTOR R&D PROGRAM started.



Summary and Outlook

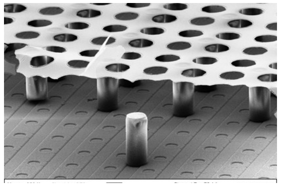


GridPixes are seeing a transition from Timepix to Timepix3.

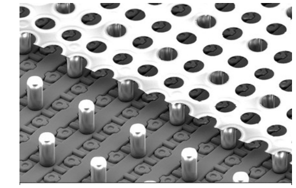
The grid production can soon be done in Bonn, which will open possibilities for new ideas and R&D.

More projects are becoming interested in testing the devices and evaluate them for their applications.

There is quite a large interest in the possible PID performance of GridPixes in particular if cluster counting can be exploited.



Acknowledgment



This is of course the work of many people.

In Bonn these are:
Yevgen Bilevych, S. Hartung (who build the InGrids)
C. Krieger, S. Schmidt, T. Schiffer, J. von Oy (CAST/IAXO),
M. Lupberger, D. Danilov, A. Hamann (LCTPC).
M. Gruber, V. Plesanovs (Polarimetry)
M. Köhli, D. Pal, T. Block (Neutron TPC)
and of course Klaus Desch.

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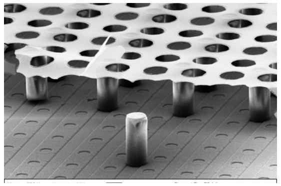
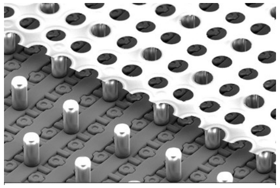
well as the electronics and mechanical workshops.

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

and even more on smaller projects.

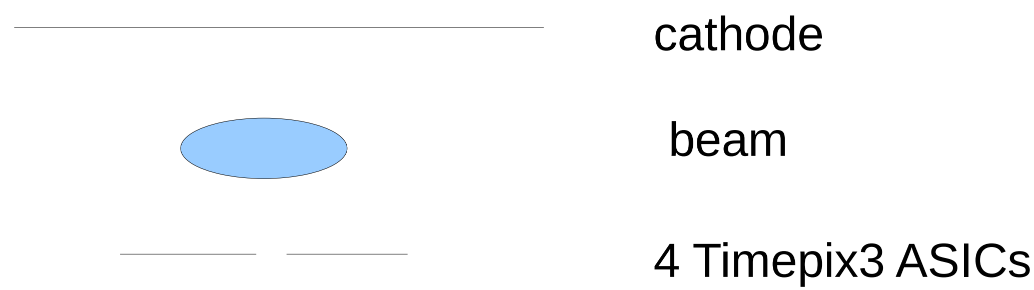


Beam Instrumentation



Developed at CERN: non-destructive beam position monitor

Use rest gas in accelerator as a gaseous detector and make an ionization chamber With Timepix3 readout



Operated in low vaccuum (SPS)

We are working on a similar project: MCP-based neutron detector:
Also 4 Timepix3 ASICs operated in vacuum (10^{-6} mbar)