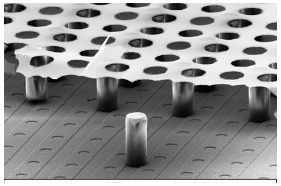

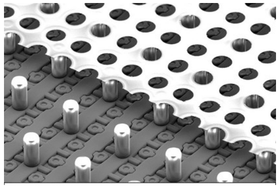

GridPixes and their Application

Jochen Kaminski

University of Bonn

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

RD51 Collabration Meeting
CERN
6.12.2023

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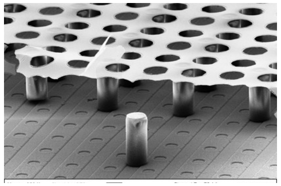
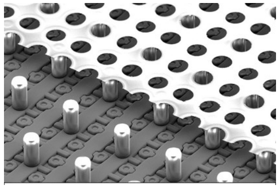
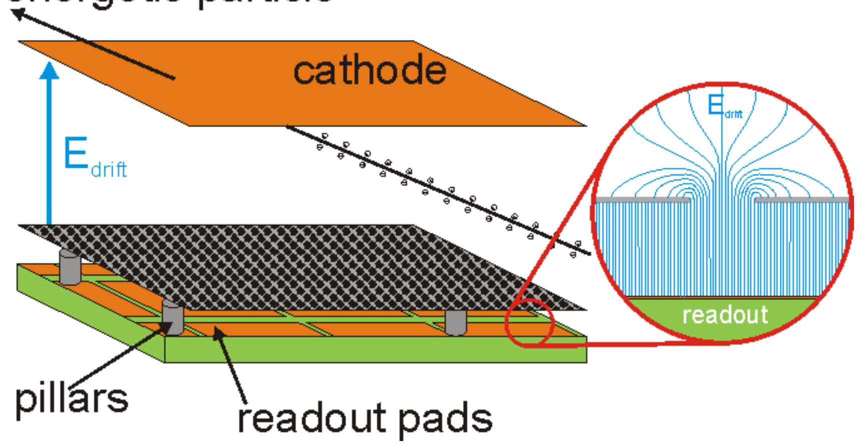


From Micromegas to GridPix





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

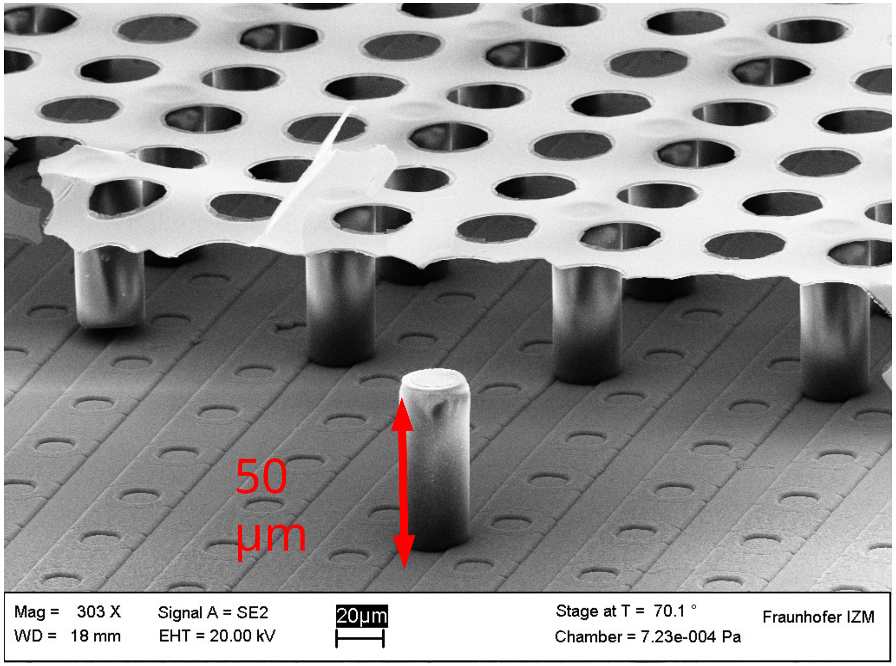
$Ar:CF_4:iC_4H_{10}$ 95:3:2 → σ = 11 µm

Smaller pads/pixels could result in better resolution!

At NIKHEF the GridPix was invented.

Standard charge collection:
Pads / long strips

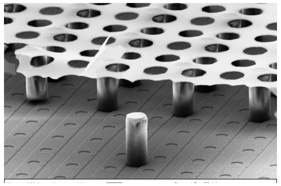
Instead: Bump bond pads are used as charge collection pads.



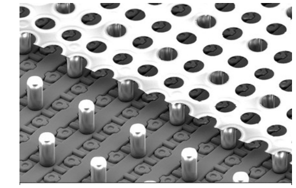
Charge avalanche is collected by one pixel

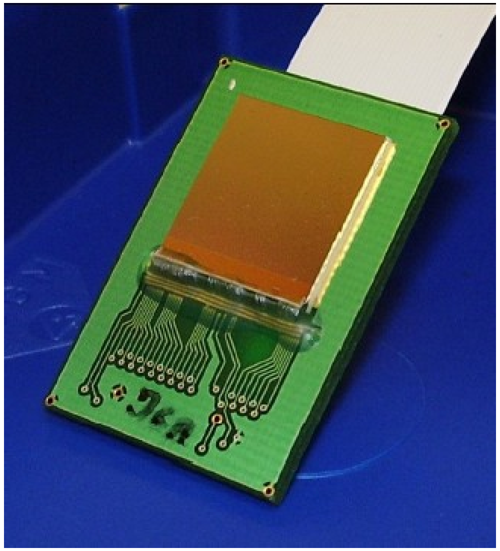
→ one hit corresponds to one primary electron

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



The ASICs - Timepix(3)





Timepix: Available for tests since Nov. 2006

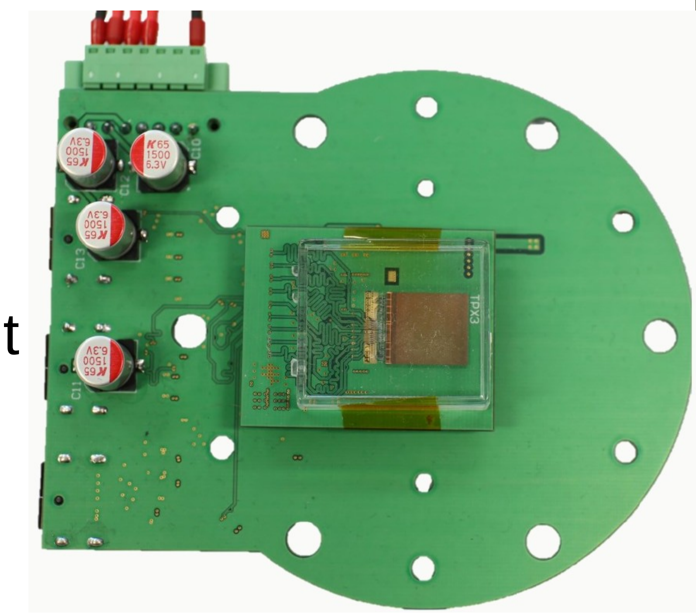
Number of pixels: 256 × 256 pixels
Pixel pitch: 55 × 55 µm²
Chip dimensions: 1.4 × 1.4 cm²
ENC: ~ 90 e⁻

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

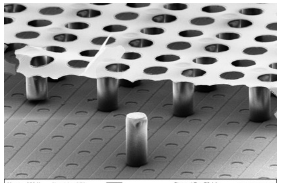
Timepix3: Available for tests since 2012

Number of pixels: 256 × 256 pixels
Pixel pitch: 55 × 55 µm²
ENC: ~ 70 e⁻

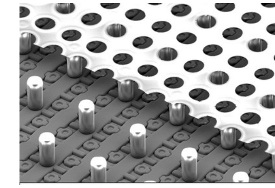
- Charge (ToT) and time (ToA) available for each hit
- Timing resolution: 1.56 ns for duration of ~410 µs
- Zero suppression on chip (sparse readout)
- Multi-hit capable
- Output rate up to 5.12 Gbps



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



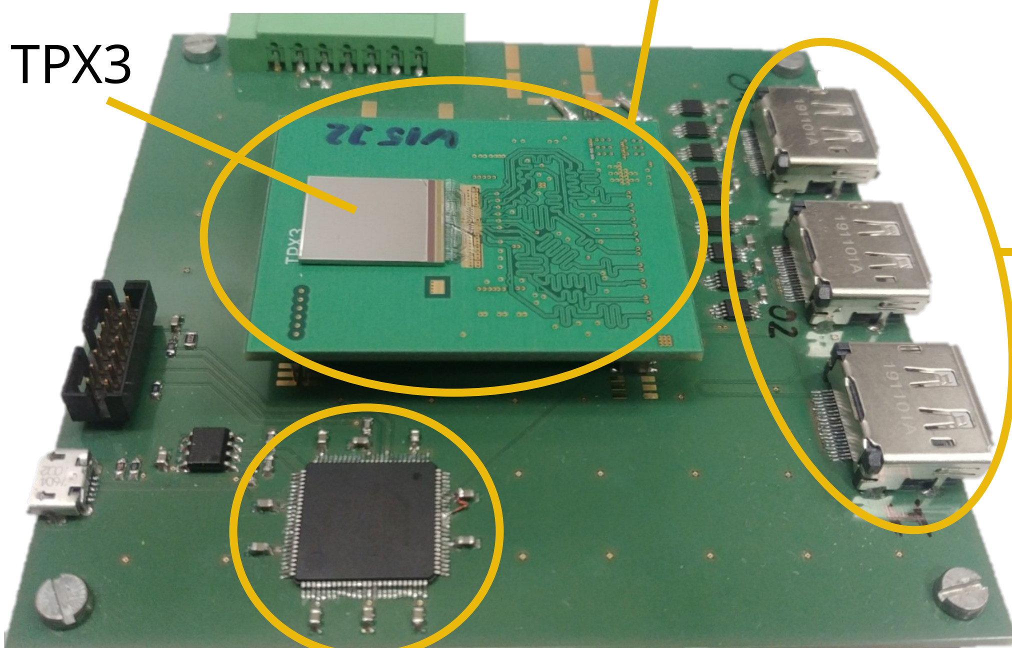
Timepix3 Readout in SRS

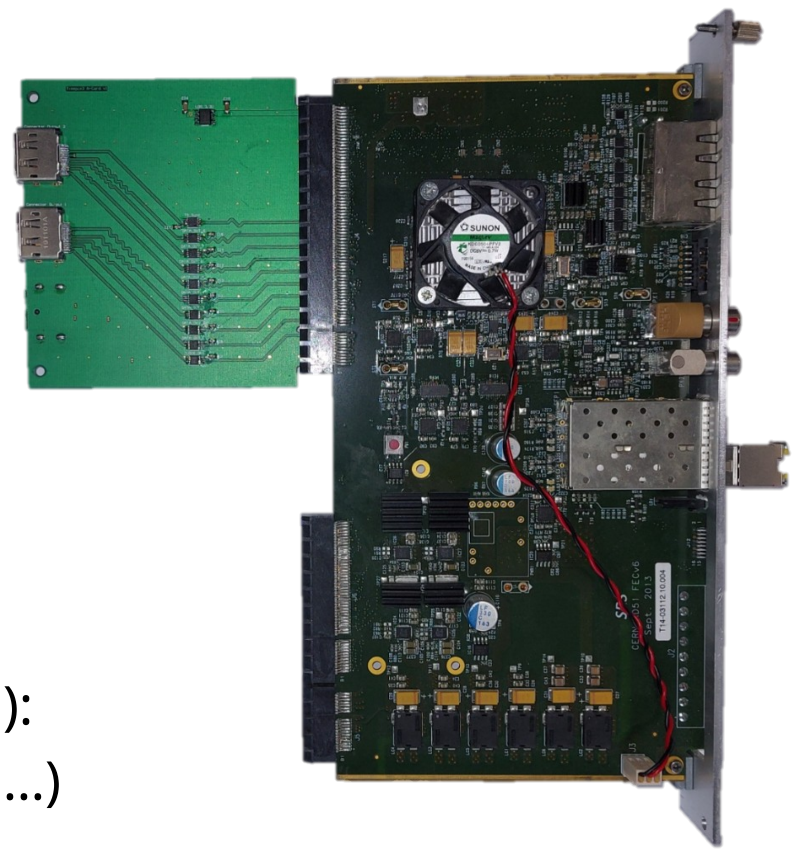


Carrier board (plugged into Intermediate board)

Shape and number of chips depending on the detector

TPX3



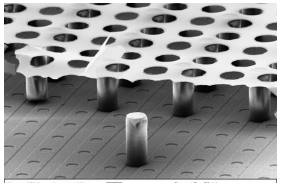


Microcontroller (read out via separate USB):

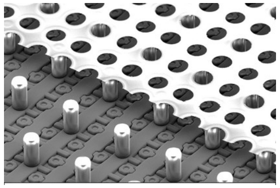
- Monitoring (Temperature, Voltages, …)
- Analog TPX3 DAC readout
- External TPX3 DACs

FEC and A-card

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



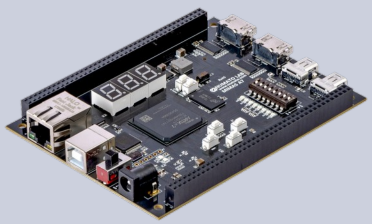
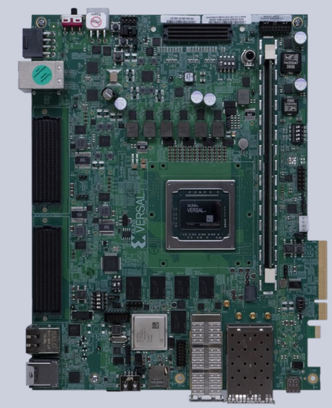
Timepix3 Readout in SRS

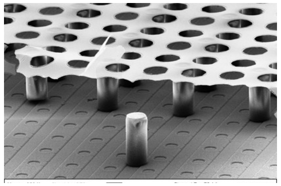


Software and firmware open source

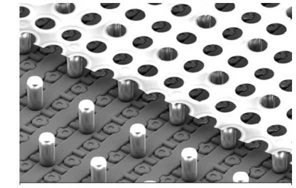
Several user interfaces (CLI, GUI, scripting)

So far used with one ASIC at max. 2.5 Mhits/s - Working on multichip and rate upgrades

	MIMAS A7	ML605	SRSv6	VCK190
Picture				
Status	Implemented	Implemented	Implemented	Ongoing
FPGA	Artix-7	Virtex-6	Virtex-6	Versal Prime (AI)
Capability	2 links @ 320 Mbps	8 links @ 320 Mbps	8 links @ 320 Mbps	> 8 links @ 640 Mbps



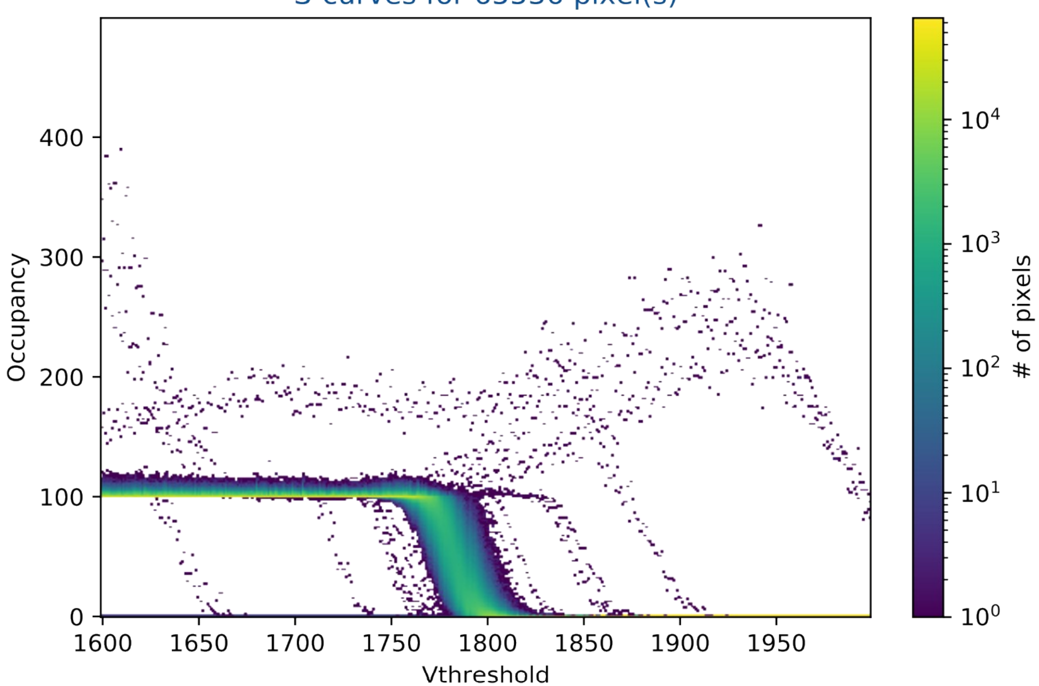
Timepix3 Readout in SRS



Injection of 100 pulses
Readout in HitCounter mode

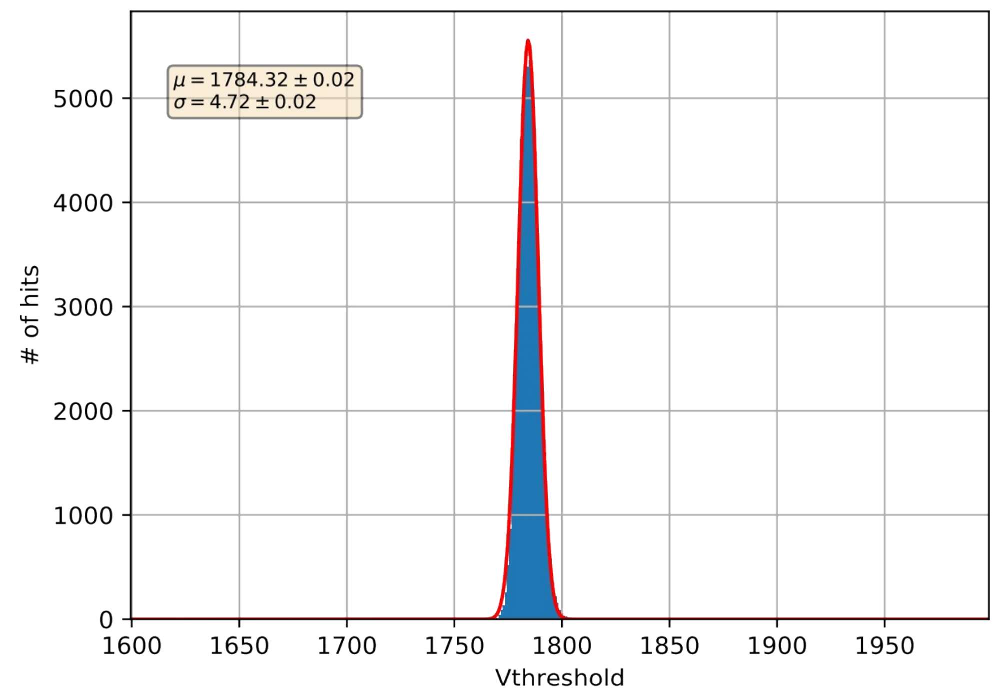
S-curve fit for each pixel

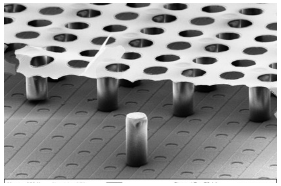
Gaussian distribution of threshold per pixel



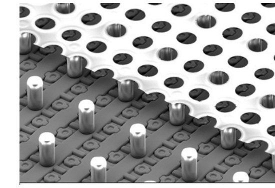
All pulses above threshold

All pulses below threshold

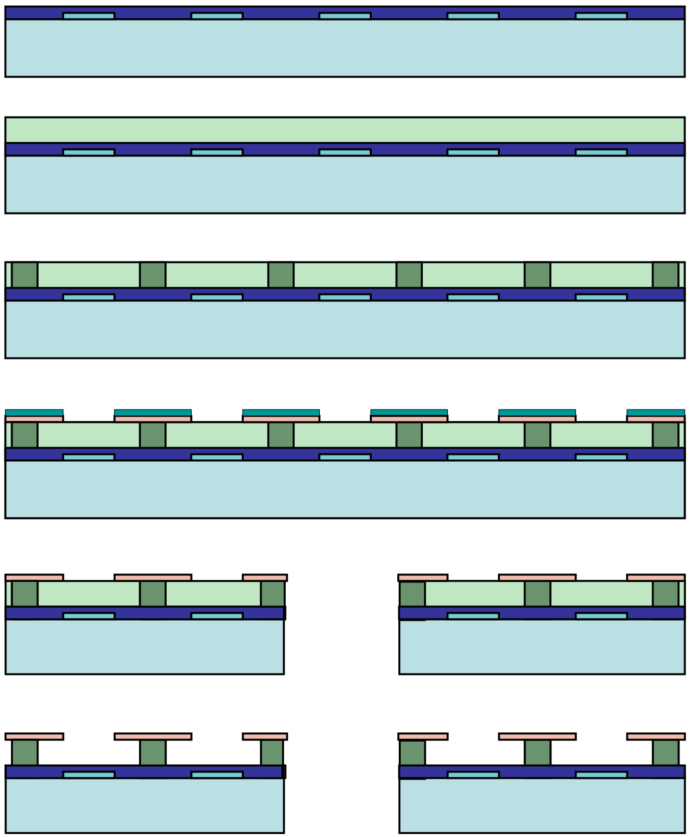




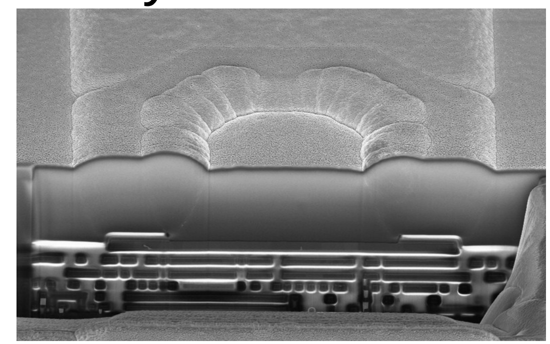
GridPix - Production

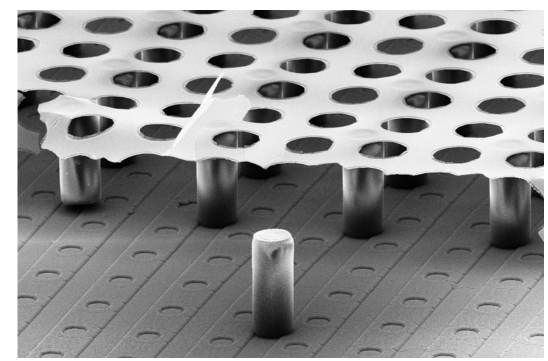


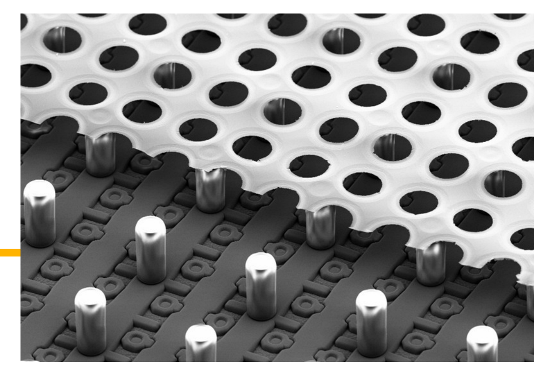
A wafer-based production was set up at the Fraunhofer Institut IZM at Berlin. One wafer (107 chips) is processed at a time.



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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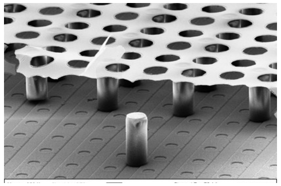
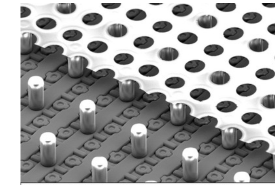
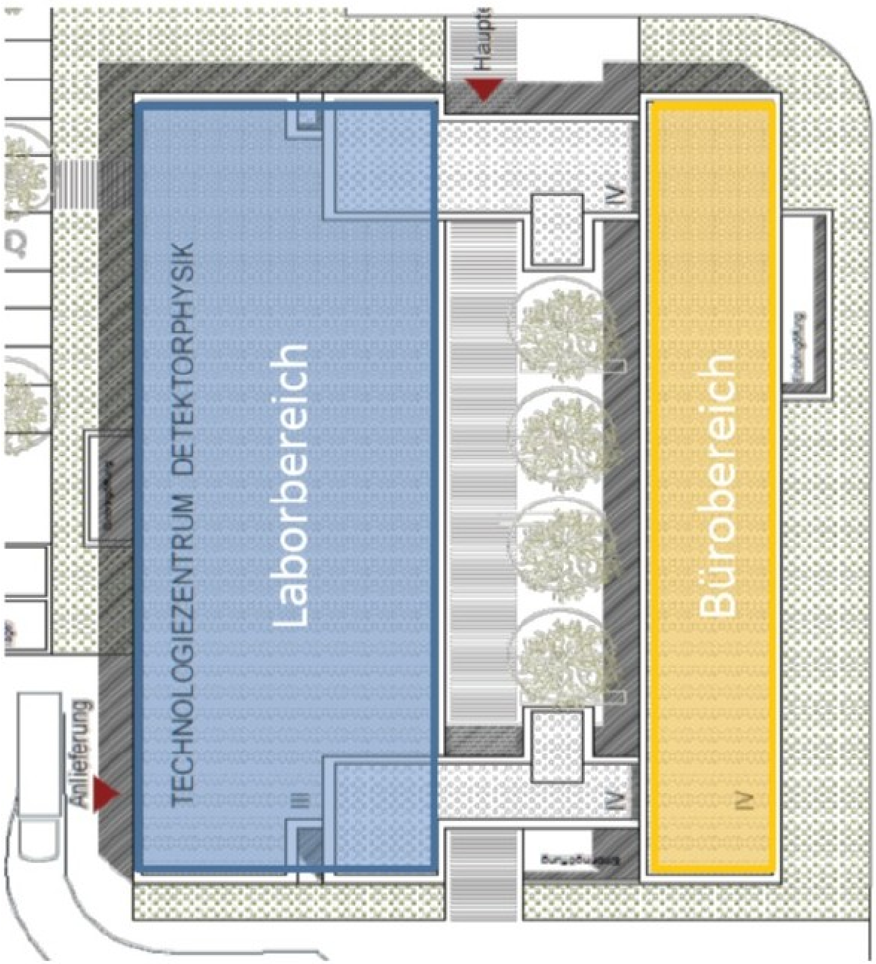
Fraunhofer IZM

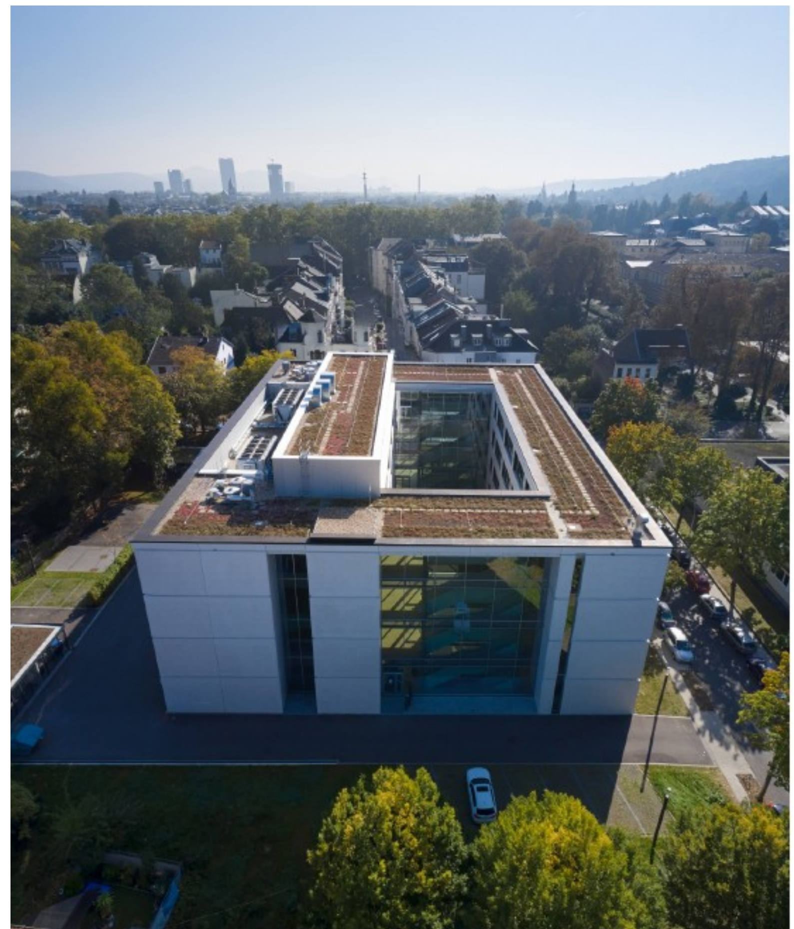




Forschungs- und Technologiezentrum Detektorphysik

First stone laying ceremony 2.11.2016
Inauguration ceremony 8.11.2021





Office space:
- 880 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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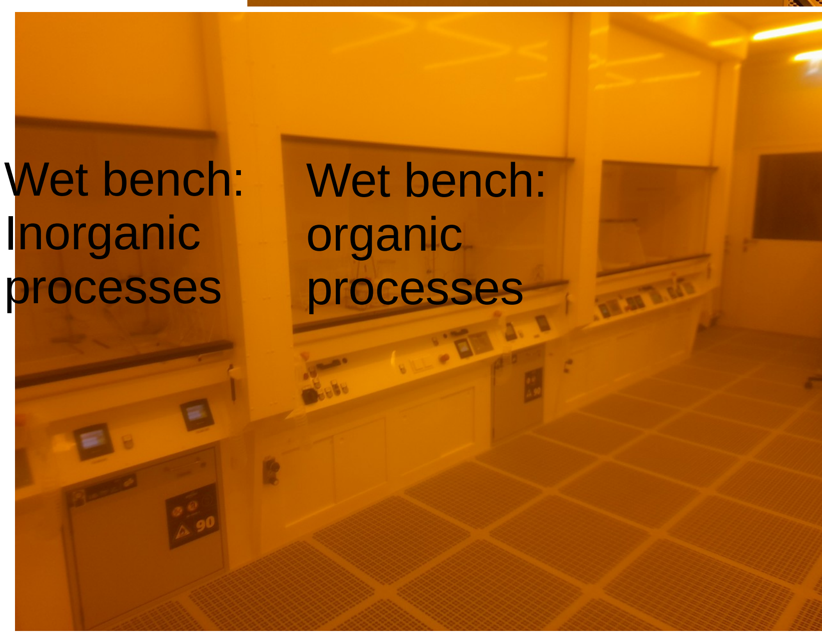
Cleanroom

ISO 7

Maskless
Aligner

ISO 6

ISO 5



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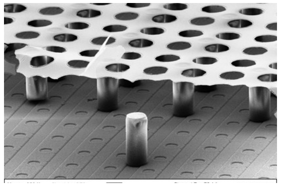
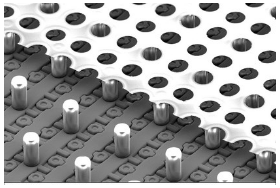
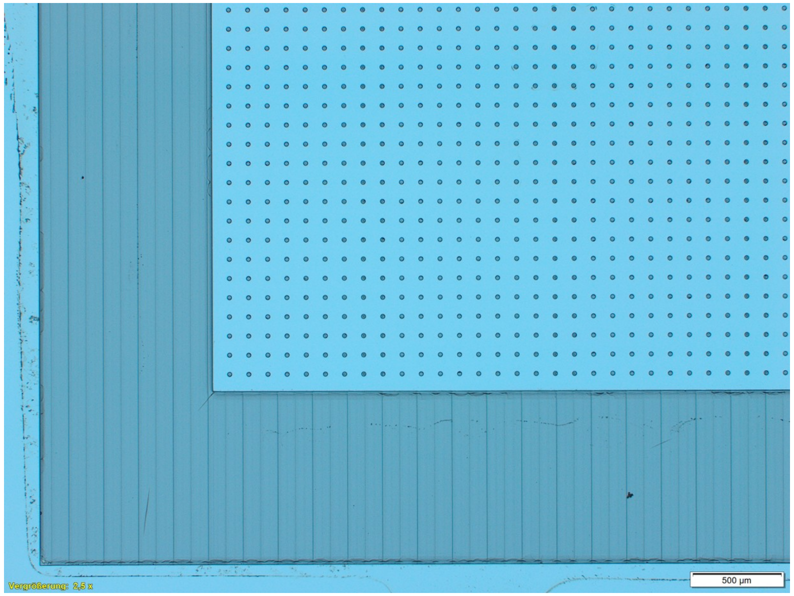
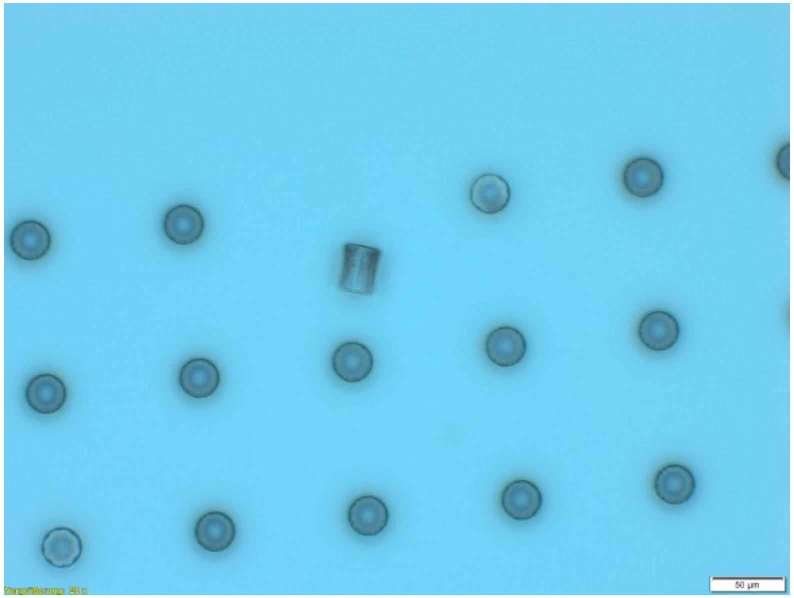




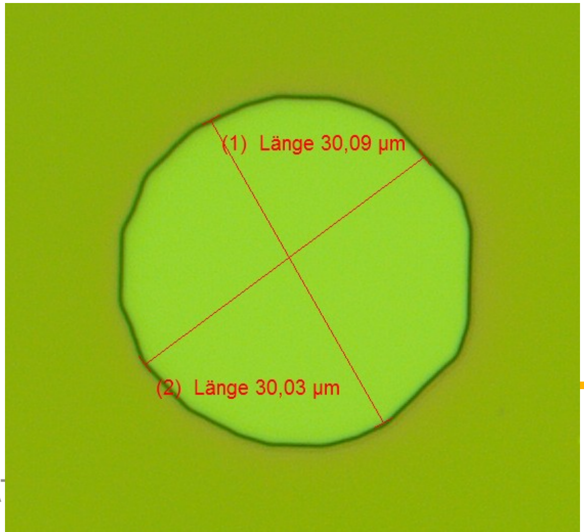
First Steps Towards “GridPixes made in Bonn”

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

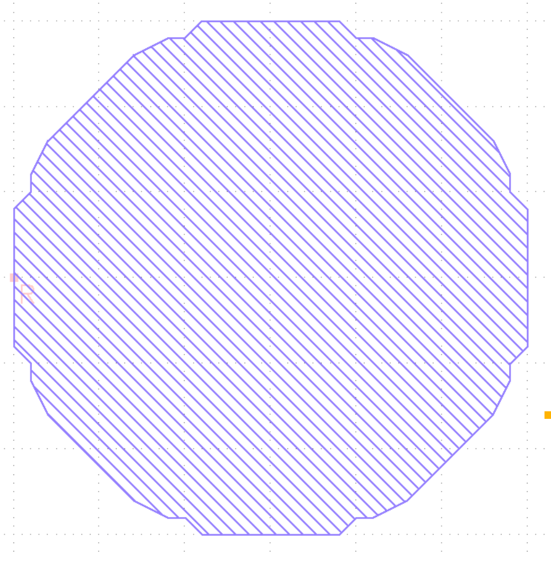


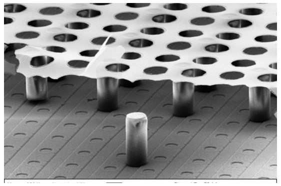


Holes in SU8 layer

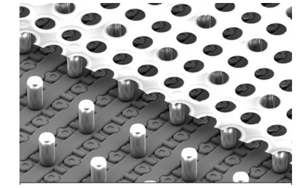


Shape caused by software to create the mask

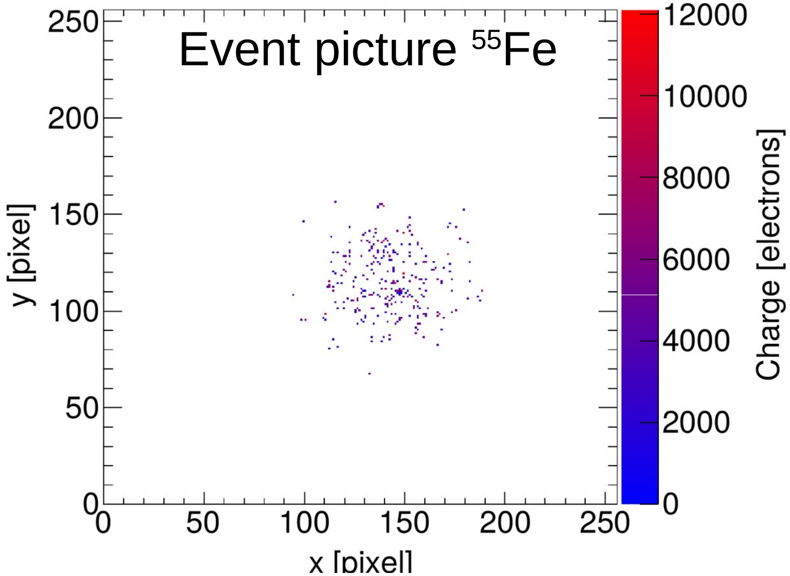


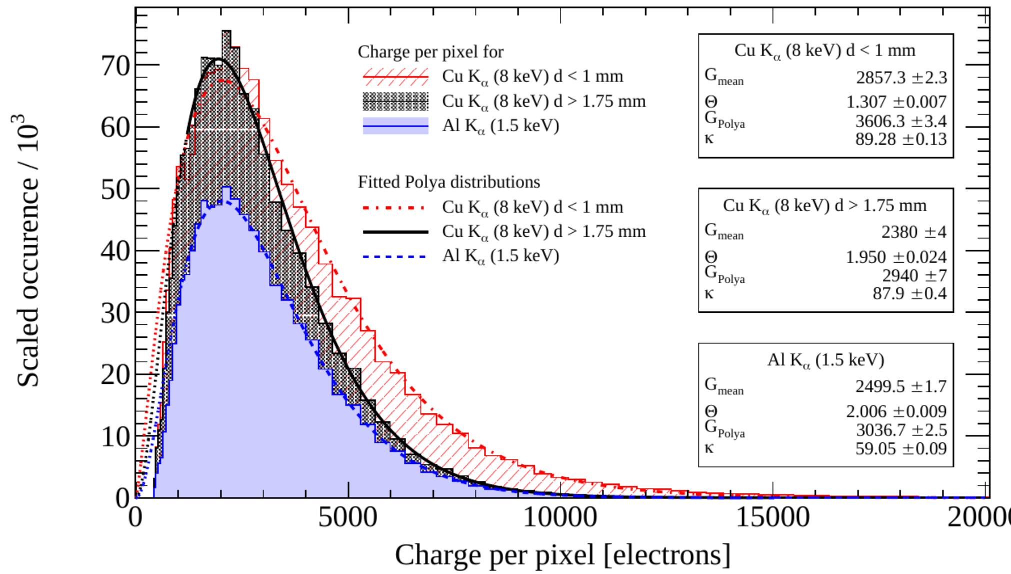


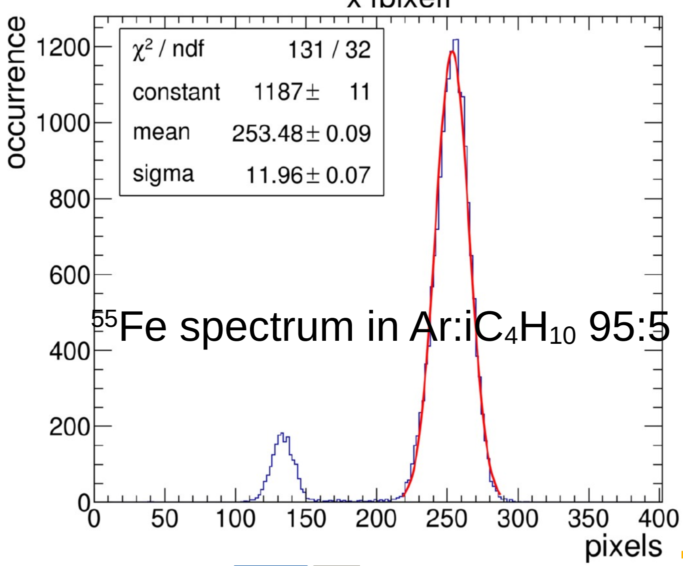
GridPix – Single Primary Electrons



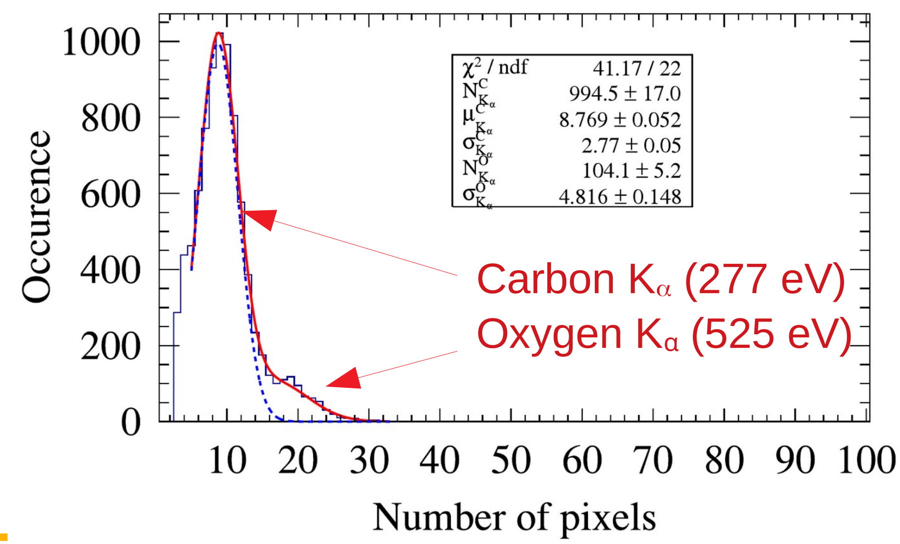
Single primary electrons can be counted leading to excellent energy resolution.







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



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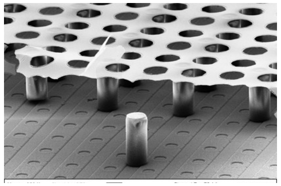
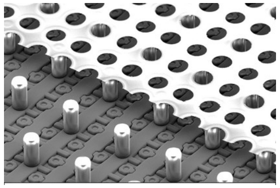
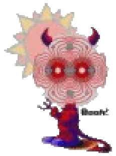
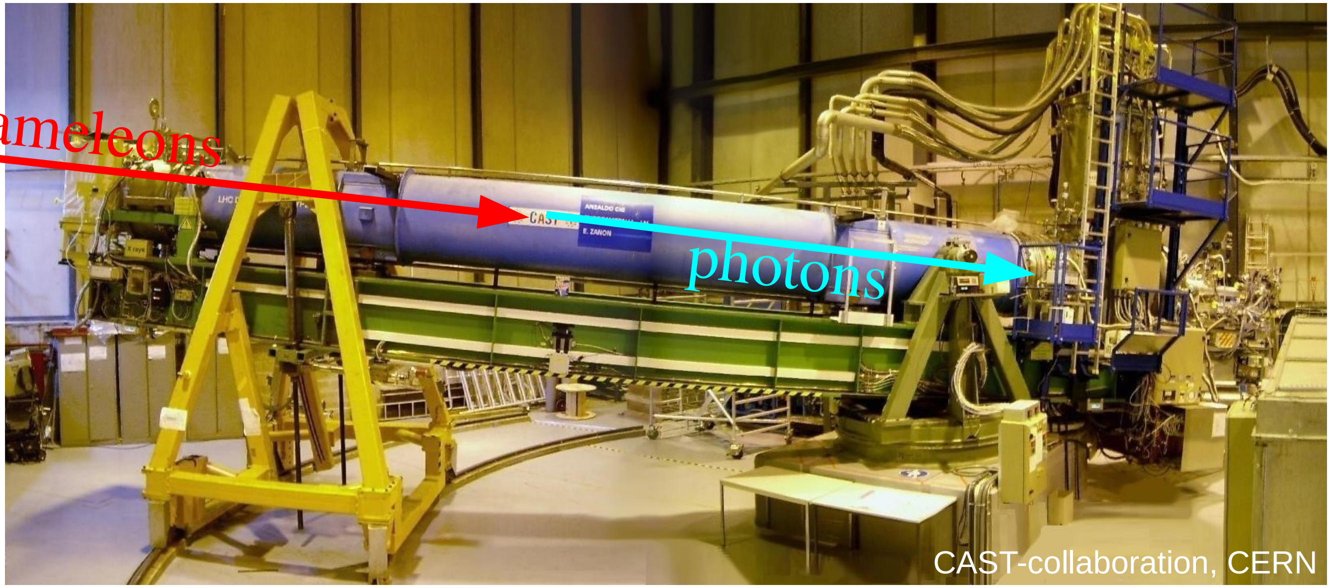
NIMA 893 (2018) 26-34



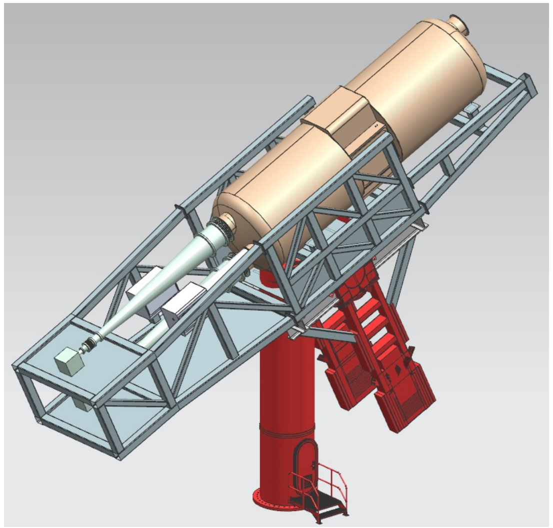
CAST/IAXO –
Search for Solar Axions



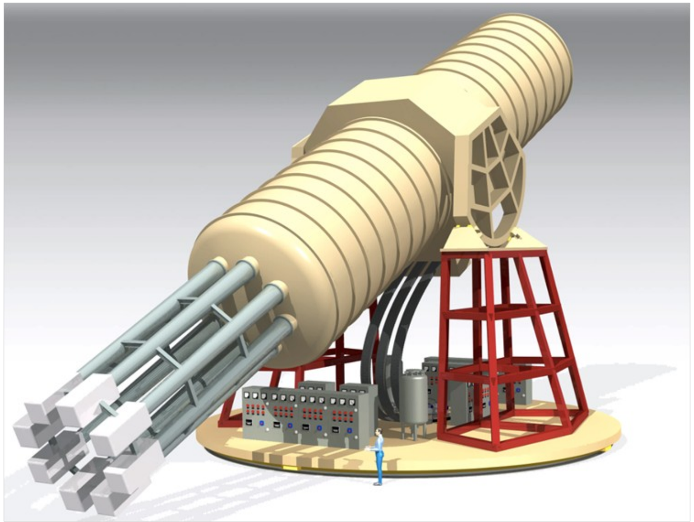




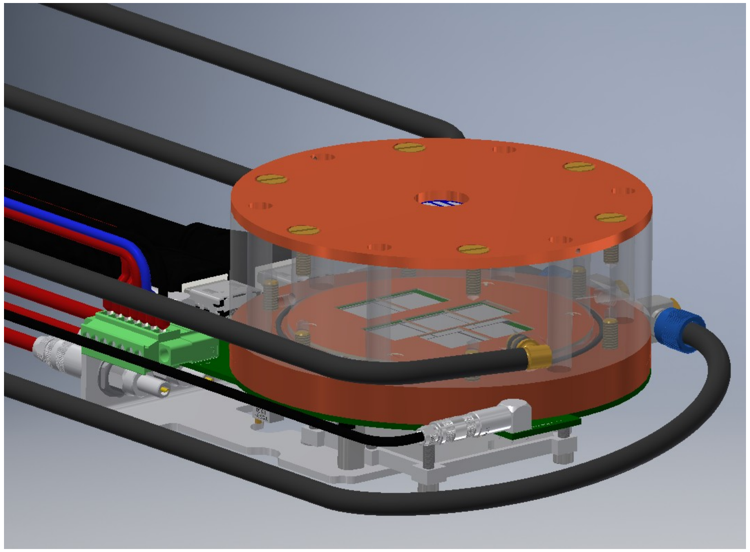
CAST: Decommissioned LHC-magnet is pointed to the Sun. Axions and Chameleons produced in the Sun convert into X-ray photons.



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



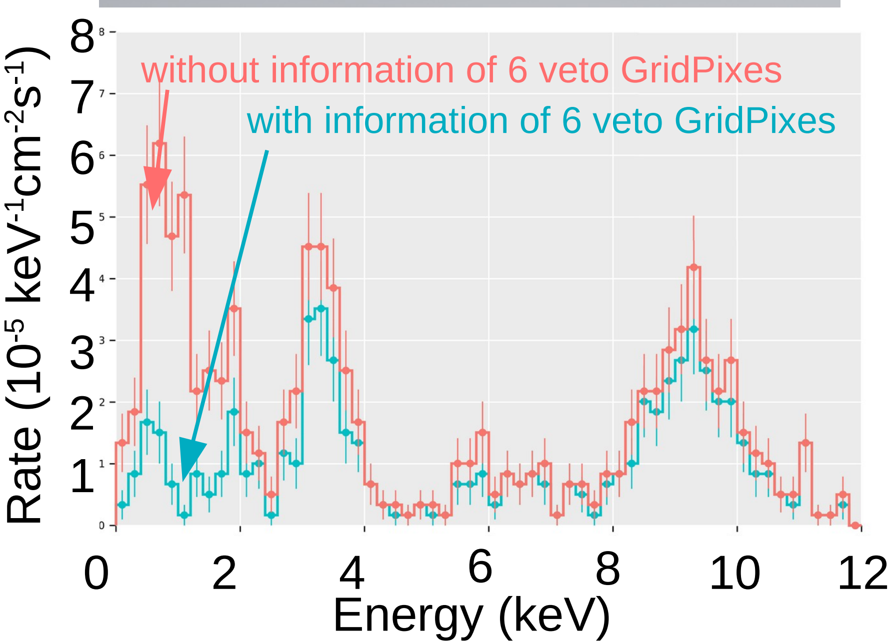
CAST

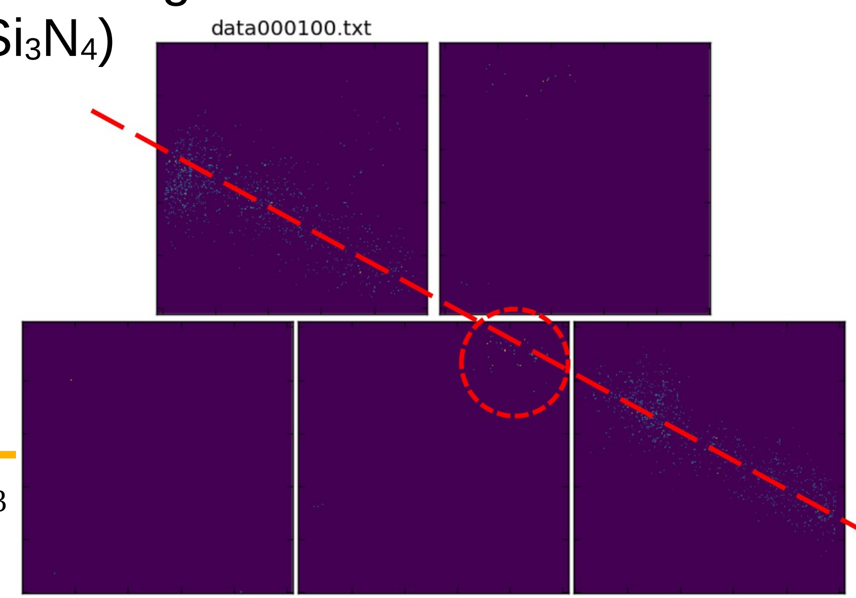


1. data run 2014/15 → Data published
2. data run 2017/18 → Analysis is finalized

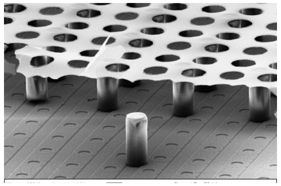
Data Run 2 had several improvements in the detector:

- 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)

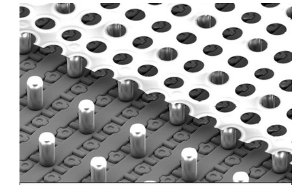


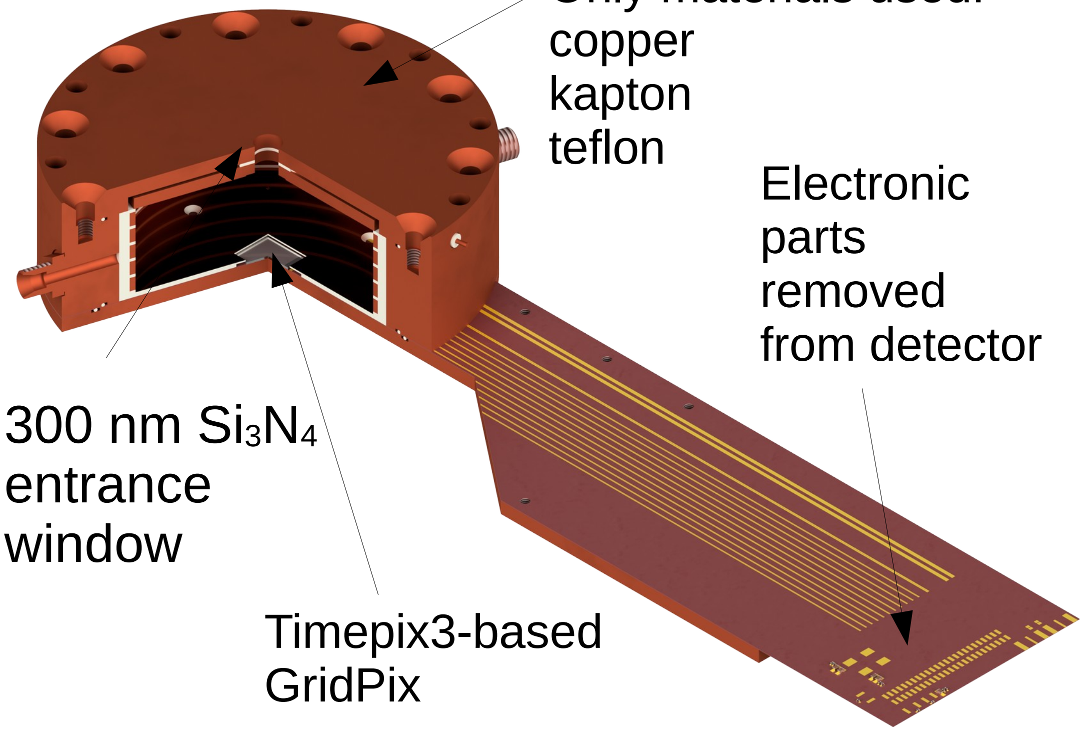


NIM A867 (2017) 101-107
JCAP 01 (2019) 032



BabyIAXO Prototype Detector

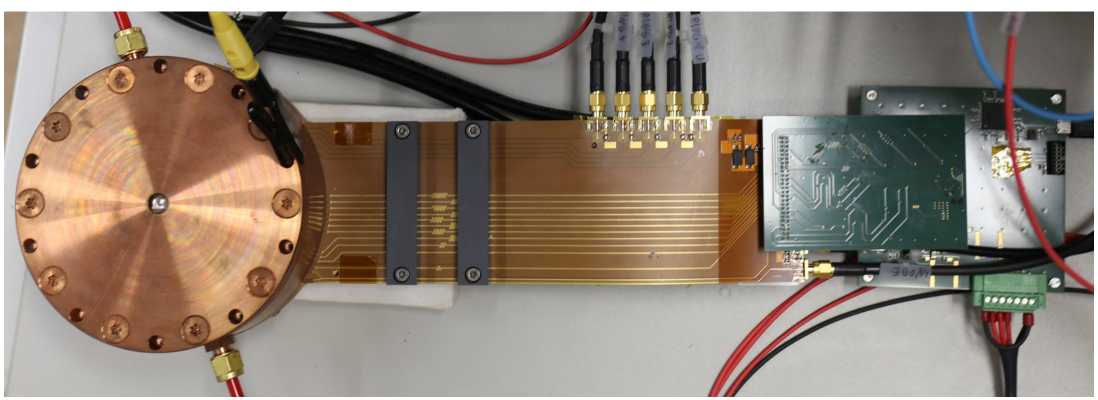


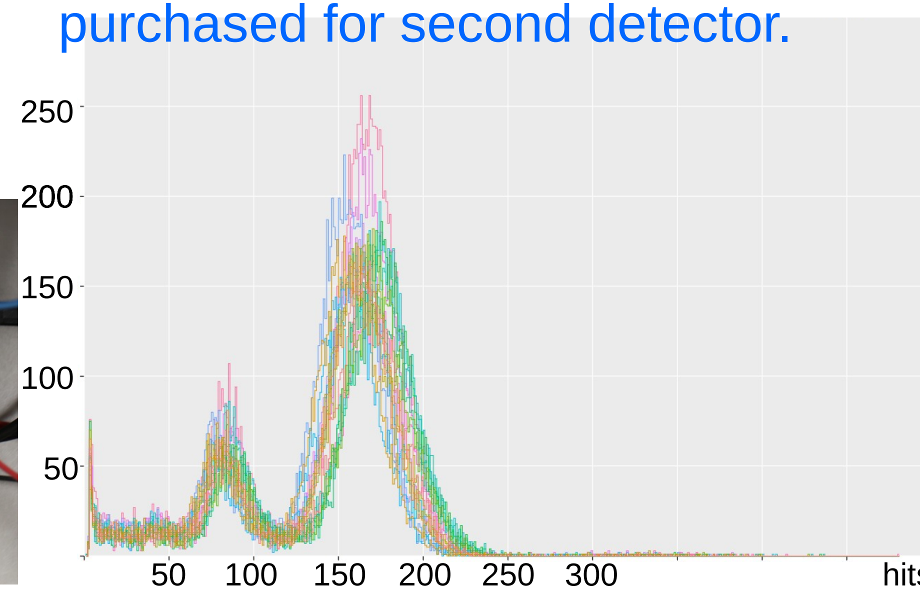


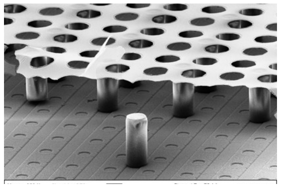
Further improvements of the CAST detector:

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

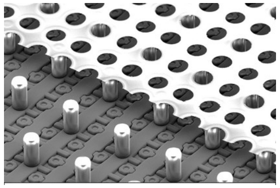
First prototype without radiopure copper/cleaning works well.
Currently, radiopure materials are purchased for second detector.



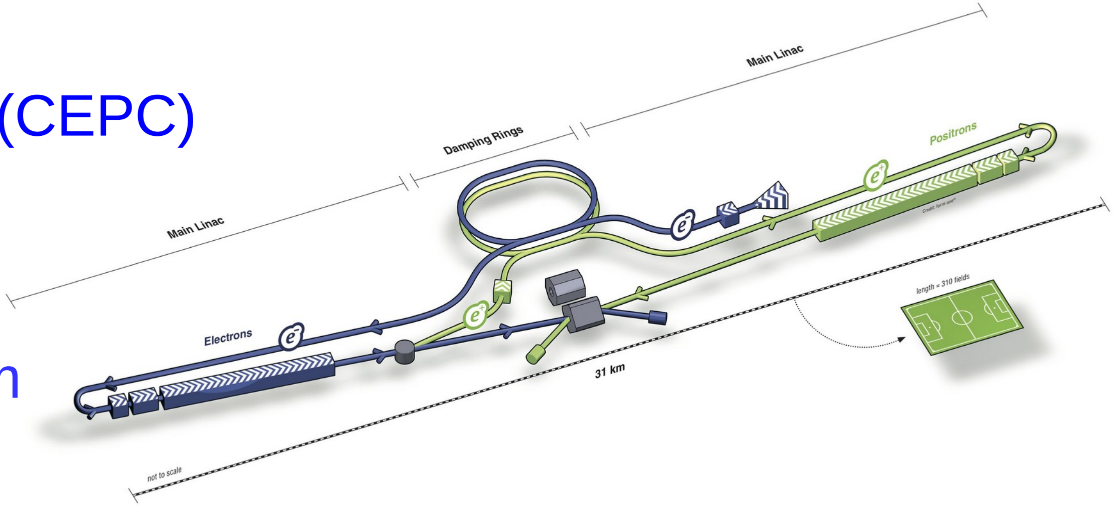




Tracker for Future Higgs Factories



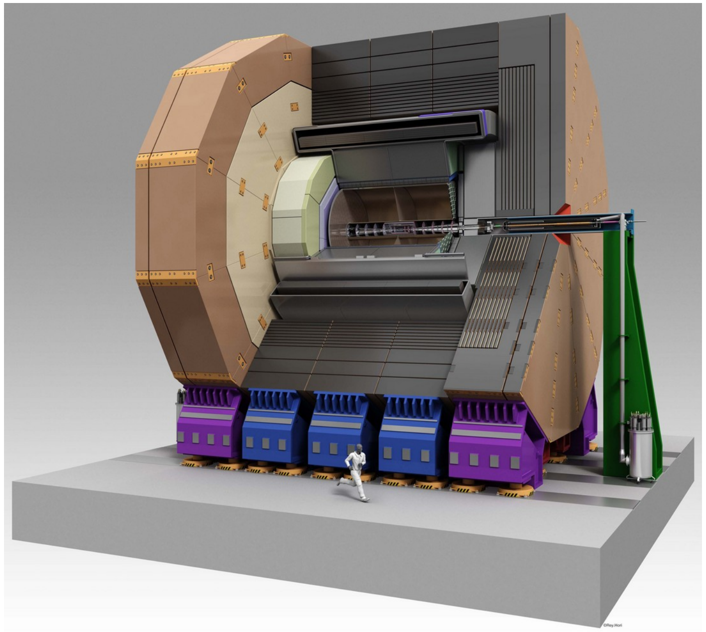
International Linear Collider (ILC) /
Chinese Electron Position Collider (CEPC)
Future Circular Collider (FCCee)
are e^+e^- colliders with:
$\sqrt{s}$ = 90 GeV – 1 TeV / 90-240 GeV
Overall length of 21-50 km / 100 km



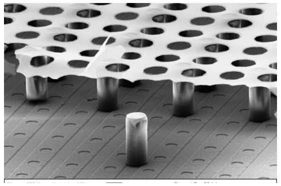
Requirements of TPC from
ILC TDR vol. 4

Parameter	
Geometrical parameters	r_{in} 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 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)

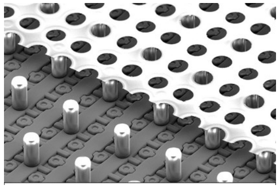
In addition: very high efficiency for particle of more than 1 GeV.



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

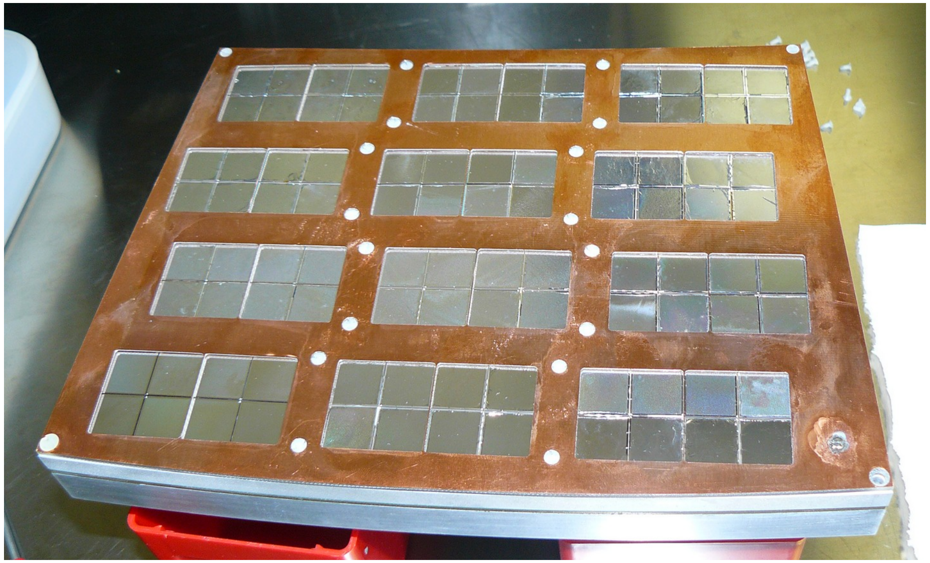


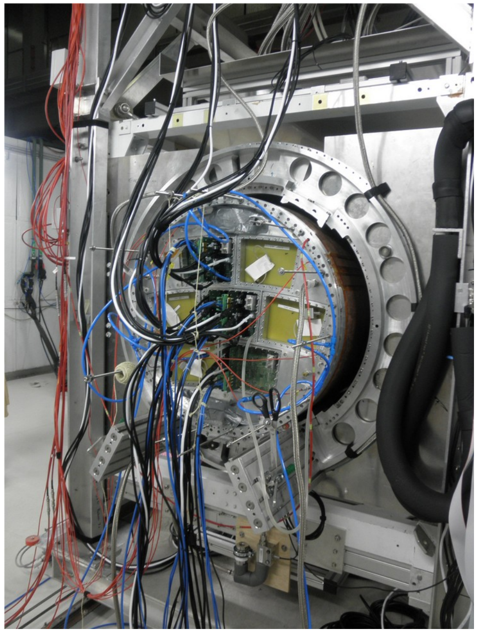
PixelTPC for tracking at Colliders

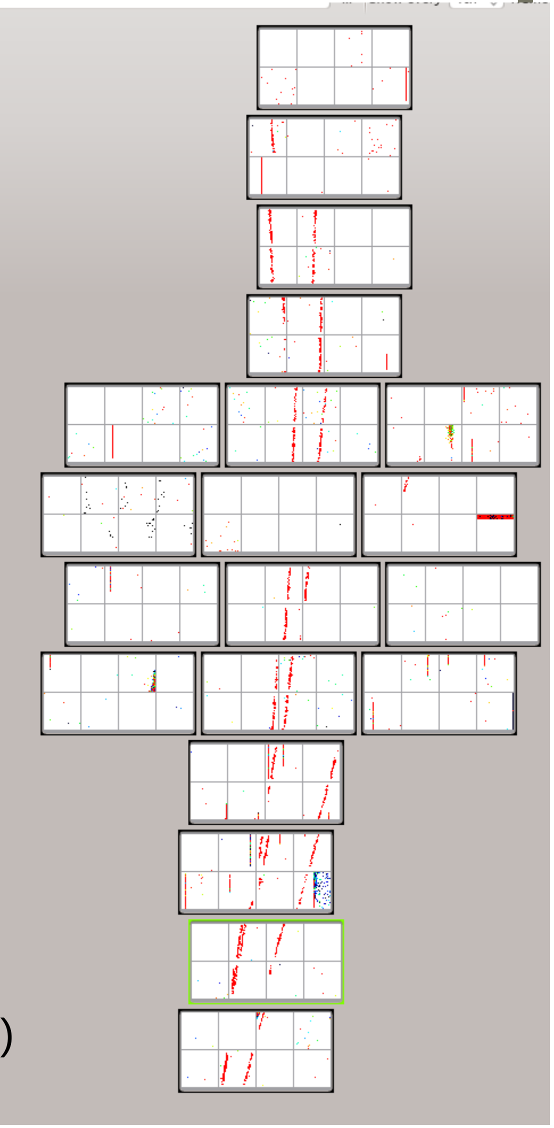


A pixelTPC has some advantages compared to a conventional pad TPC
- Lower occupancy → easier track reconstruction at higher backgrounds
- Improved dE/dx: <4% seems possible with electron or even cluster counting
- Removal of δ-rays and kink removal
- No angular pad effect

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.







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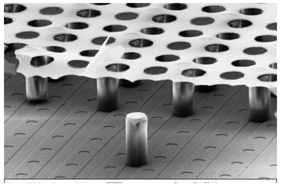
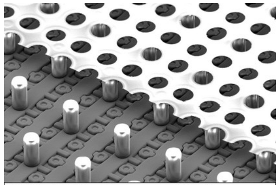
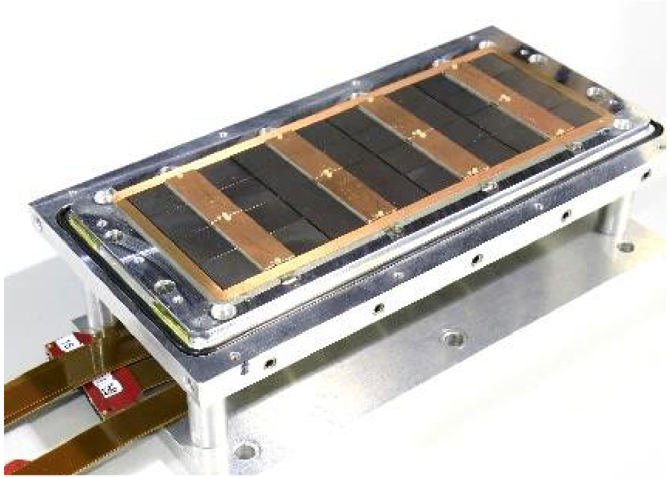
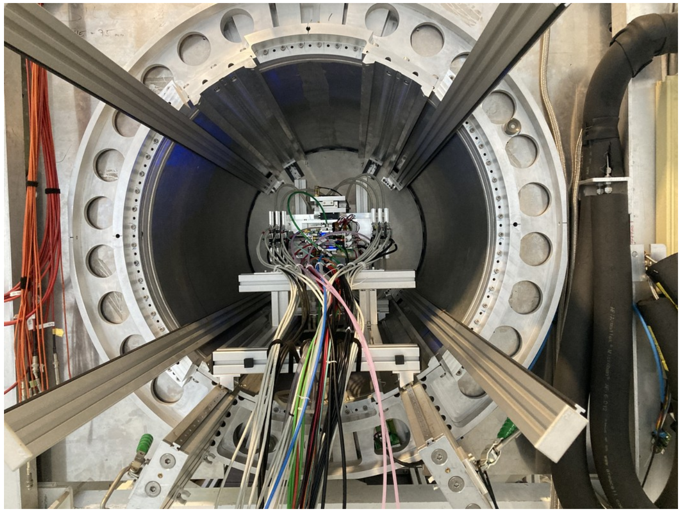
Tracking with Timepix3



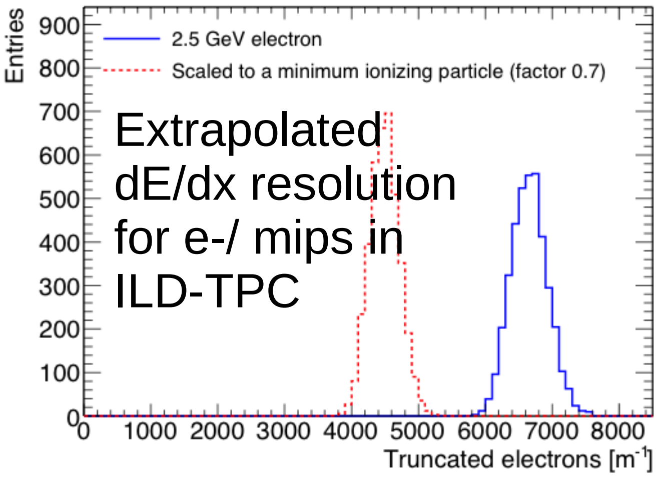


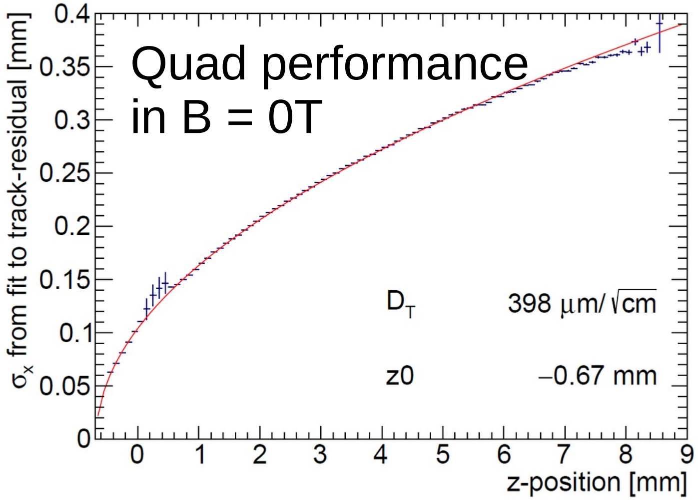
New effort to build larger modules with Timepix3 based GridPixes:
First single chip (2017), then quads (2018), finally 8 quads (June 2021).

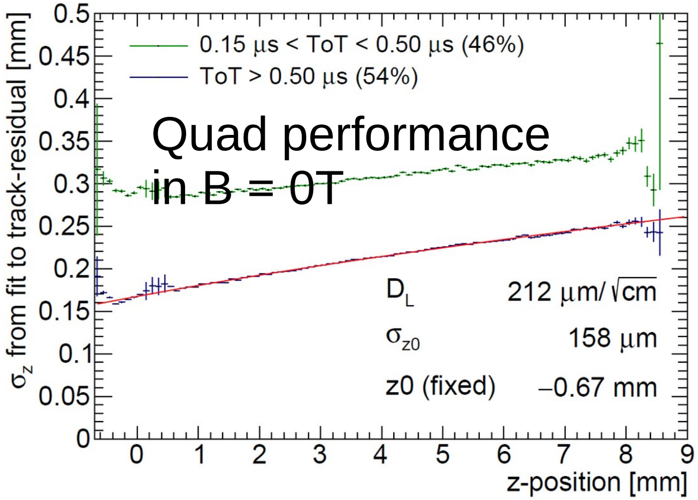




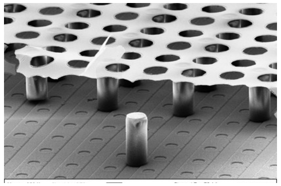
Quad coverage: 68.9 %



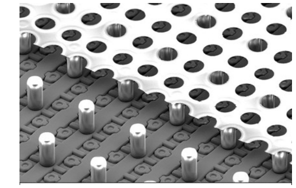




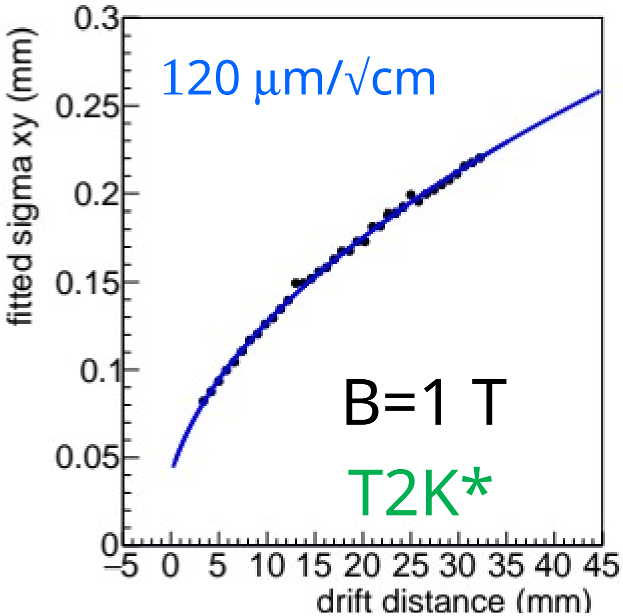
NIM A908 (2018) 18-23
NIM A956 (2020) 163331



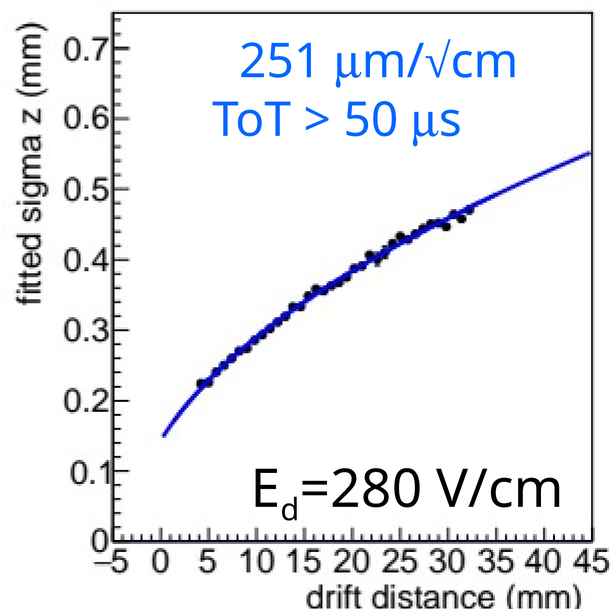
Tracking with Timepix3

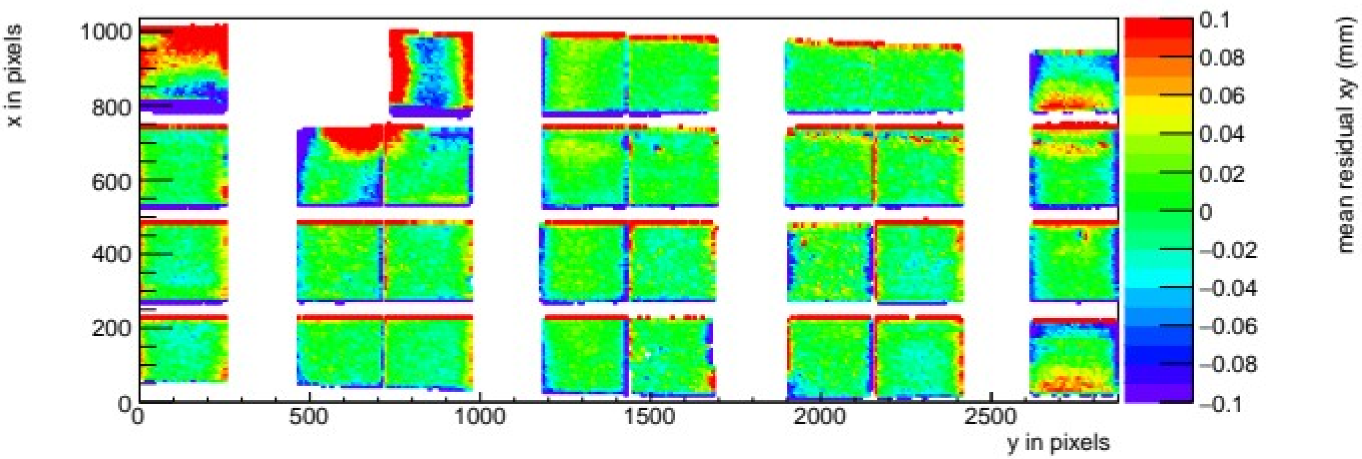


Example result with B = 1T and p = 6 GeV



Preliminary

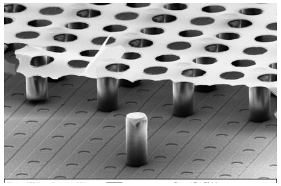




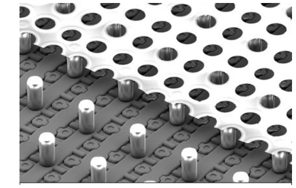
Tracks have about 1000 hits (on ~16 cm track length)

Mean residuals are close to zero. The rms of mean residuals is ~10-11 µm for B = 0T and 12-14 µm for B = 1T.

Publication close to final.



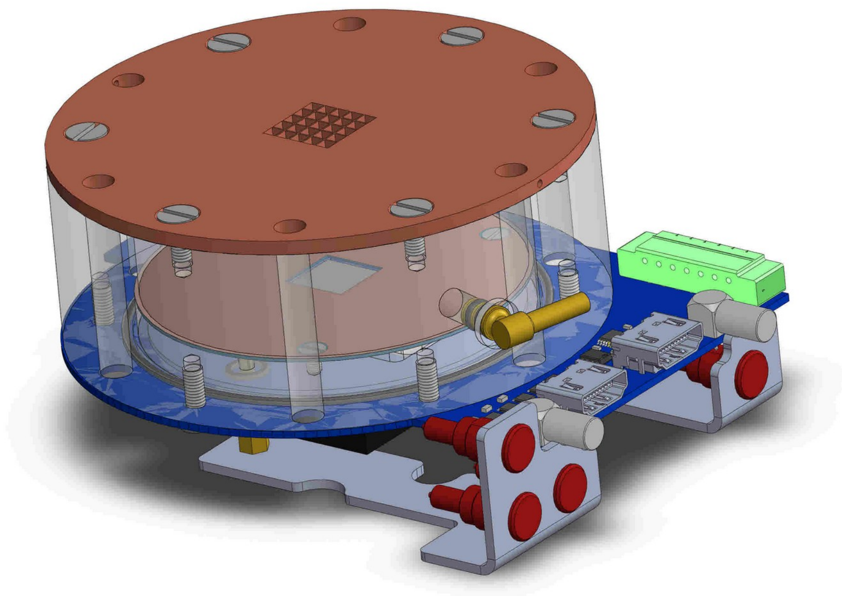
X-ray Polarimetry



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

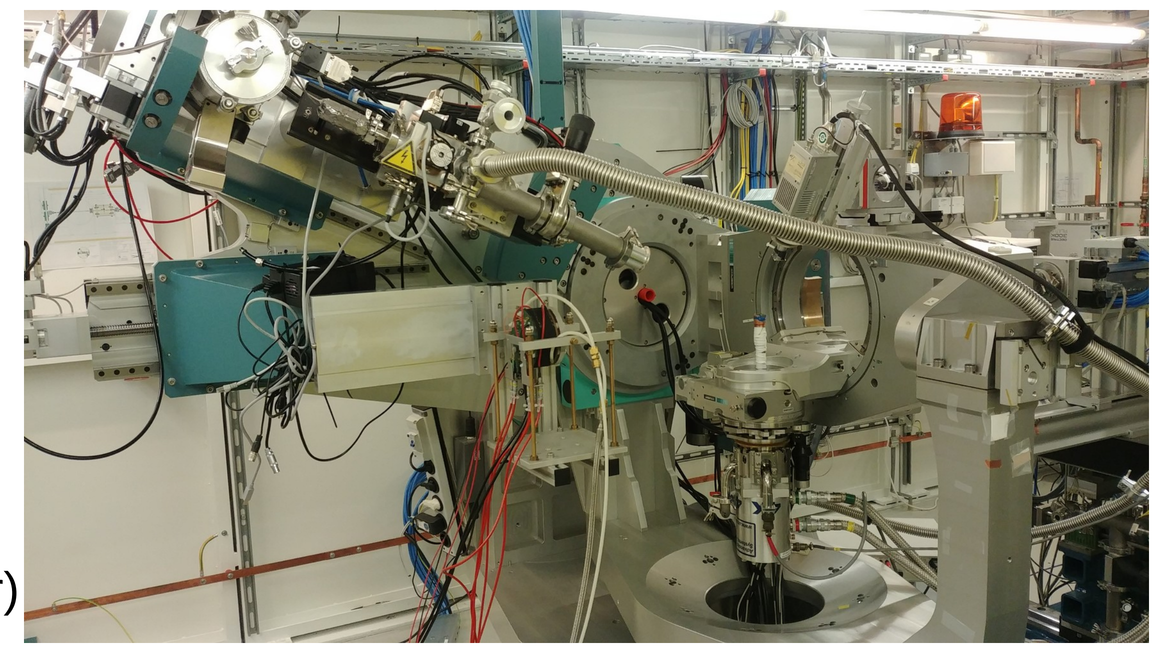
Photoelectrons follow E-field of polarization

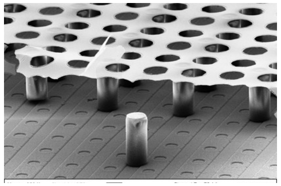
=> need gaseous detectors with high resolutions (GridPixes 🙂)



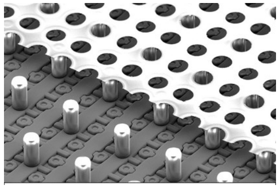
- CAST type detector with 3 cm drift
- Different He-based gas mixtures with CO_2 or DME
- Test beam at PETRA III (DESY) and KARA (KIT)
- Beam energies 4-11 keV
- Beam is >95 % linearly polarized

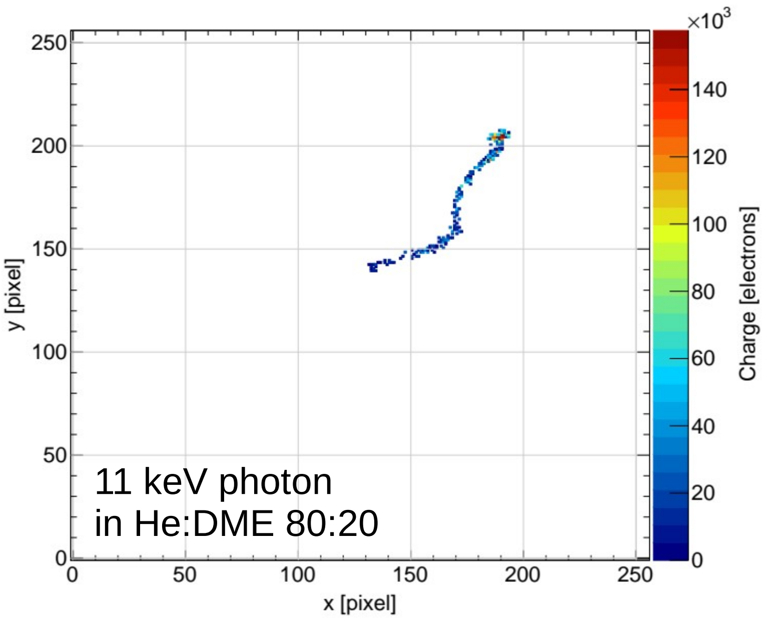
→ reconstructed polarization 76% (sofar)



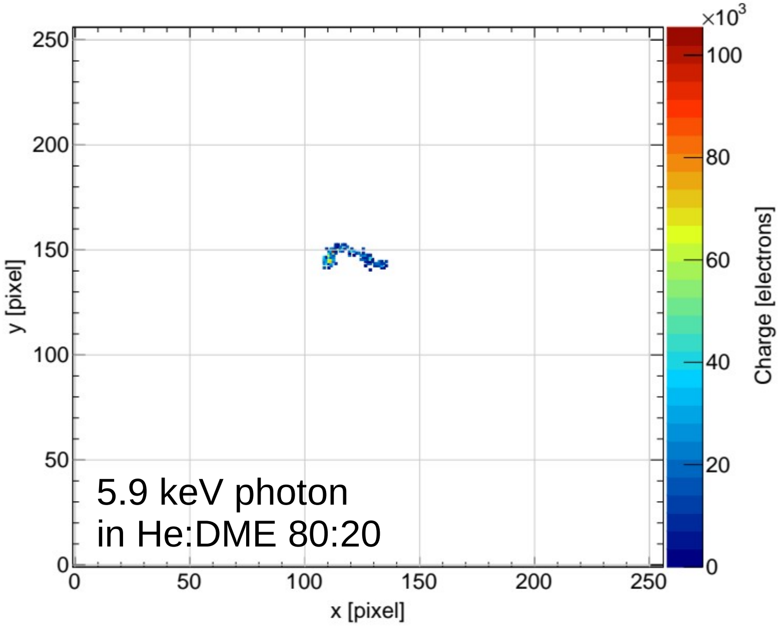


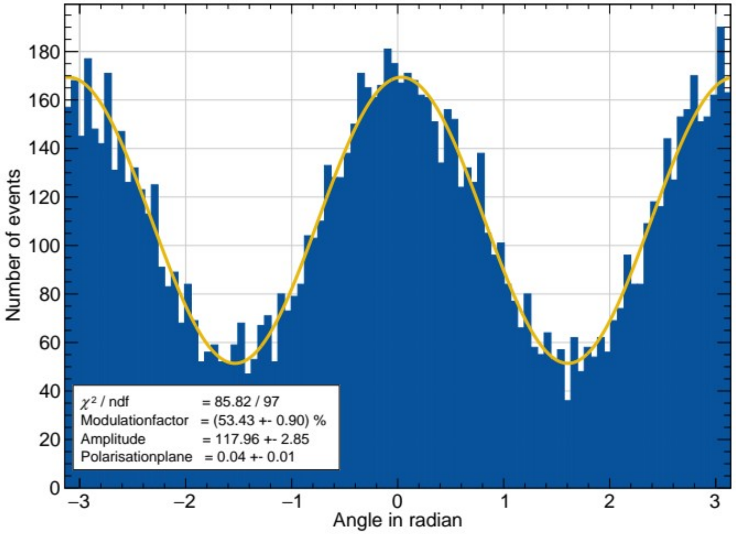
X-ray Polarimetry

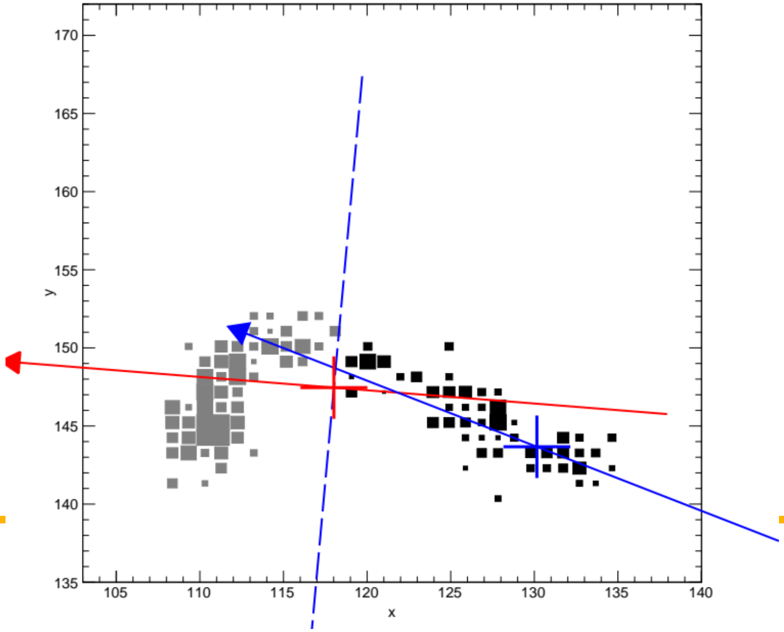


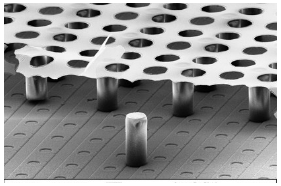


Reconstruction:
- Find center of event
- Split track
- Find end with higher ioniz.
- Reconstruct the other end
- Determine direction

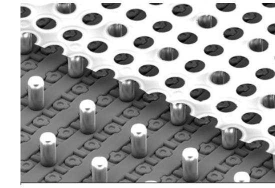






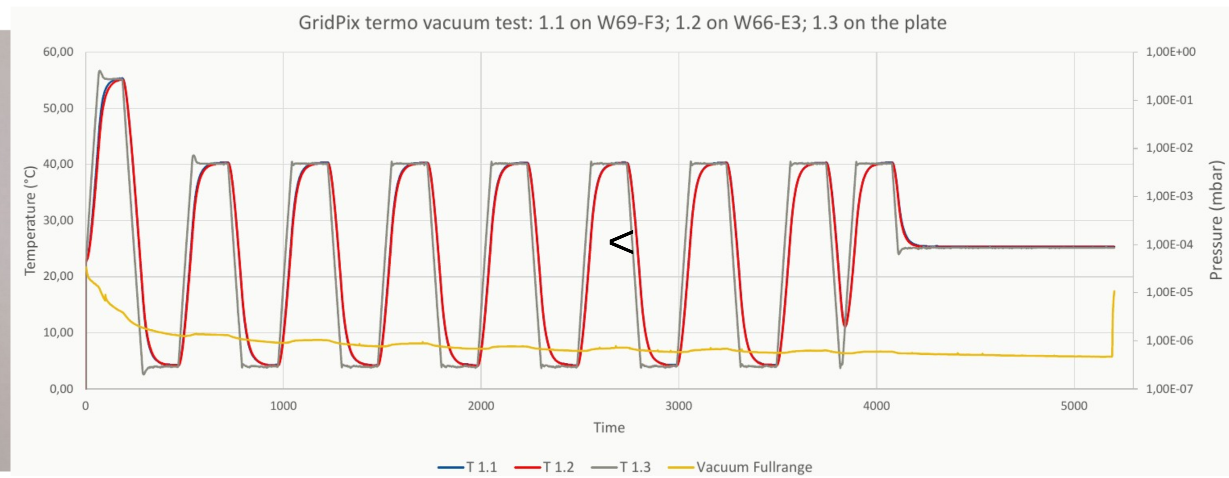


X-ray Polarimetry in Astrophysics



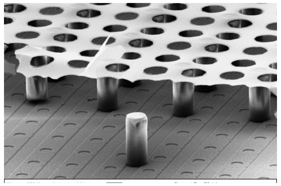
Project by the X-ray polarimetry group at INAF-IAPS (lead by Paolo Soffitta). Idea is to prepare and propose a follow-up mission of the IXPE satellite, potentially using a GridPix instead of a Gas Pixel Detector.
Important first tests have been performed with 2 standard GridPixes:

1.) Thermo vacuum tests

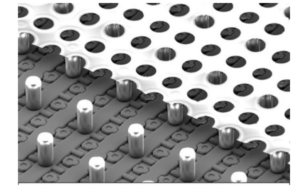


2.) random vibration test → no resonances found up to 2 kHz

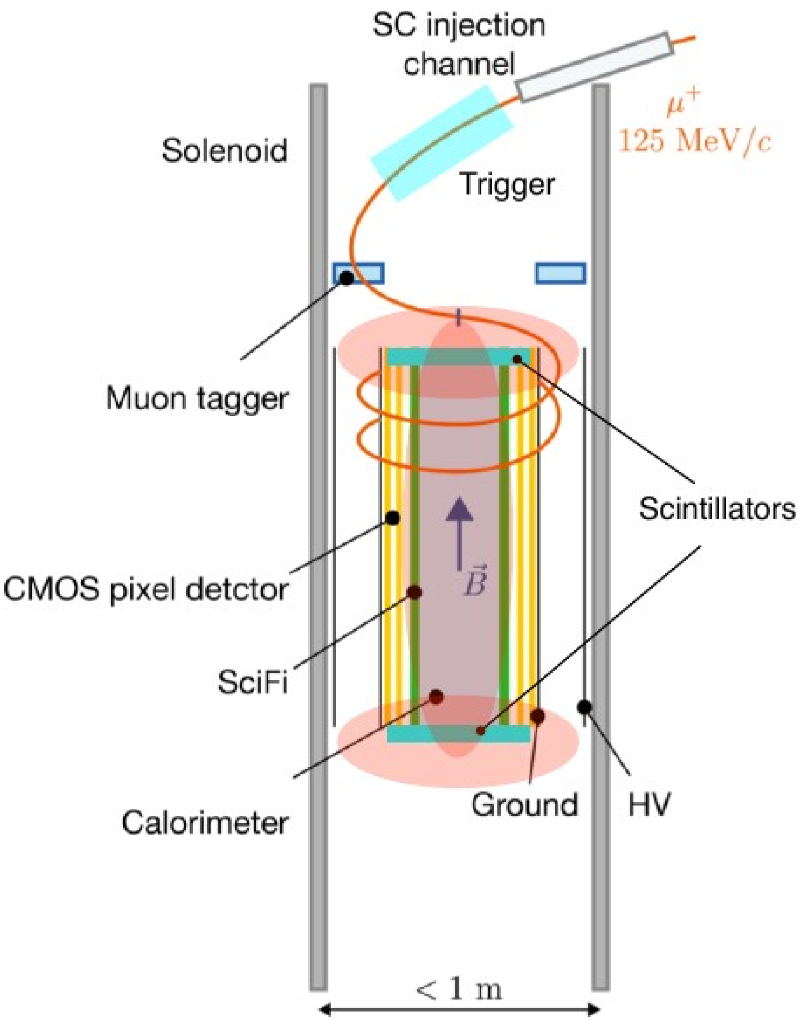
Before and after the two environmental tests high resolution pictures of the grid were taken and the ASICs were tested electronically → no differences were found



Muon EDM at PSI

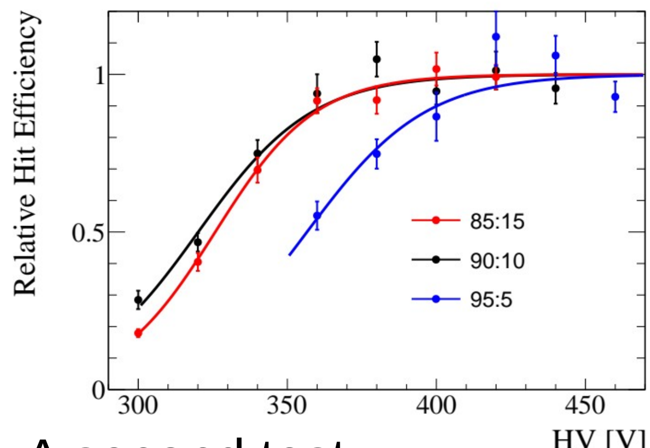


A new project for a dedicated measurement of the muon EDM



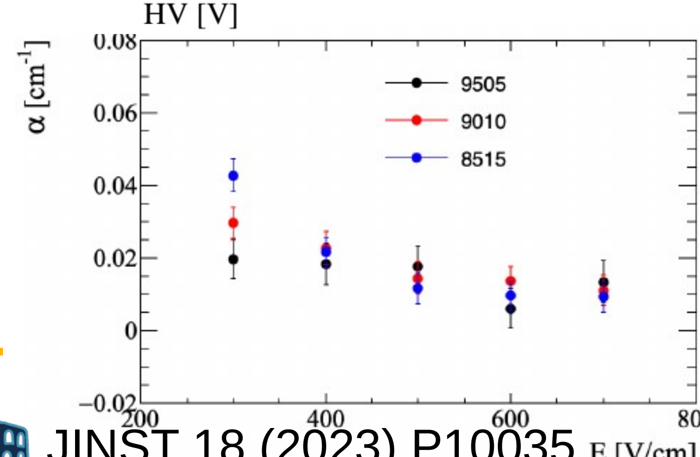
First tests to evaluate GridPix-TPC (F. Renga, INFN Roma) to characterize the muon beam during the commissioning of the phase-I experiment (2025-2026).

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 $He:CO_2$ was performed, now tests with p < 1 atm.



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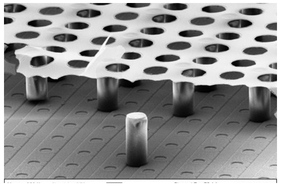
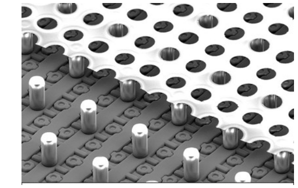
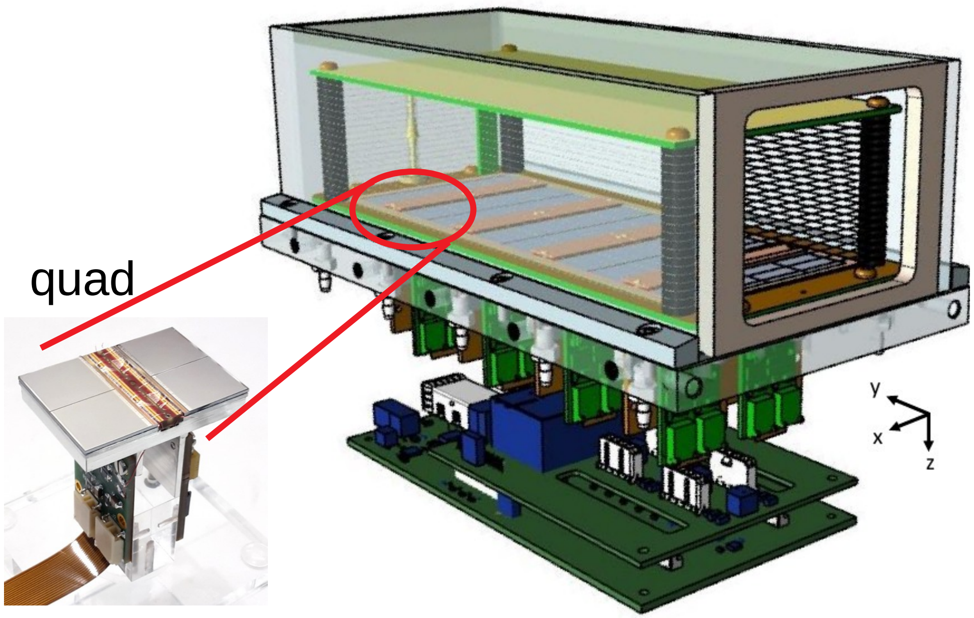


Negative Ion TPC

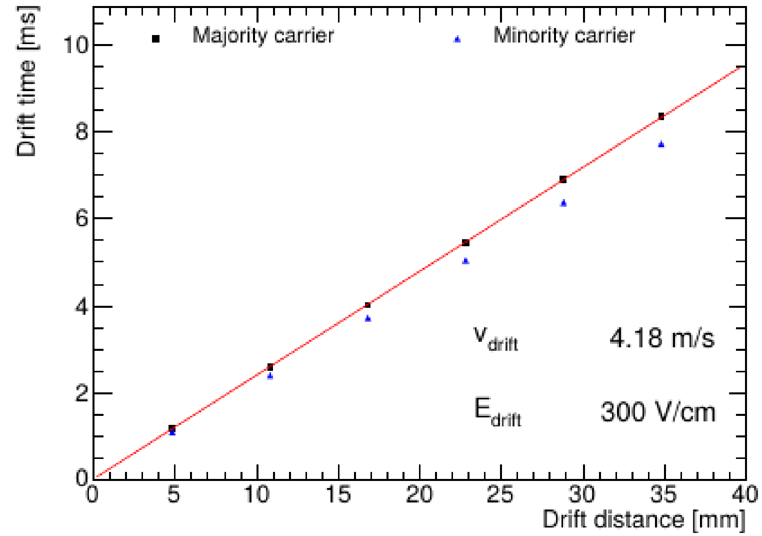


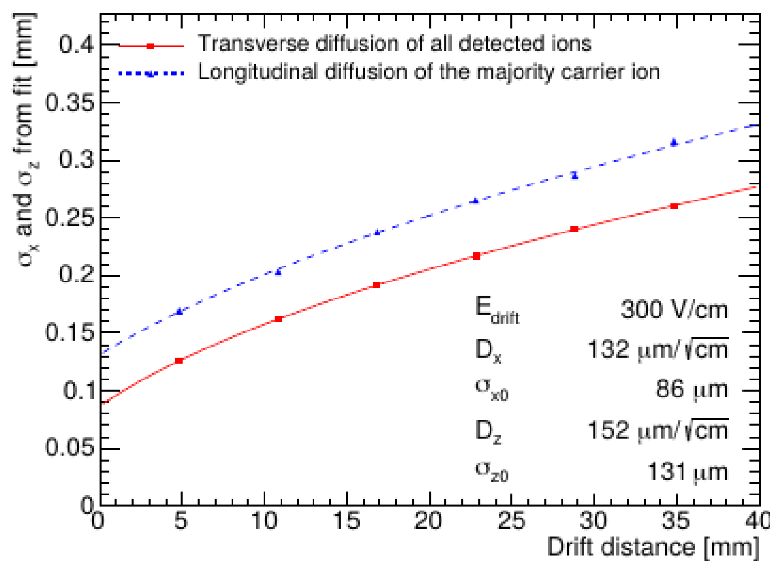


Detector with 32 GridPixes based on Timepix3 → Nikhef setup

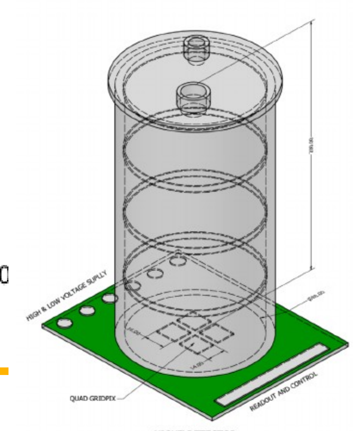
UV laser (337nm) used to generate tracks.

<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
- Preparing new setup at Bonn



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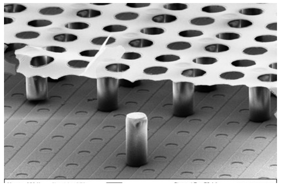
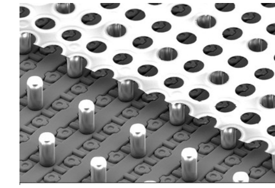
Nikhef

NIM A1014 (2021) 165706



GridPix Production in the Future



Once the GridPix production is reestablished we have several ideas
- revisit hole size/amplification study
  → interesting for higher / lower gas pressures
- reduce resistivity of protective layer
- double / triple grid structure (see next slide)

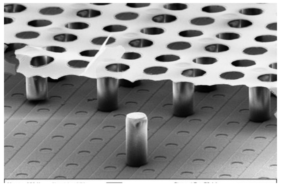
(-investigate low power mode of Timepix3 – 1/10 of regular power are claimed)

Other ASICs:

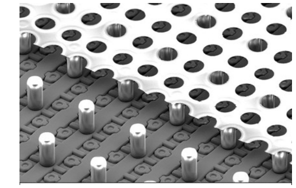
With the flexible setup in Bonn, other designs of the grid can be easily implemented

→ Any chips are welcome

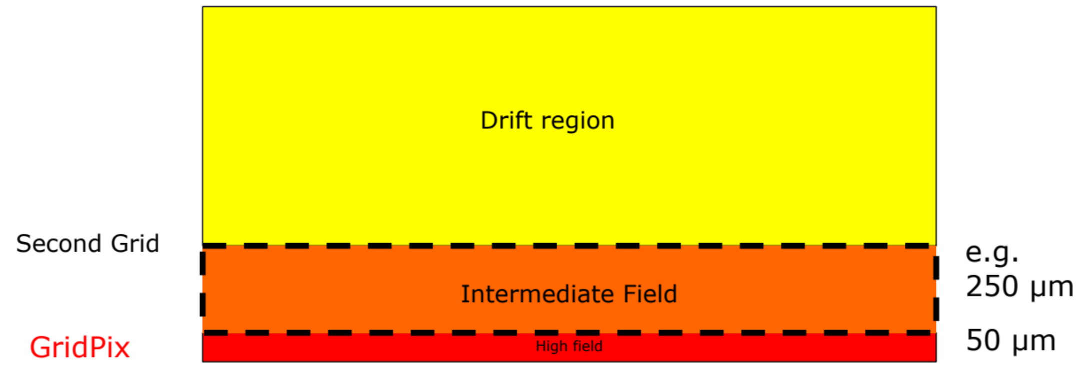
Timepix4:
- larger area (4x Timepix3), 4-sided buttable, slightly better time resolution, lower power consumption
- we can certainly do grids on Timepix4, if someone wants them, but we will not switch as a standard because
  * machines are laid out for 20 cm not 30 cm diameter
  * can't afford to implement in readout system
  * large reticle size reduces yield significantly



Reducing the IBF in a Pixel TPC

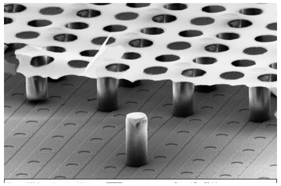


The Ion back flow can be reduced by adding a second grid to the device. It is important that the holes of the grids are aligned. The Ion back flow is a function of the geometry and electric fields. Detailed simulations – validated by data.

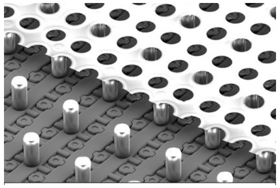


Ion backflow	Hole 30 µm	Hole 25 µm	Hole 20 µm
Top grid	2.2%	1.2%	0.7%
GridPix	5.5%	2.8%	1.7%
Total	$12\ 10^{-4}$	$3\ 10^{-4}$	$1\ 10^{-4}$
transparancy	100%	99.4%	91.7%

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.



Summary and Outlook

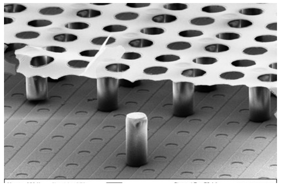


GridPixes are seeing a transition from Timepix to Timepix3.

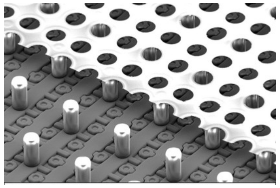
The grid production can soon be done in Bonn, which will open possibilities for new ideas and R&D.

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)
L. , A. Hoverath (SchulTPC/CLEOPATRA)
and of course Klaus Desch.

Special thanks goes to our technical team
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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.