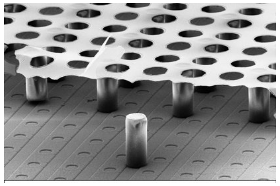

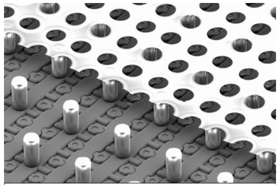

GridPix - A high resolution gaseous detector

Jochen Kaminski

University of Bonn

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

Topical Workshop on FE electronics
for gas detectors
16.6.2021

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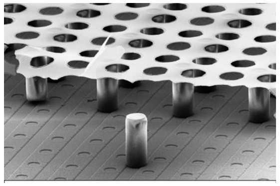

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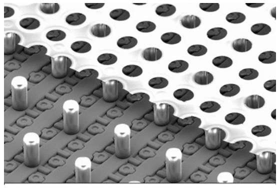
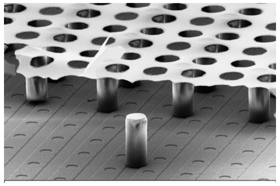
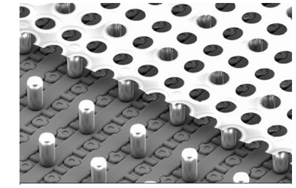


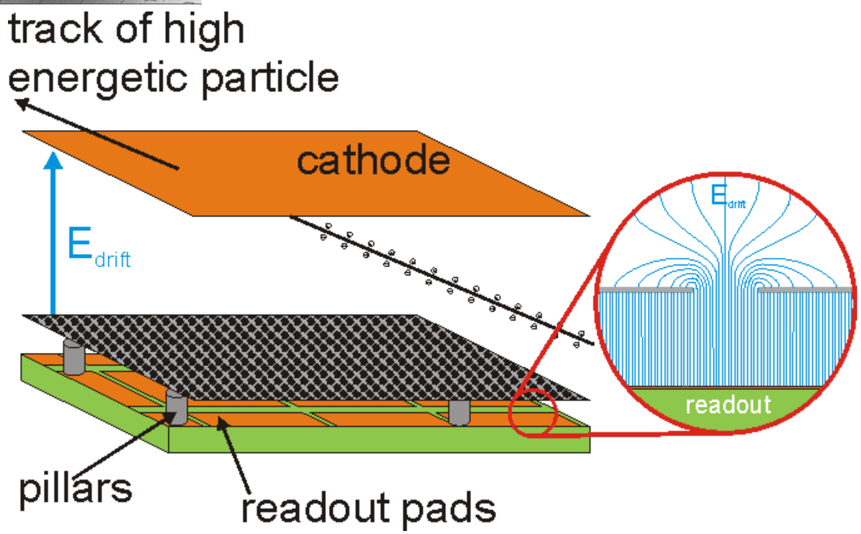
- GridPix Detectors
  - Ingredients
  - Production
  - Optimization

- Applications
  - Tracking detector
  - X-ray detector
    - X-ray polarimeter
    - TR detector
  - Neutron Detector
  - GridPix in a Negative Ion TPC

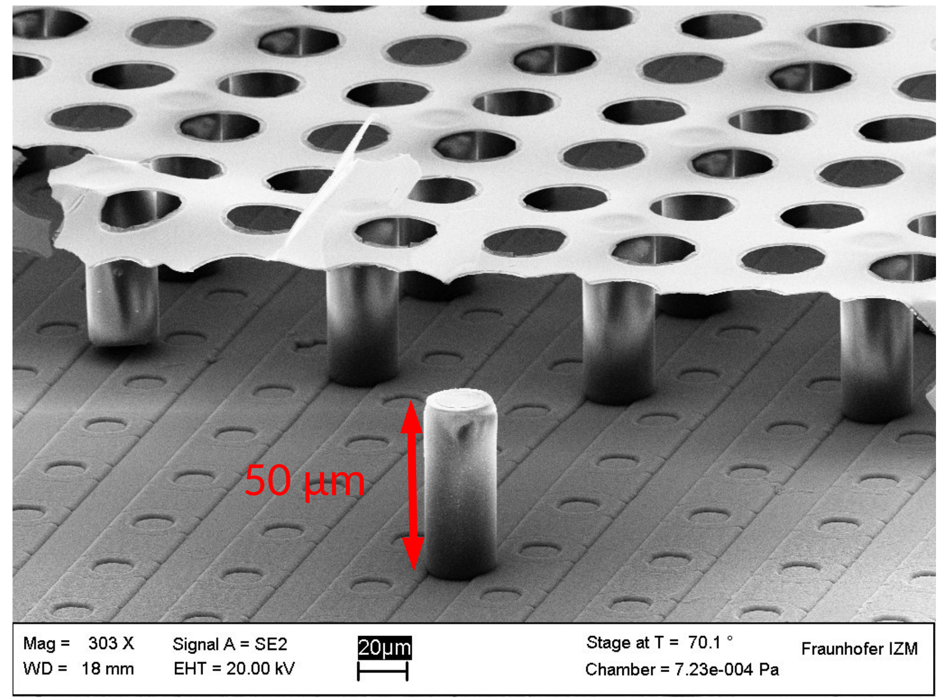




From Micromegas to GridPix



Standard charge collection:
Pads / long strips
Instead: Bump bond pads are used as charge collection pads.



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.

- Single electrons entering a hole are amplified
- Complete Avalanche collected on one pixel
  → every signal above threshold corresponds to one primary electron

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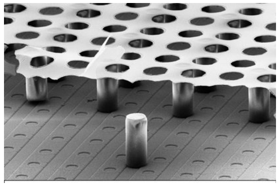
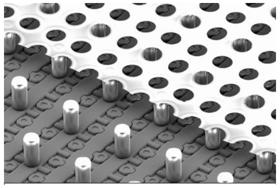
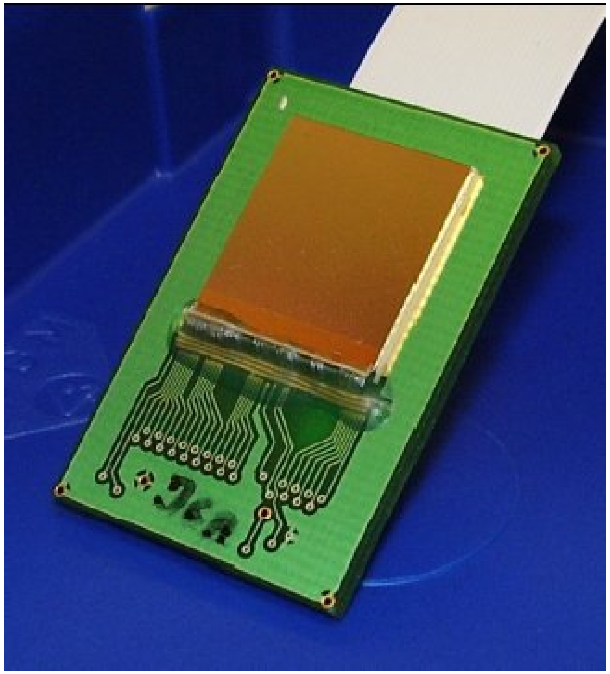
NIM A535 (2004) 506-510
NIM A845 (2017) 233-235





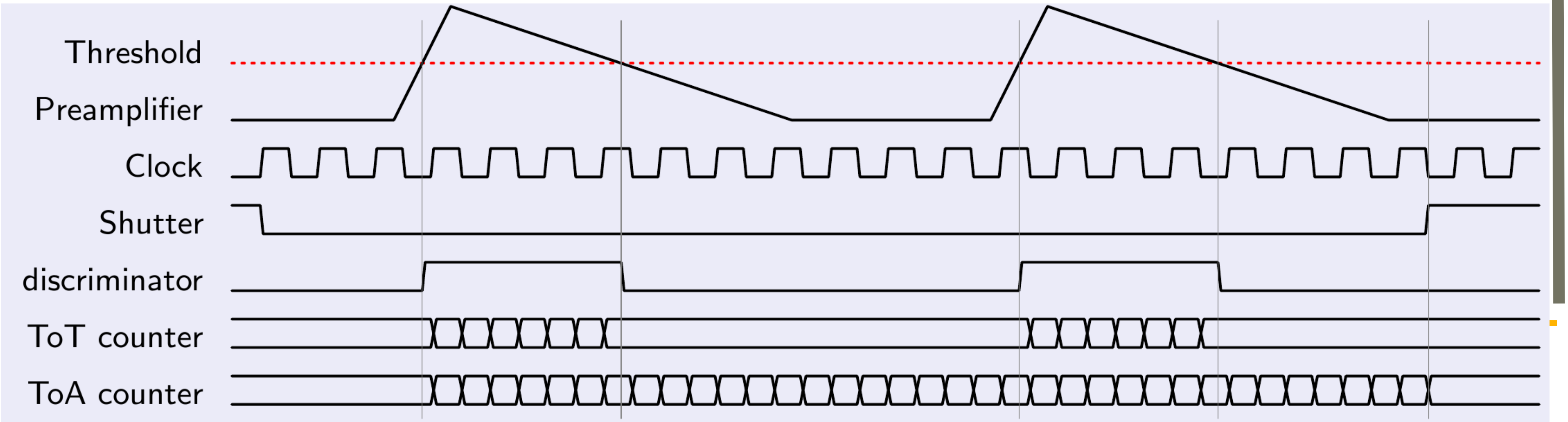
Timepix ASIC

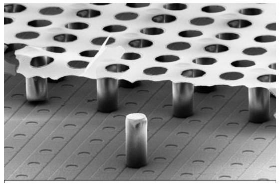


Available for tests since Nov. 2006

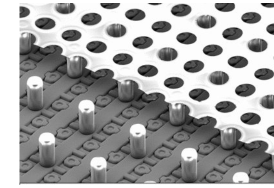
Number of pixels: 256 × 256 pixels
Pixel pitch: 55 × 55 μm²
Chip dimensions: 1.4 × 1.4 cm²
ENC: ~ 90 e⁻

<u>Limitations:</u> 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.





Protection Layer



Institute for Nanotechnology

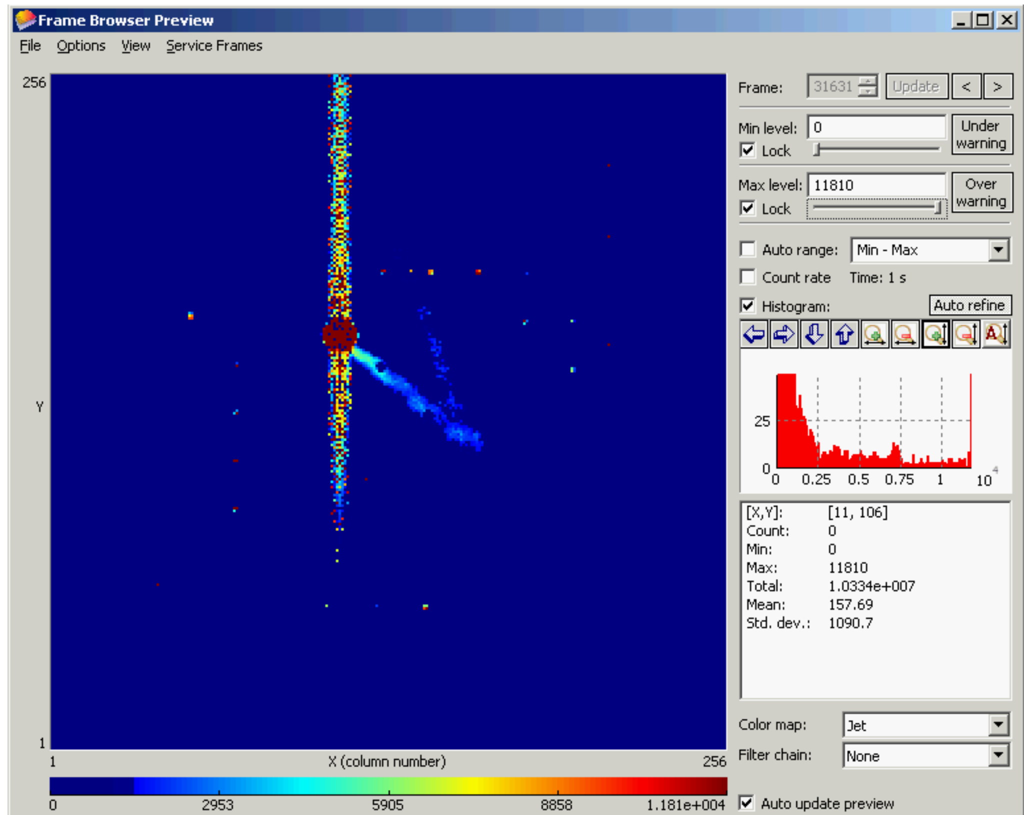
Discharges triggered for example by highly ionizing particles could easily destroy the chip. The charge collected by one pixel was too high.

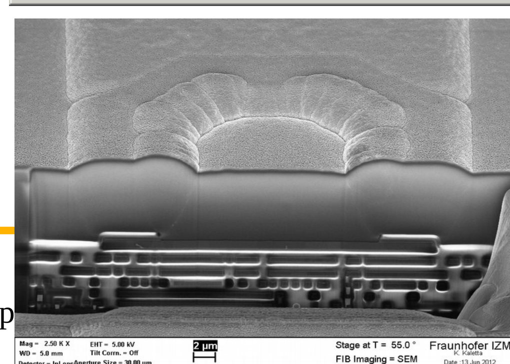
A protection layer is placed on the chip to disperse the charge on many pixels and thus lower the input current per pixel. Besides, the charge is removed slowly and thus quenches the discharge.

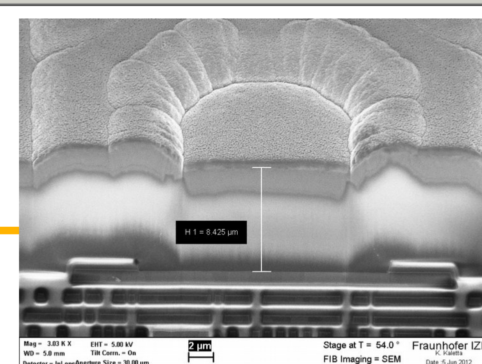
<u>high resistive material</u>

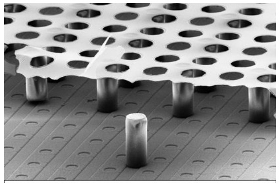
4 µm Si_XN_Y (~10^{12} Ω·cm)

Chips survive several million discharges.

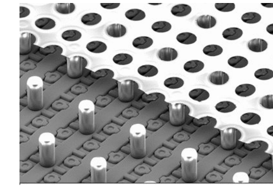


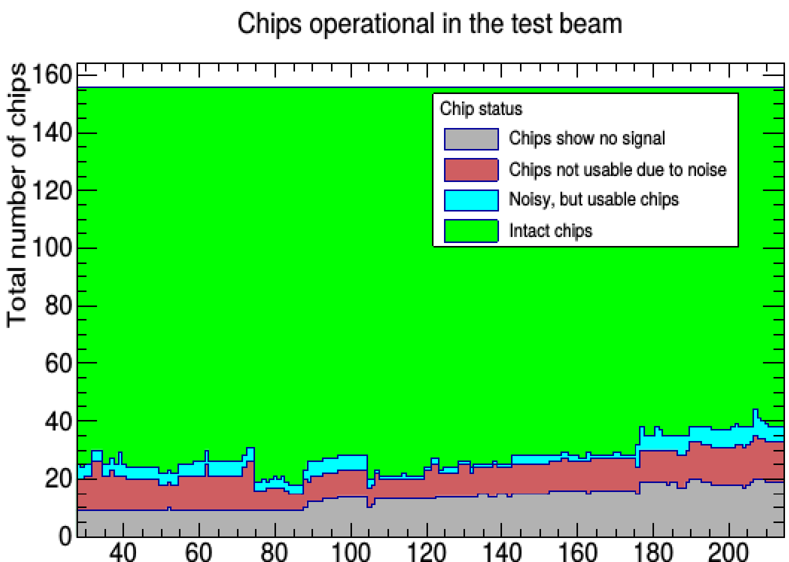






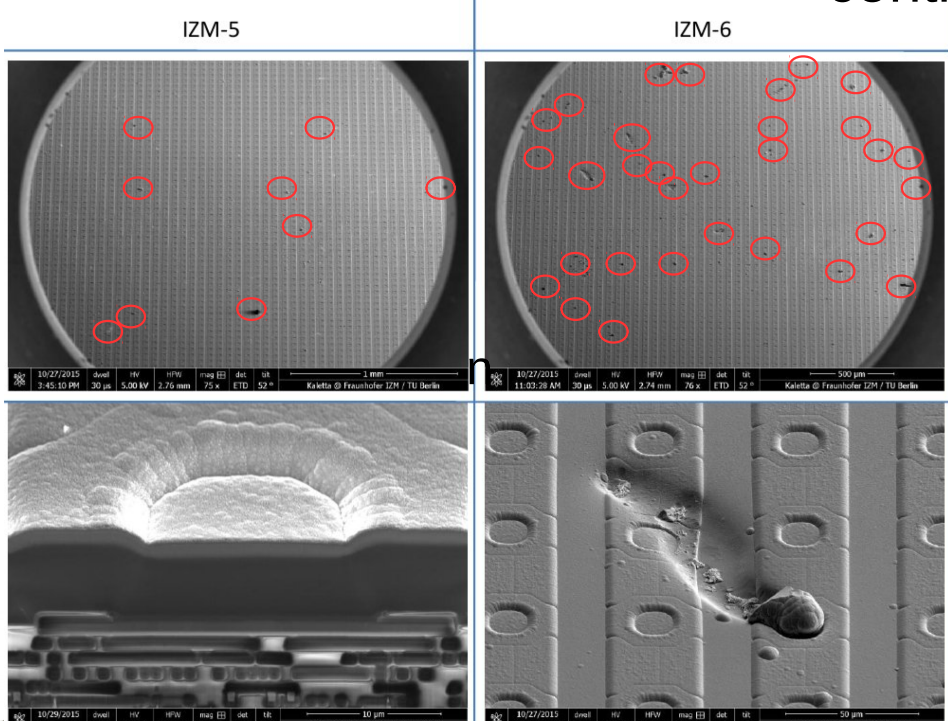
Failure of the Protection Layer

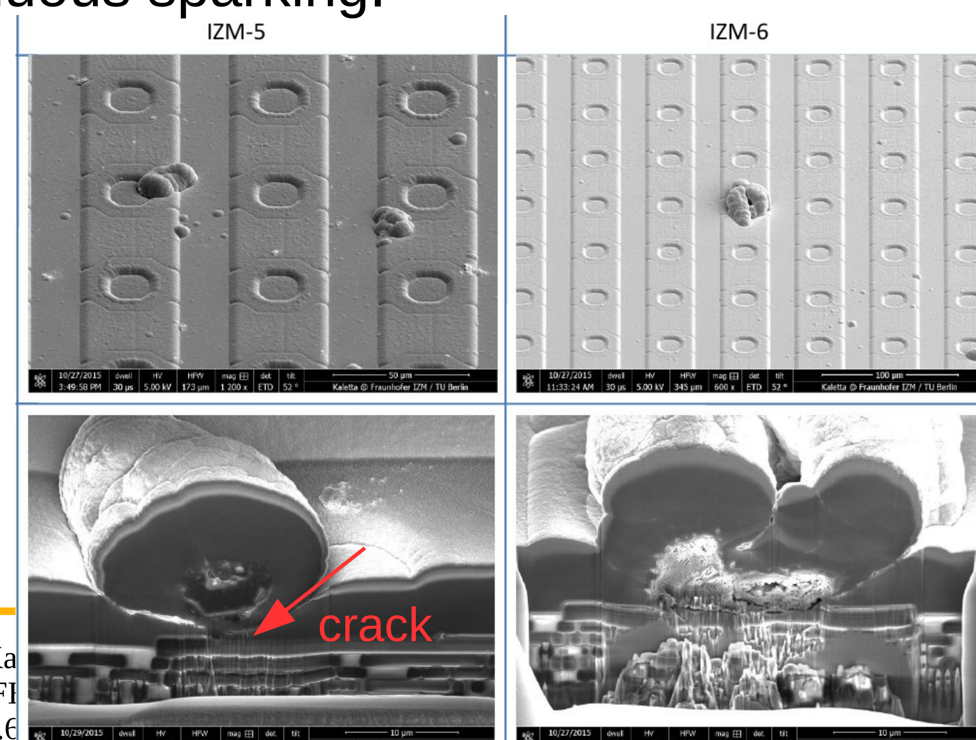


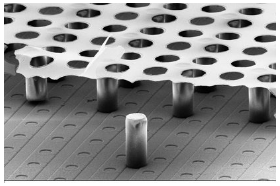


During test beam with 160 GridPixes, a number of Timepixes were damaged:

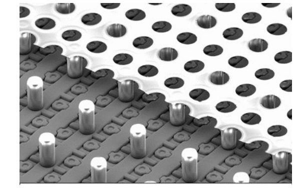
Problem could be traces to faulty machine at Mesa+ which lead to defects in the protection layer.
With new machine the protection layer is good again, chips survive hours of continuous sparking.



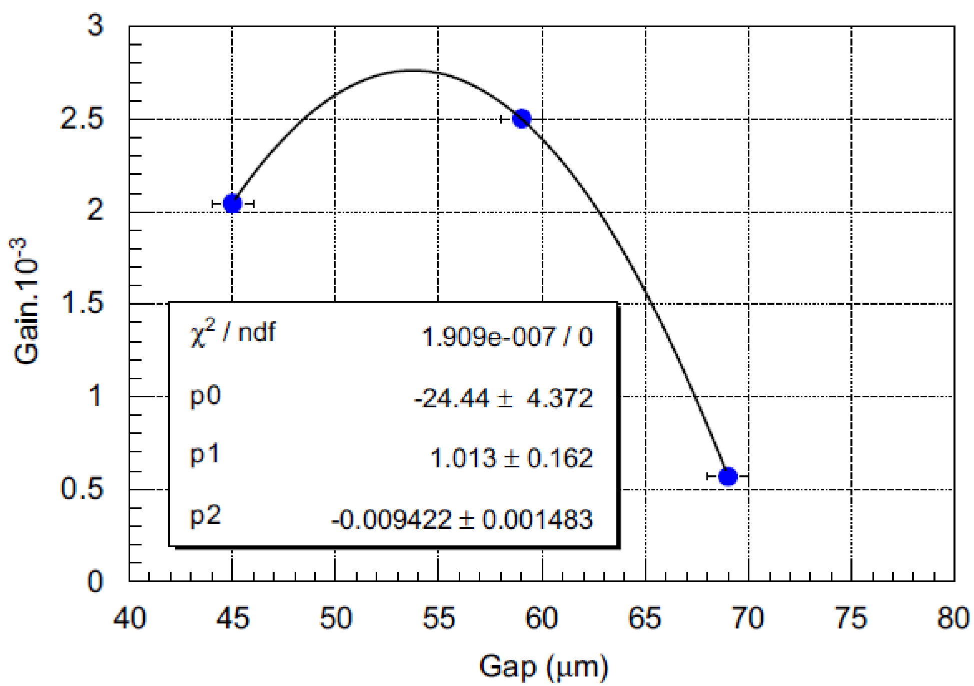




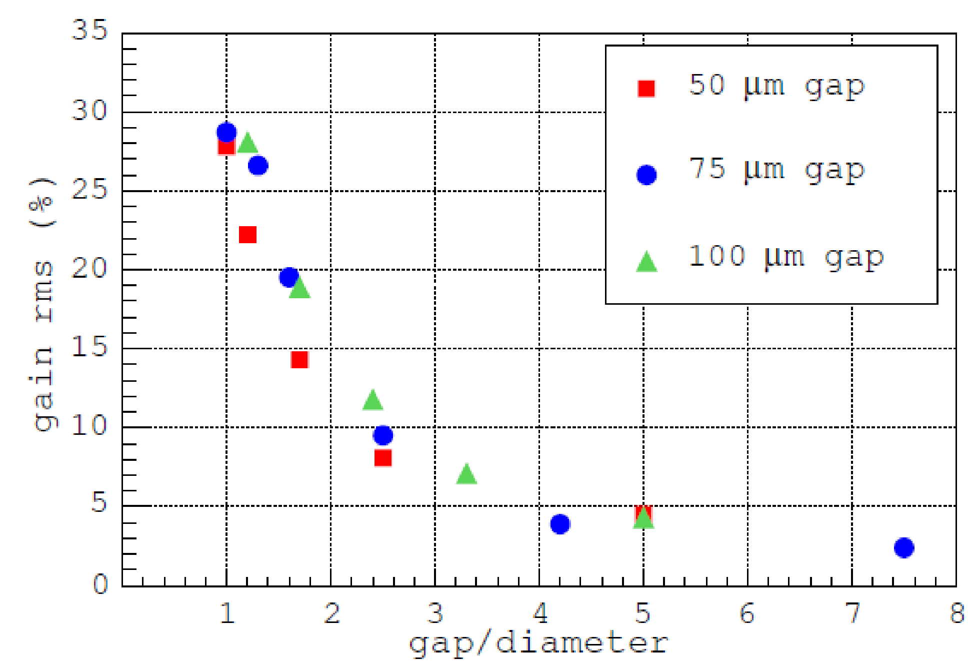
Optimization of InGrids



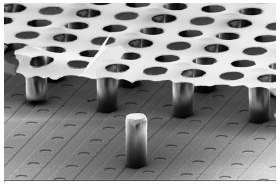
Detailed studies have been performed to optimize the layout of the structure. (NIMA 591, pp. 147, 2008, PhD. Thesis of M. Chefdeville, Nikhef)



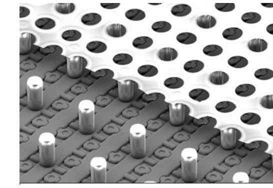
The influence of the gap size and hole diameters on gain, energy resolution, ion feedback and collection efficiency were measured.



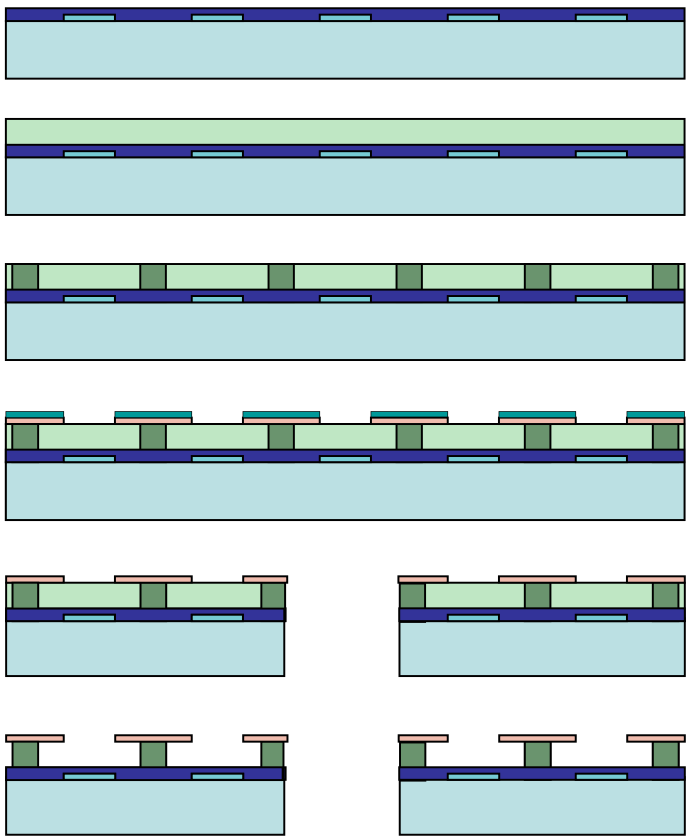
Also the layout of the supporting structures (pillars and dikes) was optimized to give the highest mechanical strength.



Wafer-based Production

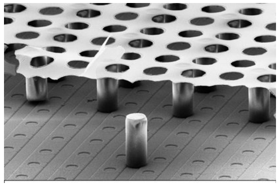


Production at Twente was based on a 1 to 9 chips process.
This could not satisfy the increasing demands of R&D projects.
A new production was set up at the Fraunhofer Institut IZM at Berlin.
This process is wafer-based → 1 wafer (107 chips) is processed at a time.

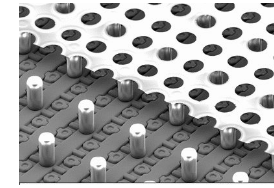


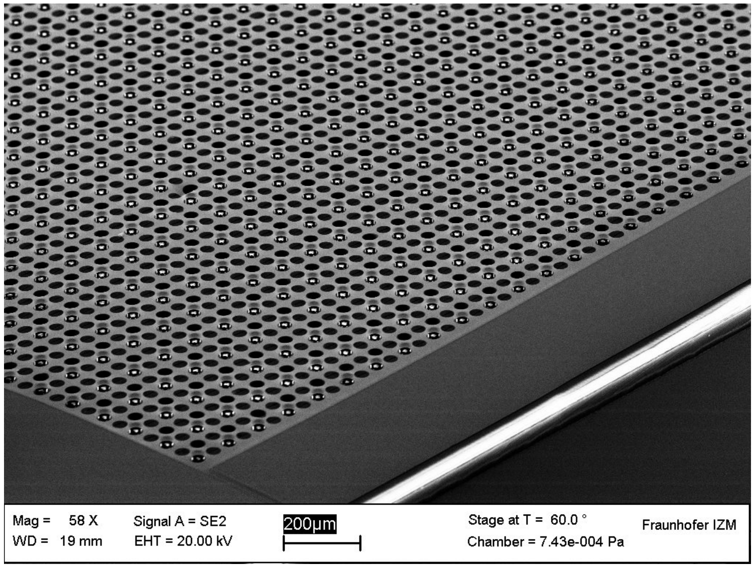
1. Formation of Si_xN_y protection layer
2. Deposition of SU-8
3. Pillar structure formation
4. Formation of Al grid
5. Dicing of wafer
6. Development of SU-8

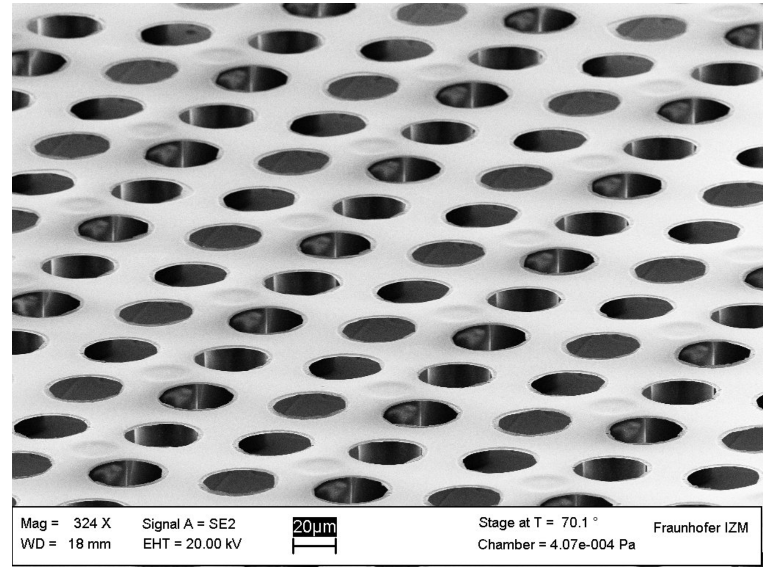
The process will be transferred to the FTD at Bonn in 2022.

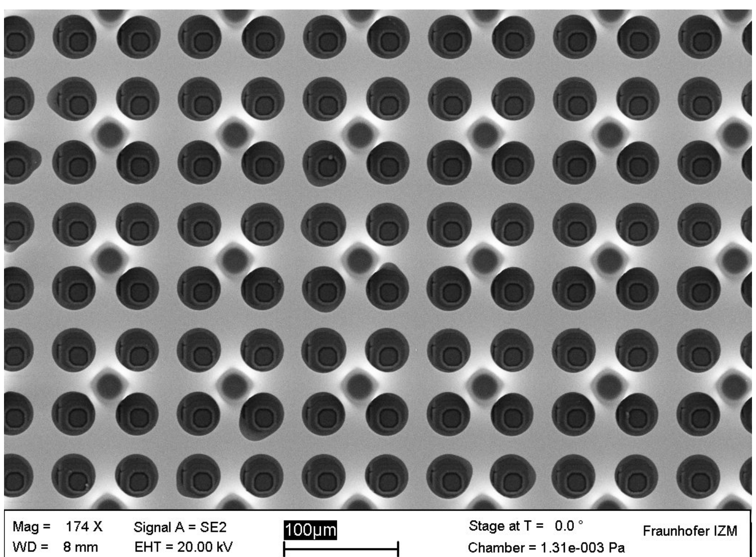


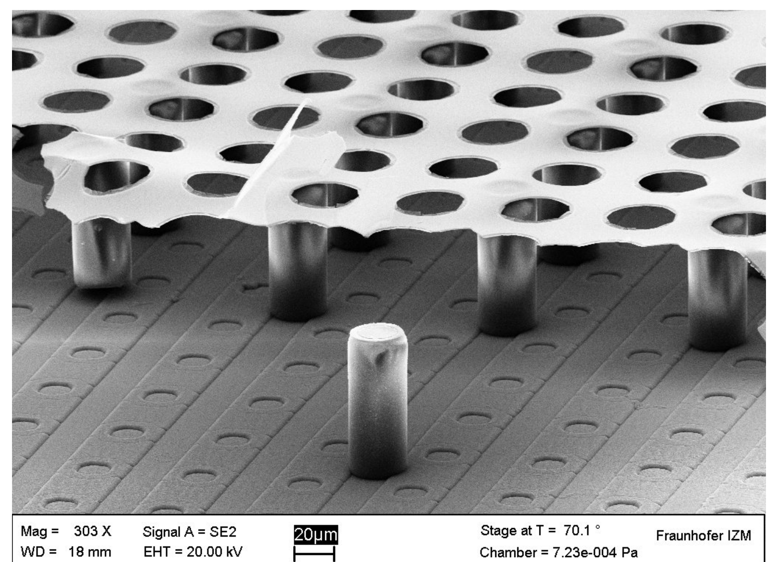
SEM Pictures

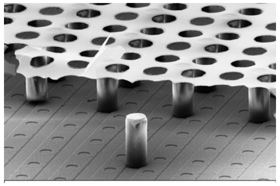




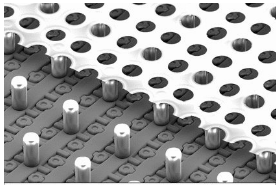




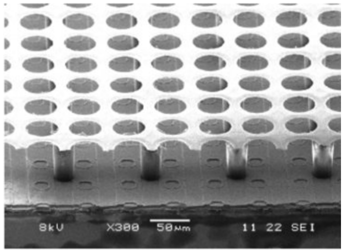




Nomenclature

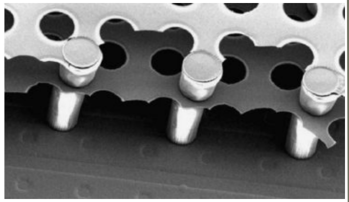


Timepix / Timepix3: CMOS-ASIC designed by the Medipix collaboration, originally planned as an imaging chip for medical applications (NIMA 581, pp. 485, 2006)

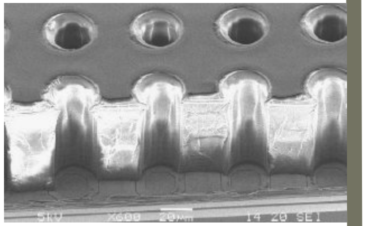


InGrid: Integrated Grid: Micromegas structure built on top of pixel chip with industrial postprocessing techniques (NIMA 556, pp. 490, 2006)

GridPix: complete detector based on InGrids + Pixel chip including cathode, gas volume etc.

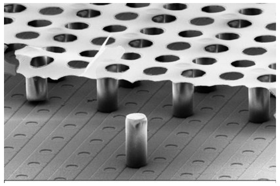


TwinGrid: two grids on top of each other (NIMA 610, pp. 644, 2009)

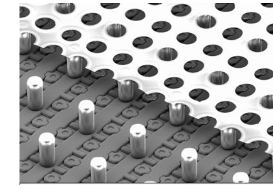


GEMGrid: Same as InGrid, but grid rests on solid layer with holes, instead of pillars (NIMA 608, pp. 96, 2009)

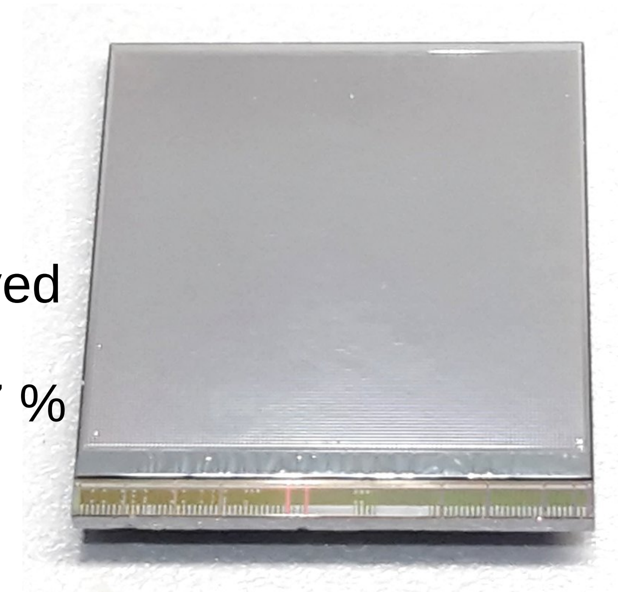
Gossip: Gas On Slimmed Silicon Pixels, a very thin GridPix detector with minimal material budget, e.g. 1 mm of gas gap, thinned ASIC

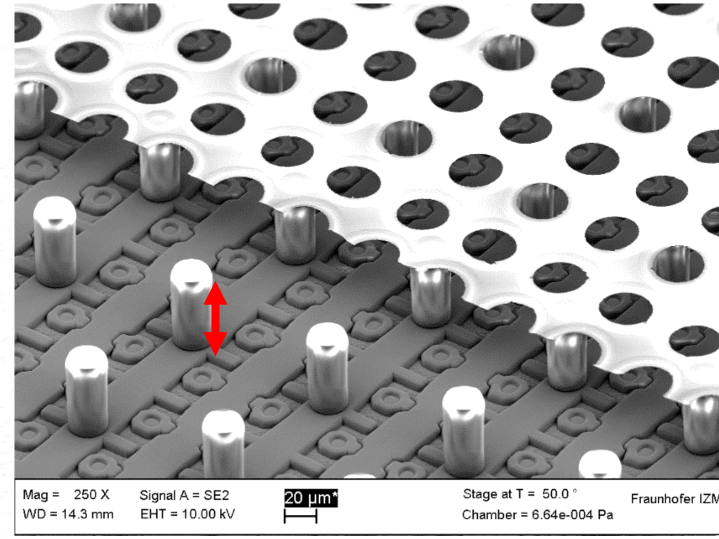


GridPix based on Timepix3



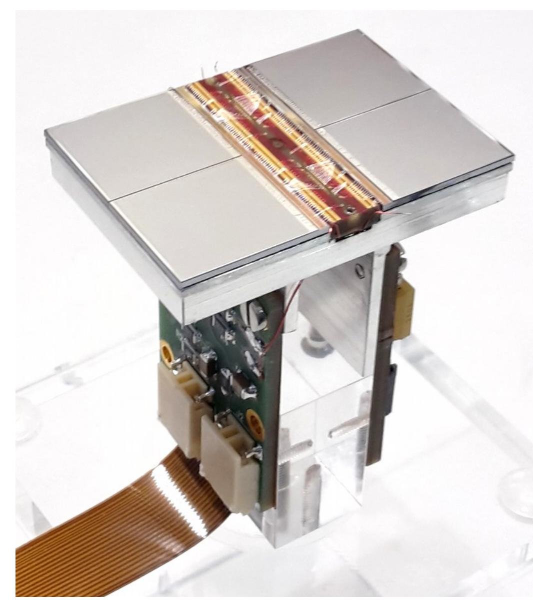
GridPix detectors have moved from Timepix to Timepix3 ASICs.
The grid layout was improved to have an active area increase from 91.3 % to 97.7 % of pixel matrix.

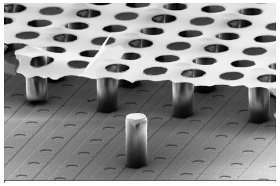




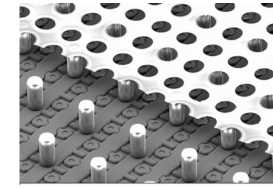
- Number of pixels: 256 × 256 pixels
- Pixel pitch: 55 × 55 µm²
- ENC: ~ 60 e$^-$
- Charge (ToT) and time (ToA) available for each hit
- Timing resolution: 1.56 ns for duration of ~410 µs
- Zero suppression on chip (sparse readout)
- Multi-hit capable (pixels sensitive after t_{ToT}+475 ns)

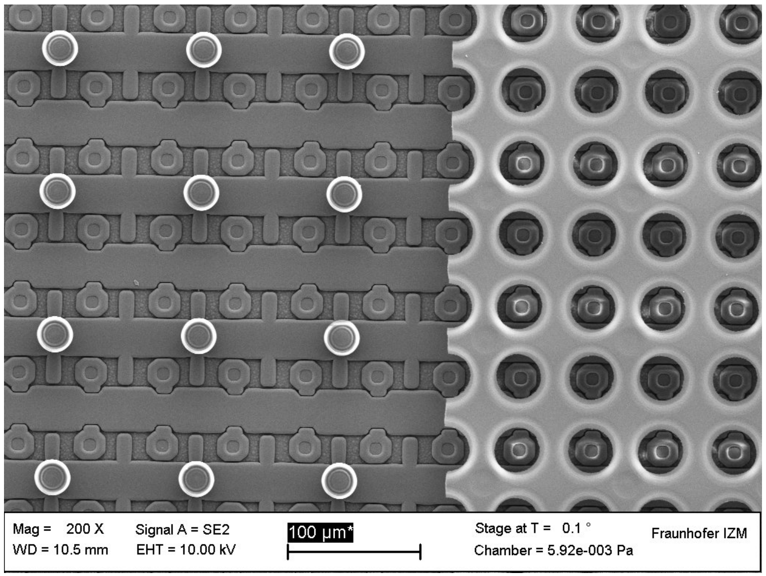
  Super-pixels store hits for some time
- Output rate up to 5.12 Gbps
- Power pulsing possible (800 ns for start up)

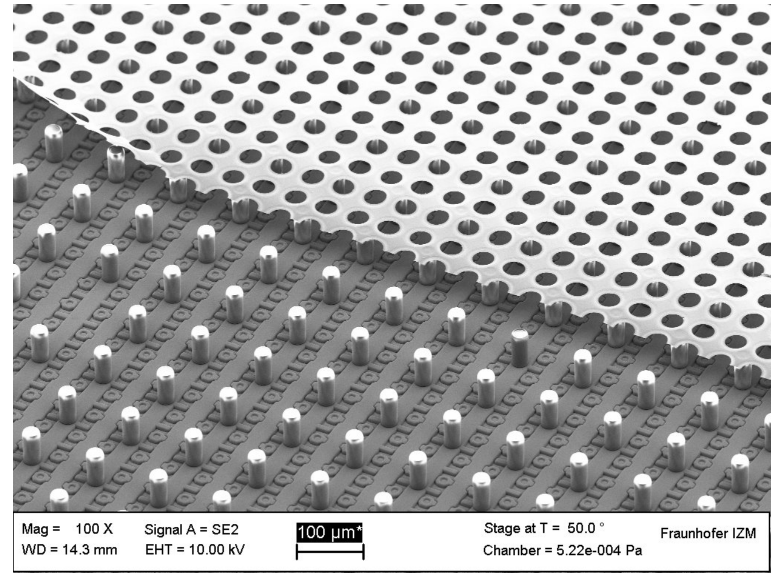


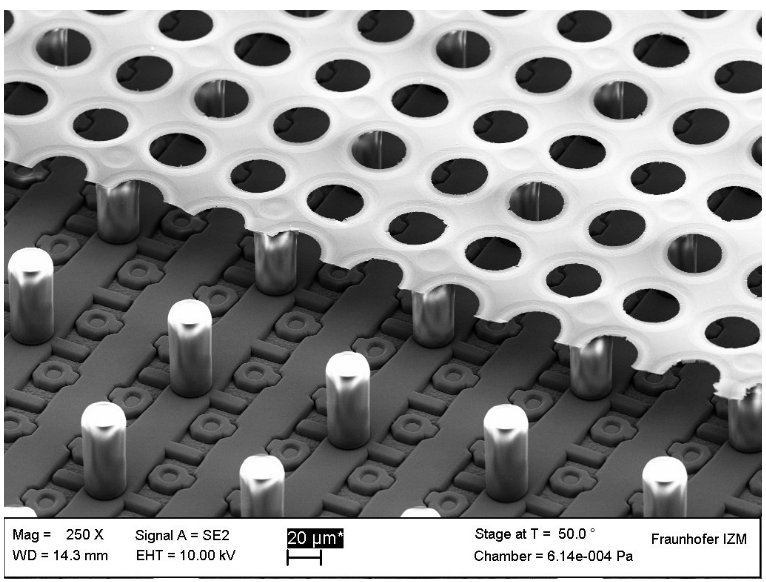


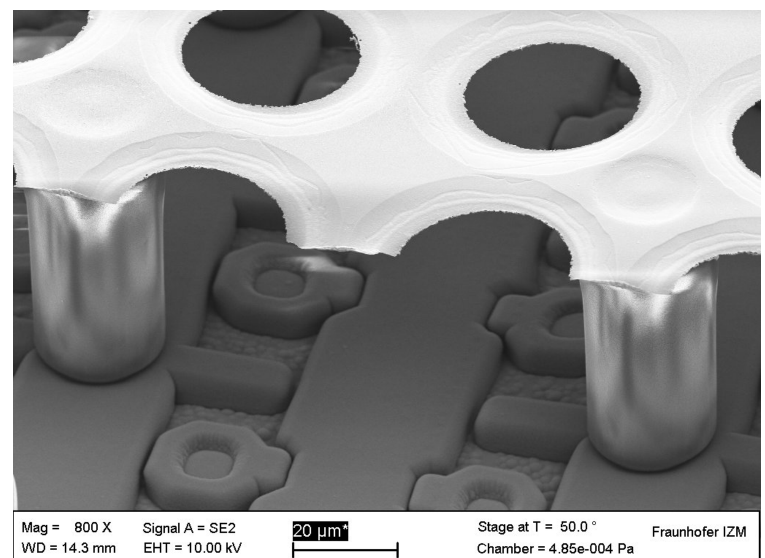
Pictures

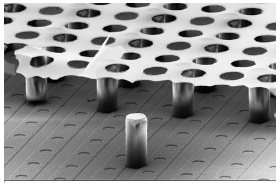



Mag = 200 X
WD = 10.5 mm
Signal A = SE2
EHT = 10.00 kV
100 µm*
Stage at T = 0.1 °
Chamber = 5.92e-003 Pa
Fraunhofer IZM

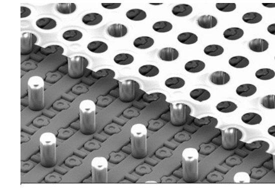

Mag = 100 X
WD = 14.3 mm
Signal A = SE2
EHT = 10.00 kV
100 µm*
Stage at T = 50.0 °
Chamber = 5.22e-004 Pa
Fraunhofer IZM


Mag = 250 X
WD = 14.3 mm
Signal A = SE2
EHT = 10.00 kV
20 µm*
Stage at T = 50.0 °
Chamber = 6.14e-004 Pa
Fraunhofer IZM


Mag = 800 X
WD = 14.3 mm
Signal A = SE2
EHT = 10.00 kV
20 µm*
Stage at T = 50.0 °
Chamber = 4.85e-004 Pa
Fraunhofer IZM



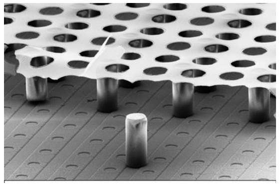
Readout Electronics



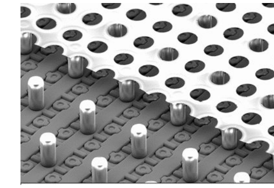
For Timepix and Timepix3 there is quite a variety of readout electronics.
They differ in specific performance parameters and should be chosen according to the envisioned application.
Here are some (certainly I have overlooked several):

Timepix:
- MUROS developed by Nikhef (deprecated?, relying on NI card)
- USB-device/FitPix developed by U. Prag,
- PRIAM developed by ESRF Grenoble
- DEMAS developed by IFEA Barcelona
- SRS developed by U. Bonn, open source, scalability to 160 ASICs proven

Timepix3:
- SPIDR developed by Nikhef: 2015 JINST 10 C12028 / 2017 JINST 12 C02040
- USB 3.0 developed by Advacam: 2016 JINST 11 C12065
- Katherine developed by U.s. Prague: 2017 JINST 12 C11001
- SRS developed by U. Bonn: s. next slide.



Benefits of GridPixes



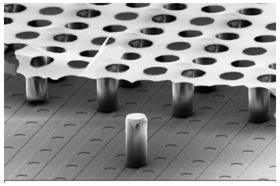
The main feature of GridPix is to be sensitive to single primary electrons with a spatial resolution of down to 55 µm/sqrt(12) ~ 15.9 µm.

Depending on the application this has many benefits, for example

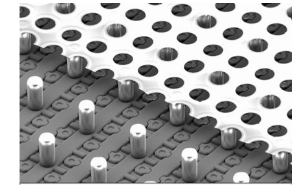
1.) Tracking (TPC style):
- Lower occupancy → easier track reconstruction
- Removal of δ-rays and kink removal
- Improved dE/dx (4% seems possible, electron or cluster counting)
- No angular pad effect

2.) X-ray detection:
- high energy resolution (counting primary electrons)
- detection of photoelectron (X-ray polarimetry)
- low detection threshold (in principle 1 e^-, in practice 3 e^- → E_γ = 25-75 eV)

3.) Neutron detection:
- good head/tail separation



Content



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  - GridPix in a Negative Ion TPC

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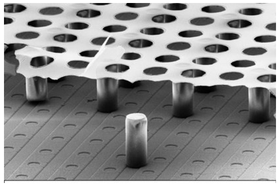
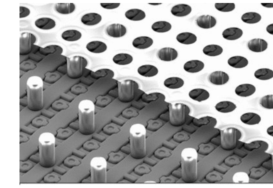
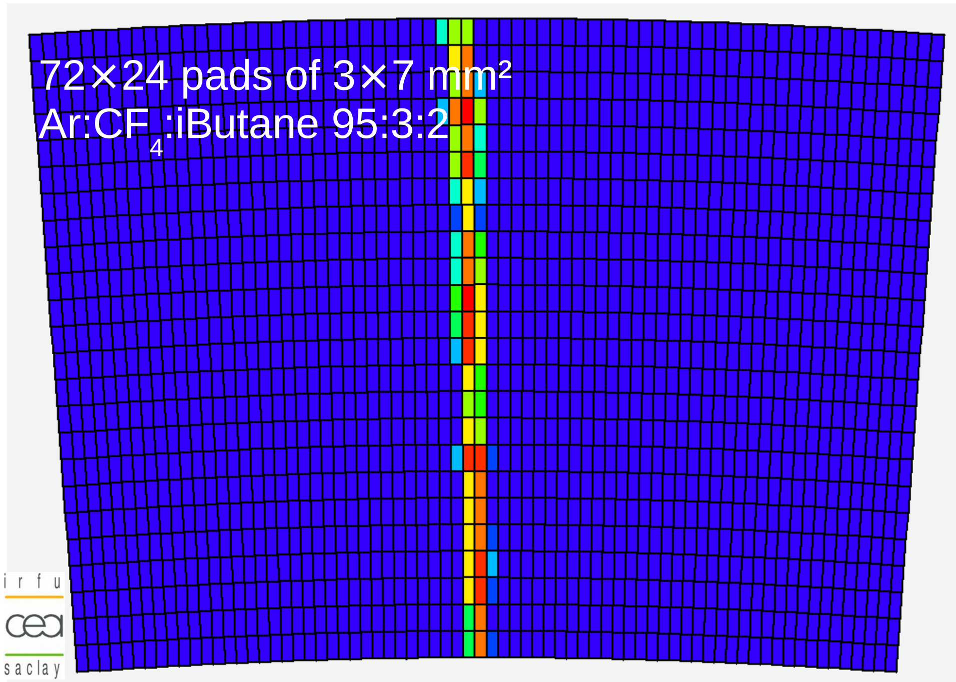


Comparison Pads vs. Pixels

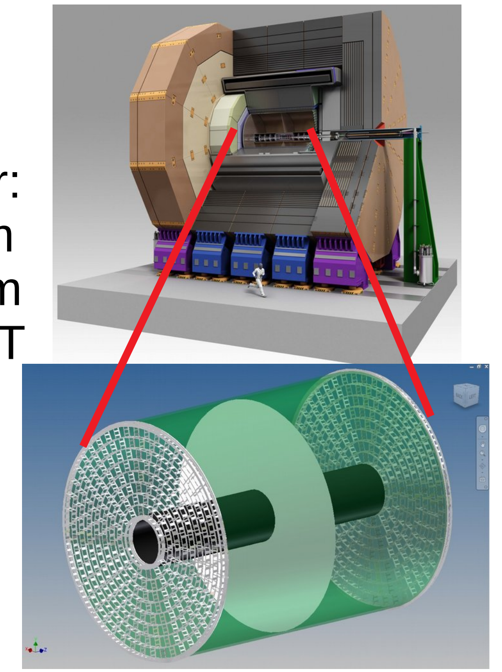


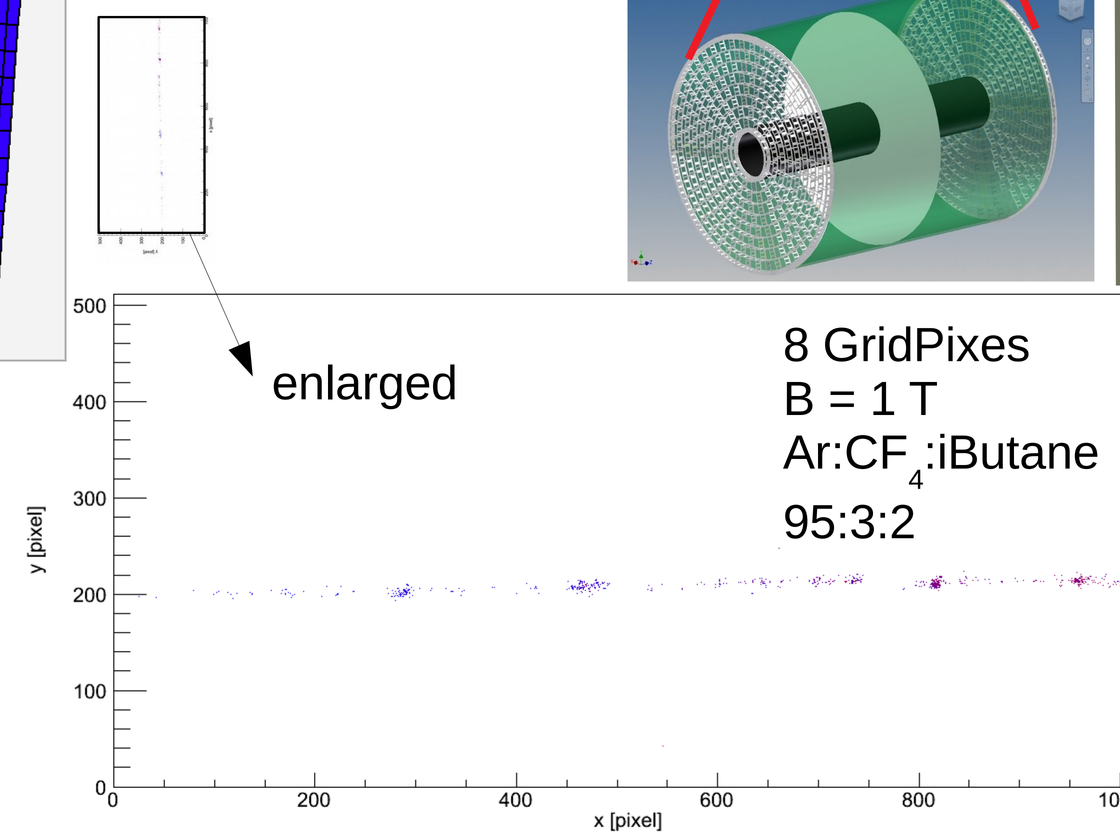
Standard charge collection: Pads of several mm²



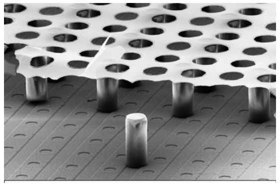
ILD foresees a TPC as central tracking detector:

Length:	2x 2.35 m
Radius:	0.33 - 1.8 m
B:	3.5 T

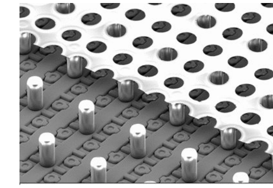




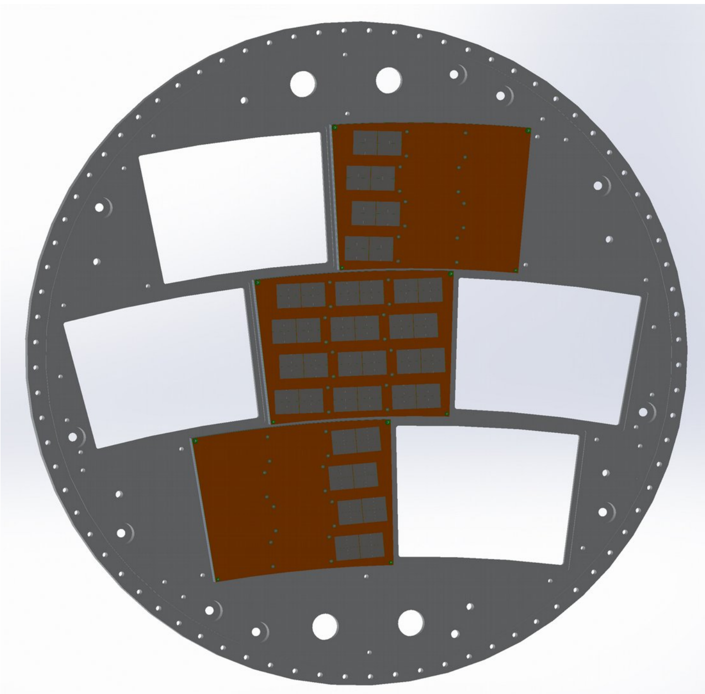
To readout the ILD-TPC with GridPixes:
~100-120 chips/module
→50000-60000 GridPixes

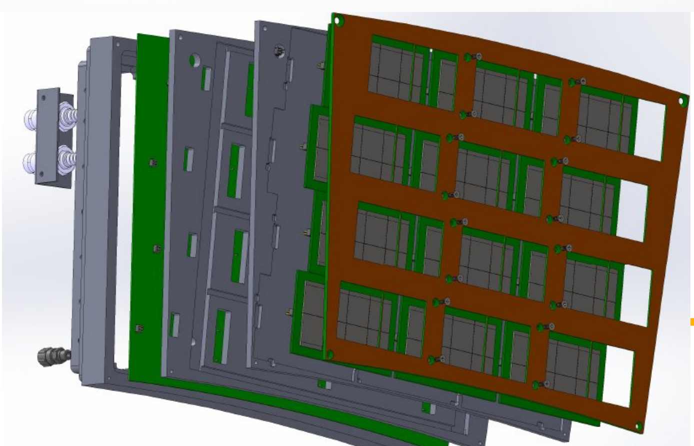


Test with 160 GridPix Detectors

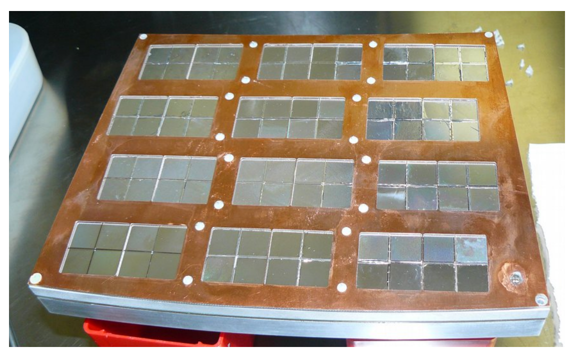


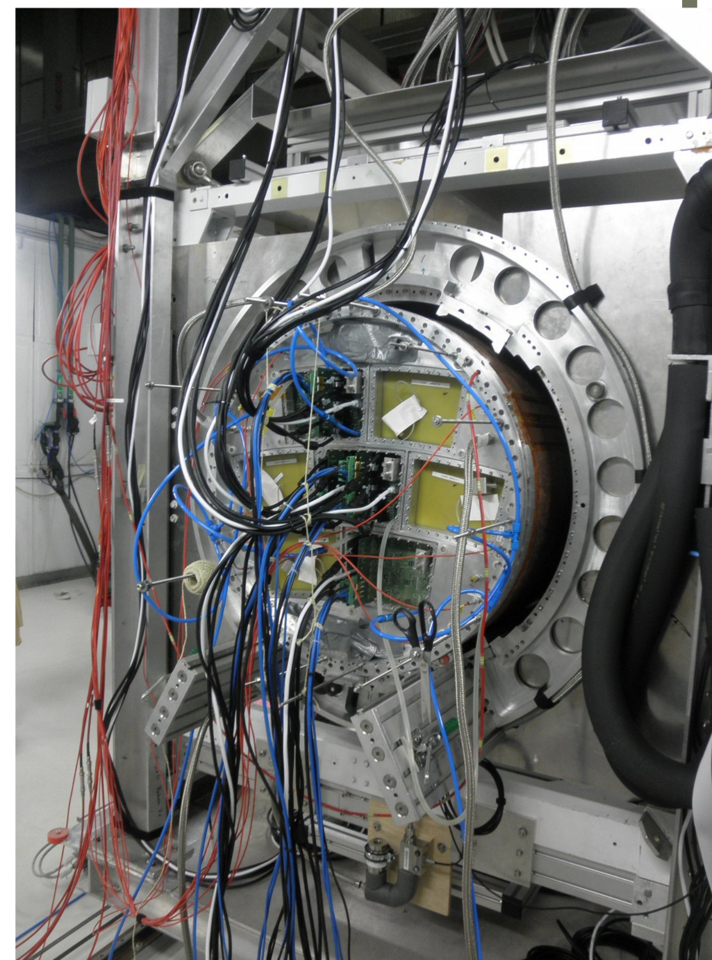
Demonstration of mass production: One LP-module covered completely with GridPixes (96 → coverage 50%) and two partially covered modules.
In total 160 GridPixes covered an active area of 320 cm² (10M pixel detector).



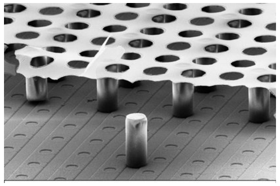


The test beam was a huge success: A pixel TPC is realistic.
During the test beam we collected ~10^6 frames at a rate of 4.3-5.1 Hz.

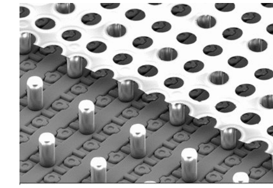


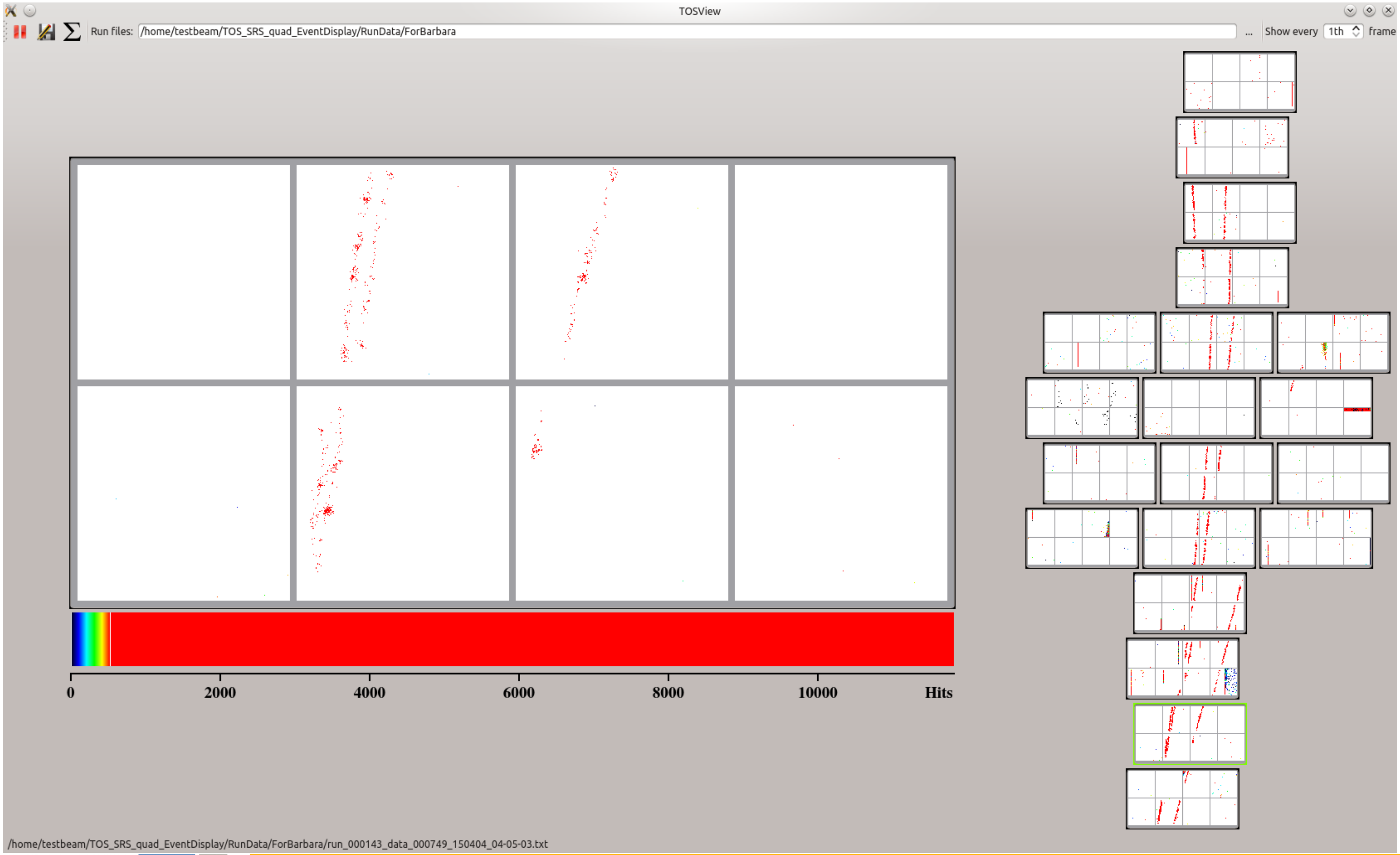


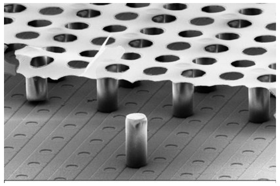
IEEE TNS 64 (2017) 1150



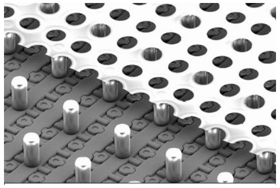
Event Picture



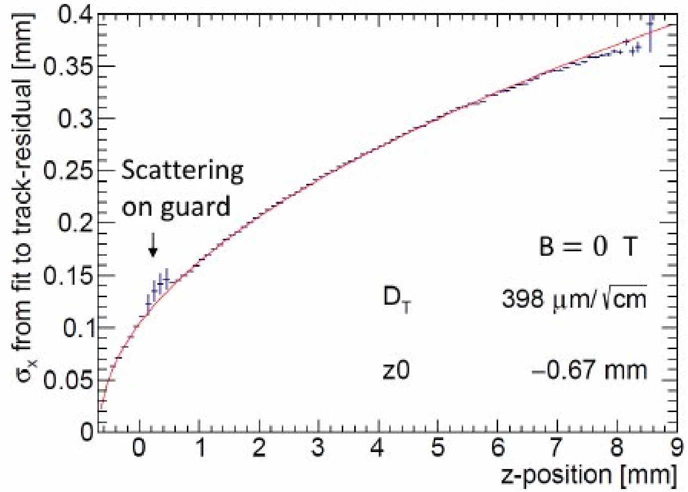


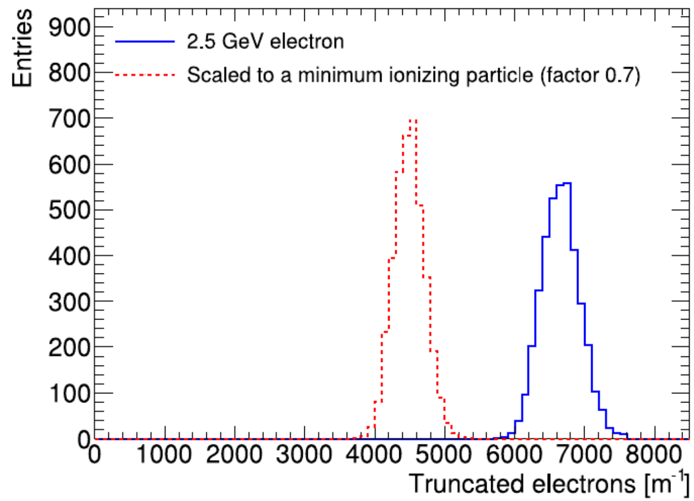


First Detectors with GridPix based on Timepix3



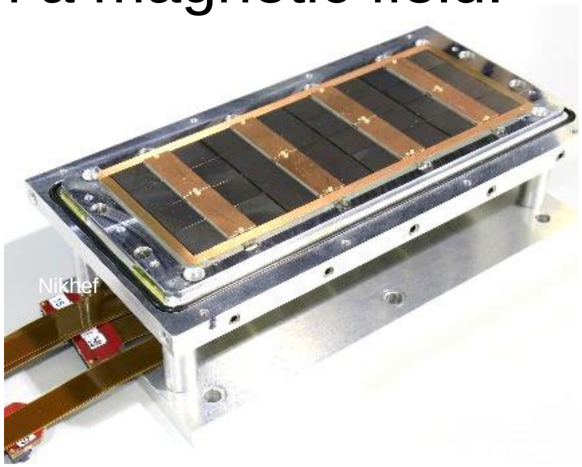
GridPix detector have moved from Timepix to Timepix3 ASICs. Tests with single and quad devices have been successfully done and published.





A first module with 32 GridPixes has been constructed and is being tested in a test beam at DESY - including a test in a magnetic field.

The ion back flow of the module has been measured and can be further reduced by applying a double grid. Also the resistivity of the protection layer will have to be reduced.



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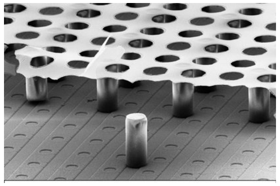
Nikhef

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



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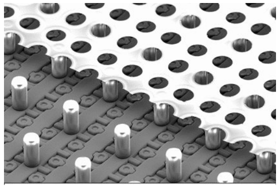
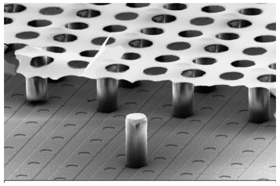
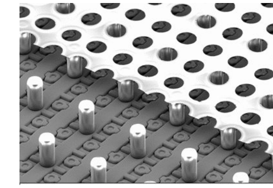
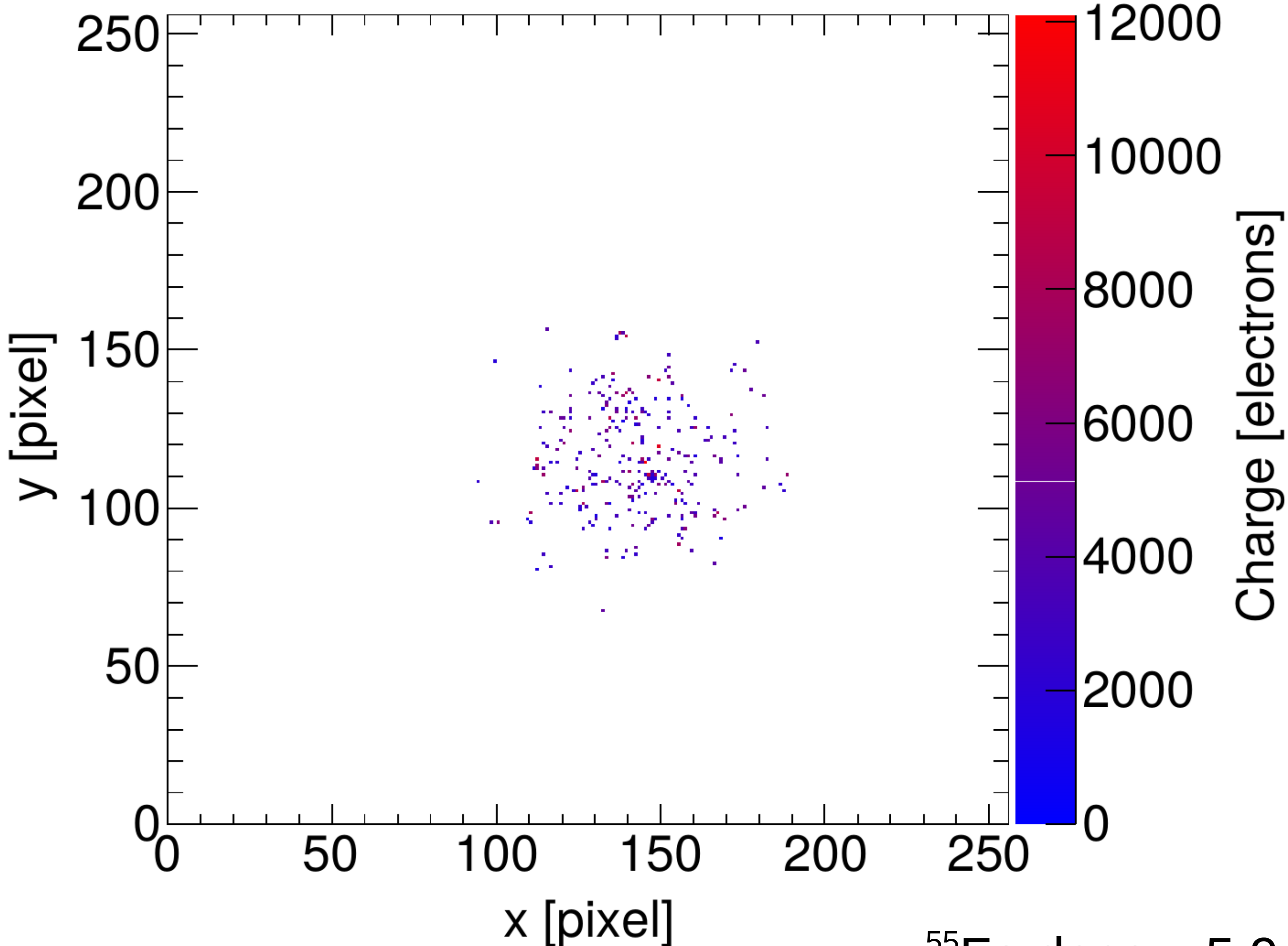


- GridPix Detectors
  - Ingredients
  - Production
  - Optimization
- Applications
  - Tracking detector
  - X-ray detector
    - X-ray polarimeter
    - TR detector
  - Neutron Detector
  - GridPix in a Negative Ion TPC

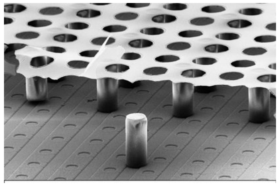


X-ray Event

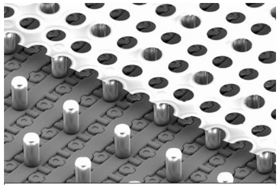




^{55}Fe decay: 5.9 keV photon
→ ~225 electrons

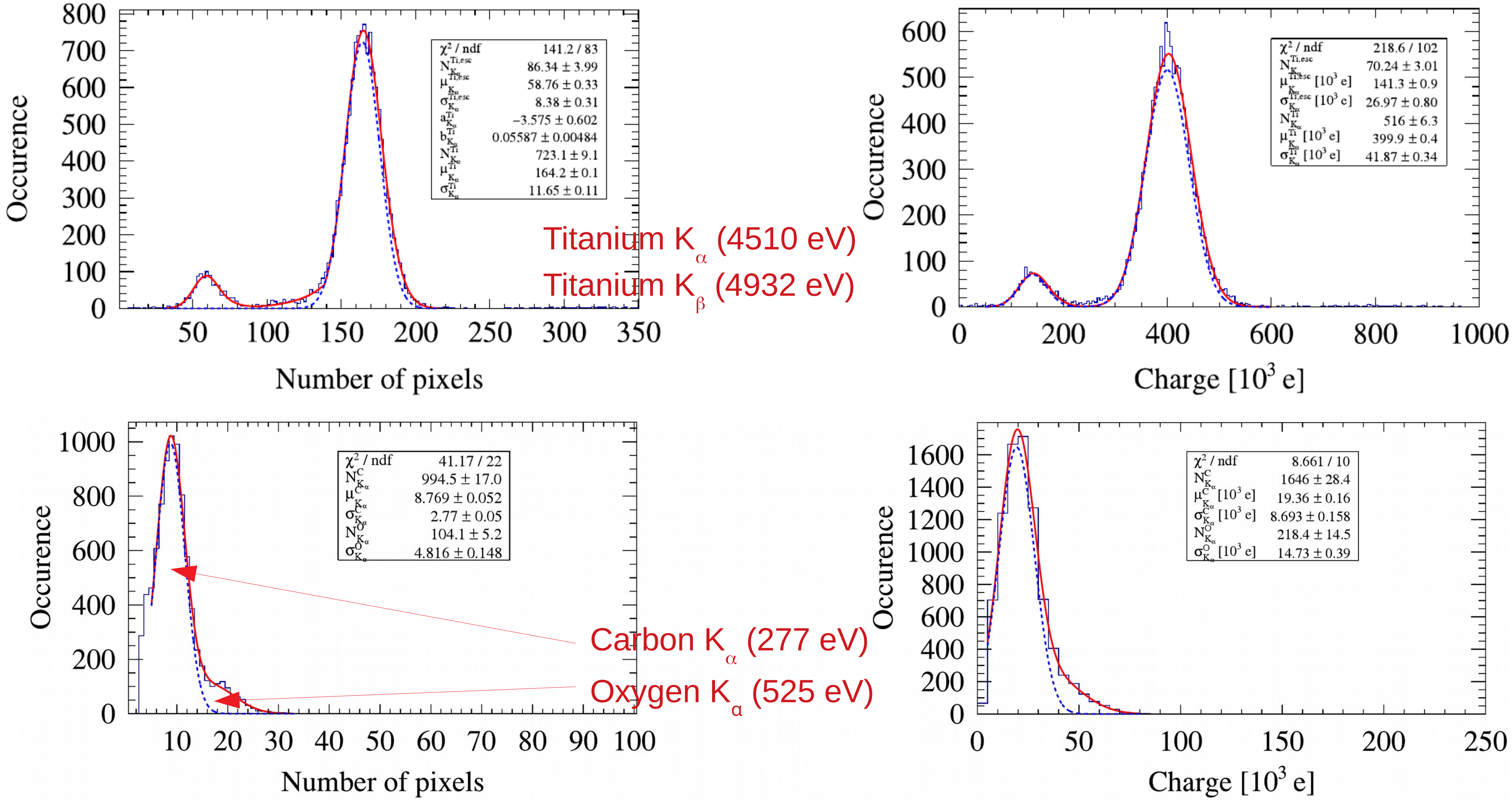


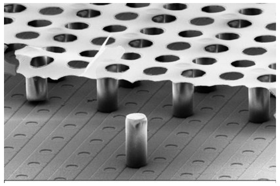
Some X-ray Lines



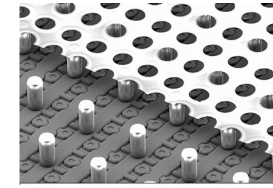
Electron Counting

Charge Summation



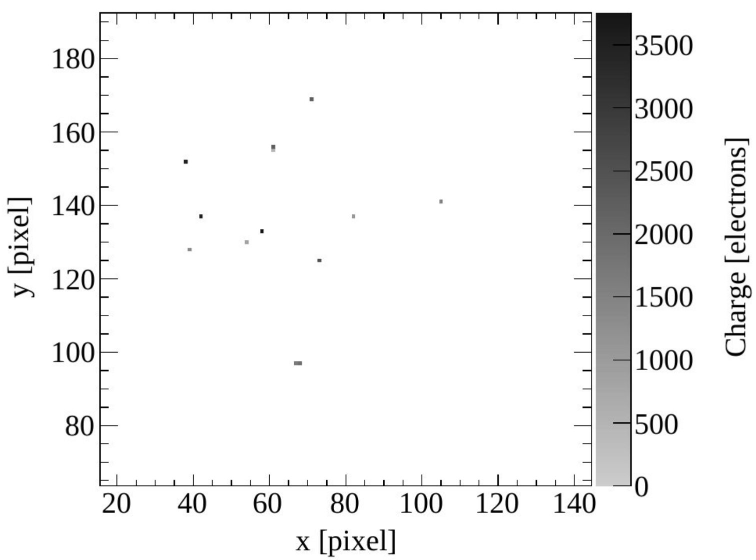


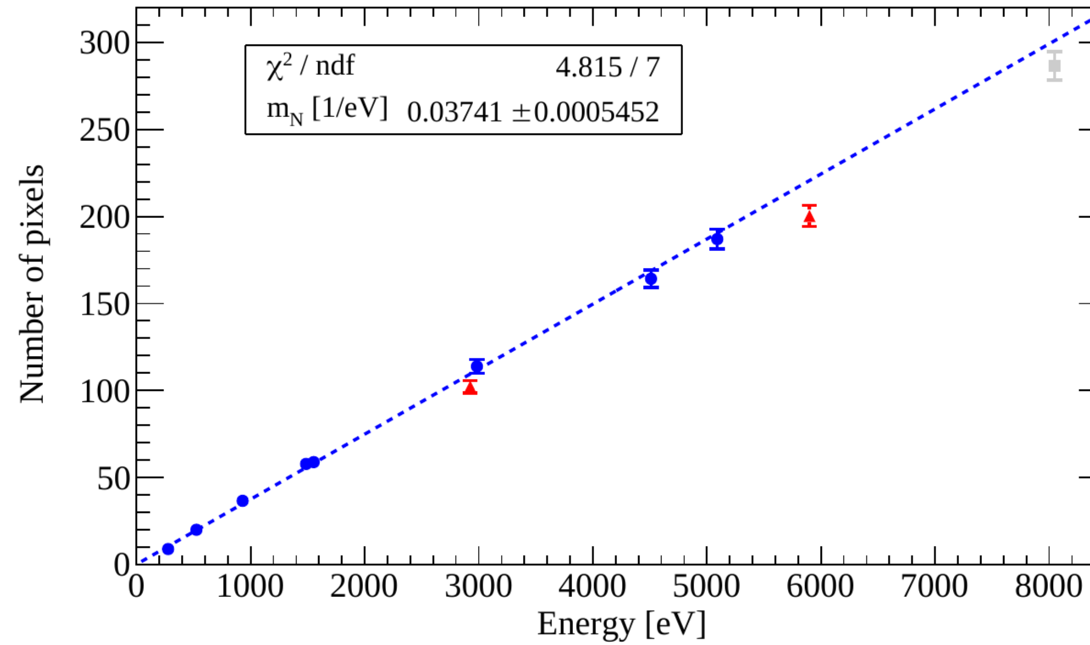
Energy Calibration

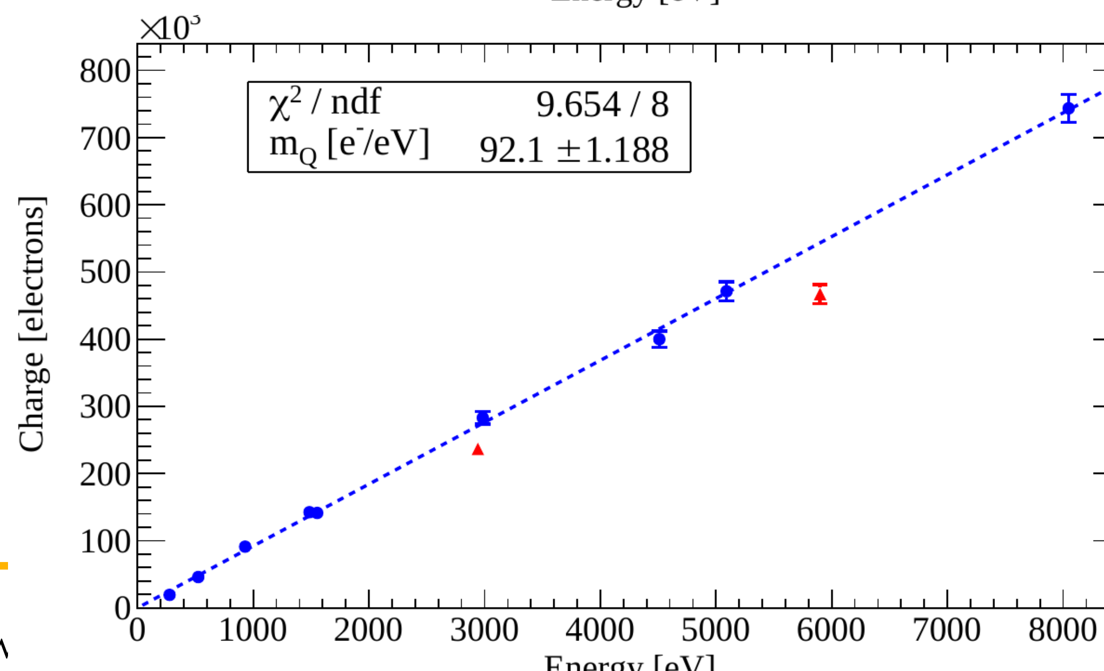


Pixel counting starts failing, if diffusion is not large enough and more than 1 electron ends upon a pixel.
Energy measurement based on collected charge still works fine.

Carbon K_α event (277 eV)







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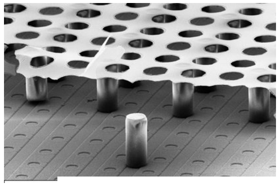
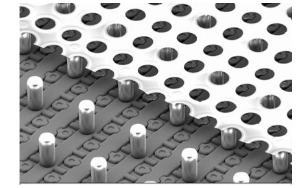
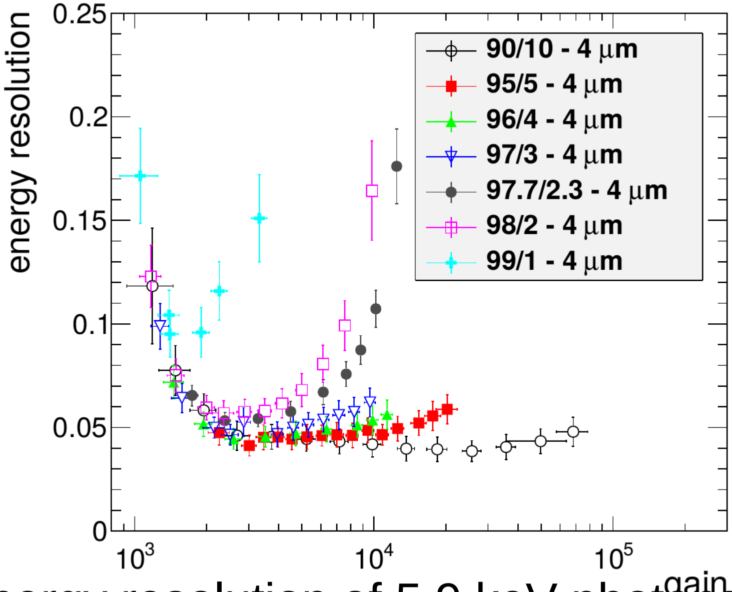
Energy Resolution

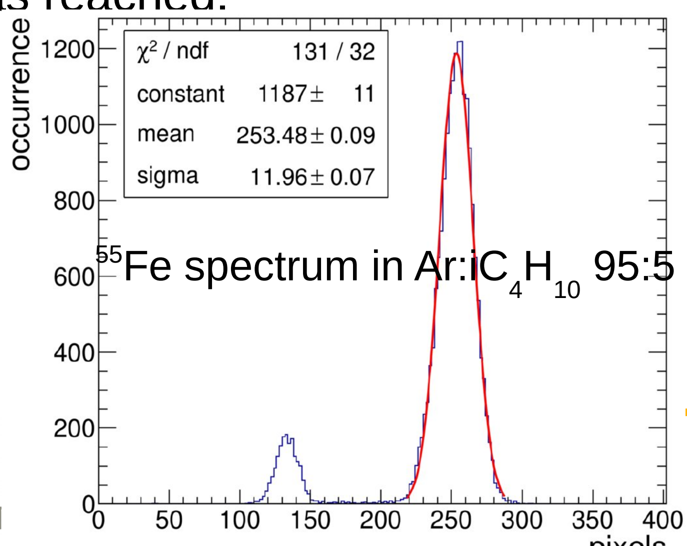






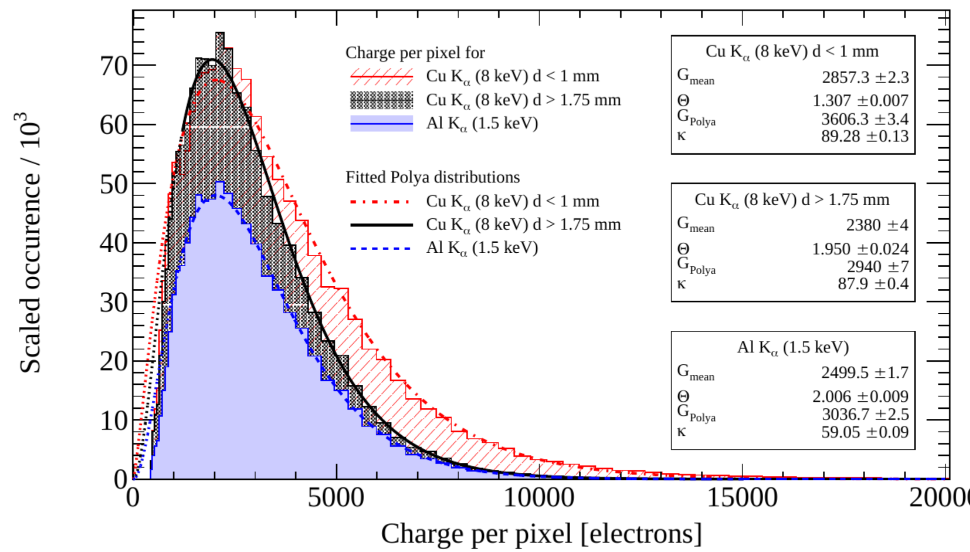
Energy resolution of 5.9 keV photons in various Ar:iC_4H_{10} mixtures.

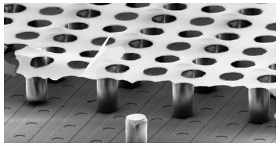
Energy resolution σ_E/E of down to 3.85 % was reached.



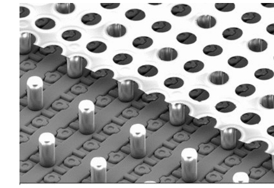
For CAST detailed studies with X-rays.
electron counting = pixel counting
→ high diffusion necessary
Detailed study with variable X-ray source: NIMA 893 (2018) 26-34

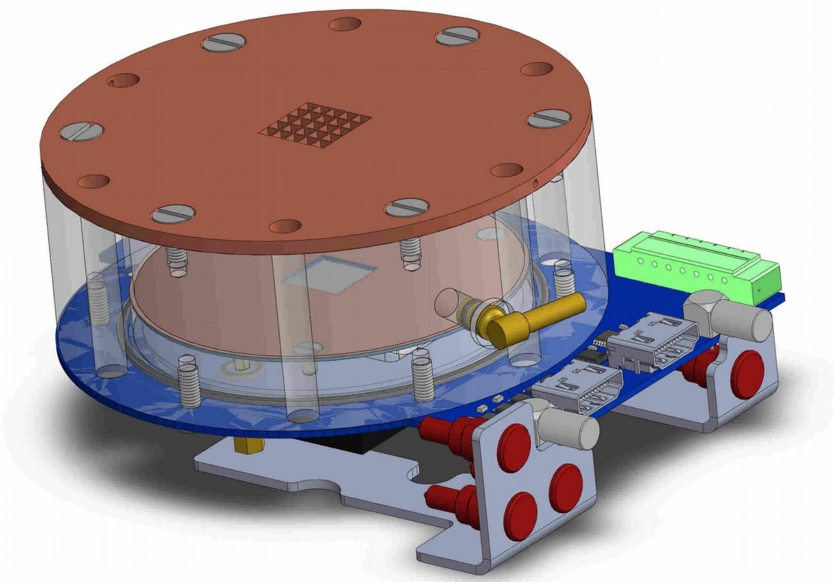
Single pixels show Polya distribution of gas gain

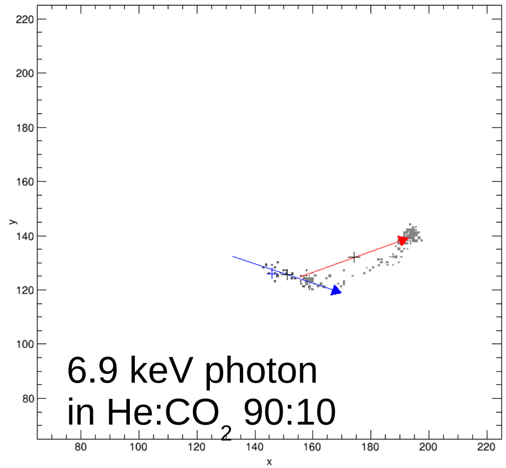


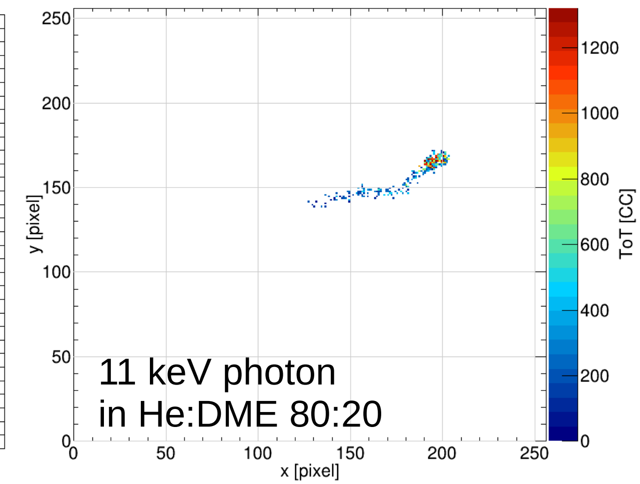


X-ray Polarimetry

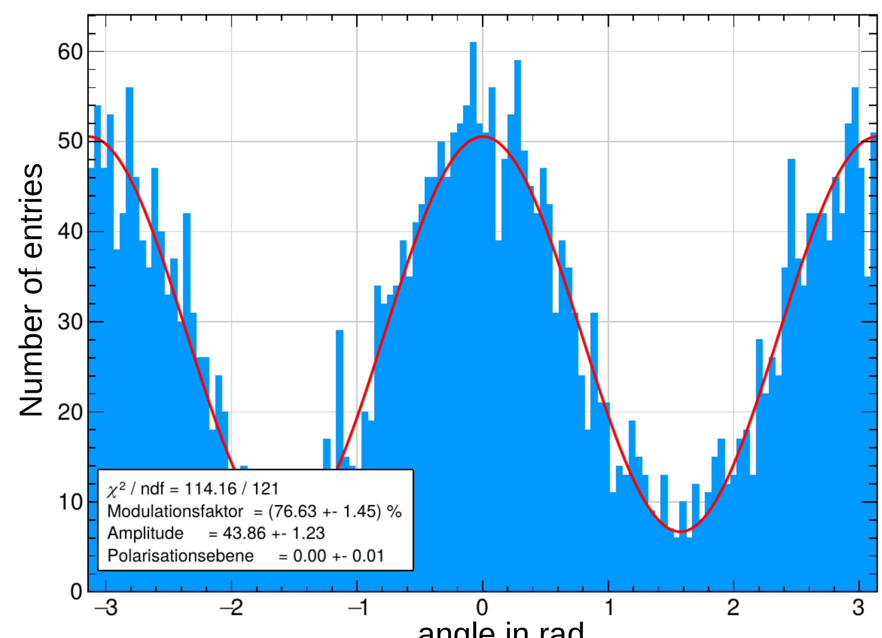


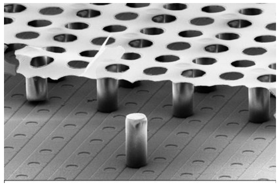




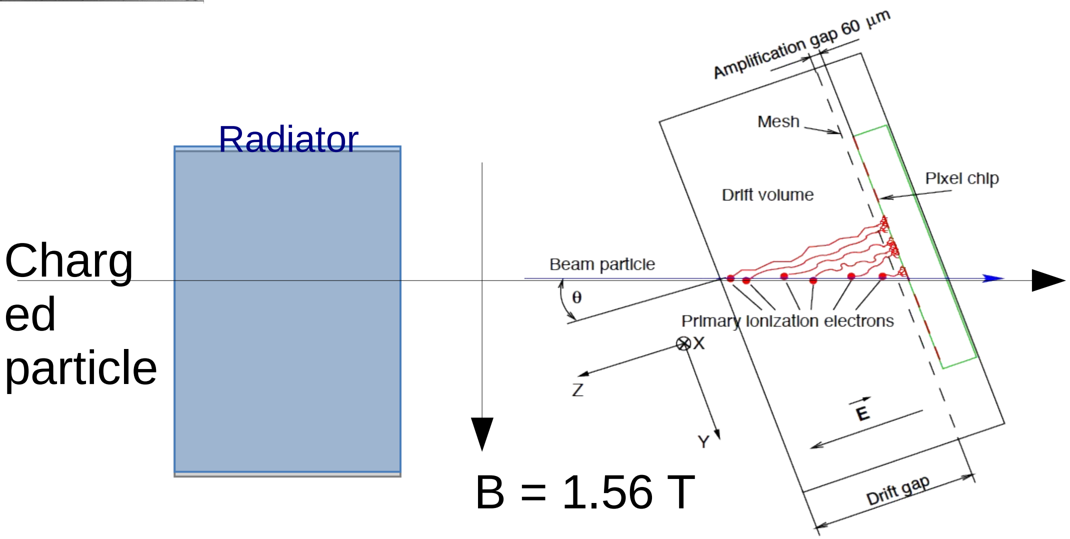


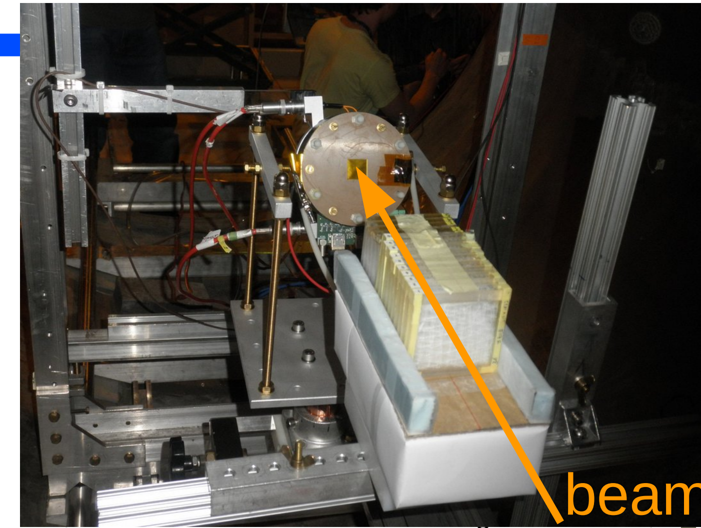
- CAST type detector with 3 cm drift
- Different He-based gas mixtures with CO_2 or DME
- Test beam at PETRA III (DESY) and KARA (KIT)
- Beam energies 4-11 keV
- Track of photoelectron can be reconstructed
- Track follows E-field of polarization
- Beam is >95 % linearly polarized
  - → reconstructed polarization 76 % (sofar)
- Track reconstruction to be improved



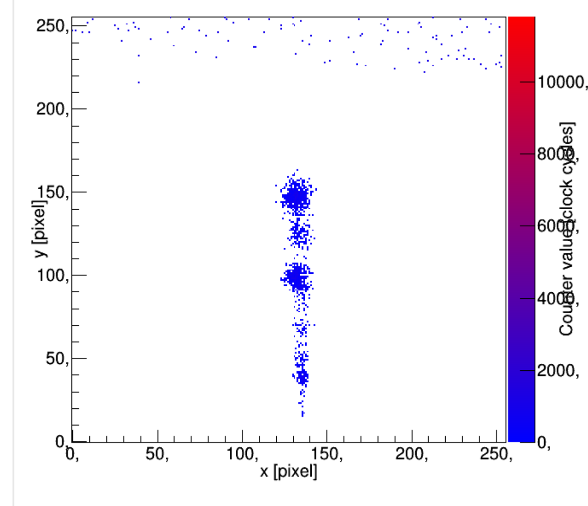


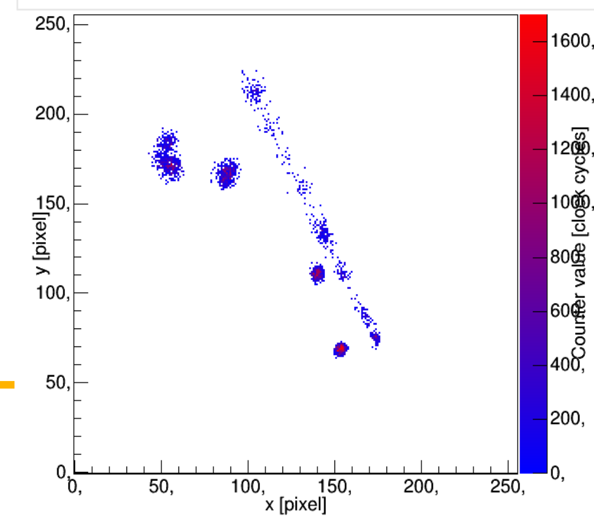
TR Detector





- The particle passes through the detector perpendicular to the grid.
- Free electrons will drift to the grid (Lorentz angle).
- In the magnetic field the track is bent away (~1mm).
- The TR photons will convert at some depth in the drift volume of the detector, not being effected before by the magnetic field.
- Gas mixtures Xe:CO_2:CF_4 80:10:10 and Kr:iC_4H_{10} 80:20





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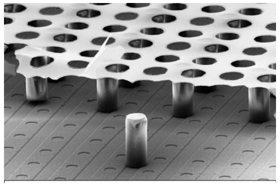

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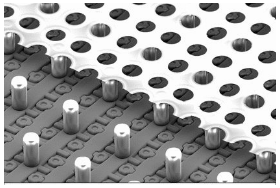

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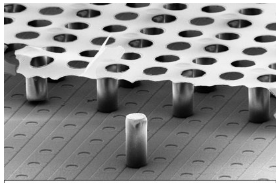
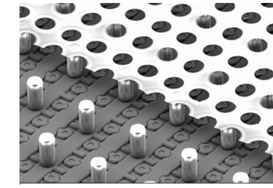
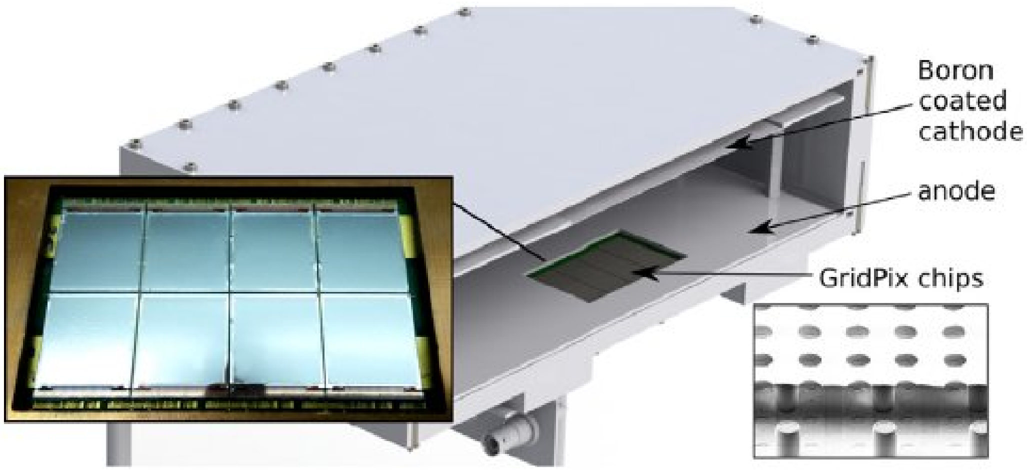
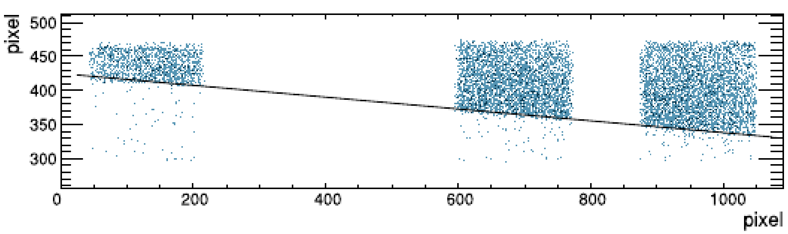


Neutron Detection

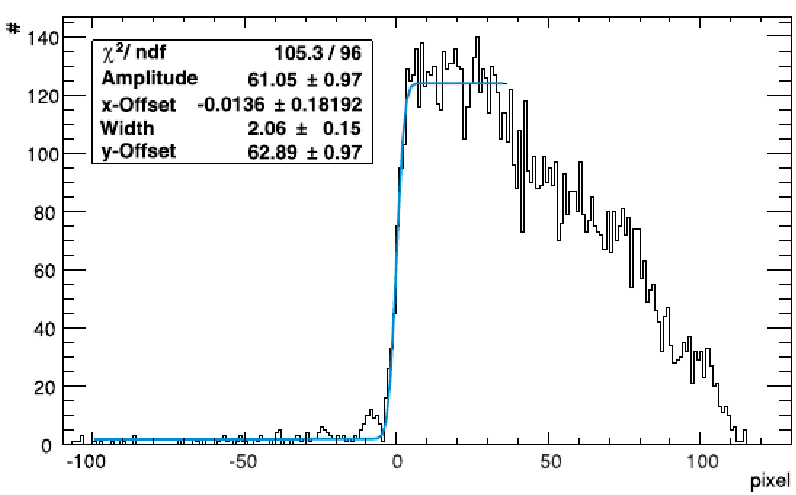




- 8 GridPixes based on Timepix used.
- Placed strip with $^{10}B_4C$ inclined across the GridPixes at a distance of 3.8 cm
- Neutron sources with non-directional beam
- Observed α and Li^{3+} tracks
- Reconstruct head of track
  → point of conversion
- Spatial resolution < 100 µm

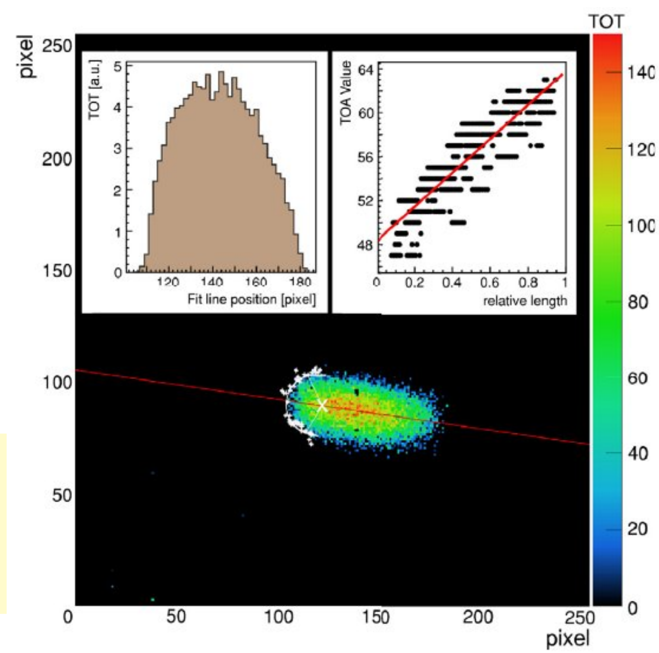


Occupancy of run



Projection along edge

Ideal for directional WIMP search!



Track of α:

- Charge
- dE/dx
- Time of arrival

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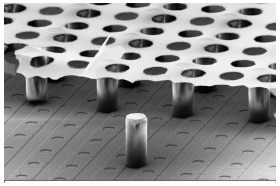
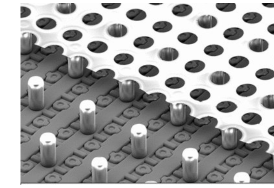
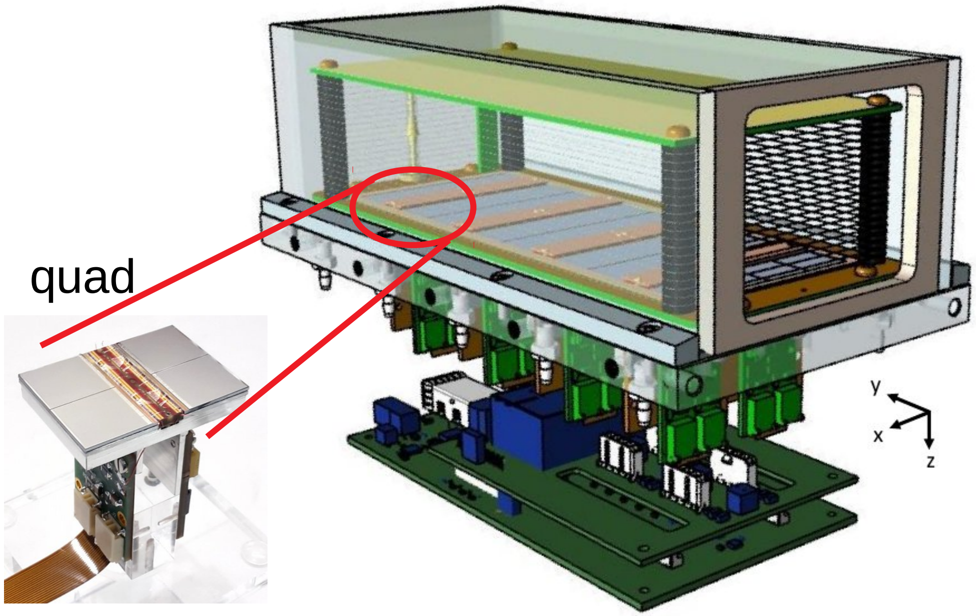


Negative Ion TPC





Detector with 32 GridPixes based on Timepix3

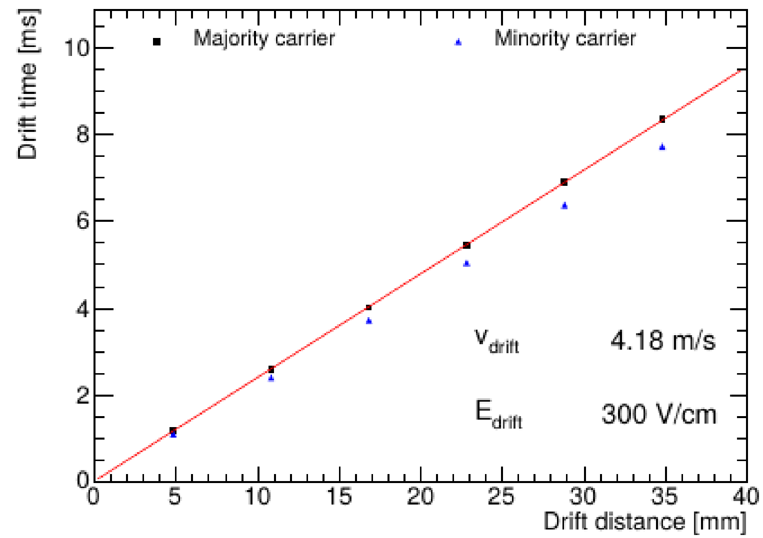
UV laser (337nm) used to generate tracks.

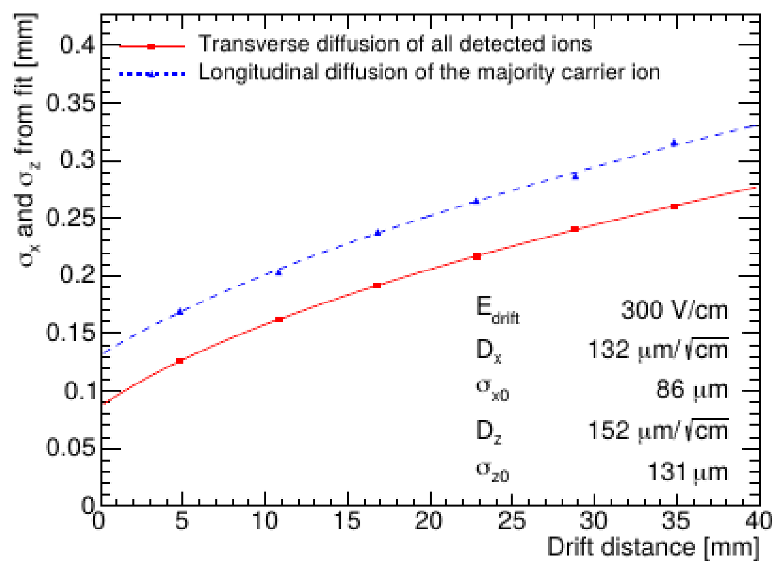
<u>Gas mixtures:</u>

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

+ O_2 (650-1150 ppm) -minority carrier

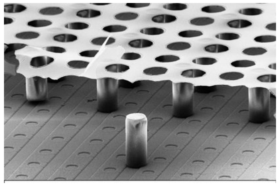
+ TMPD (to enhance sensitivity to laser)



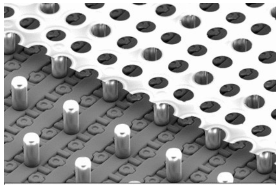


- Gas at atmospheric pressure
- Both majority (CS_2) and minority (O_2) carriers observed
- Transverse diffusion at thermal limit
- Have to optimize gas mixture.

C. Ligtenberg, et al. ‘On the properties of a negative-ion TPC prototype with GridPix readout’ Submitted to NIM



Summary



GridPix gives a detailed, high resolution picture of of the event.

GridPixes based on Timepix can be operated reliably and in large numbers (up to 160).

GridPixes based on Timepix3 are being tested at the moment. Operation with an SRS-based readout system is starting.

Production of GridPixes will be transferred from Berlin to Bonn next year.

Acknowledgements: This is of course the work of many people. In Bonn these are:
Yevgen Bilevych (who builds the InGrids), Christoph Krieger, S. Schmidt, T. Schiffer (CAST), Michael Lupberger (LCTPC), Markus Gruber (X-ray polarimetry), Markus Köhli, Saime Gürbüz, Divya Pal (n detectors) and of course Klaus Desch.
Special thanks goes to our technical team: H. Blank, W. Ockenfels, S. Zigann-Wack, as well as the electronics and mechanical workshops.
Also at Nikhef many colleagues are working on this.