Characterization of SiC Timepix3 Detector and Spectral-Tracking Response to Protons and Mono-Energetic Fast Neutrons

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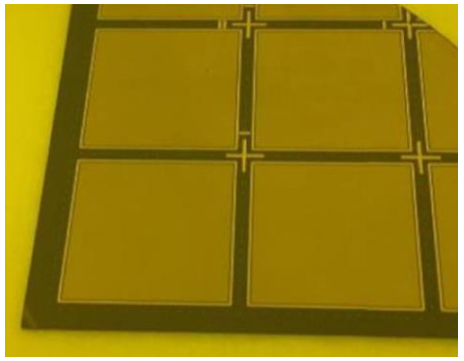
4H-SiC sensor development: motivation

- **4H-SiC sensor overview:**
  – high breakdown voltage, large displacement energy, high electron mobility and electron saturation drift velocity,
  – **suitable for high radiation dose applications**,
  – prepared as a very thin **80/100 µm thick epitaxial layer**,
  – bump-bonded to Timepix3 chip [1] (see poster P2.2 by Bohumir Zatko),
  – due to the the bias voltage limit of 200 V, **only 65 µm fully depleted**.

- Four 4H-SiC sensors prepared, **two fully functioning detectors**.
- Measurements at proton and fast neutron sources were performed – **response characterisation** to well-defined and mixed radiation field components.
- High-resolution pattern recognition analysis and spectral tracking of single particles.
  - Inspection and **characterisation** of the 4H-SiC **sensor signal**, **charge collection response** and its **homogeneity**.
  - The goal is to use this device as a particle tracker for composition and spectral **characterization of radiation fields in radiation harsh environments**.



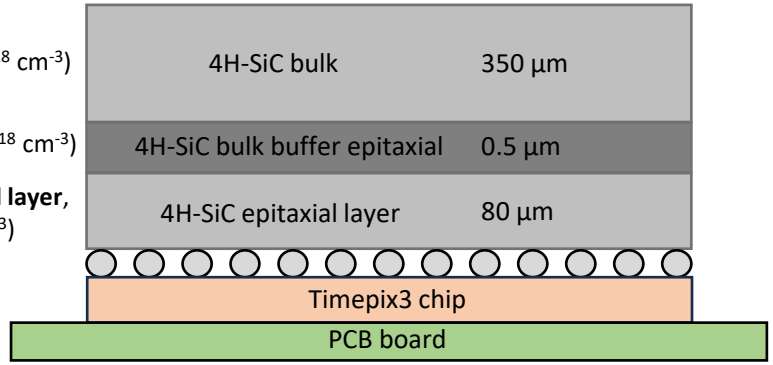
Prepared pixelated structure on 4H-SiC epitaxial layer.

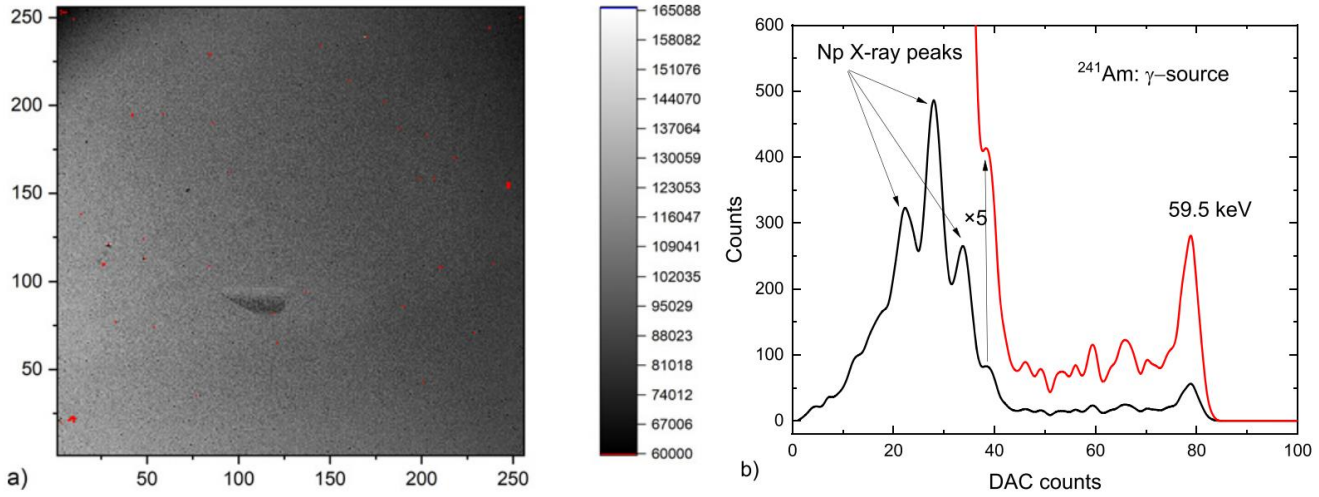
MiniPIX Timepix3 hybrid pixel detector with 4H-SiC sensor

„From a single silicon carbide detector to pixelated structure for radiation imaging camera“, B. Zat'ko *et al* 2022 *JINST* **17** C12005 – in the references you can find multiple publications on 4H-SiC material characterisation and initial preparation for Timepix3 chip.

4H-SiC sensor development: sensor performance

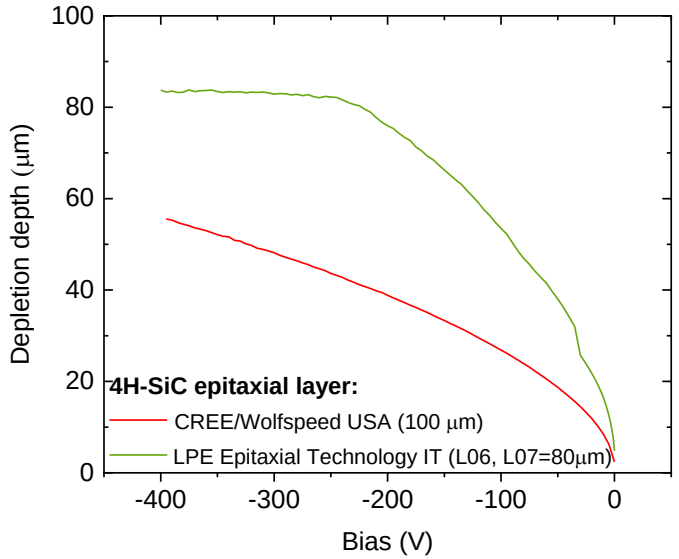
- Pixel structure was prepared for hybrid pixel detector Timepix3.
- 4H-SiC sensor – **epitaxial layer of 80 µm** thickness.
- **Four sensors were tested – two working properly**, bump-bonded to TPX3.
  - Sensor 1 (LPE 80 µm, **L07-W0048**) – bias voltage 200V.
  - Sensor 3 (LPE 80 µm, **L06-W0048**) – bias voltage 200V, better performance.
- **LPE sensors tested and calibrated** – sensor not fully depleted, **requires long exposures**.
- Spectral performance results of L06 – demonstrated in [2].





X-ray open-beam illumination

γ-ray spectrum generated by ^{241}Am for single selected pixel

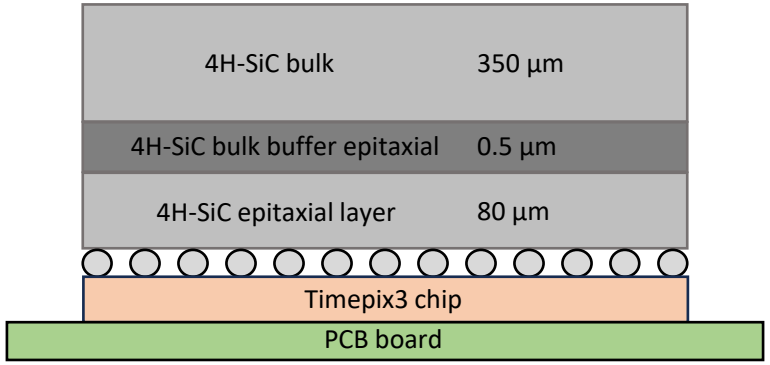


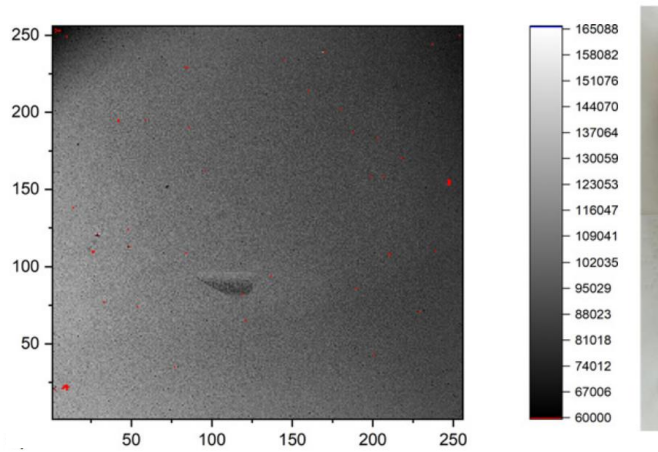
The depletion depth as a function of reverse bias voltage from C-V measurement. Four 4H-SiC sensors were acquired from two suppliers, green line corresponds to the best L06 sensor supplied by LPE Epitaxial Technology.

X-ray radiography with MiniPIX-Timepix3 4H-SiC detector

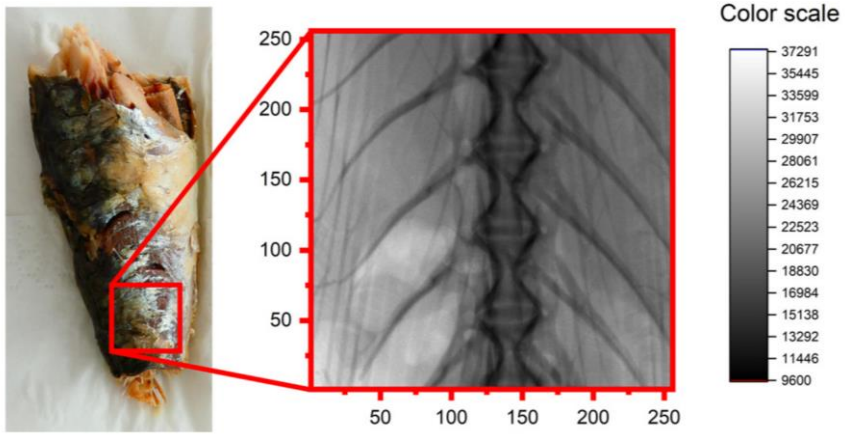
- Open-beam image and sardine X-ray – first SiC X-ray image [1].
- **Active thickness of SiC is 65 µm at 200 V bias**.
- Comparison with 300 µm fully depleted Si sensor.
- **Visible result of SiC dead zone** (365.5 µm thick SiC) on top of active layer.

- **Future remarks** – improve the SiC sensor desing to prevent shortages at larger bias – **full sensor depletion at approximately 300 V**.

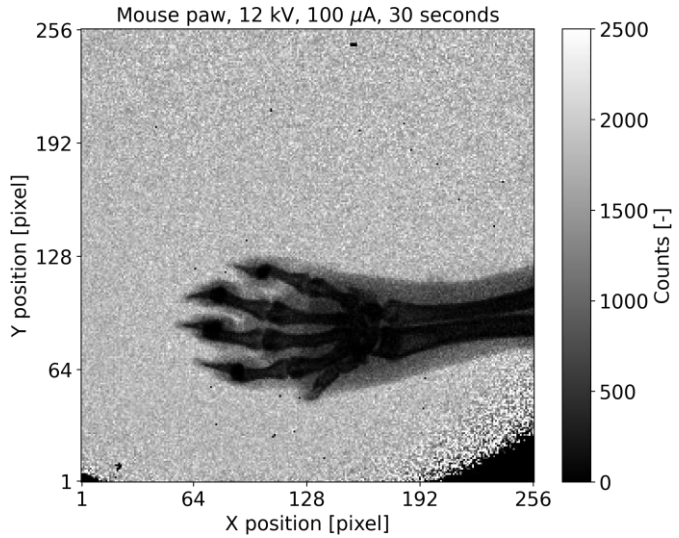




X-ray open beam image TPX3 L06 4H-SiC 65 µm

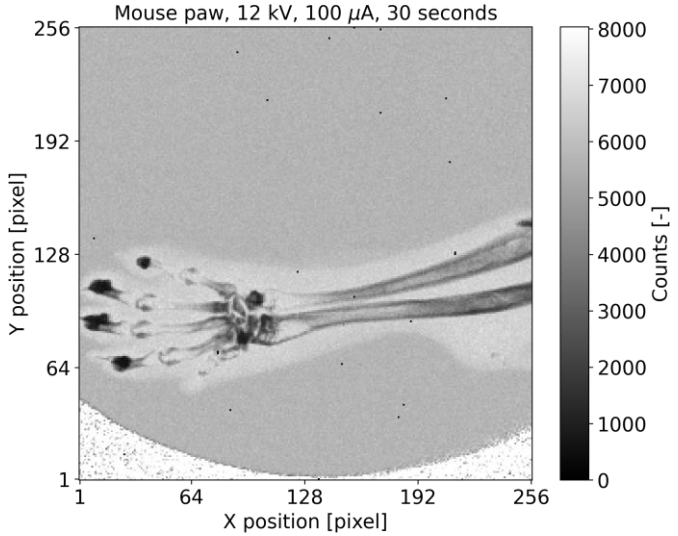


X-ray image of sardine fish using TPX3 L06 4H-SiC 65 µm



TPX3 L06 SiC 65 µm, 300 frames, 0.1 s, flat-field corrected

X-ray tube with 12 kV, 100 µA, Ag anode
Samples of mouse paws – courtesy of Mgr. Andrej Feješ, Medical Faculty, Comenius University in Bratislava



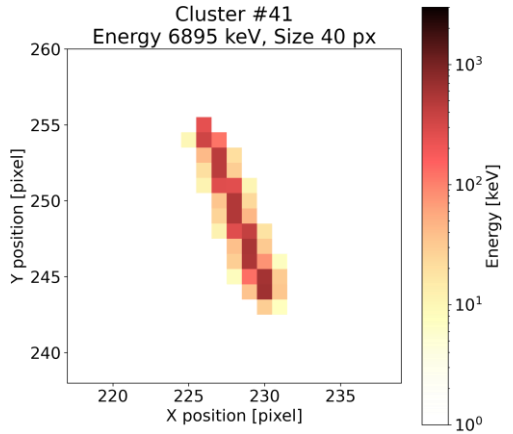
TPX3 C05 Si 300 µm, 300 frames, 0.1 s, flat-field corrected

Proton and neutron calibrations: MiniPIX Timepix3 4H-SiC

- **Two 4H-SiC TPX3 MiniPIX detectors (L06, L07)** used for spectral tracking of **protons** at experiments at two cyclotrons
  - **U-120M** – proton cyclotron accelerator, 13, 22 and **31 MeV**, **rotation scan** – 0 (perpendicular), 45, 60, 75, 80, 88, 90 (parallel) degrees.
  - **Proteus-235** – proton cyclotron accelerator, 100 MeV, 226 MeV, rotation scan 0 (perpendicular), 45, 75, 90 (parallel) degrees.
- **Mono-energetic fast neutrons – D-D/D-T reaction at Van de Graaf accelerator** IEAP, CTU Prague. Fast neutron energies from 0.3 to 17.5 MeV.

- Data analysed using the **Data Processing Engine (DPE)**, a tool for extensive and systematic data processing of TPX/2/3 data. In development by Advacam + ESA (see poster P 1.14 by Lukáš Marek).
- Pre-processed data further analysed and filtered in parameter ranges to separate particle groups in the acquired data.

31 MeV proton,
88° angle of beam incidence



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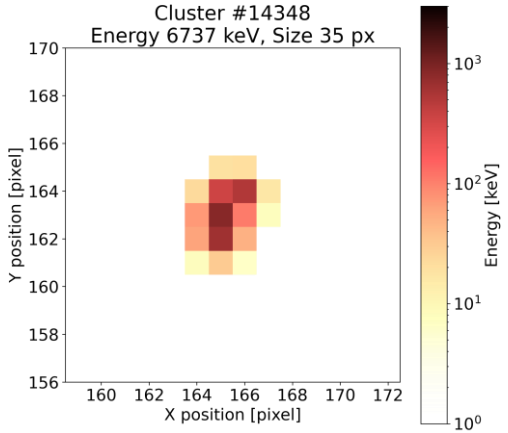
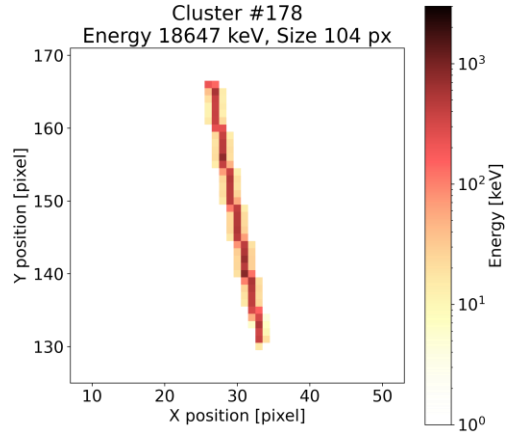
15.5 MeV mono-energetic
fast neutron interaction



PROTON THERAPY CENTER

226 MeV proton,
90° angle of beam incidence



Mono-energetic fast neutrons 15.5 MeV: deposited energy and cluster size distribution

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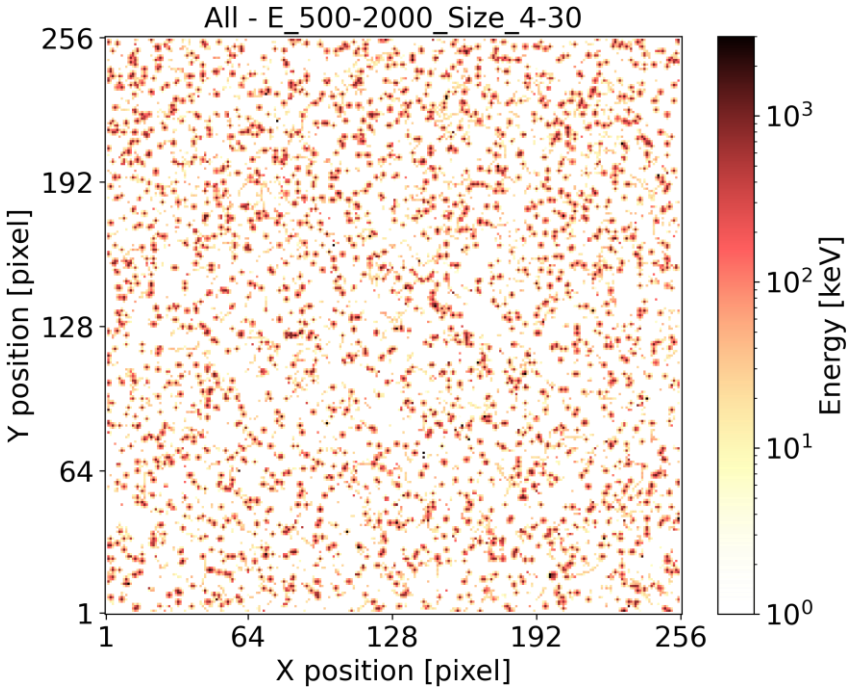
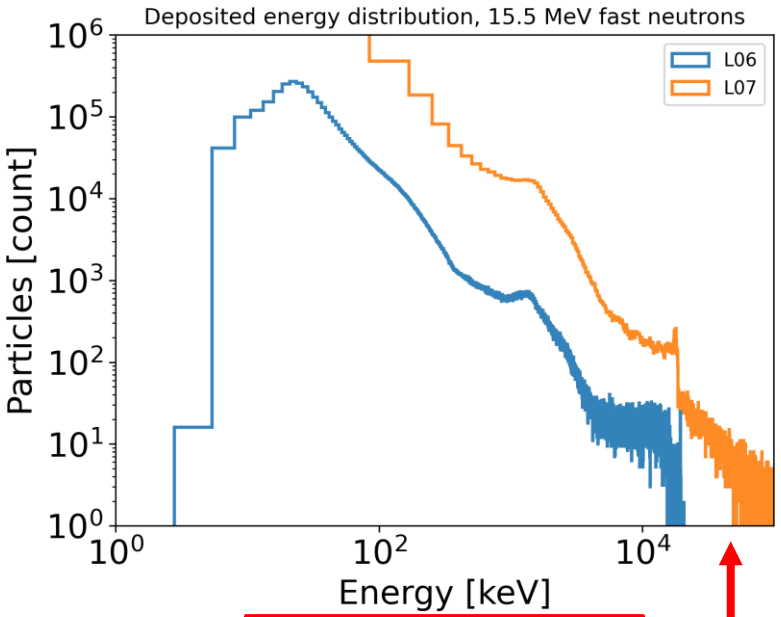
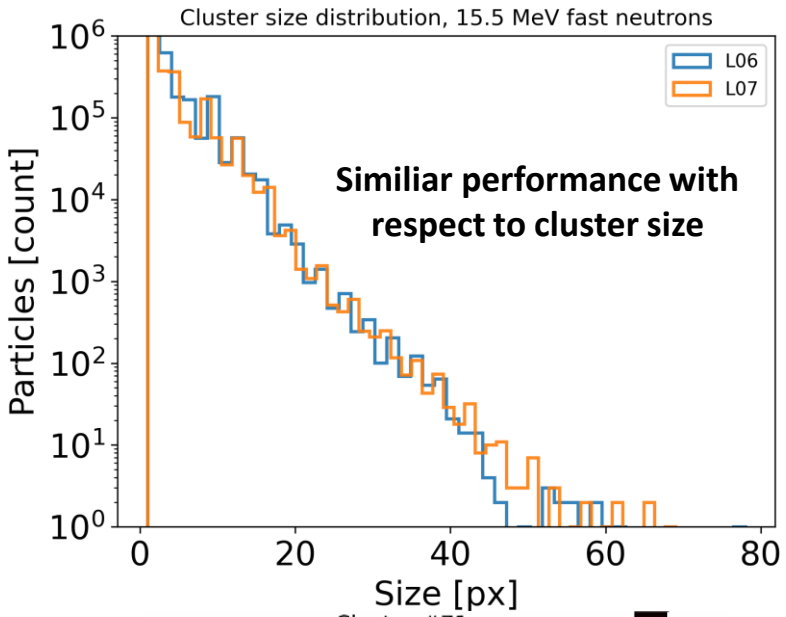
Full pixel matrix of deposited energy in L06
– filtered events in the **medium energy/size range**.
– LE electrons, protons/heavy ions passing through the sensor under low angle.
– main contribution to the specra – LE events and photons.

2000 filtered events in medium range



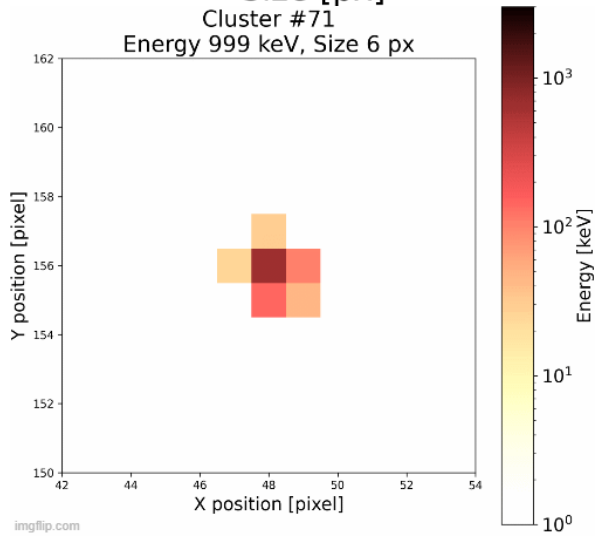




Noise? Requires further investigration

Single particle track visualization in 65 µm 4H-SiC sensor on Timepix3, medium energy/size range

Range	Energy [keV]	Size [px]
Low	0-500	0-4
Medium	**500-2000**	**4-30**
High	2000-8000	30-100



Mono-energetic fast neutrons 15.5 MeV: cluster height and LET distribution

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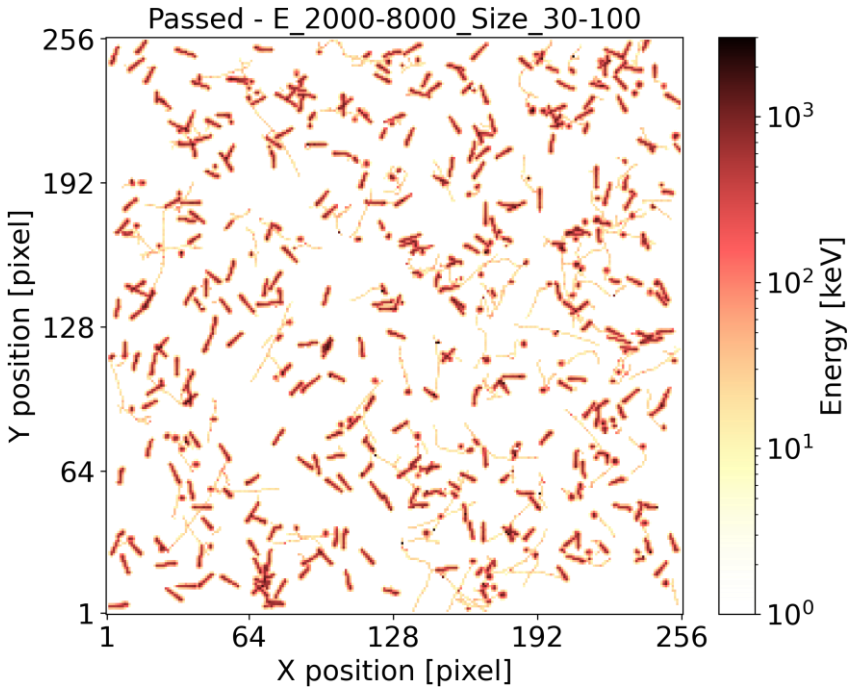
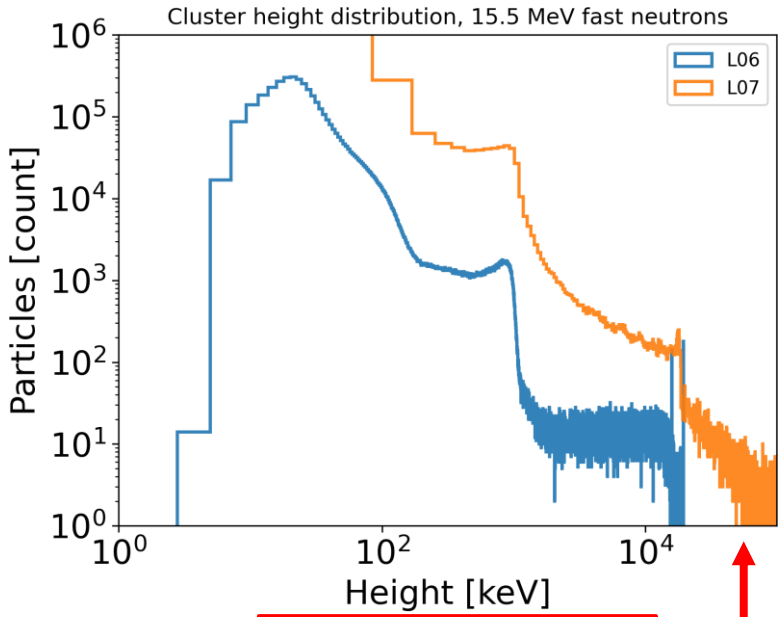
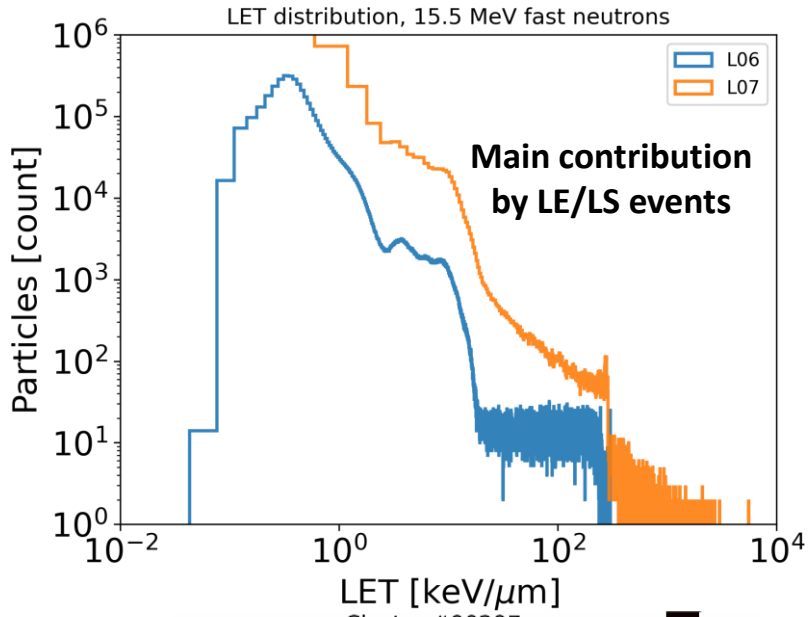
Full pixel matrix of deposited energy in L06
– filtered events in the **high energy/size range**.
– protons/heavy ions passing through the sensor under higher angle.
– electrons traversing in the sensor plane.

Filtered events in high range







Noise? Requires further investigration

Single particle track visualization in 65 µm 4H-SiC sensor on Timepix3, high energy/size range

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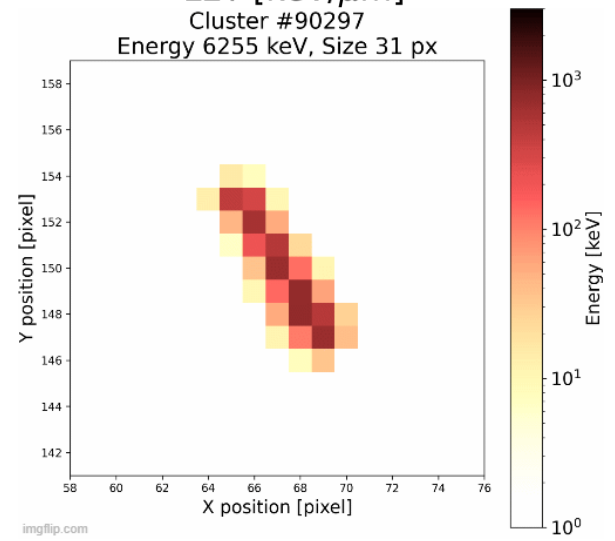


Spectral tracking of 31 MeV protons: deposited energy and cluster size distribution

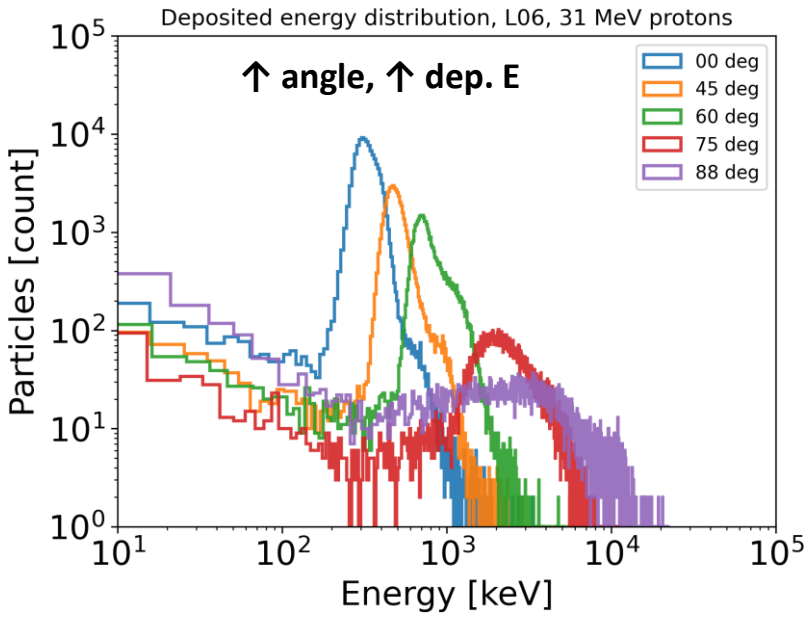
Light ion cyclotron accelerator U-120M, UJF Rez.

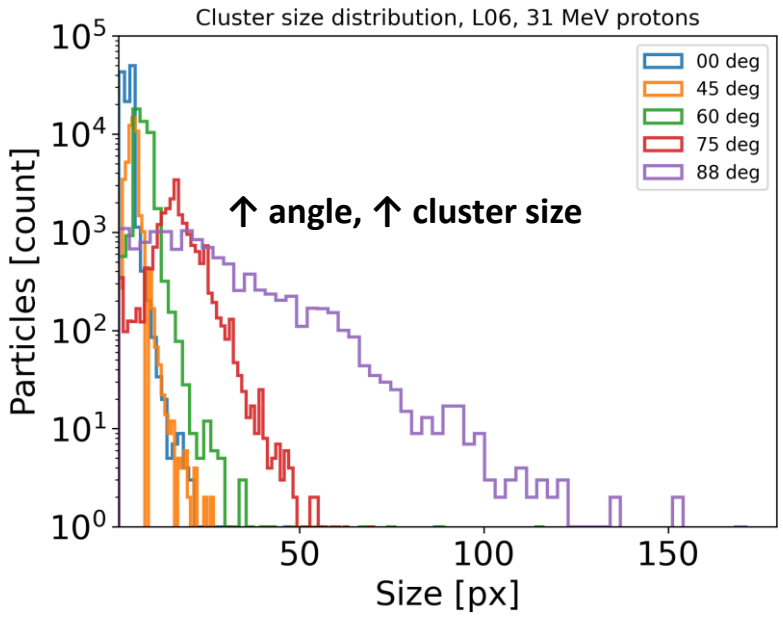
Full pixel matrix of deposited energy in L06

– filtered events in the **medium energy/size range**.

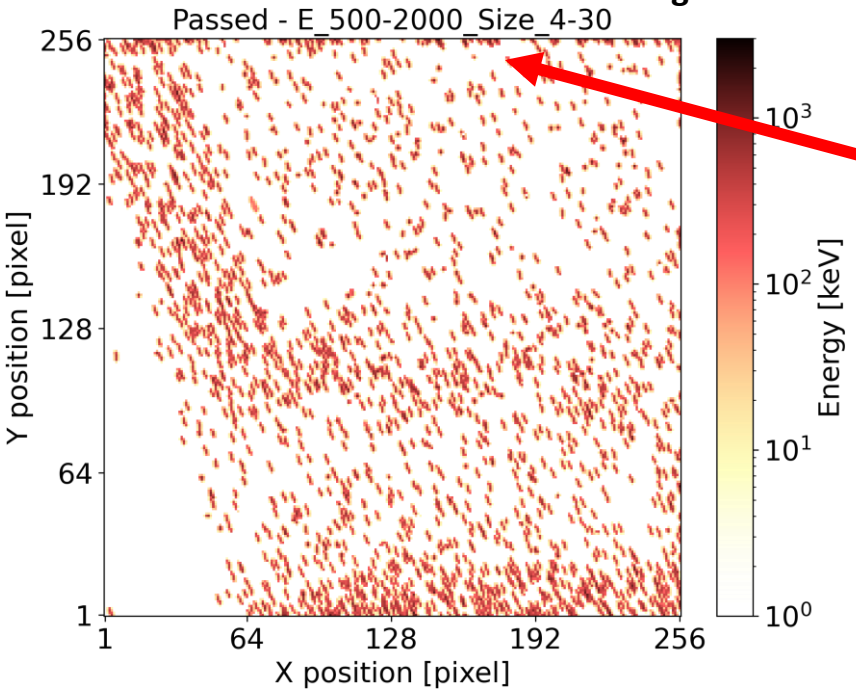
– filtered protons, rotation scan.

– increased angle, higher deposited energy, larger cluster size.



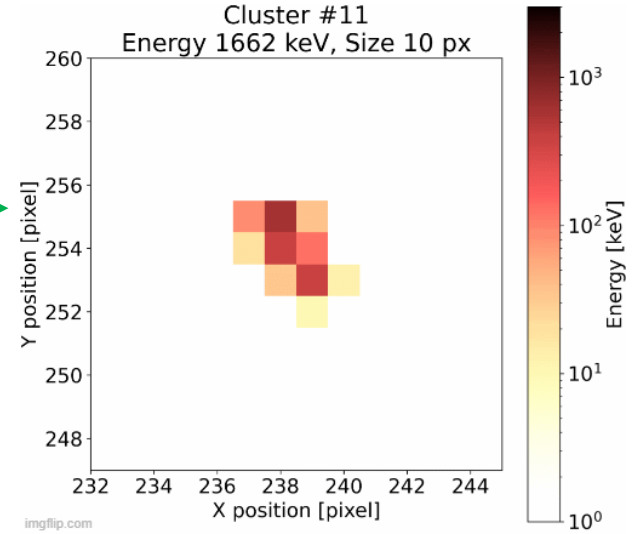


2000 filtered events in medium range



At high angles, protons enter from the sensor's side (shown 75° angle)

Proton tracks, medium energy/size range, 85° angle of proton beam incidence



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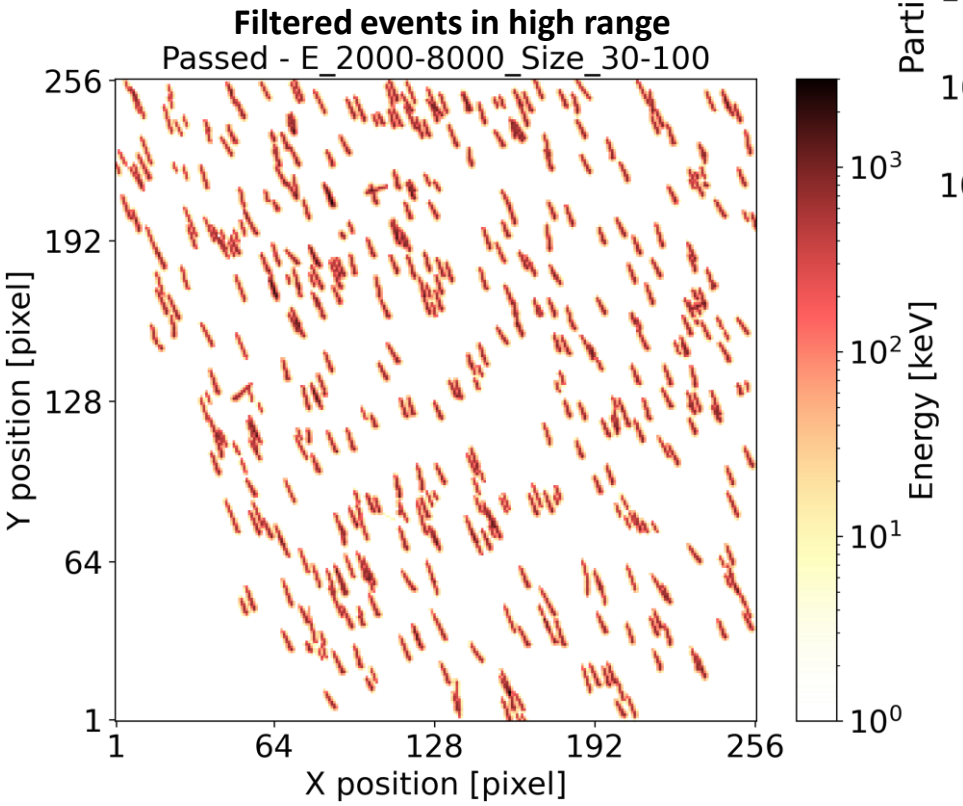
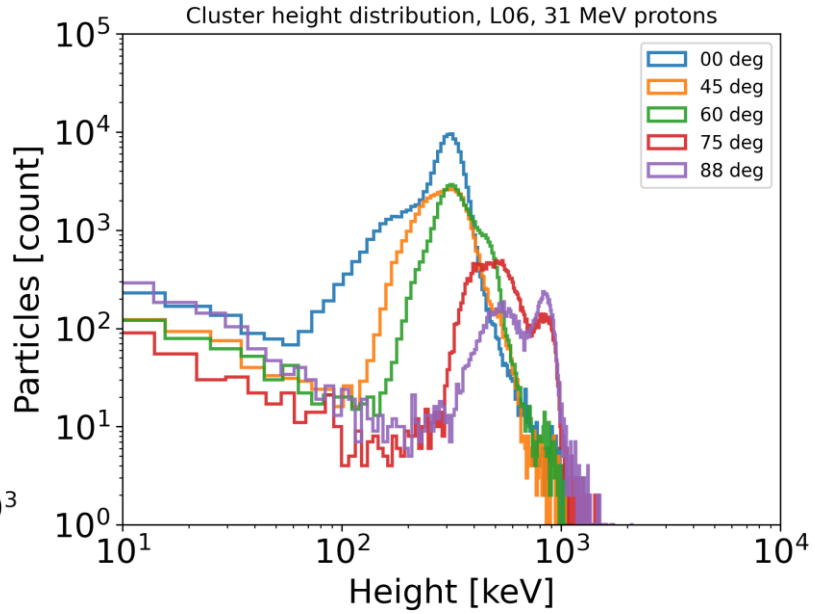
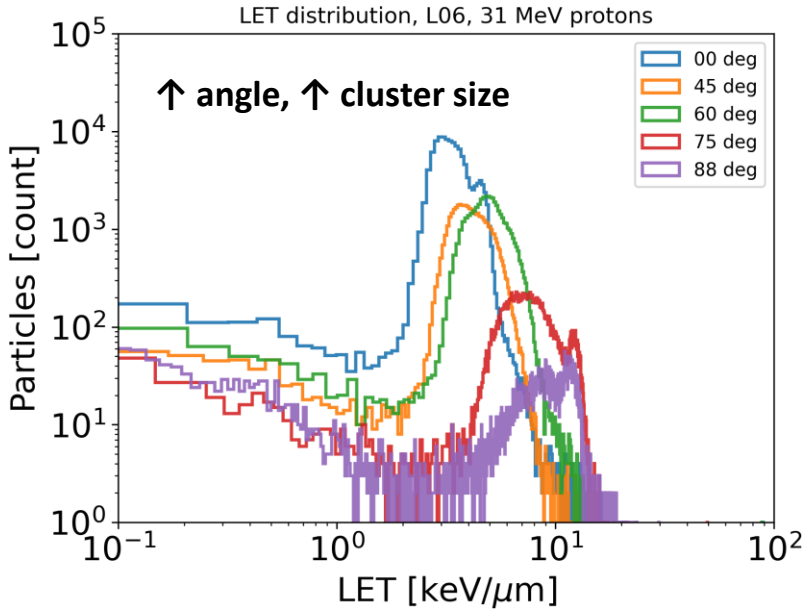
Spectral tracking of 31 MeV protons: cluster height and LET distribution

Full pixel matrix of deposited energy in L06
– filtered events in the **high energy/size range**.
– filtered protons, rotation scan.
– increased angle, higher deposited energy, larger cluster size.

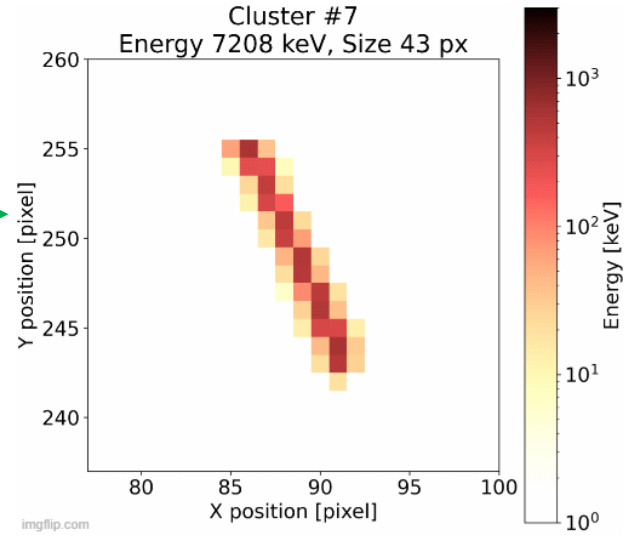






Proton tracks, high energy/size range, 85° angle of proton beam incidence

Range	Energy [keV]	Size [px]
Low	0-500	0-4
Medium	500-2000	4-30
High	**2000-8000**	**30-100**



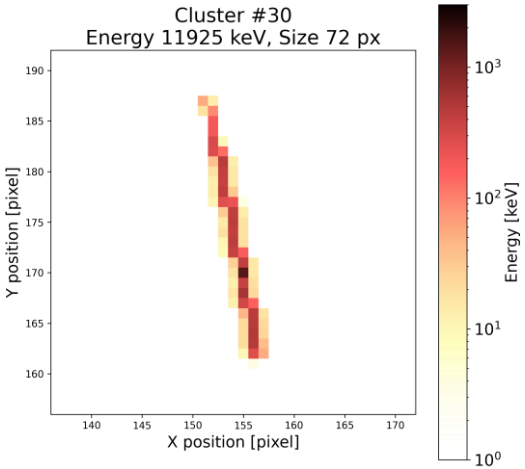
Conclusion and future remarks

- **New 4H-SiC sensors were manufactured and tested**.
- At 200V bias, **65 µm fully depleted** out of 80 µm epitaxial layer.
- The 4H-SiC sensor is **homogeneous**.
- **Threshold level low and homogeneous**.
- As a result **particle tracks are smooth** and continuous (not broken).
- The per-pixel spectral response of both L06 and L07 is homogeneous with good response.
- The possibility of use of the 4H-SiC sensor for imaging as well as for broad spectrum component detection.

- Future work:
- improve the sensor design to allow **higher applicable bias** – 4H-SiC full depletion requires ~300V.
- **Determine absolute detection efficiency for fast neutrons** – further analyse the existing calibrated data and by perform calibrations in a well-defined neutron fields.
- Verify the detector's **performance at varying temperatures**.
- Experimentally measure the sensor's **radiation hardness** (expected to be **$10^3\times$ higher compared to Si**).

MiniPIX Timepix3 hybrid pixel detector with 4H-SiC sensor

MiniPIX Timepix3 hybrid pixel detector with 4H-SiC sensor and sulful layer applied



Proton detected by L07-W0048 at Proton Therapy Center Prague, 225 MeV, 90° angle of proton beam incidence

Thanks to the iWoRiD organizers

We are open to collaboration

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