Gain suppression studies on LGAD sensors at the CENPA tandem accelerator (PIONEER Experiment)

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43rd RD50 Workshop, 28. November – 1. December 2023

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PIONEER Experiment

- New pion decay experiment approved at PSI, data taking to be started in 2028
- First beam time assigned in May 2022, second in November 2023

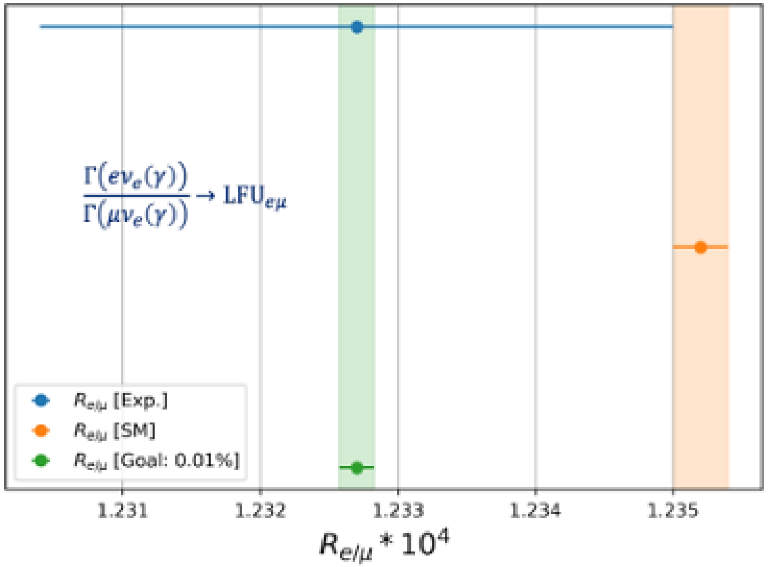
Phase 1

$$R_{e/\mu} = \frac{\Gamma(\pi^+ \rightarrow e^+(\gamma))}{\Gamma(\pi^+ \rightarrow \mu^+(\gamma))}$$

Lepton flavor universality → charged lepton flavor universality violation?

SM prediction ca. 15x more precise than experiment!

Phase 2 (3)

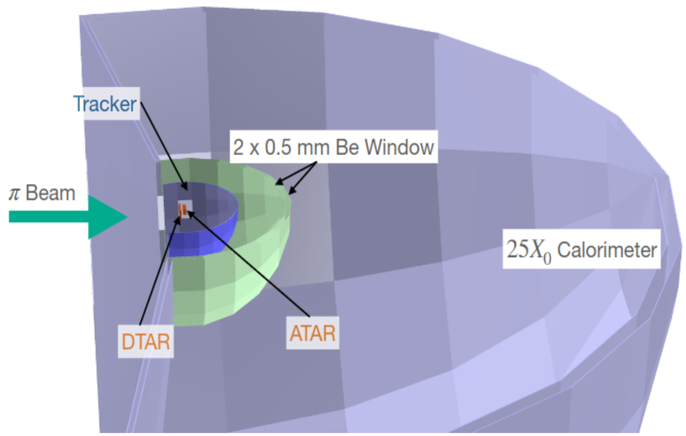


https://arxiv.org/abs/2203.01981

Detectors in PIONEER

Tracker
μ-RWELL

- Nominal design: homogeneous, cylindrical tracker
- Optimized experiment geometry: bullet-shaped or spherical?

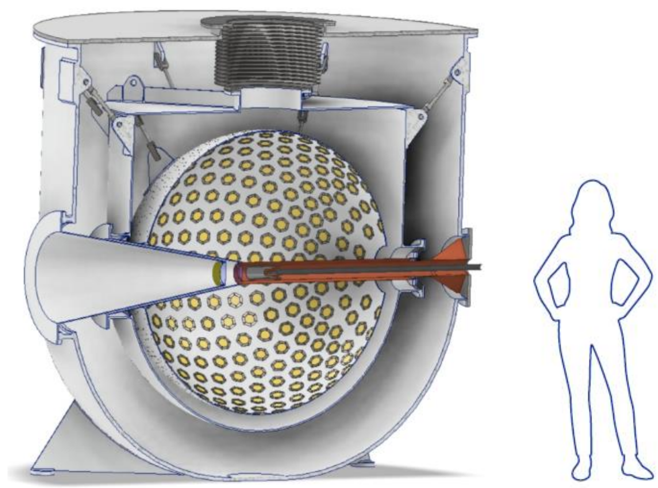


3π calorimeter
7t LXe

- Dense, uniform
- Fast response, excellent energy resolution

- Challenges: photosensors, cost, photonuclear effects
- **Alternative: LYSO:Ce crystal scintillators**

Active Target



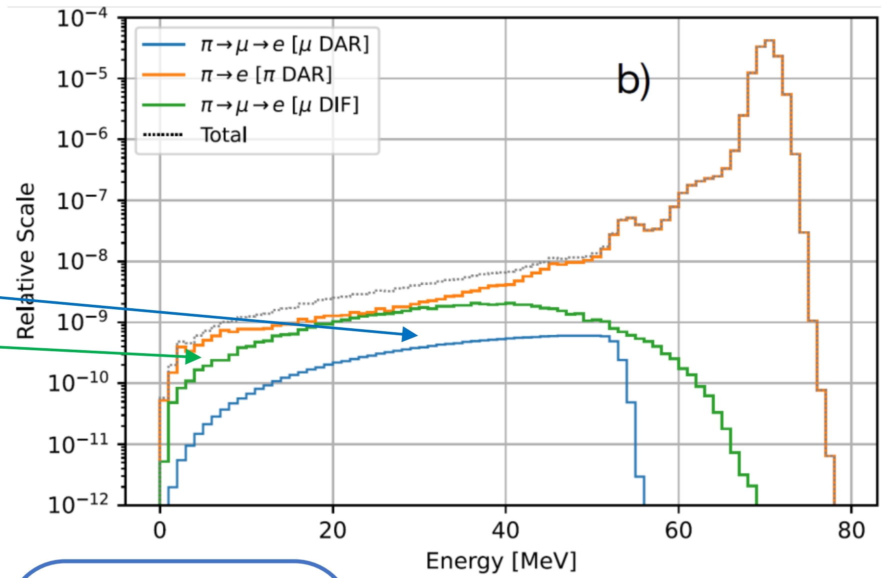
Degrader Target

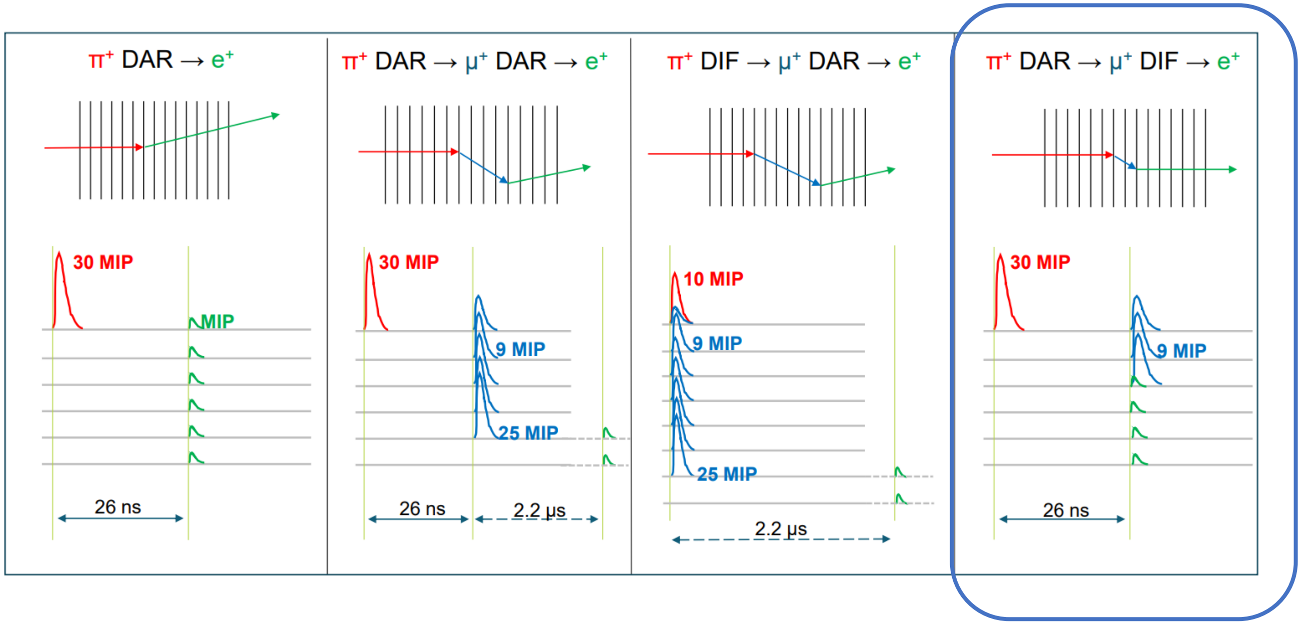
- Additional planes to slow down pion beam and potentially provide backward trigger/veto

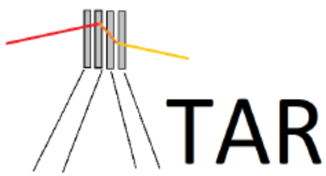
Towards 4D (5D) tracking: Active TARget detector

J. Ott et al, Gain suppression studies at CENPA, 43rd RD50 Workshop

To achieve the PIONEER physics goal, it will be crucial to **separate the low-energy tail of *π*→e events from *π*→*μ* →e decays in-flight and at-rest**

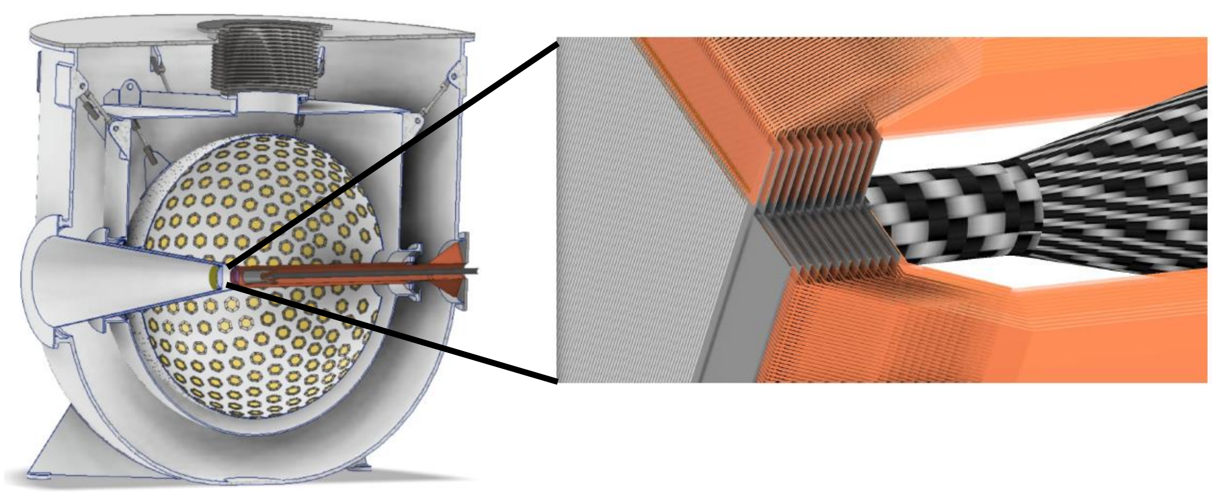






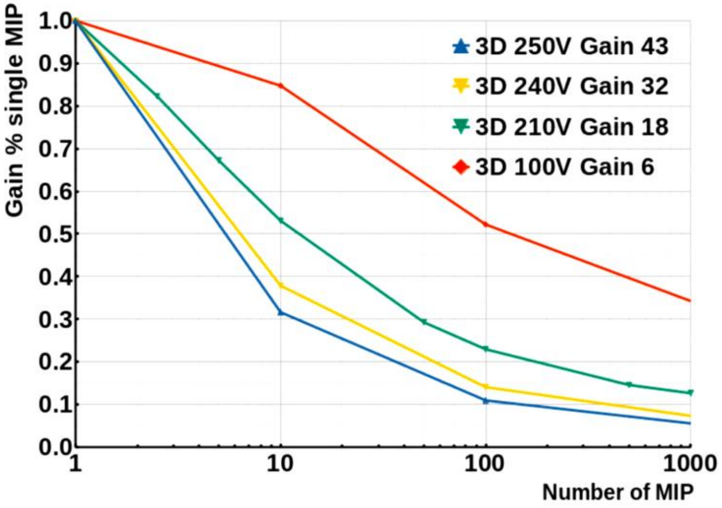
Towards 4D (5D) tracking: Active TARget detector

- Active TARget: 2x2 cm^2 area, ca. 6 mm thick to stop 60-75 MeV pions
- Requirements:
  - Spatial resolution <200 μm
  - Timing resolution < 100 ps
  - Large fill factor: traditional LGADs with gain termination structures not feasible
  - Inactive material not desirable! Support wafers cannot be used.
  - ➢ **Design baseline: 48 stacked planes of 120 μm thick AC-LGAD strips, pitch ca. 200 μm**
- Challenge: large energy deposits by stopping particles
  - Investigating possibility of using pin sensors: simplification of energy response, but drawbacks in spatial resolution, signal-to-noise ratio, electronics integration time / timing resolution requirements



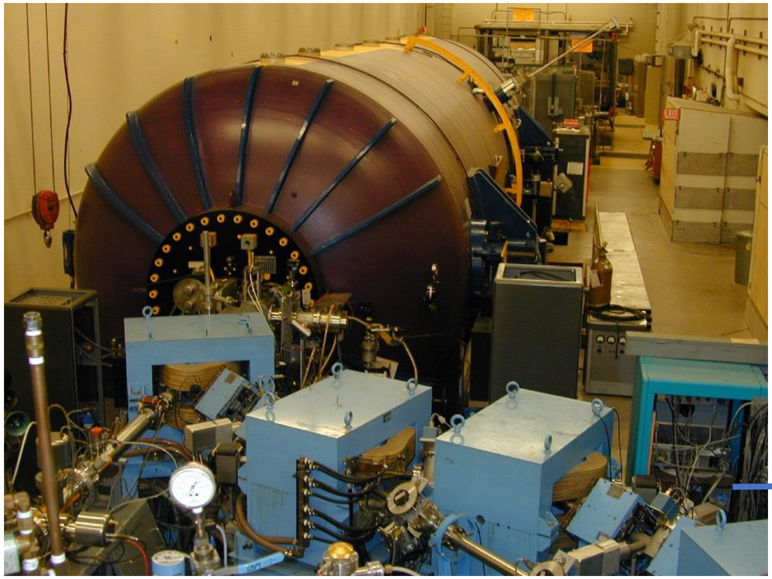
Gain suppression

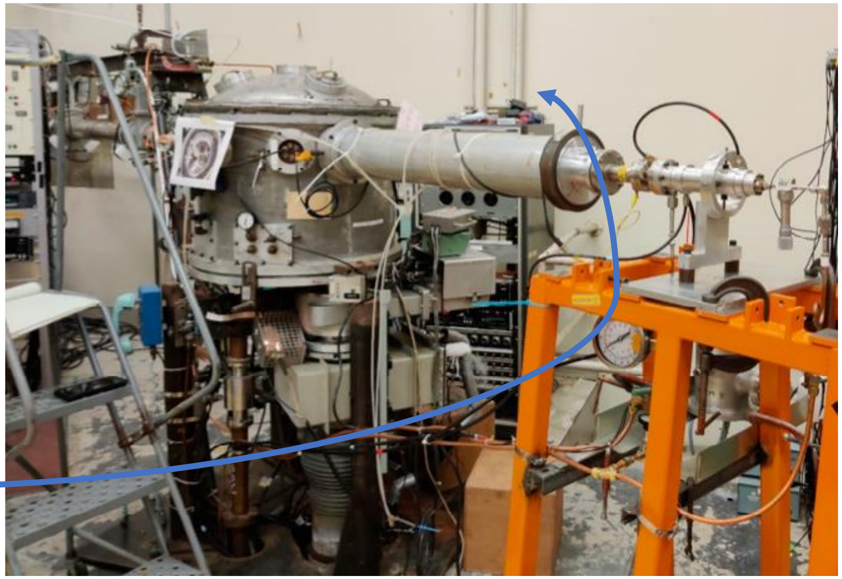
- Large dynamic range is required for the ATAR readout electronics to resolve MIP-like energies as well as hits from pions and muons – in particular, muon track from positron
- **Limitations not only in the electronics: suppression of the gain** has been reported in LGADs at high gain and/or large charge deposits
  - Cloud of charges in the gain layer generates electric field counteracting the external field, and thus reduces or prevents multiplication of subsequent charge carriers
- Investigation of gain suppression:
  - *Injection with the laser higher power*
  - Alpha particles
  - X-rays (cf. Simone's presentation)
  - Degraded charged particle beam
  - TCAD simulations (e.g. Y. Zhao, CPAD 2022)
  - **Low-energy charged particle beam**



Experimental setup at CENPA

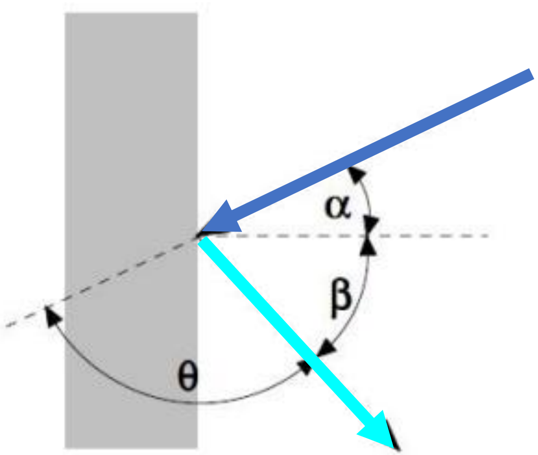
- Center for Experimental Nuclear Physics and Astrophysics at University of Washington
- Van de Graaff tandem accelerator: negative ions are injected and accelerated, electrons are stripped away and beam is emitted as positive ions
  - E.g. hydrogen gas to provide **protons**
  - Beam energy controlled by electric potential
  - **Energies used in this study: 1.8, 2, 3, 5 MeV**





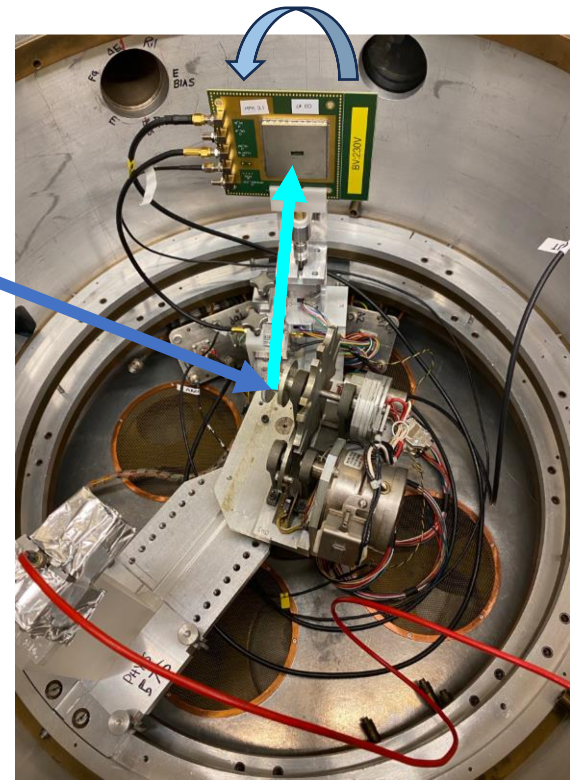
Experimental setup at CENPA

- Utilizing Rutherford Backscattering on a gold foil target to avoid direct exposure of the DUT to the beam
  - Scattering angle 110°
- Test board was mounted on a rotation stepping motor to vary the angle of the sensor with respect to the scattered beam
  - **Scanned 0°-75°**



p+ beam

scattered beam

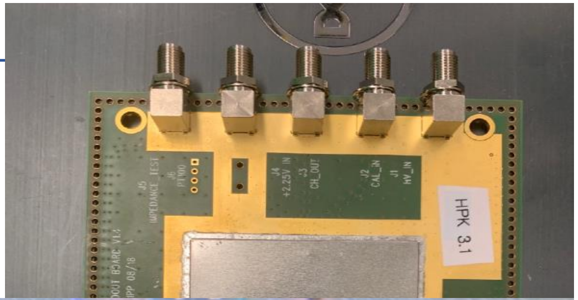


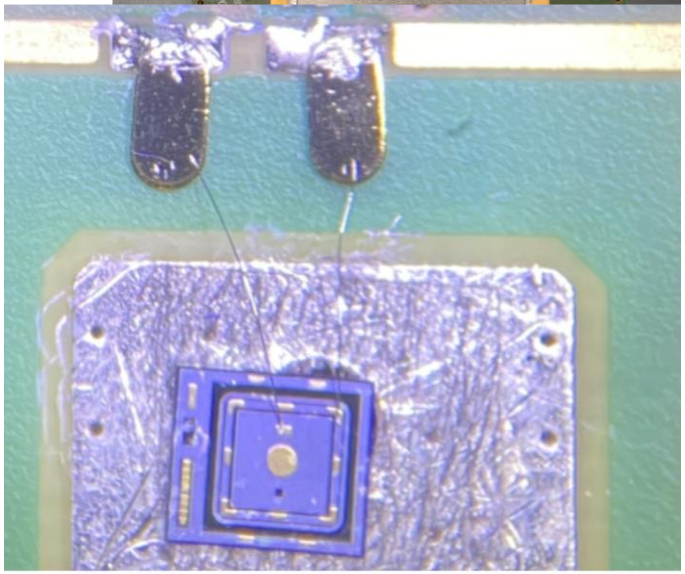
Test board with sensor

Au foil target

Sensors tested

- Focus on a ‘simple system’: single-pad, standard DC-coupled LGADs
- Read out with UCSC 1-ch transimpedance amplifier board + 20 dB RF amplifier, and Tektronix DPO 7104 1 GHz oscilloscope
- **Sensors tested at different bias voltages** to study the effect of the gain itself on gain suppression

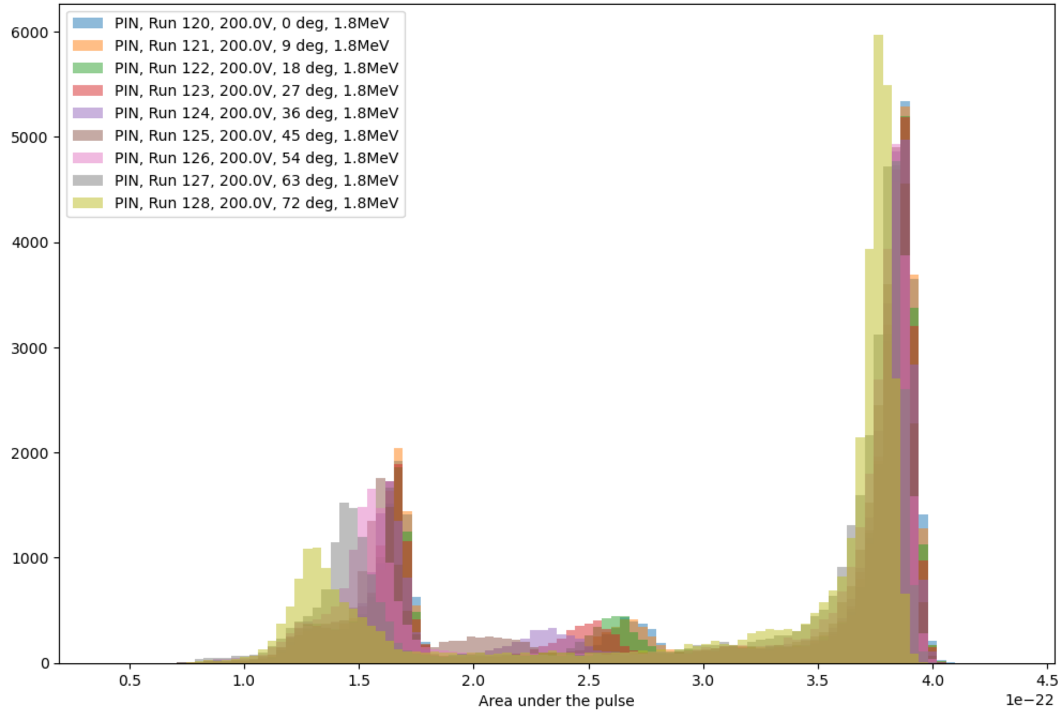




Sensor	Breakdown voltage (V)	Gain layer	Thickness (µm)	Pad size (mm)
HPK 3.1	230	Shallow (0.5-1µm)	50	1.3x1.3
HPK 3.2	130	Deep (1-2 µm)	50	1.3x1.3
HPK 3.2 pin	400	No gain	50	1.3x1.3

Pin sensor results

- At **1.8 and 2 MeV** beam energy, beam stops in the sensor even at normal incidence and protons deposit maximum energy
- At 3 MeV, signal charge increases with angle/$\sqrt{2}$ before stopping of the protons at ca. 50°



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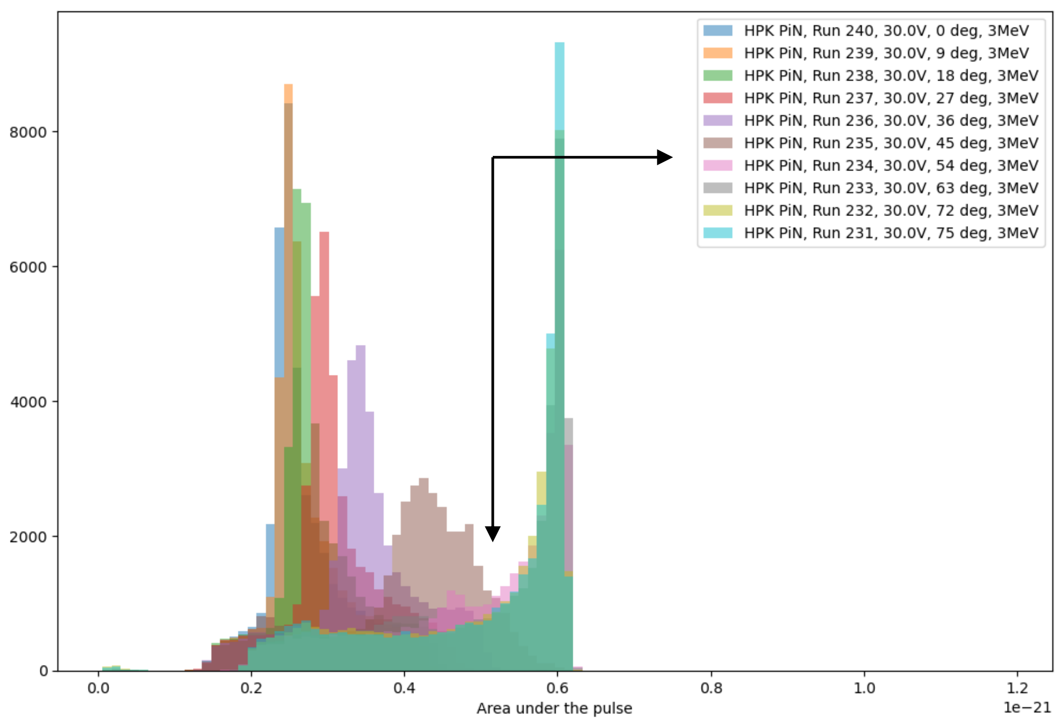
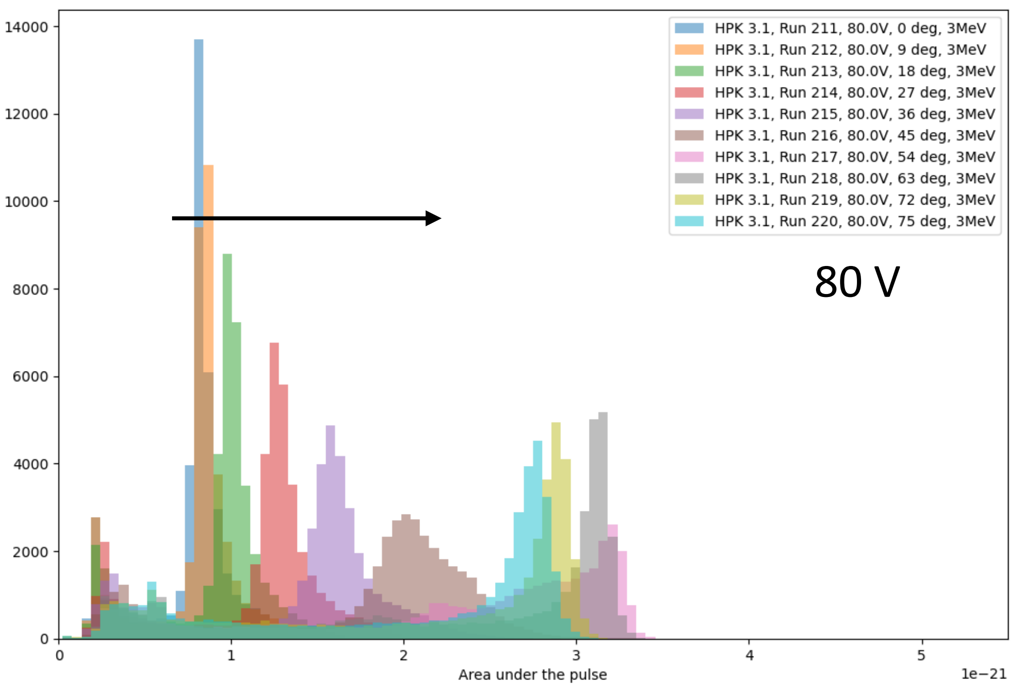
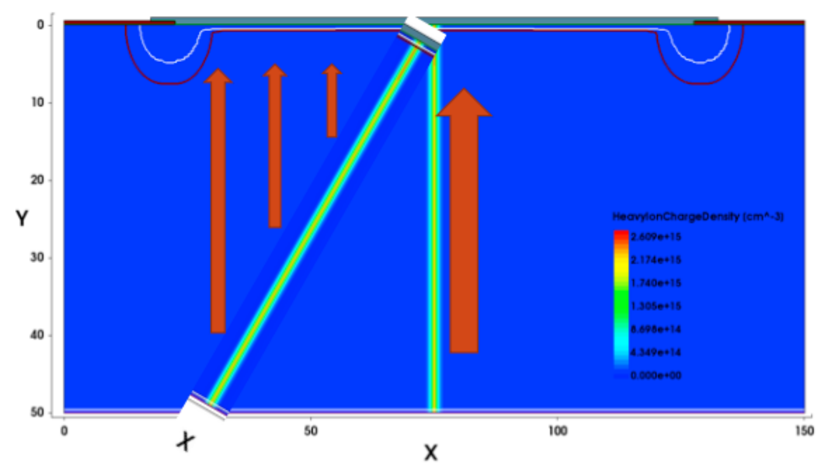


HPK 3.1 LGAD at 3 MeV

- Angular dependence of gain

- At <10°, energy deposit within the same area: gain suppressed
- At increasing incident angles, gain increases as proton energy deposit is spread out over wider depth

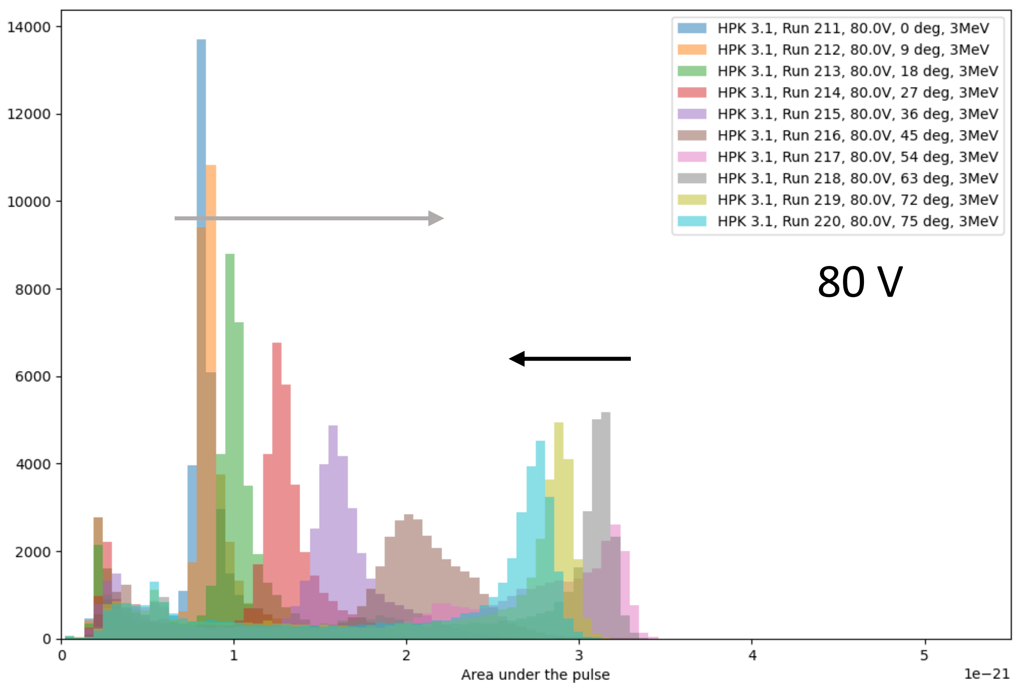


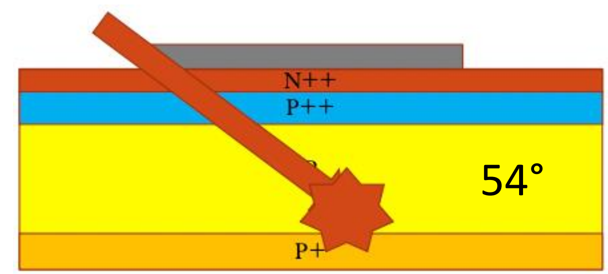


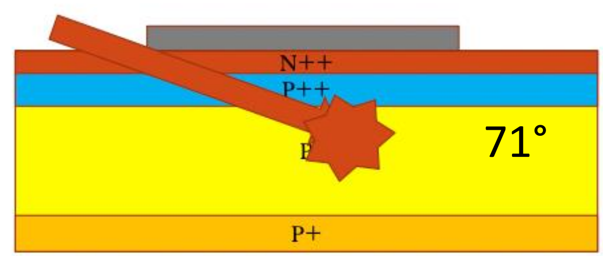
HPK 3.1 LGAD at 3 MeV

- Angular dependence of gain

- At higher angles (with the proton stopping in the sensor), the gain is suppressed again
    - Main energy deposit closer to the gain layer

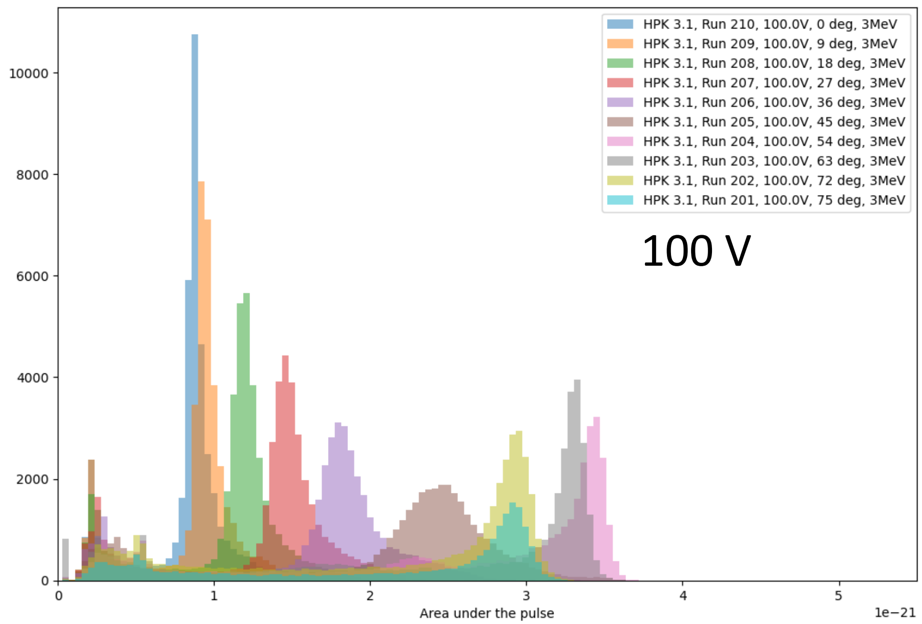


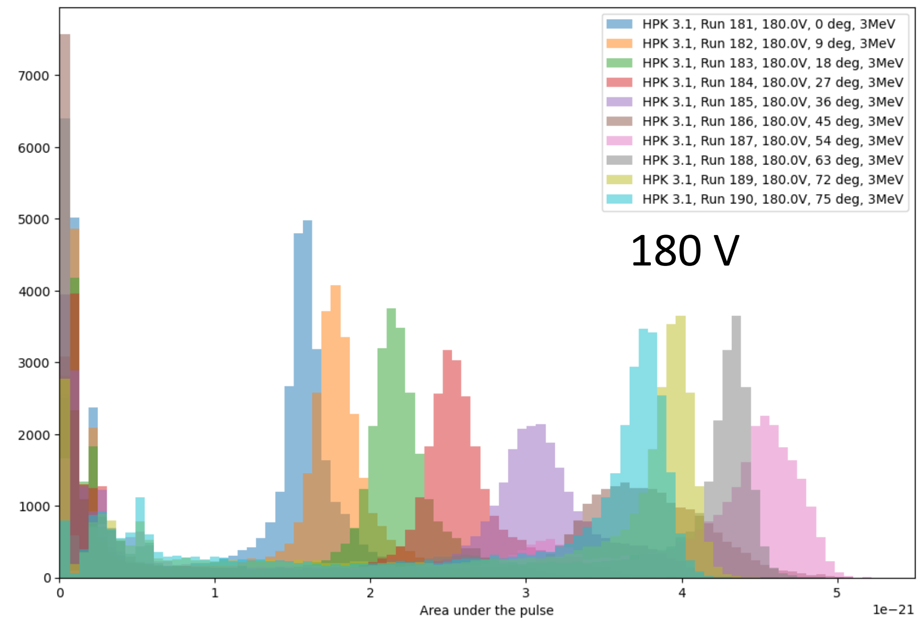




Effect of bias voltage

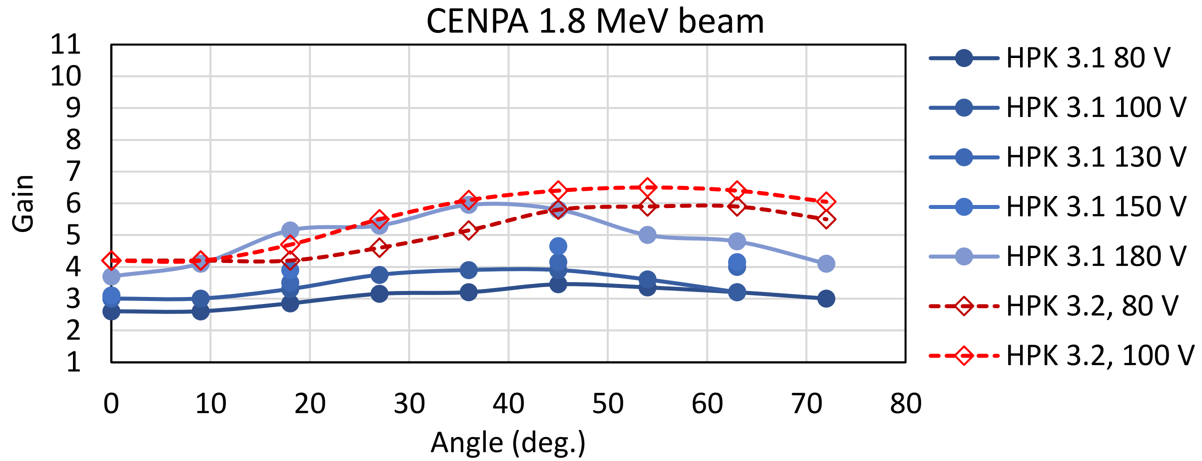
- Higher bias voltage: higher initial gain
  - ➢ Larger gain increase and spread
  - ➢ Stronger gain suppression effect
- Similar for HPK 3.2, but less suppression with angle?

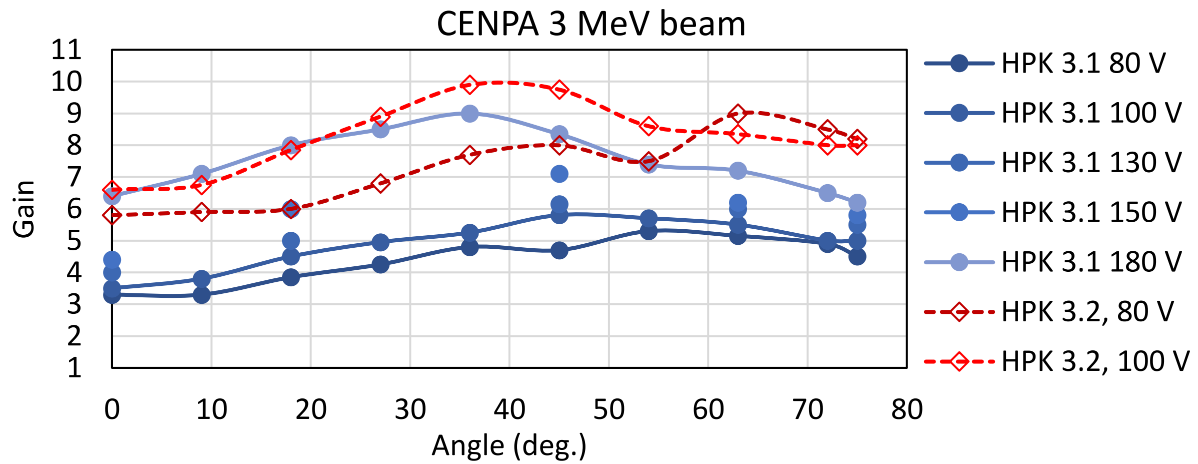




Gain as function of incidence angle

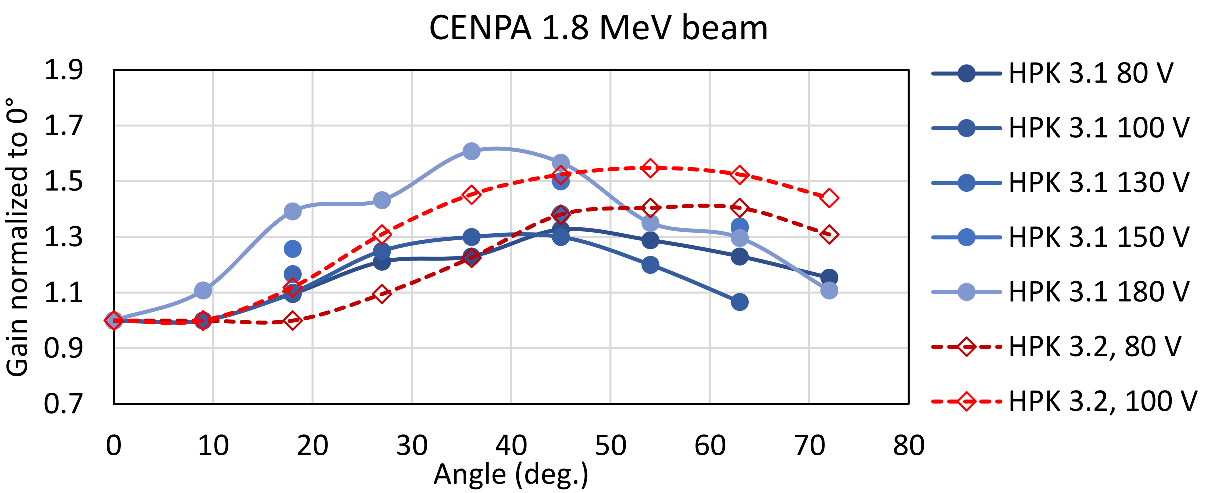
- Gain: pulse_area(device)/pulse_area(pin) for each angle and each bias voltage; pin at 200 V
- Higher gain for 3 MeV protons
- Less variation for HPK 3.2
- Gain suppression effect as function of incidence angle is stronger for higher bias voltages

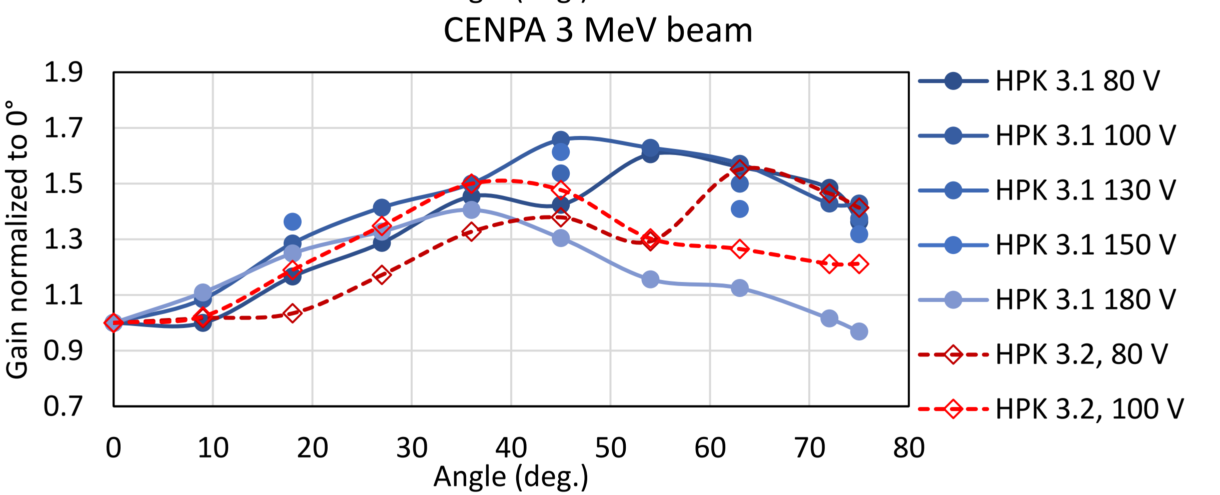




Gain relative to angle

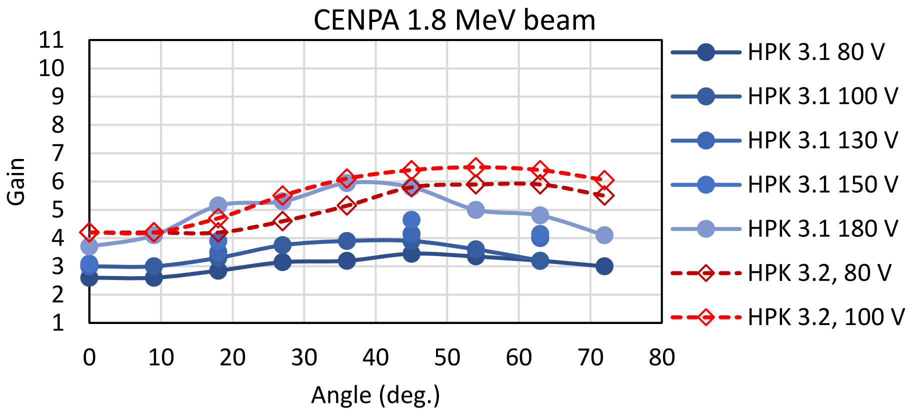
- Less variation, less gain suppression for HPK 3.2
- At 1.8 MeV, higher bias voltages still provide high gain – at 3 MeV, angular dependence of gain suppression is more pronounced

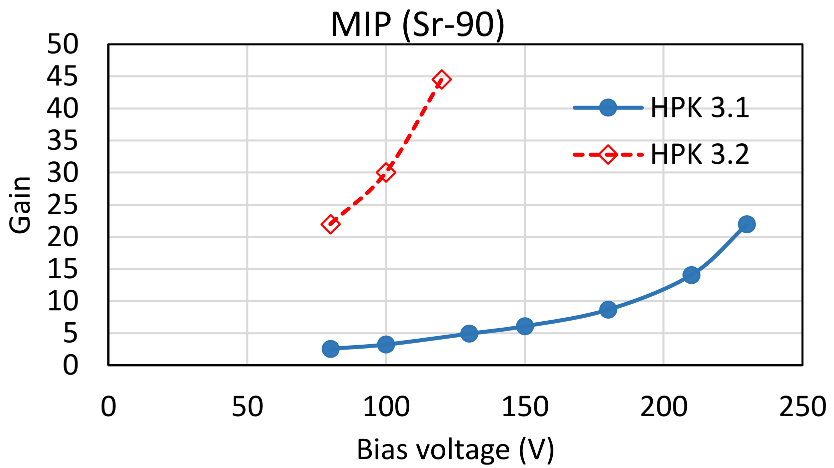


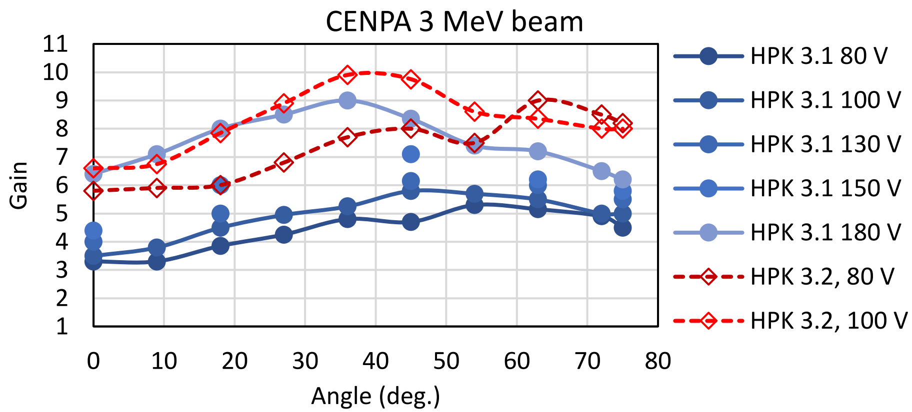


Gain suppression compared to MIPs

- Indeed less variation for HPK 3.2, but this may be due to its gain being already heavily suppressed compared to MIP charge deposition
- Relation of HPK 3.1 data to gain determined with Sr-90 not entirely clear
- Some technical challenges:
  - It was not possible to consistently bias the sensors to the higher voltages = higher gains at the CENPA beamline: due to operation in vacuum? Ionization damage to the sensor surface or even the boards?
  - Measurements in the laboratory before and after CENPA test beam show some differences: not well understood; sensors possibly damaged during testing in beamline







Conclusions

- Single-pad LGAD and pin sensors from HPK were tested with a proton beam at the University of Washington CENPA tandem accelerator for the first time
  - Beam energy, sensor bias voltage and incidence angle were varied
  - Gain suppression and stopping of protons were observed
- The gain suppression phenomenon is limiting, or at least complicating, energy resolution in LGADs for large charges deposited in a small volume and close to the gain layer
- For PIONEER, potentially other applications as well: explore gain layer fabrication options to **reduce the gain, i.e. ensure saturation of velocities** at moderate voltages before gain-induced breakdown
- Next tests: BNL sensor production with thicker sensors and modified gain layer – also open to testing other devices!

- **Angular dependence of gain – and signal sharing – to be studied more extensively in the laboratory: more complex for strip sensors and AC-LGADs!**
  - **2D laser scans**
  - **Alpha particle testing station in vacuum chamber**
- Simulations: gain suppression is observed in simulations (cf. Michael's and Sebastian's talks) and can be explained with existing physics models
- 3D simulations require a lot of computing capacity, but are needed for accurate reproduction of the experimental data

My first RD50 workshop:
Krakow 2017

Backup

PIONEER Collaboration

PIONEER

A next generation rare pion decay experiment

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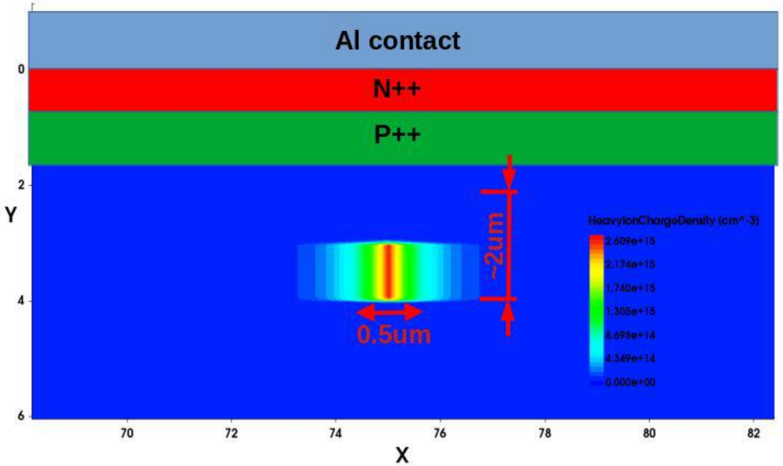
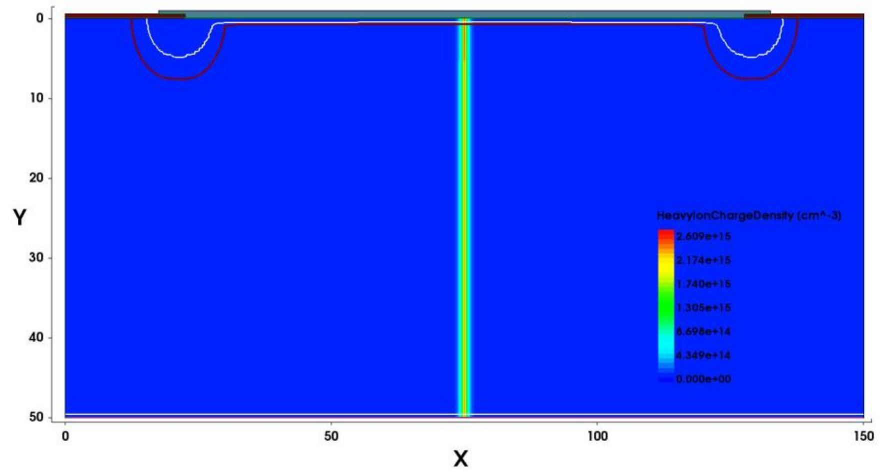
Supported by the U.S. Department of Energy, Office of Science, Offices of High Energy Physics and Nuclear Physics; the U.S. National Science Foundation; JSPS KAKENHI (Japan); Natural Sciences and Engineering Research Council (Canada); TRIUMF; the Swiss National Science Foundation and PSI.

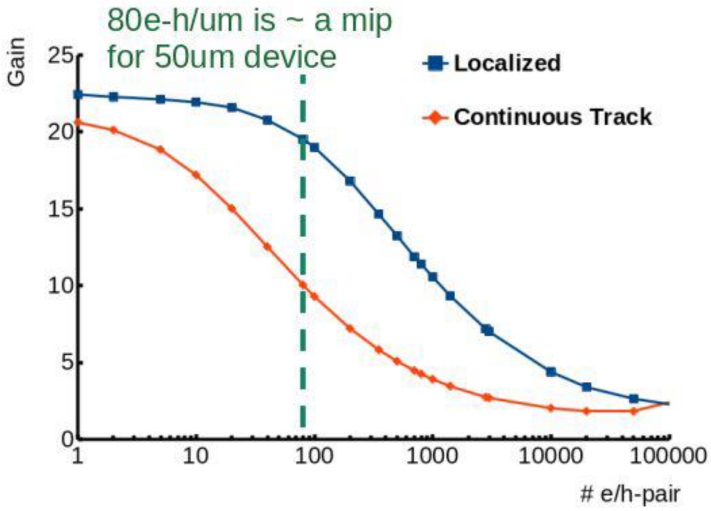
TCAD simulations: localized and spread charge

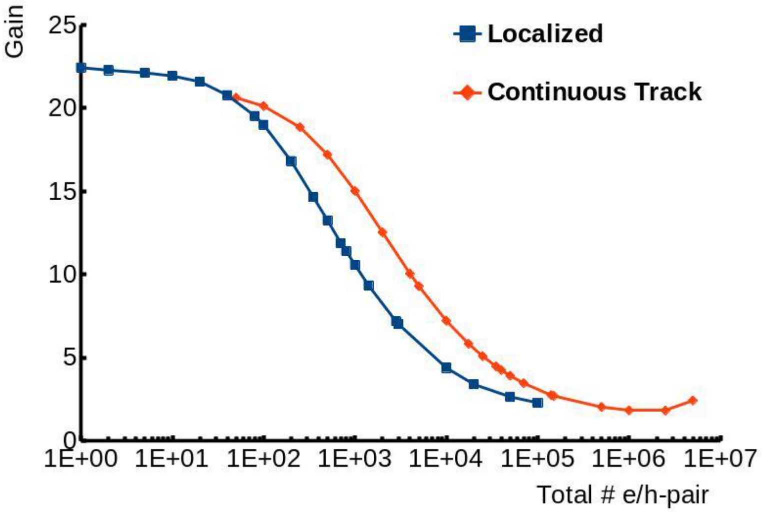
Localized charge



Track

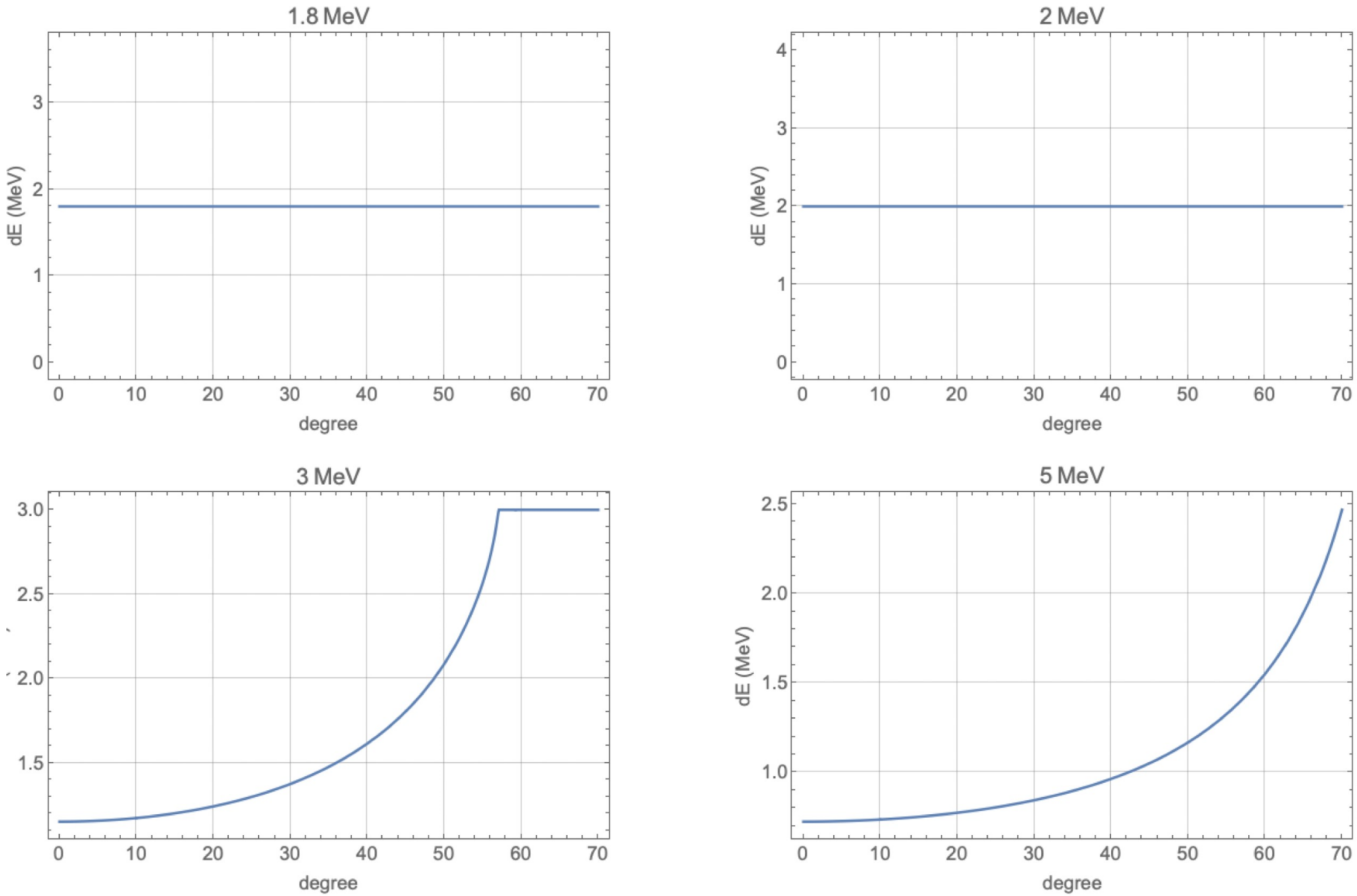






Y. Zhao, CPAD 2022

Energy deposit of protons in Si



HPK 3.2 LGAD at 3 MeV