ÖAW AUSTRIAN ACADEMY OF SCIENCES

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

Measurements and Simulations of High Rate 4H-SiC Particle Detectors

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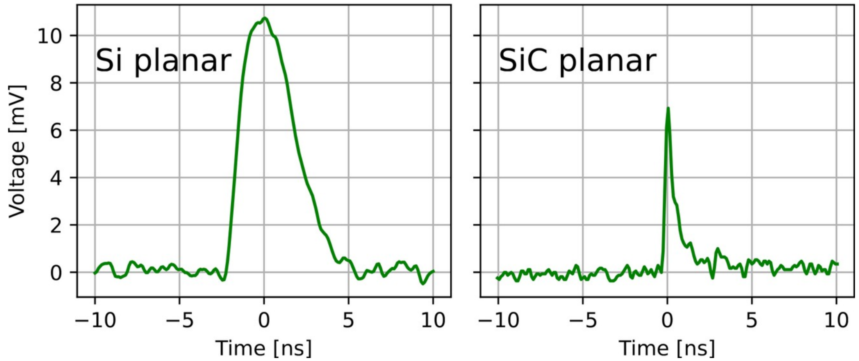
Silicon Carbide (SiC)

- Recently has become more available due to interest in power electronics industry
- Insensitive to optical light and can be operated without any cooling
- Currently only thin (< 100 µm) epi layers possible (limited by defect density).
- For MIP particles and typical detectors:
  - SiC: 50 µm * 57 e/µm ~ 2.8 ke
  - Si: 300 µm* 72 e/µm ~ 21ke

Property	Si	4H-SiC
Bandgap energy E_g [eV]	1.12	3.27
Ionization energy E_i [eV]	3.64	5-8 [2,3]
e/h pairs per µm for MIPs (MPV)	~ 72	~57 [2]
Atomic displacement threshold [eV]	13-20	22-35
Breakdown field [MV/cm]	0.3	$\perp$: 4.0; $\parallel$: 3.0
Saturated electron velocity v [10^7 cm/s]	1	2.2
Electron mobility [cm²/V/s] (at 300K)	1300	800-1000 [3]
Hole mobility [cm²/V/s] (at 300K)	460	115
Impact ionization coefficient	$\alpha_e > \alpha_h$ [3]	$\alpha_e < \alpha_h$ [3]

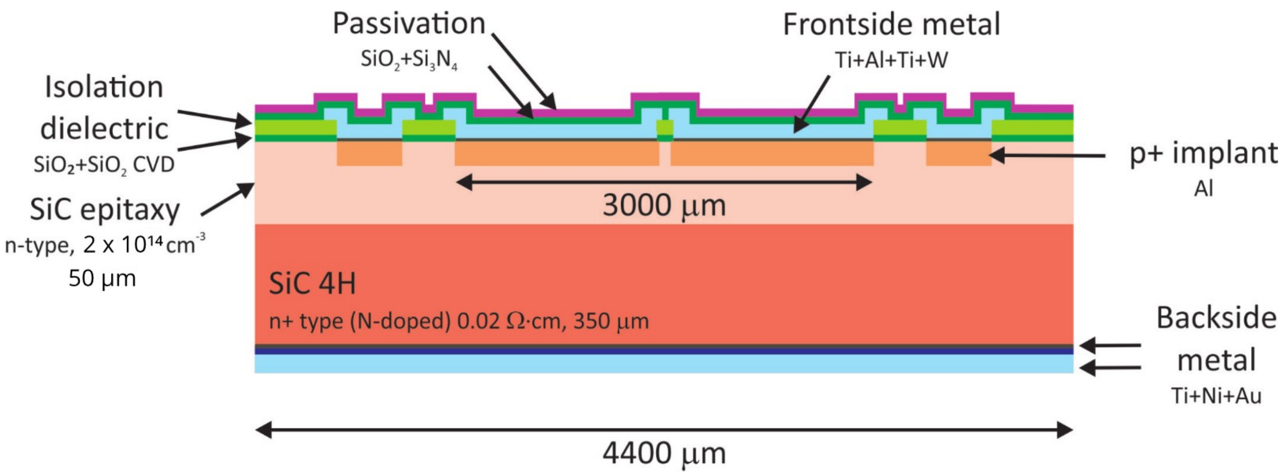
Data taken from [1] if not noted otherwise

Typical measured waveforms for planar Si and SiC diodes

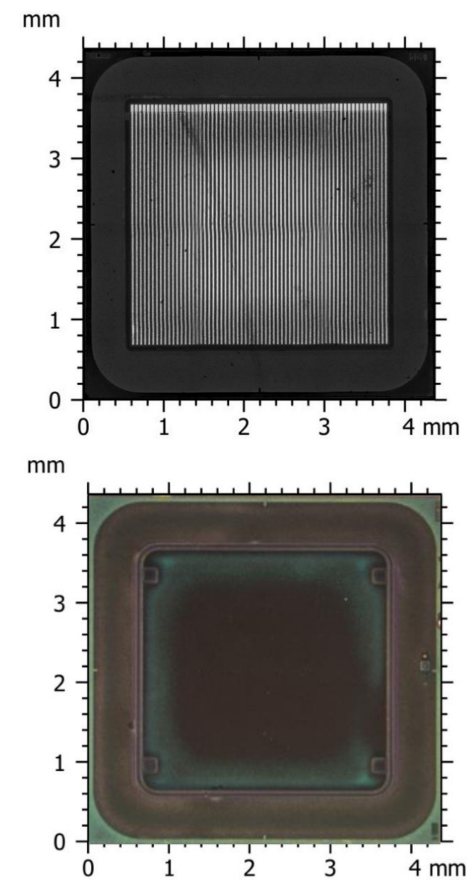


SiC Samples

- p on n diode, 3 x 3 mm² active area, 50 µm nominal thickness
- Planar and strip (64 strips, 50 µm pitch) diodes
- Samples from Run 13575 of IMB-CNM-CSIC Barcelona
- V_{depl} = 300 V, Leakage Current < 10 pA for V_{bias} < 600 V and planar sensor



Geometry of SiC samples (without segmentation) [4]



SiC strip (top) and planar sensor (bottom) samples [5]

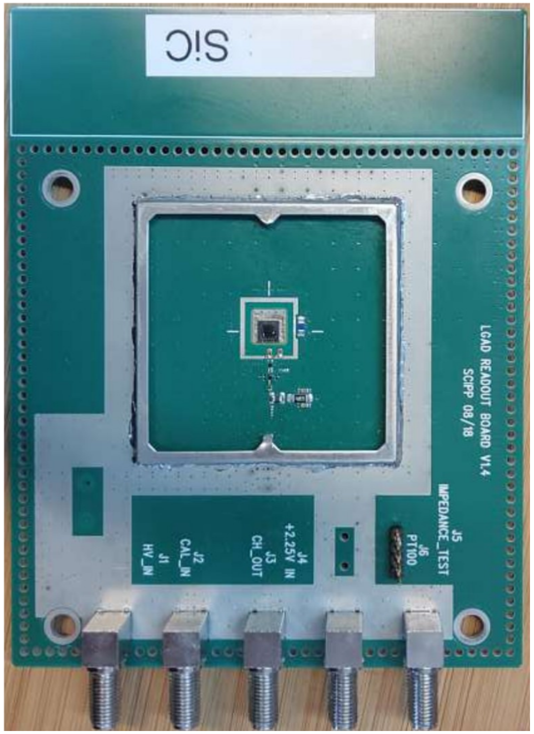
Readout Electronics

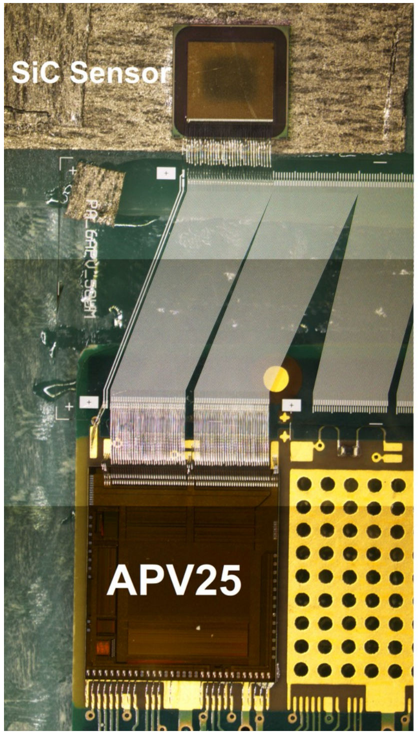
- UCSC "LGAD" board for planar diodes and APV25 ASIC [6] for strip detectors
- Waveform digitization using R&S RTP164 oscilloscope or DRS4 evaluation board

~ 200 k€
40 Gs/s, 16 GHz

~1 k€
5 Gs/s, 700 MHz

[7]





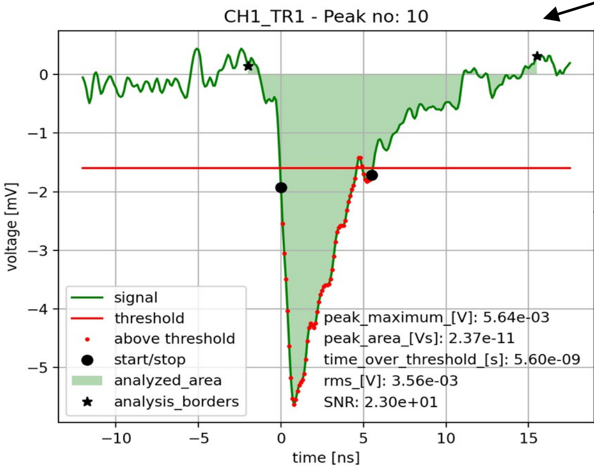
UCSC "LGAD" readout board with planar SiC sample (left) and APV25 ASIC with SiC strip detector (right) [5]

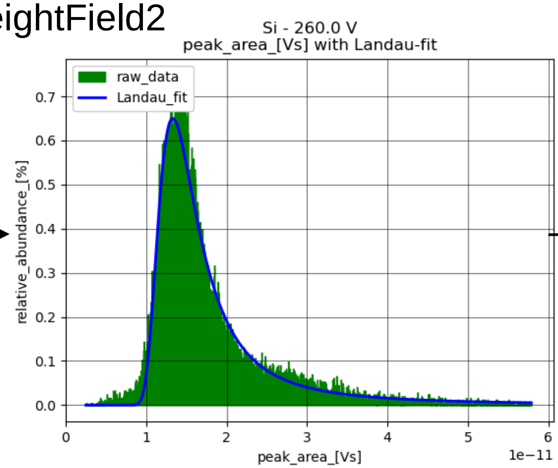
Pulse Analysis Software

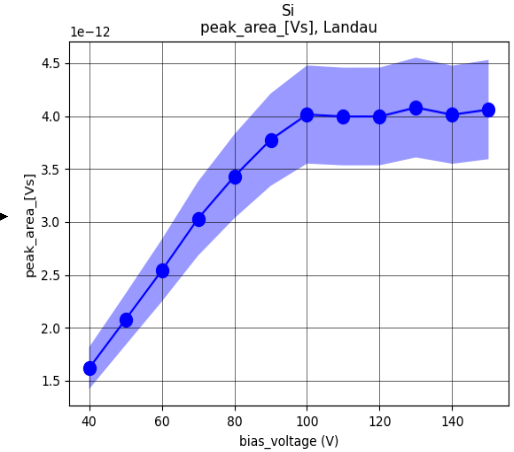
- Import data from oscilloscopes or simulations (AllPix², WeightField2, ...)
- Fixed treshold or constant fraction discrimination (CFD) analysis
- Calculation of pulse area, maximum and time-over-treshold as well as SNR.
- Landau/Gauss fits and voltage ramp evaluation

https://gitlab.com/dd-hephy/HiBPM/RS_DRS4_run_analysis

WeightField2

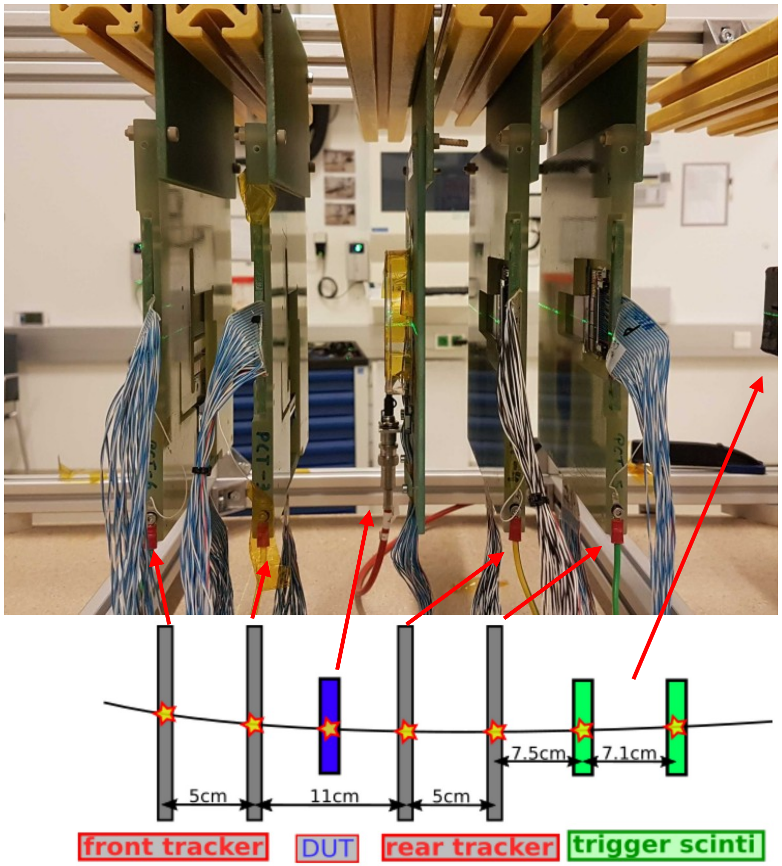




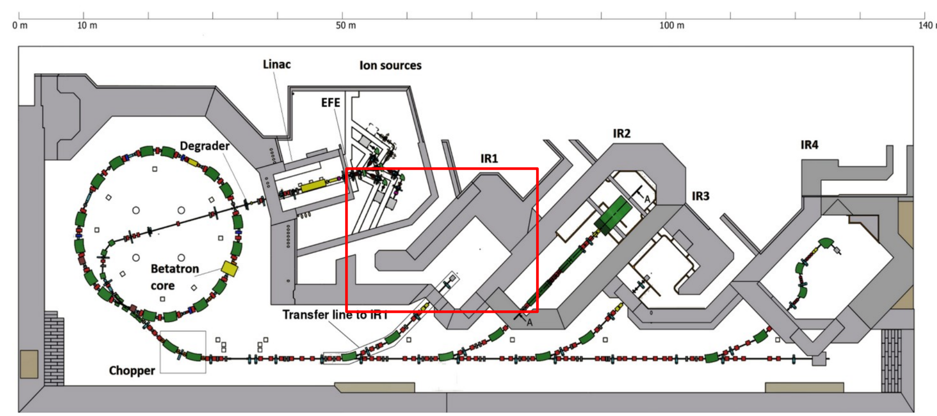


Proton Beam Measurements: Energy Scan

- Measurements performed at the MedAustron (Wiener Neustadt) ion beam therapy center [9]
  - 60 – 800 MeV protons
  - Using special low flux (~5·10⁶ protons/s) settings [10].
  - Beam extracted in spills of 5-10 s
- Beam telescope using a SiC strip detector and two DSSD + trigger scintillators [2].



Experimental Setup [5]



Overview of the MedAustron accelerator. Proton beams, as well as carbon and (soon) helium beams are available [10]

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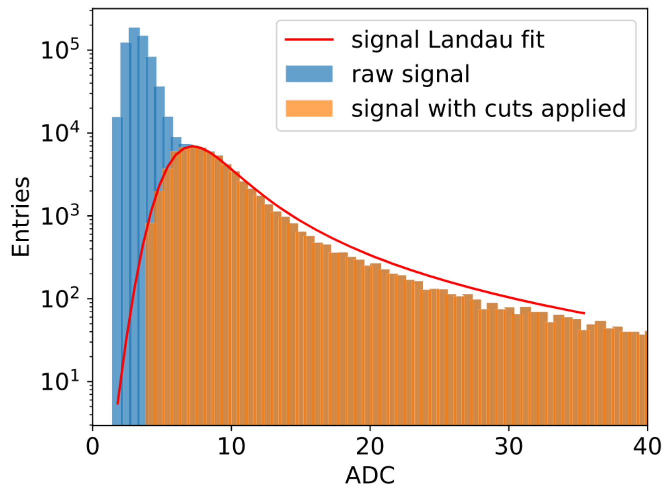
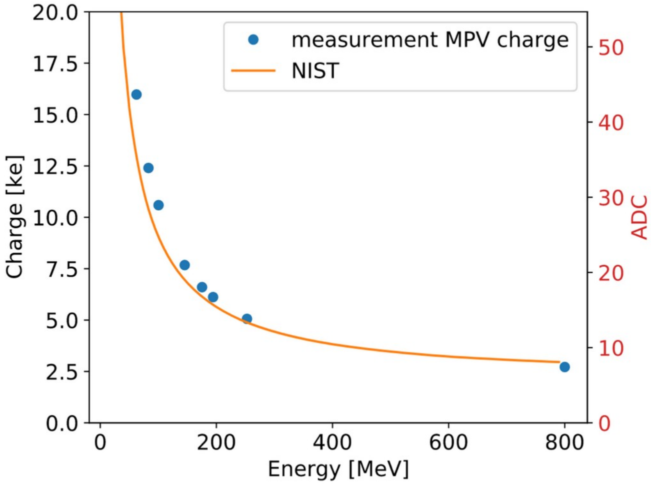
Proton Beam Measurements: Energy Scan

- Small SiC Signals → Landau distributed energy loss overlaps with Gaussian noise
- Employ cuts on samples-over-threshold and use tracks to separate signal and noise peaks.



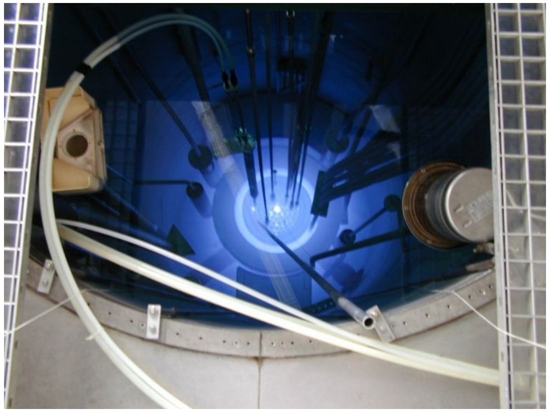


Left: Fitted Landau distribution for 800 MeV protons after applying cuts.
Right: ADC counts as a function of the incident beam energy [5]

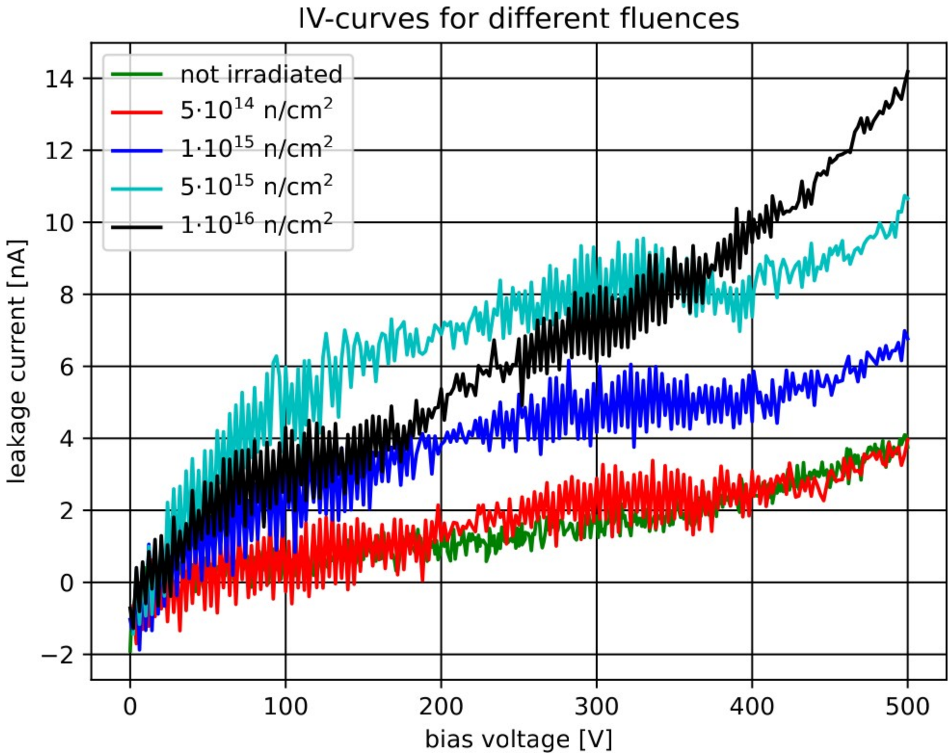
- Measured E_i = 5.85 eV via calibration with a Silicon detector
- Extrapolated charge carrier creation to ~2'800 e/h pairs for a MIP particle in 50 µm SiC
- 57 ± 4 eh-pairs/µm for a MIP particle (in 45 µm thickness), matching with literature [1]

Irradiation Studies

- Irradiation of planar samples using MeV neutrons at the TRIGA Mark-II reactor in Vienna [10].
- Investigated equivalent fluences between $5 \cdot 10^{14}\ n_{eq}/cm^2$ and $1 \cdot 10^{16}\ n_{eq}/cm^2$ with UV-TCT and proton beam measurements



TRIGA Mark-II reactor [11]

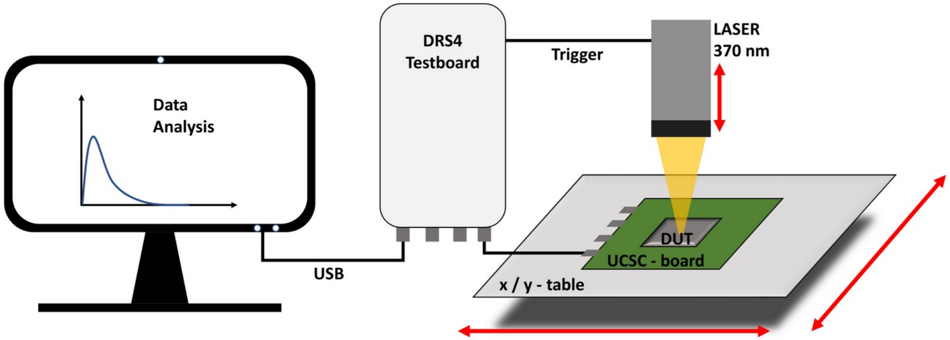


Leakage current (with UCSC board) for different fluences [12]. Even for very high fluences, the leakage current is not a limiting factor.

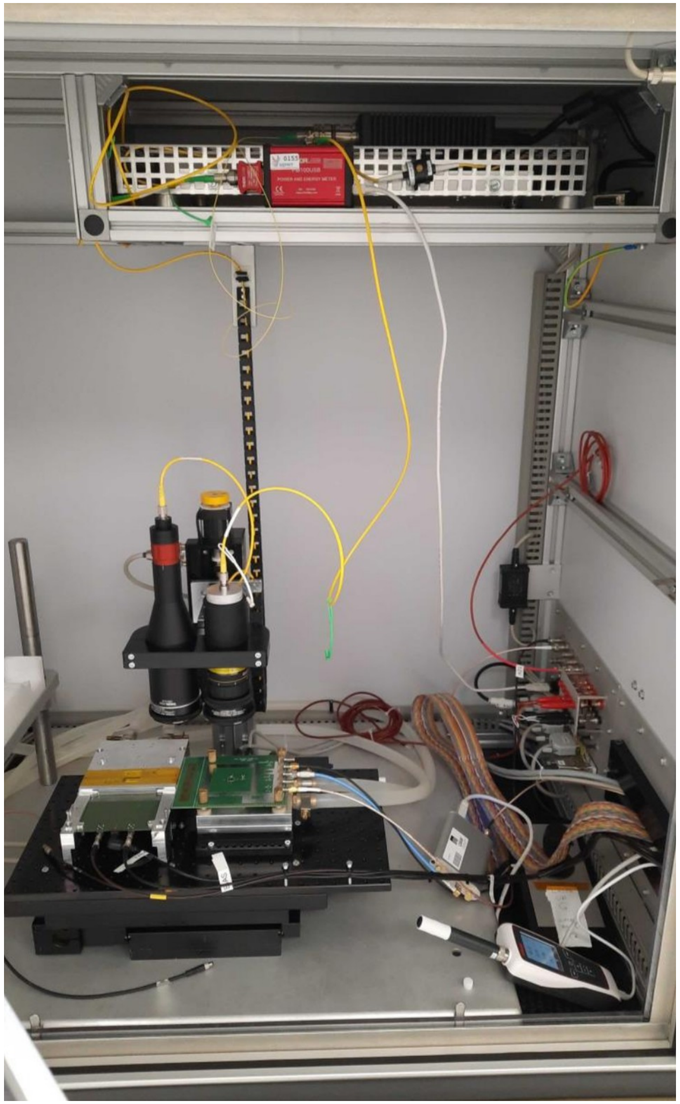
UV TCT

- UV- Top **T**ransient **C**urrent **T**echnique (UV has enough energy to overcome SiC bandgap)
- PILAS DX PiL037-FC Laser, $\lambda = 370$ nm (→ 3.35 eV) , pulse width < 70 ps [13], custom UV beam optics, spot size < 10 µm.
- Absorption coefficient in 4H-SiC: $\alpha \approx 42.2\ cm^{-1}$ [14]

  → uniform charge deposition in detector
- Large, Gaussian distributed signals (around $4 \cdot 10^6$ e/h pairs per pulse)



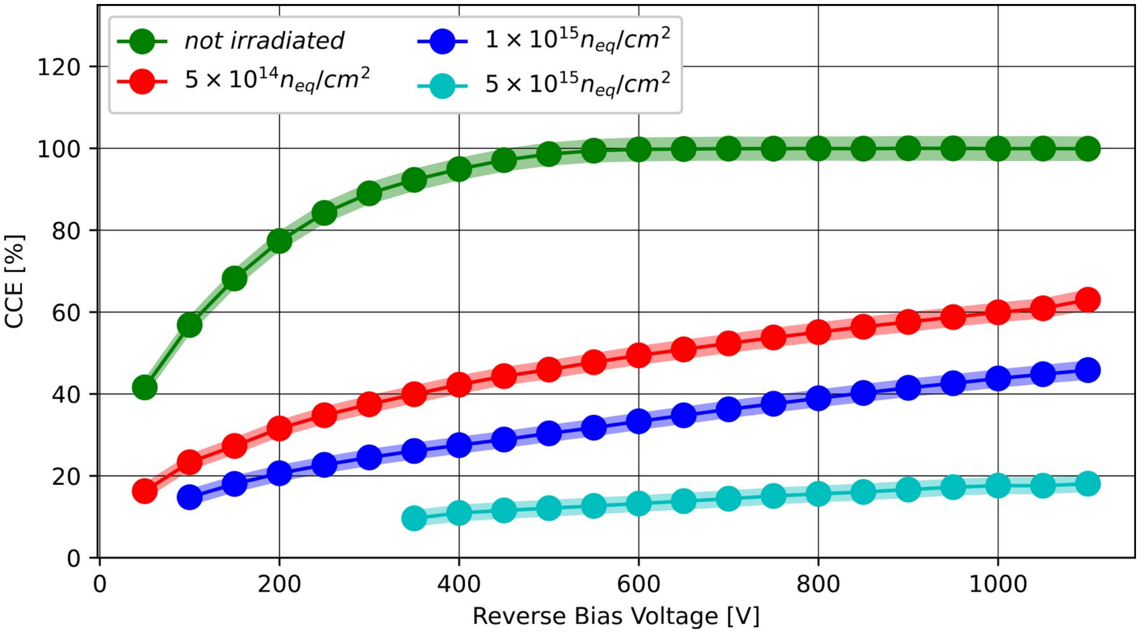
UV-TCT Scheme [12]



UV-TCT setup at HEPHY [12]

Irradiated Samples: UV-TCT

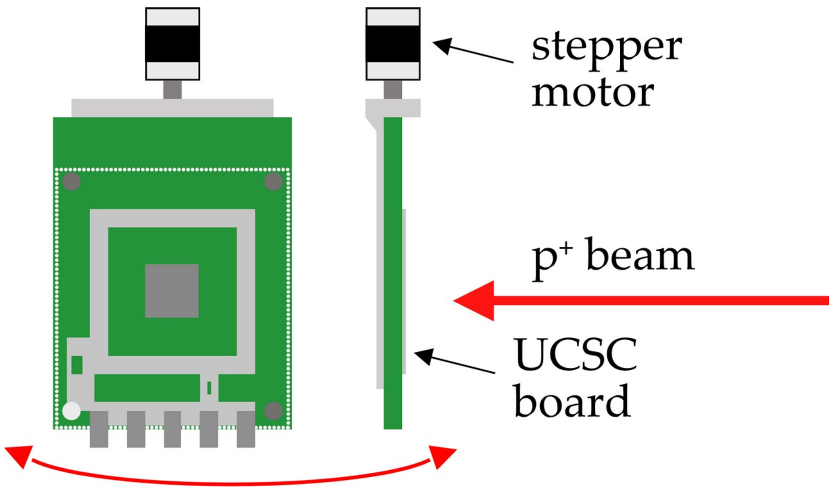
- No saturation reached in collected charge for irradiated samples (the voltage range in this measurement was limited by the SMU)
- Signals become smaller and shorter for higher fluences
- Charge collection efficiency CCE (normalized to non-irradiated sample) compares well to other measurements (using a α-source) [15]
- No Signals from detector with $1 \cdot 10^{16}$ n_{eq}/cm^2 irradiation



Irradiated Samples: Protons

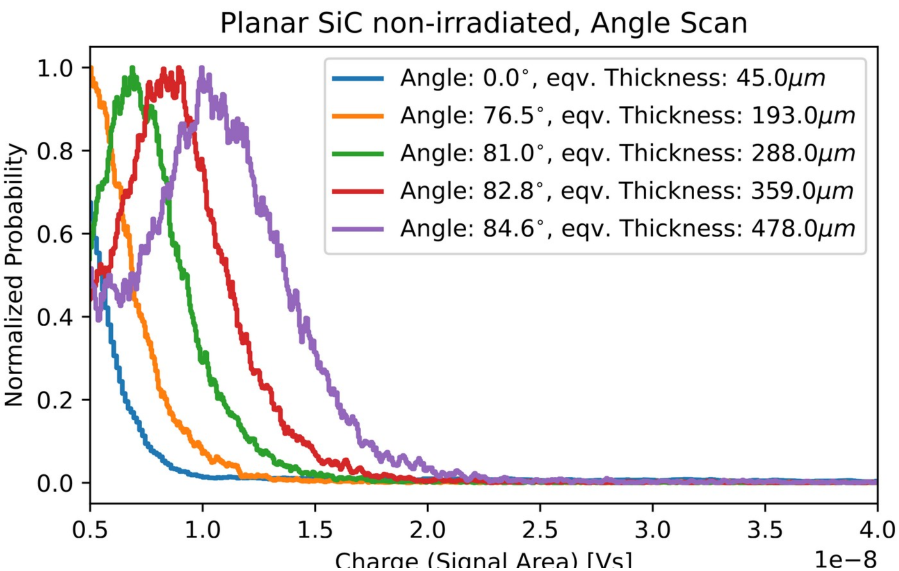
- As seen in the proton beam energy scan, SiC signals are very challenging to measure for our samples because of the low amount of produced charge carriers
- For irradiated samples with a lower CCE, this problem will be even worse

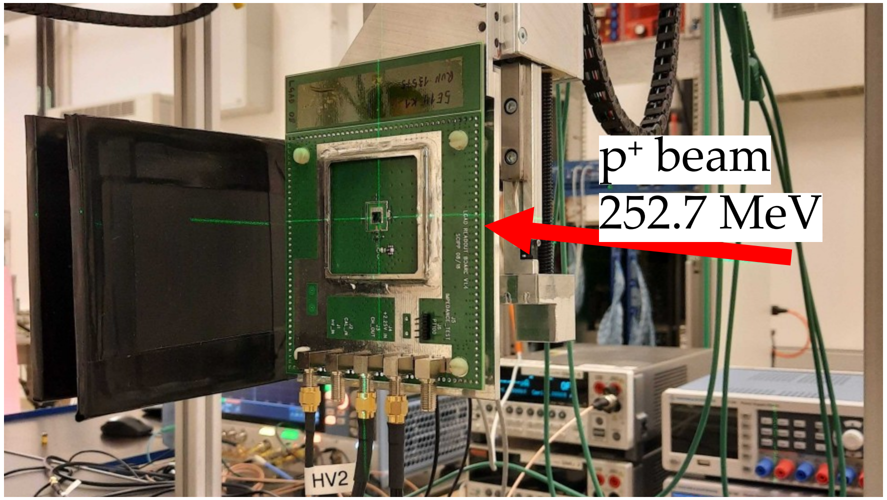
  → Need to somehow increase the deposited charge
- Can not use same tracking setup as for the energy scan because only planar sensors were irradiated
- Idea: “Simulate” thicker sensor by varying the indicence angle of the beam



Proton Beam Angle Scan

- For lower incidence angles only the Landau tail is observable, as the SiC signal overlaps with the Gaussian noise peak
- For higher incidence angles (= longer track length in detector), the entire peak (now Gaussian) can be measured
- Conclusion: Use an incidence angle of 90° (similar to edge TCT) for irradiated samples

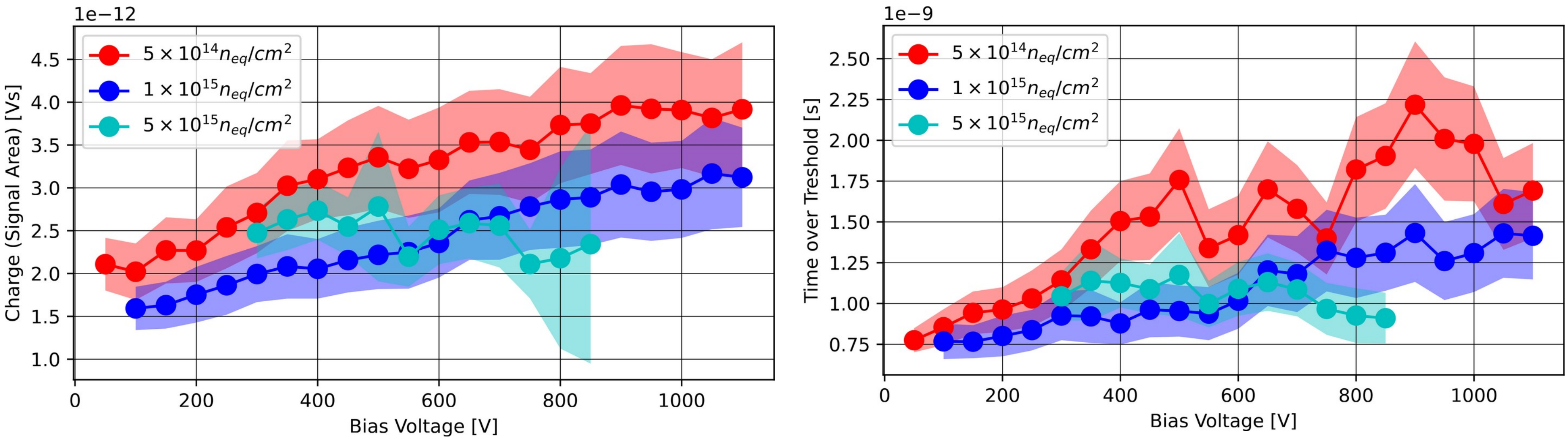




Setup at the MedAustron accelerator with green alignment lasers [12]

Proton Beam Measurements: Irradiated Samples

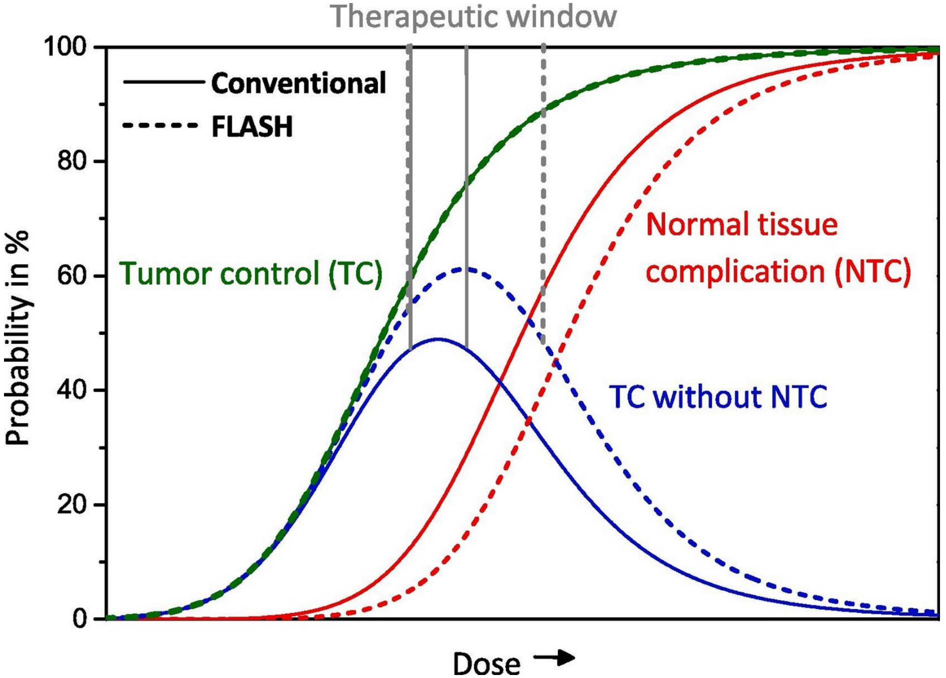
- CCE unfortunately not available due to electrical issues during the measurement of the non-irradiated sample
- Collected charge (proportional to signal area) increases with bias voltage, except for most heavily irradiated sample.
- Charge collected for sample with fluence $1 \cdot 10^{15}$ n_{eq}/cm^2(cyan) hard to discriminate from noise
- Time-over-threshold is very short (< 1 ns) for highly irradiated samples



Signal area vs. reverse bias voltage (left) and time-over-treshold (right) for irradiated samples in 90° orientation and 252.7 MeV protons

High Proton Beam Rates

- Very large interest in ultra high dose rate (UHD) radio therapy [16,17].
- FLASH effect: Preliminary evidence for better normal tissue sparing at high dose rates (> 40 Gy/s)[17].
- Challenges in UHD dosimetry because of dose rate dependencies
- Silicon (relative) dosimeters show non-negligible dose rate dependencies, especially after irradiation. [18]
- SiC could be an interesting candidate for UHD dosimetry [19]
- Can achieve higher dose rates at MedAustron by decreasing the synchrotron extraction time (nominal 5-10s)



Tumor control vs. normal tissue complication probabilities for conventional and FLASH radiotherapy [16]

High Proton Beam Rates

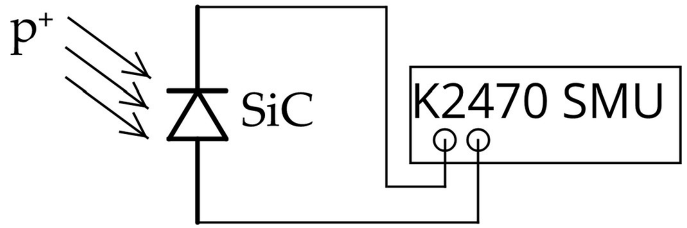
- Measure particle flux via leakage current through planar SiC detector:

- Flux [$cm^{-2}\ s^{-1}$] ≅ I_{SMU} / (5.6 ke) / (3 mm x 3 mm)

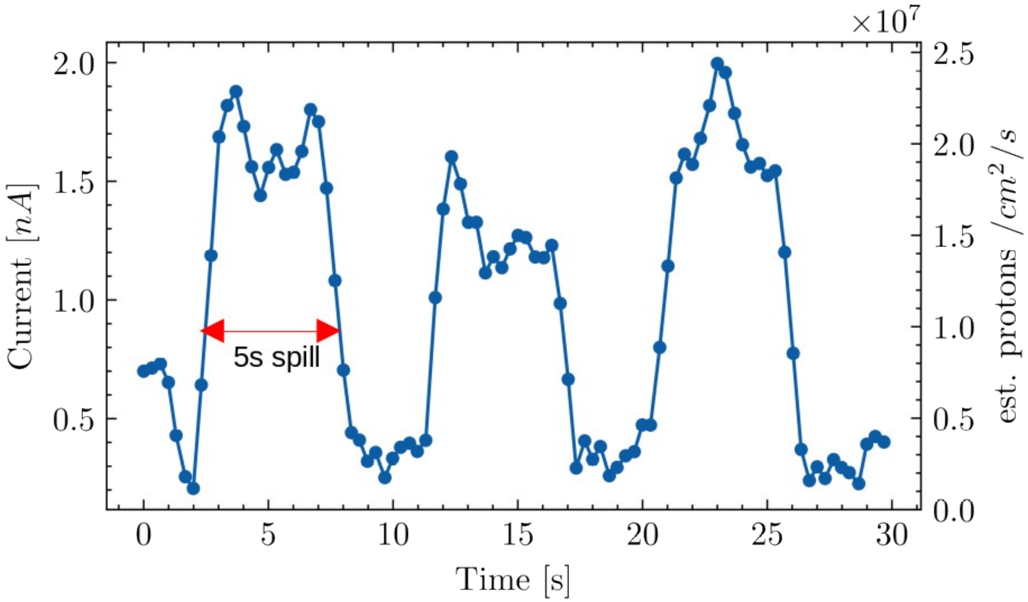
MPV of generated e/h pairs for a 252.7 MeV proton in 50 µm SiC

Active area of detector

Experimental Setup



- For medical beam rates (5s extraction of ~10^{10} protons), we measure a flux of **~ 2 · 10^7 p/cm²/s**

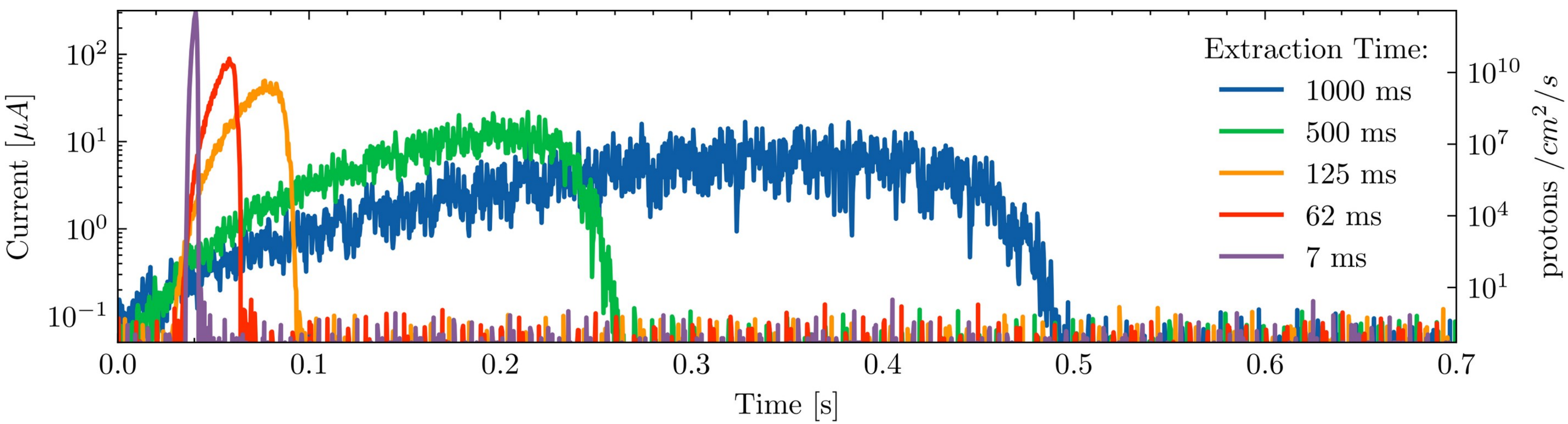


High Proton Beam Rates

- Tested extraction times from 1 s down to 7 ms using “Constant Optics Slow Extraction” COSE [20].
- Fast sampling (2.8 kHz) using the Keithley 2470 SMU
- No saturation observed up to a leakage current of 300 μA, corresponding to a flux of

  ~ 3 · 10^{12} protons / cm^2 /s

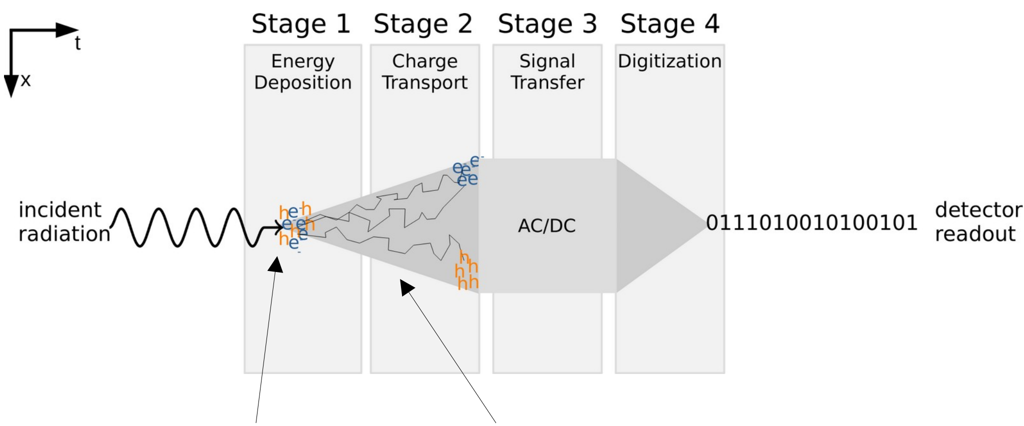
- Because of the experimental accelerator settings, the beam is likely lost after the first half of the extraction.



AllPix² Simulation of SiC Sensors

- Materials other than Si are not always supported by solid state detector frameworks
- For frameworks that support SiC, the material parameters are not always correct (WeightField2) or numerical issues exists (convergence issues in Synopsys TCAD)
- AllPix² [8] is a modular framework, where each submodule can be modifed and adapted to SiC.
- Often used for testbeam setups (integration with Corryvreckan) but simulating single detectors is also possible
- Physics models (for ex. e/h mobility model) can be defined using a macro language → no need to recompile.
- Energy deposition using Geant4
- Electric/Weighting fields can be imported from TCAD / COMSOL

Overview of the AllPix² simulation process [8]



- Geant4 parameters:
- SiC cross sections, E_i **(see measurement previous slides)**, Fano factor

- SiC e/h mobility / defect models (need to be validated!)

Our Simulation Workflow

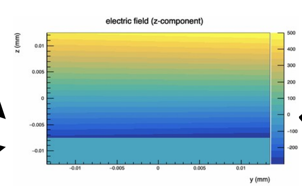
GEANT4 A SIMULATION TOOLKIT

ap² allpix squared

HEPHY Fork

COMSOL

SYNOPSYS®

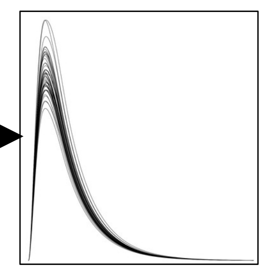


Electric Field
Weighting Field

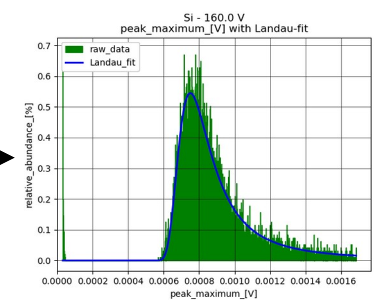
HTCondor

docker

https://gitlab.cern.ch/allpix-squared/allpix-squared/-/merge_requests/759



Transient Pulses



Analysis Software

Benchmarks with planar Si detectors ongoing, SiC as a next step

Next Steps

- New run with CNM aiming at planar SiC detectors with a thickness of 100 µm
- Work towards SiC LGADs
- Simulate SiC planar sensors and LGADs in AllPix²
- Ongoing development of a high rate / integrating ASIC, first prototypes expected to arrive in Autumn
- Further investigate SiC detectors at very high dose rates (higher time resolution, dosimetric comparisons)

References + Acknowledgments

We thank IMB-CNM-CSIC for the SiC samples.
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References:

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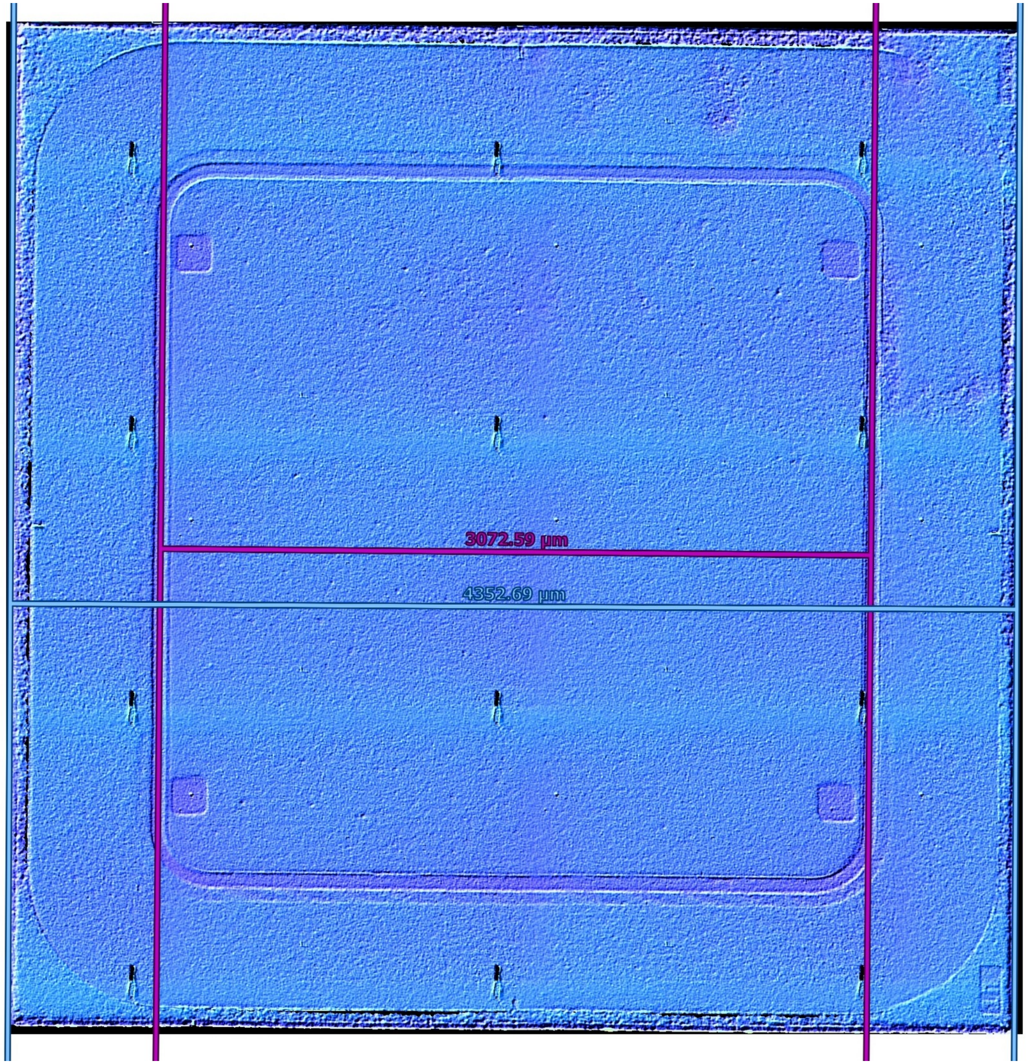
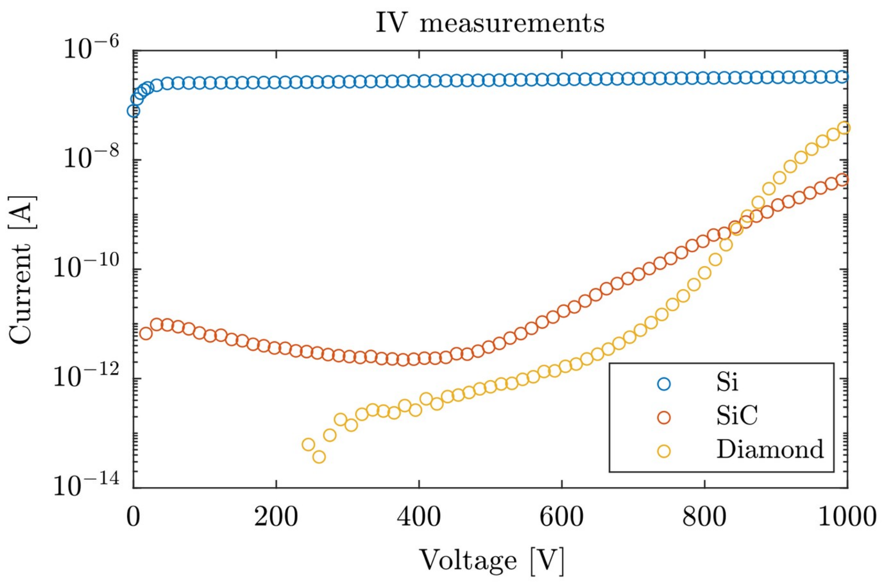
[19] : Petringa, G et al., First characterization of a new Silicon Carbide detector for dosimetric applications. J. Inst. 15, C05023–C05023 (2020).
[20] : Prokopovich, D. A. et al. INVESTIGATION OF CONSTANT OPTICS SLOW EXTRACTION (COSE) AT MEDAUSTRON.

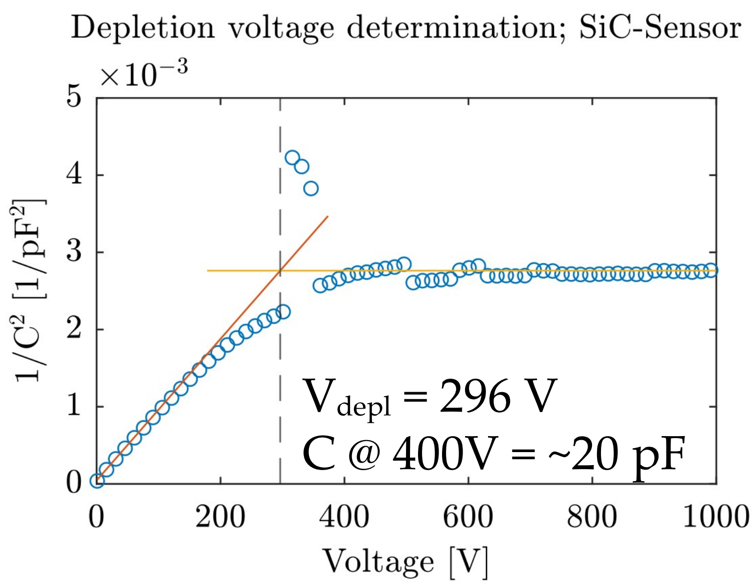
BACKUP SLIDES

Microscope Image of Planar SiC sample



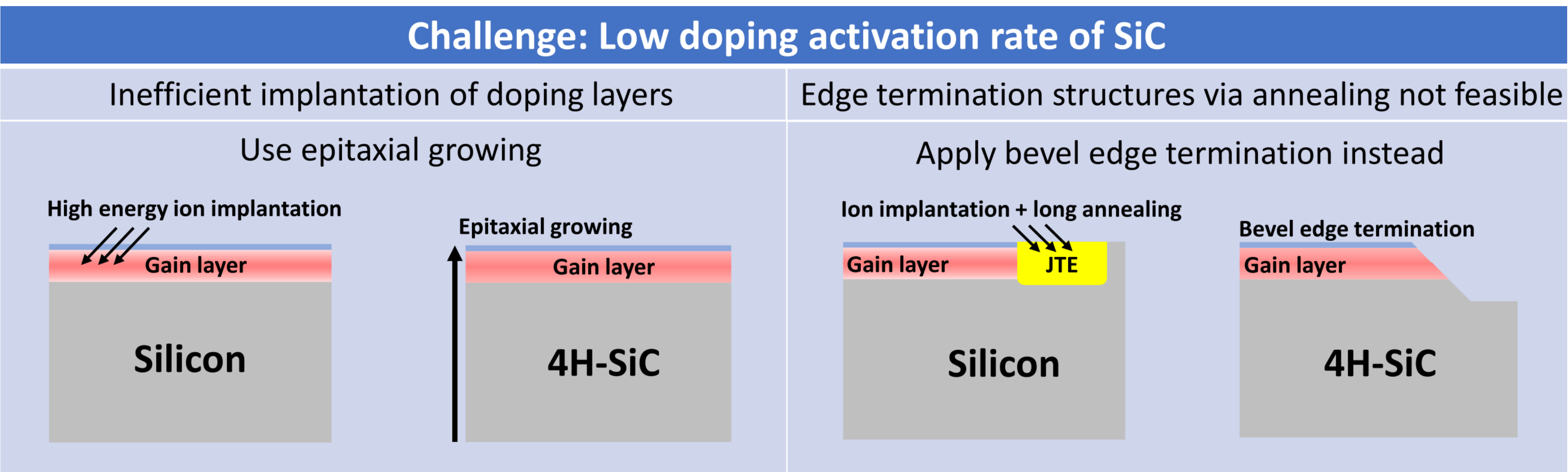
Electrical Characterization of planar SiC samples





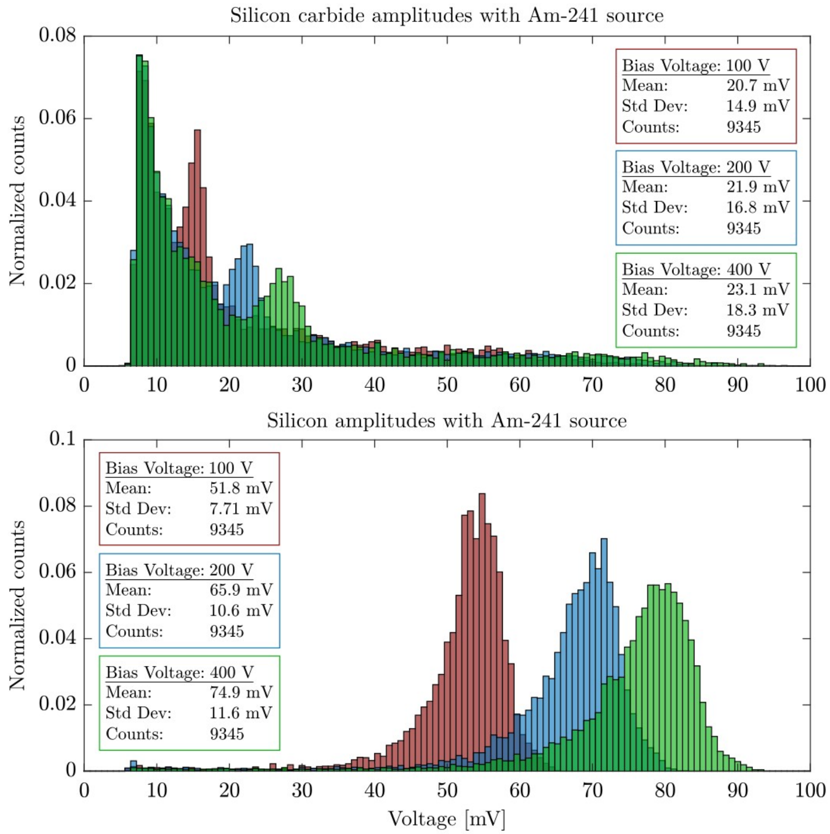
Electrical Characterization of SiC samples [5]

SiC LGAD production



Challenges in SiC LGAD prodution [7]

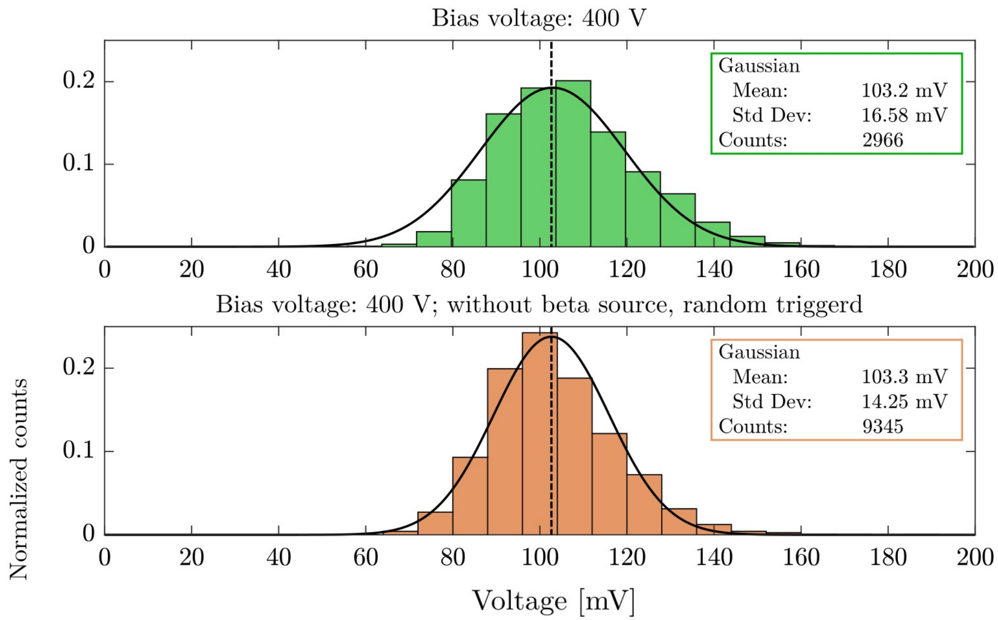
Planar SiC Am-241 (α) Measurements



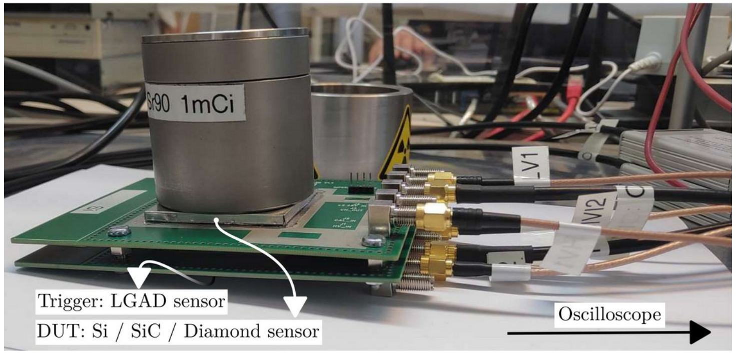
Comparison of signals induced by α-particles in SiC (above) and Si (below) [5]

Planar SiC Sr-90 (β) Measurements

For a Sr-90 source, the induced signals in our SiC sample are too small to be distinguished from noise.

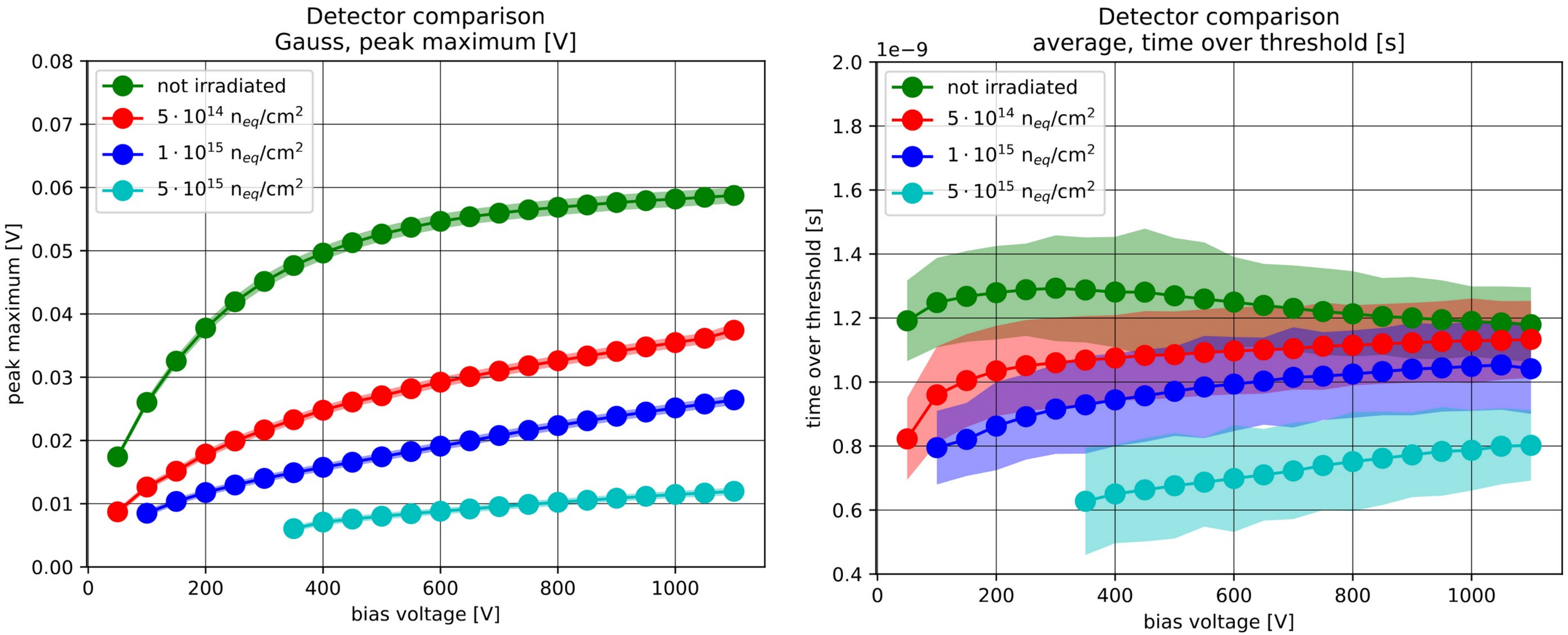


Histogram of Signal amplitudes with a beta source (green) and a random trigger (orange) [5]



Experimental Setup [5]

Irradiated Samples: UV-TCT

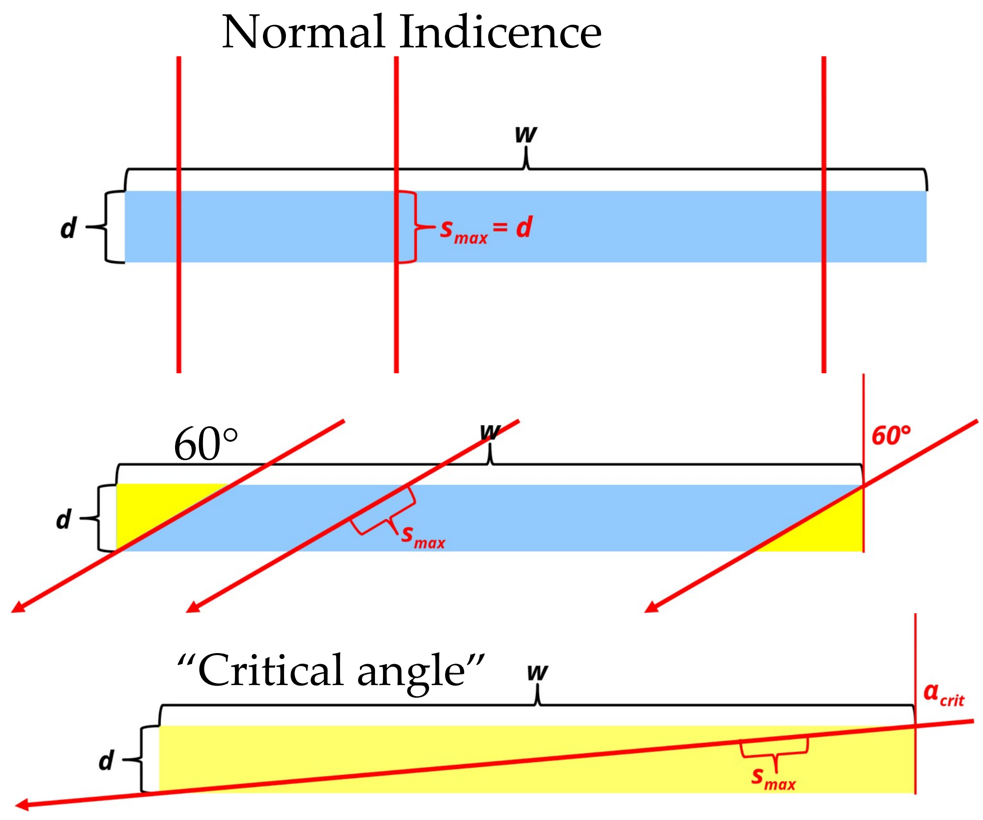


Pulse maximum and ToT as a function of the bias voltage

Proton Beam Angle Scan

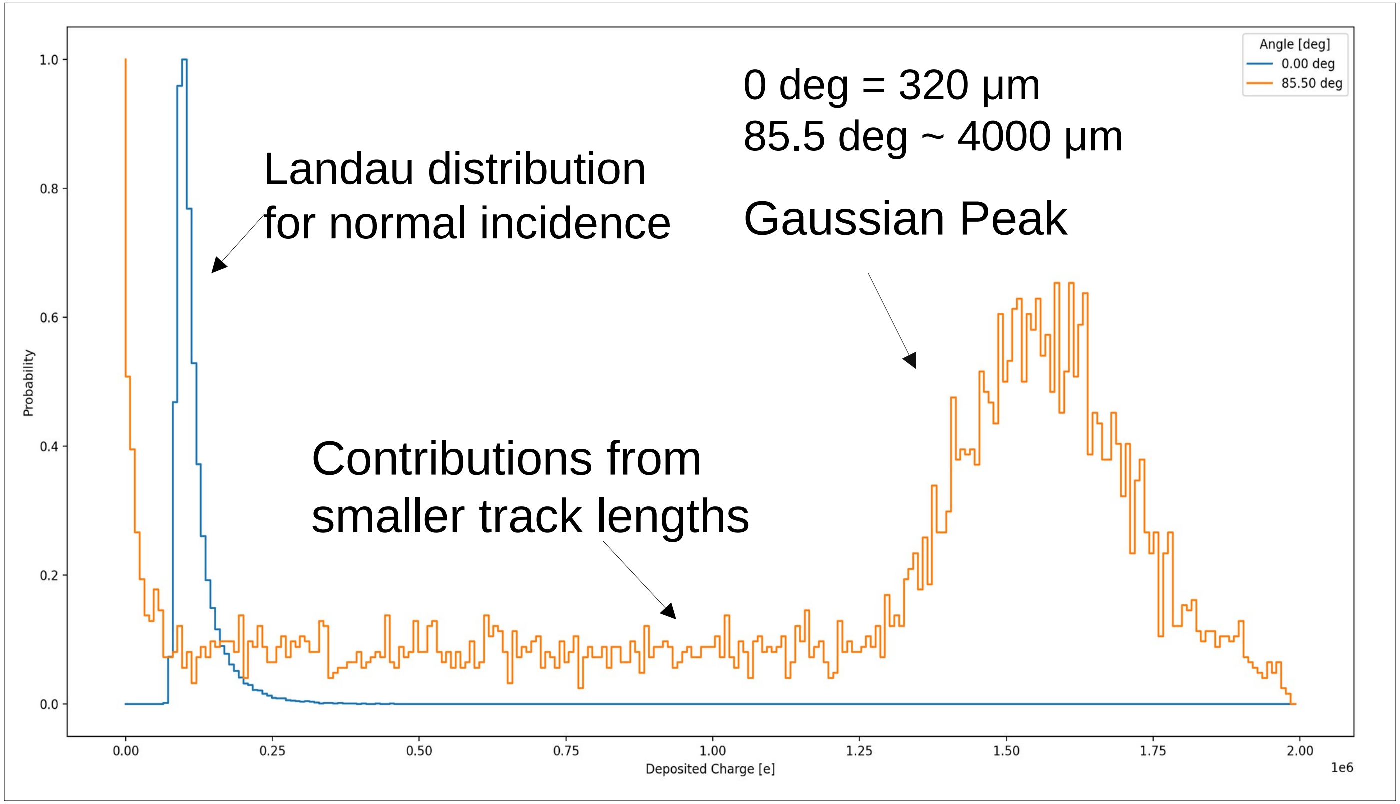
- At normal incidence, each particle "sees" the same detector thickness
- Because our detector is not infinitely large, some tracks will be cut off and "see" a lower thickness
  → **Overlap of Landau distributions for different detector thickness**

- At a "critial angle" α_{crit} , all track lengths between the diagonal through the detector and zero are equally likely

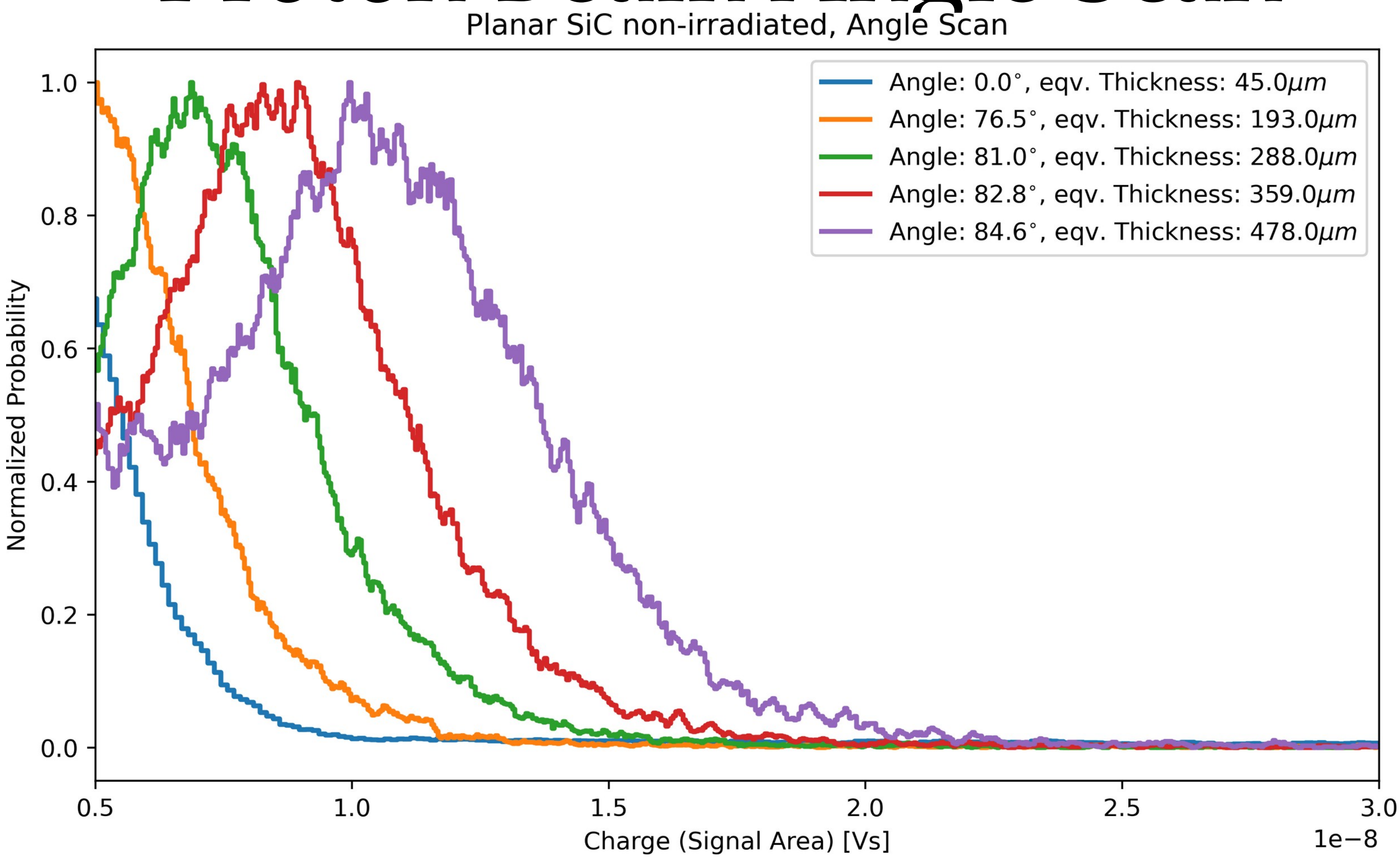


Proton Beam Angle Scan

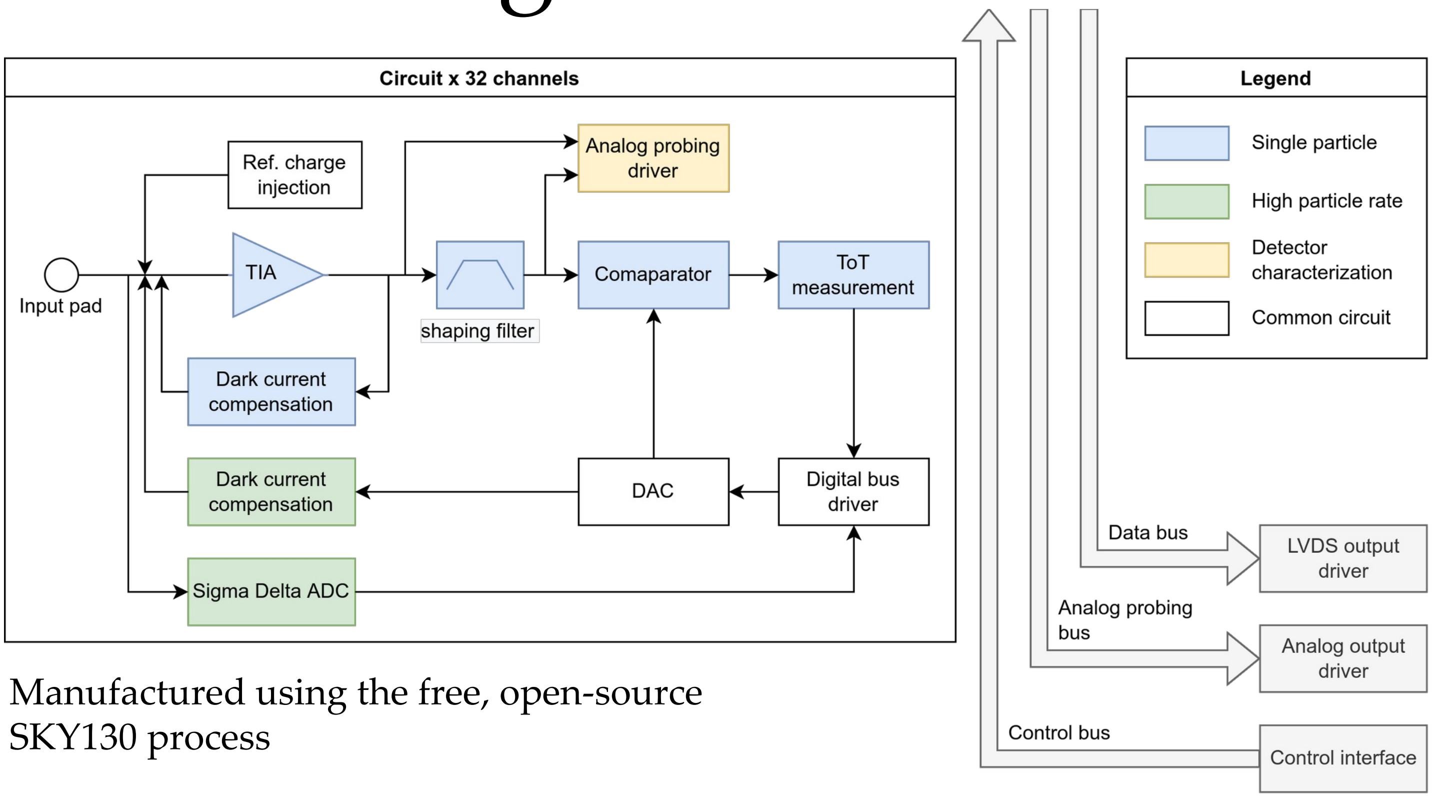
GEANT4 simulation of deposited charge in 320 μm Si for different incidence angles



Proton Beam Angle Scan



ASIC for High Rate Beam Monitor

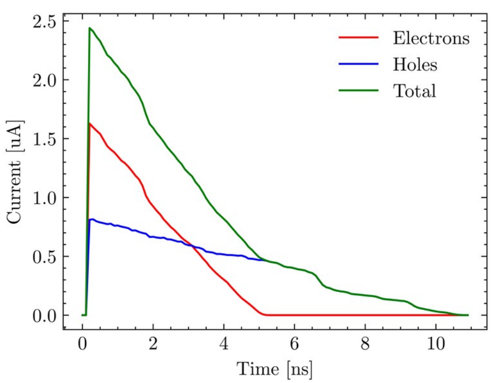


Manufactured using the free, open-source SKY130 process

Preliminary architecture of the readout ASIC under development. The ASIC has two signal pathes. The first signal path (shown in blue) is used for counting individual particles, the second is used to measure the bulk particle flux (green).

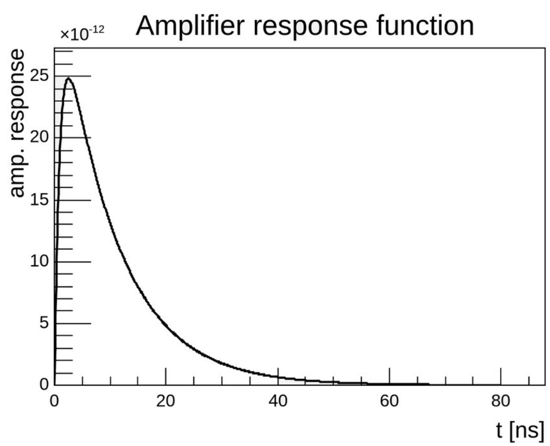
AllPix²: Transient Signals

- Current at readout electrode is calculated using Ramo’s theorem during each propagation step
- Convolution of current with amplifier response function yields signal



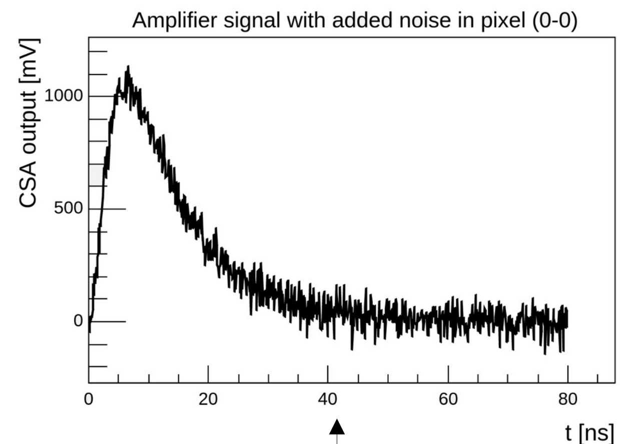
Electron and Hole current for a MIP in a planar Si sensor with 320 µm thickness

*



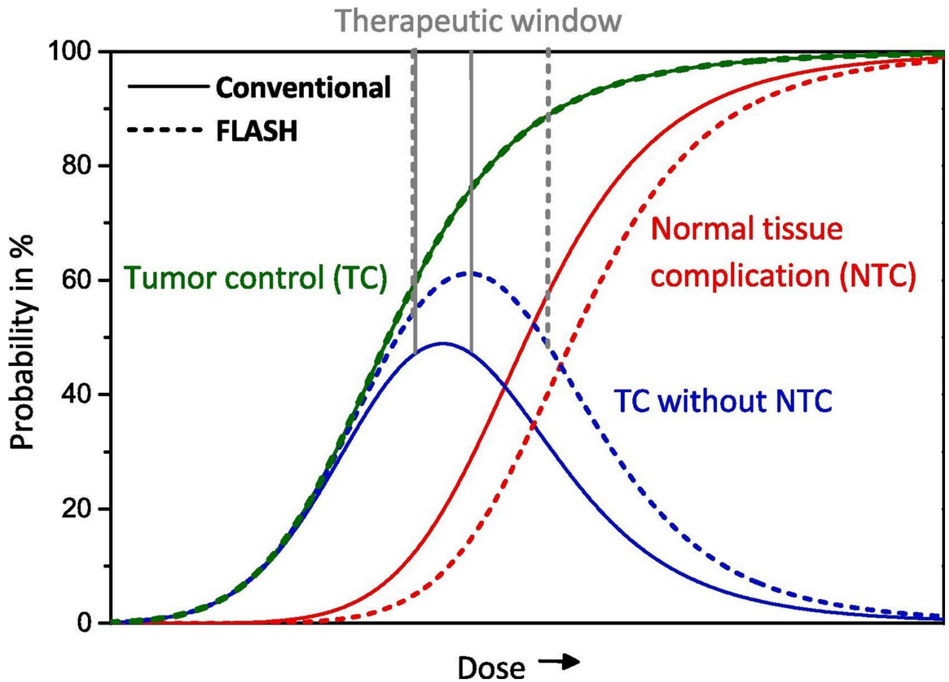
+ Gaussian noise

=



“PixelPulse” object, see https://gitlab.cern.ch/allpix-squared/allpix-squared/-/merge_requests/759

FLASH effect



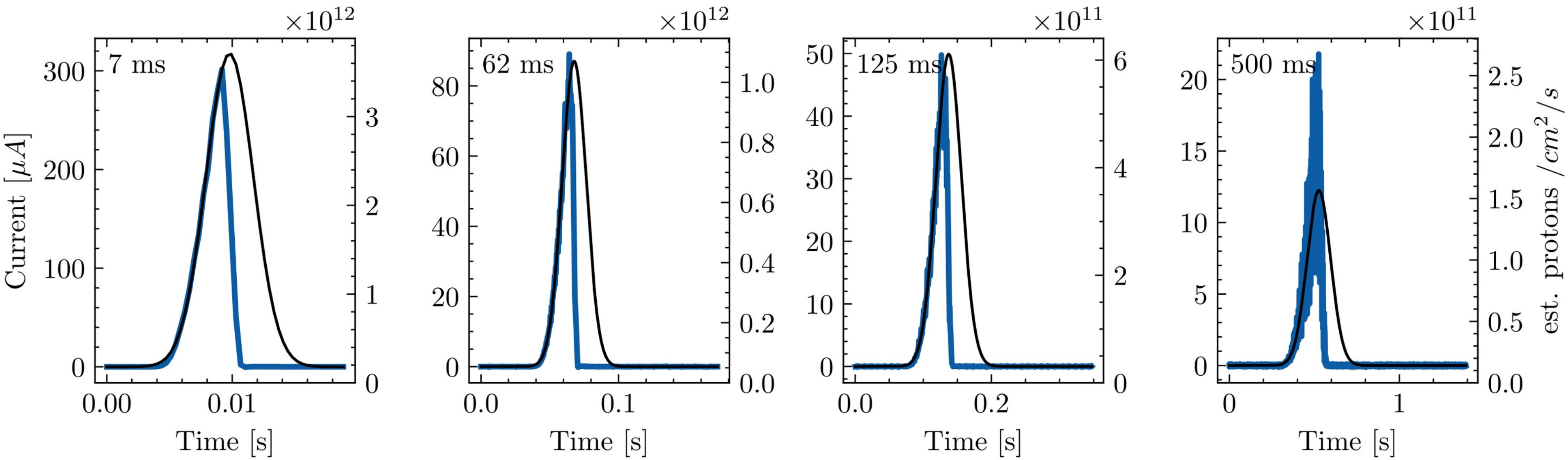
Tumor control vs. normal tissue complication probabilities for conventional and FLASH radiotherapy [16]

FLASH offers a larger therapeutic index (= TC/NTC), which means that tumors can be irradiated with higher doses, increasing TC.

The actual mechanism of the FLASH effect (normal tissue sparing) is still unknown. One leading theory is oxygen depletion [17].

High Proton Beam Rates

- Constant optics slow extraction (COSE) should result in a Gaussian extraction of the stored beam as a function of time.
- Gaussian fits matches well to measurements

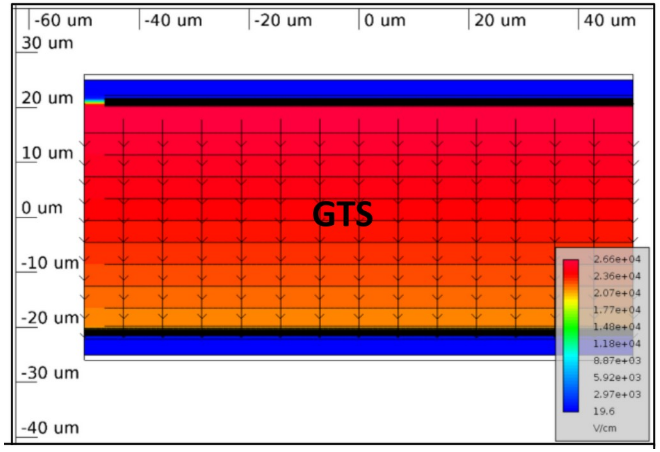


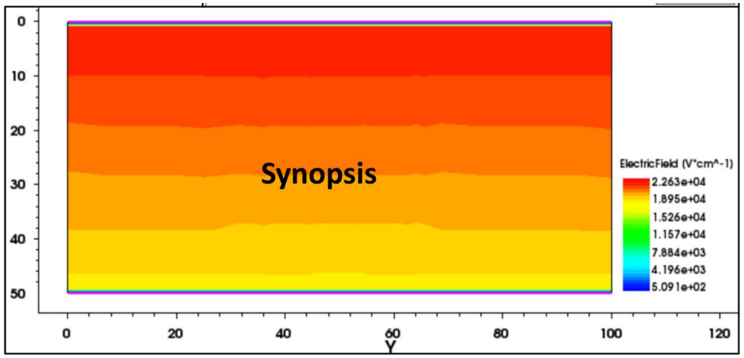
Measured SMU current (blue) together with a Gaussian fit (black) for different extraction times.

SiC Simulation Challenges : TCAD

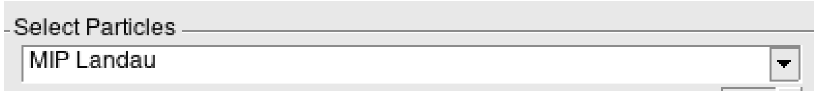
From [7]:

- SiC poorly implemented in most material databases
- Insufficient adaption for drift diffusion and impact ionization
- Convergence issues for due to low current densities
  → Floating point precision is essential
- Active cooperation with Global TCAD Solutions (GTS) to improve software regarding SiC simulation

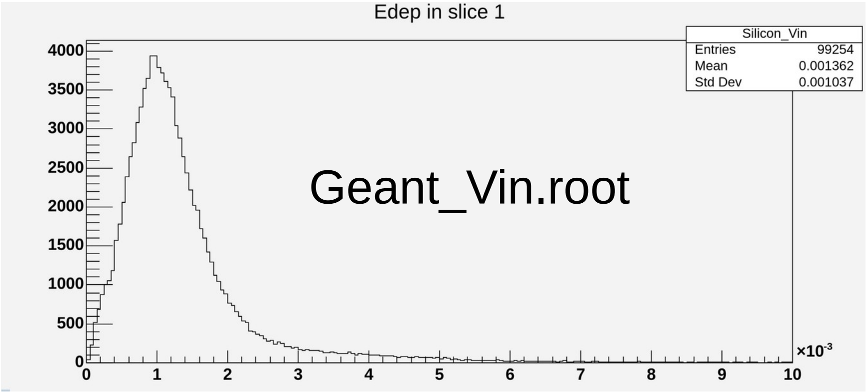




SiC Simulation Challenges : WeightField2 (v5.2)



- For the "MIP Landau" particle type, WF2 uses either a deposited energy spectrum for Si or Diamond ("Silicon_Vin" or "Diamond_Vin" in *Geant_Vin.root*. For SiC no distribution is available and the Si one is used
- For "MIP Landau" the pair creation energy of Si (3.6 eV) is used instead of the one for SiC (5-8 eV).
- In order to handle different detector thicknesses, WF2 rescales the Landau distributions according to measurements and fits for Si [21]. This is incorrect for Diamond and SiC.
- The dielectric constant for SiC is also incorrect, at $\varepsilon_r = 11.9$ (taken from Si) instead of $\varepsilon_r \sim 9.6$ for SiC



[21]: 1.Meroli, S., Passeri, D. & Servoli, L. Energy loss measurement for charged particles in very thin silicon layers. J. Inst. 6, P06013–P06013 (2011).