Wide-bandgap material Silicon-Carbide (SiC) as high-rate particle detector

Philipp Gaggl

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- Readout
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  - Integration mode
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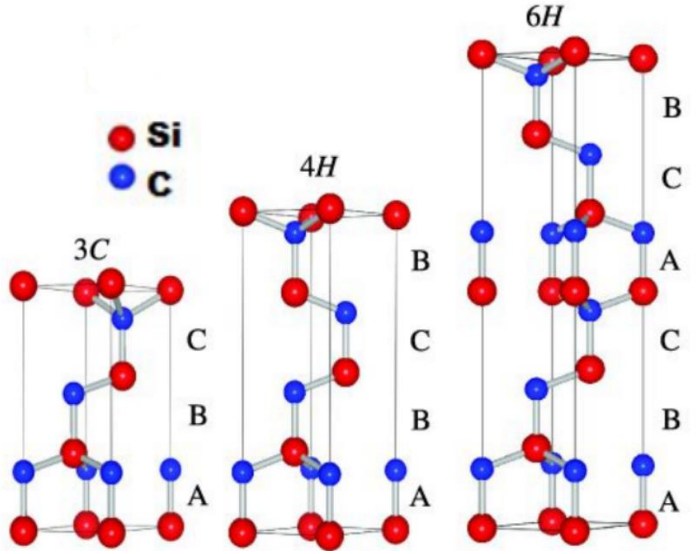
- Summary

Introduction: Why (4H-)SiC?

- Research profits from recent interest of power electronics in SiC
- Various SiC polytypes with different properties
- Characterized by the bonding stacking order of a lattice layer
- Focus on 4H-SiC → Promising candidate for durable single particle detection at high luminosity environments

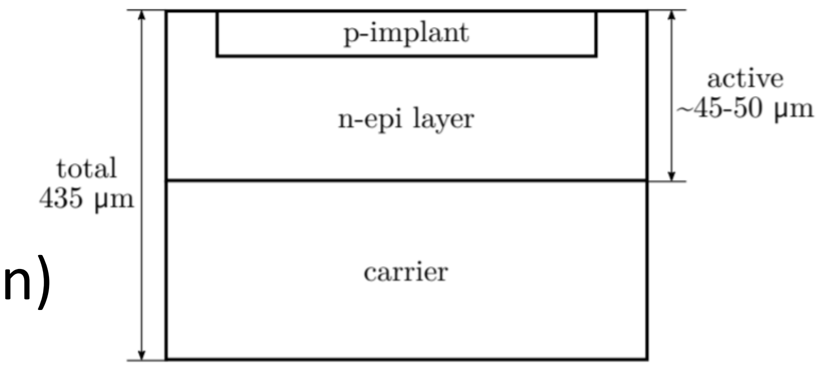


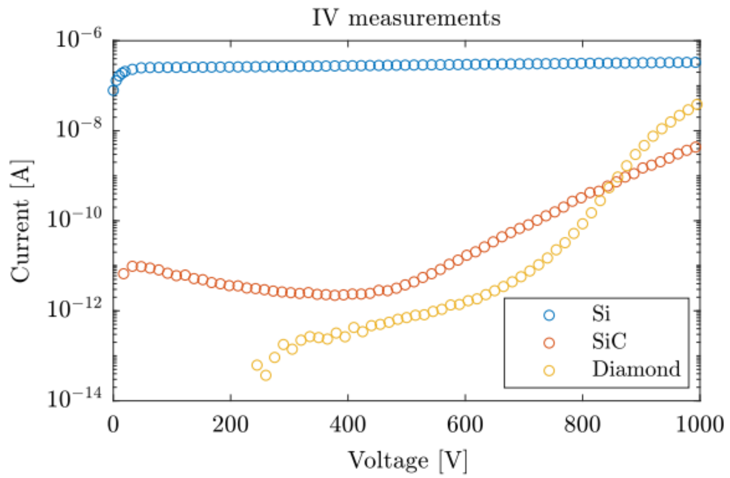
Property	Si	4H-SiC	Advantage
Bandgap [eV]	1.12 [1]	3.27 [1]	Low dark current levels, room temperature
Saturation electron velocity [10^7 cm/s]	1.0 [1]	2.0 [1]	High intrinsic time resolution
Breakdown field [MV/cm]	0.3 [1]	⊥: 4.0; ǁ: 3.0 [1]	High operation voltages
Atomic displacement threshold [eV]	13-20 [1]	22-35 [1]	High radiation resistance
Thermal conductivity [W/cmK]	1.5 [2]	5.0 [2]	Good cooling properties

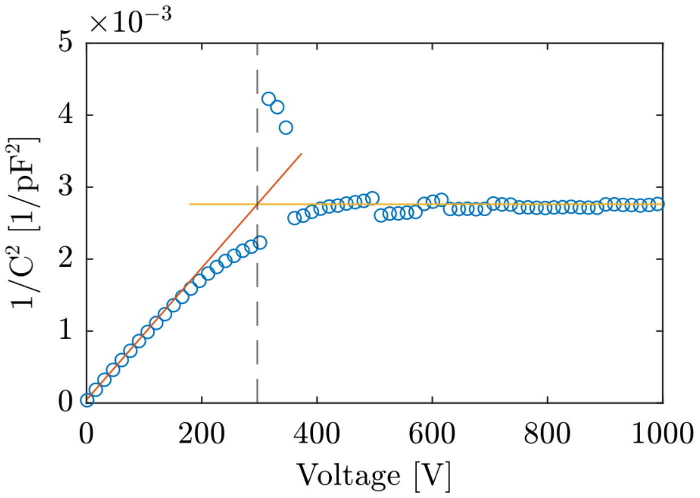
[3]

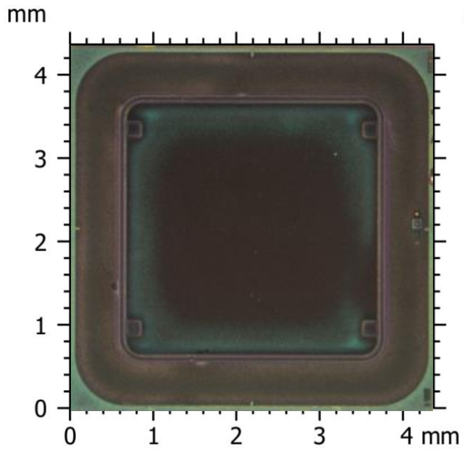
Introduction: SiC samples

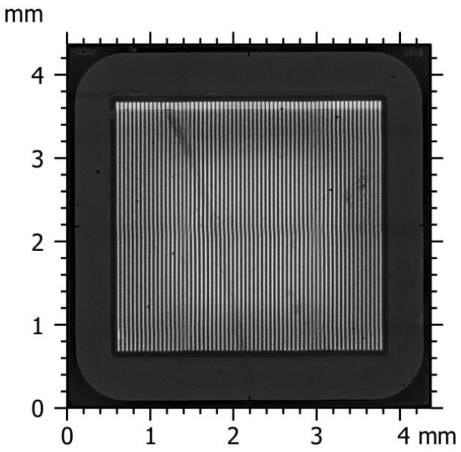
- Provided by CNM (**C**entro **N**acional de **M**icroelectronica, Spain) for evaluation purposes
- 3x3 mm p-on-n diodes with 45-50 µm epi-layer
- Planar diodes and strip sensors (64 strips, 50 µm pitch)
- Preceding simulations (Weightfield, Synopsis, Corryvreckan)
- Extensive experiments in-lab and at ion-beam facility









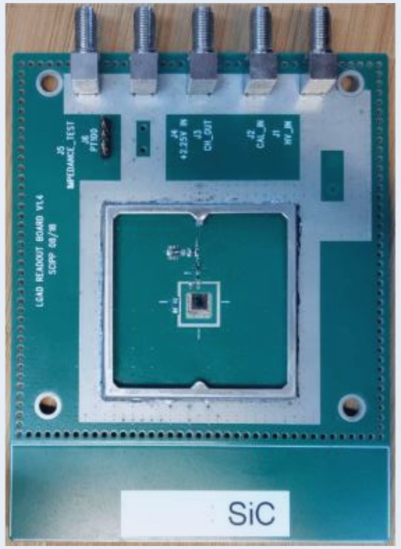


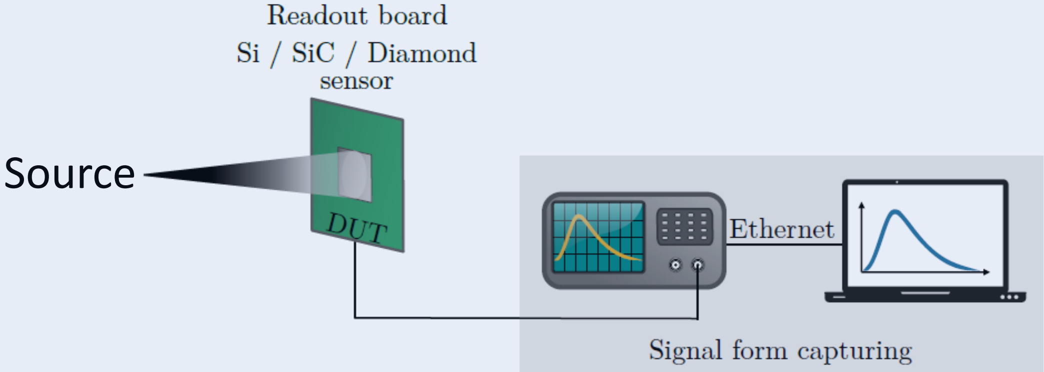
[2, 3]

Introduction: Samples readout

Planar Diode

- UCSC-LGAD-board
- Single channel testboard for different devices (Si, SiC, LGAD, diamond)
- Widely validated and used





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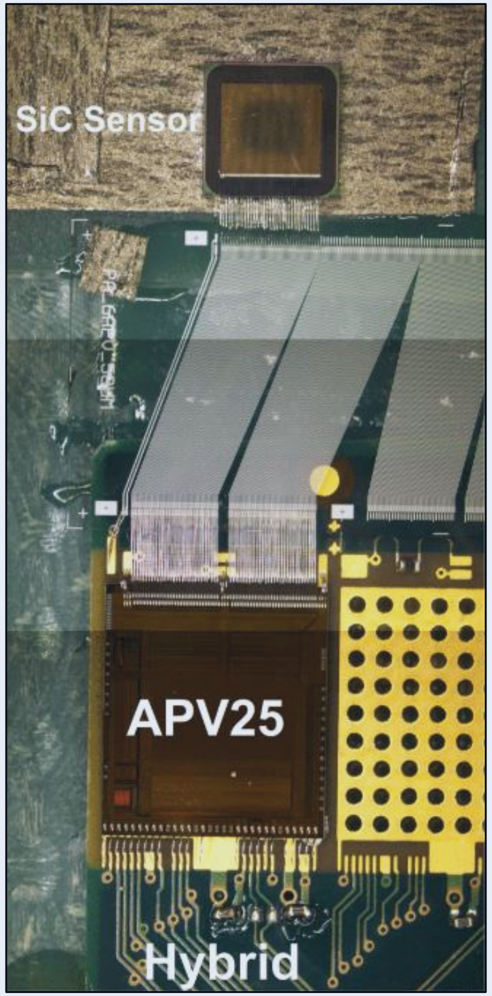
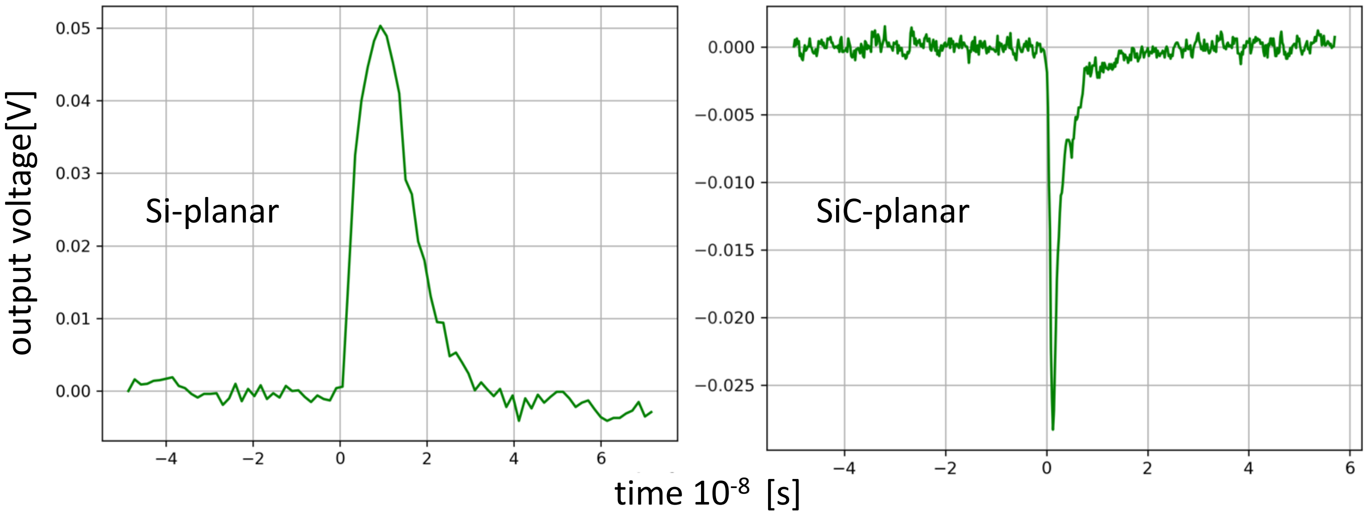
Strip sensor

- APV25 readout chip (128 channels)
- Readout chain originally developed for the Belle-II silicon vertex detector

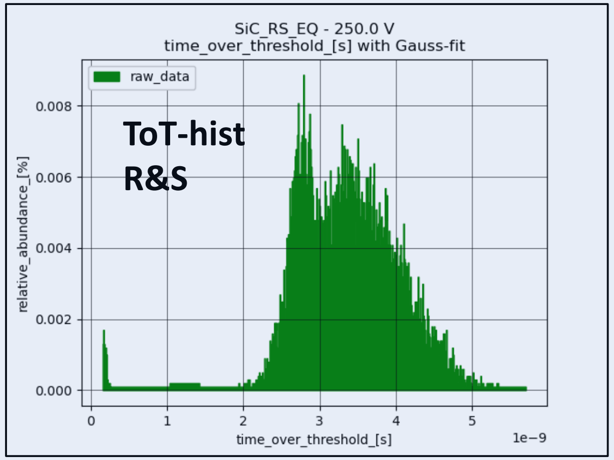


Single channel readout

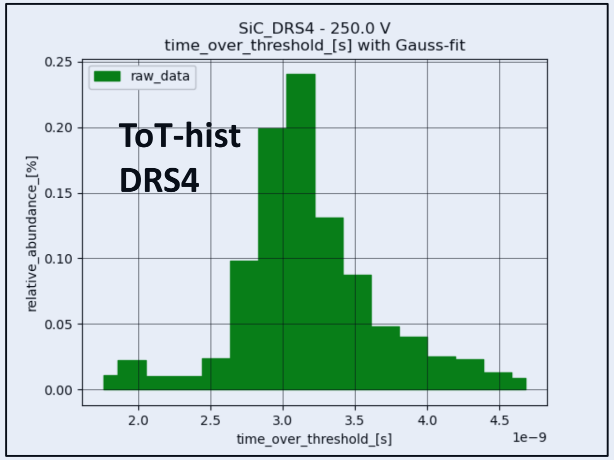
- Epitaxial layer thickness is limited by increasing defect density (< 100 µm)
- Low charge generation per µm and MIP SiC: 57; Si: 80 - 90
- Short signal pulses
- Sufficient readout hardware required



Rohde & Schwarz
Costs ≈ 200.000 €
40 Gsamples / s
16 GHz



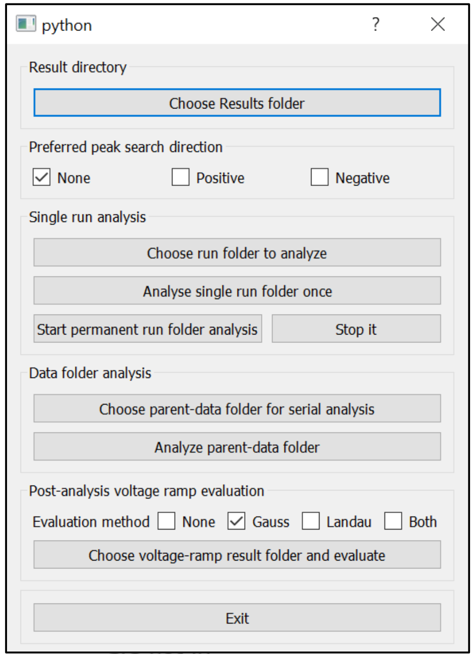
DRS4 test board
Costs ≈ 1.000 €
5 Gsamples / s
700 MHz

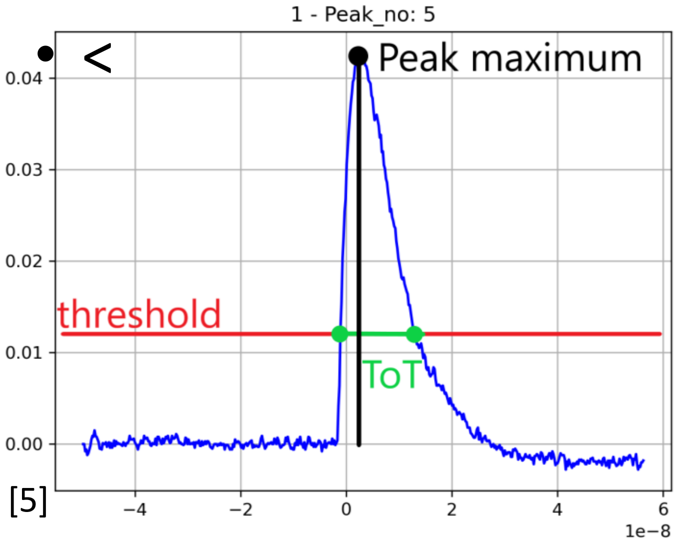


Introduction: Signal analysis

- Developed a Python framework for automated detector analysis
- Peak finding/analysis algorithm to obtain statistics of peak parameters

  → area, maximum, time over threshold, SNR
- Individual noise level calculation, user friendly GUI’s
- Gauss/Landau fitting of histograms for voltage ramp evaluation





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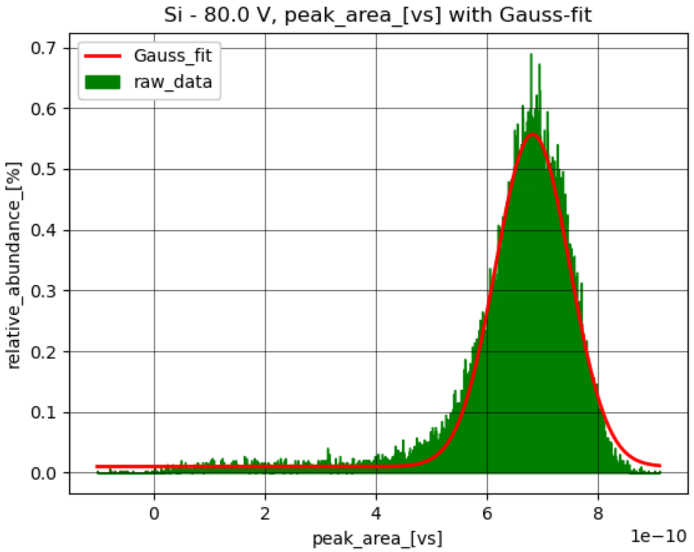
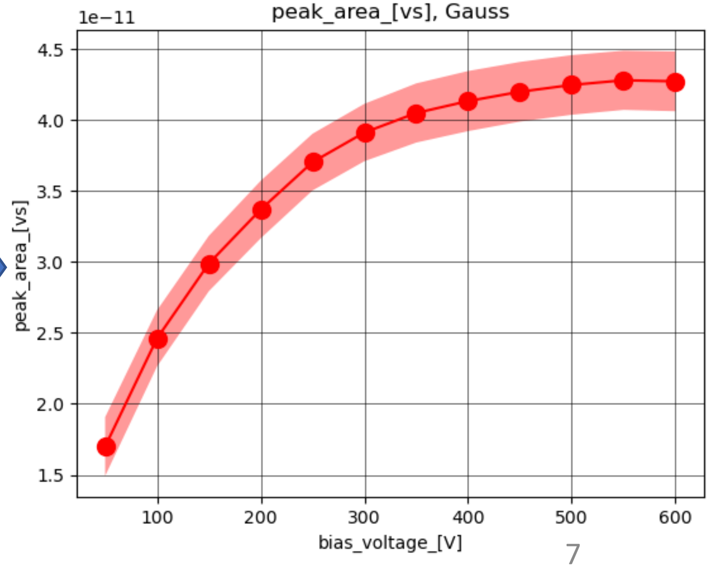
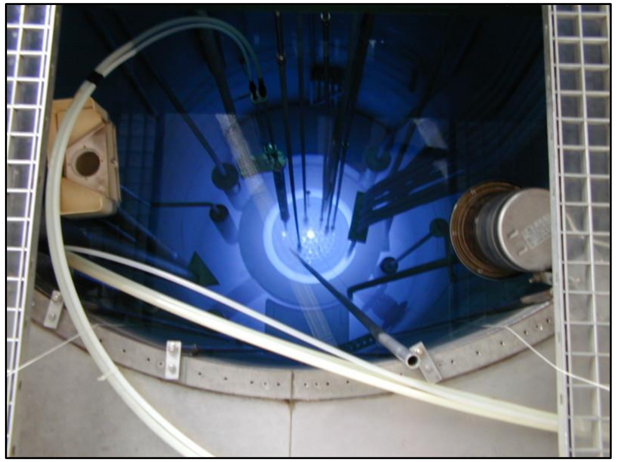
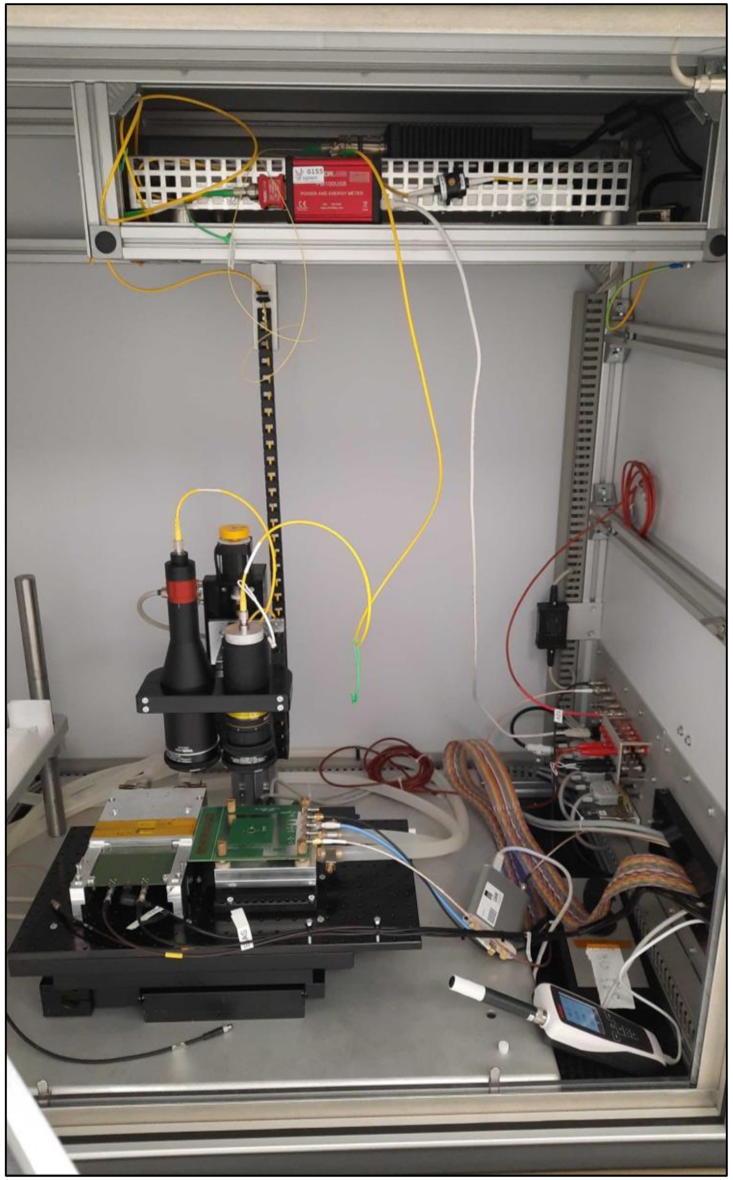




Measurements: UV-TCT

- UV-TCT (**T**ransient **C**urrent **T**echnique) at HEPHY-lab
  - Imitation of traversing particle through short laser pulses
  - Short pulses (< 60 ps) at constant high intensity
  - UV-laser (NKT): $\lambda \approx 375$ nm→ Sufficient for SiC bandgap
  - Efficient triggering
- Samples neutron irradiated at TRIGA Mark-II research reactor (Technical University of Vienna)





- Investigated fluences [cm^{-2}]: $5{\cdot}10^{14}$ / $1{\cdot}10^{15}$ / $5{\cdot}10^{15}$ / $1{\cdot}10^{16}$

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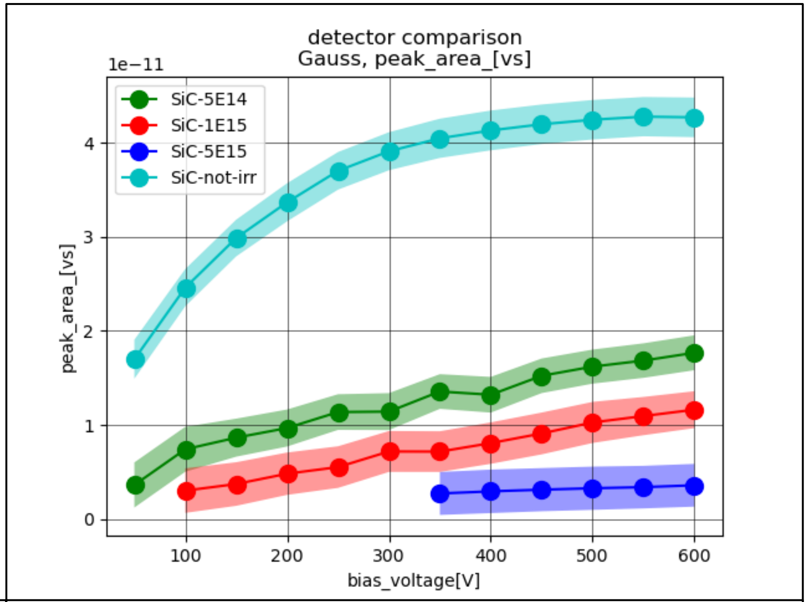
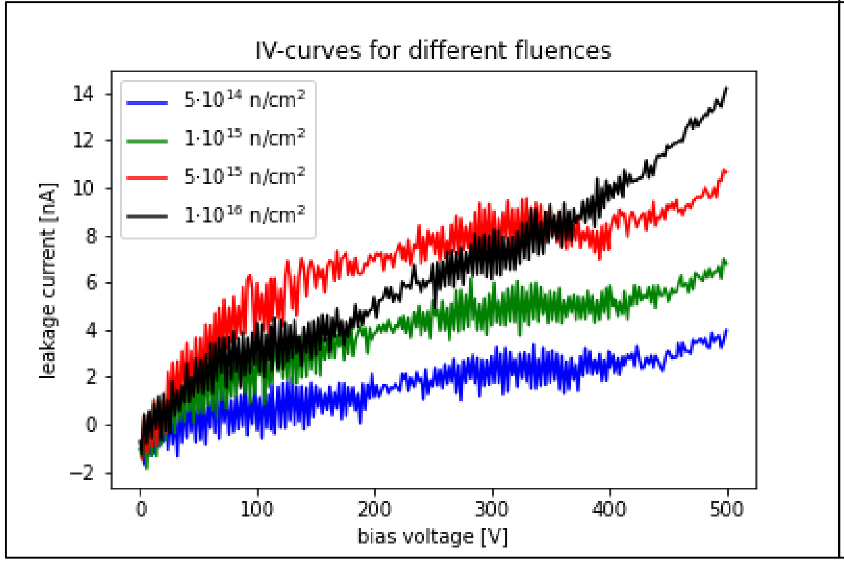
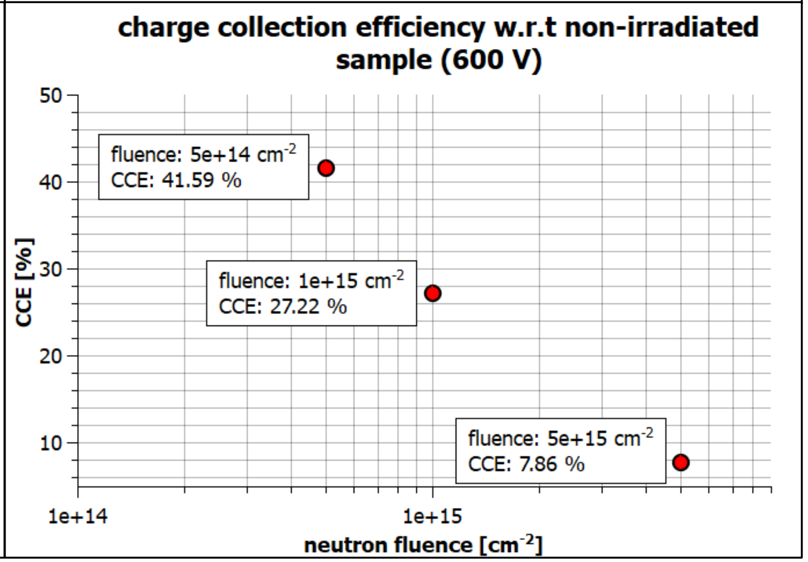
Measurements: UV-TCT

- Analyzed peak area → proportional to collected charge
- Non-irradiated sample saturates at about 500 V
- No saturation for irradiated samples up to 600 V
- Decent efficiency for fluence of $5 \cdot 10^{14}$ & $1 \cdot 10^{15}$ cm^{-2}
- Increasing leakage current with irradiation, but remains at low level



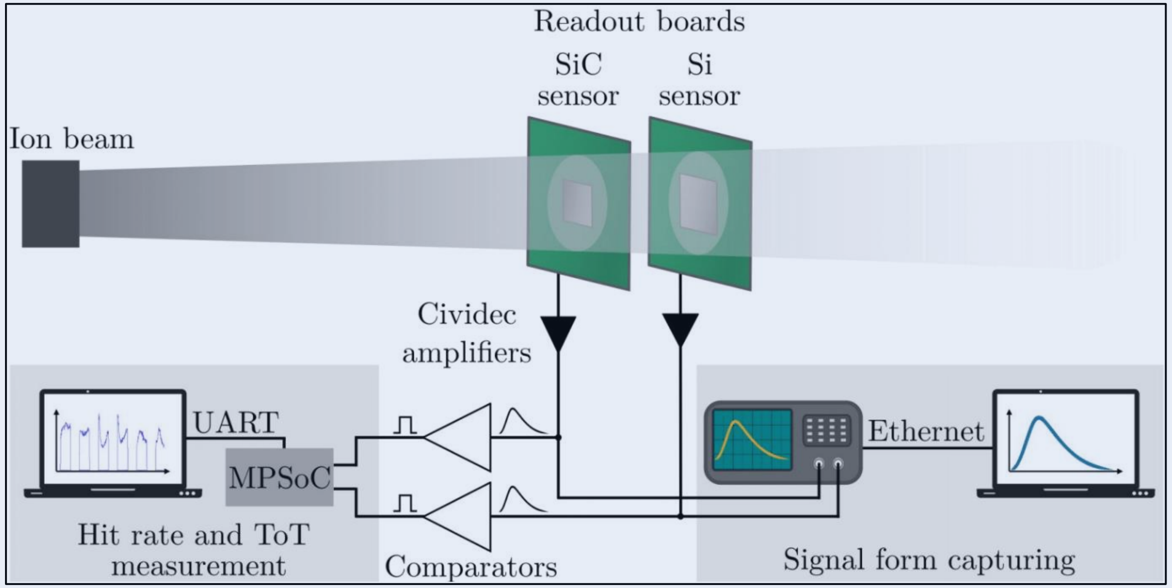




Measurements: Ion Beam

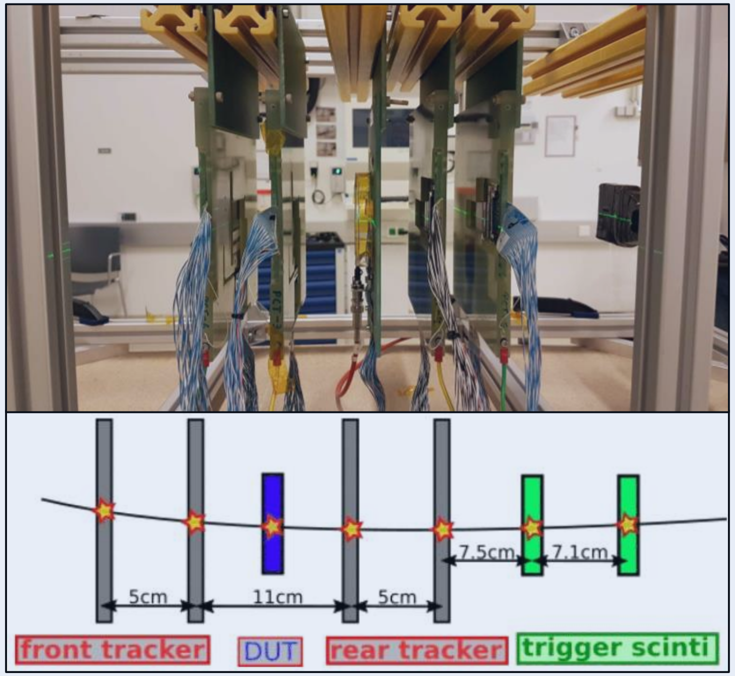
Planar Diode

- SiC signal triggered by Si signal
- Signals discriminated by comparator
- Counted by an FPGA



Strip sensor

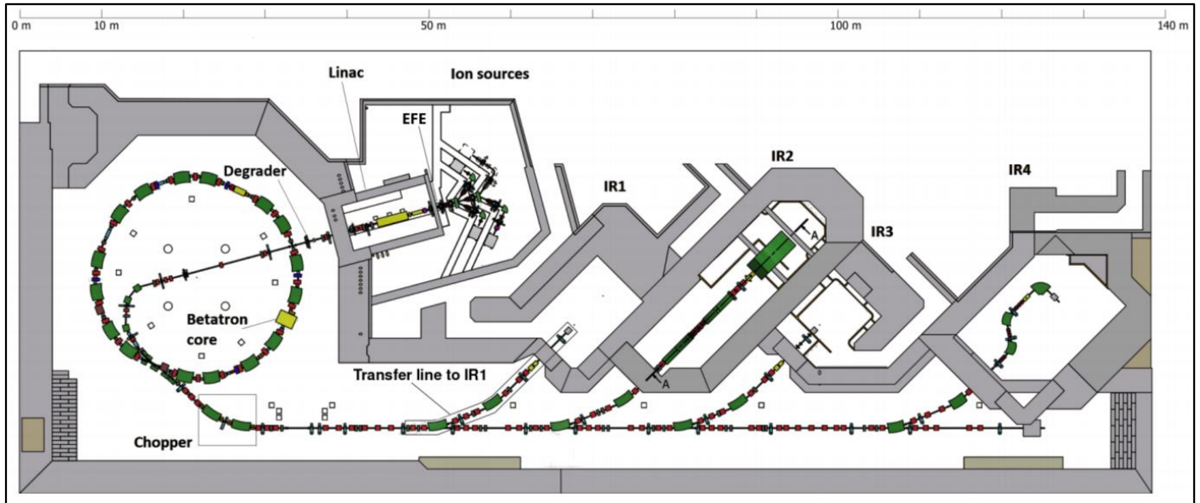
- Telescope setup
  - Si sensors for output comparison
  - Scintillators for event-triggering

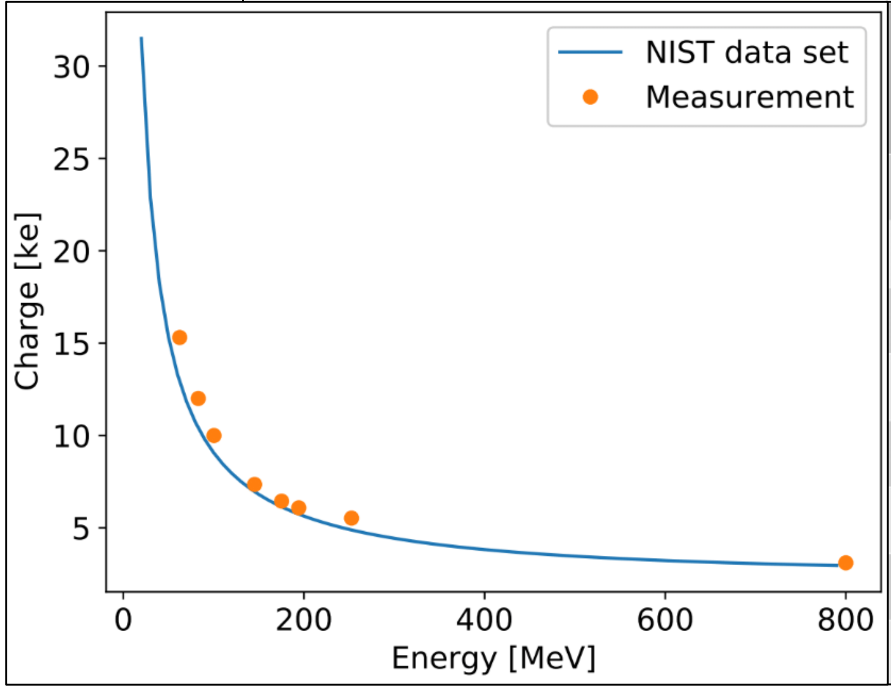


[2, 3]

Measurements: Ion Beam

- Conducted at MedAustron (Wiener Neustadt)
- Cancer treatment center exploiting the Bragg-peak of protons and Carbon ions
- Available flux settings between 10^3 - 10^9 / s
- Accessible particle energies up to 800 MeV
- Allows for experiments at various energy depositions



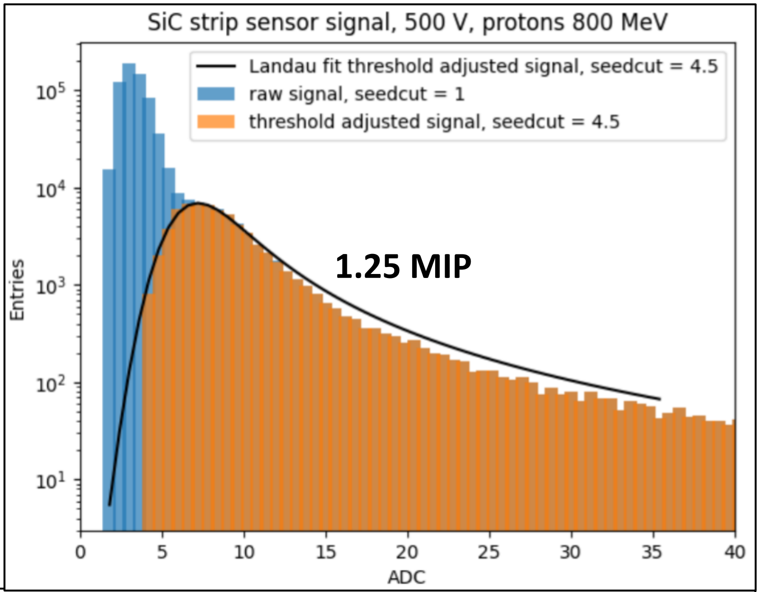


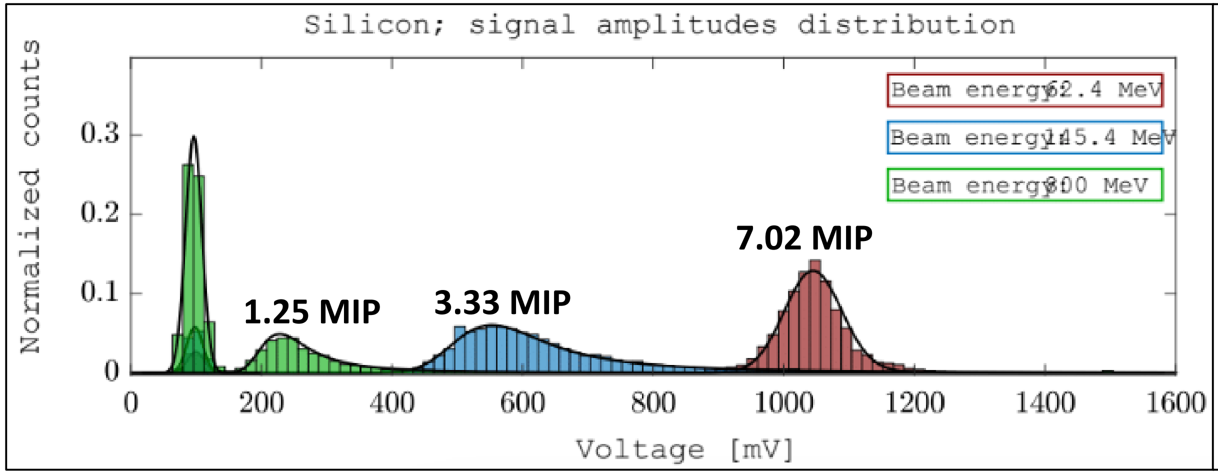
Energy in MeV	MIP charge generation equivalent
62	7.02
83	5.49
100	4.67
145	3.33
175	2.97
194	2.74
252	2.29
800	1.25

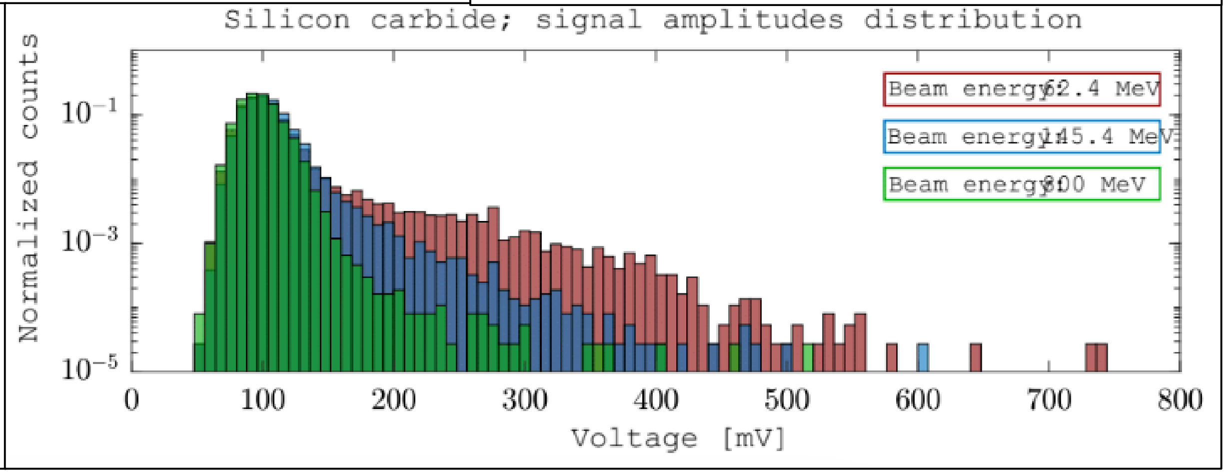
[2, 3, 8]

Measurements: Ion Beam

- Small signal amplitudes of SiC overlap with noise
  - → Effective filtering using minimal samples above threshold
- Ionization energy determined via comparison with Si-results
  - → 5.85 eV; literature: 5 - 8 eV [9, 10, 11]
- Results normalized to sensor thickness and MIP-charge generation equivalent
  - → One MIP generates 57.1 e/h pairs per µm SiC; literature: 55 [12]







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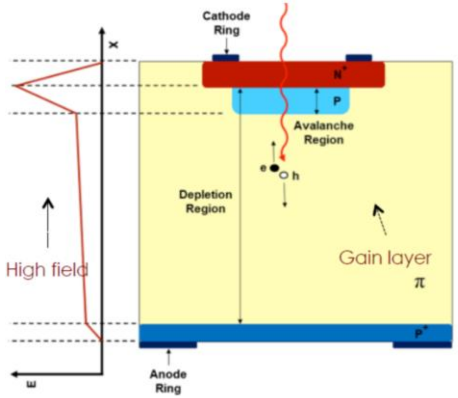
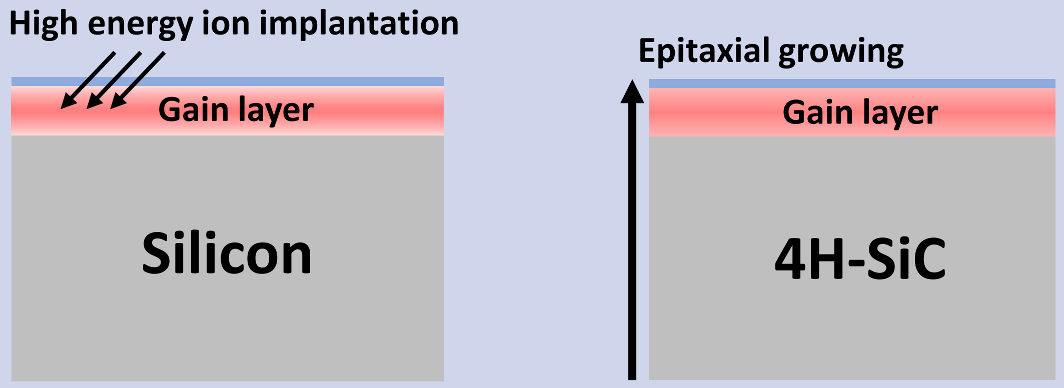
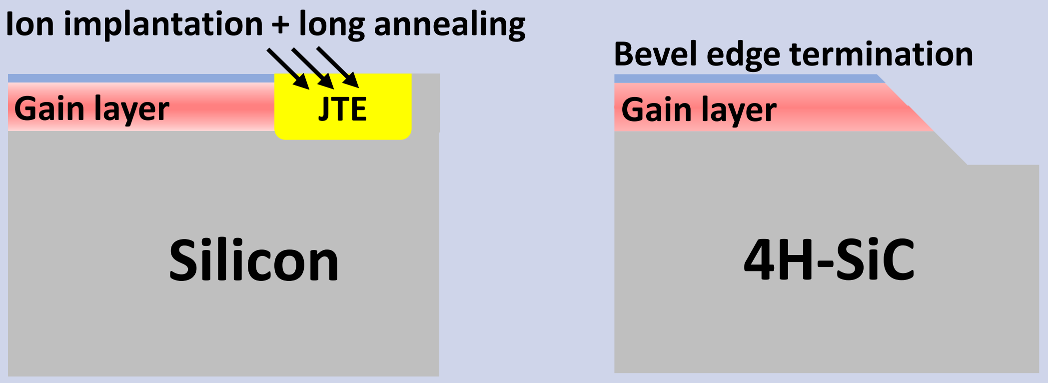
SiC - LGAD: Challenges

- Strong field region realized by additional gain layer → Avalanche effect
- Higher signal amplitudes and improved time resolution
- Produce SiC-LGAD prototypes in cooperation with CNM



Challenge: Low doping activation rate of SiC	
Inefficient implantation of doping layers	Edge termination structures via annealing not feasible
Use epitaxial growing	Apply bevel edge termination instead





[6]

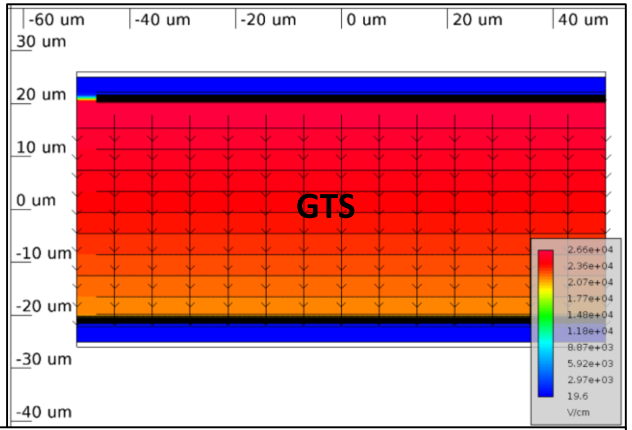
SiC - LGAD: Simulation

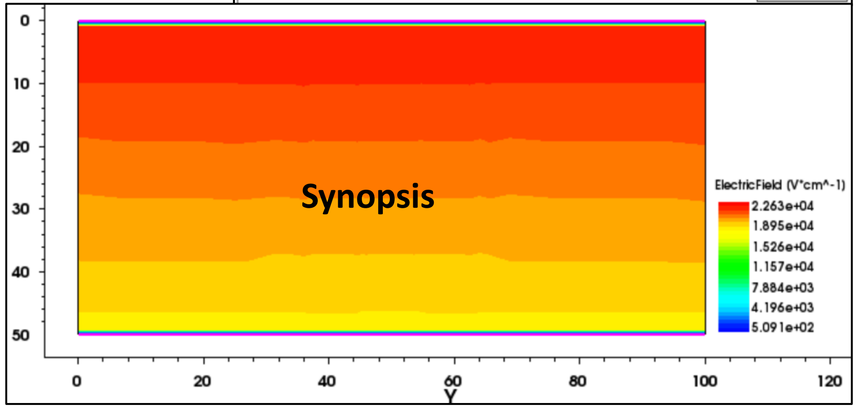
- Approach using a combination of different simulation tools

Single device — Synopsis, GTS → **Signal output** — Synopsis, Weightfield → **Experimental setup** — Geant4, Allpix^2

- Obstacles regarding simulation of SiC:
  - 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[13]) to improve software regarding SiC simulation





Application of SiC sensors

Fast tracking sensors

- Strip or pixel detectors
- Short pulse lengths
- At lower beam rates sufficient for particle beam monitoring
- Standard: Si detectors

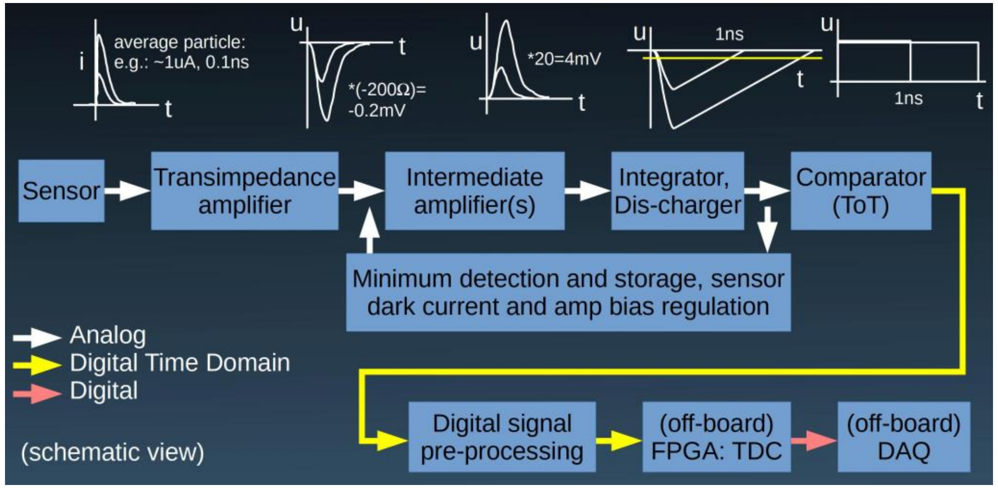
High intensity monitors

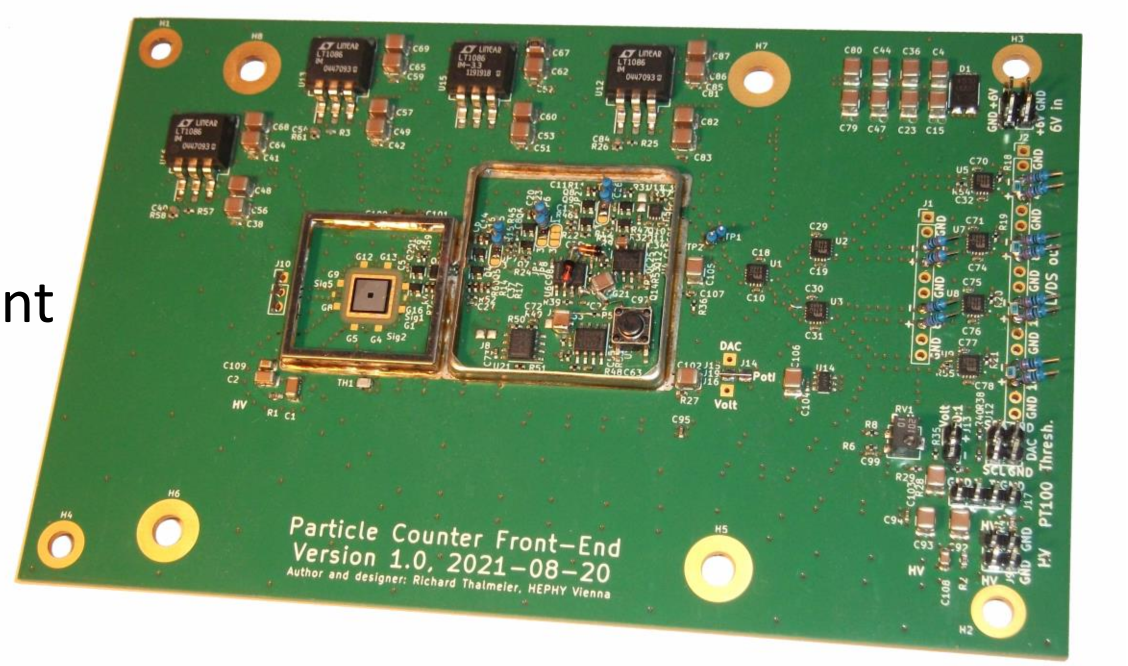
- Integrating collected charge to monitor beam rates and properties
- Operation at wide ranges of particle rates and energies (e.g., MedAustron)
- Radiation hard material
- Standard: Diamond

SiC-LGADs could be used for both purposes, provided sufficient readout-electronics

Readout: Single particle mode

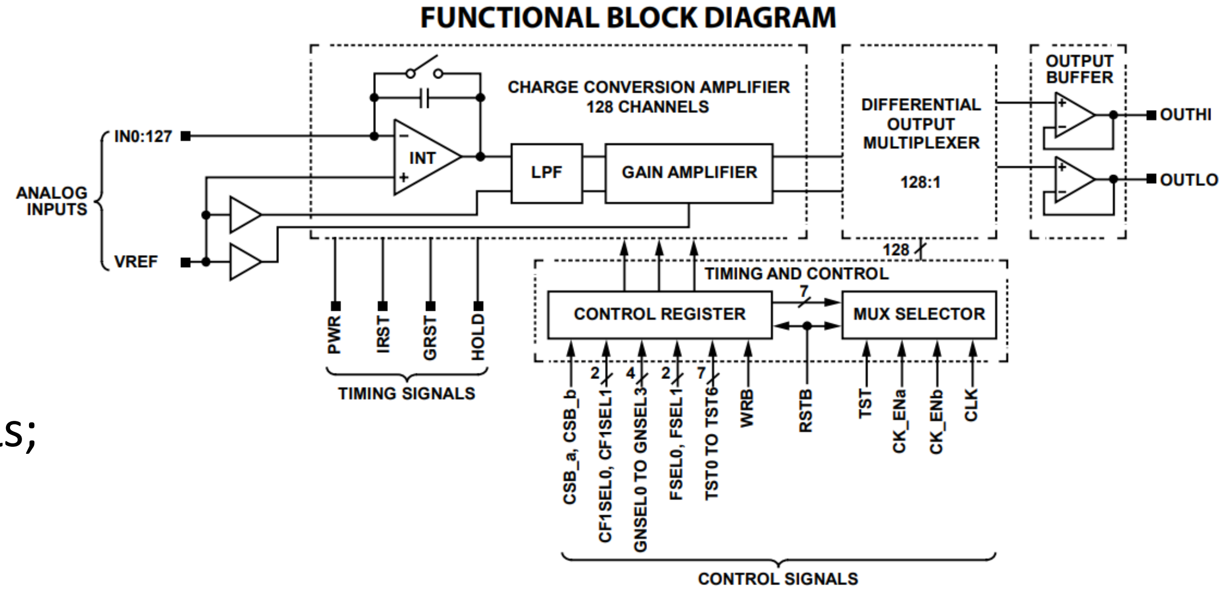
- Prototype for beam monitoring at MedAustron
  - One single channel
  - Continuous detection of single particles up to „GHz“
  - Detection of pile-ups up to about 50 particles
  - A few seconds pause after each „spill“
- Adapt-able for different sensors
  - Silicon, silicon carbide, diamond, LGAD, ...
- Amplifier chain built using discrete components
  - Fully DC coupled from sensor to comparator
- Tested using an oscilloscope for time measurement
  Later per FPGA or ASIC (e.g., vernier TDC)
- Currently in optimization phase
- Later an integration into an ASIC is intended

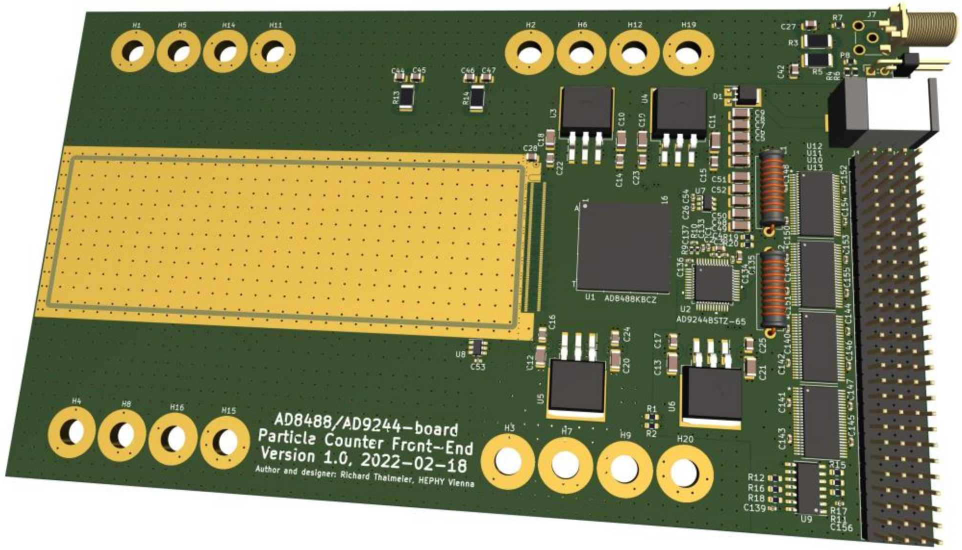




Readout: Integration mode

- Prototype designed to measure up to 128 channels of high luminosity particle rates
- Exploiting a commercial X-ray imaging front-end chip
  - Each channel integrates the current of one detector strip into an individual capacitor for 12µs; all channels do that simultaneously
  - A multiplexer then reads out the storage capacitors sequentially within 15µs; the setup is "blind" meanwhile
- Analogue data sequence is converted by an ADC and passed on to an external FPGA board
- To study the suitability of integrating amplifiers
- Currently in production

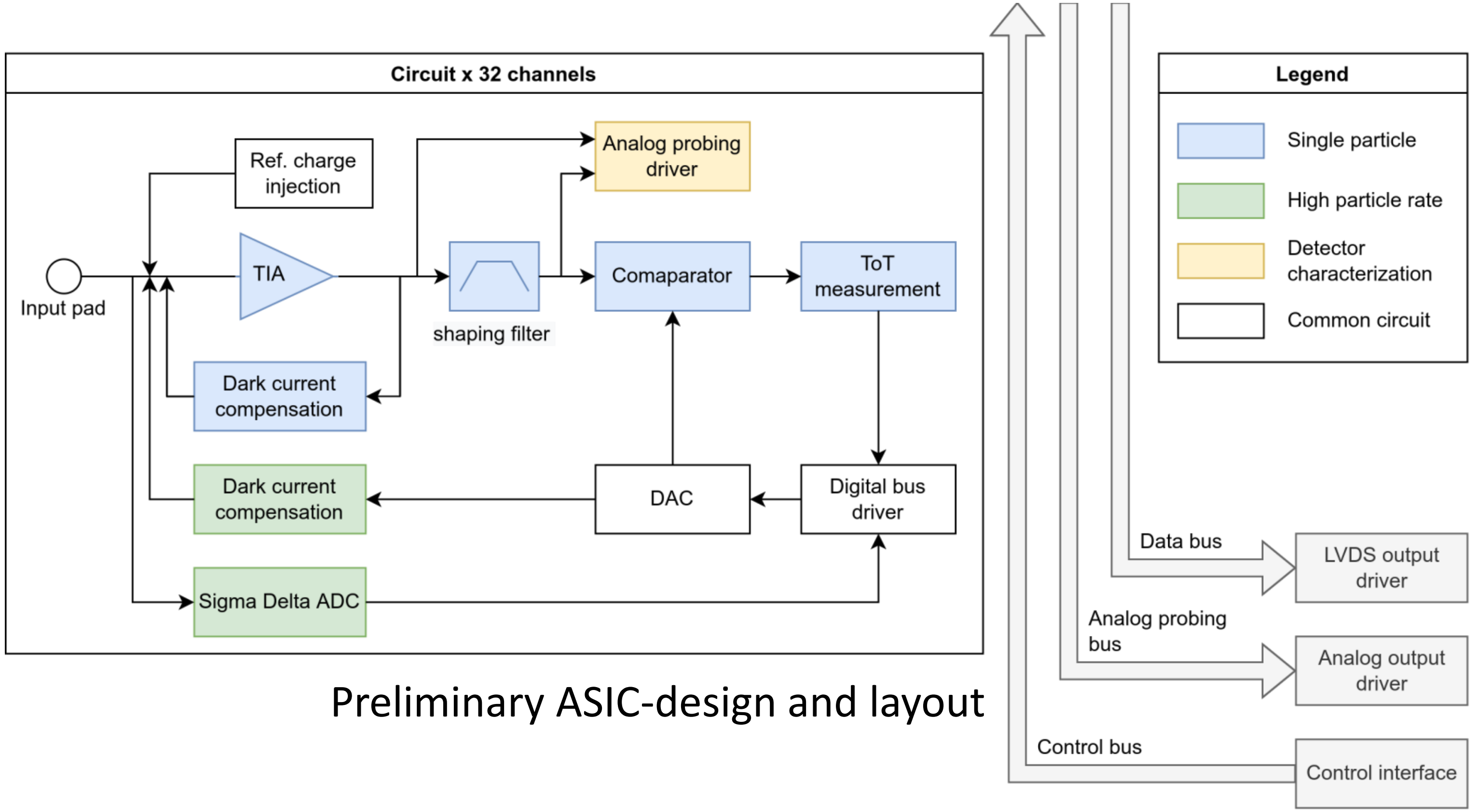




Dual application

Current objectives:

- Integrate both readout options into an ASIC
- Develop an FPGA suitable to exploit the characteristics of SiC-LGADs



Preliminary ASIC-design and layout

Summary & Outlook

- Promising detector material:
  - More accessible due to recent advancements in power electronics
  - Fast signal pulses
  - Low dark current (also after radiation)
  - Potentially higher radiation hardness
- Benchmark of samples using measurements in-lab and at MedAustron, also irradiated
- But: Limited sensor thickness; lower charge generation → low signal amplitudes
- SiC-LGAD:
  - TCAD simulations challenging for SiC (adapted models and materials, floating point precision)
  - Collaboration with GTS to adapt TCAD software for SiC
  - Development of prototypes
- Two-fold electronic readout approach for studying devices (single particle, integrating)
- Implementation into ASIC and development of FPGA

Sources

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