Investigation of Neutron Radiation Damage in 4H-SiC p-n Diodes

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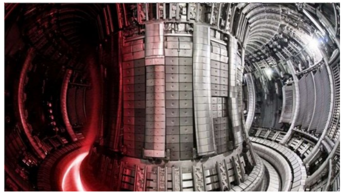
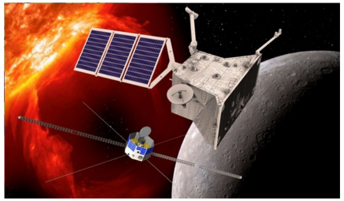
Silicon Carbide Detectors

- Wide bandgap semiconductor (3.26 eV) : Low leakage currents, insensitivity to visible light
- Renewed interest: High quality wafers from power electronics industry

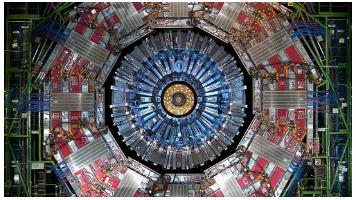
+ High breakdown field and saturation velocity : timing applications
+ Potentially higher radiation hardness (displacement energy), no cooling needed after irradiation
- Higher ionization energy (~30% less signal per µm) [1]
- Limitations in wafer thickness and resistivity

Dosimetry: µDOS, FLASH [2]

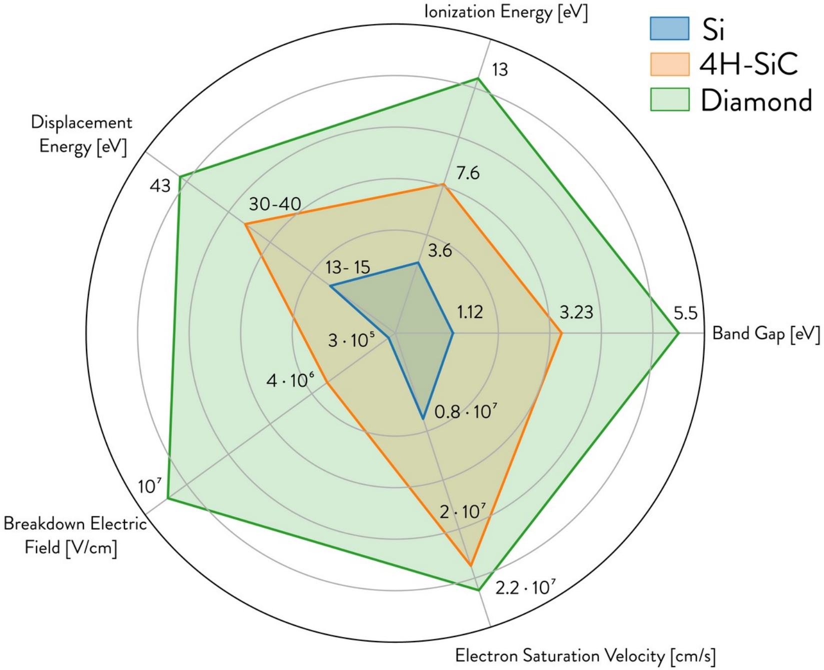




Space, harsh environments (fusion) [3]



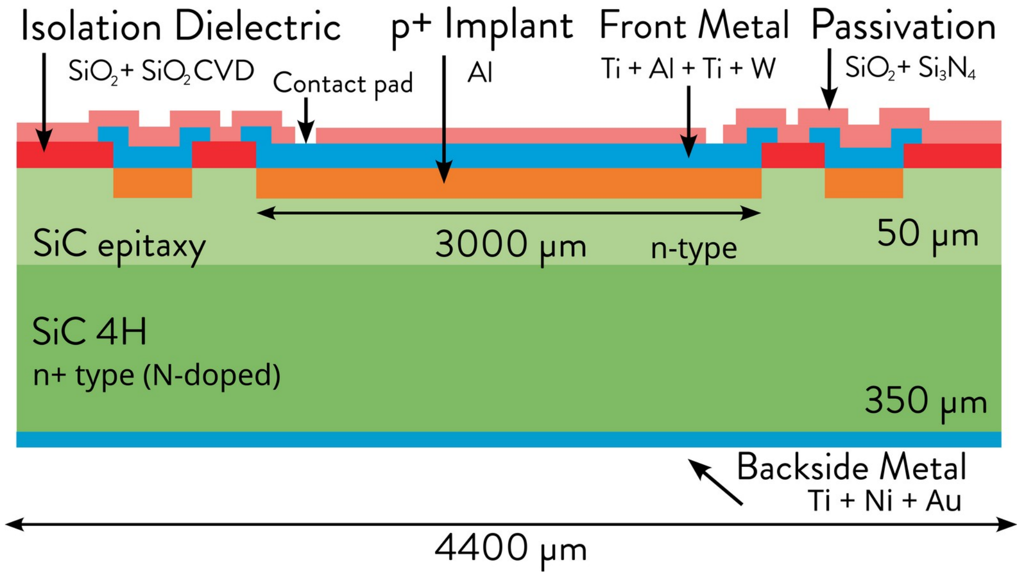
Beam monitoring, radiation hard large area detectors [4]



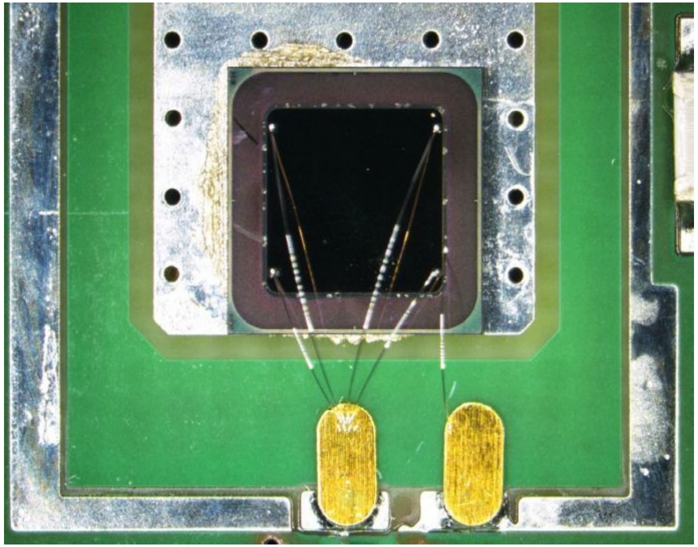
Advantages and disadvantages of 4H-SiC compared to Si

SiC Samples

- 4H-SiC p-n planar diodes from Run 13575 of CNM [5]
- 3 x 3 mm^2 active area, 50 μm epi
- Full depletion voltage : 400 V, C_{det} = 18 pF



Device cross-section (adapted from [5])



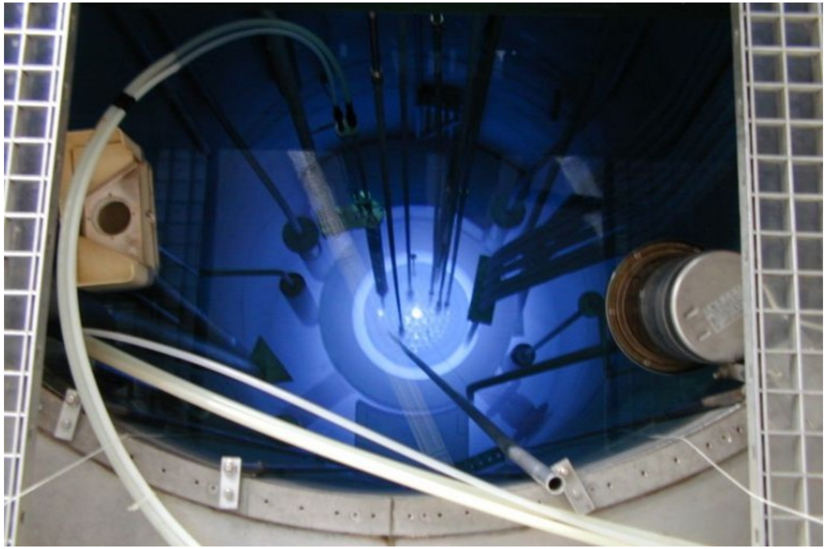
4H-SiC pad diode on readout board

Neutron Irradiation Studies

- Neutron irradiated ($5 \cdot 10^{14} - 1 \cdot 10^{16}$ n_{eq}/cm^2) at ATI Vienna [6]
- Previous studies [7,8]

- Deep level defects ($Z_{1/2}$ and $EH_{6/7}$) introduced by radiation damage [9]
- In Si: Leakage current increase, reduction of signal [10]

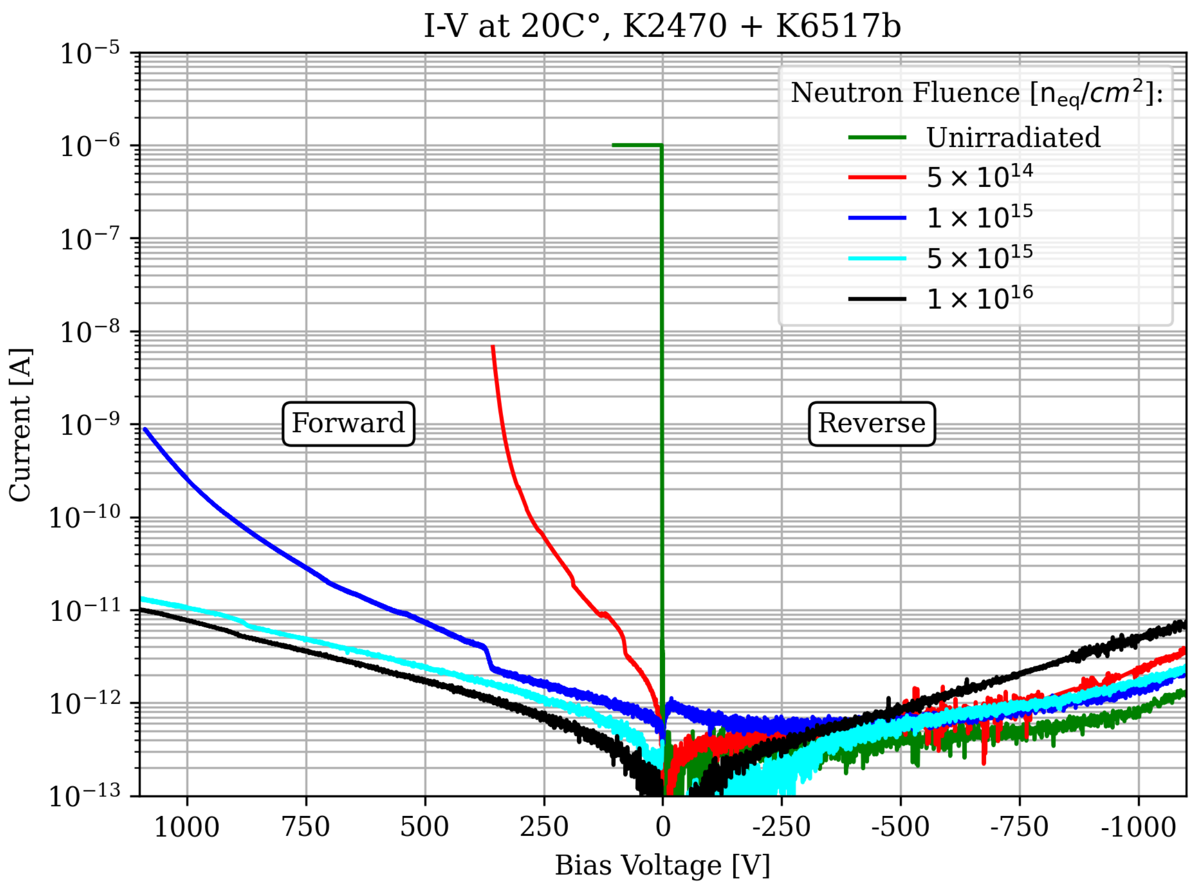
- Electrical Characterization (I-V, C-V)
- Particle detection (α, p^+, UV-TCT)
- Simulation Results



TRIGA Mark II reactor at ATI Vienna [x]

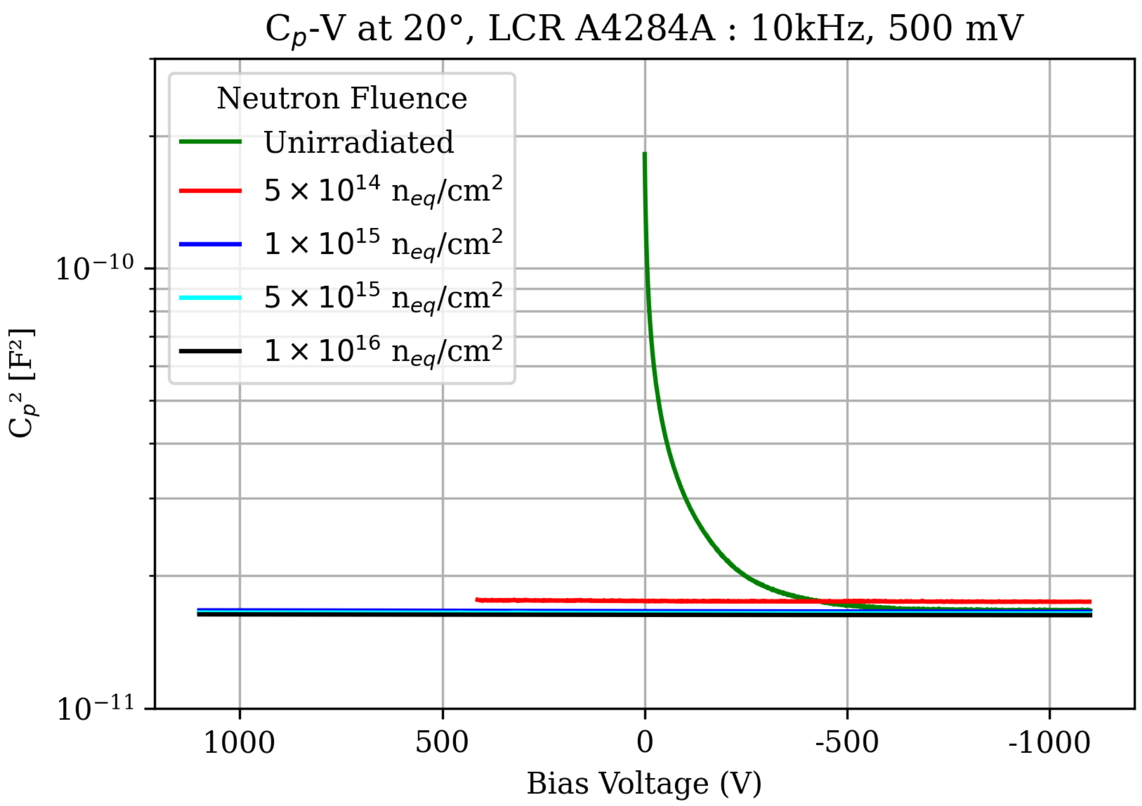
Current – Voltage Characteristics

- Leakage currents < 10 pA after irradiation (up to 1 kV) at room temperature
- Forward Bias: Reduction in current
- Indicative of n-doped epi layer becoming intrinsic due to deep-level defects [11, 12]
- Reverse bias limited by sparking on surface around 1.6 kV



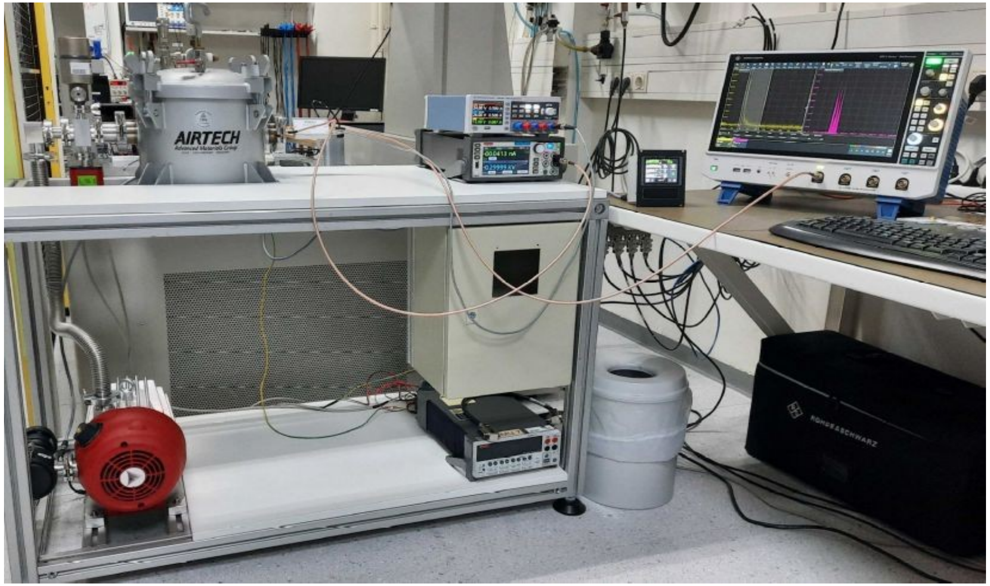
Capacitance – Voltage Characteristics

- Full depletion at 400V for unirradiated sample
- Diode-like depletion lost after irradiation, fixed capacitance regardless of forward / reverse bias
- Fixed capacitance compatible with 50 µm thickness
- Intrinsic epi layer after irradiation



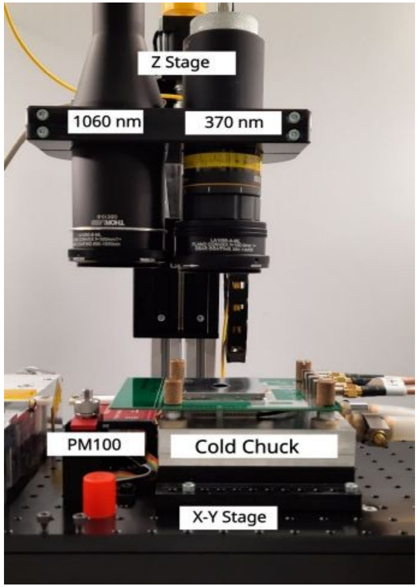
CCE Measurements

- Charge collection efficiency (CCE) is the most relevant metric for detectors
- Room temperature measurements
- Signals collected in forward and reverse bias



Tri-Alpha in Vacuum (^{239}Pu, ^{241}Am, ^{244}Cm)

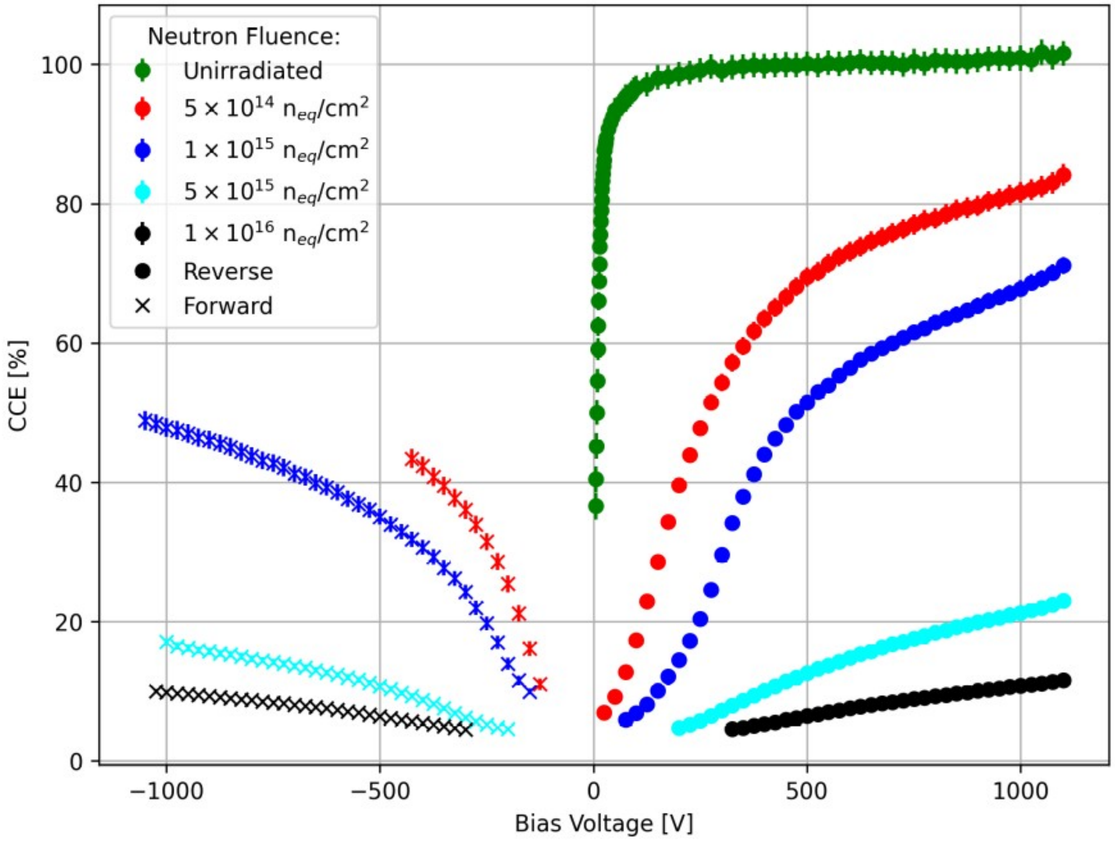
62.4 MeV p^+ at MedAustron (AT)



UV-LASER (370nm)
< 100 ps pulse length

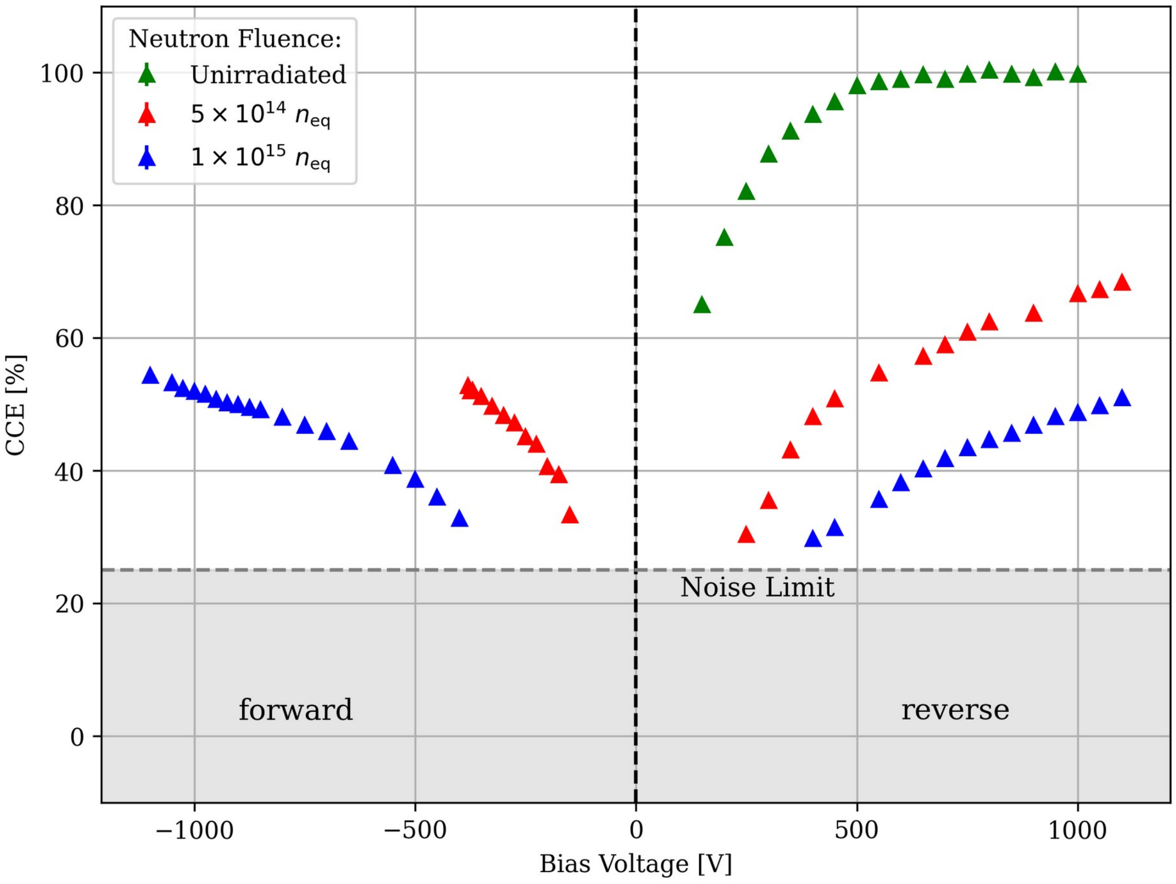
Alpha Measurements

- Signals obtained even at highest fluences, in forward and reverse bias
- Bias voltage limited by readout
- Would expect higher CCE in forward bias due to trap filling [12]
- At highest fluences, forward and reverse bias identical



62.4 MeV p⁺ at MedAustron

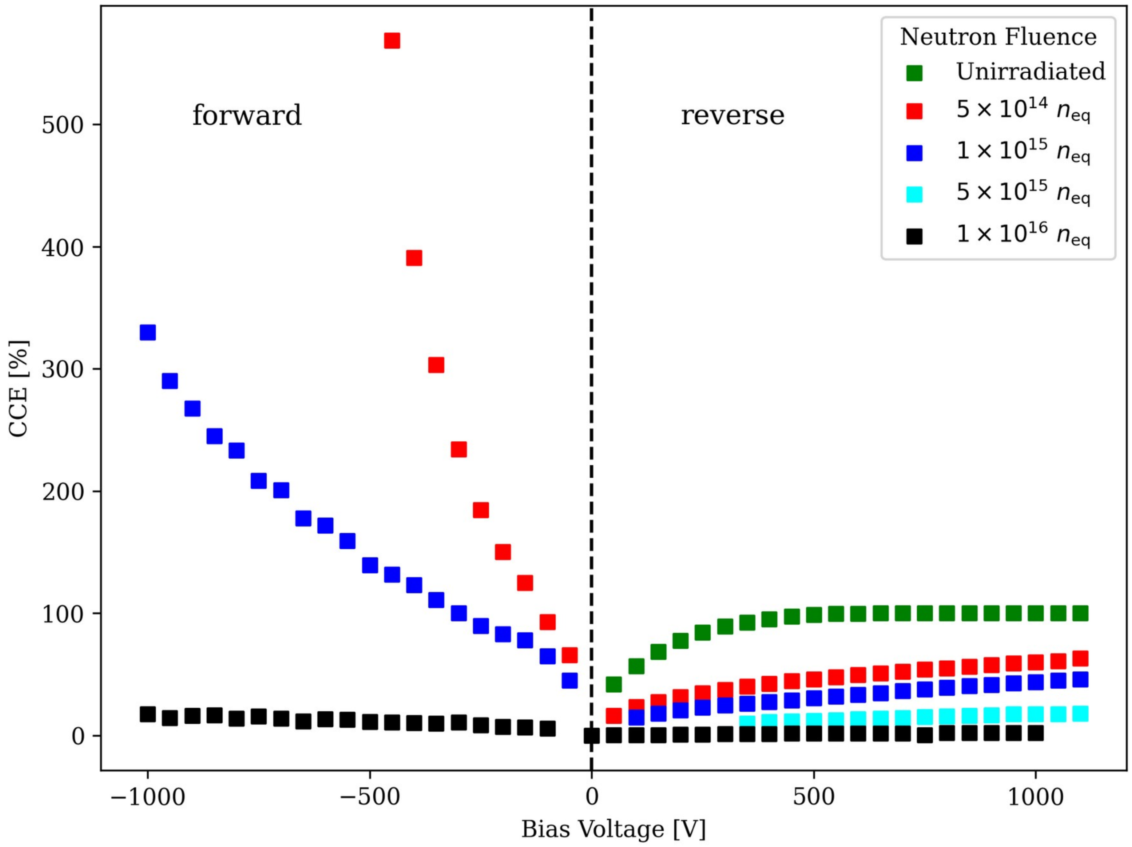
- Signals obtained for fluences up to $1 \cdot 10^{15}$ n_{eq}/cm^2 (limited by noise and thin detectors)
- For unirradiated sensors : in accordance with depletion width
- Slightly higher CCE in forward bias than in reverse
  - Trap filling by forward current



UV LASER

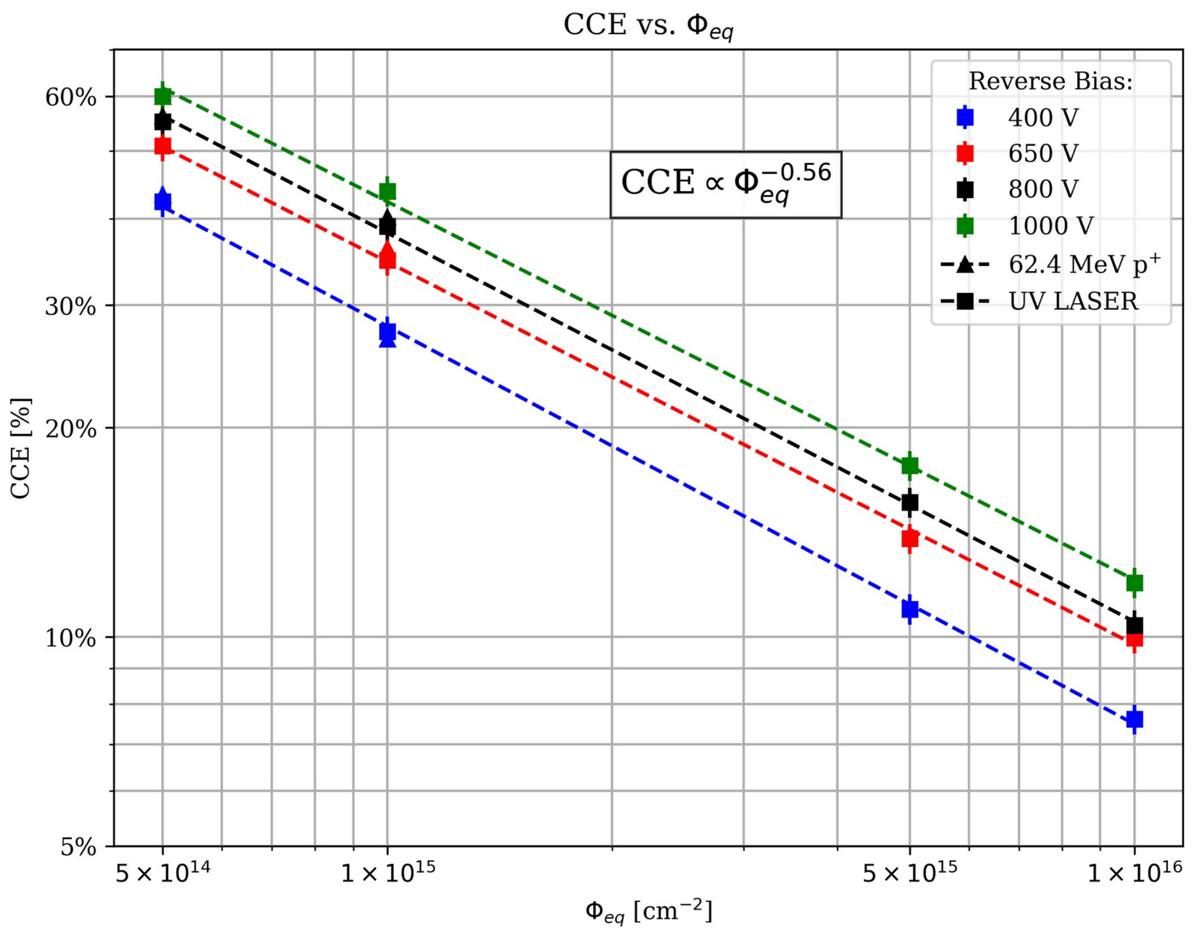
- 370nm LASER, < 100 ps pulse length
- High charge deposition (~ 10 MeV) and waveform averaging → very good SNR
- Results in reverse bias agree well with p+

- Charge gain observed in forward bias
- Also observed in TPA-TCT [13], likely related to the very high charge deposition



CCE vs Fluence

- CCE follows a power law ($\propto \Phi^{-0.56}$), even for different bias voltages
- CCE > 10% for $1 \cdot 10^{16}$ n_{eq}/cm^2
- More work needed to increase radiation hardness of SiC:
  - Annealing [12]
  - Defect engineering

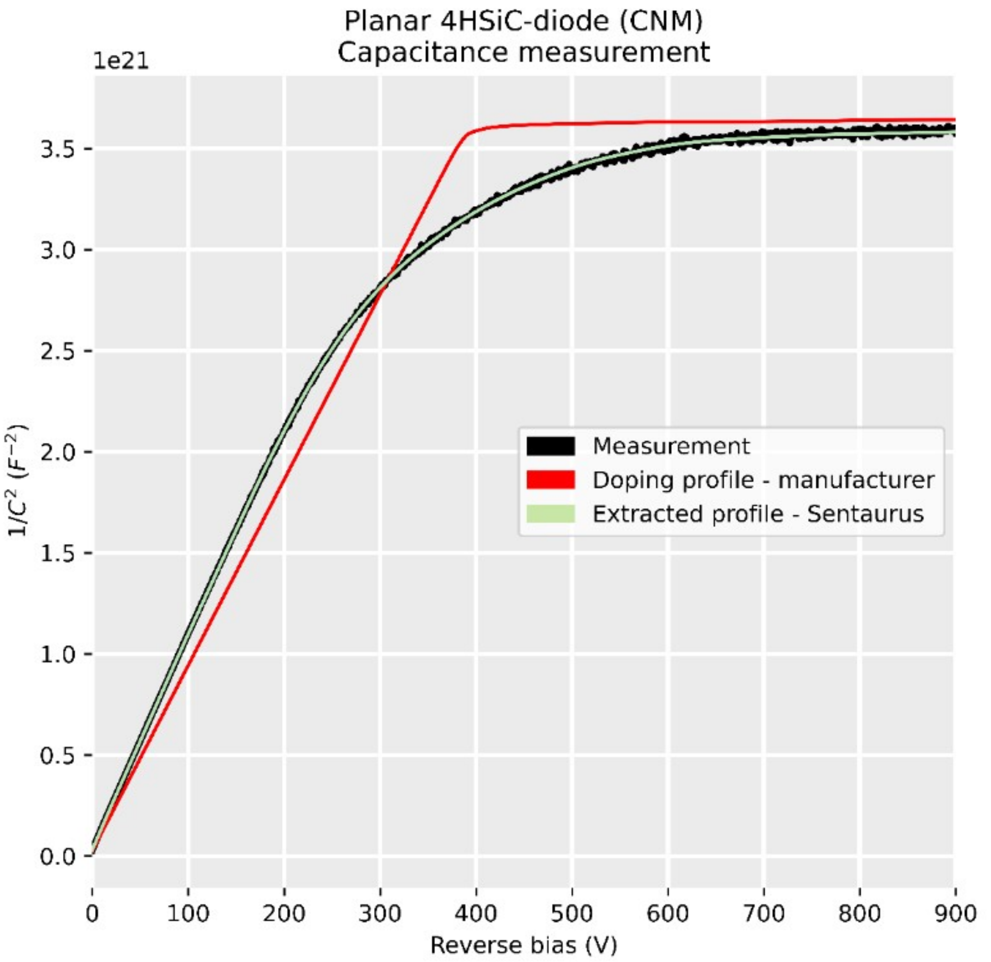


TCAD Simulations

- Doping profile extracted from $1/C^2$ measurements
- 4H-SiC parameters not always accurate in TCAD applications
  → extensive literature review

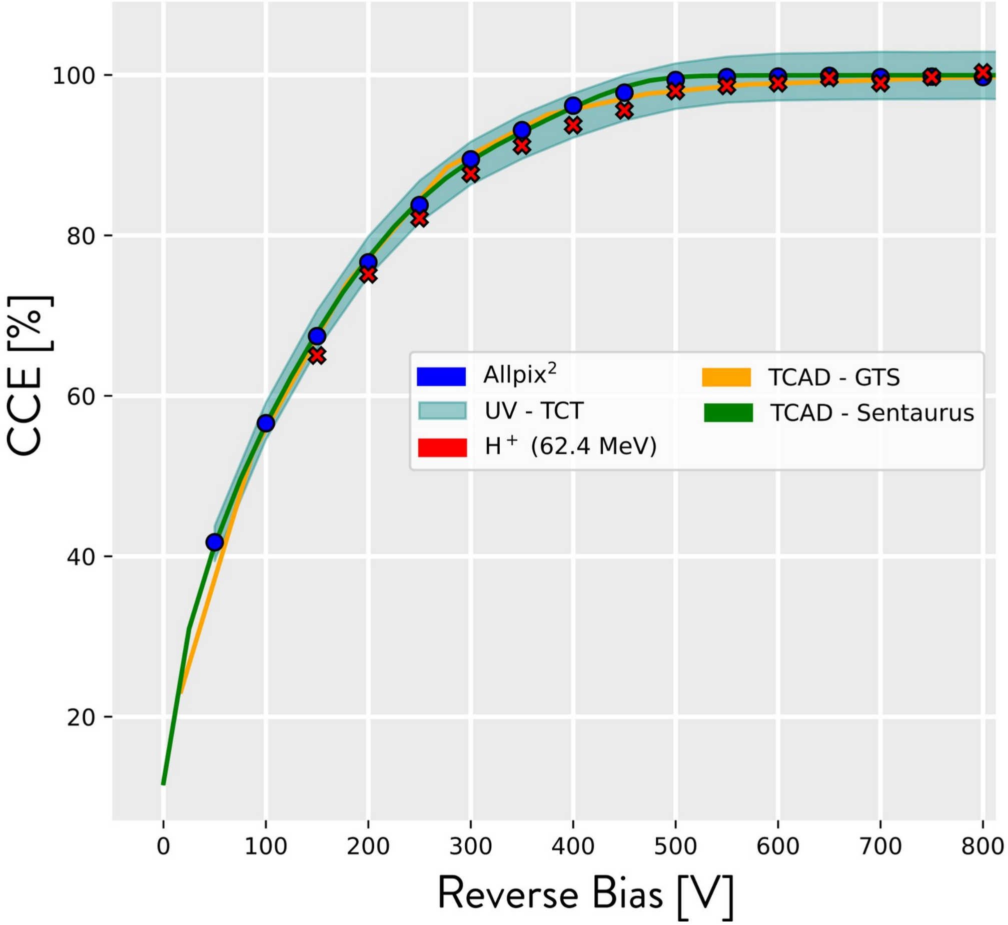
4H-SiC Parameters		
Band structure	**Charge carriers**	**Recombination**

• Permittivity
• BG-narrowing (SB)
• Incomplete ionization Al (p) and N (n) doping
• Split energy levels (N)
	• Mobility:
	  • Temperature dep.
	  • Doping dep.
	  • High field saturation
	• Impact ionization
		• SRH
		• Surface-SRH
		• Auger
		• Traps ($Z_{1/2}$-defect)
		• Radiative



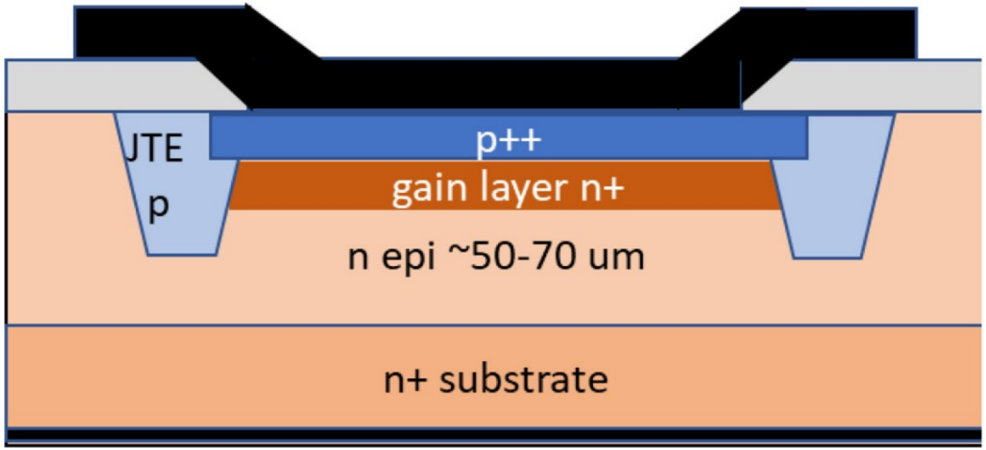
CCE Comparison

- Full device simulation + *HeavyIon* model:
  - Synopsys Sentaurus
  - Global TCAD Solutions (AT) (part of an ongoing collaboration) [14]
- Geant4 simulations (using AllPix²[15]):
  - Electric field / weighting potential imported from TCAD
- Good agreement with measured data

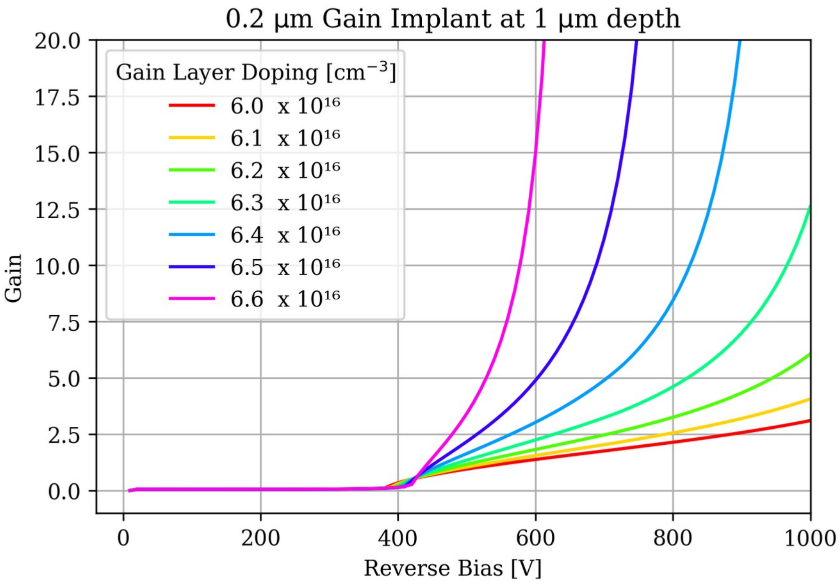


Next Steps : SiC-LGAD

- LGAD : Low Gain Avalanche Diode [16], wide-spread usage for Si
- Attractive for SiC (large signal from thin detectors, timing)
- RD50 common project [17], ongoing work at IHEP / NJU [18-20]
- Started TCAD studies to optimize design



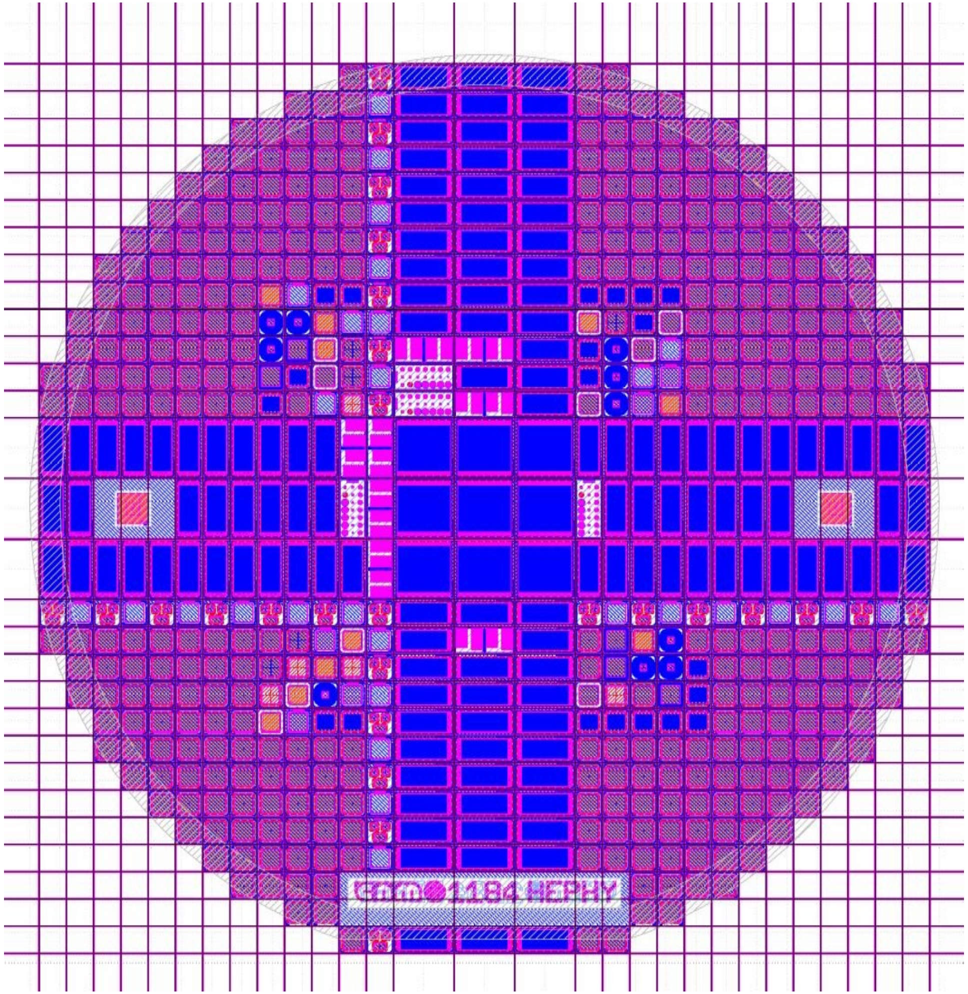
Idealized 4H-SiC LGAD structure [20]



TCAD Simulation of 4H-SiC LGADs with different gain doping

Next Steps: 4H-SiC Run with CNM

- 50 µm and 100 µm epi wafers (6-inch)
- Tapeout Spring 2023, expected Winter 2023
- <u>Guard structure optimized using TCAD</u>
- Pad detectors
- Strip detectors
- Test vehicles
  - MOSCAPs, MOSFETs
  - Process test structures
  - Gate controlled diodes
- Other structures
  - Pixel arrays
  - Resistive detectors



Summary

- 4H-SiC features extremely low leakage currents even after irradiation up to $1 \cdot 10^{16}\ n_{eq}/cm^2$
- CCE scales with fluence $\propto \Phi_{eq}^{-0.56}$
- Unirradiated devices can be accurately simulated using TCAD

- Ongoing work on SiC LGAD, promising for timing applications
- New wafer run due Winter 2023

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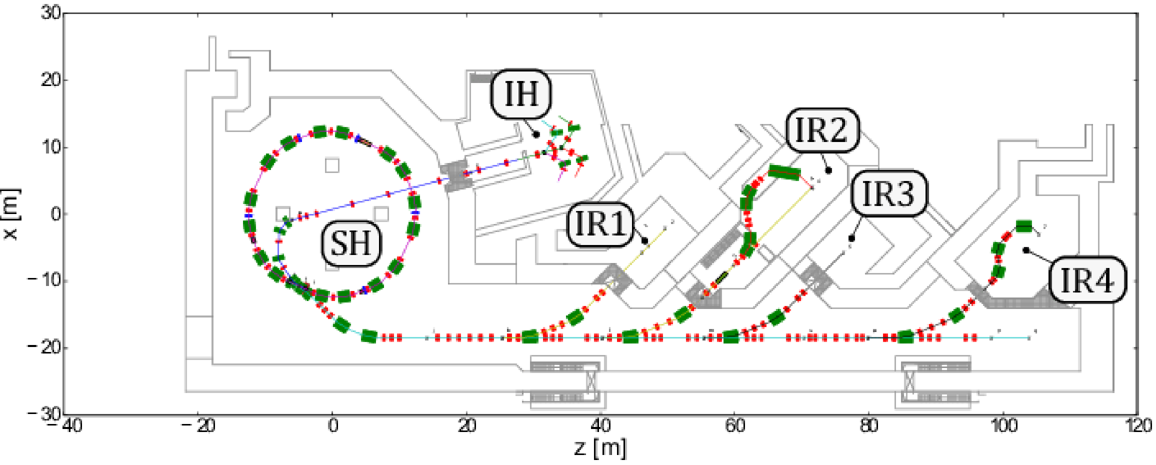
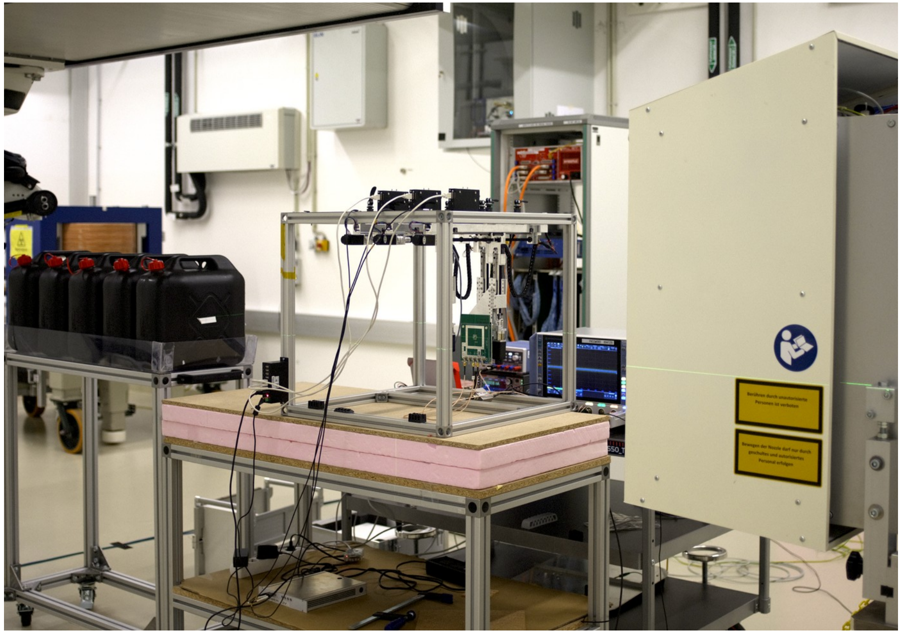
BACKUP

MedAustron Ion Therapy Center

- Synchrotron providing protons, carbon and (soon) helium ions for medical therapy
- 1 dedicated non-clinical research beamline (IR1)
- Energies up to 800 MeV for p^+ ($\approx$ 1.3 MIPs), commissioned together with HEPHY
- Intensities from kHz/cm^2 to 10^{12} /s /cm^2

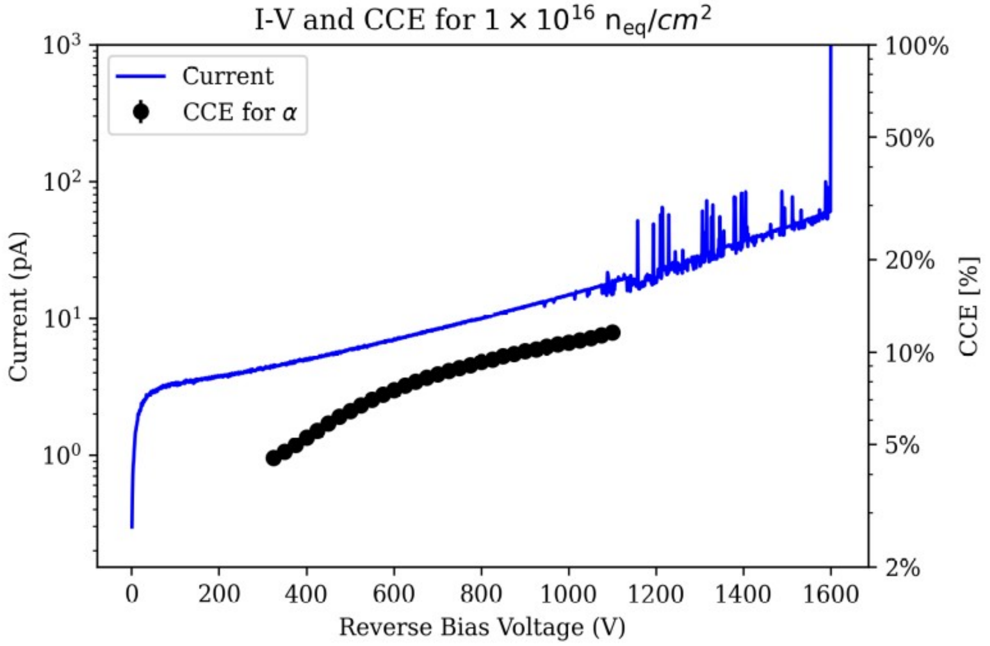
- Silicon tracker + beam rate monitor built by HEPHY

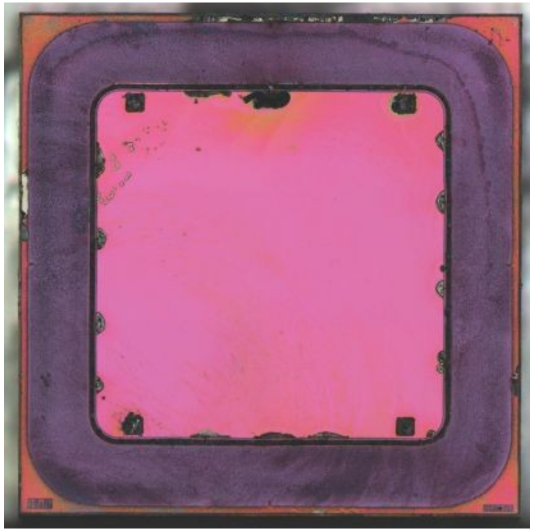




High Bias Voltages Required

- CCE reduction by radiation damage can be mitigated using higher voltages
- Maximum voltage is not limited by material, but by HV sparking on surface
- Challenges for read-out electronics above 1kV
- → Use conformal coating

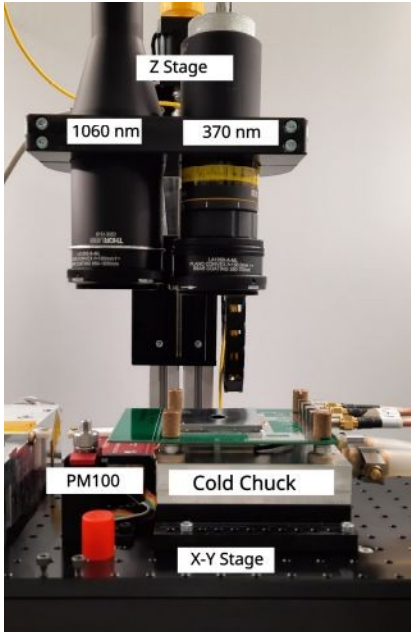


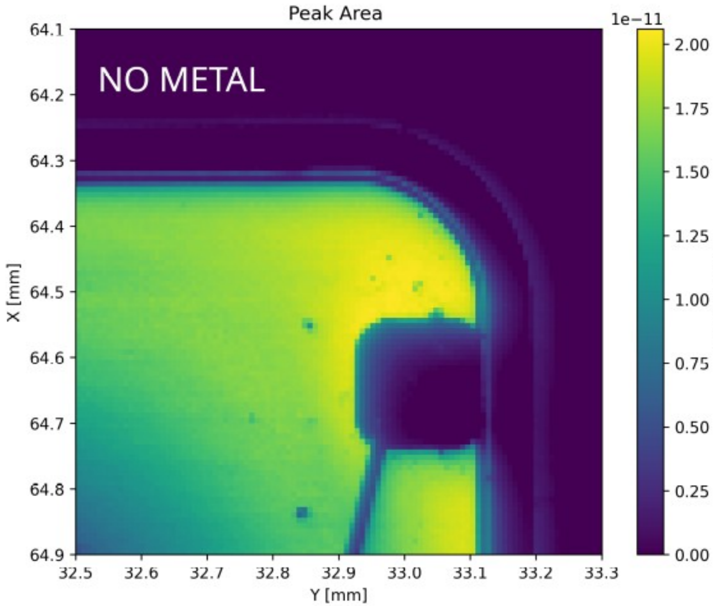


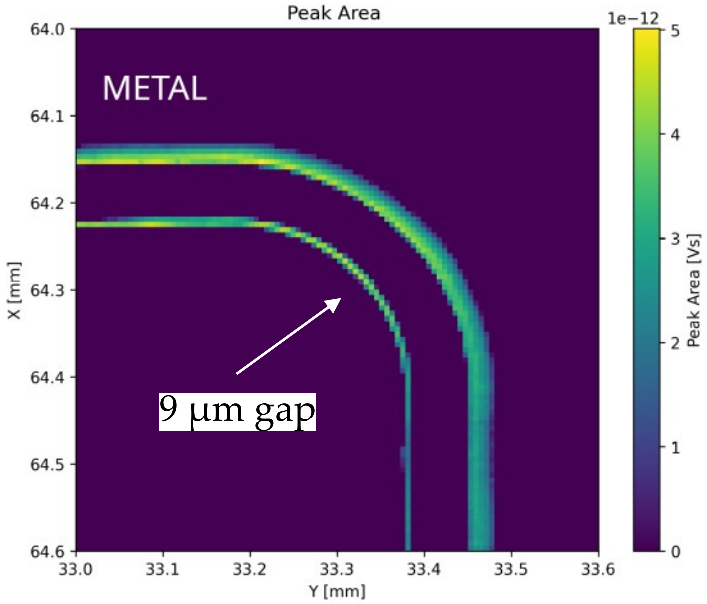
Sample with surface damage after 1.6 kV

UV LASER Setup

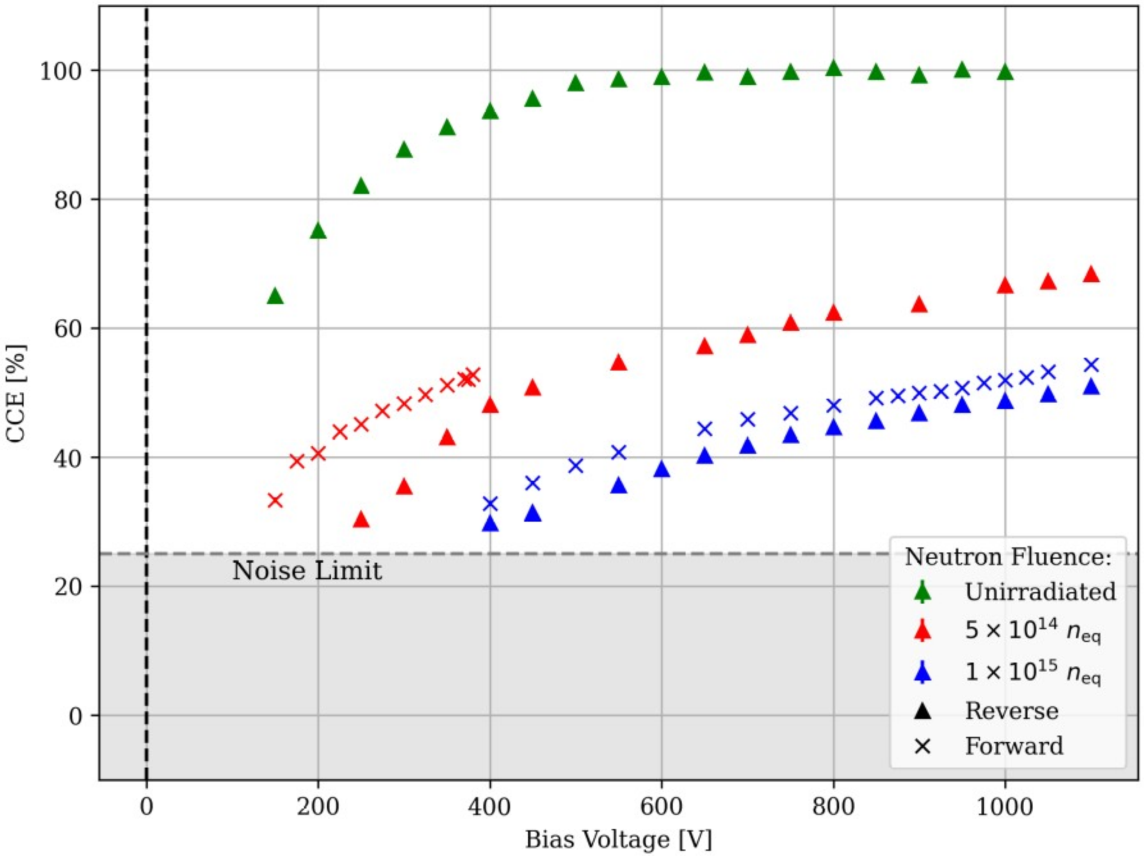
- UV-LASER : PILAS PIL1-037-40FC, 370 nm, < 100 ps pulse width
- 370 nm : $\alpha \approx 40\ \mathrm{cm}^{-1}$ → uniform charge deposition
- SiC samples with and without metalization
- UCSC board and RTP 164 (16 GHz, 40 GSa/s) for readout, [pulse analysis code]



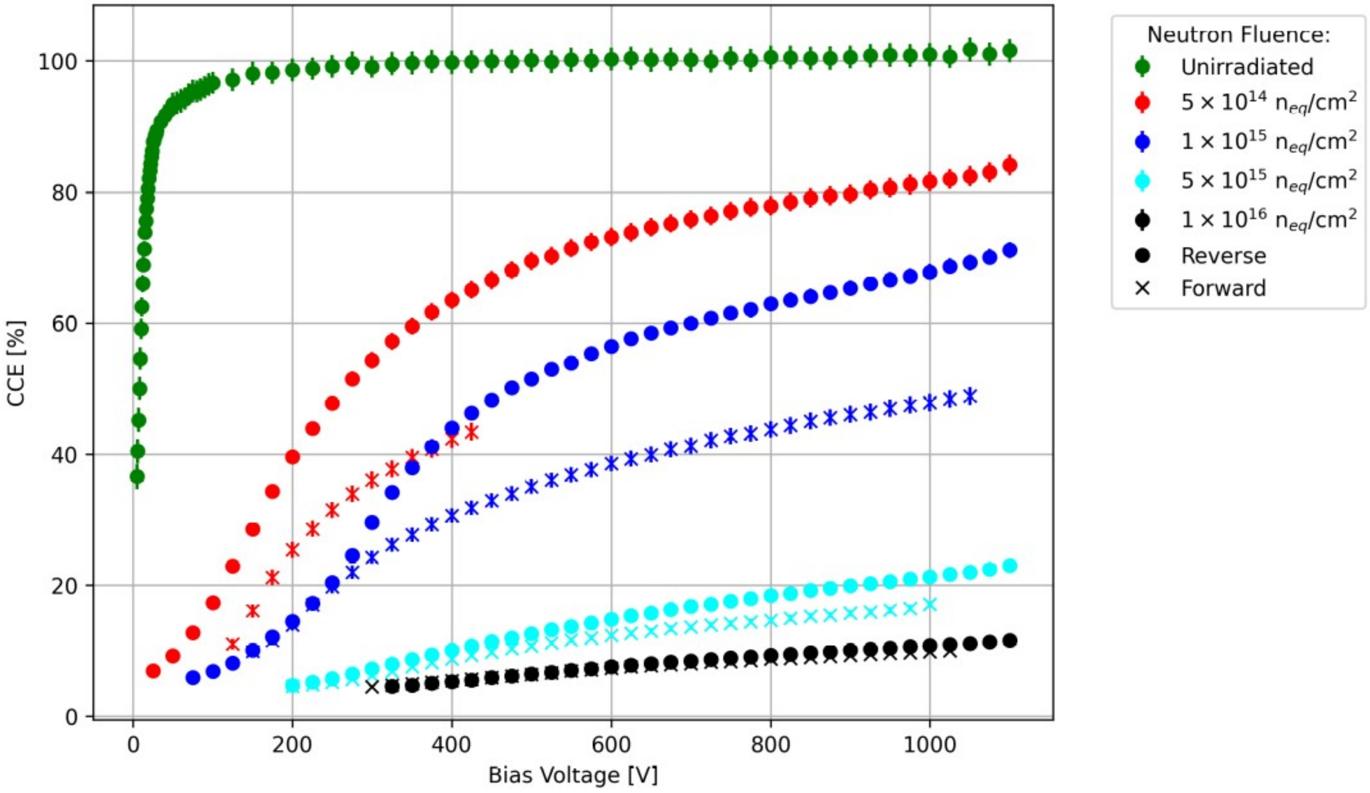




Proton CCE (forward + reverse)

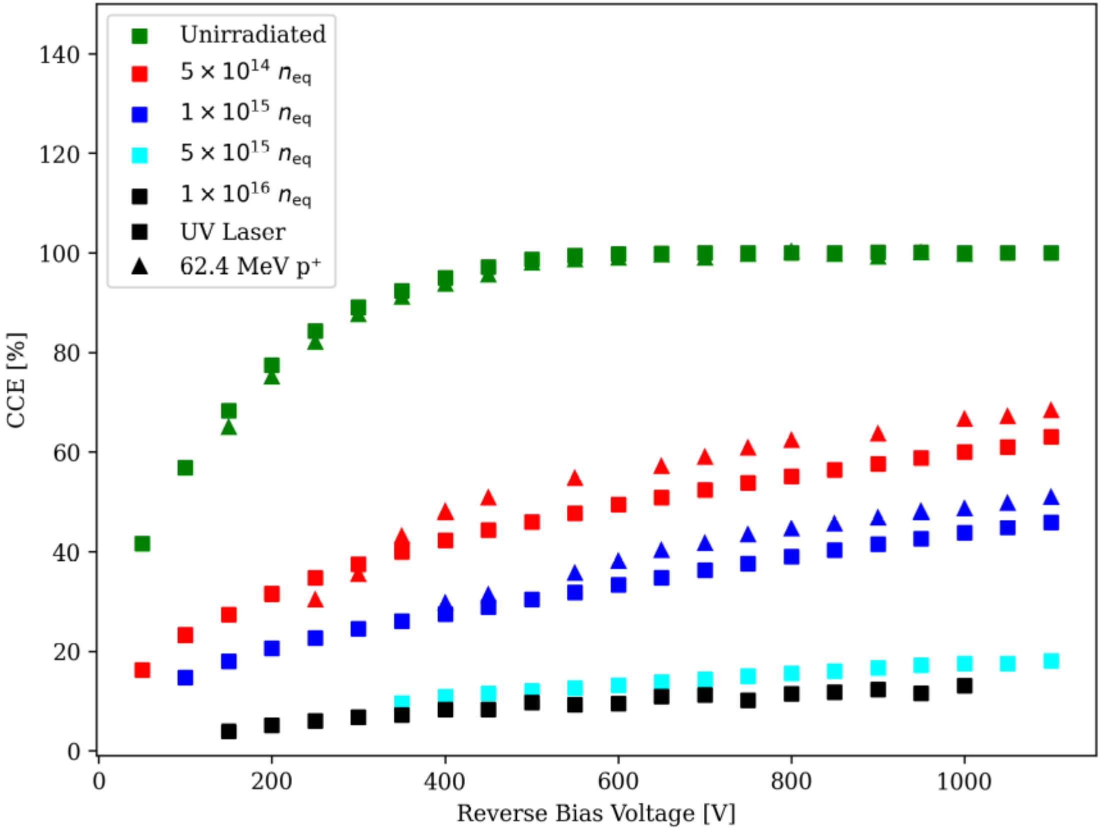


Alpha Forward vs. Reverse



UV LASER vs. 62.4 MeV p^+

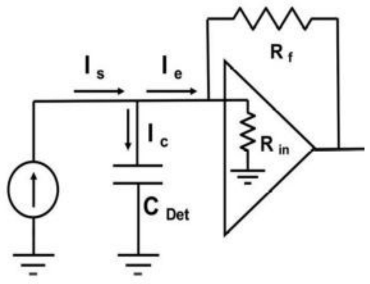
- High charge deposition (~ 10 MeV) and waveform averaging
- UV Results agree well with proton data
- Discrepancies likely to UV laser alignment on metal gap



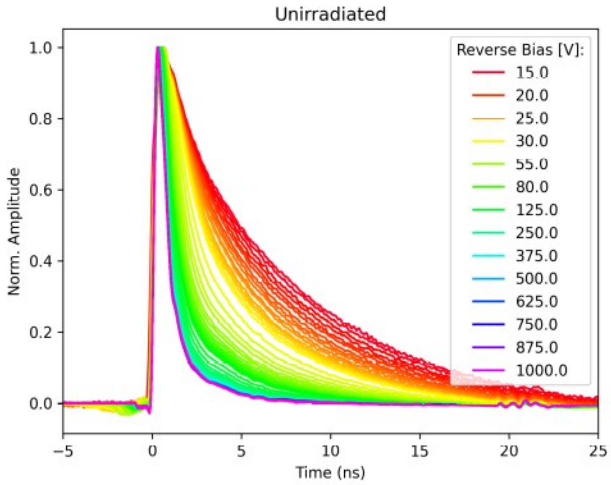
TCT Limitations in UV Setup

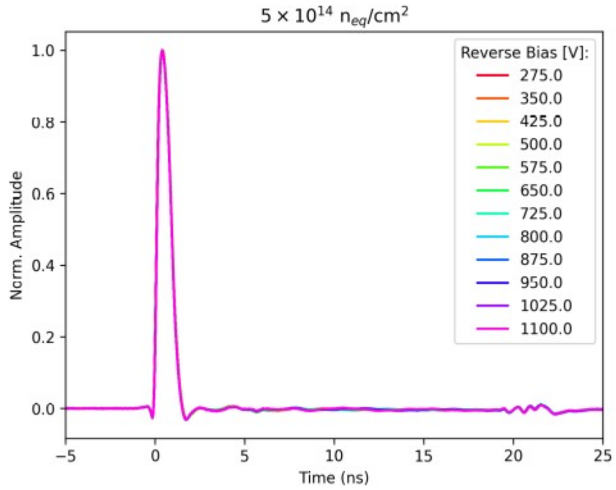
- UCSC Board bandwidth limited by detector capacitance
  $\tau_{det} = C_{det}\ R_{in}$, $\tau_{TIA} = 1 / (2\pi f_c)$
- Thin detectors → Fast signals (< 1 ns) , large capacitance (18 pF full depletion)
- At low voltages (high capacitances), UCSC TIA acts as a CSA
  - For irradiated samples, the waveforms are identical (except scaling)

➔ Decrease capacitance, reduce input impedance



Simplified Amplifier Model

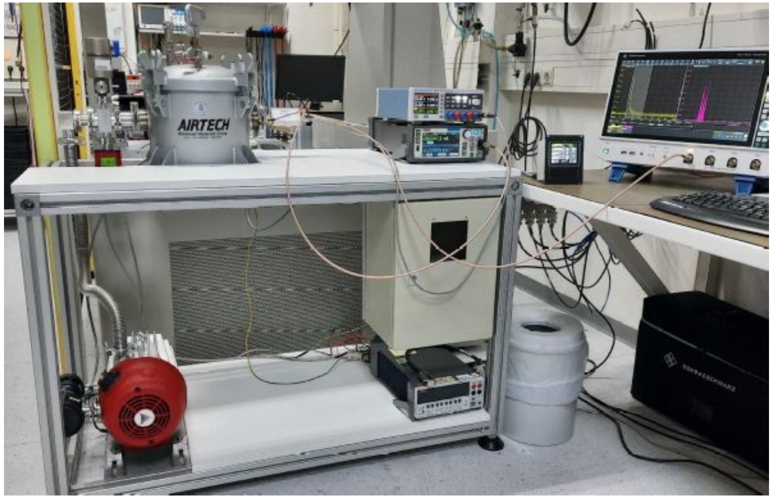




Ionization Energy + Fano Factor

- Quite a large spread in literature values for ε_{SiC} and F_{SiC}
- Verify literature values using a comparison between Si and SiC detectors
- Tri-Alpha source (Pu^{239}, Am^{241}, Cm^{244}) in rough vacuum (10^{-1} mBar)
- Spectroscopic CSA (Cividec Cx-L, 1.2 µs shaping time)

Si (left) and SiC sensors (right) sensors



Vacuum Setup in HEPHY clean room

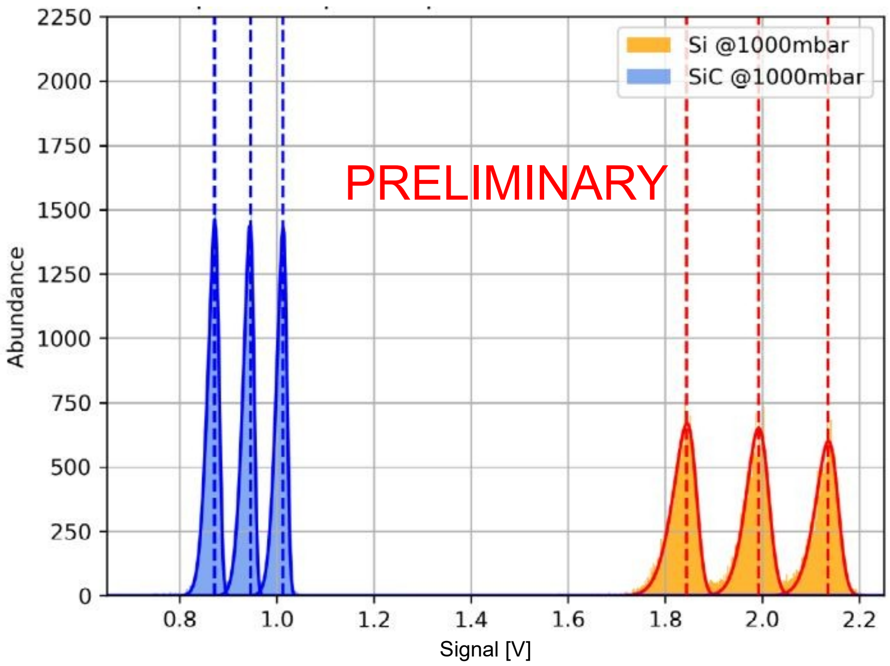
Ionization Energy + Fano Factor

- Need to take into account ~ 1 µm of passivation and metalization on top of sensors using a Geant4 simulation
- Good agreement to recent literature values

ε_{SiC} = 7.7 ± 0.1 eV

PRELIMINARY

F_{SiC} = 0.10 ± 0.01



Comparison between Si and SiC spectra used to compute the ionization energy and Fano factor for 4H-SiC