Systematic Study of Proton- and Neutron-Induced Radiation Damage in 4H-SiC PN Diodes

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PSD14

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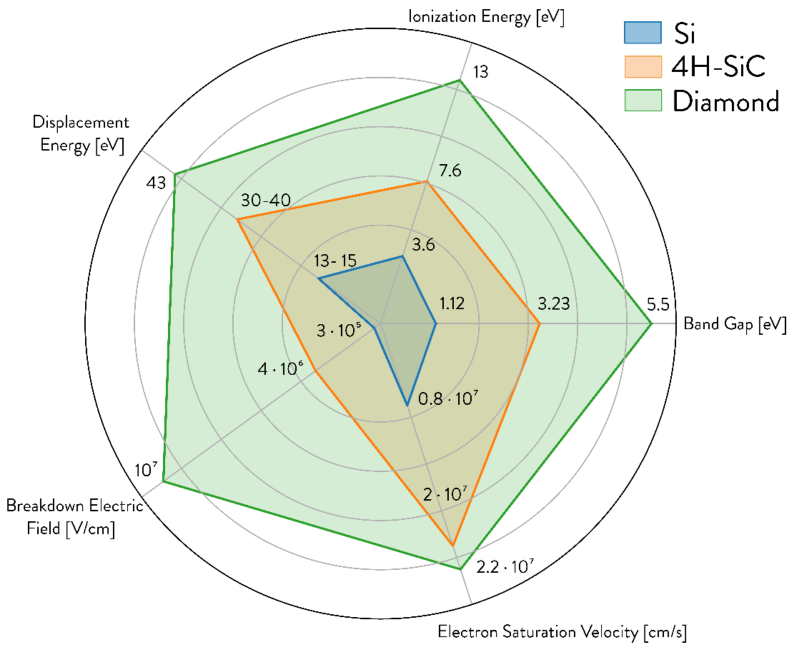
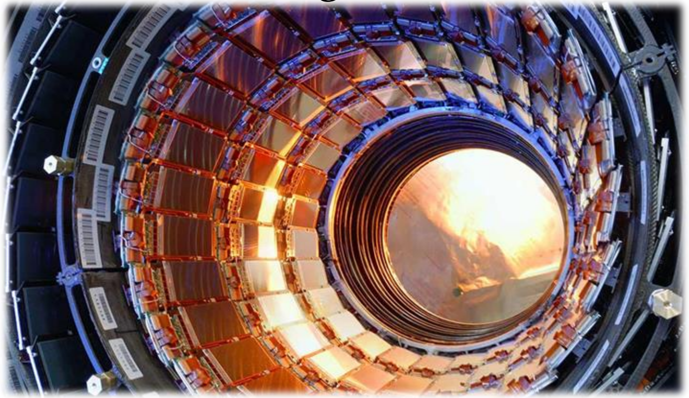
4H-SiC for Radiation Detection

- Attractive for power electronics & automotive industry
  ⇒ Increased availability and lower costs
- Wide bandgap (Si: 1.12eV, 4H-SiC: 3.26eV)
  - low leakage current & thermal noise at room temperature and after irradiation ⇒ no cooling
  - insensitive to visible light, thermal robustness (up to 300°C)
- Low doped & high quality material <100μm thick (Si: ~300μm) + higher ε_i ⇒ less signal yield

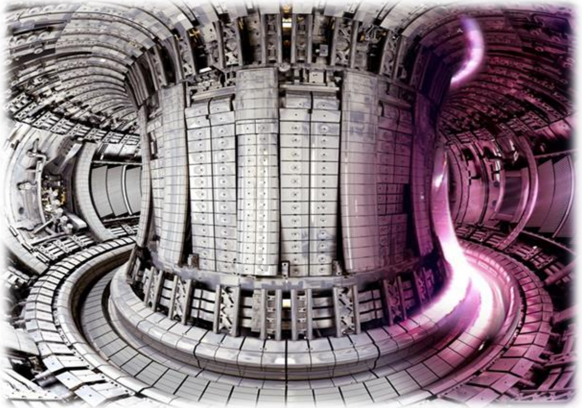


High Energy Physics
No cooling, SiC LGADs



Proton/Ion therapy
Beam monitoring, dosimetry

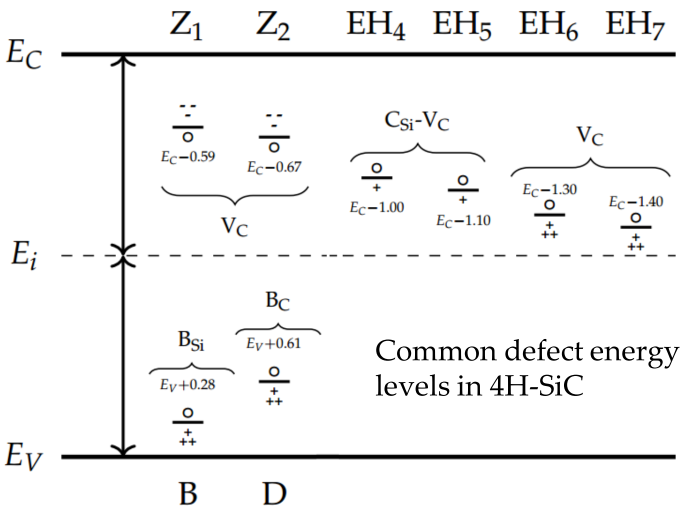
Upcoming: Fusion Diagnostics
Munoz et. al., „Characterization of 4H-SiC p-n Junction Detectors for Alpha Particle Detection in Plasma Diagnostics", Talk at 3rd DRD3 Week, 2025



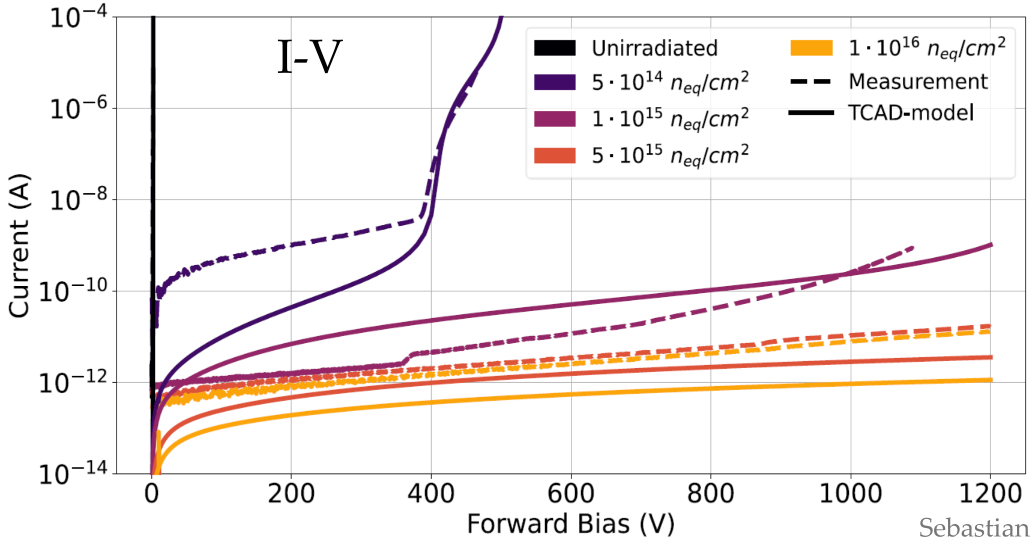
Symbolic image. Taken from: https://www.nature.com/articles/d41586-021-00408-1

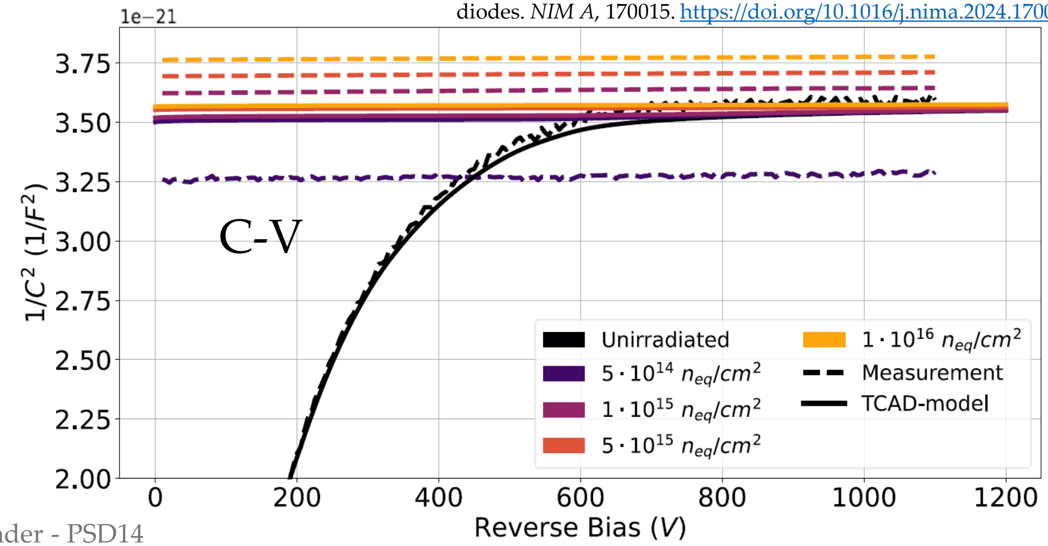
Radiation Damage in 4H-SiC

- Radiation damage in 4H-SiC is dominated by deep level traps ($Z_{1/2}$, $EH_{4/5}$, $EH_{6/7}$):
  - Negligible increase in leakage current
  - Voltage-independent, flatlining capacitance
  - Loss of rectification
- TCAD radiation damage model:
  - Preliminary Vienna model for neutron irradiation yields qualitative results
  - Based on small fluence range and single devices per fluence
  - ⇒ larger study with more fluences and more samples



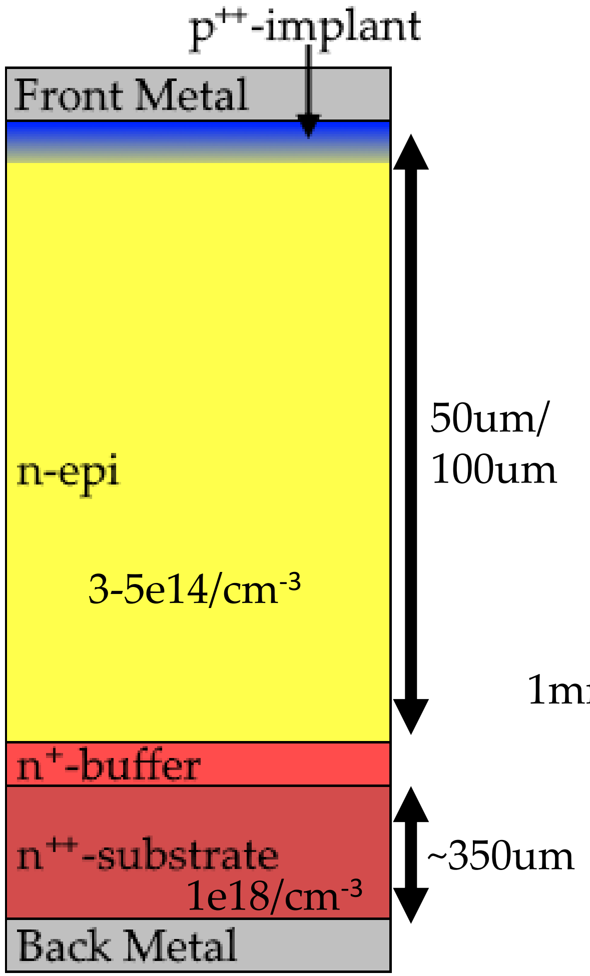
P. Gaggl, et. al. (2024). TCAD modeling of radiation-induced defects in 4H-SiC diodes. *NIM A*, 170015. https://doi.org/10.1016/j.nima.2024.170015





Irradiation Campaign

- **181 total PN diodes** included in study:
  - 2 epitaxial thicknesses: 50µm and 100µm
  - 3 device areas: 3x3mm², 1x2mm², 1x1mm²
  - Average doping of 3-5e14cm^{-3} (depending on epi thickness) ⇒ 100um only partially depleted
- 4-6 diodes per particle, epi thickness and fluence
- 24 GeV protons (CERN IRRAD): 8 fluences, 5e12 - 5e15 p/cm²
- Neutrons (JSI): 11 fluences, 1e13 - 1e18 $n_{eq,Si}$/cm²
- Characterization techniques:
  - I-V and C-V
  - UV-laser-based CCE measurements



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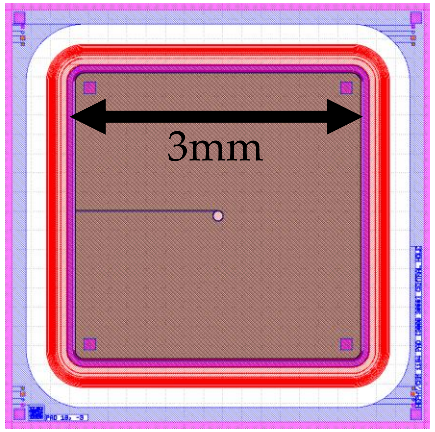
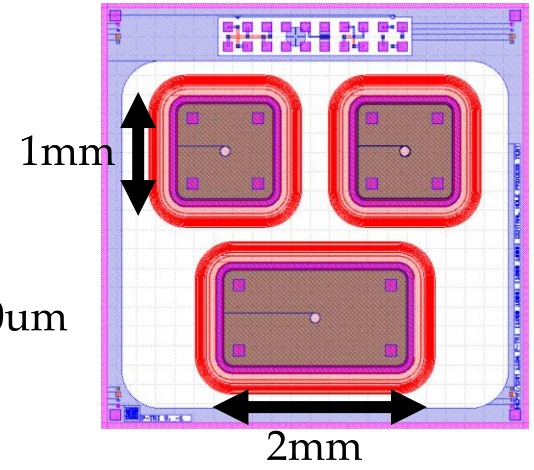
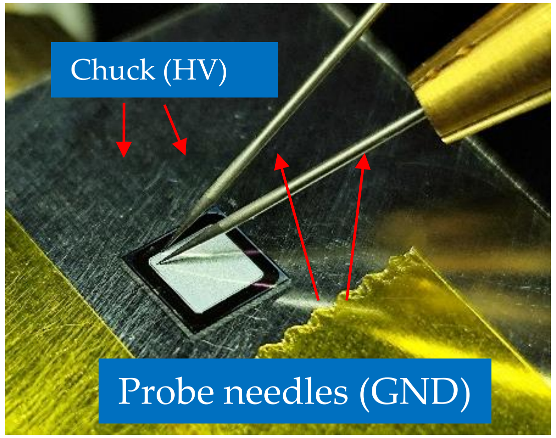


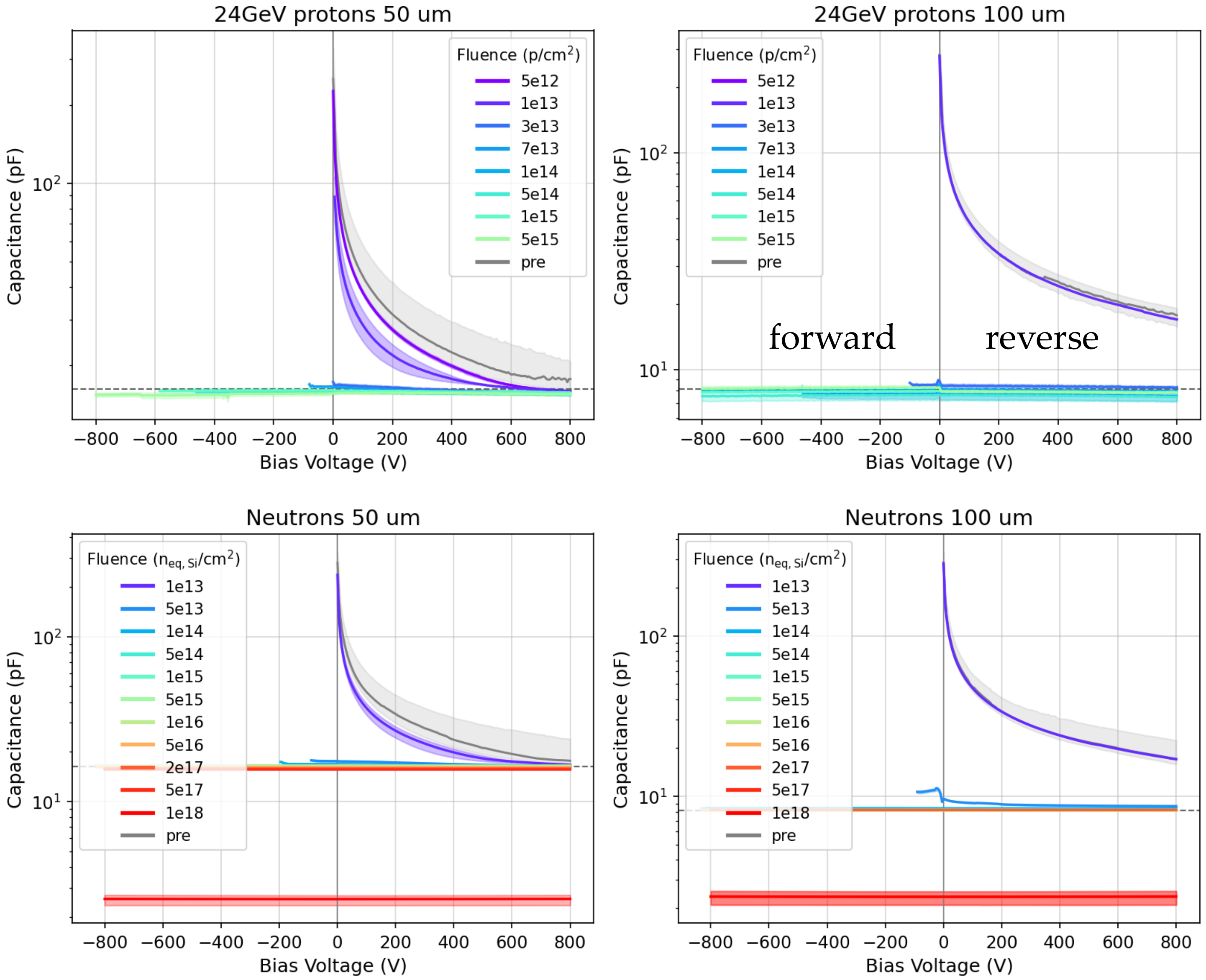


CV Characteristics

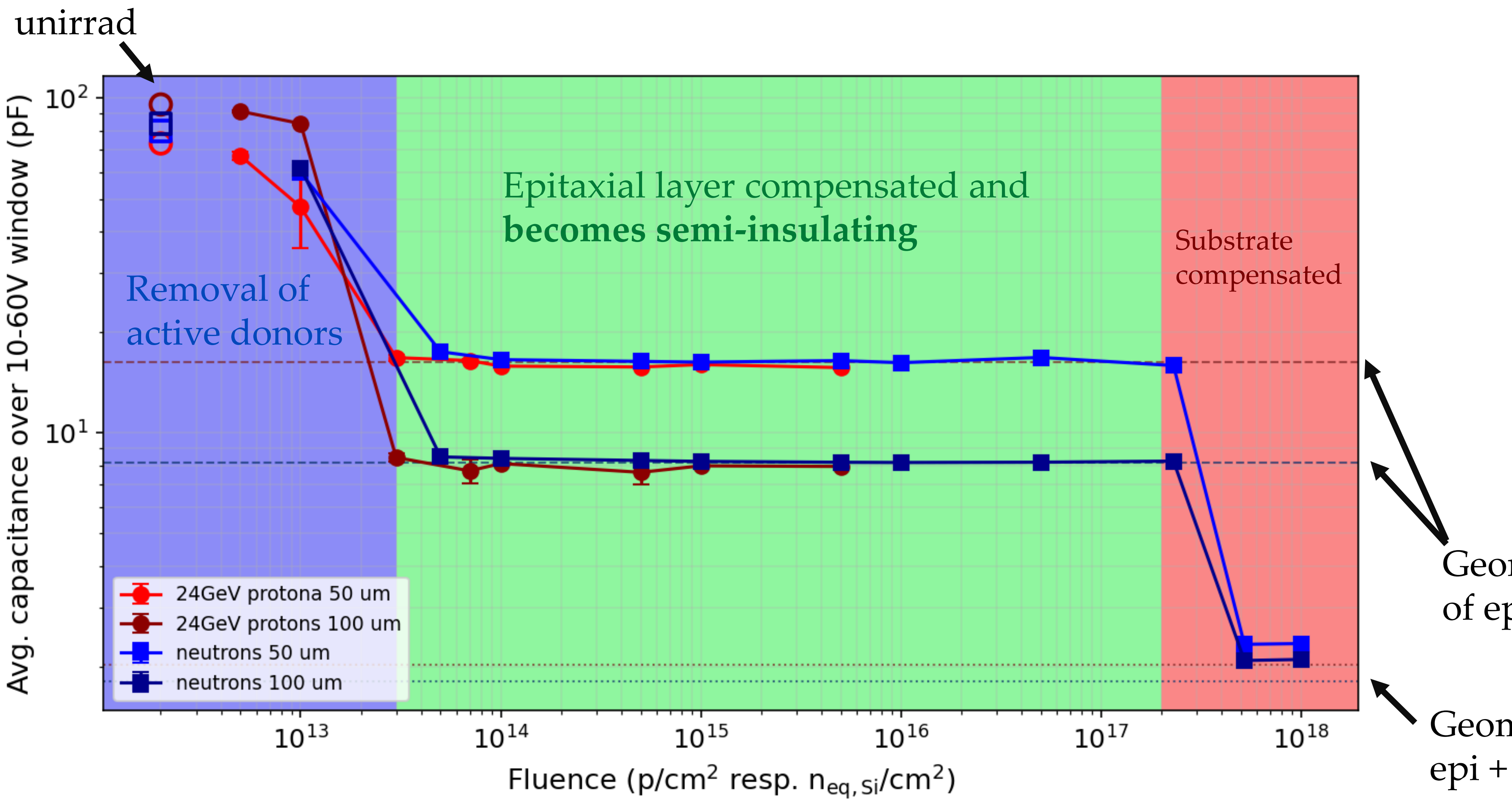
Bias-independent capacitance after 3e13 p/cm² resp. 5e13 $n_{eq,Si}$/cm²

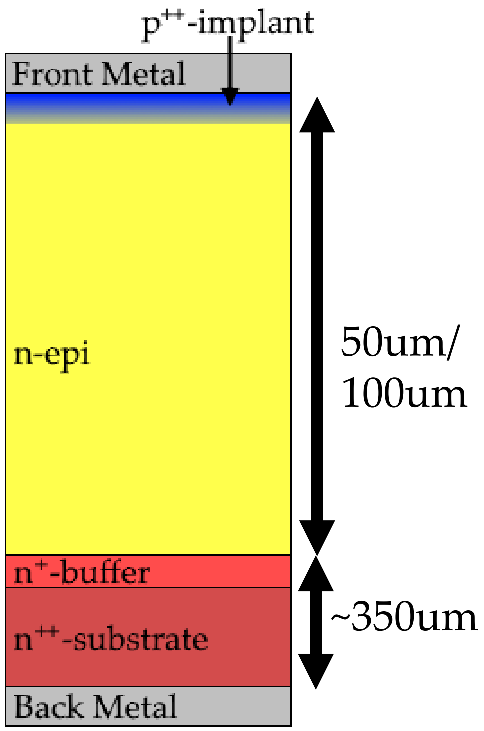
f=100kHz, V_{AC}=250mV





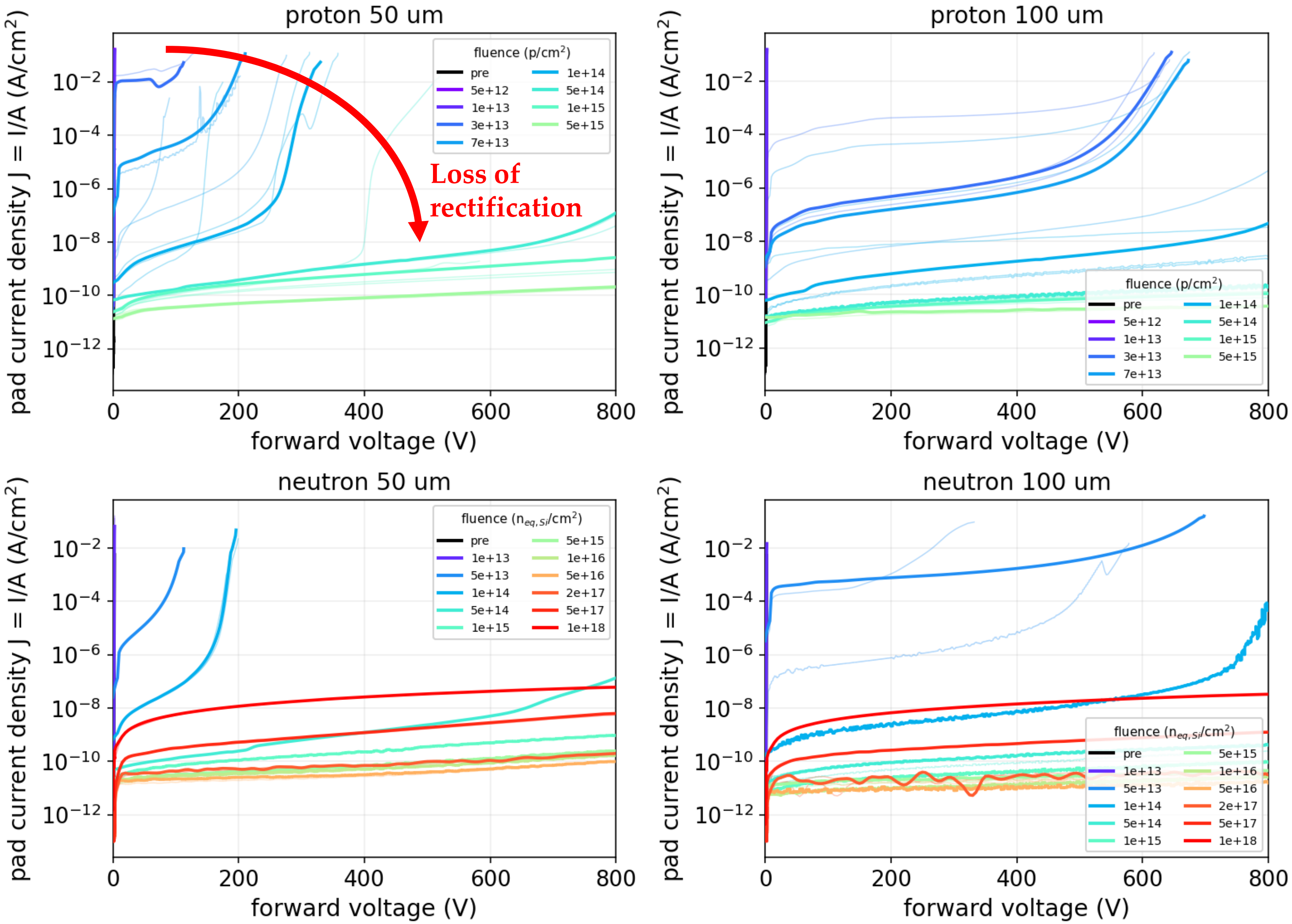
Capacitance vs. Fluence





Forward IV Characteristics

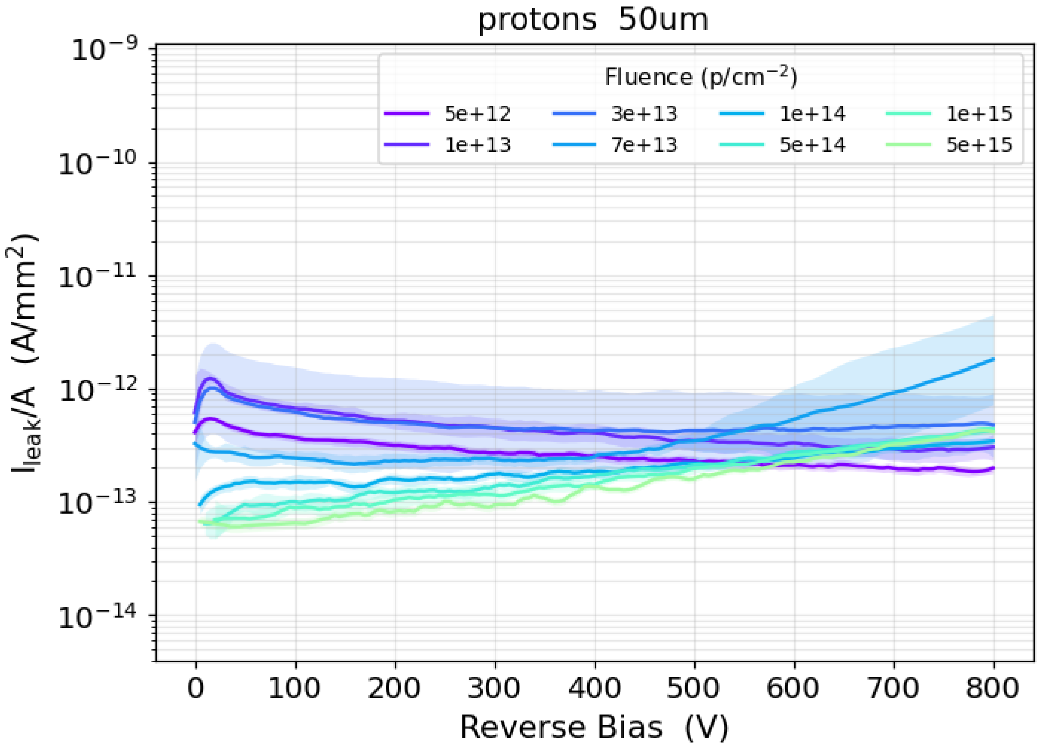
- Up to 1e13/cm²:
  - Characteristic turn-on voltage of ~2.7V
  - Ideality factor jumps from ~1.2 to ~2 (see backup)
- Up to ~5e14/cm²:
  - Forward current reduction
  - Turn-on voltage gradually shifted to higher voltage (on-resistance increase due to compensation)
- From ~5e14/cm²:
  - Forward current becomes similar to reverse current
  - **Total loss of rectification**

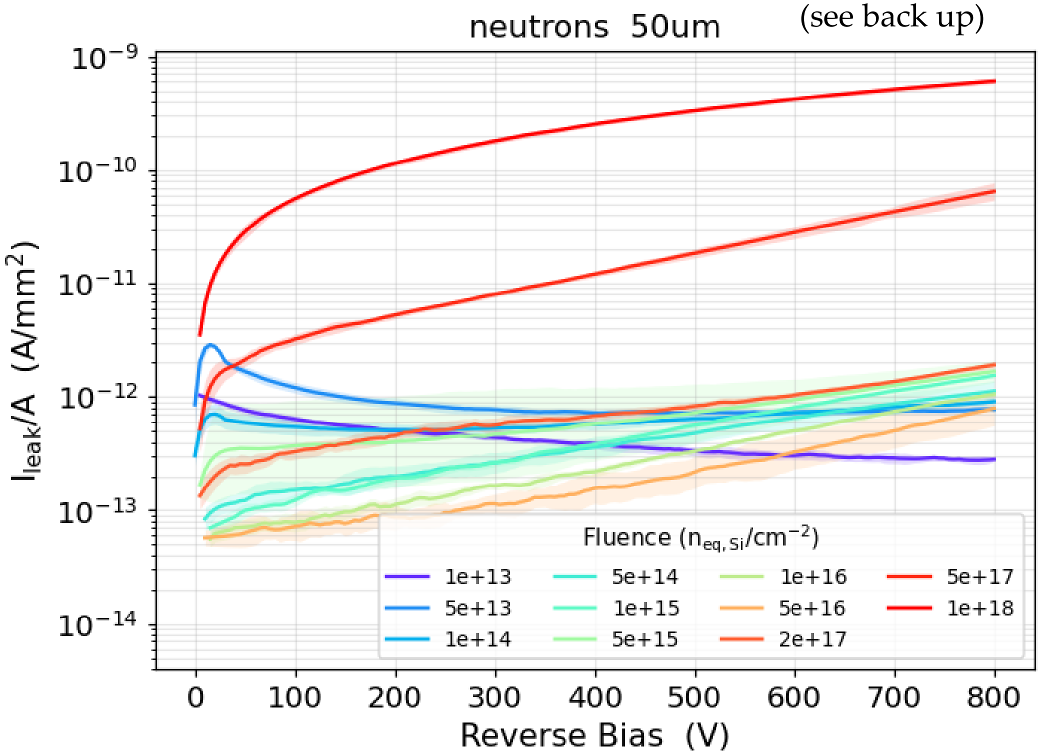


Reverse IV Characteristics

- <1e14/cm²: transient-dominated, likely slow detrapping (τ ~ 40s)
- 1e14/cm² to 5e16/cm²: current grows with V, but decreases with fluence → field-driven generation/emmission and compensation compete
- From 2e17/cm²: generation-dominated, increase to nA currents

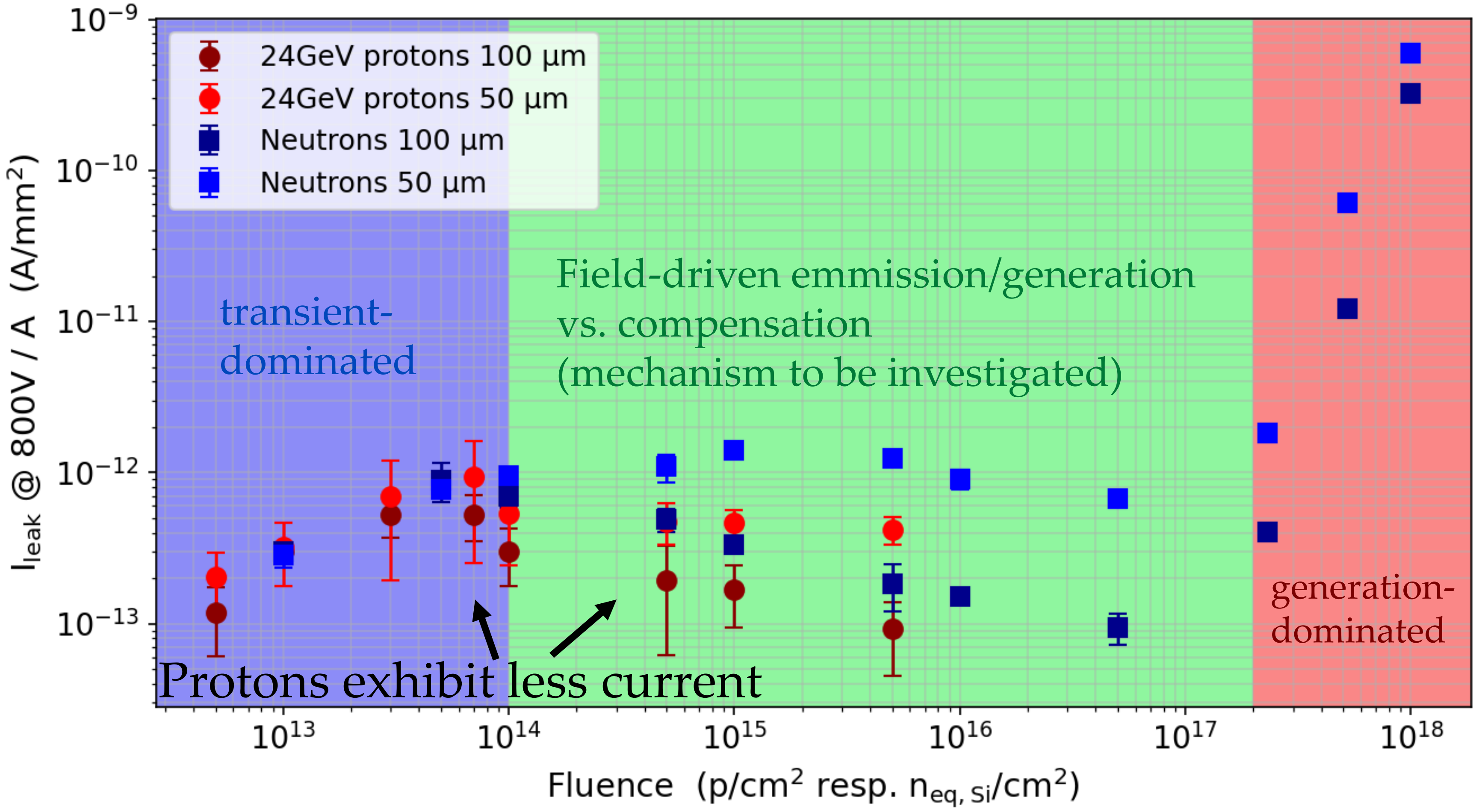
behaviour is analogous in 100µm (see back up)





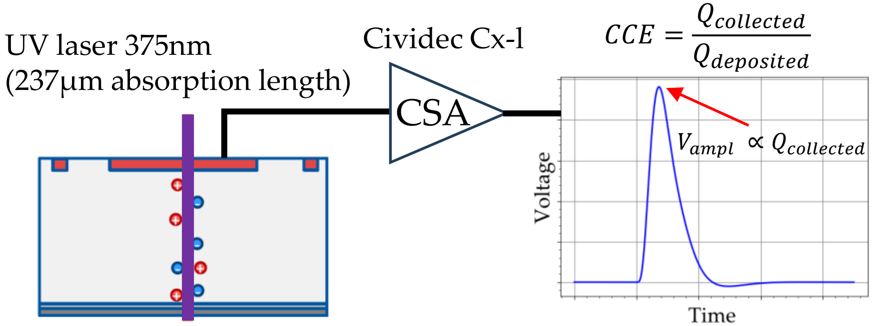
Reverse IV vs. Fluence

- Leakage stays below 10pA/mm², followed by sharp increase >2e17$n_{eq,Si}$/cm² to nA/mm²
- **Not compatible with established damage model in Si ($\Delta I = \alpha \Phi V$)**

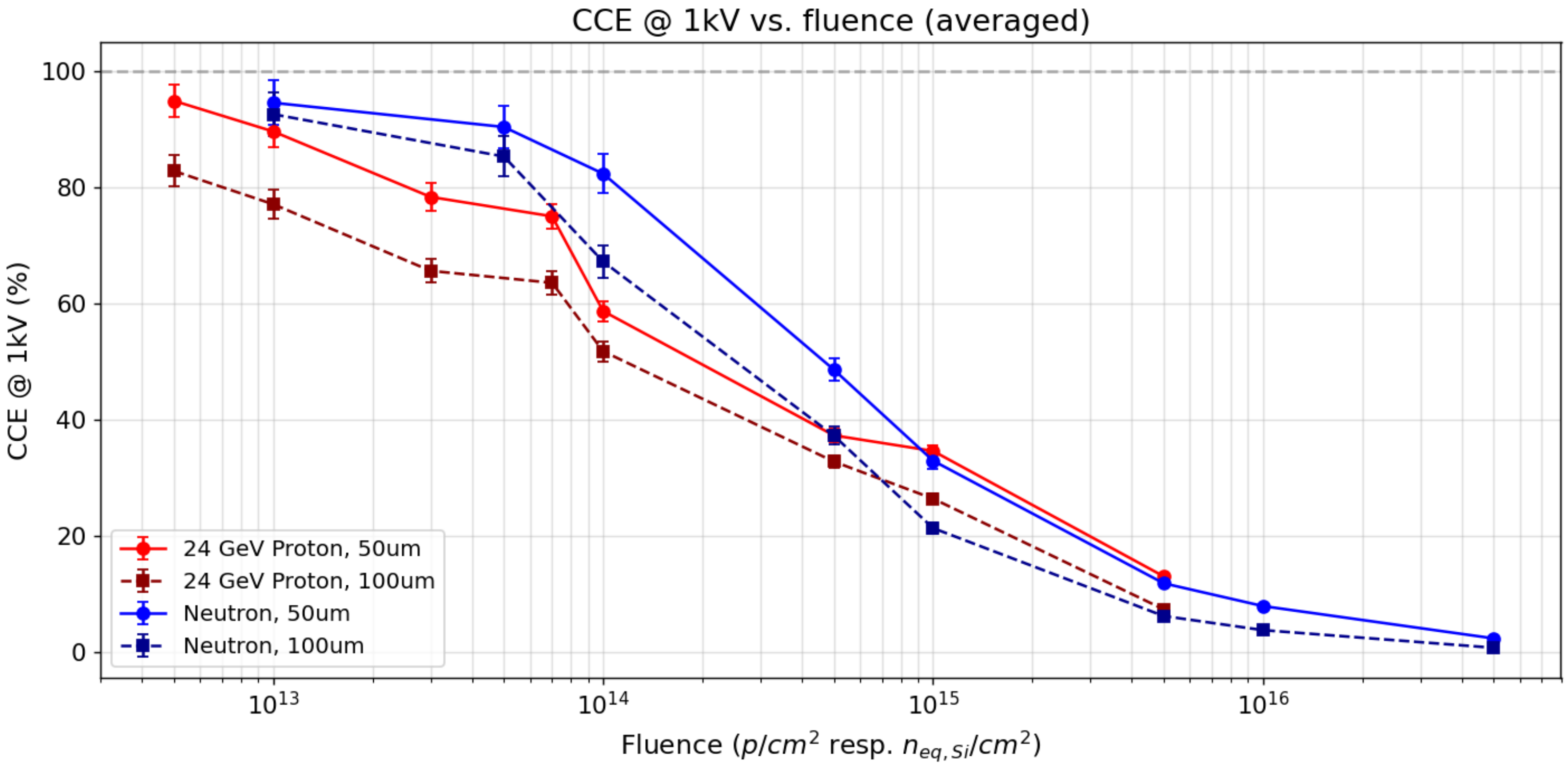


CCE vs. Fluence

- CCE determined relative to unirradiated device @1kV
- Lower CCE in 100um samples → likely an artifact of partial depletion
- Slightly stronger decline of CCE from 24GeV protons (other way around in Si)

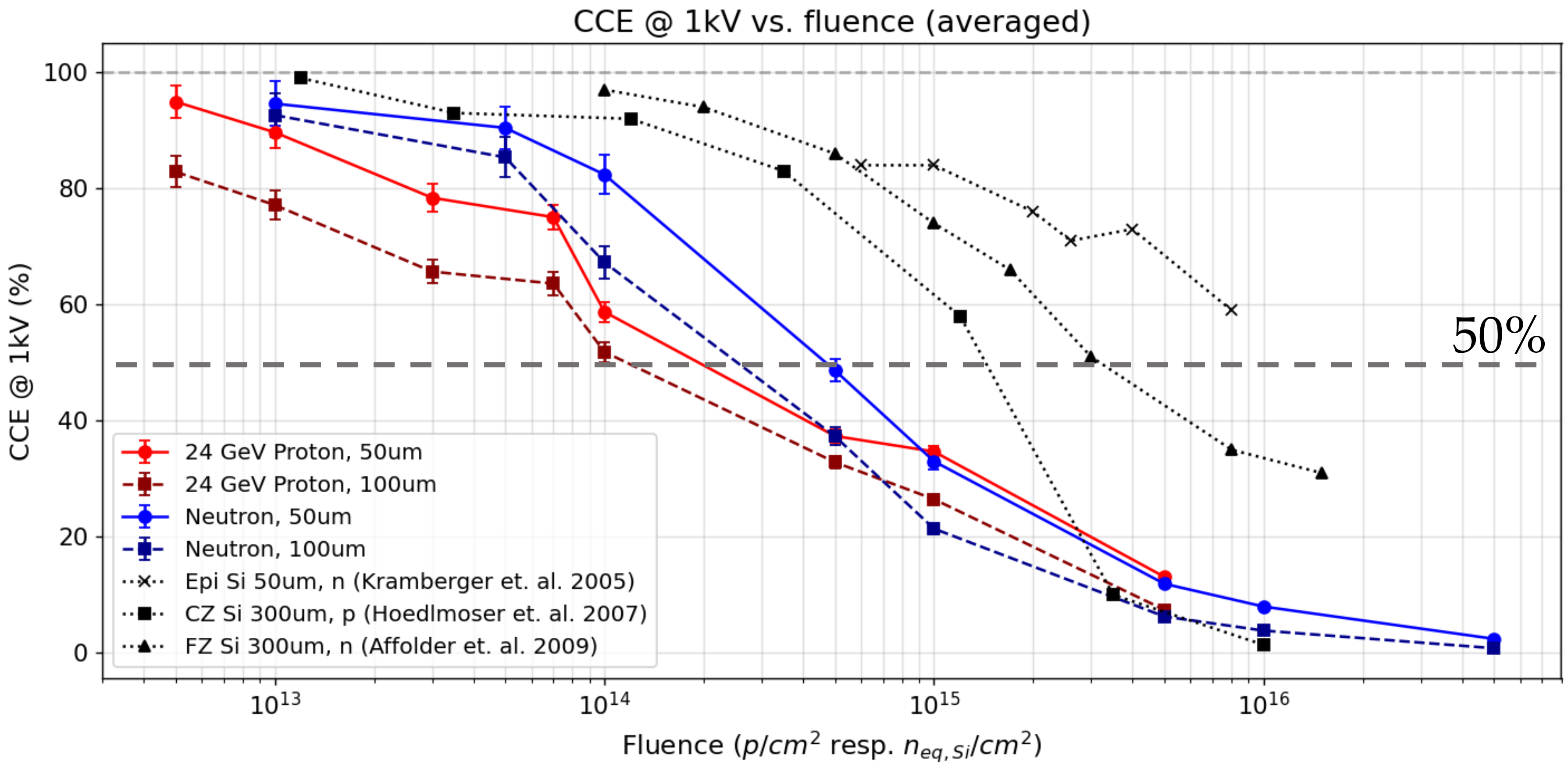


CCE measurement principle using a UV laser and charge sensitive amplifier (CSA)



CCE: 4H-SiC vs. Si

- 4H-SiC falls below 50% by approx. one order of magnitude earlier than Si
- **⇒ In terms of charge collection, 4H-SiC PN diodes are not radiation harder than Si**



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Summary

- Large irradiation study on 4H-SiC PN-diodes: **181 diodes**, 24 GeV protons & reactor neutrons, 2 epi thicknesses, fluences over >4 orders of magnitude
- **CV / doping:** donor removal up to ~1e13; device then becomes semi-insulating (geometric capacitance)
- **Forward IV:** turn-on shifts to higher voltage ⇒ progressive loss of rectification
- **Reverse IV:** leakage stays remarkably low (<10 pA/mm²) up to 2e17; **not described by the Si damage model ($\Delta I = \alpha \Phi V$)**
- **CCE:** drops below 50% roughly **one order of magnitude earlier than Si**
  ⇒ In terms of charge collection, 4H-SiC PN diodes are not radiation harder than silicon
  - **Bad news for HEP applications: MIP detection becomes very challenging ⇒ SiC LGADs**
  - **Ion therapy and fusion: higher energy deposition of particles compensates for lower CCE i.e. low leakage and thermal robustness still offer significant advantages**
- **Outlook:** dataset feeds refinement of the Vienna TCAD damage model; hardness-factor / NIEL analysis follows (e.g. protons degrade CCE slightly faster); temperature dependent studies in the next step

Thank you!

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Production and development of the 4H-SiC samples was supported by the Spanish State Research Agency (AEI) and the European Regional Development Fund (ERDF), ref. RTC-2017-6369-3.
The production of the planar 6''-SiC samples has been supported in part by the RD50 collaboration (RD50-SiC-LGAD common project)

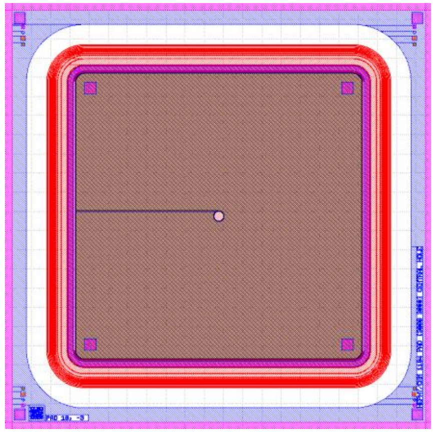
This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511 (EURO-LABS)."

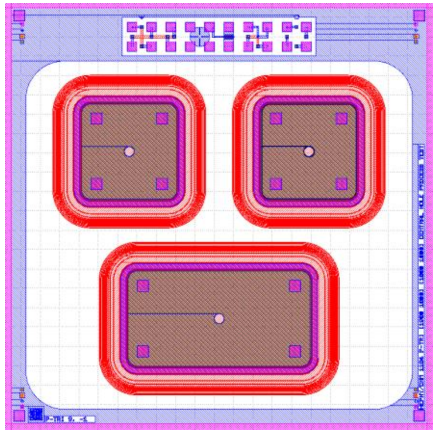
Special thanks to colleagues from CTU and FZU Prague for organizing the irradiation at CERN IRRAD and letting us participate with the devices irradiated as part of this study.

Back Up

Devices Under Test

- **181 total diodes** included in study
  - PN diodes
  - 3 areas: $3x3mm^2$, $1x2mm^2$, $1x1mm^2$
- Irradiated using
  - 24 GeV protons (CERN IRRAD)
  - Neutrons (JSI)

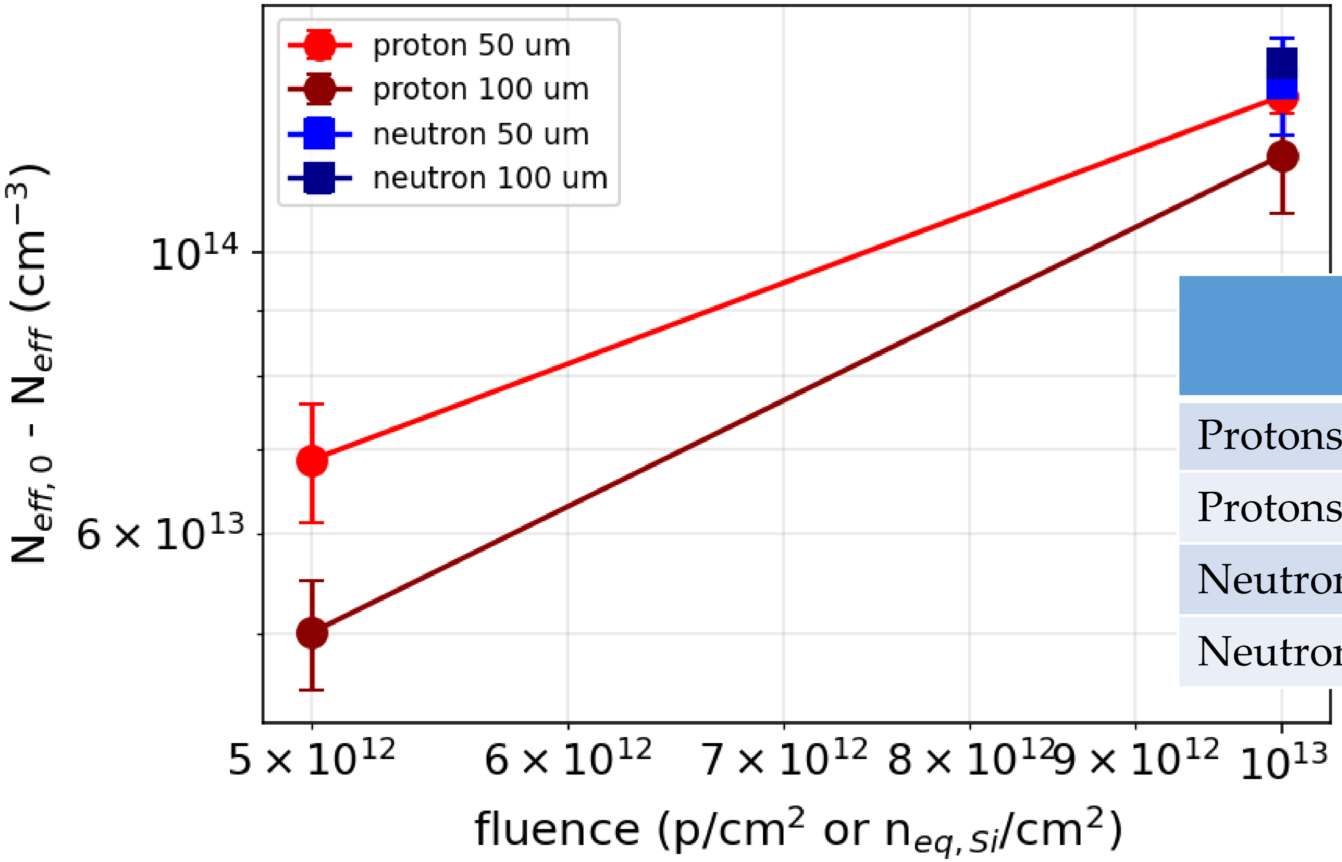




Fluence (p/cm^2 resp. $n_{eq,Si}/cm^2$)	5e12	1e13	3e13	5e13	7e13	1e14	5e14	1e15	5e15	1e16	5e16	2e17	5e17	1e18
24GeV Protons 50µm	5	5	5	-	5	5	5	5	5	-	-	-	-	-
24GeV Protons 100µm	5	5	5	-	5	5	5	5	5	-	-	-	-	-
Neutrons 50µm	5	4	-	5	-	4	5	5	5	5	5	5	5	5
Neutrons 100µm	6	4	-	6	-	4	6	4	6	4	6	5	5	5

Donor Removal

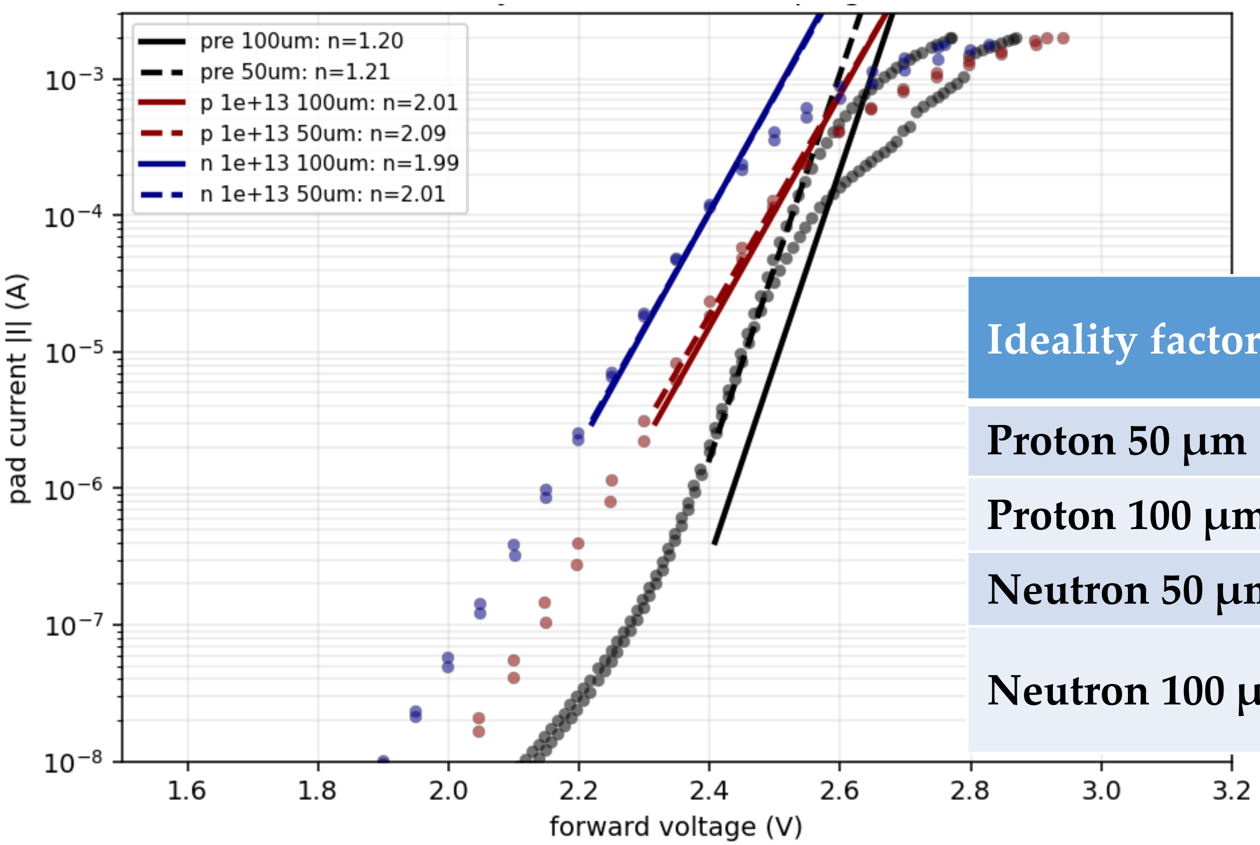
- CV curves flatten out after 3e13p/cm² resp. 5e13$n_{eq,Si}$/cm²
  ⇒ Decrease of effective doping concentration only visible up to 1e13/cm²



	g (cm^{-1})	Avg. $N_{eff,0}$ ($10^{14}cm^{-3}$)
Protons 50µm	13.4 ± 0.7	2.91 ± 0.15
Protons 100µm	11.9 ± 1.9	5.00 ± 0.05
Neutrons 50µm	13.6 ± 0.9	3.53 ± 0.11
Neutrons 100µm	14.1 ± 0.7	3.78 ± 0.05

Forward IV - Ideality Factor

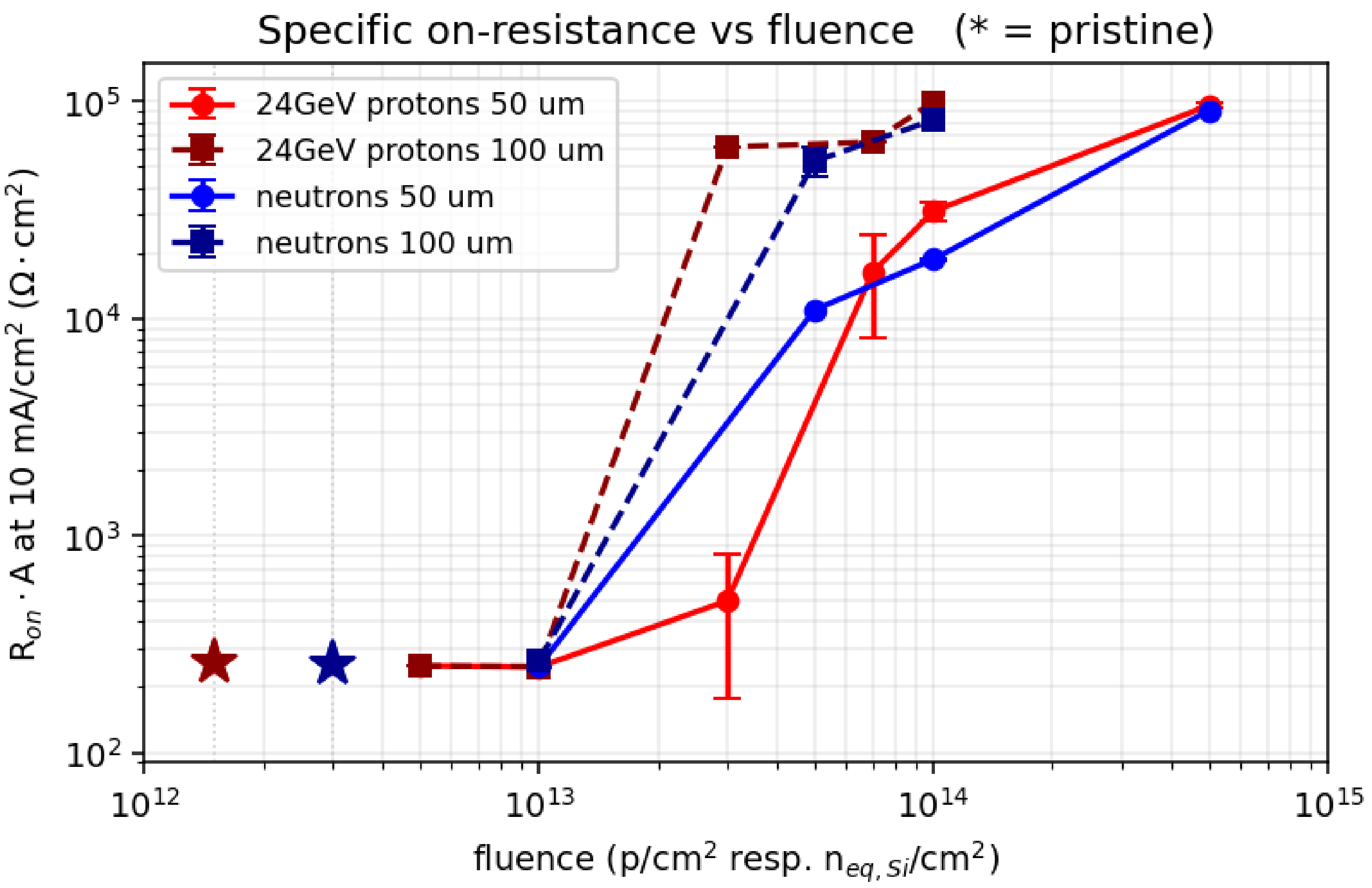
- Ideality factor jumps from ~1.1-1.2 to ~2 within one fluence step



Ideality factor n	Pristine	5E12 (p/cm² resp. $n_{eq,Si}$/cm²)	1E13 (p/cm² resp. $n_{eq,Si}$/cm²)
Proton 50 µm	1.19 ± 0.06	2.00 ± 0.03	2.10 ± 0.04
Proton 100 µm	1.17 ± 0.01	1.93 ± 0.01	2.01 ± 0.04
Neutron 50 µm	1.11 ± 0.11	–	2.01 ± 0.01
Neutron 100 µm	1.13 ± 0.17	–	1.99 ± 0.04

On-Resistance vs. Fluence

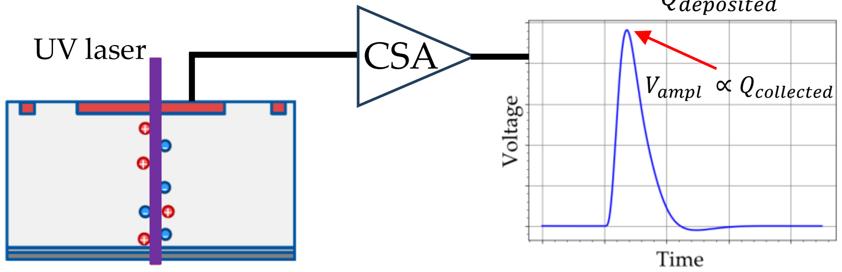
- As the turn-on voltage grows beyond 1e13/cm² the on-resistance explodes
- ⇒ diodes become increasingly semi-insulating



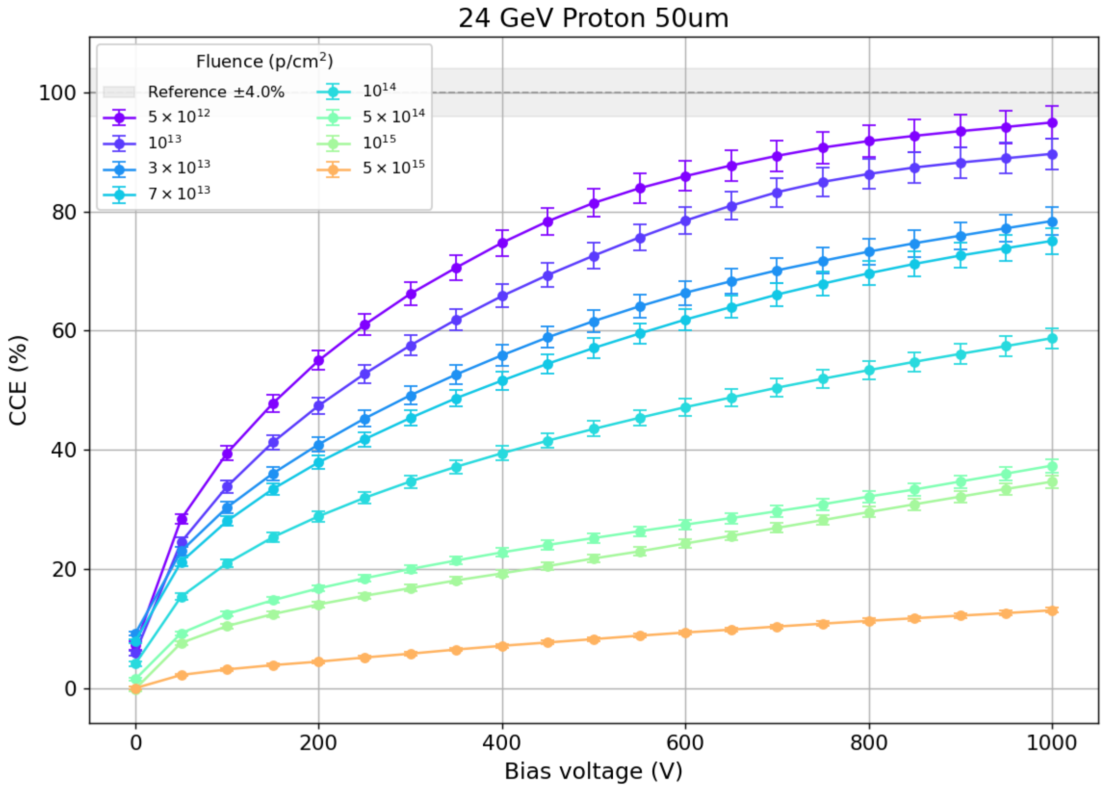
CCE vs. Fluence

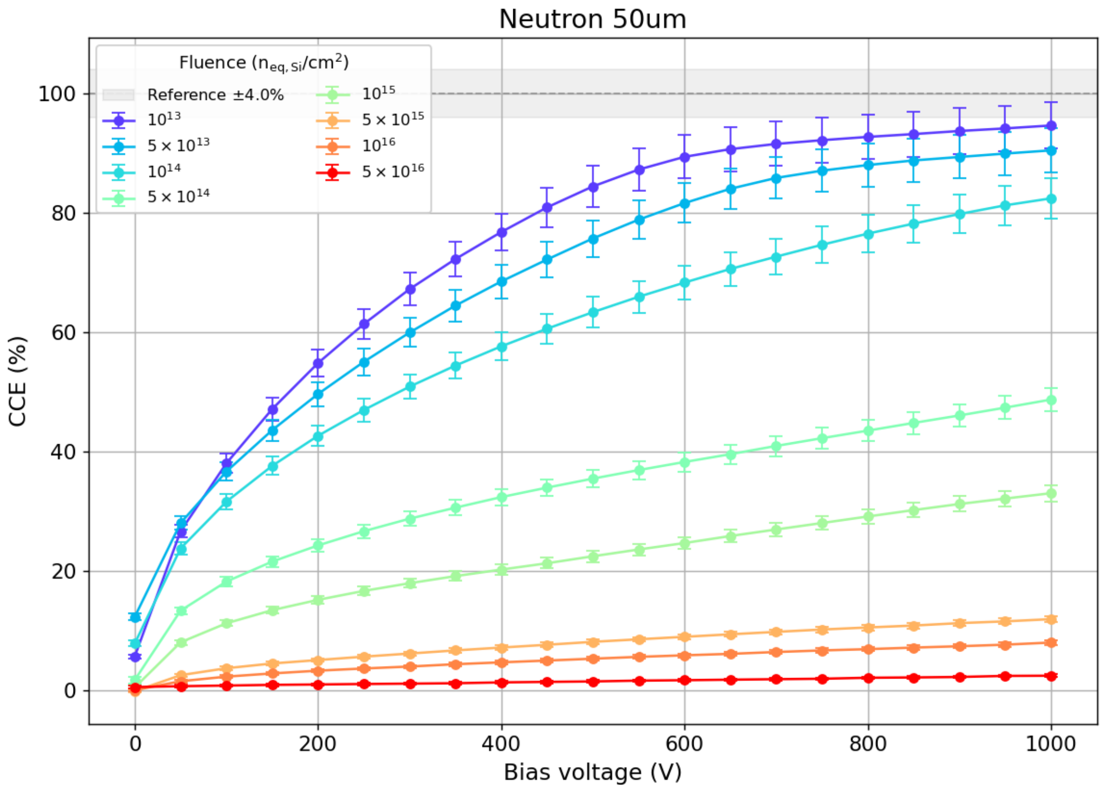
- 375nm laser (absorption length of ~237µm)
- Charge information via Cividec Cx-L charge sensitive amplifier
- CCE determined relative to unirradiated device

$$CCE = \frac{Q_{collected}}{Q_{deposited}}$$

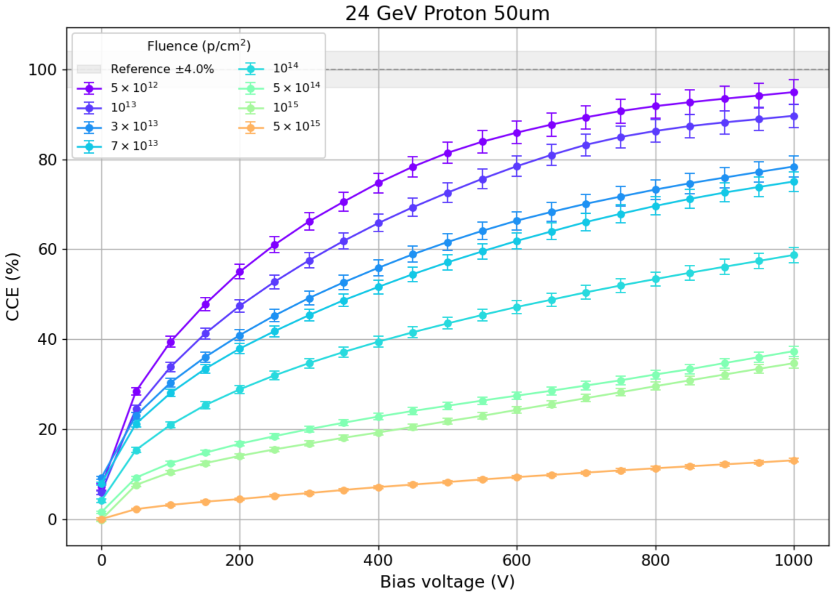


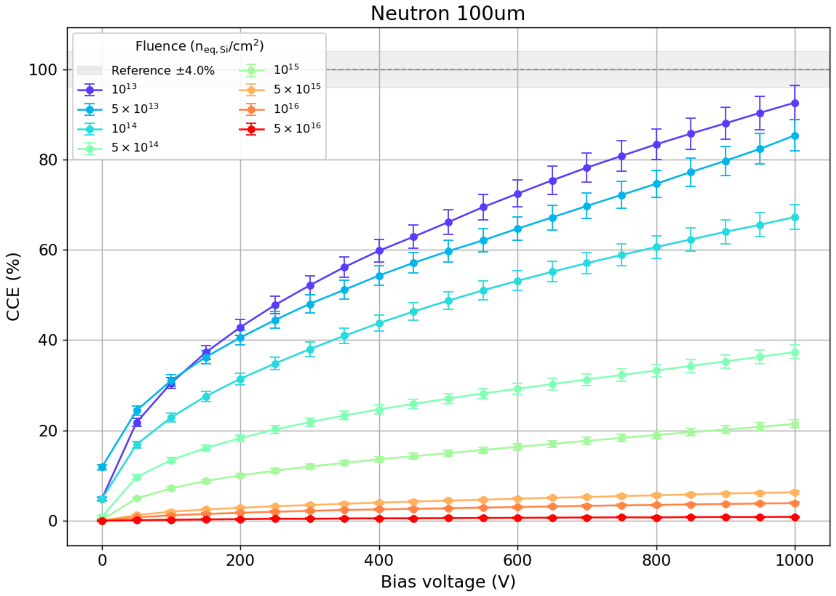
CCE measurement principle using a UV laser and charge sensitive amplifier (CSA)

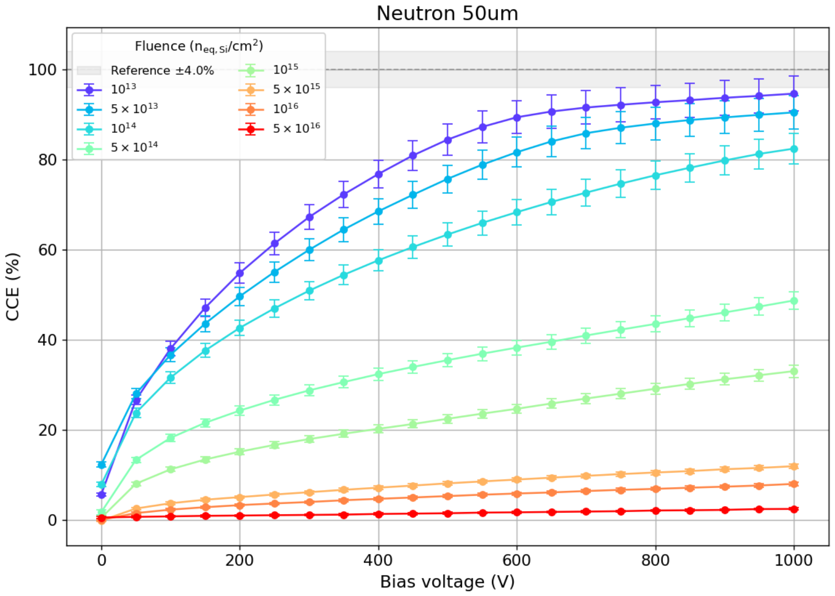


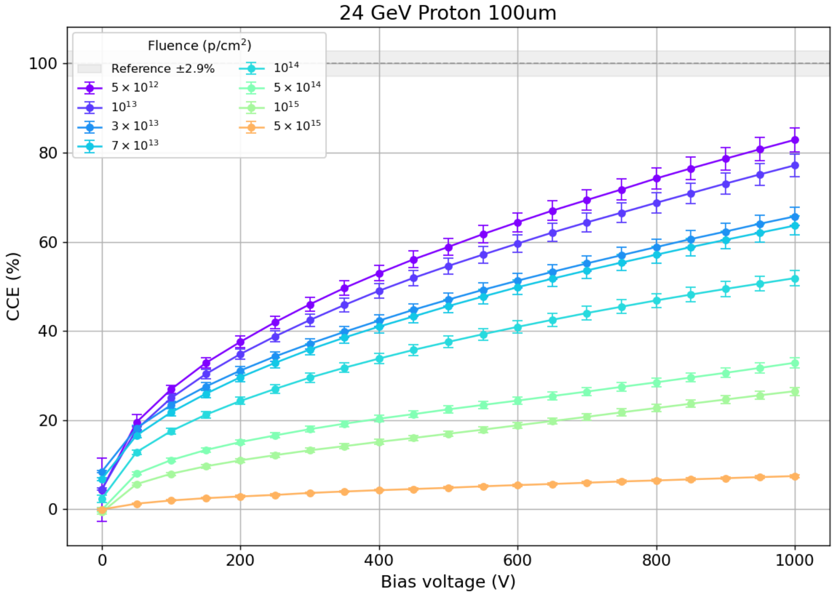


CCE at a Glance









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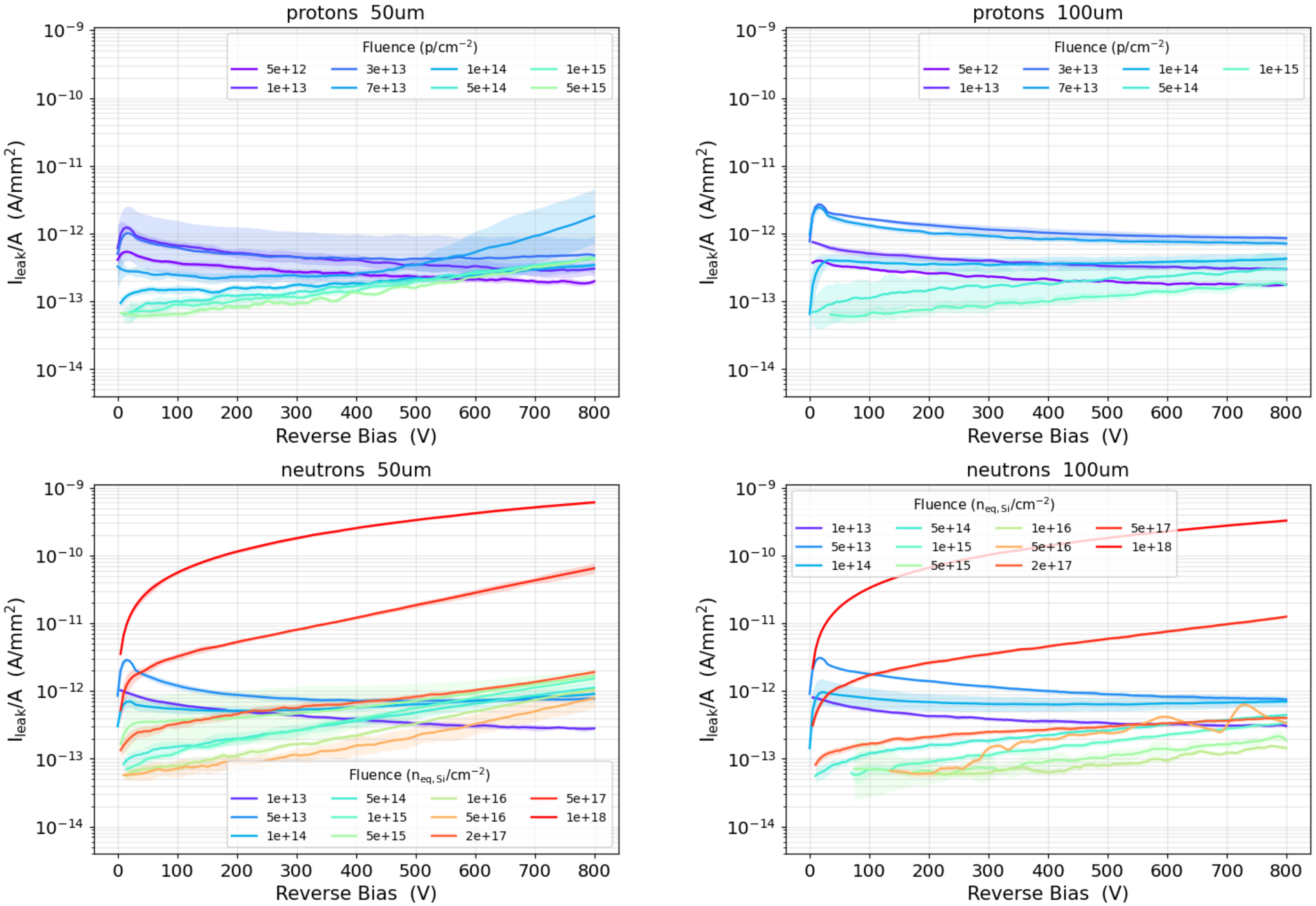
Reverse IV at a Glance



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Damage by 24GeV Protons

- Irradiation can change atomic composition of 4H-SiC

- Neutrons:
  - Main process: neutron capture
  - Mainly turns Si and C into other Si and C isotopes

- **24GeV protons**:
  - Creates a large array of spallation products, see https://doi.org/10.1134/S1063782607030190
  - Creates a concentration of **~1e13 to ~1e16/cm³ of stable isotopes** across the probed dose range (1e13 to 1e16 p/cm²)
  - Among the stable isotopes are e.g. N, Al, O, Na
  - Radiation damage from protons potentially more complex than from neutrons

Influence of irradiation by 24 GeV protons on the properties of 4H–SiC radiation detectors

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[b] Institute of Physics, Savanorių 231, LT-02300 Vilnius, Lithuania

Available online 12 December 2006

Detector no.	The irradiation dose, cm^{-2}	^{28}Si	^{27}Al	^{26}Mg	^{25}Mg	^{24}Mg	^{23}Na	^{22}Ne	^{21}Ne
1	1×10^{13}	1.6×10^{6}	1.7×10^{7}	2.6×10^{6}	1.3×10^{10}	4.3×10^{9}	1.2×10^{9}	6.6×10^{6}	1.6×10^{9}
2	1×10^{14}	1.3×10^{7}	1.3×10^{8}	2.1×10^{7}	9.7×10^{10}	3.4×10^{10}	1.0×10^{10}	5.2×10^{7}	1.3×10^{10}
3	1×10^{15}	8.1×10^{7}	8.4×10^{8}	1.3×10^{8}	6.6×10^{11}	2.7×10^{11}	6.4×10^{10}	2.5×10^{8}	8.2×10^{10}
4	3×10^{15}	2.8×10^{8}	2.9×10^{9}	4.5×10^{8}	2.2×10^{12}	7.6×10^{11}	2.1×10^{11}	1.2×10^{9}	2.8×10^{11}
5	1×10^{16}	7.5×10^{8}	7.8×10^{9}	1.1×10^{9}	5.8×10^{12}	1.9×10^{12}	5.6×10^{11}	2.9×10^{9}	7.5×10^{11}

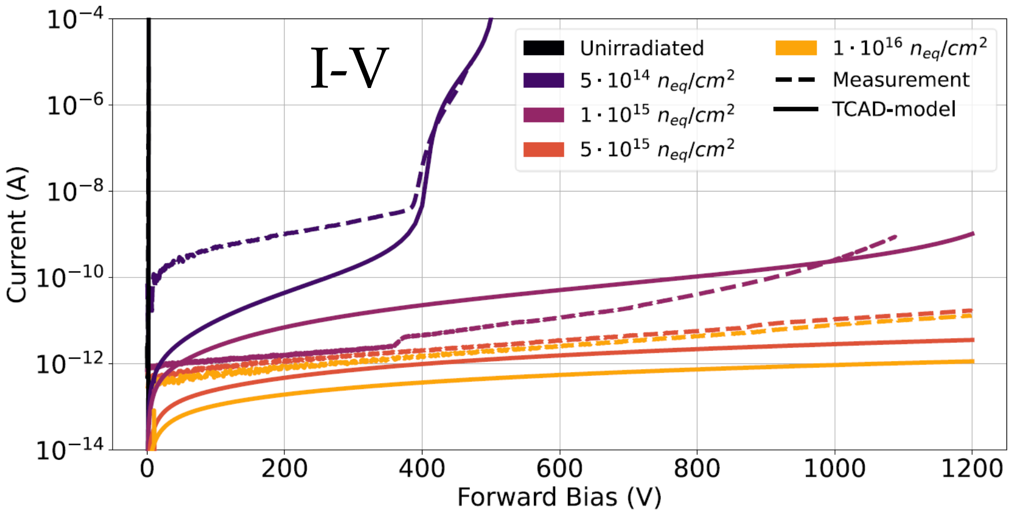
Detector no.	The irradiation dose, cm^{-2}	^{20}Ne	^{19}F	^{18}O	^{17}O	^{16}O	^{15}N	^{14}N
1	1×10^{13}	6.6×10^{9}	2.1×10^{9}	5.9×10^{8}	2.8×10^{9}	8.2×10^{8}	3.5×10^{9}	1.0×10^{10}
2	1×10^{14}	5.1×10^{10}	1.7×10^{10}	4.5×10^{9}	2.2×10^{10}	6.4×10^{9}	2.8×10^{10}	8.0×10^{10}
3	1×10^{15}	3.4×10^{11}	9.8×10^{10}	2.9×10^{10}	1.4×10^{11}	4.1×10^{10}	1.8×10^{11}	5.1×10^{11}
4	3×10^{15}	1.1×10^{12}	3.7×10^{11}	1.0×10^{11}	4.9×10^{11}	1.4×10^{11}	6.2×10^{11}	1.8×10^{12}
5	1×10^{16}	3.1×10^{12}	9.8×10^{11}	2.7×10^{11}	1.3×10^{12}	3.8×10^{11}	1.6×10^{12}	4.7×10^{12}

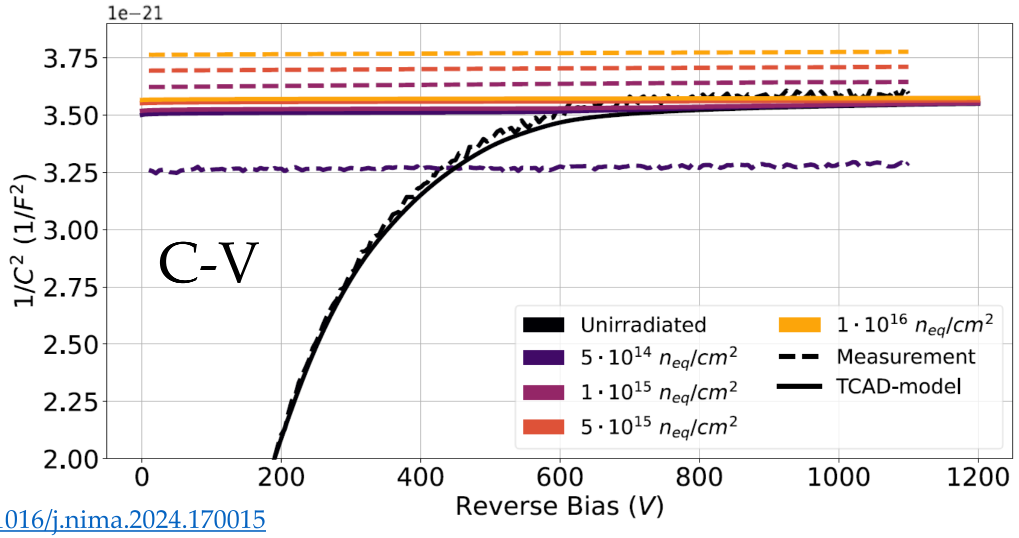
Radiation Damage Model

- Radiation damage model (preliminary) via radiation induced traps for simulation in TCAD
- Material and defect parameters deviate across literature:
  - Initial guesses from literature
  - Optimized by fitting simulation results to measurement
- Qualitative agreement

Defect	Type	Energy	g_{int} [cm^{-1}]	σ_e [cm^2]	σ_h [cm^2]
$Z_{1,2}$	Acceptor	$E_C - 0.67\,\mathrm{eV}$	5.0	2e−14	3.5e−14
$EH_{6,7}$	Donor	$E_C - 1.6\,\mathrm{eV}$	1.6	9e−12	3.8e−14
EH_4	Acceptor	$E_C - 1.03\,\mathrm{eV}$	2.4	5e−13	5.0e−14

(most significant trap levels)

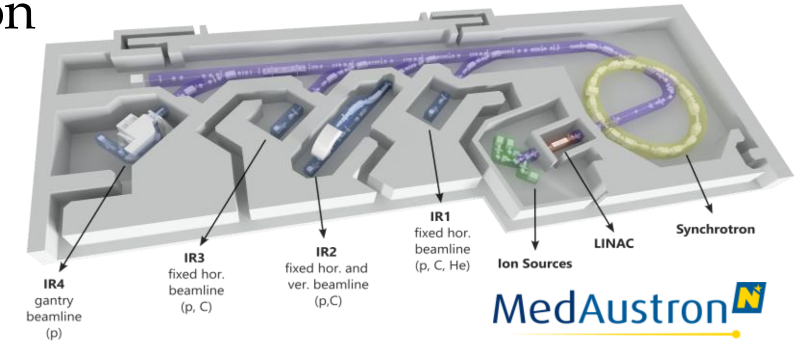


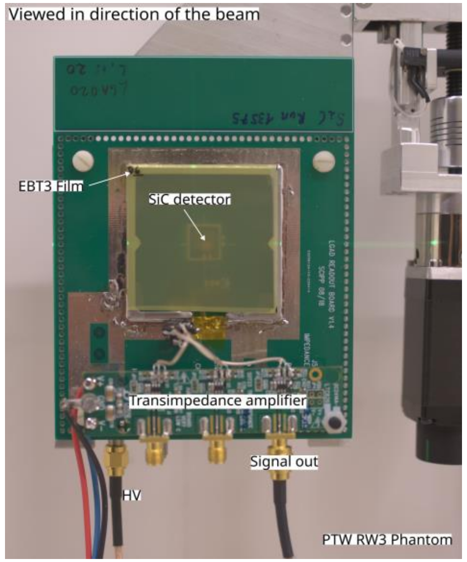


P. Gaggl, et. al. (2024). TCAD modeling of radiation-induced defects in 4H-SiC diodes. *NIM A*, 170015. https://doi.org/10.1016/j.nima.2024.170015
J. Burin, et.al. (2024). TCAD Simulations of Radiation Damage in 4H-SiC. Austrochip 2024. https://doi.org/10.1109/Austrochip62761.2024.10716221.

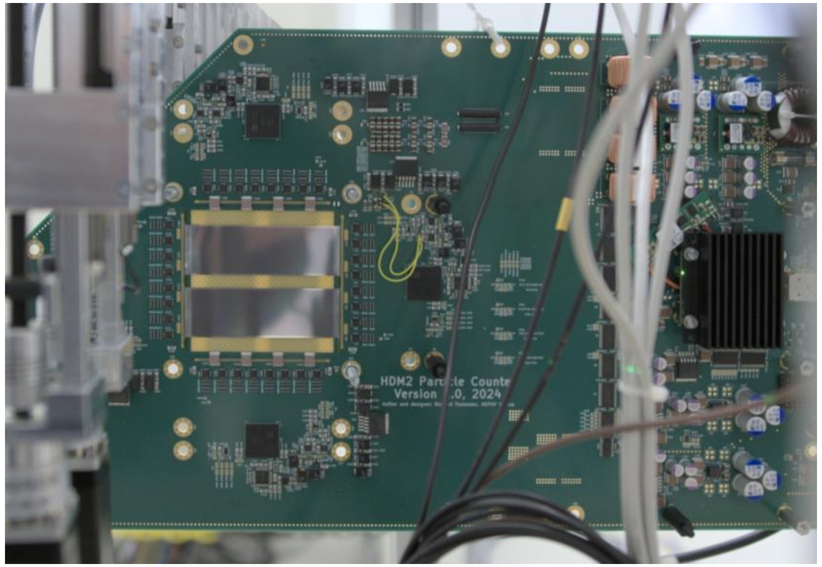
Medical Applications: Beam Monitor & Dosimetry

- Collaboration Partner: ion beam radiotherapy center MedAustron
- Low leakage currents, after irradiation and at room-temperature ⇒ DC readout
- Insensitive to visible light, better tissue equivalence
- Beam monitoring for clinical therapy beams (p^+ and ^{12}C)
- Microdosimetry: single particle dose deposition on length scale of cells (<10μm) ⇒ thin sensors

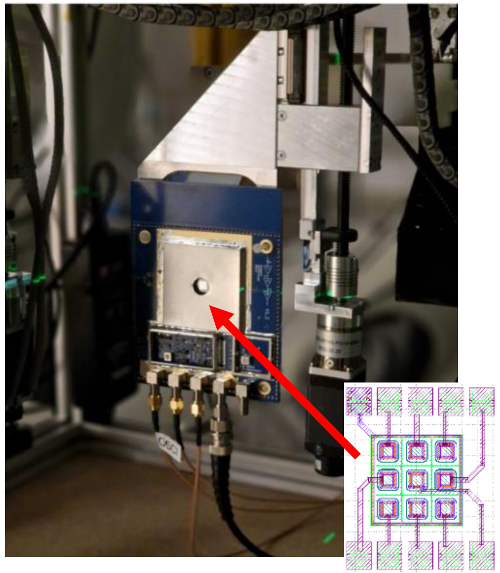




UHDR beam monitor prototype (planar SiC sensor)



New SiC-based beam monitor for a wide dynamic beam intensity range and FLASH-like beams in the future



Soon: SiC Microdosimeter (50μm x 50μm pitch, 10μm epi)