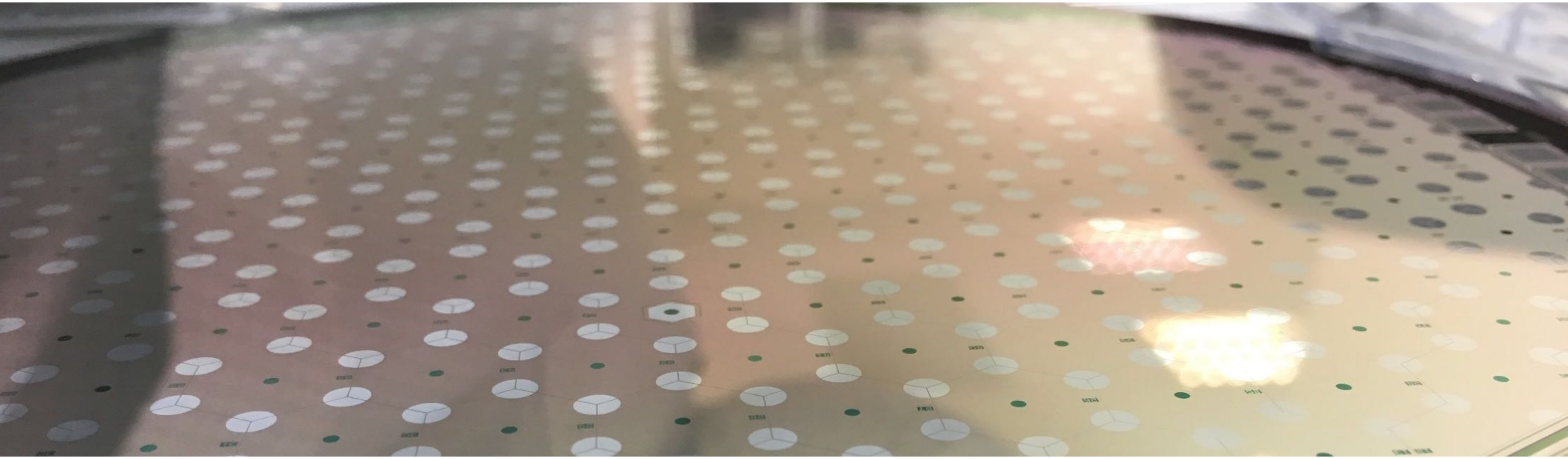


Silicon Carbide Characterization at HEPHY Vienna towards SiC-LGAD

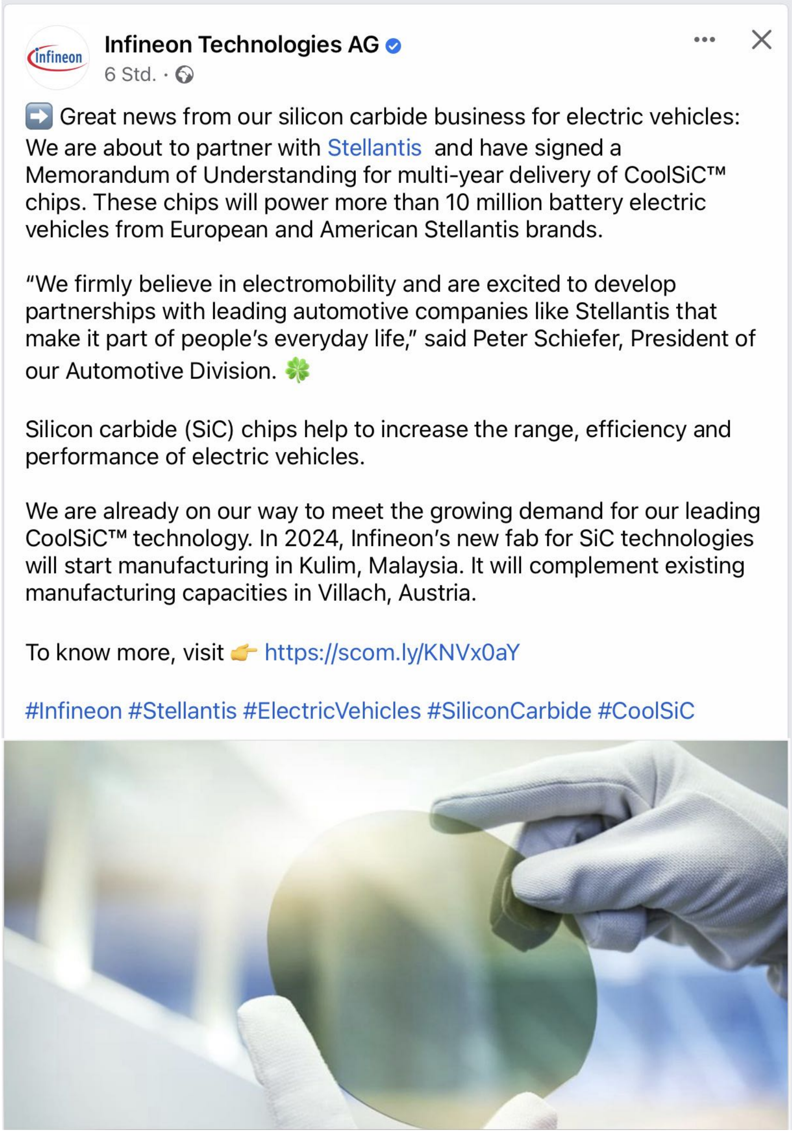
T. Bergauer[1], P. Gaggl[1], A. Gsponer[1], M. Knopf[1], P. Kraus[1], S. Onder[1], R.Thalmeier[1], S. Waid[1], G. Pellegrini[2]

1) HEPHY Vienna
2) CNM Barcelona

30 Nov 2022

Silicon Carbide

- Material known in principle for 100 years
- Investigated as detector material already 20 years ago
  - I. Pintile [1], F. Moscatelli [2] and others
- Recently got attention because of chip industries' interest in the renewable energy revolution
  - Power-efficient transistors in power supplies
  - Photovoltaic inverters
  - Electric car drive train
- Becomes easier available and economically interesting again


Infineon Technologies AG
6 Std. ·

➡️ Great news from our silicon carbide business for electric vehicles: We are about to partner with Stellantis and have signed a Memorandum of Understanding for multi-year delivery of CoolSiC™ chips. These chips will power more than 10 million battery electric vehicles from European and American Stellantis brands.

"We firmly believe in electromobility and are excited to develop partnerships with leading automotive companies like Stellantis that make it part of people's everyday life," said Peter Schiefer, President of our Automotive Division. 🍀

Silicon carbide (SiC) chips help to increase the range, efficiency and performance of electric vehicles.

We are already on our way to meet the growing demand for our leading CoolSiC™ technology. In 2024, Infineon's new fab for SiC technologies will start manufacturing in Kulim, Malaysia. It will complement existing manufacturing capacities in Villach, Austria.

To know more, visit 👉 https://scom.ly/KNVx0aY

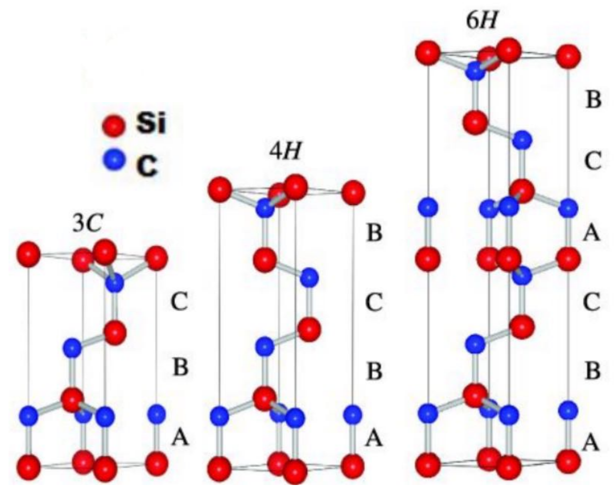
#Infineon #Stellantis #ElectricVehicles #SiliconCarbide #CoolSiC

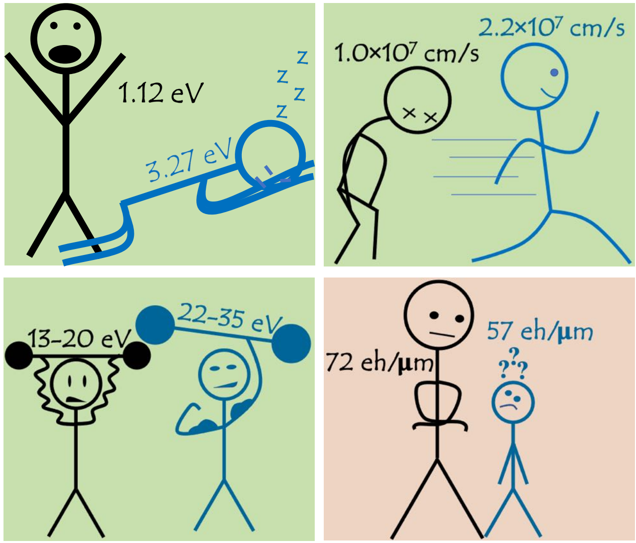
[1] 10.1063/1.3457906
[2] 10.1016/j.nima.2005.03.048

Silicon Carbide

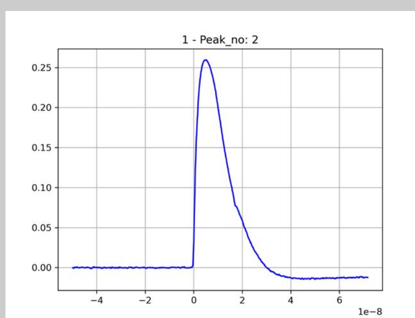
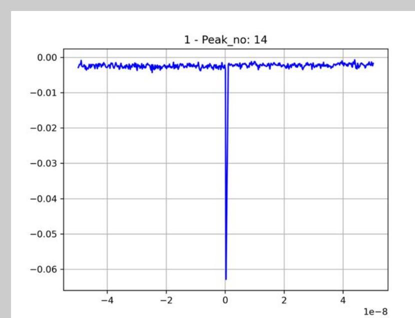
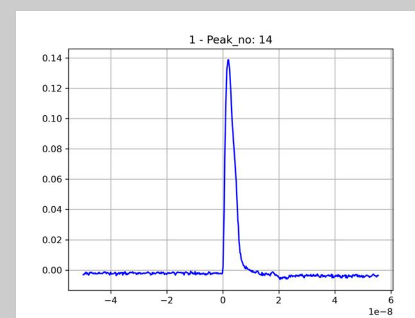
Wide band gap material **Silicon Carbide (SiC)** as particle detector material:

- Pros:
  - Bandgap between silicon and diamond
  - Higher saturation velocity and breakdown field
  - larger atomic displacement threshold
- Cons:
  - Different polytypes (3C, 4H, 6H)
  - Anisotropy
  - higher ionization energy → smaller signals
  - Epitaxial-grown substrate is currently limited to ~150µm thickness
  - Not (yet) properly modeled in simulation tools
- Macroscopic properties:
  - No dark current increase after irradiation
  - No cooling needs
  - no sensitivity to visible light
  - Faster signals than silicon
  - potentially more radiation hard



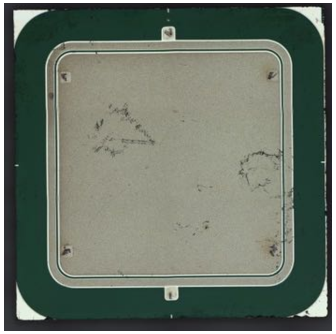


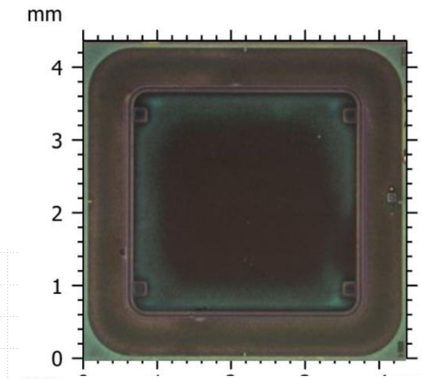
Detector Properties

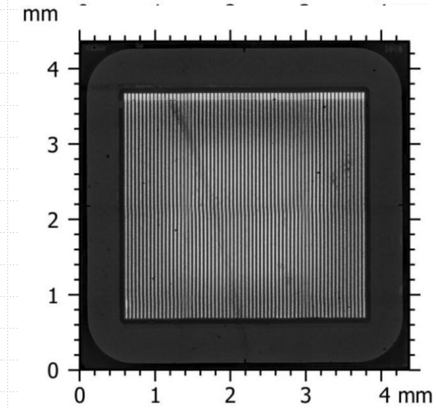
	Silicon	**4H-Silicon carbide**	**CVD Diamond**
Band gap [eV]	1.1	3.26	5.5
Ionization energy [eV]	3.6	5 – 8	12.86
atomic displacement threshold	13-20 eV	20-35	43
Density [g/cm^3]	2.33	3.22	3.52
Electron Mobility [cm^2/Vs]	1430	⊥ c: 800; ‖ c: 900	1800-2200
Hole Mobility [cm^2/Vs]	480	115	1200-1600
Saturation electron velocity [10^7 cm/s]	1	2.2	2.7
Breakdown Field [MV/cm]	0.5	⊥ c: 4.0; ‖ c: 3.0	10
e/h pairs per µm	72	57	36
Typical active thickness [µm]	300	<150µm epi layer possible (50µm studied by us)	<400 (charge collection distance)
Material	Float zone	Epitaxially grown	chemical vapor deposition
e/h pairs MPV	21,600	2,850 (50µm)	14,000
Typical signal (recently measured myself at proton beam with UCSC LGAD-readout board and DRS4-based digitizer			
Wafer costs	O(<100€)	O(1000€)	O(100,000€)

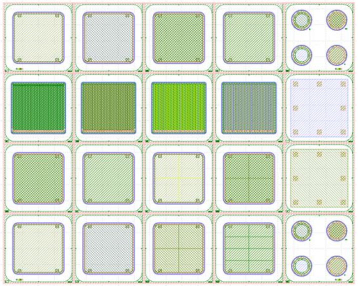
Studied SiC Samples

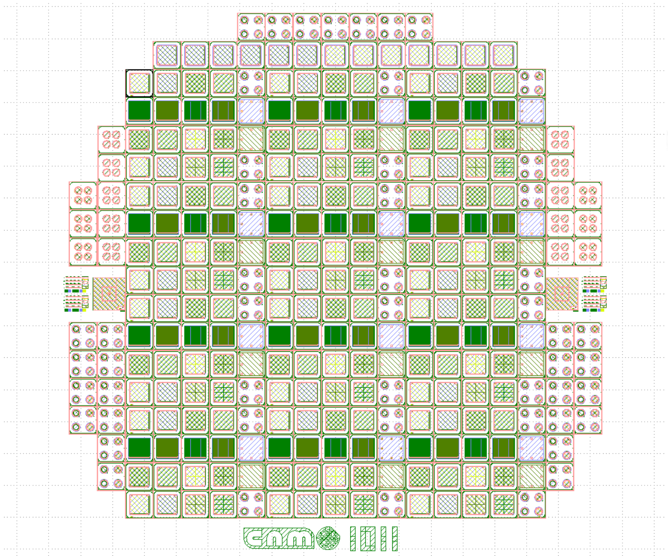
- Two production runs by CNM
  - Old run 8435
  - New run 13575
- p-on-n 50µm planar devices
- Basic structures 3 x 3 mm^2 active area each
  - Reticle with 20 structures, repeated 12 times on wafer
  - Pad diodes
  - Strip sensors
  - […]











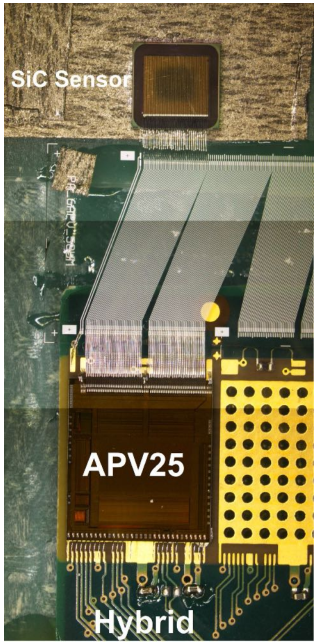
e/h pairs in SiC

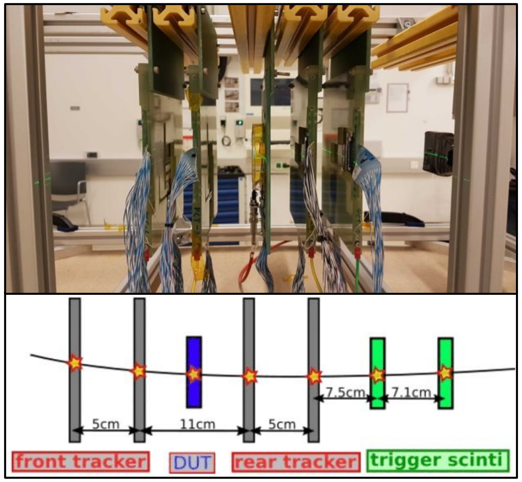
Planar SiC strip sensor

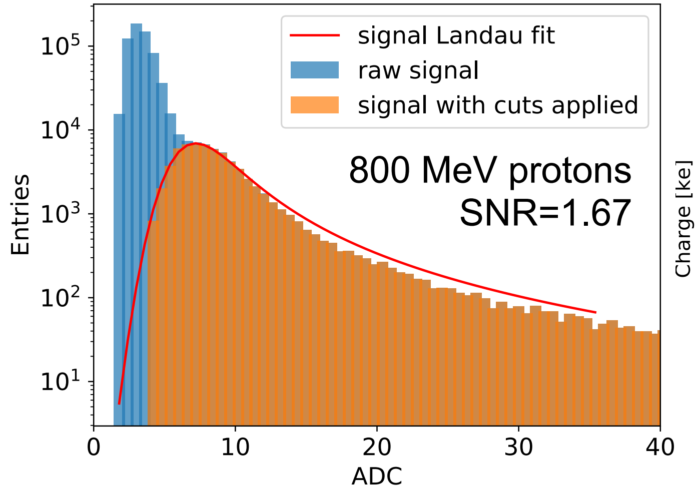
- 64 strips, pitch 100µm, Strip length 3 mm, DC-coupled

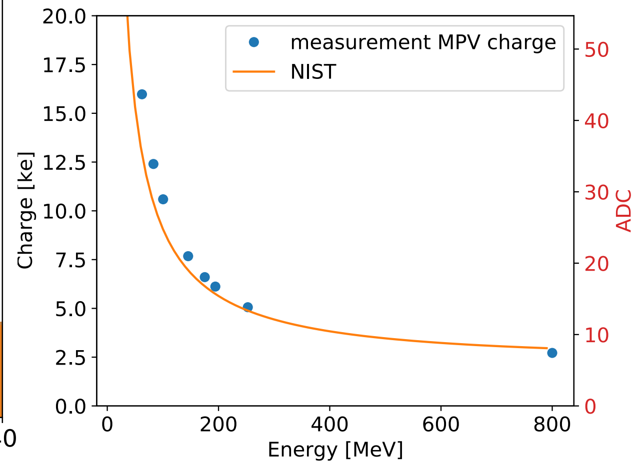
Beam test with protons between 60 and 800 MeV at MedAustron

- DAQ system based on APV25 chip and Belle-II FADC system
  - Separation of Signal and noise at 800 MeV (1.25 x MIP) is challenging and only possible by “hit-time finding”
- Operated together with DSSD Si sensor telescope
  - Used to determine the average **number of e/h pairs to 57.1 per µm**
  - by comparing relative signals of Si and SiC (no calibration necessary)



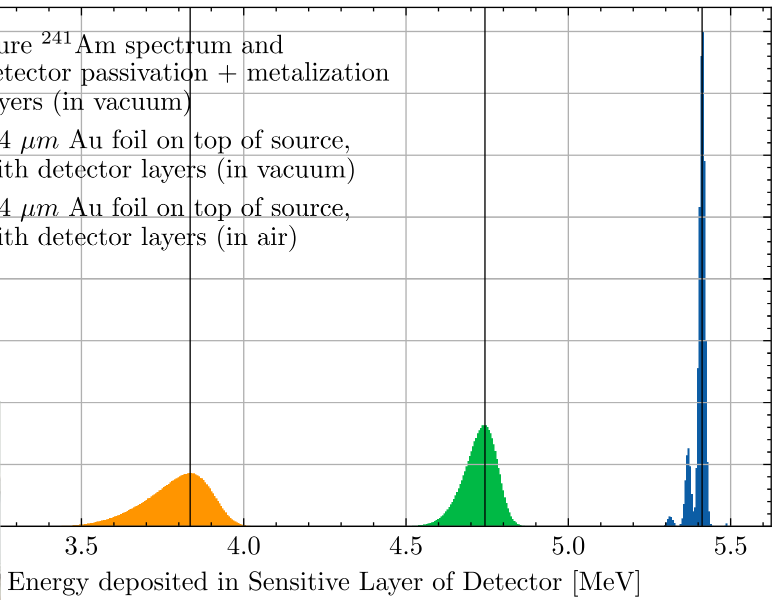


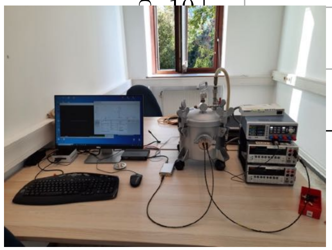




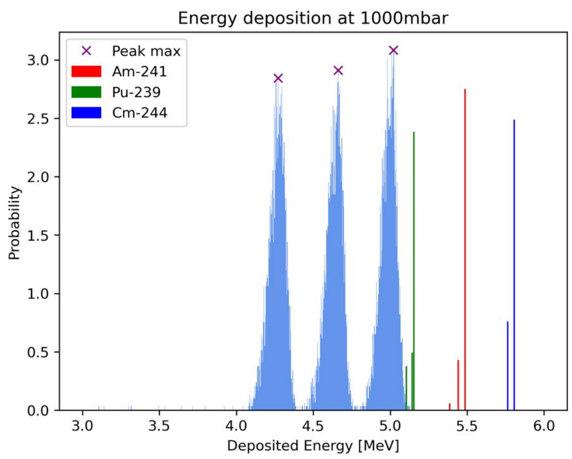
Alpha Measurements

- Single Americium-241 source
  - Suffering from scattering in air and gold passivation
  - no energy calibration possible
  - Mitigation: Vacuum Tank to suppress Alpha scattering in air
- Mixed Alpha Source
  - 3kBq total with nuclides Am-241, Cm-244, Pu-239
- Two readout chains:
  - Broadband (HF)
    - Amplifier on LGAD board or Broadband Cividec C2-HV or C2-TCT
    - 4/16 GHz HF Oscilloscope
  - Spectroscopic:
    - Cividec shaping amplifier Cx-L with shaping time of 1.2µs
    - CAEN DT5781 Multi-channel analyzer

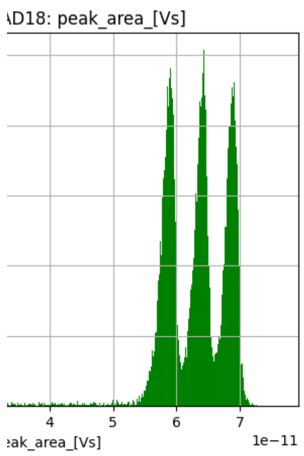




GATE simulation:

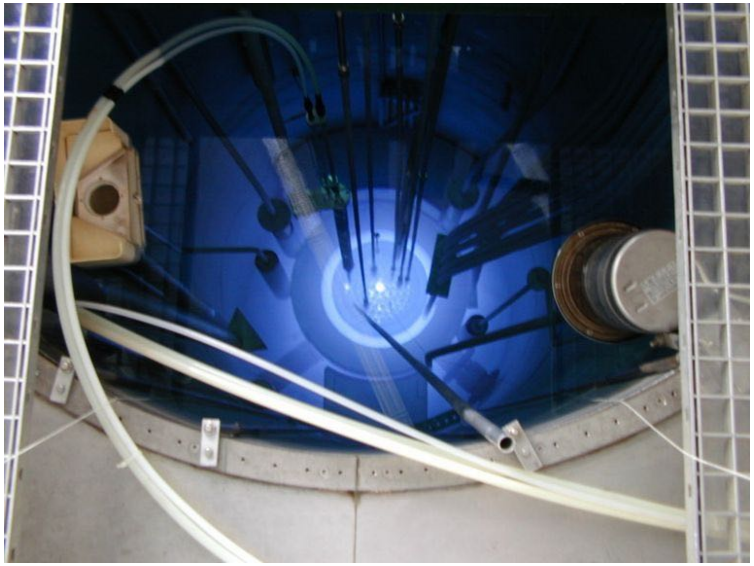


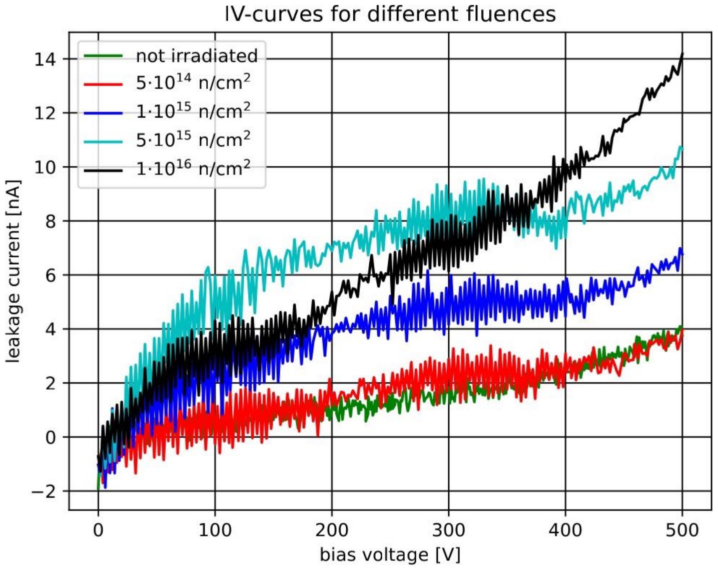
Measurement



Neutron Irradiation

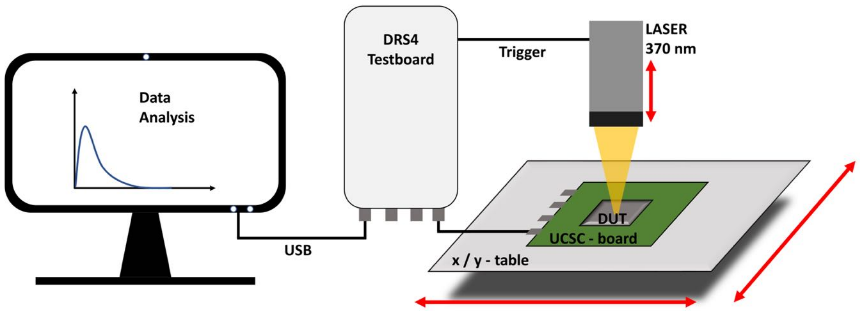
- Neutron irradiation of samples at the TRIGA Mark-II reactor in Vienna [6]
- Investigated fluences between $5 \cdot 10^{14}$ n_{eq}/cm^2 and $1 \cdot 10^{16}$ n_{eq}/cm^2 using different setups
- Virtually no current increase after irradiation

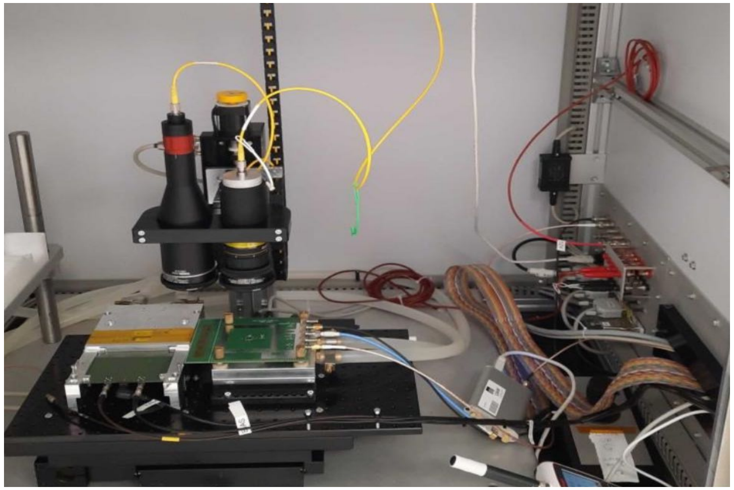




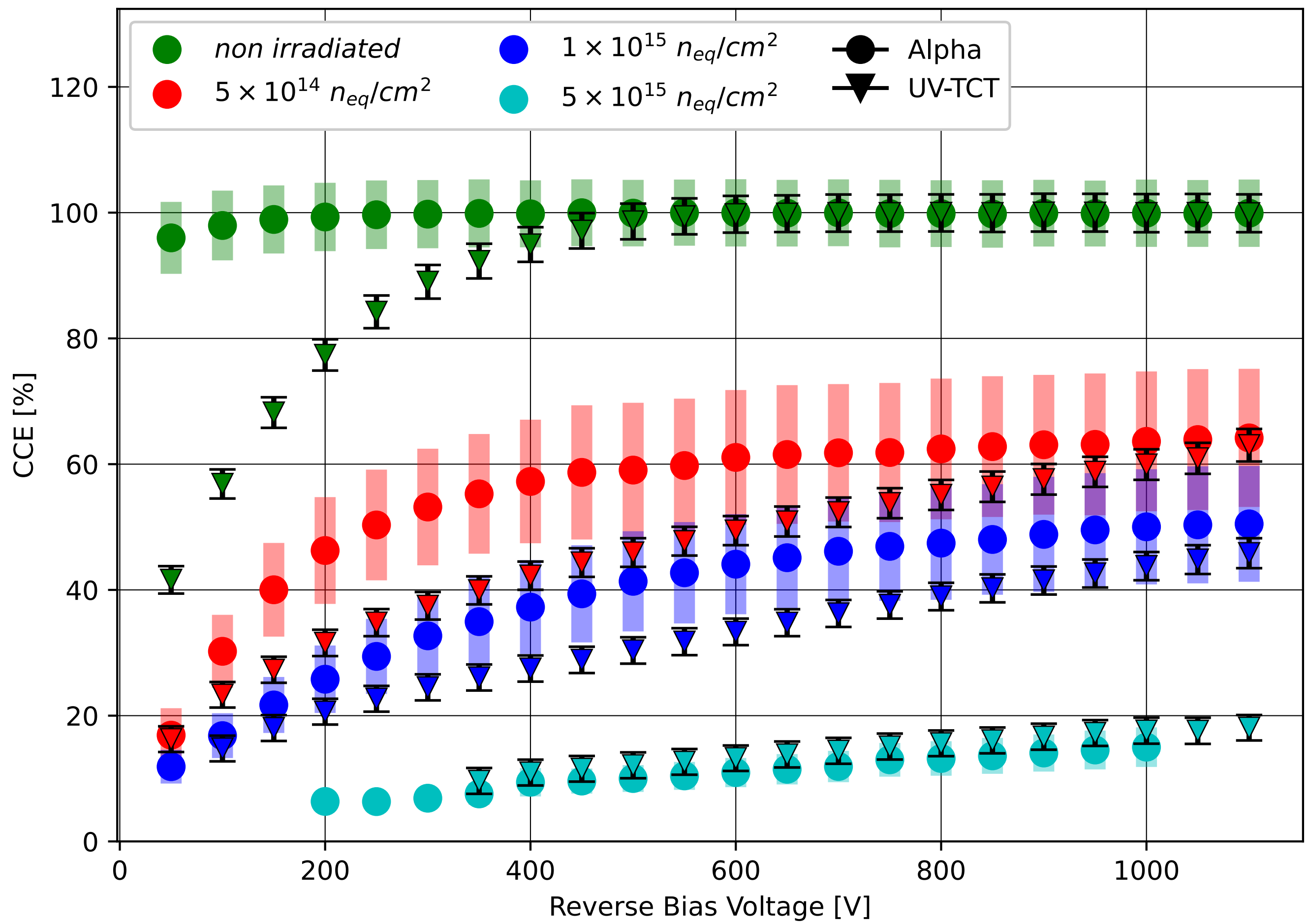
UV-TCT Setup

- Top-TCT system extended with UV laser
  - has enough energy to overcome SiC bandgap
  - PILAS DX PiL037-FC Laser, $\lambda = 370$ nm ($\rightarrow$ 3.35 eV) , pulse width < 70 ps [13]
  - custom UV beam optics, spot size < 10 µm.
- Absorption coefficient in 4H-SiC: $\alpha \approx 42.2\ cm^{-1}$ similar to 1060nm (IR) laser in Silicon
- Mip calibration with Sr-90 particles not possible due to very small mip signal in 50µm thick SiC





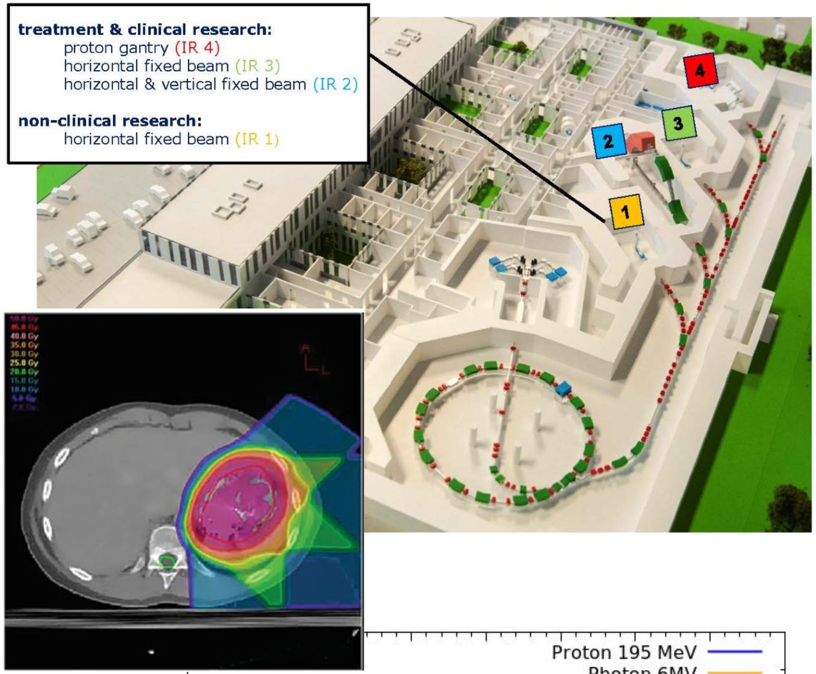
UV TCT vs. Alpha

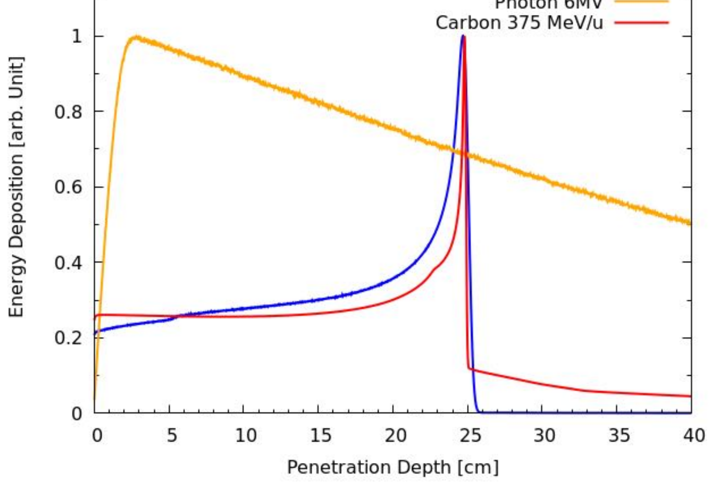


MedAustron

MedAustron: Austrian hadron cancer therapy center

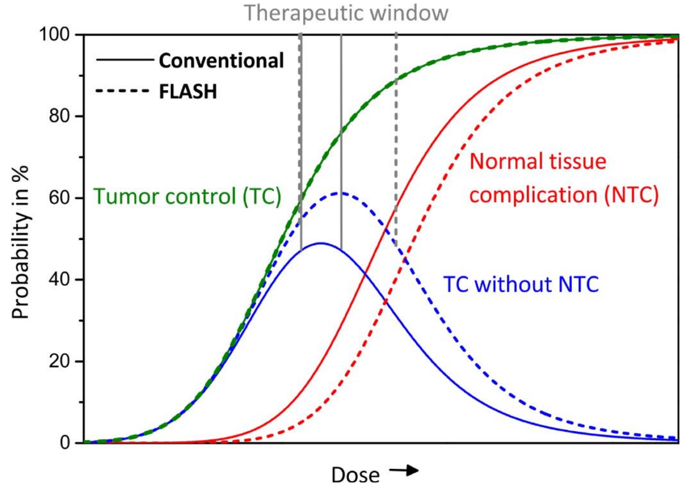
- Became operational in 2017
- Patient treatment using proton and carbon beams utilizing Bragg peak
  - Protons: 60 MeV to 252 MeV (clinical)
  - Carbon ions: 120 MeV/u to 400 MeV/u
- Dedicated non-clinical irradiation room (IR1) for research
  - Protons up to 800 MeV
- We are collaborating with MedAustron for different topics:
  - Ion-CT system and upgrades (ToF LGAD)
  - SiC-based Beam position and intensity monitor
  - FLASH radiotherapy using SiC instrumentation
  - (Micro-)dosimetry

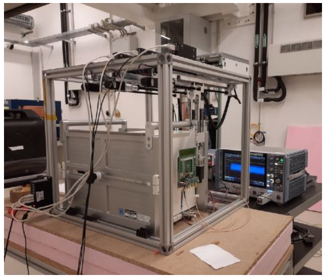


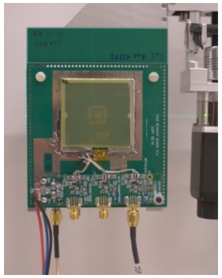


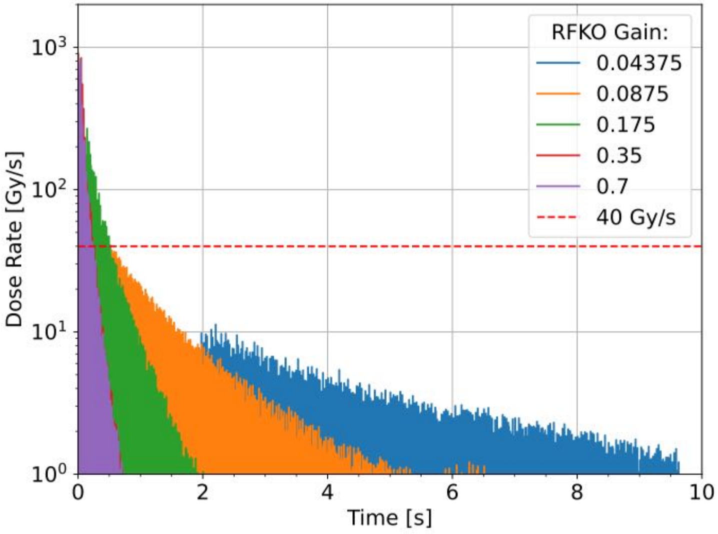
FLASH radiotherapy

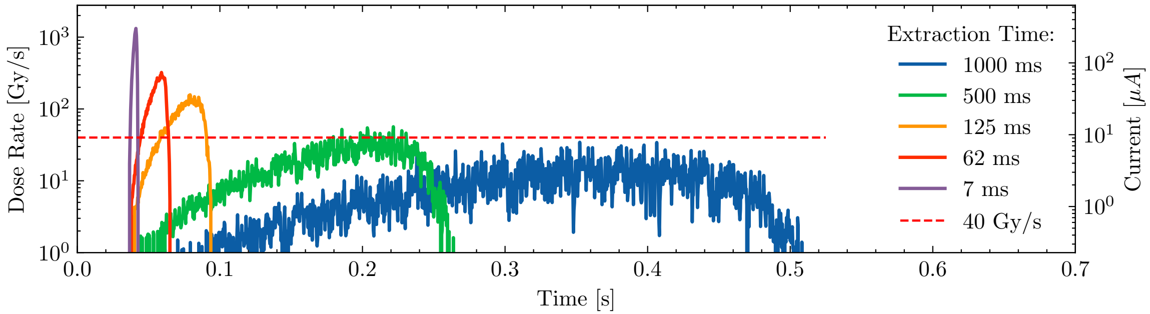
- FLASH effect: Preliminary evidence of better normal tissue sparing at high dose rates > 40 Gy s−1
- Synergies between requirements for FLASH and high energy particle physics: Time resolution and radiation hardness
- Measurements of Dose rate and beam intensity using SiC pad diodes



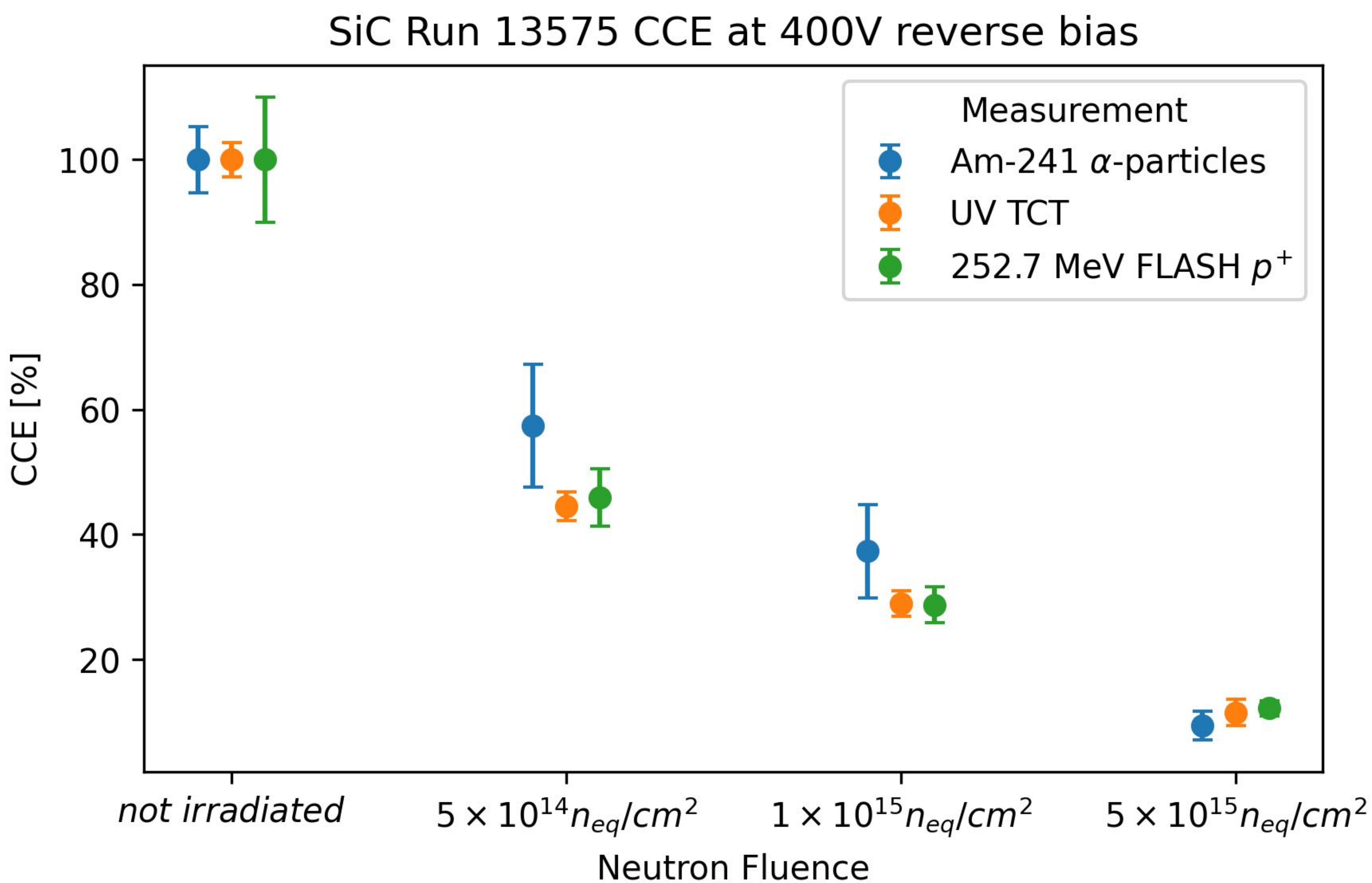






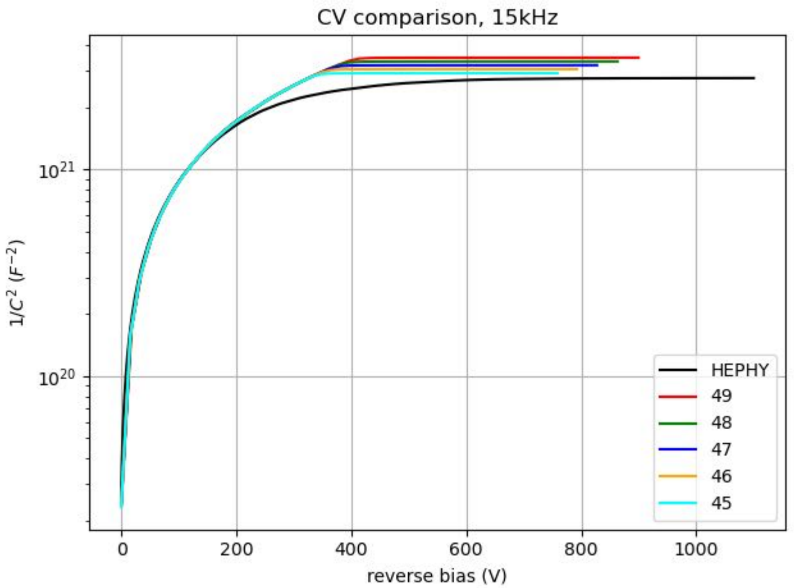


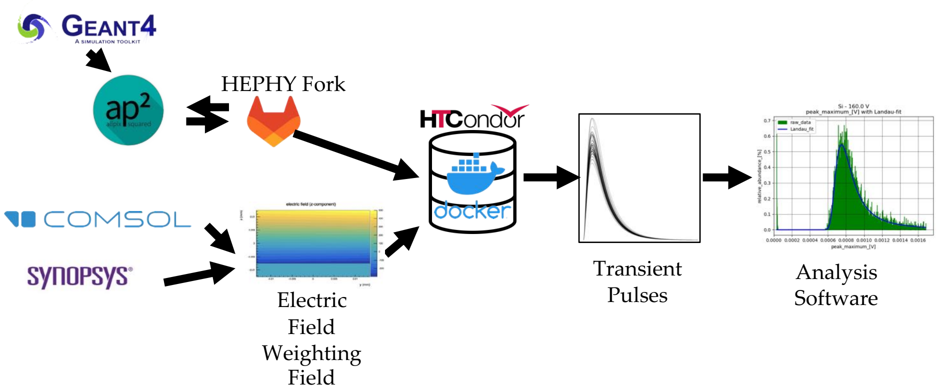
Final CCE comparison



Simulation Tools

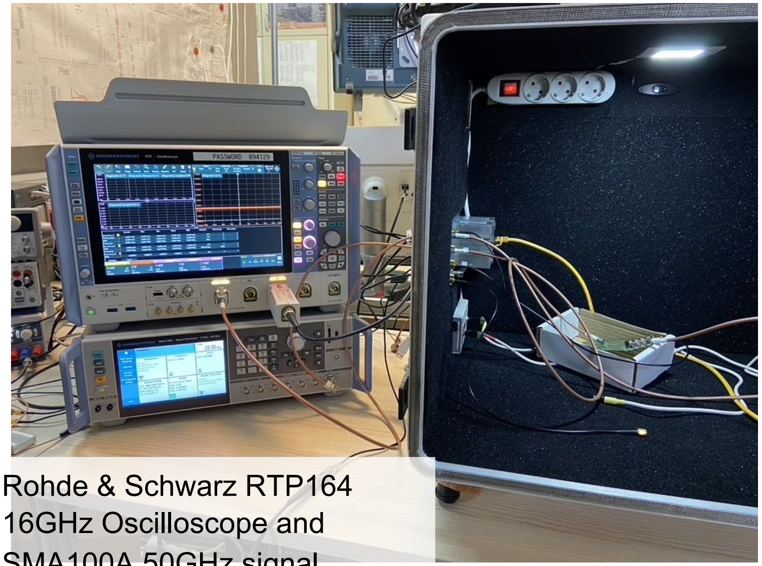
- Synopsis TCAD
  - Parameter file „Silicon“: 4000 lines, „SiliconCarbide“: 400 lines, „4HSiC“: 100 lines
  - Bandgap narrowing, Mobility, Impact ionization to be verified
  - Anisotropy taken into account
- Allpix2
  - SiC available as a detector material (since v2.3, May 2022)
  - correctly calculates the energy deposition (via Geant4) and uses material-specific ionization energies and Fano factors.
  - No SiC-specific mobility models, though
- Weightfield2
  - SiC option available, but uses Si measurements for Landau energy distribution
  - uses Si pair creation energy (3.6 eV) as SiC pair creation energy



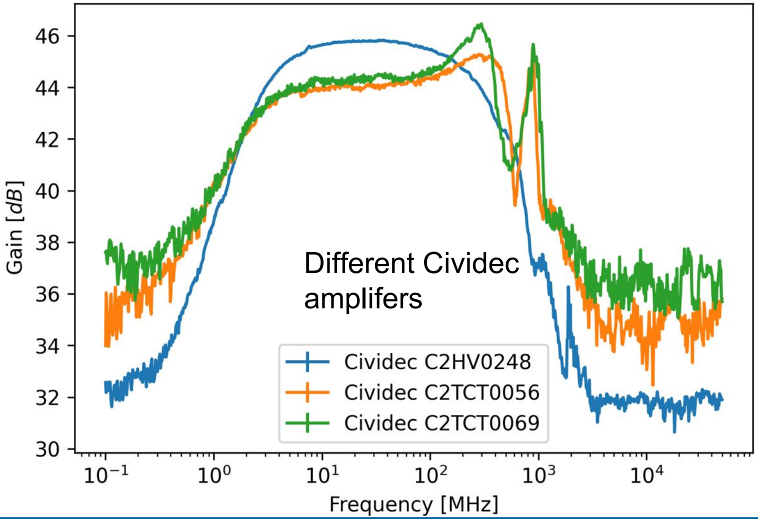


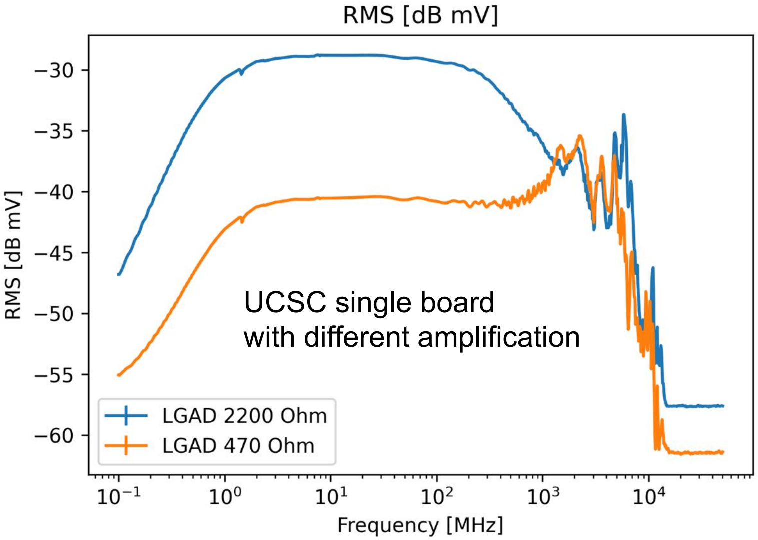
Readout electronics

- To determine mobility and other material properties by measuring detector response to Laser/particles, the whole readout chain contributes
  - Measure transfer function of various readout chains by HF network analyzer
  - Integrate this into simulation
- Electronics of readout to study:
  - UCSC single LGAD board with different amplification
  - 16-ch FNAL board
  - Cividec amplifiers



Rohde & Schwarz RTP164 16GHz Oscilloscope and SMA100A 50GHz signal generator





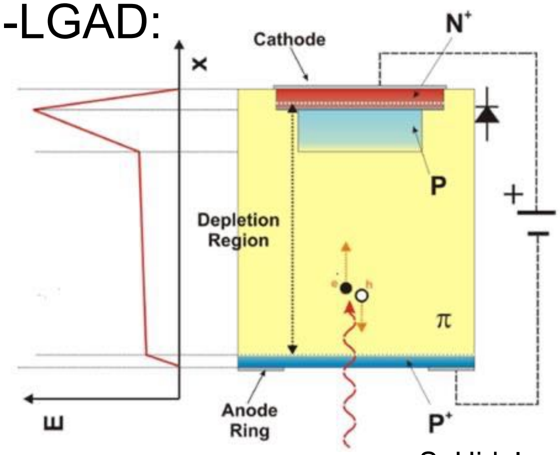
SiC-LGAD: The Idea

- Silicon carbide well suited already for
  - Spectrometric measurements of alpha radiation
  - Beam monitor for O(MeV) ions due to higher signals
- Applications in HEP
  - Signal very small due to limited thickness of epi growth process

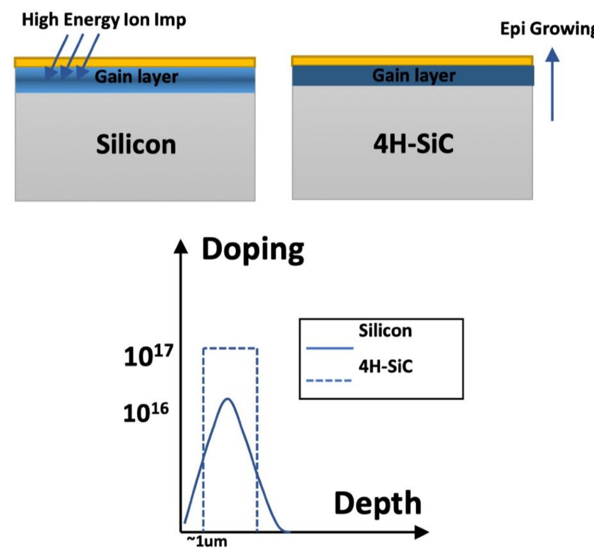
➢ **Implement a gain layer into Silicon Carbide to mitigate the small signals**

Challenges:
- Only n-type substrates available, which implies N-LGAD structure (see also Jairo's talk tomorrow on Si-N-LGAD)
- Creation of deep gain layer not achievable by "normal" ion implantation (as usually done for Si-LGAD) due to high displacement energy and thermal conductivity of SiC
- Gain layer could be implemented during epitaxial growth
  - involvement of wafer supplier necessary in formation of gain layer
  - We know that wafer supplier can grow sandwich of N-/P layers.
  - Alternative: high-energy implantation and high-energy annealing

Si-LGAD:



S. Hidalgo



Yang Tao, 39th RD50 workshop

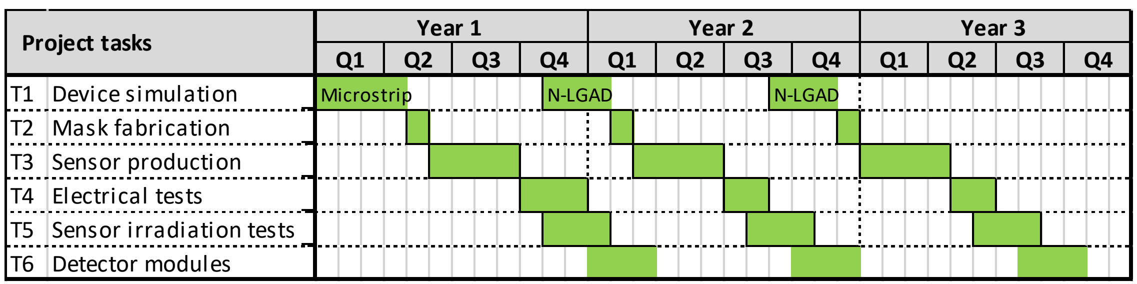
HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

RD50 common project

ÖAW

Develop of a SiC-LGAD

- Work plan
  - Test of planar samples by IV, CV, UV-TCT
  - Verification and extension of SiC models in simulation tools
  - Design and simulation of SiC-LGAD
  - Production of SiC-LGAD at CNM
  - Characterizations, Irradiations



- Participants:
  - IMB-CNM (G. Pellegrini), CERN (S. Kühn, M. Moll), INFN Perugia (F. Moscatelli), IFCA Santander (I. Vila), HEPHY (T. Bergauer)

Summary

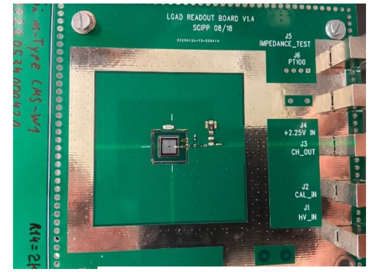
- Silicon carbide is an attractive candidate for instrumentation
  - (Micro-) dosimetry and beam position monitor for ion therapy accelerators for wide intensity range
  - HEP: vertex and tracking detector, timing
- Material needs more studies to address open topics
  - Mobility models, permittivity, conductivity, band gap, temperature dependence, recombination, ionization
  - Radiation hardness
- MIP detection needs larger signals by adding gain layer

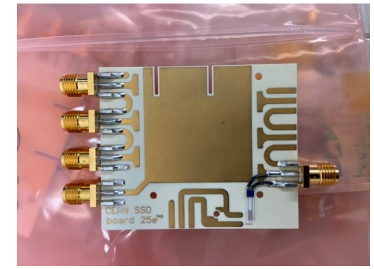
THE END

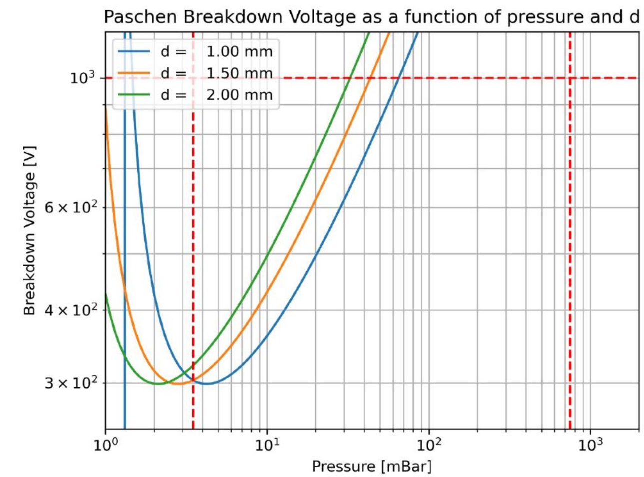
High Voltage compatibility

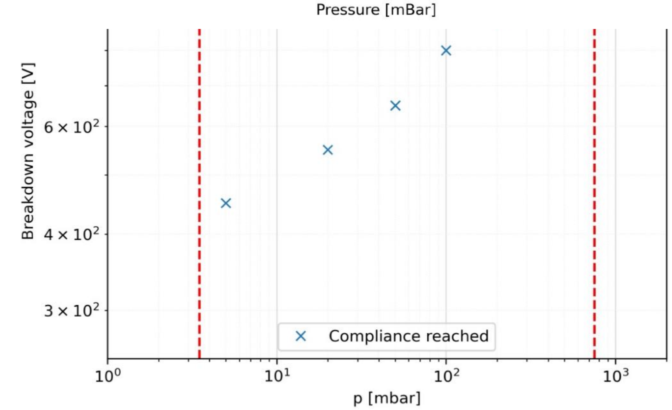
- SiC needs very high bias voltages to mitigate low mobility and take advantage of high breakdown field
  - Distances between HV and GND becomes important
- Paschen law: vacuum reduces breakdown voltage even further

$$V_b = \frac{Bpd}{\ln[Apd/\ln(1+1/\gamma)]}$$





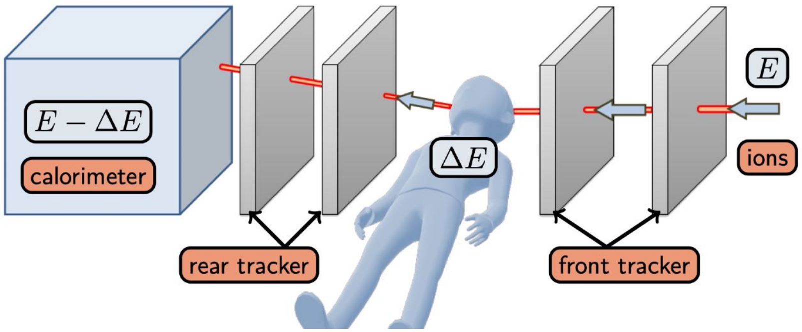


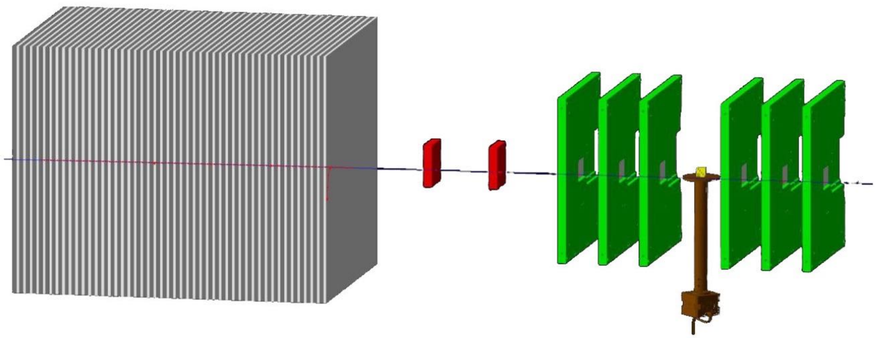


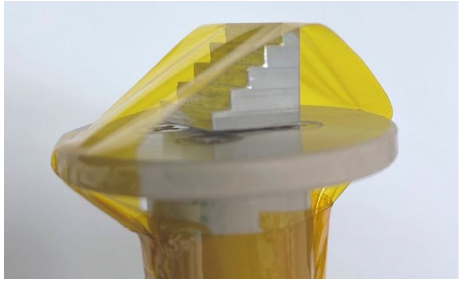
Ion Imaging at MedAustron

"Ion CT" by measuring stopping power in object per voxel needs

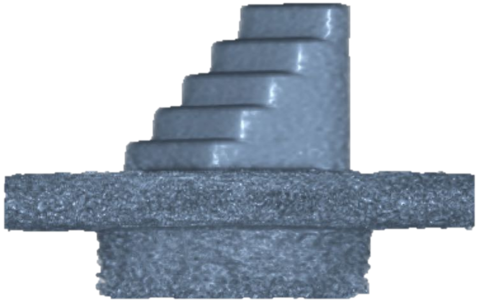
- Tracker (similar beam telescope)
  - DSSDs → **DMAPS**
- Calorimeter to measure residual energy
  - Sandwich calo using scintillator planes and SiPM readout → **LGAD ToF**
- Image Reconstruction
  - Geant4, GATE, TIGRE@GPU,..



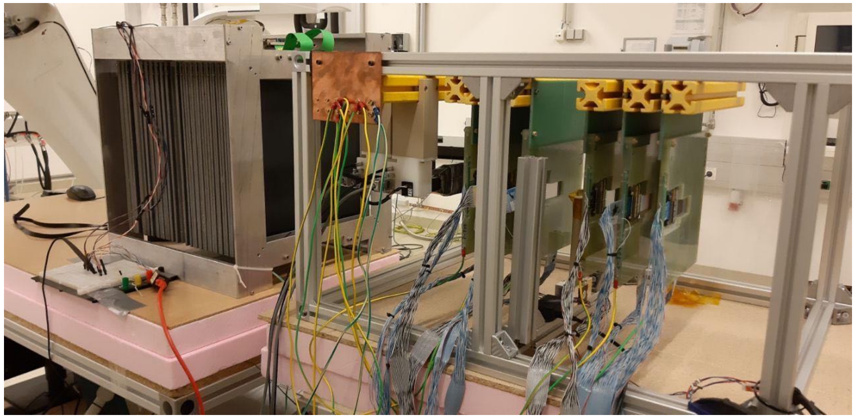




Phantom



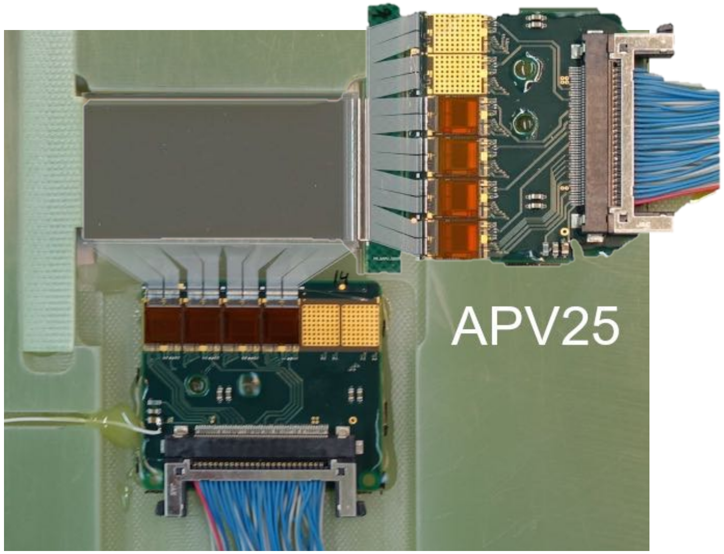
Reconstructed image



Ion Imaging Tracker

Currently using Double-sided strip sensors and FADC readout very similar to Belle-II SVD

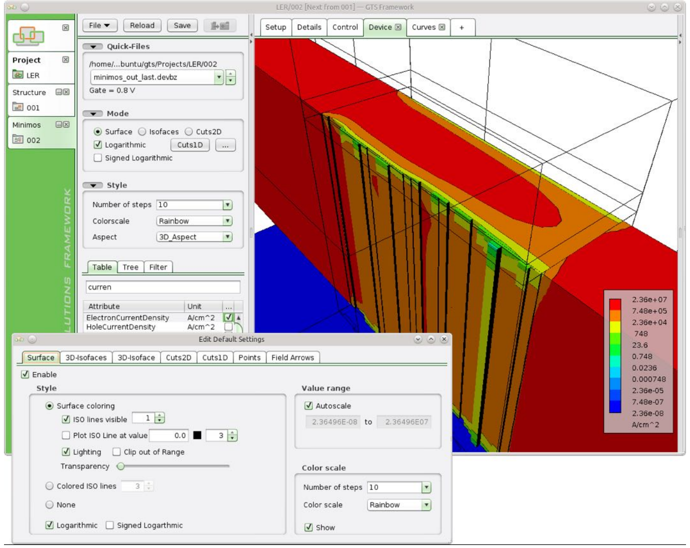
- Sensors:
  - Size: (2.56 × 5.12) cm^2
  - Thickness: 300 µm
  - Pitch 50 / 100 µm (Strips: 512)
- DAQ:
  - Readout chain APV → FADC → VME
  - Max. event rate: 500Hz
    → 90 minutes to record one image with 1E6 tracks
    → 11 days for full iCT 3D reconstruction (many images under different angles)
  - Planned short-term upgrade: Gbit Ethernet instead of VME readout to increase speed (will also implemented into SVD for speeding up local runs)



- Particle rates for clinical use (10^9 particles/s) are too high for both
  - detectors (ghost, pile-up) and
  - readout (trigger rate max 100kHz)

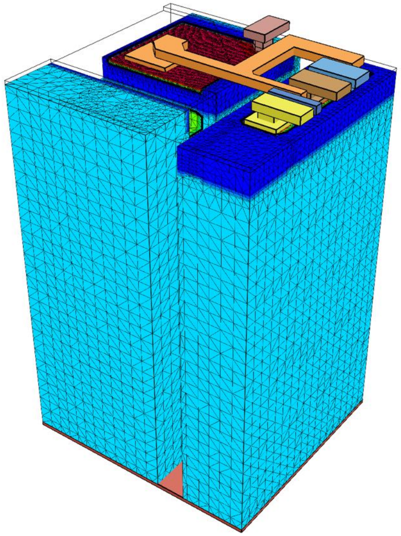
Global TCAD Solutions

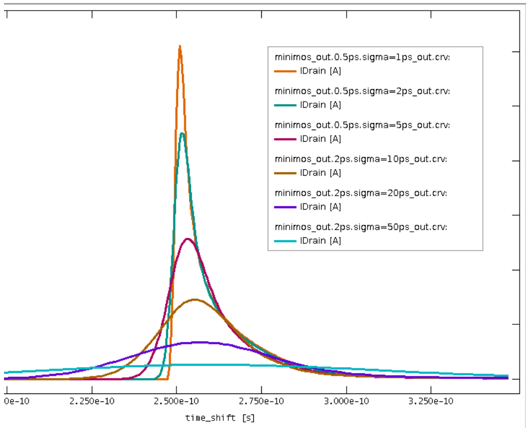
- Silicon carbide is not (yet) modeled correctly in standard TCAD simulation tools
- We want to address this by
  - TCAD Simulation of particle passage in SiC
  - SiC Radiation damage model
  - Validation against Synopsis, Allpix^2, Weightfield2
  - Validation with real measurements (IV,CV, TCT, proton beam)



- Joint project between HEPHY and GTS*)

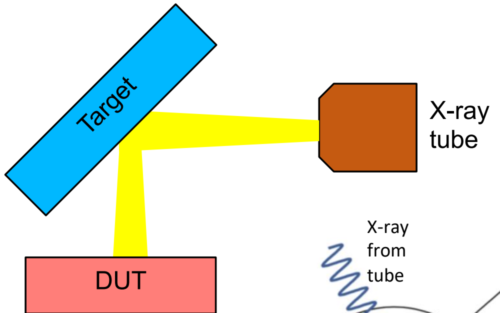
  *) Global TCAD Solutions GmbH (GTS)
  - European EDA / TCAD provider
  - founded in 2008 as a spin-off company of the TU Wien, located in Vienna

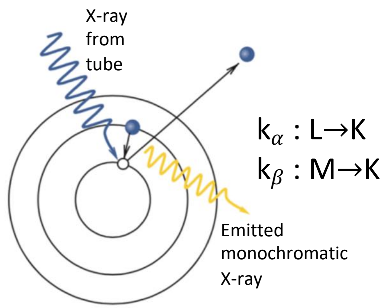


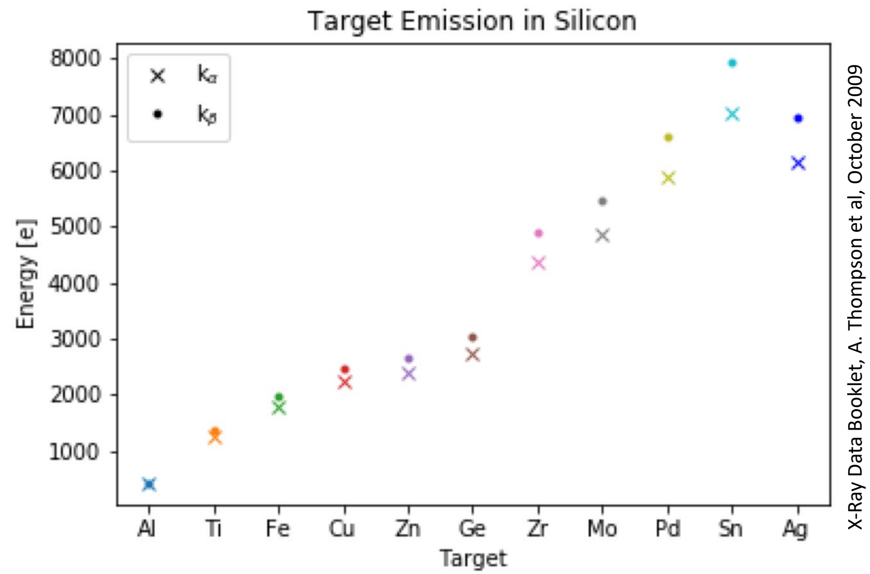


X-Ray Fluorescence

- Method to calibrate and study the linearity of response of new pixel modules in the lab
- Allows measurement of charge spectra and energy resolution







- **Targets:** Aluminum (Al), Titanium (Ti), Iron (Fe), Copper (Cu), Zinc (Zn), Germanium (Ge), Zirconium (Zr), Molybdenum (Mo), Palladium (Pd) and Tin (Sn)
- Amptek Mini-X2 X-ray tube (50kV, 200 μA, 4W, Ag)

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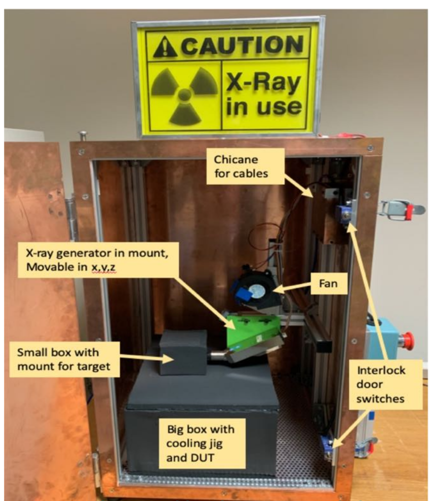

Sascha Dungs/Susanne Kühn

https://indico.cern.ch/event/861434/contributions/3628840/subcontributions/292230/attachments/2131493/3589795/2020-10-28_gentner_talk.pdf