Silicon Carbide for Beam Monitoring and Ion FLASH Beams

Andreas Gsponer[a], Simon Waid[a], Elisabeth Renner[b], Claus Schmitzer[c]
Philipp Gaggl[a], Jürgen Burin[a], Sebastian Onder[a] and Thomas Bergauer[a]

andreas.gsponer@oeaw.ac.at

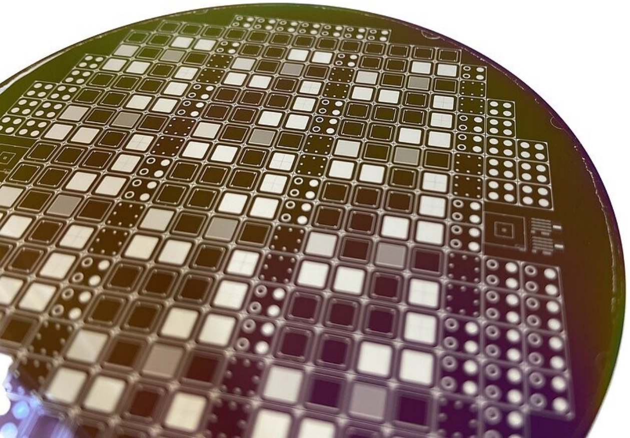
[a] Institute of High Energy Physics of the Austrian Academy of Sciences
[b] Atominstitut, Technische Universität Wien
[c] EBG MedAustron GmbH

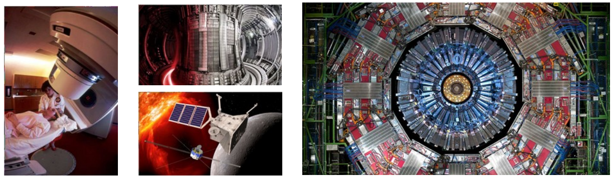
Silicon Carbide (SiC)

(4H)-Silicon Carbide is a wide bandgap semiconductor with many advantages:

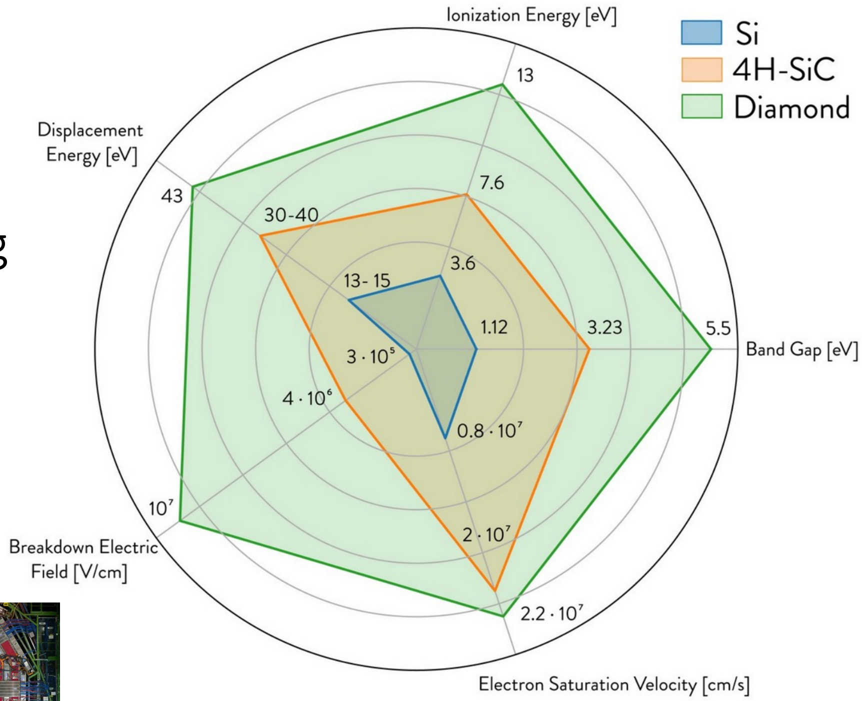
- insensitive to visible light
- extremely low leakage currents (< 1 pA/mm²)
- Ability to work at high temperatures (> 600 °C)
- Higher breakdown field and drift velocity → better timing

Drawbacks : Lower signal than Si, limitations on thickness





SiC Applications



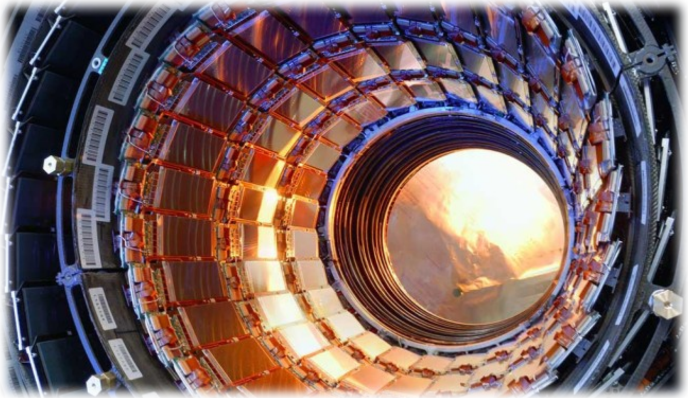
SiC Research at HEPHY

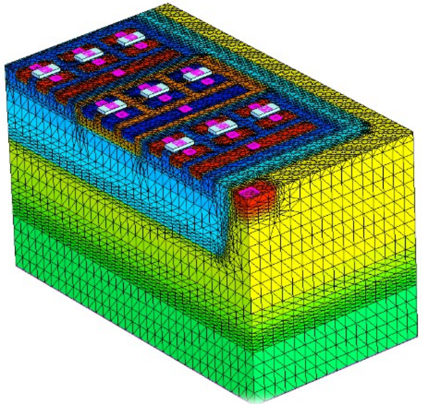
- SiC research ongoing at HEPHY since 2021
- Project together with MedAustron aiming to build a beam monitor,
  - based on SiC Strip detectors,
  - with a wide dynamic range : single particles to medical intensity

High Energy Physics
Timing, Radiation Hardness Studies

Medical Applications
Beam Monitoring, FLASH
Ion imaging (in the future)

Simulations
TCAD, Material Parameters
Design of novel detectors





FLASH RT with Ions

- Still not a lot of (pre-) clinical studies with p^+ FLASH beams (however, commercial availability of FLASH systems has increased a lot!)
- Carbon / helium beams only available at a few research / treatment centers

Take the first step and contribute to the implementation of FLASH beams at MedAustron

Extraction + **Instrumentation**

Elisabeth Renner (TU Wien)
Claus Schmitzer (MedAustron)

CONV-RT

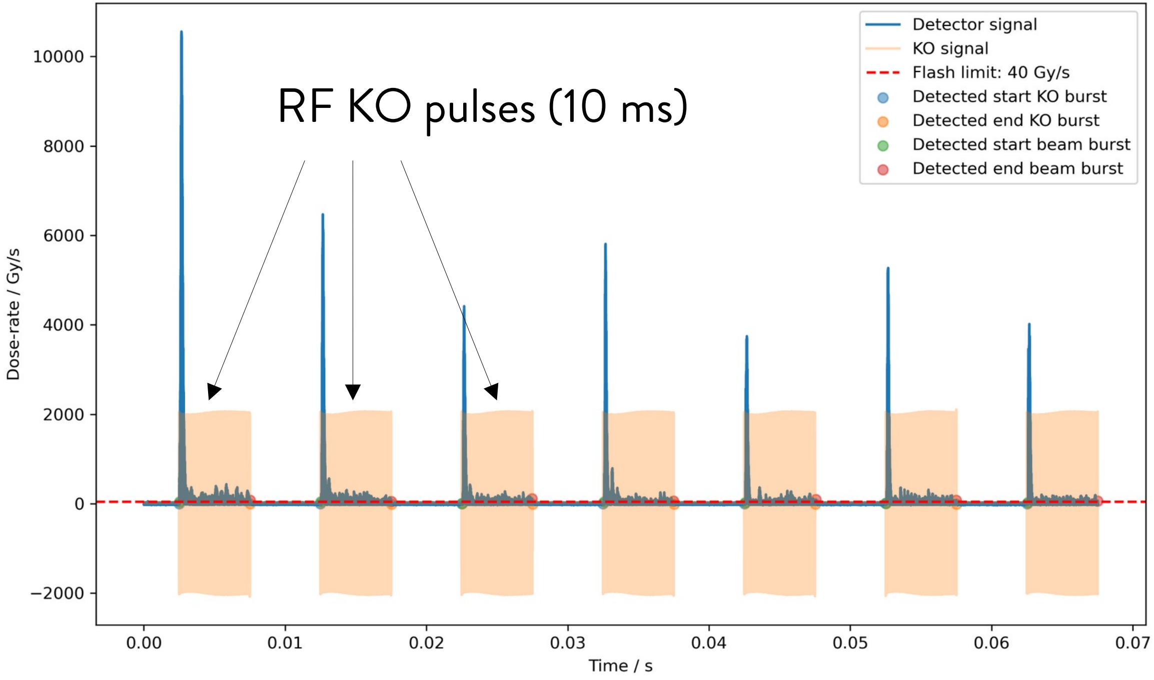
FLASH-RT

FLASH Extraction

Many ways to extract a beam quickly:
- RF KO, PDE, COSE

Shown today : RF KO
- Horizontal excitation of beam, extracted by electrostatic septum
- Can be modulated: amplitude, phase, frequency
- Works very quickly (~ MHz)

We are using *pulsed* RF KO



ÖAW AUSTRIAN ACADEMY OF SCIENCES

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

Why pulsed RF KO?

- Medical Device safety (*IEC 60601-2-64*): need to terminate irradiation in <0.25 Gy
- Single FLASH pulse (SPLASH) hard to implement safely

PAPER

10.1088/1361-6560/ad5072

Pulsed RF knock-out extraction: a potential enabler for FLASH hadrontherapy in the Bragg peak

Simon Waid[1], Andreas Gsponer[1,2,*], Elisabeth Renner[2], Claus Schmitzer[3], Florian Kühteubl[2], Clara Becker[2], Jürgen Burin[1], Philipp Gaggl[1], Dale Prokopovich[3] and Thomas Bergauer[1]

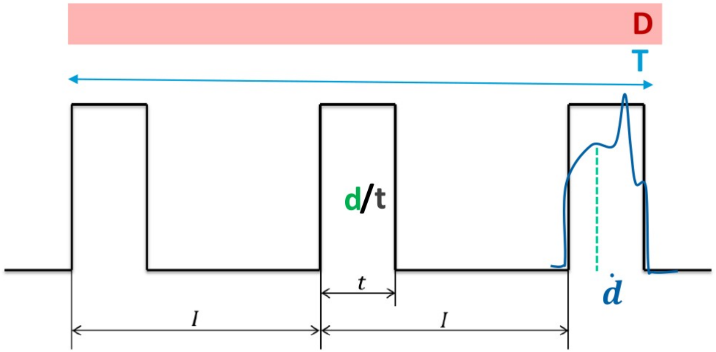
1 Austrian Academy of Sciences, Institute for High Energy Physics, Vienna, Austria
2 Technische Universität Wien, Vienna, Austria
3 MedAustron GmbH, Wiener Neustadt, Austria
* Author to whom any correspondence should be addressed.

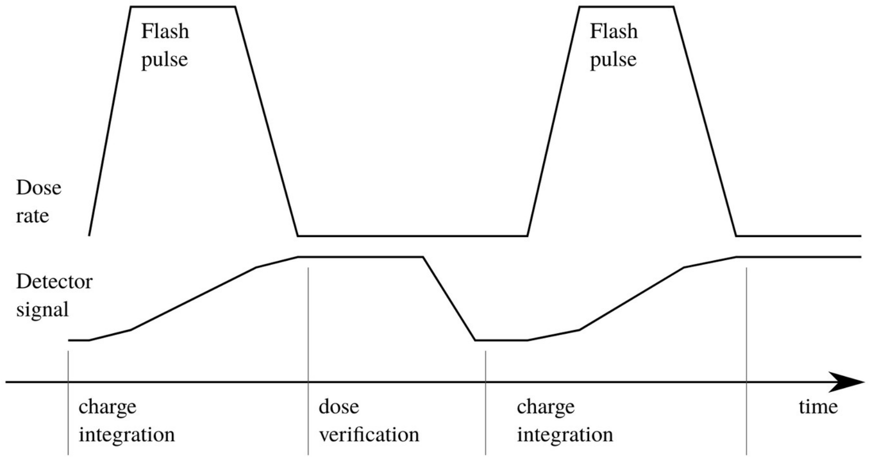
E-mail: andreas.gsponer@oeaw.ac.at

Keywords: RFKO, FLASH, Hadrontherapy, Bragg-Peak

Customized beams for systematic FLASH studies:

- pulse length
- pulse separation
- dose per pulse

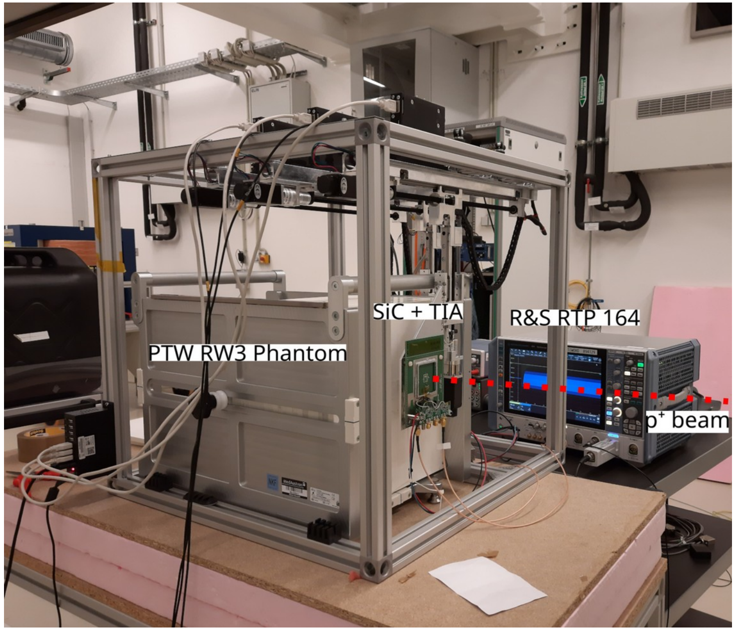


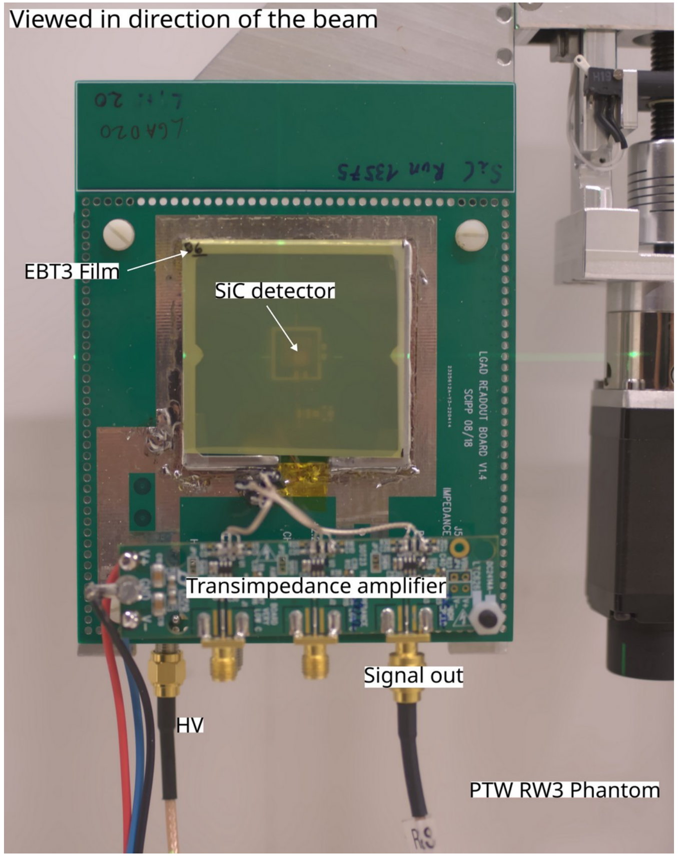


MedAustron TU WIEN

SiC Intensity Monitor

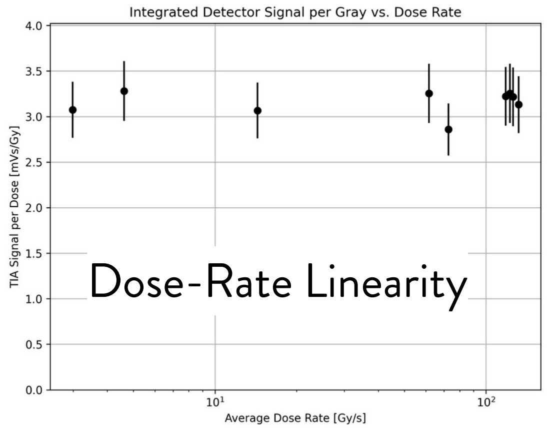
- 3x3 mm^2 SiC diode with 50 um thickness
- DC-coupled to transimpedance amplifier (Signal ∝ dose rate) with 20 MHz bandwidth
- EBT3 films (IC and Bragg peak) for dose calibration

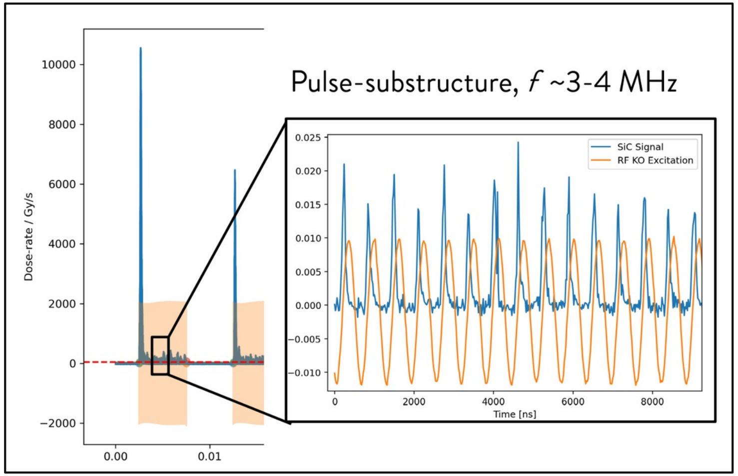




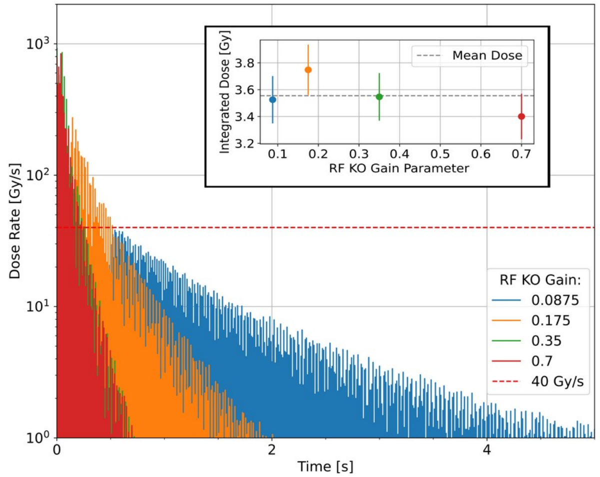
Selected RF KO FLASH Results

- Average dose rates of about 1 kGy/s can be reached (instantenous dose even rate higher)
- Extremely good temporal resolution of beam intensity monitor (can observe individual RF KO cycle with 20 MHz bandwidth)
- No dose-rate dependencies / saturation observed for SiC detector

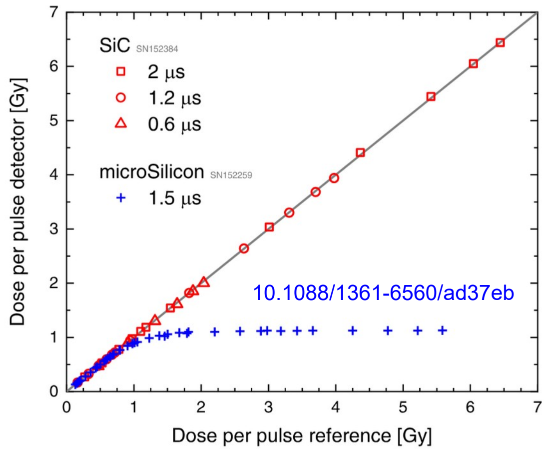




Temporal resolution of beam intensity monitor



Non-pulsed RF KO extraction



Flexibility of RF KO

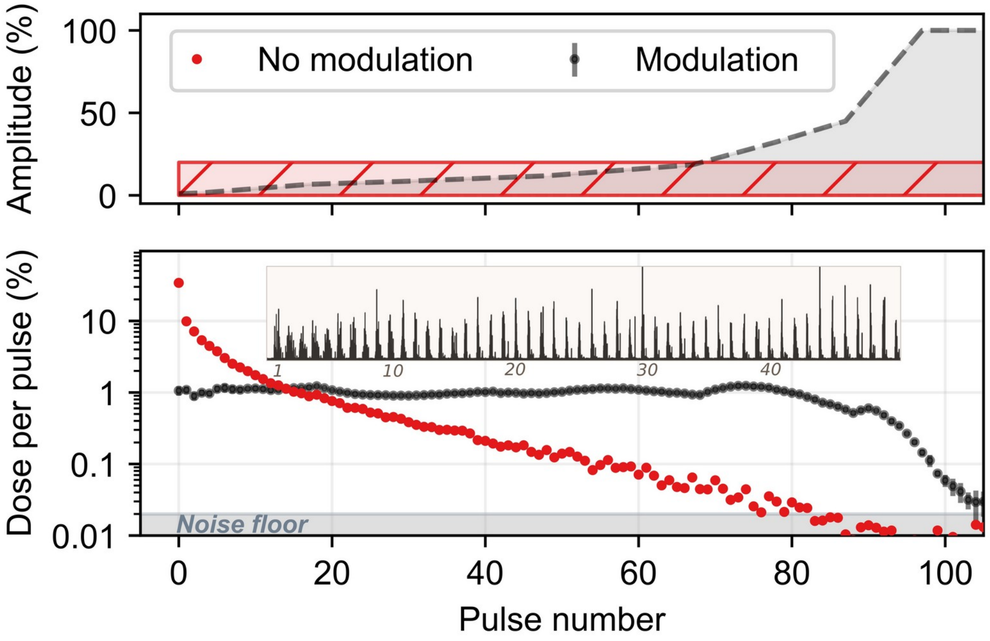
- Pulse frequency: 250 Hz - 10 kHz
- Duty cycle : 10-90%
- Random pulse-to-pulse spacing

Turn-off-dose is below 1 mGy

Amplitude modulation :

- ~80 RF KO pulses with uniform amplitude can be obtained

For biological / pre-clinical studies:
Combine everything into a prototype FLASH dose-delivery system



ÖAW AUSTRIAN ACADEMY OF SCIENCES

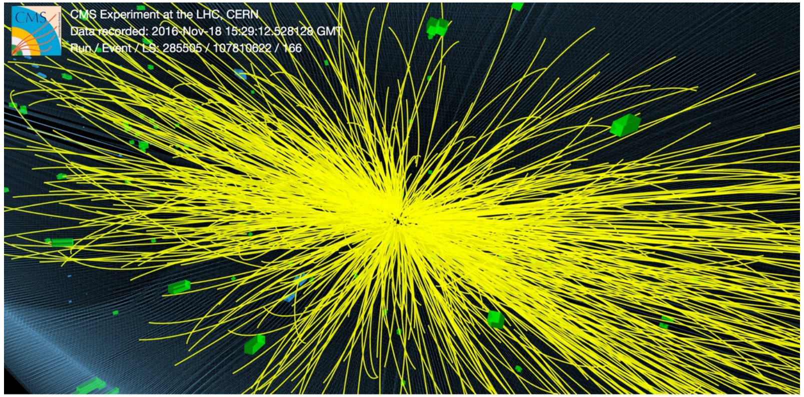
Silicon Carbide Timing Detectors

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

- Large effort in HEP towards fast and radiation hard timing detectors $\mathcal{O}(< 30\text{-}50 \text{ ps})$
- Application in ion imaging (ToF-iCT)

- SiC: fast drift velocity → faster signals
- Need low-gain avalanche diodes (LGADs) to obtain sufficient SNR

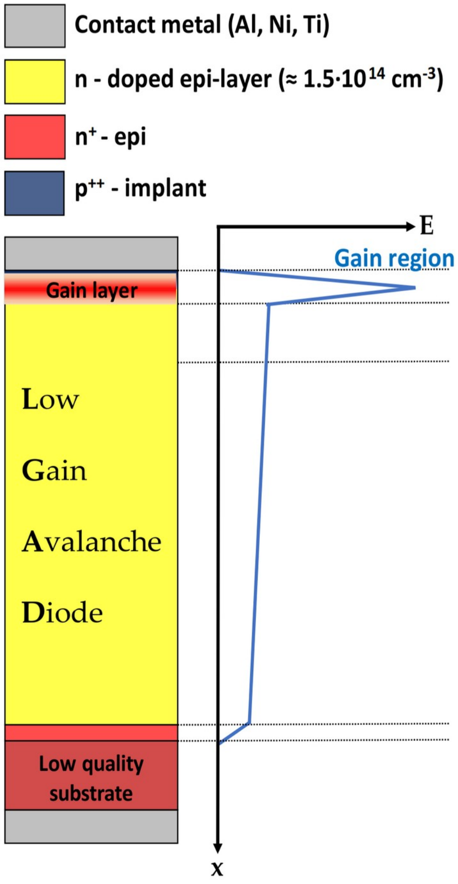
- SiC-LGADs might surpass Si-LGADs



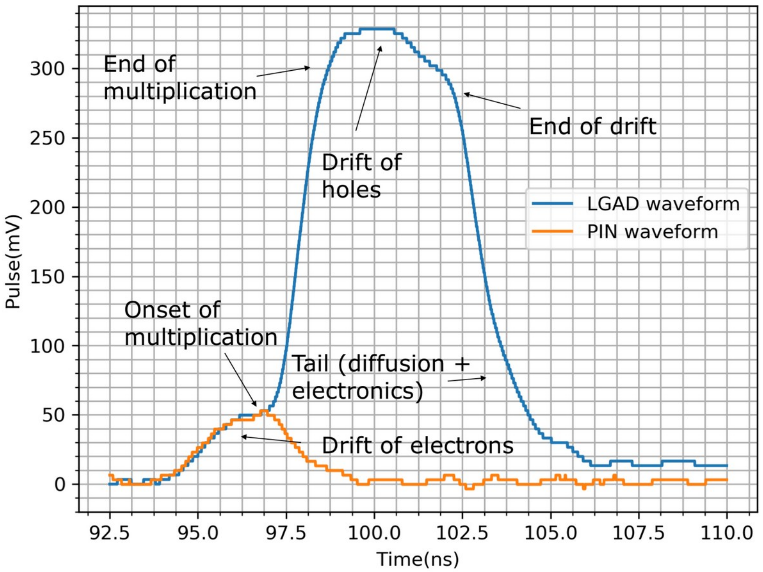
High multiplicity event in CMS

$$\sigma_{\text{Jitter}} \approx \frac{t_{\text{r}}}{S/N}$$

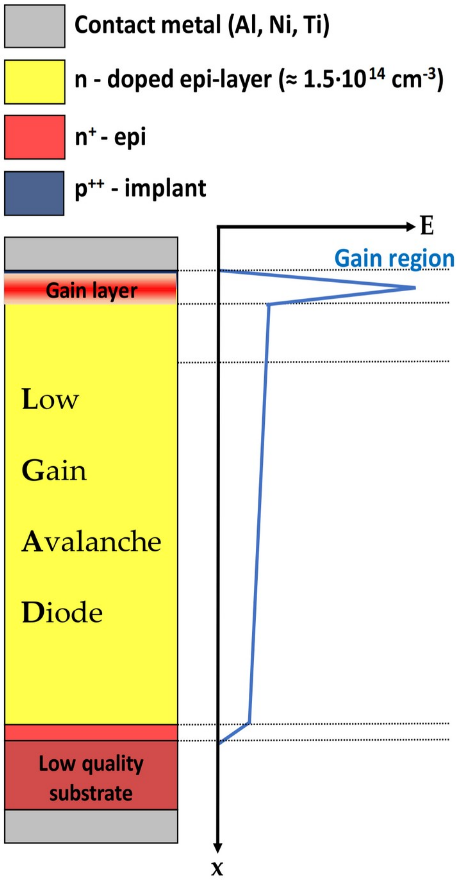
Silicon Carbide LGADs



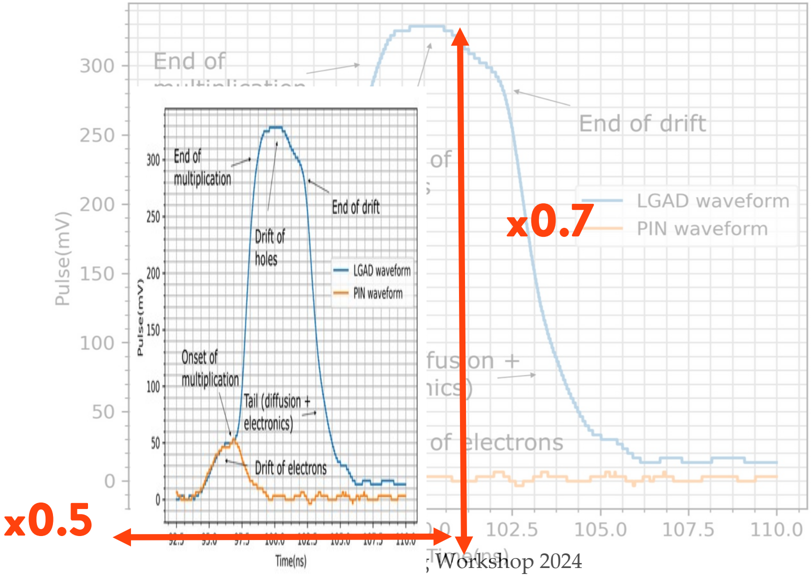
- LGAD maximal signal when all charge carriers have drifted to the gain layer (where they multiply)
- Worse risetime than planar sensors, but much better SNR



Silicon Carbide LGADs



- LGAD maximal signal when all charge carriers have drifted to the gain layer (where they multiply)
- Worse risetime than planar sensors, but much better SNR

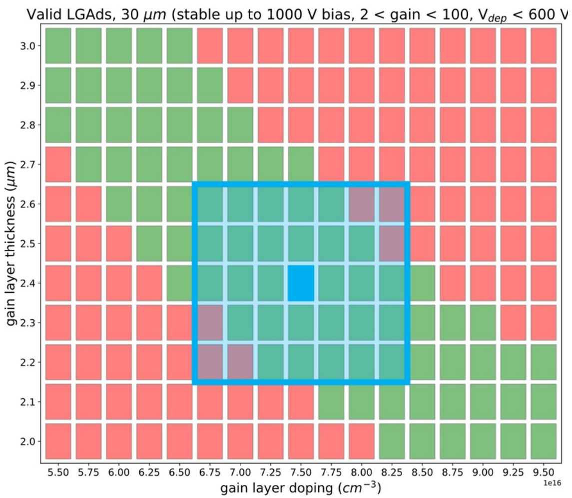


For SiC:

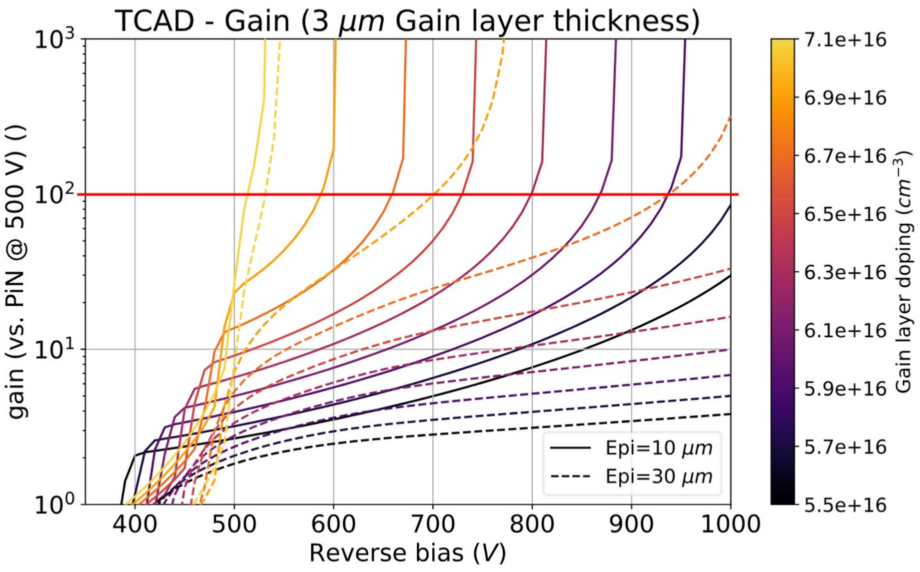
- ~ 30% smaller signals
- **But ~twice as fast**

SiC-LGAD Production

- Gain layer needs to be epitaxially grown, can not be implanted
- Ongoing project in the CERN RD50 (now DRD3) collaboration
- 10 6-inch wafers gain layer, wafer design by HEPHY
- Processing to start early 2025



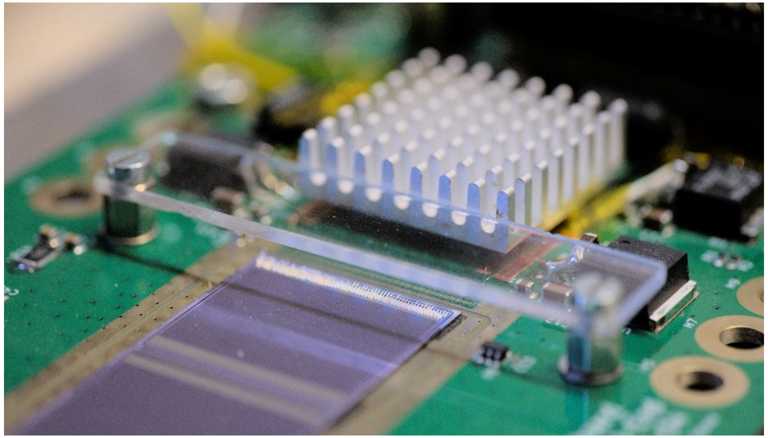
Gain layer doping study

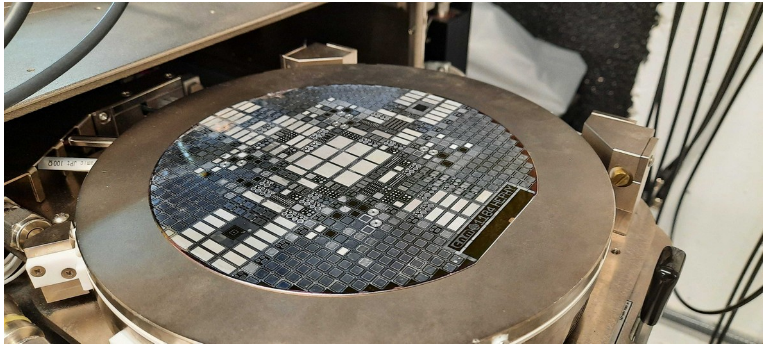


Projected performance for different gain layer concentrations

Future Plans

- Continue work on FLASH beams
- Study of SiC material parameters
- Beam monitor based on SiC strip detectors and COTS (FLASH compatible in the future!)
- SiC LGADs for timing / ToF
- SiC-MAPS in Fraunhofer SiC-CMOS process





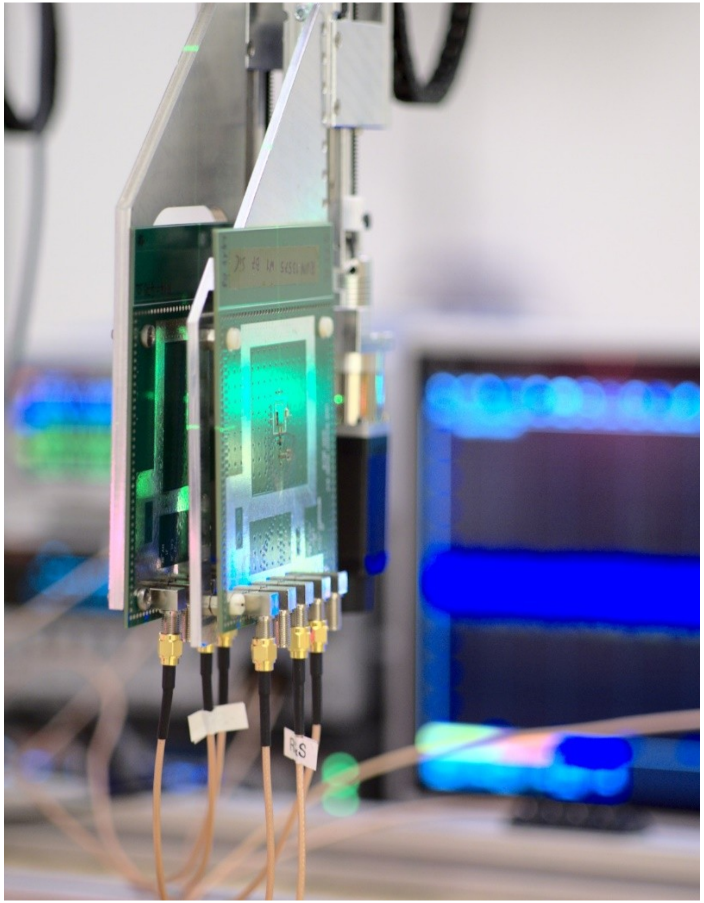
This work was supported by the Austrian research promotion agency FFG, project number 883652. The financial support of the Austrian Ministry of Education, Science and Research is gratefully acknowledged for providing beam time and research infrastructure at MedAustron.

APPENDIX

ÖAW AUSTRIAN ACADEMY OF SCIENCES

HEPHY SiC Timeline

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS



2021

- First SiC Samples from CNM run 13575
  2 Master Theses, Strip Sensor Measurements: 10.1088/1748-0221/17/01/C01060
- Start of FFG funded Project “HiBPM”
  2 PhDs and 1 Postdoc full-time on SiC

2022

- Neutron irradiation at ATI Vienna, CCE Characterization with UV-TCT / Alphas
  10.1016/j.nima.2022.167218, 10.1088/1748-0221/18/01/C01042, 10.1088/1748-0221/18/11/C11027
- Medical applications (ion therapy): Beam monitoring / FLASH dosimetry
  10.1088/1748-0221/19/04/C04055, 10.1088/1748-0221/19/04/C04055, 10.1007/s00502-023-01201-w
- TCAD simulations for unirradiated sensors

2023

- Start of RD50 SiC-LGAD common project
- Measurement of electron-hole pair creation energy 10.1016/j.nima.2024.169412
- Planar SiC run designed and submitted

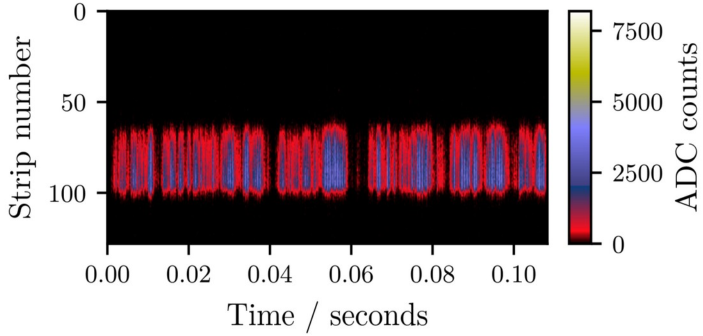
2024

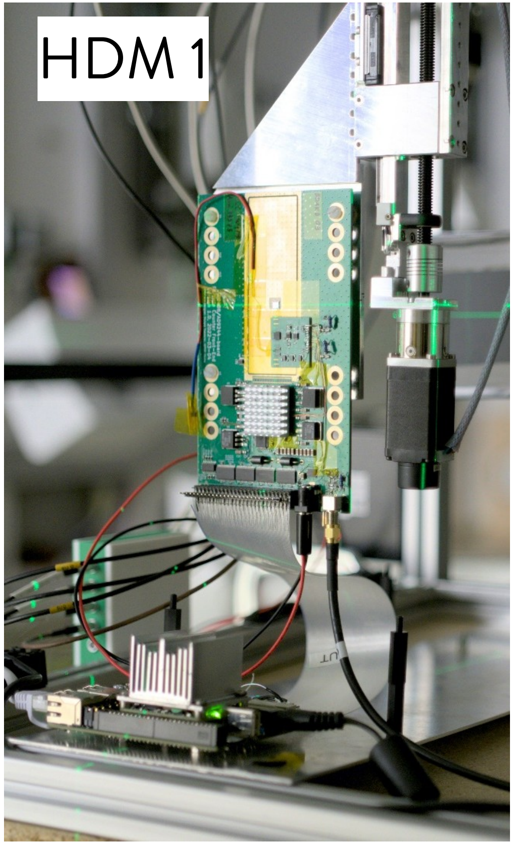
- Characterization of first planar run (CNM 16886 and 17407) DRD3
- TCAD model describing radiation damage in 4H-SiC arXiv:2407.11776, arXiv:2407.16710
- SiC-LGAD design and layout

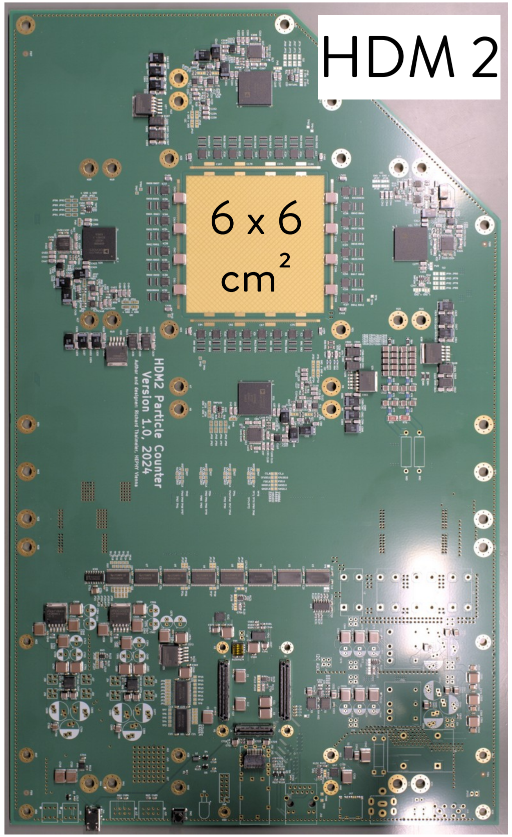
HiBPM Beam Monitor (HDM)

- Based on Analog Devices AD8488 (x-ray frontend chip) (off-the-shelf)
- 128 channels per IC, read-out at 37 kHz
- HDM1 : Prototype with 128 channels
- HDM2 : Demonstrator with 4 ICs, covering 6x6 cm^2 using daisy-chained SiC strip detectors
- Future FLASH compability: tunable gain / **attenuation** for each channel

X-profile of beam vs. time

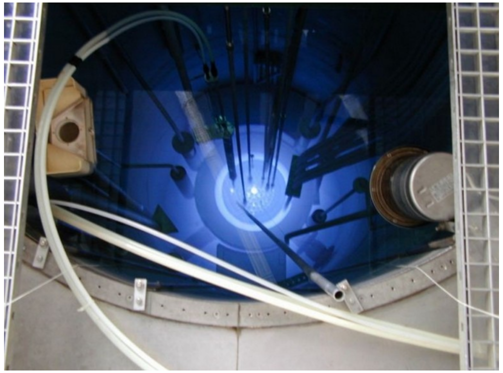


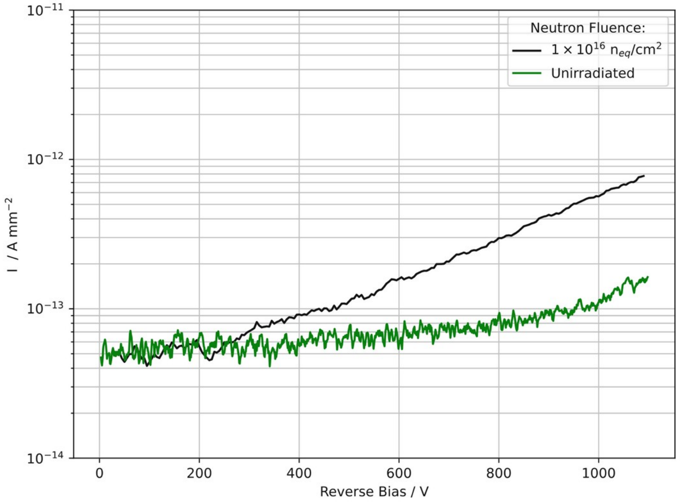


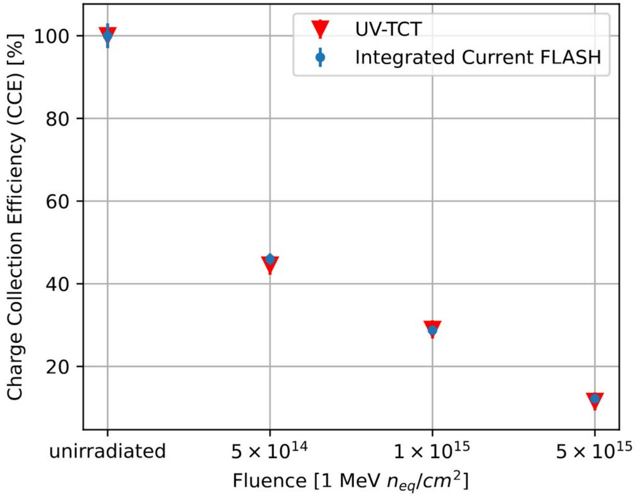


SiC Radiation Hardness

- Irradiation at TRIGA MK II reactor at ATI Vienna
- Fluences up to 1 x 10^{16} n_{eq}/cm^2, $\mathcal{O}$(CMS inner layers)
- Almost no increase in leakage current (still < 1 pA/mm^2)
- Reduction in charge collection efficiency





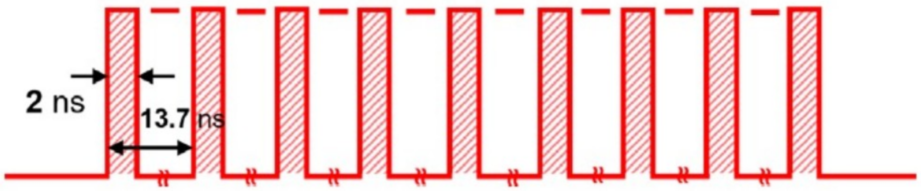


UHDR Pulses

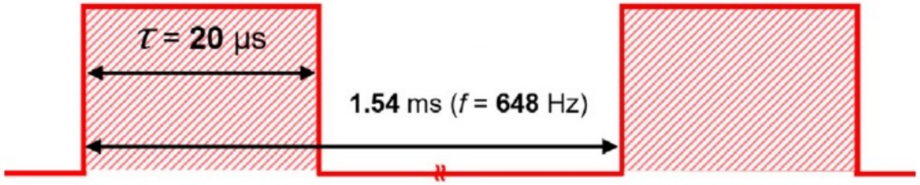
protons

$\dot{d}$ < 500 Gy/s

Isochronous cyclotron (quasi-continuous radiation)
(f=**72.8** MHz, **2nd** Harmonic)



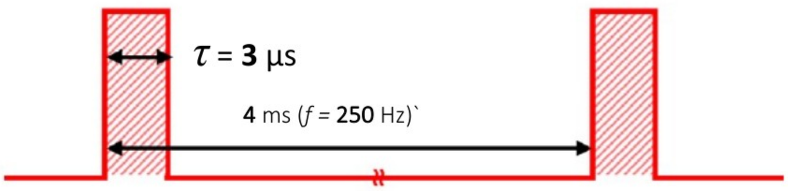
Synchrocyclotron (FLASH dose rate) $\dot{d}$ < 10 kGy/s



electrons

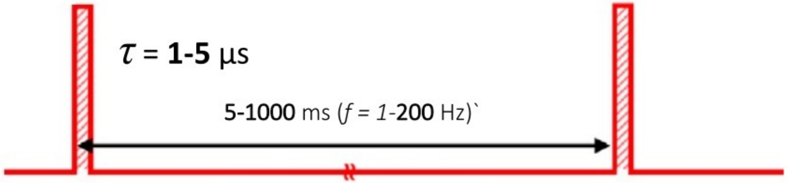
$\dot{d}$ < 100 kGy/s

Clinical LINAC for Radiotherapy (modified)



$\dot{d}$ < 5 MGy/s

Research LINAC for pre-clinical studies



F. Romano *et al*. Med. Phys. (2022)