Radiation-Hard Silicon Carbide Dosimeters for Electron and Proton FLASH QA

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3 Institut Curie
4 Universidade de Santiago de Compostela

Outline

- Introduction: FLASH radiotherapy
- Devices fabricated at IMB-CNM
- Dosimetry in UHDR beams
  - Electrons
  - Protons
  - Radiation hardness tests
  - Spatially resolved dosimetry
- Conclusions

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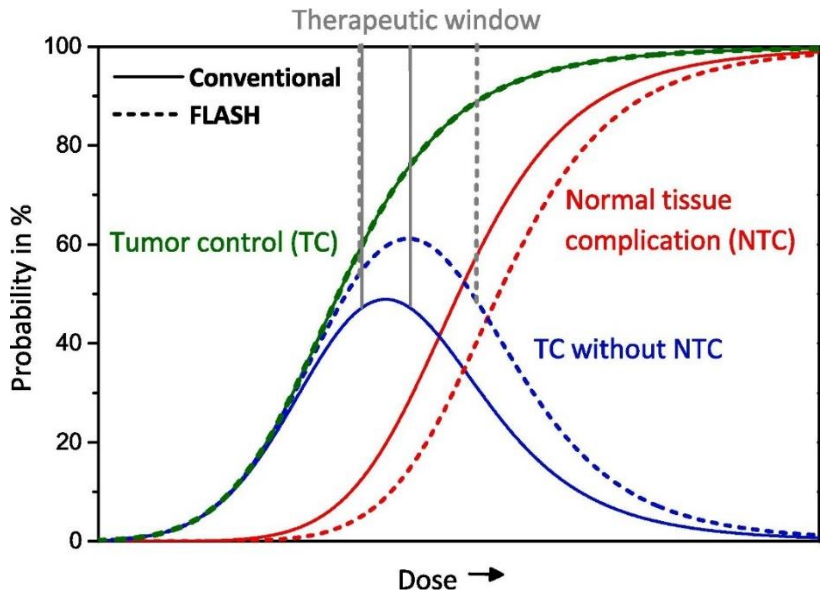
Motivation: UHDR radiotherapy

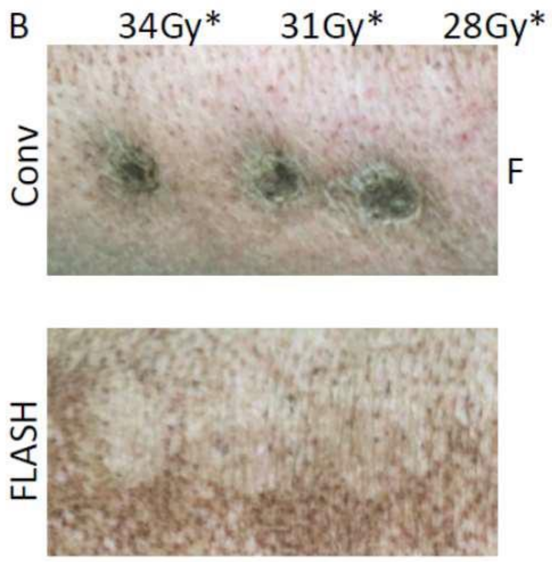
FLASH effect *(Favaudon et al., Sci Transl Med 6 (2014))*:

Irradiations with **Ultra-High Dose Rate (UHDR) pulsed radiation** reduce adverse effects in healthy tissues

FLASH dose rate ≥ 40 Gy/s (conventional radiotherapy ≈ 0.05 Gy/s)

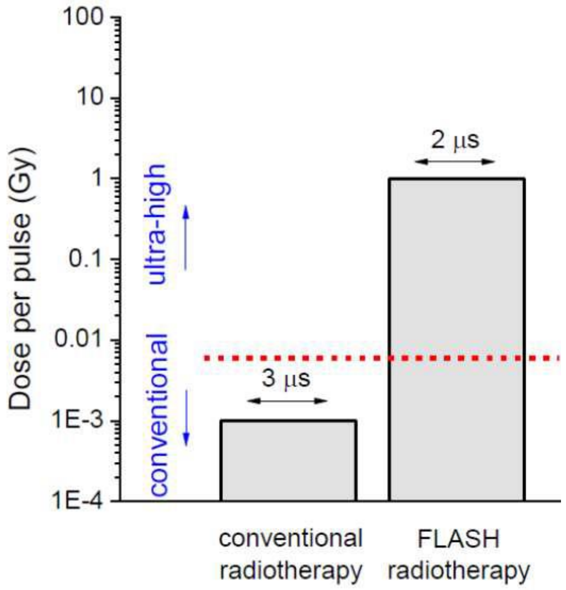


Schüller et al., Physica Medica 80 (2020)



Vozenin et al., Clin Cancer Res 25 (2019)

Motivation: UHDR radiotherapy



w	pulse width	[0.5 – 2.2] µs
f	pulse repetition frequency	[10 – 200] Hz
D^*_p	dose-rate in pulse	$[10^3 - 5 \cdot 10^6]$ Gy/s
$D_p = D^*_p \cdot w$	dose per pulse	$[10^{-3} - 5]$ Gy
$D^*_m = D^*_p \cdot w \cdot f$	mean dose-rate	$[10^{-2} - 1000]$ Gy/s

1 Gy in water of 160 MeV protons ≈ **1E9 p/cm2** per pulse of ~1µs

(dose = fluence × mass stopping power)

- Saturation of conventional active dosimeters (gas and silicon)
- Need real-time, precise, radiation hard dosimeters: **SiC**

Why SiC?

	Silicon	4H-SiC	CVD diamond
Band gap [eV]	1.12	3.23	5.5
Ionization energy [eV/e-h]	3.6	7.6 – 8.4	13.6
Atomic displacement threshold [eV]	13-15	30 – 40	43
Density [g/cm3]	2.33	3.22	3.52
Electron mobility [cm2/Vs]	1450	800 – 900	1700
Hole mobility [cm2/Vs]	450	115	2100
Electr. sat. velocity [1E7 cm/s]	1	2.2	2.7
Breakdown field [MV/cm]	0.3	3 – 4	10
Thermal conductivity [W/cmK]	1.5	5	20
Yield [fC/MeV]	44.4	21.0	11.8
Sensitivity [pC/mGy/mm3]	644	425	259
Wafer cost	O(<100€)	O(1,000€)	O(100,000€)*

- Wide bandgap energy
  - Not affected by T variations
  - Low leakage current
  - Transparent to visible light
- High atomic displacement threshold energy
  - Radiation hardness
- High saturation velocity and breakdown field
  - Timing
- **Good price-to-performance ratio**

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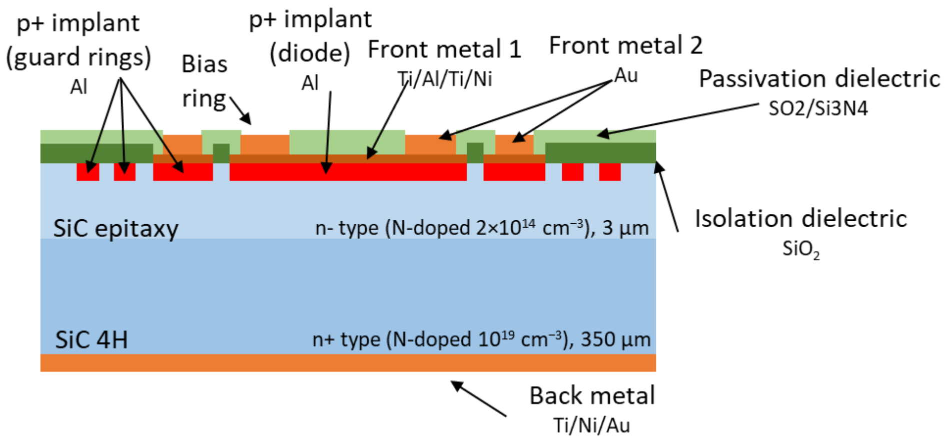
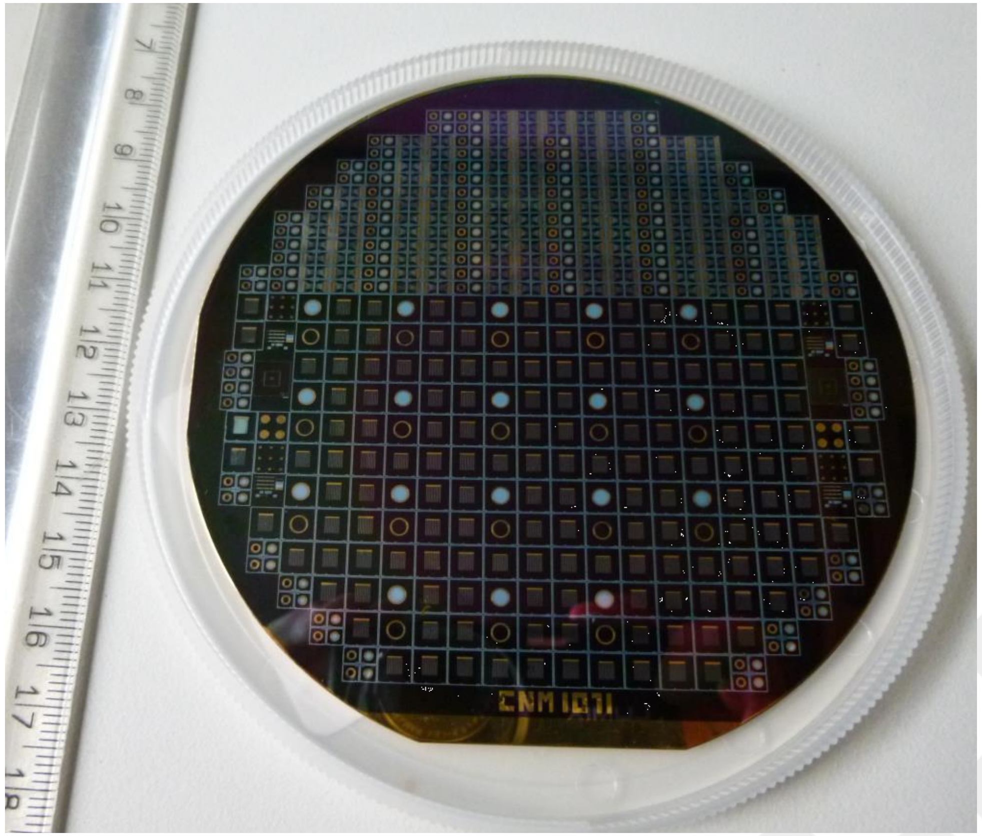
CNM SiC diodes for UHDR dosimetry

- P-N junction implanted diodes
- 4H-SiC, 100 mm wafers
- 3 μm high resistivity n-type doped epilayer
- **Operated without external bias, readout with electrometer**





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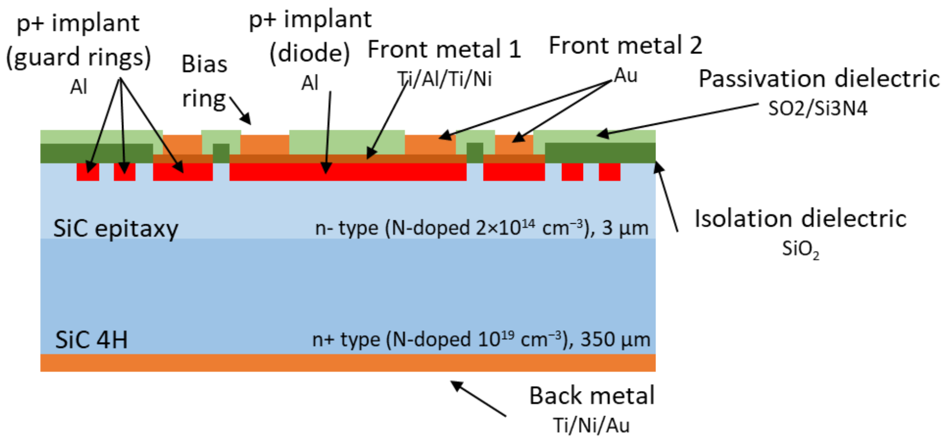
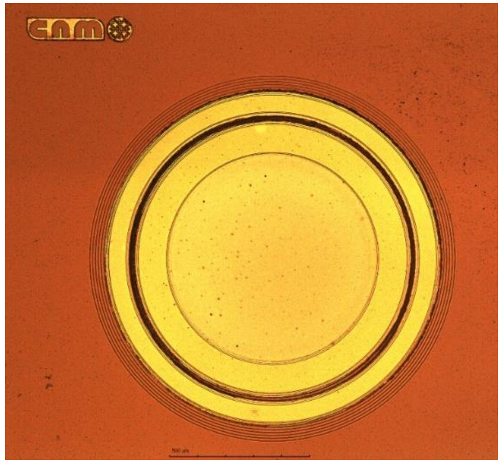
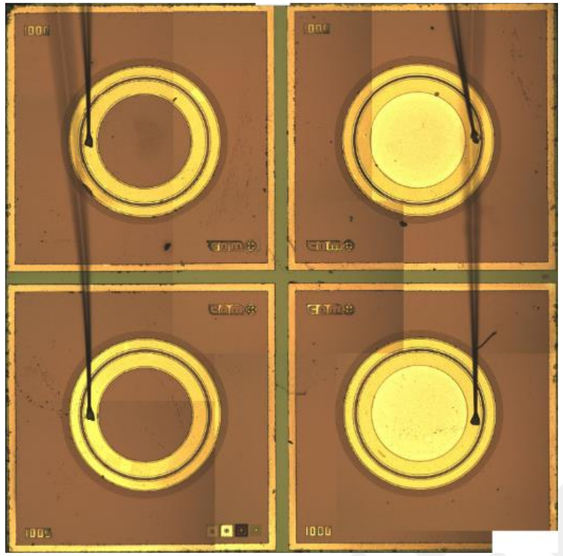
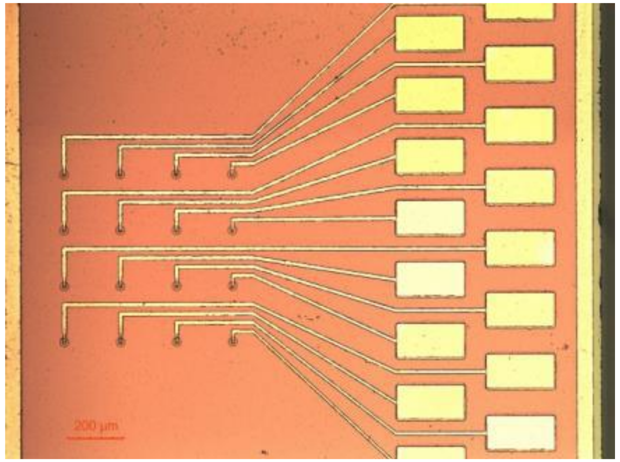




2.2 mm diode



1 mm array



30 µm array

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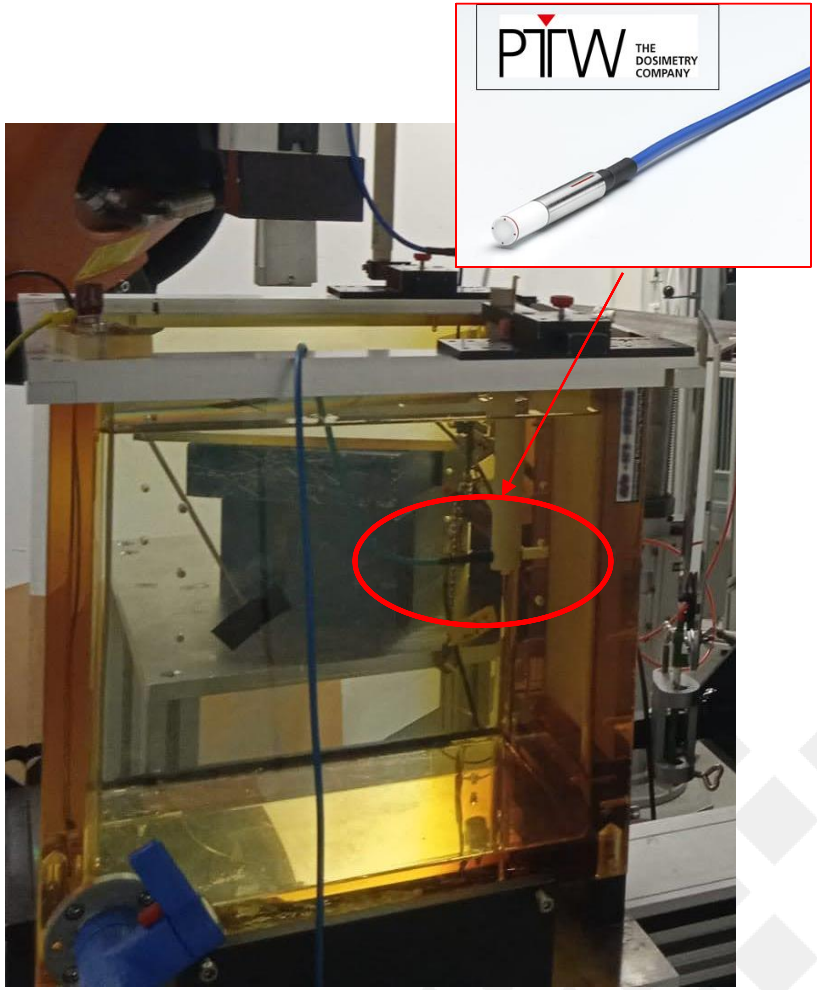
Dosimetry of FLASH electrons

EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States
UHDpulse

- **20 MeV FLASH electrons** at PTB reference beam
- Reference dosimetry
  - Alanine
  - flashDiamond prototype (*M. Marinelli et al., Med Phys 2022*)
- SiC diode
  - 1 mm
  - Encapsulation by PTW

C. Fleta et al., Phys Med Biol 69 (2024) 095013



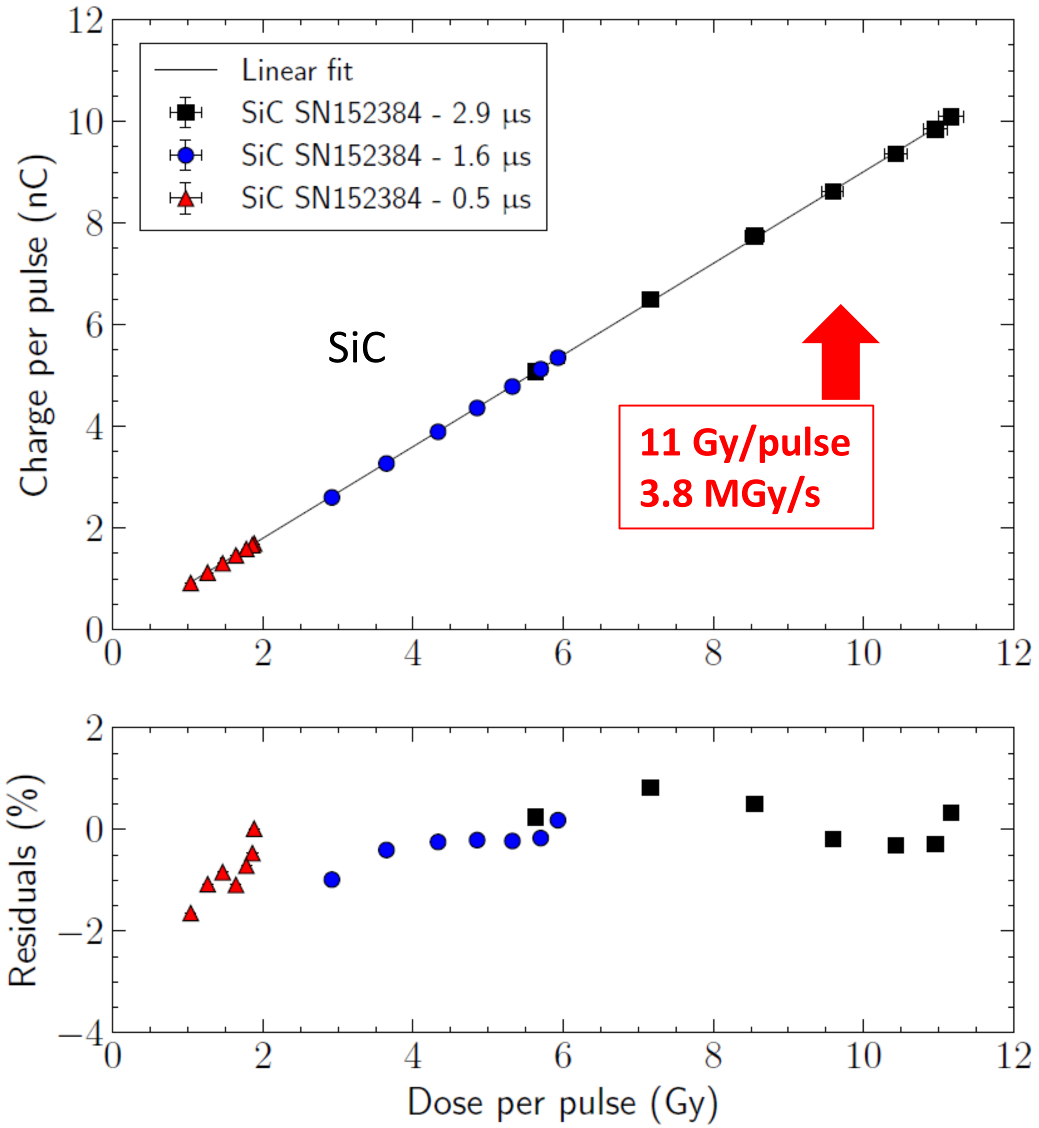
SiC diode in water phantom at PTB

Dosimetry of FLASH electrons

Detector linearity

- Response independent both of DPP and of instantaneous dose rate
- Signal linearity **up to at least 11 Gy/pulse (3.8 MGy/s)** with a relative deviation of < 3 % *

(*) includes uncertainty of reference detector



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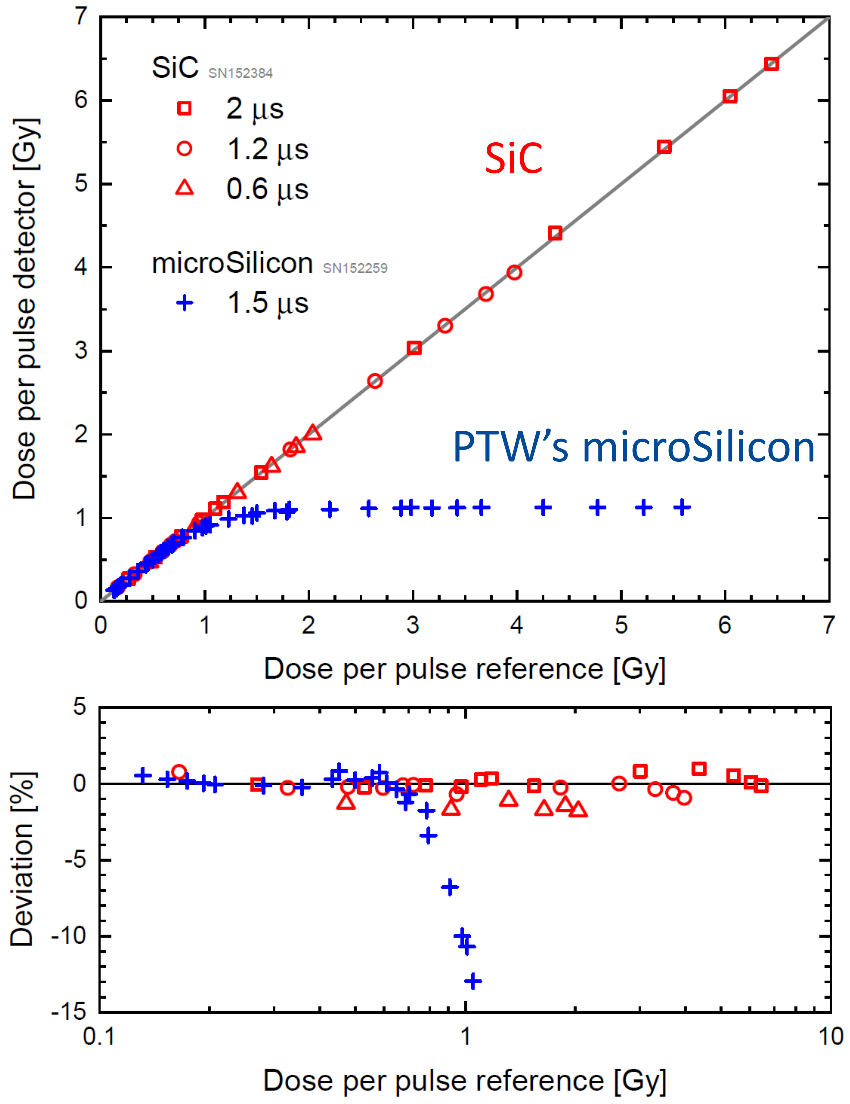


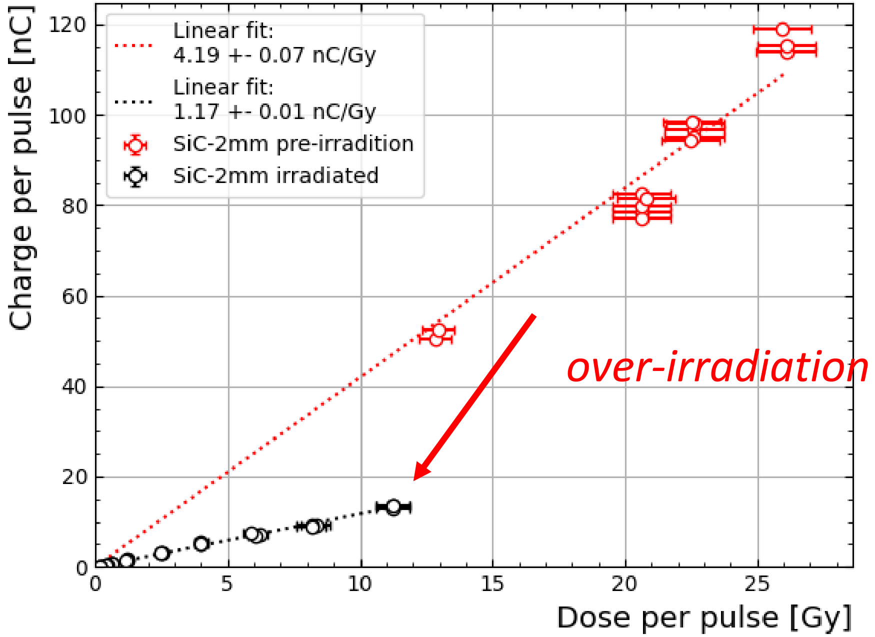
Dosimetry of FLASH protons

- **7 MeV protons** at CMAM
- FLASH beam structure: 20 µs pulses, 1.54 ms inter-pulse
- Reference dosimetry EBT4

2.2 mm diode in PCB

Fresh diode:

➢ **Linear up to 26 Gy/pulse**



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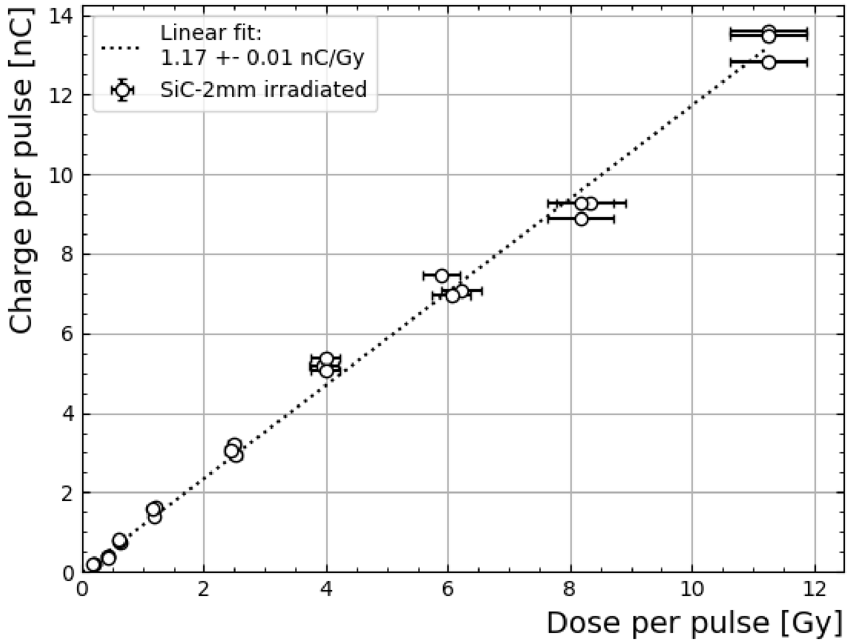
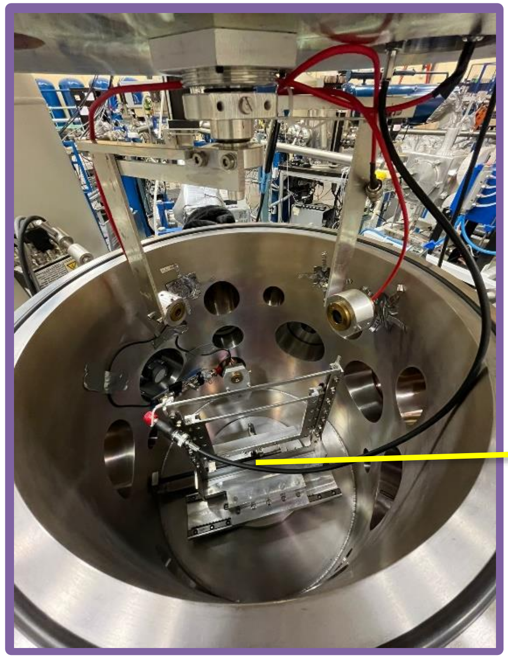
After 52 kGy of 7 MeV protons:

- Linearity is maintained up to at least 11 Gy/pulse

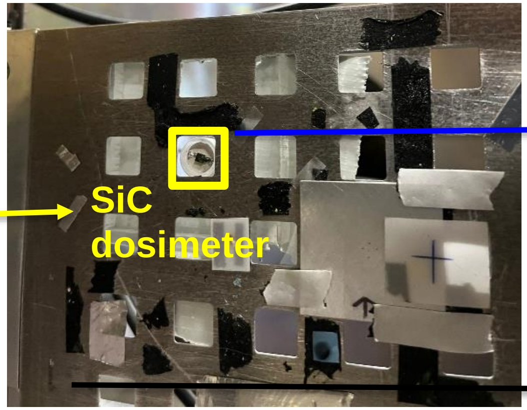
I. López-Paz et al., Med Phys 52:e17986 (2025)



Radiation hardness with FLASH protons



Vacuum chamber



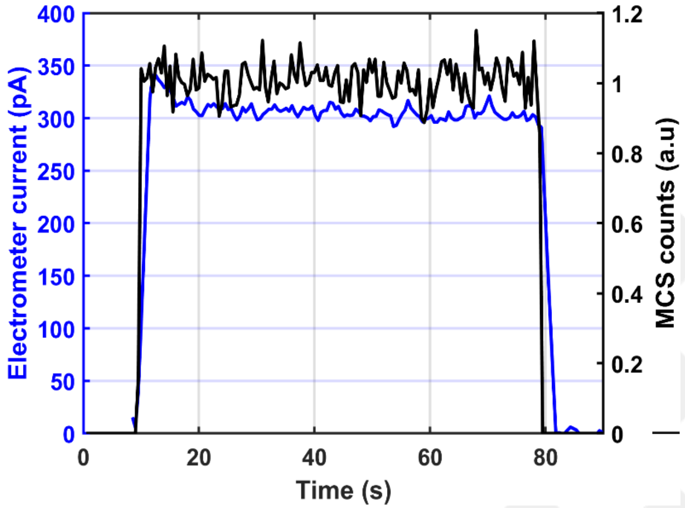
To Electrometer

To Brookhaven current integrator

Sample holder

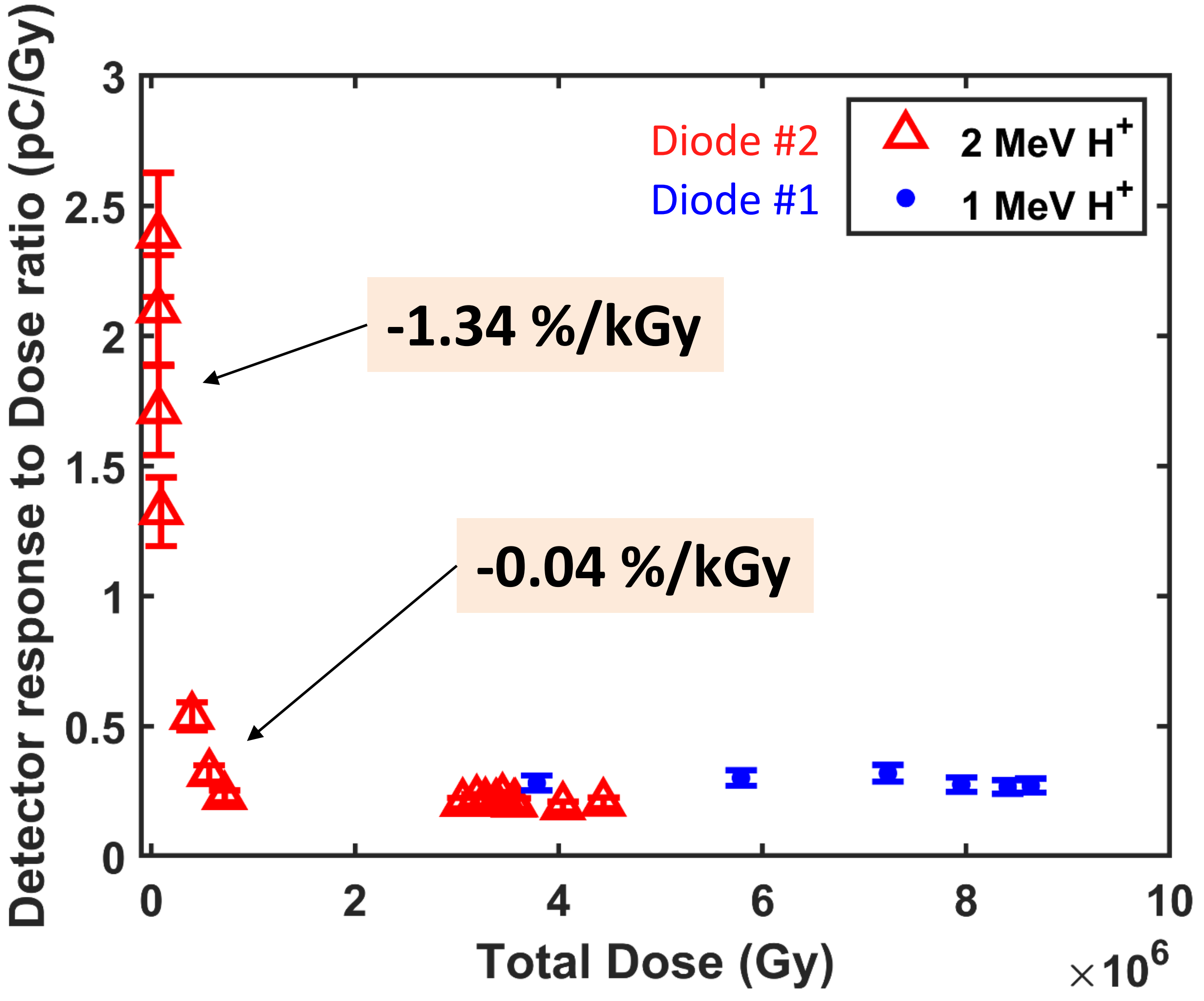
Pulsed beam current measured to calculate dose

- **1 and 2 MeV protons** at CNA (Sevilla)
- FLASH beam structure: 1-10 μs pulses, 500 Hz – 10 kHz, up to 5.6 Gy per pulse (4.6 MGy/s)
- 30 μm diameter planar microdiodes

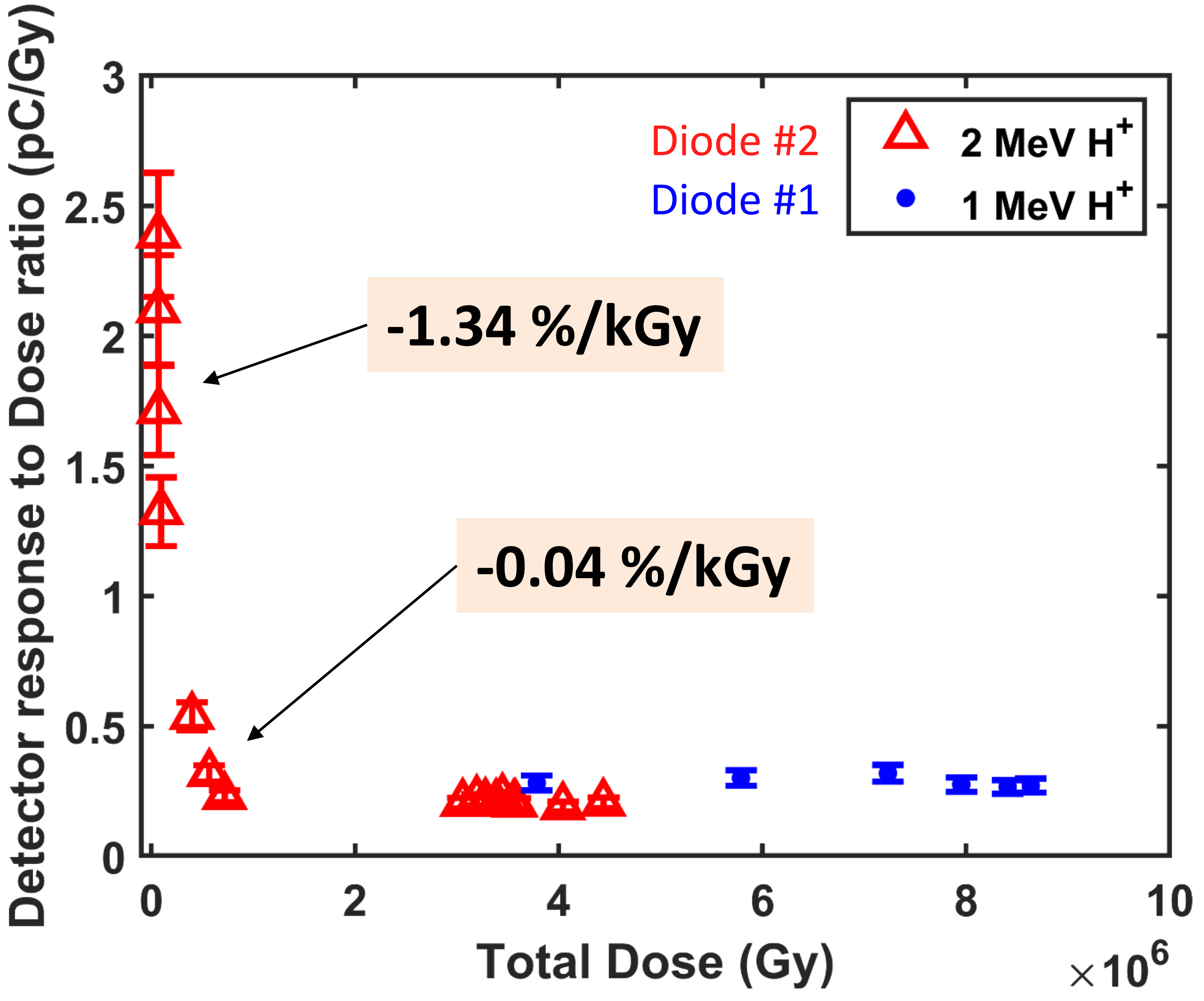


M.C. Jiménez-Ramos et al., IEEE Trans Radiat Plasma Med Sci (2025)

Radiation hardness with FLASH protons



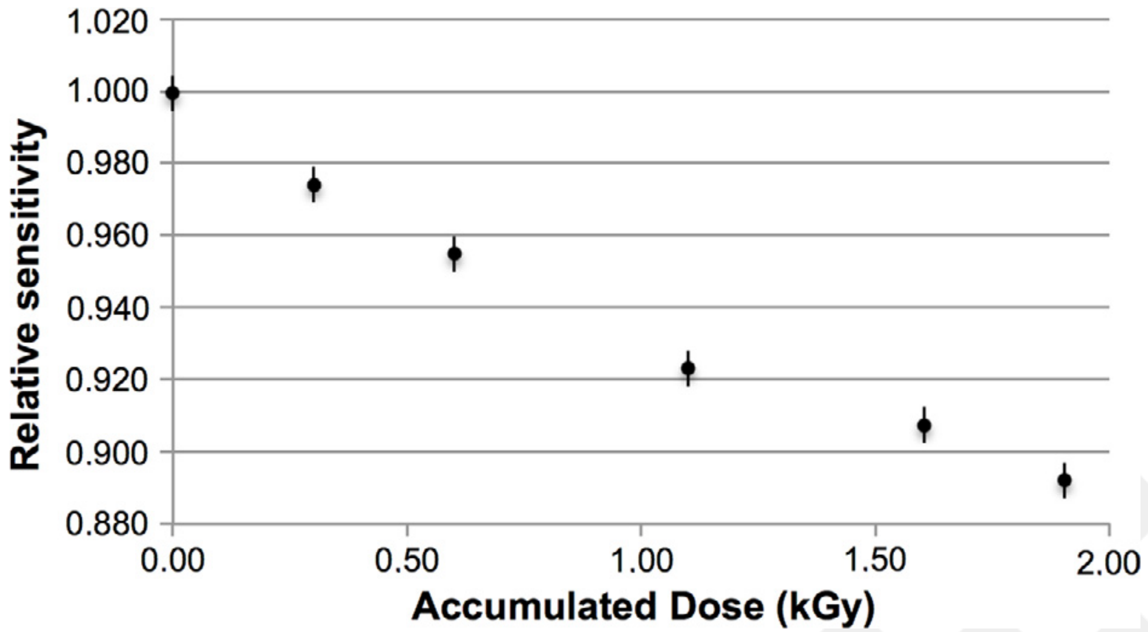
Radiation hardness with FLASH protons



Commercial silicon dosimeter:

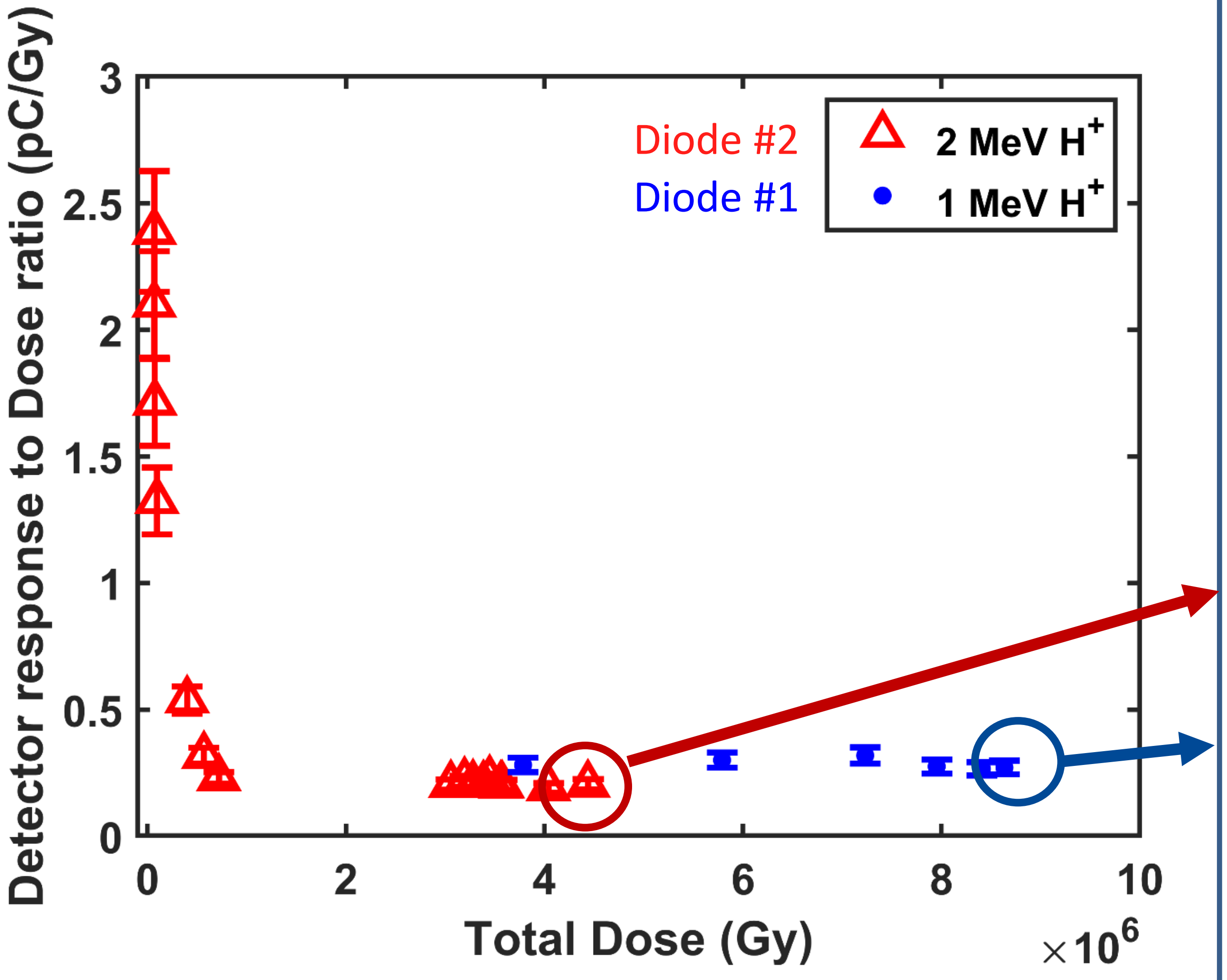
-5 %/kGy with 62MeV protons

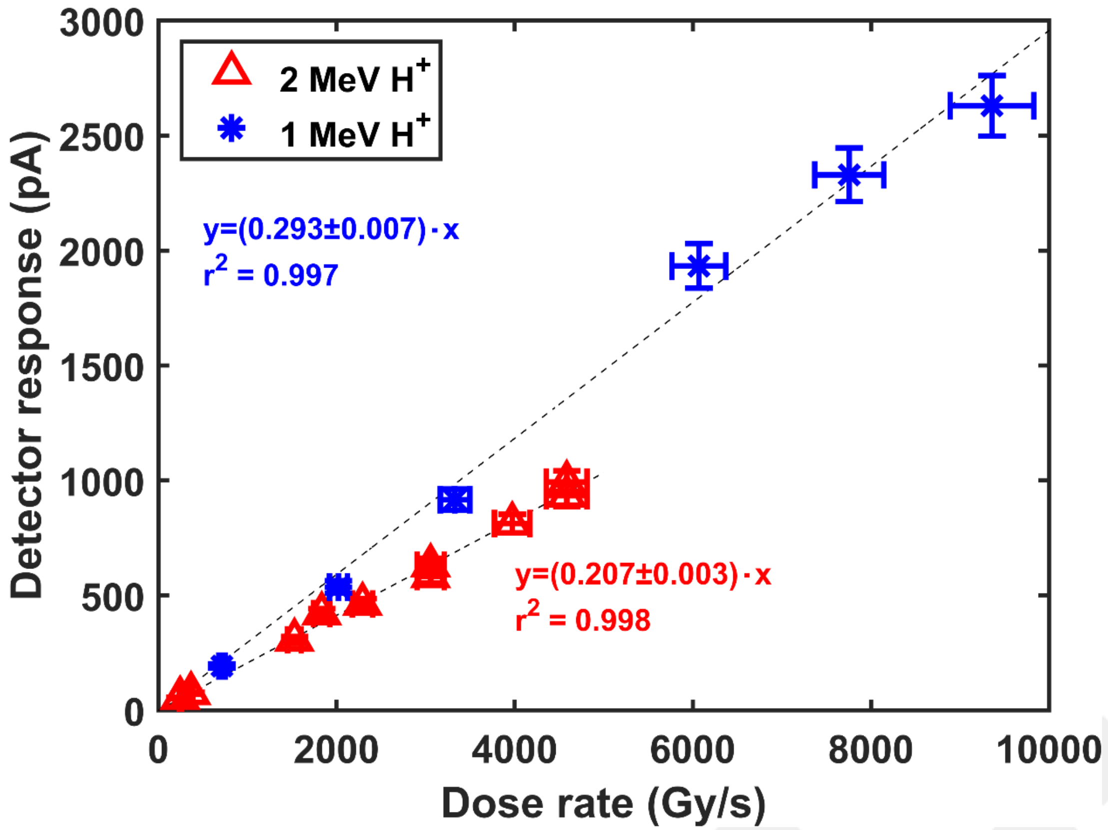
NIEL/LET (62 MeV/2MeV) ≈ 1.3



L. Raffaele et al., NIMA 891 (2018)

Radiation hardness with FLASH protons

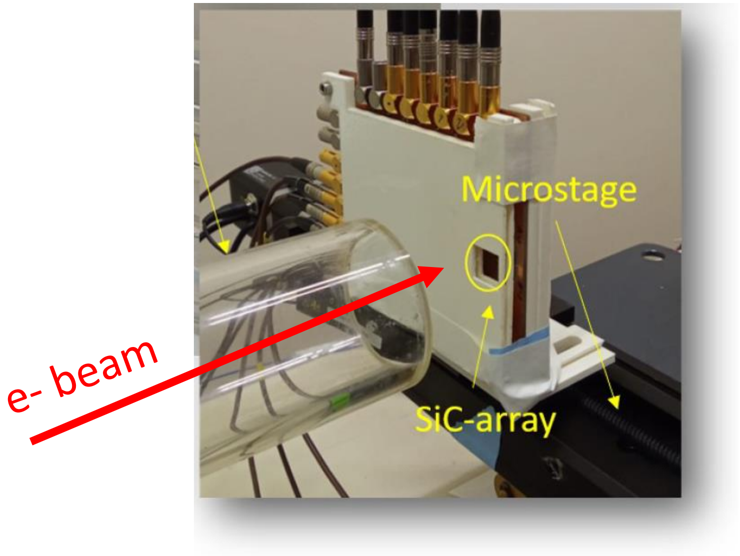


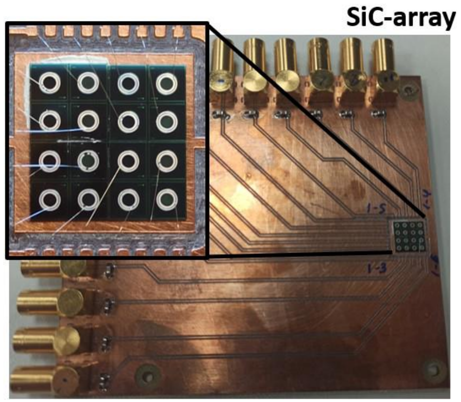


Linear behaviour for FLASH dose rates is maintained after irradiation

Towards a 2D dose monitor for FLASH

- **7 MeV e-FLASH** at Institut Curie (France)
- Pulses of 3 μs, **6 Gy per pulse**
- 12-channel electrometer (PTW MultiDOS) adapted for UHDR
- 4x4 diode array (1 mm, pitch 2.2 mm)





Iván López Paz et al., submitted to Med. Phys

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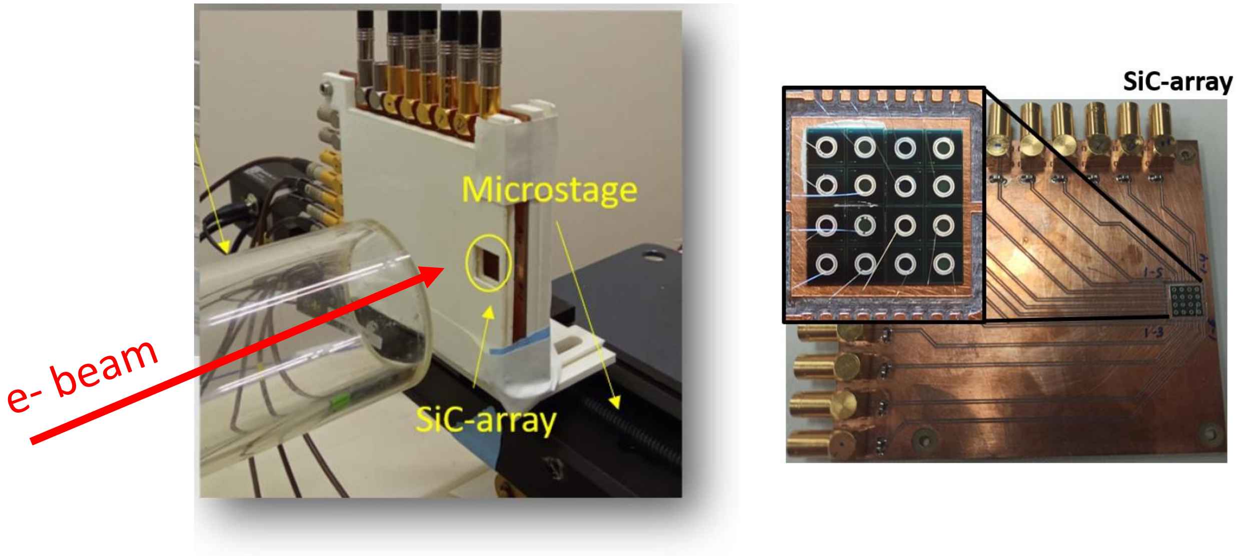
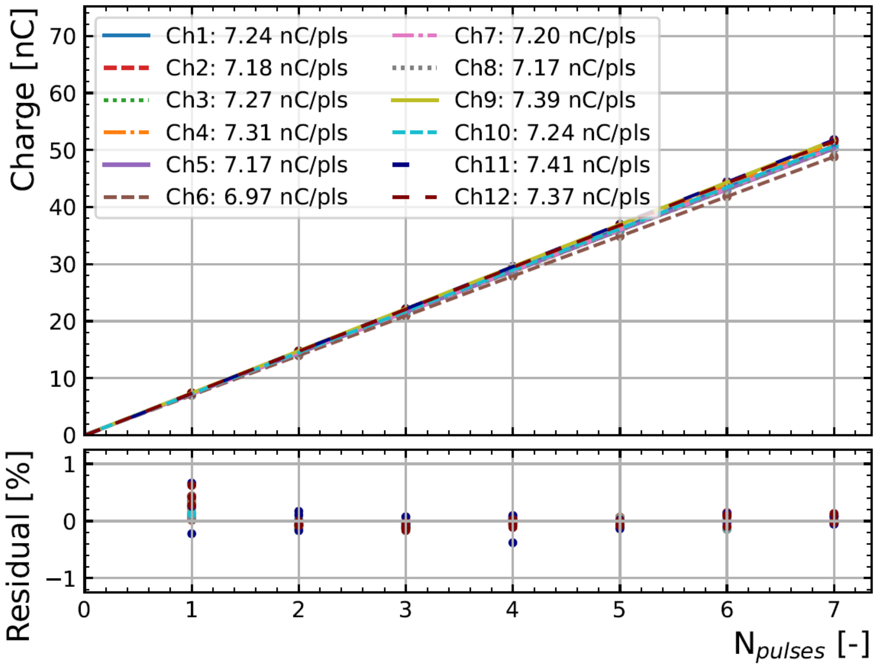
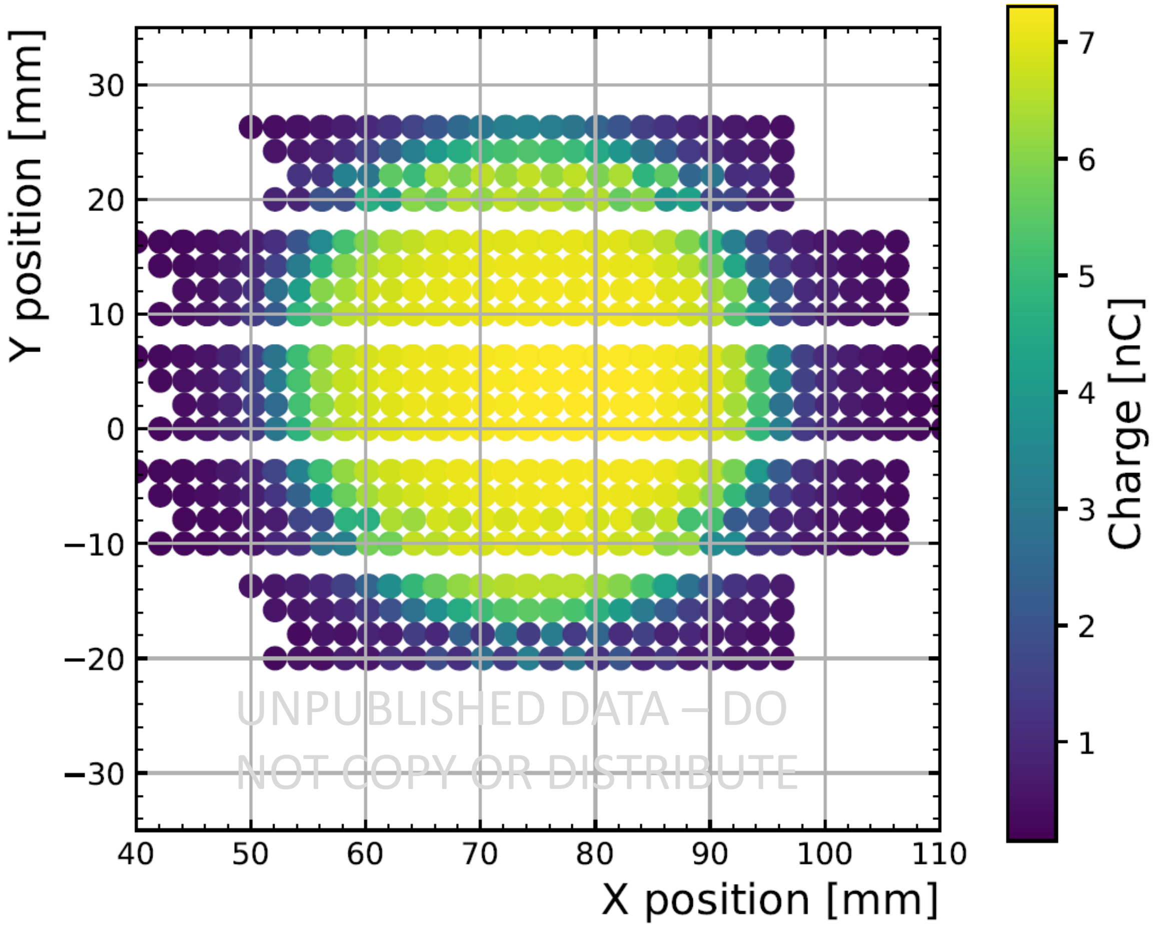




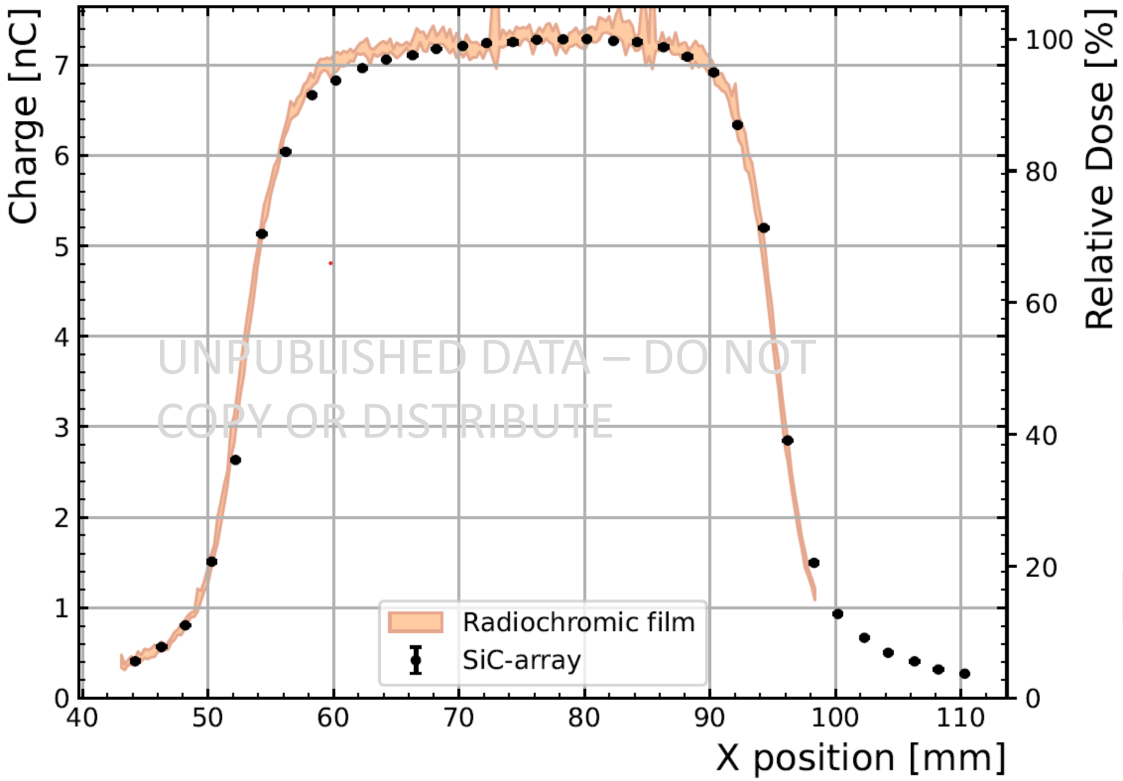
Iván López Paz et al., submitted to Med. Phys

- Sensitivity variation between pixels **< 4%**

Towards a 2D dose monitor for FLASH (2)



Fit with radiochromic reference



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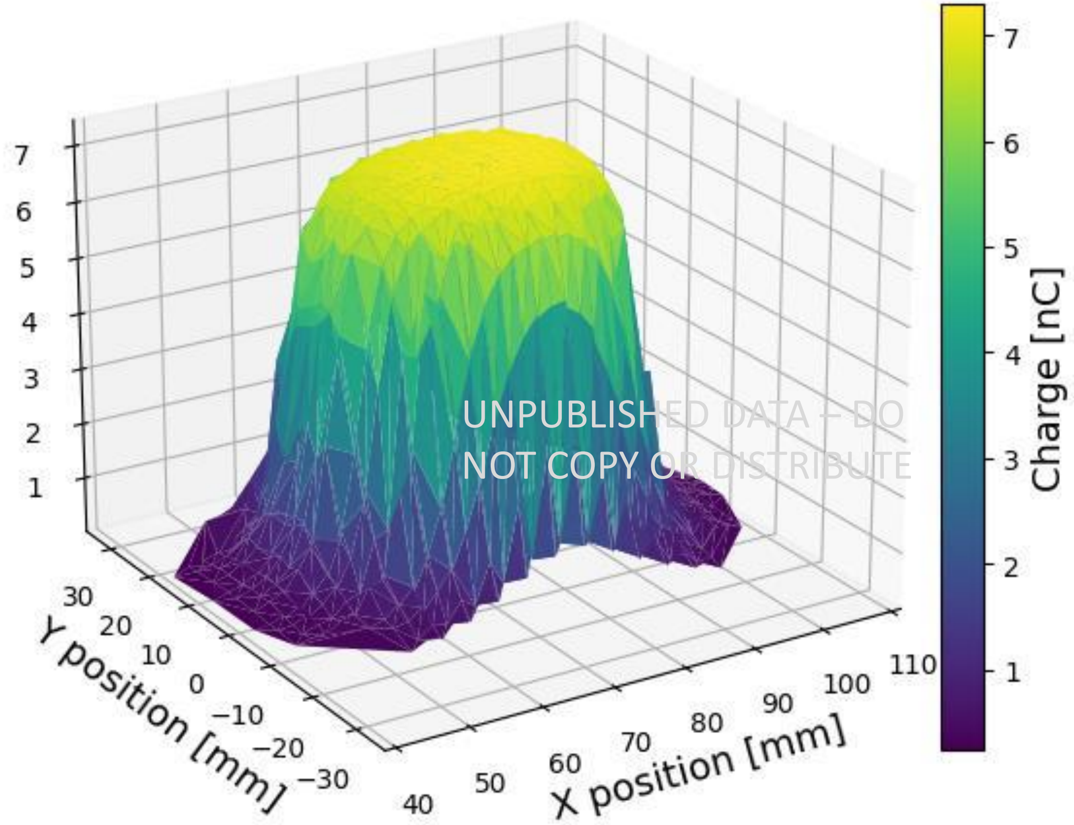

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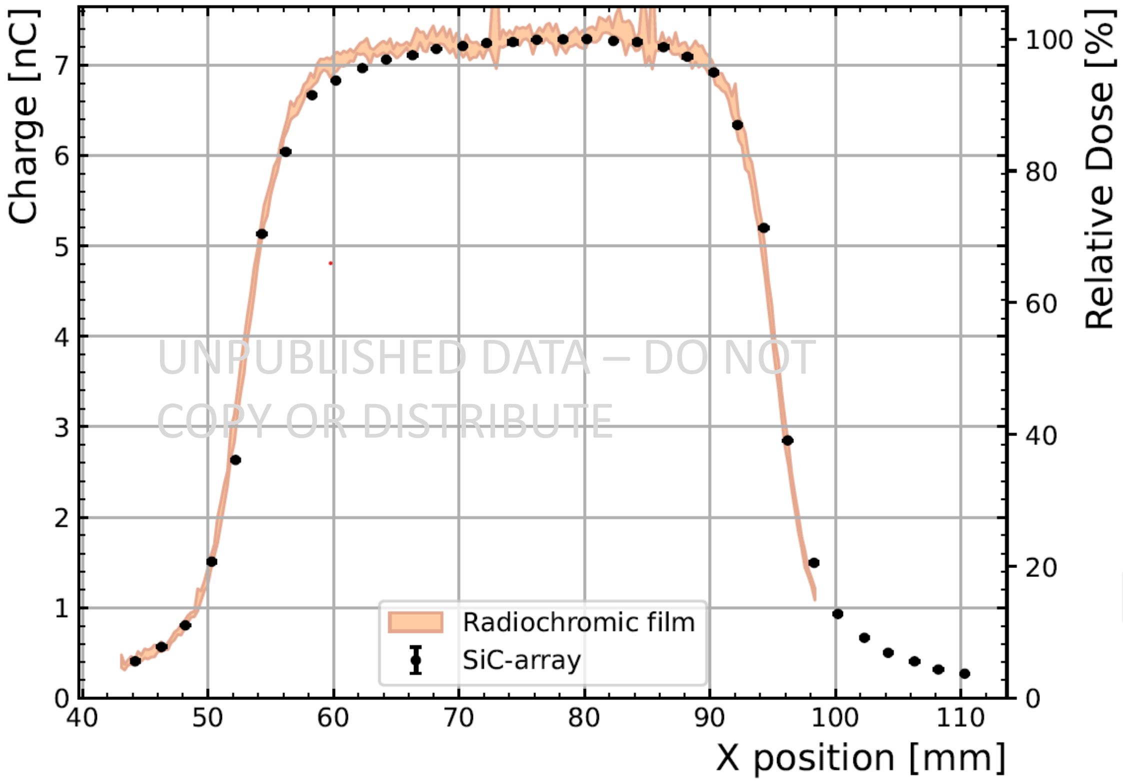

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Conclusions

IMB-CNM have produced the first SiC diodes for relative dosimetry in ultra-high dose pulsed (FLASH) medical beams

- Operation without external bias
- Validated with UHDR electrons and protons
- Radiation hard + linear performance maintained after MGy doses
- Technological demonstrator of 2D dose monitor based on 4x4 array, working towards a large SiC-based 2D dosimetry system (0.6 mm diameter, 2 mm pitch, 20x20 cm^2 area coverage, custom readout)

Outlook

- Transmissive beam monitors
- SiC microdosimeters

Acknowledgements

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- UHDPulse: the EMPIR programme cofinanced by the Participating States and from the European Union's Horizon 2020 research and innovation program (18HLT04).
- NEWDOSI: Desarrollos tecnológicos para nuevos detectores de estado solido para dosimetría avanzada (PID2021-123484OB-I00).
- CARACTERIZACION: Caracterización de dosímetros avanzados fabricados en el IMB-CNM para aplicaciones médicas (202250I185).
- Microdetectors for medical applications. Proyectos Intramurales Especiales CSIC (20225AT008).
- Dosimetry monitor for FLASH therapy. LaCaixa foundation (HR23-00718)

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Collaborators:

Andreas Schüller (PTB), Rafael Kranzer (PTW)
Paula Ibáñez, Daniel Sanchez-Parcerisa, Adrián Zazpe, Inés del Monte (Universidad Complutense de Madrid)

Thanks for your attention

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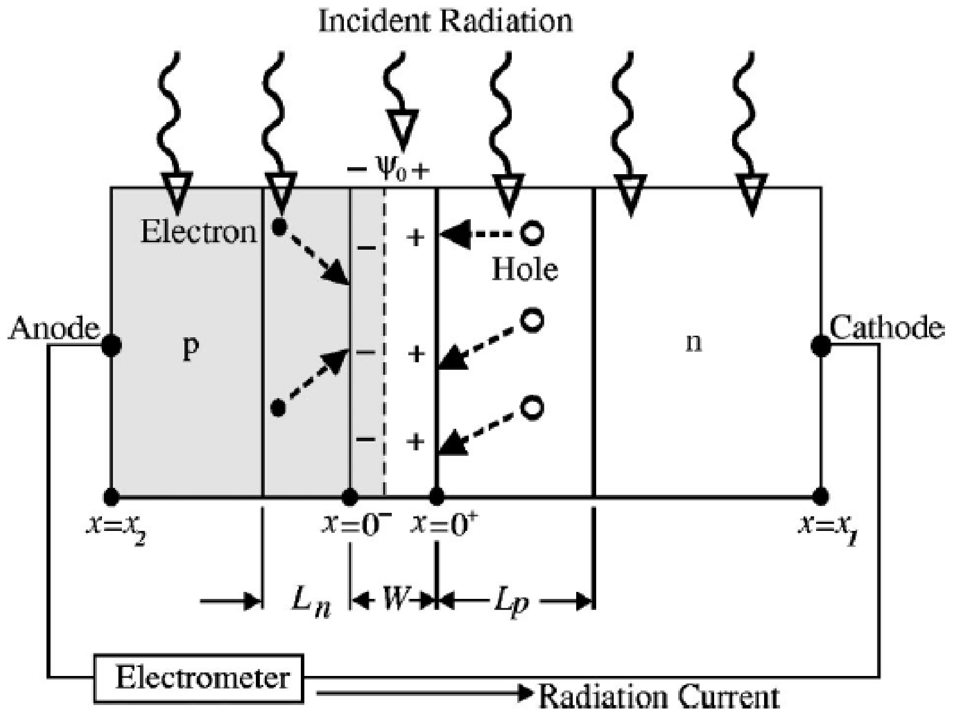
Semiconductor diode dosimeters

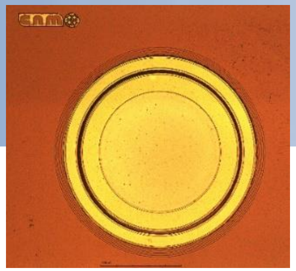
- p–n (or Schottky) junction in:
  - Current mode operation
  - Unbiased conditions

- The radiation-induced current is measured by an electrometer
- The current is proportional to the dose rate and its integration provides the absorbed dose in the semiconductor

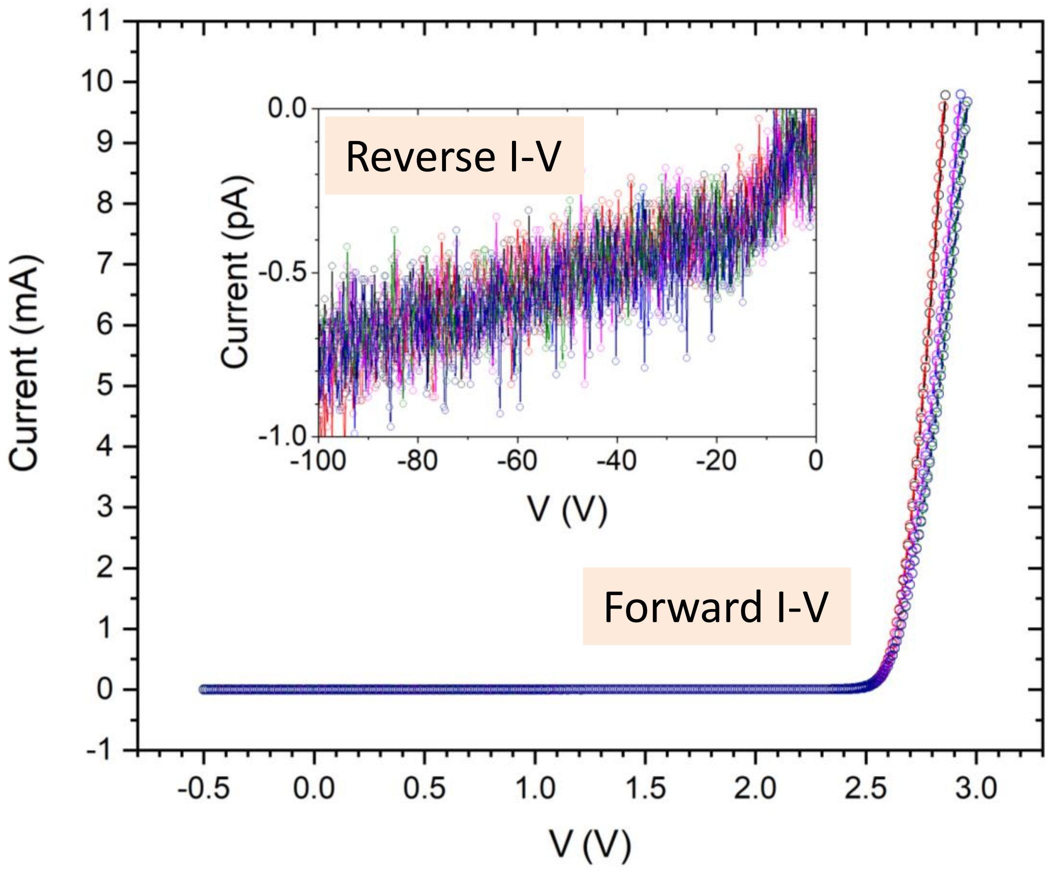


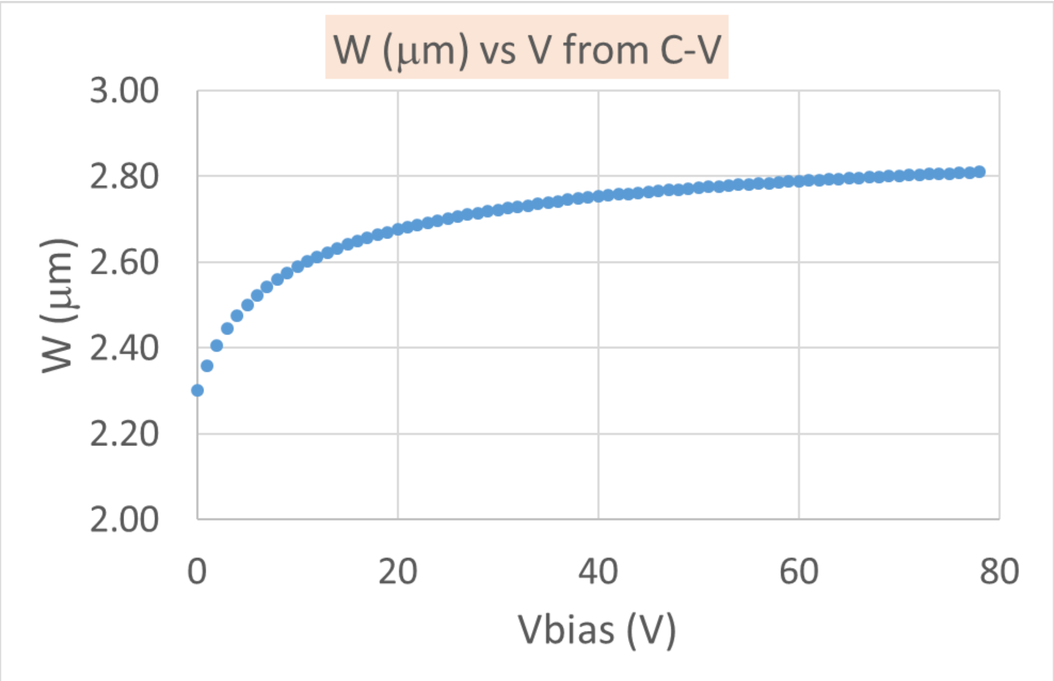
Shi et al., Med Phys 30 (2003)

Electrical test



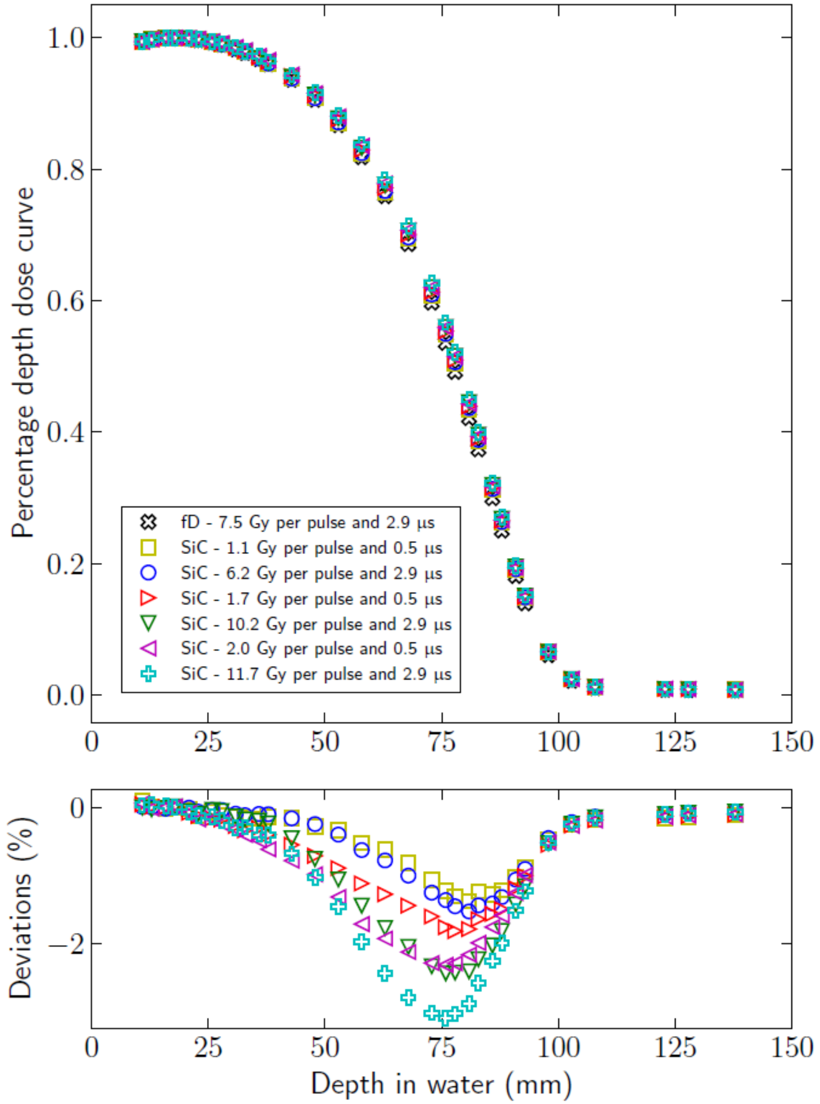
Large single diodes





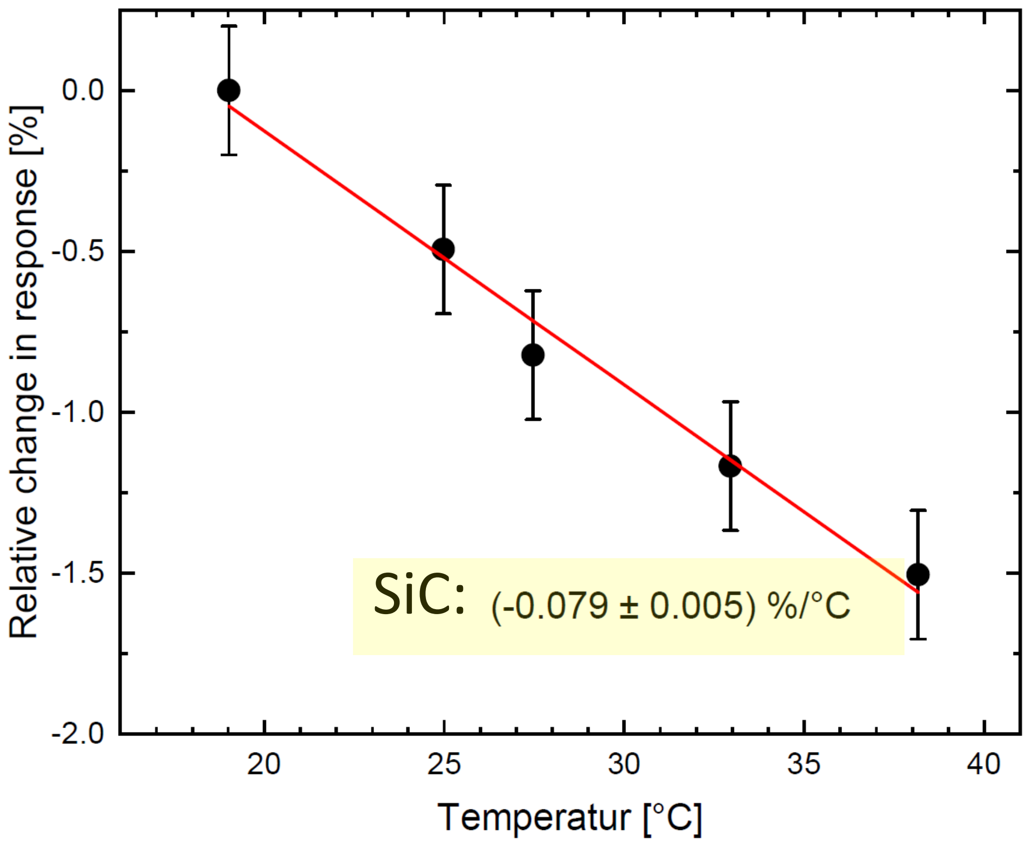
Dosimetry of FLASH electrons

PDD measurement in UHDR conditions



Dosimetry of FLASH electrons

Temperature depencence of sensitivity



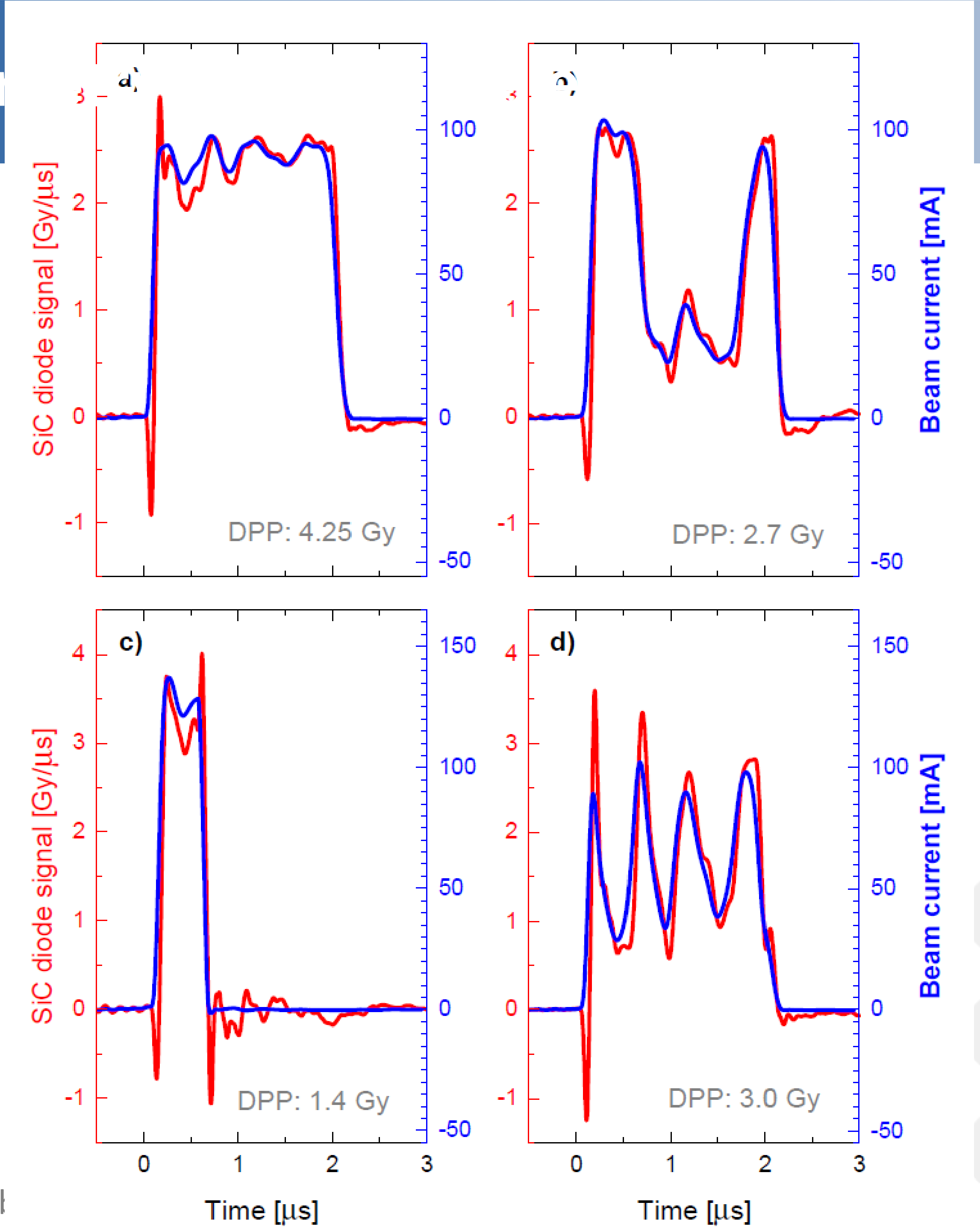
- Sensitivity reduction of **–0.08% /°C**
- Better than most commercial Si diodes + opposite trend

TABLE III. Temperature coefficients for n- and p-type diodes. All measurement were made at depth of 5 cm, 10×10 cm^2, SSD= 100 cm.

Diode type	Temperature coefficient 6 MV (%/°C)	15 or 20 MV (%/°C)	Co-60 (%/°C)
Isorad Gold 1, unirradiated	0.06	0.05 (20 MV)	0.45 (T1000)
Isorad Gold 2, unirradiated	0.08	0.10 (20 MV)	0.16 (T1000)
Isorad Red	0.22	0.21 (20 MV)	0.37 (T1000)
QED unirradiated	0.27	0.25 (15 MV)	0.34 (TPhoenix)
QED Blue Diode	0.30	0.31 (15 MV)	0.30 (T780)
QED Red Diode	0.29	0.29 (15 MV)	0.29 (T780)
Scanditronix EDP 10	0.38	0.33 (20 MV)	0.36 (T1000)
Scanditronix EDP 30	0.36	0.34 (20 MV)	0.39 (T1000)

A. S. Saini and T. C. Zhu, Med Phys 29 (2002)

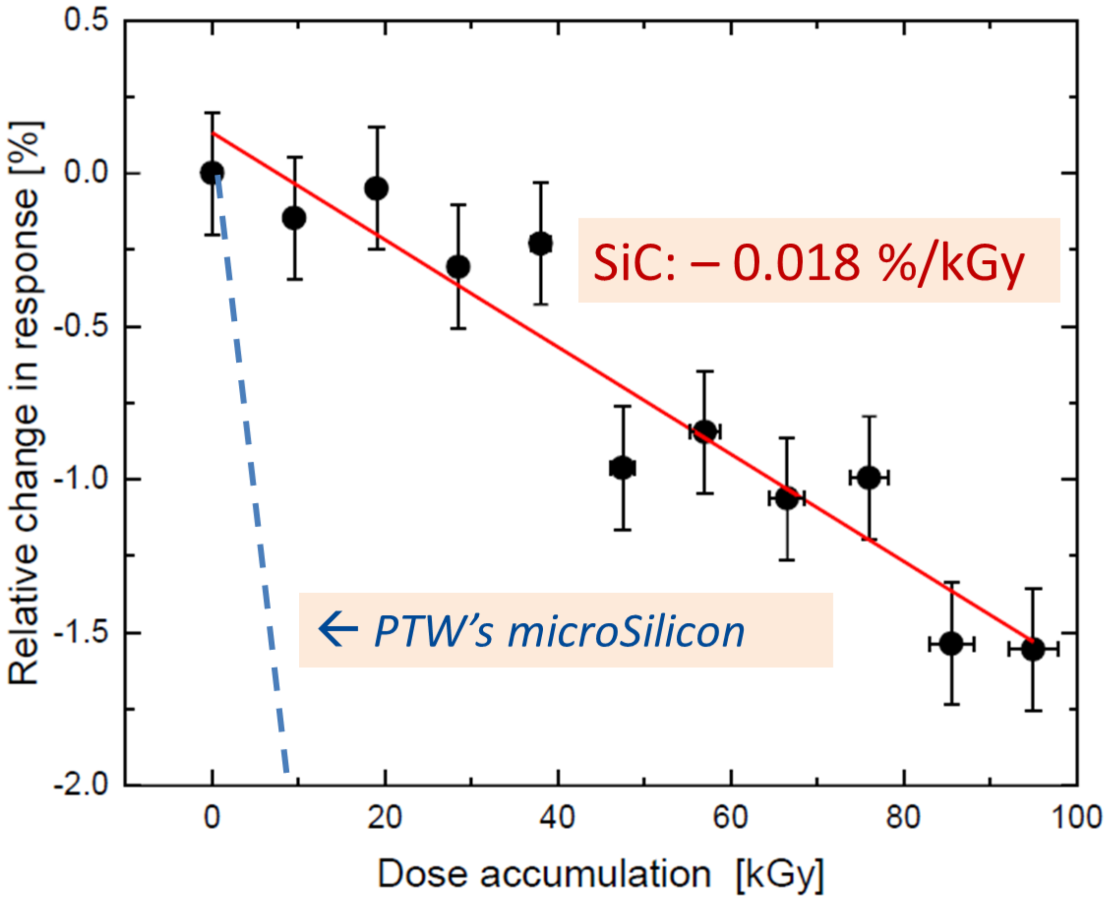
Dosi



Time-resolved signals

- The SiC diode is capable of effectively tracking the beam pulse current in FLASH conditions

Dosimetry of FLASH electrons



(initial irradiation of SiC diode (10s kGy) not shown)

Long-term radiation hardness

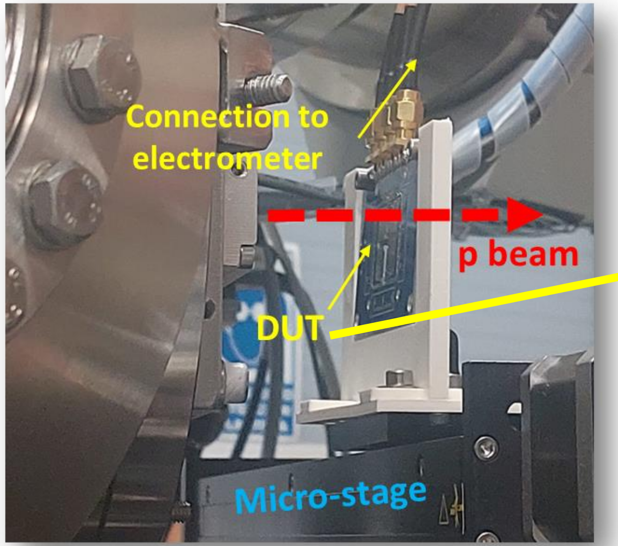
- Linear decrease of sensitivity of **0.018% / kGy** of 20 MeV electrons

→ Not as radiation hard as diamond, much better than commercial silicon diodes

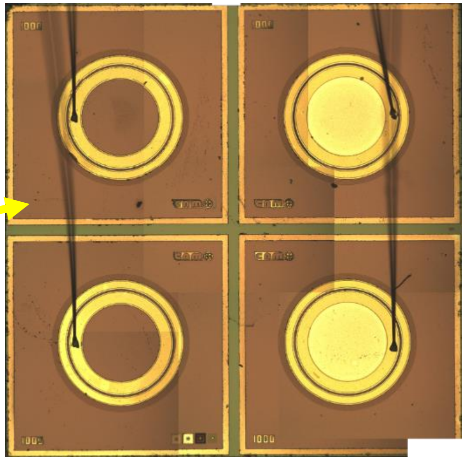
Dosimetry of FLASH protons

Position-resolved measurements

- Measured beam profiles match with radiochromic film
- Viability of a pixel array beam monitor for QA



CH1 CH4



CH2 CH3

4-channel array of 1 mm diodes