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Anthem
AdvaNced Technologies for Human-centrEd Medicine

Silicon carbide detectors for accurate temporal structure pulsed beam monitoring in FLASH radiotherapy

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INFN CATANIA
Istituto Nazionale di Fisica Nucleare
Sezione di Catania

Decreasing toxicity maintaining tumor control: the FLASH radiotherapy

FLASH radiotherapy: a promising cancer treatment modality under development → almost instantaneous delivery of a high radiation dose in a few radiation **pulses** of **ultra-high dose rate** (**UHDR**)

CONVENTIONAL RADIOTHERAPY	FLASH RADIOTHERAPY
Average Dose Rate:	*Average Dose Rate:*
~1.8 Gy/min	>40 Gy/s
Irradiation Time:	*Irradiation Time:*
few minutes	<200 ms

In vivo evidences with minipigs

36 weeks post-RT

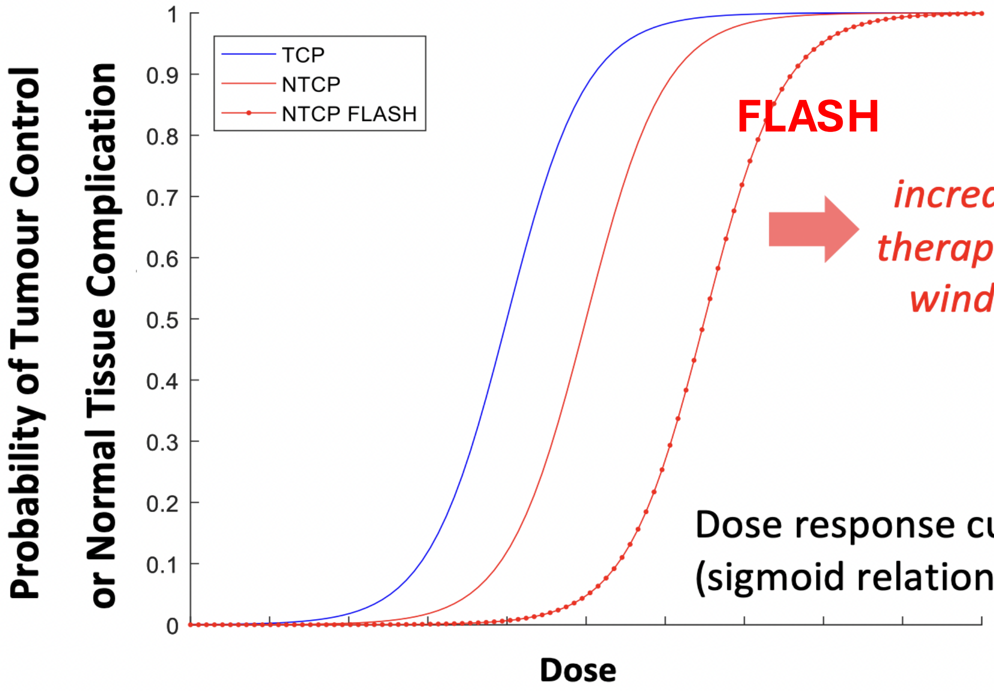
FLASH (300 Gy/s)

normal appearance of skin

Conventional (5 Gy/min)

necrotic lesions

Vozenin et al., Clin Cancer Res 25 (2019) 35



TCP = Tumour Control Probability

NTCP = Normal Tissue Complications Probability

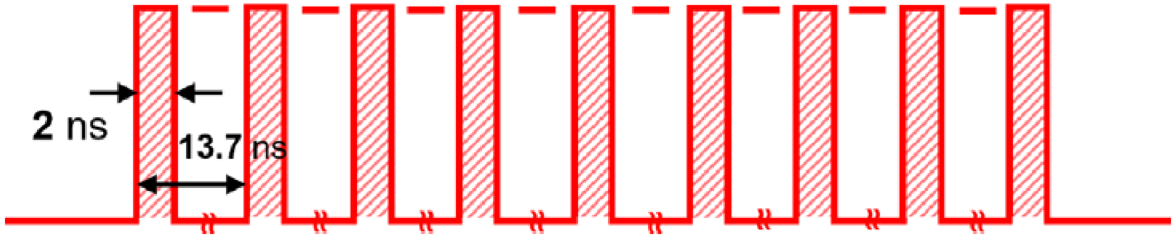
- ✓ Same biological damage to the tumor tissues
- ✓ Decreased toxicity to healthy tissues

Temporal structures for different accelerators at UHDRs

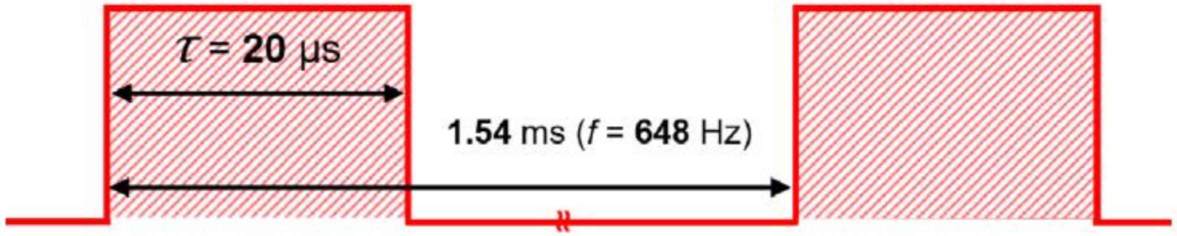
protons $\dot{d} < 500$ Gy/s

Isochronous cyclotron (quasi-continuous radiation)

(f=72.8 MHz, 2nd Harmonic)



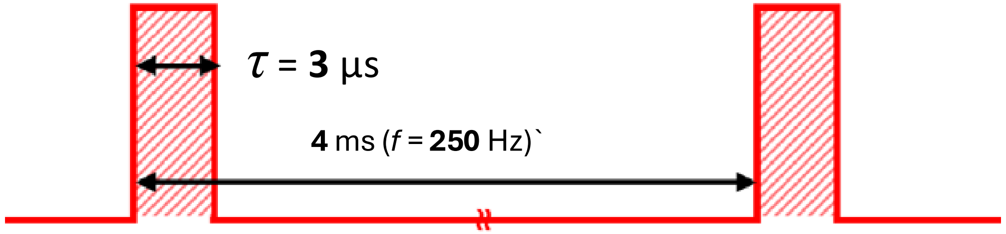
Synchrocyclotron (FLASH dose rate) $\dot{d} < 10$ kGy/s



electrons

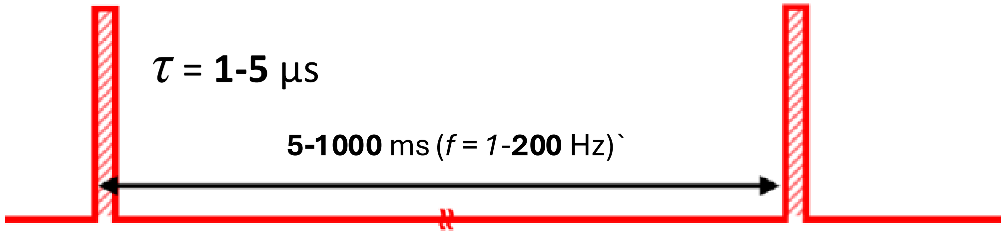
$\dot{d} < 100$ kGy/s

Clinical LINAC for Radiotherapy (modified)



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

Research LINAC for pre-clinical studies

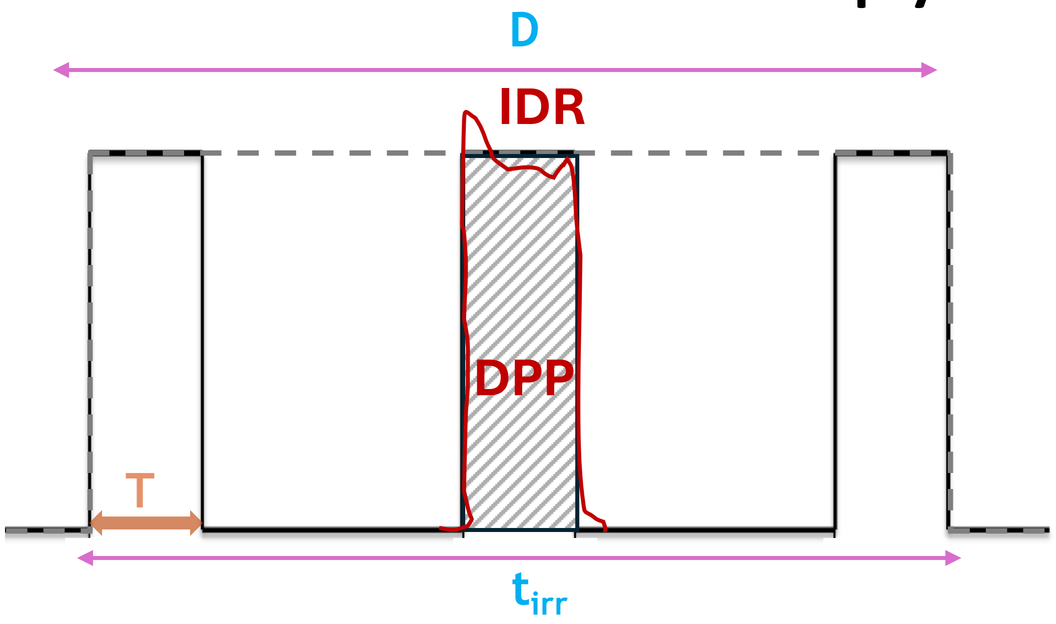


F. Romano *et al*. Med. Phys. (2022)

Involved physical parameters for FLASH radiotherapy

Physical beam parameters for conv radiotherapy:

- Particle type [e-, p, ions, X-ray, ...]
- Energy [MeV]
- Fluence [p/cm^2]
- Dose [Gy]
- **Time [s]**



Relevant dosimetric quantities

Dose delivered **D** in the total irradiation time t_{irr}

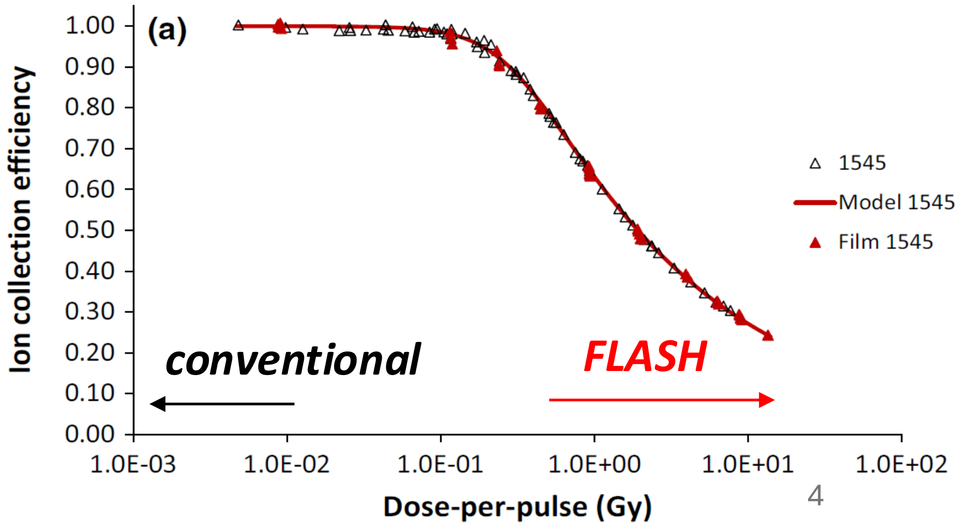
Average dose rate D/T → up to 1-2 KGy/s

Dose per pulse **DPP** within the pulse duration **T: up to 25 Gy/p**

Average Instantaneous dose rate IDR: up to 6 MGy/s

Variation of the intra-pulse instantaneous dose rate

Saturation of standard ionization chambers



Possible dosimetric approaches for FLASH RT

Dosimeter	Real time	In vivo dosimetry	Absolute/ reference dosimetry	Beam monitoring	Spatial resolution	Temporal resolution	2D dosimetry	Accuracy at conventional dose rates[a]	Other considerations
Ion chamber	Yes	No	Yes	Yes	Several mm	10–200 μs	Array	1%–2%	Significant ion recombination at UHDRs
Semiconductor	Yes	Yes	No	Yes	Sub-mm (or μm)	1–10 ns	Yes	2%–5%	Angular dependency, radiation damage, LET dependence
TLD	No	Yes	Yes	No	Several mm	N/A	No	3%–10%	Energy dependence, time consuming, LET dependence
OSLD	No	Yes	Yes	No	Sub-mm to mm	N/A	Array	3%–5%	Energy dependence, quenching in high LET fields
Scintillator	Yes	Yes	Potentially	Potentially	Sub-mm to mm	ns to μs	Array and sheet	3%–5%	Quenching in high LET fields, Cherenkov radiation
Gas scintillator	Yes	No	No	Yes	Sub-mm	N/A	Yes	1%	Beam centroid measurement
Calorimeter	Yes	No	Yes	No	cm to several mm	ms–10 ms	No	<1% at the primary standard level	Bulky, not easy to use, correction factors, time consuming
Film	No[b]	Yes	Potentially	No	Tens of μm	N/A	Yes	3%–5%	Quenching in high LET fields
Fricke	No	No	Yes	No	cm to sub-mm	N/A	Potentially	<1% at primary standard level	Time consuming, complexity
Faraday cup	Yes (for charge measurements)	No	Yes	No	N/A	<μs	No	2%–5% for commercial devices; 1%–2% for dedicated equipment[c]	Measures the total collected charge (other detectors are required for dose determination)
Nuclear track detector	No	Yes	No	No	mm; sub-mm with specialized equipment	N/A	Yes	5%–7%	Time consuming, energy dependence, LET dependence
Alanine	No	Yes	Yes	No	mm	N/A	No	2%–7% for doses larger than 10 Gy	Decreased accuracy for doses less than 10 Gy (minimum 2 Gy)
Integrated current transformer	Yes	Potentially	No	Yes	N/A	sub-μs	No	<1% for charge measurements	Lack of 2D measurements, only charge measurements

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

Semiconductors radiation detectors

SILICON

- High sensitivity, spatial res, developed technology
- Unknown factor: linearity with DR, recombination effect, radiation resistance

DIAMOND

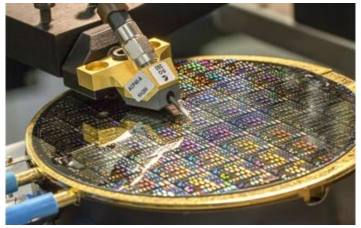
- Radiation hardness, h resistivity of intrinsic diamond, large saturated carrier velocity
- Challenging issues: possibility of straddle areas several cm^2

SIC

- Ideal compromise: h electrical stiffness, speed of charges, melting T, thermal diffusivity, industrial maturity
- Preliminary simulation: DR linearity up to 10^{11} Gy/s on X-ray beams for SiC membranes (2 μm thick)

Property	Diamond	Silicon Carbide
melting point	4500°C	2700°C
Thermal conductivity	>1500W/m/K	400W/m/K
material costs	very high	medium/low
Available crystal size	$0.25cm^2$ (5mmx5mm)	$315cm^2$ (8inch)
Quality of crystals	"optical/electrical" grade	fully industrial
Electron/Hole generation energy	13eV	7.8eV
Doping control	minimal (>1E20cm-3)	high (>5E13cm-3)
Stability of metallisations	low	high

Silicon



+

Diamond

SiC

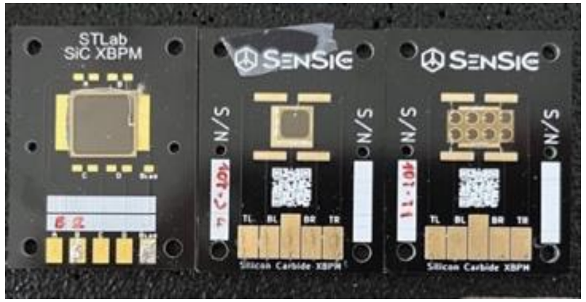
- Radiation **hardness**
- High signal to noise ratio
- High **time resolution (ns)** and fast collection time
- **Large area devices**

Diamond and SiC are expected to be ***less sensitive than Si*** *→ Advantage for UHDR application (reduce tot charge released in the sensor chn)*

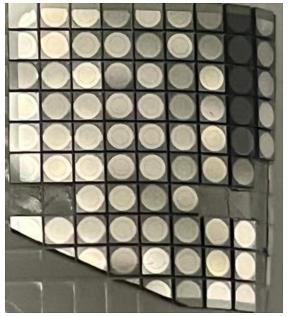
Silicon carbide detectors for dosimetry in radiotherapy

PiN diodes: 4-100 mm^2, 10 um thick

10x10 mm ^{2} 5x5 mm^2. 2x2 mm ^{2}

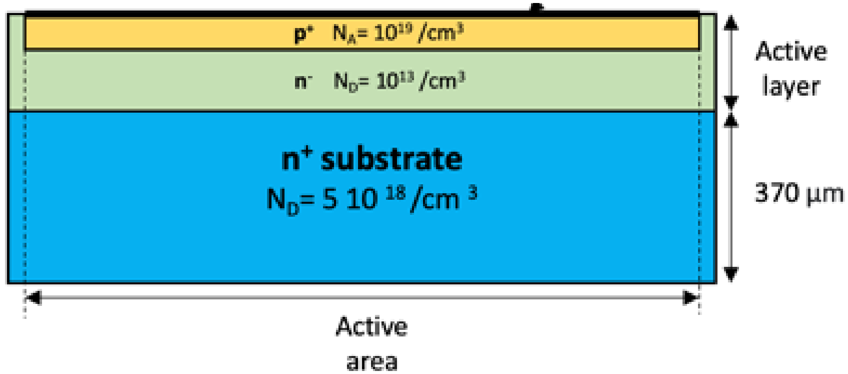


Schottky diodes: 300-800 um diameter, 22 um thick, Guard ring structure to reduce superficial leakage

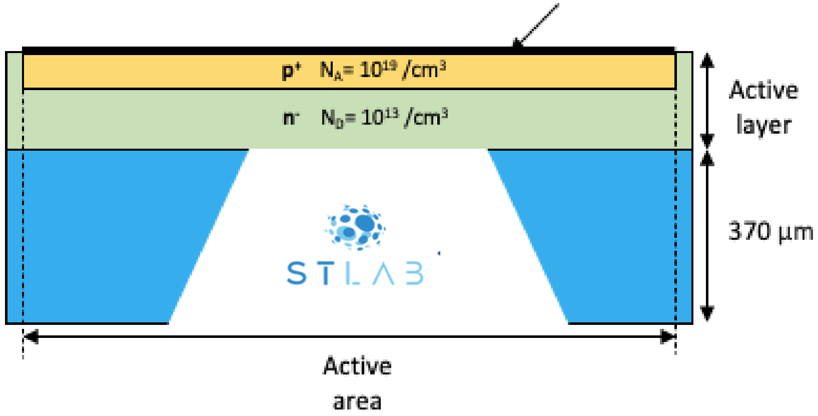


Waterproof encapsulated SiC detector for reference dosimetry

Standard configuration with thick bulk substrate



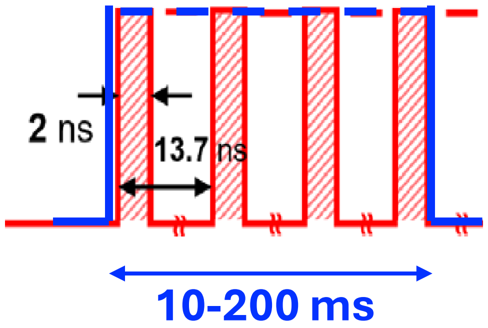
Free-standing membrane

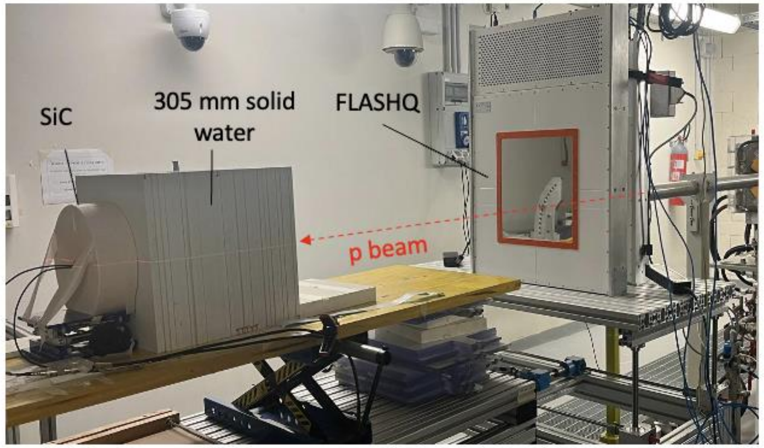


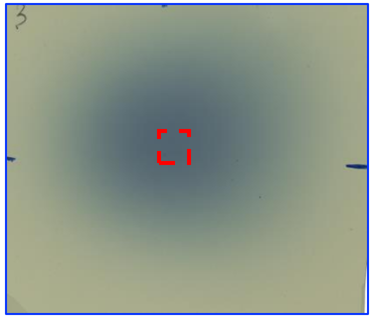
Characterization with 228 MeV UHDR **proton** beams up to 500 Gy/s

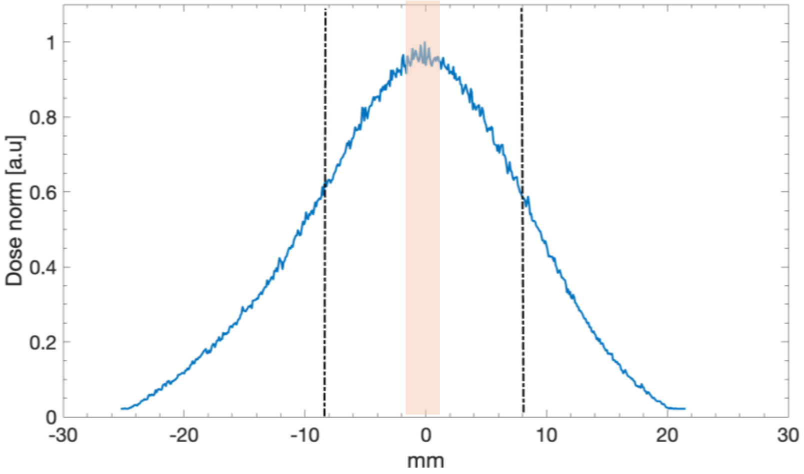
Proton beams @ 228 MeV
Variable beam current from 1 nA up to 500 nA
Variable irradiation time from 10 ms up to seconds

Azienda Provinciale per i Servizi Sanitari
Provincia Autonoma di Trento

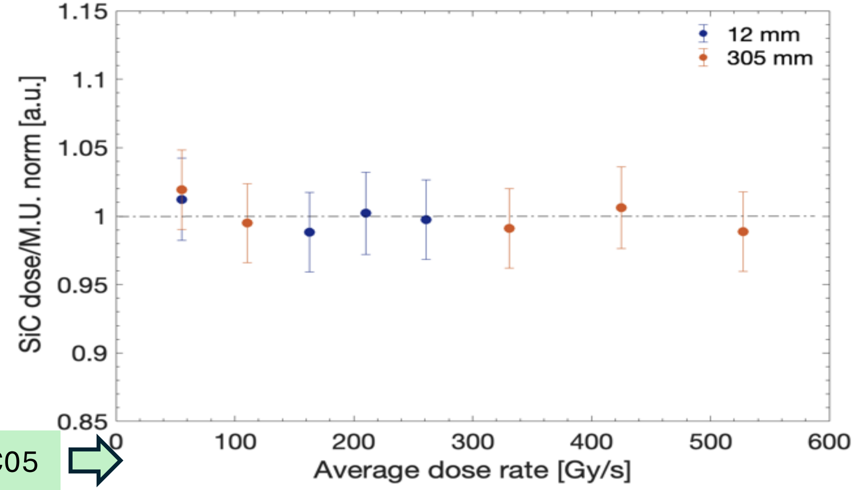






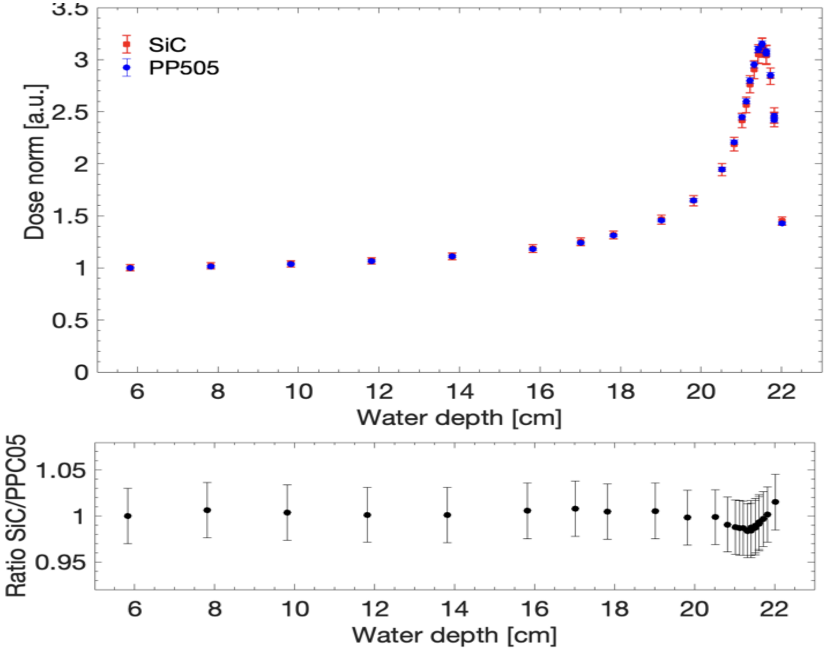


Varying the dose rate and irradiation time 30-200 ms, constant dose ~*10 Gy*



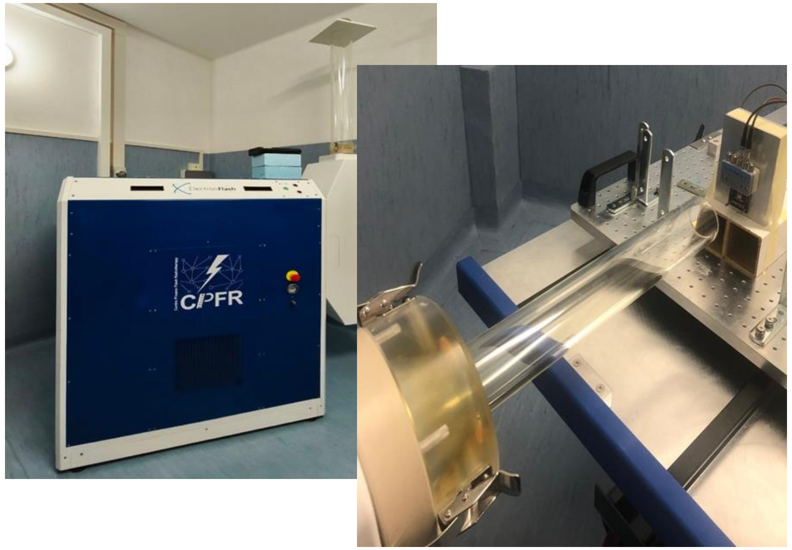
500 Gy/s

PPC05

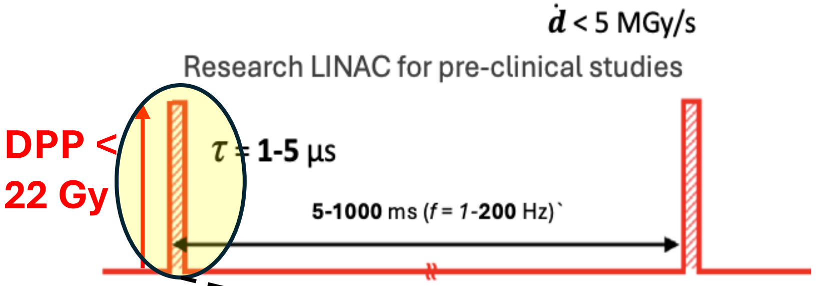


G. Milluzzo et al., accepted in Physics Medicine and Biology (2025)

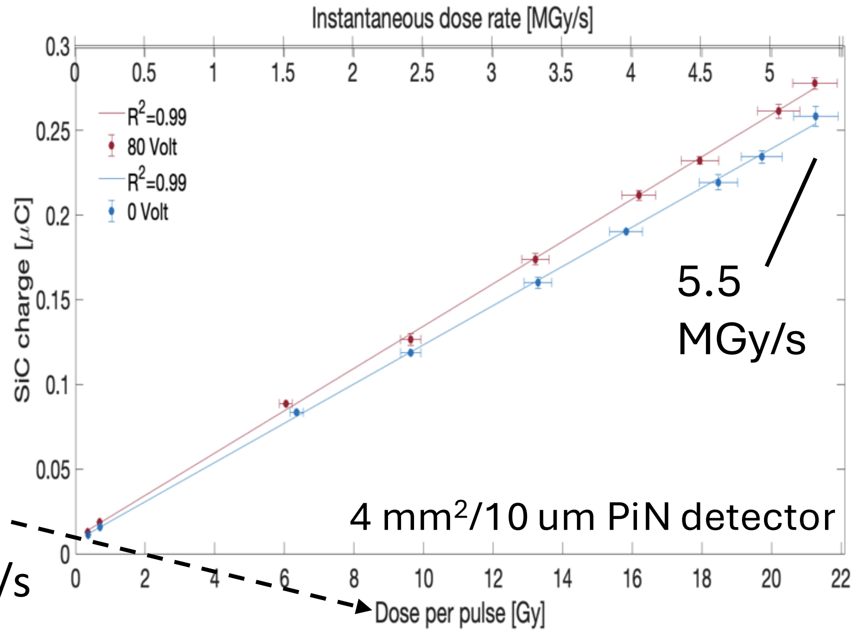
Towards higher dose rates: pulsed electron beams



Temporal structure

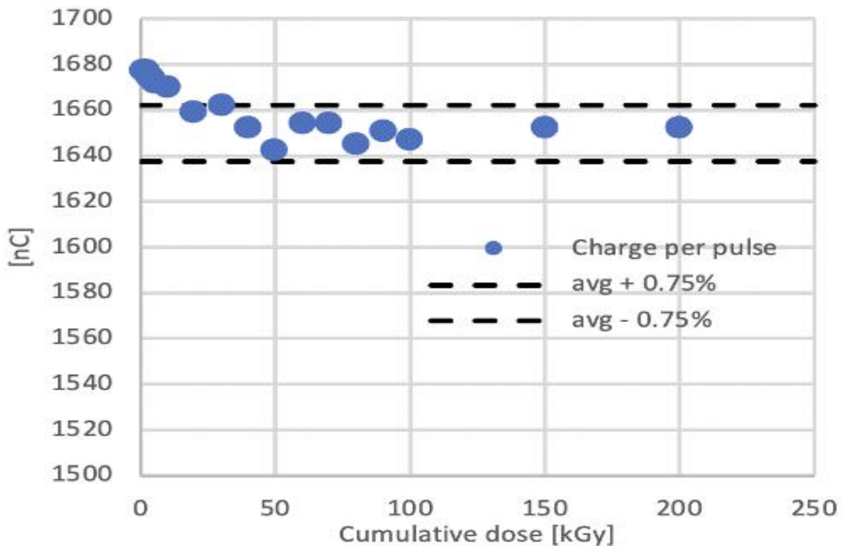


- **9 MeV pulsed electorn beams**
- Single pulse duration: 0-5-4 us
- Dose per pulse: from 0.1-20 Gy
- Instantaneous dose rates up to 5 MGy/s



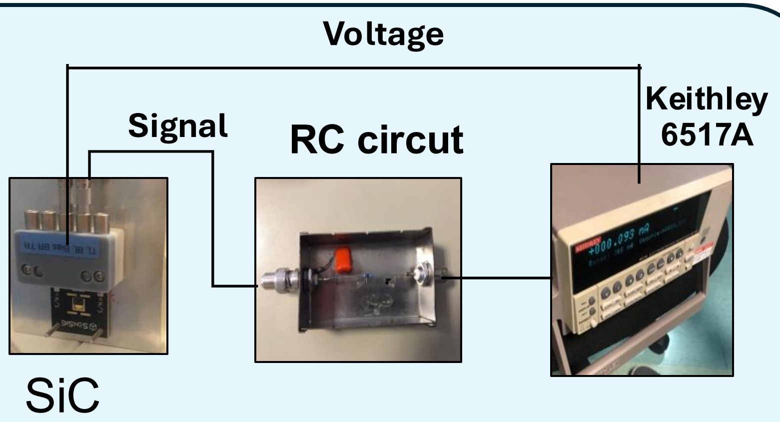
F. Romano et al., (2023), Appl Science
G. Milluzzo et al., (2024) Medical Physics
G. Milluzzo et al., (2025), Physics in Medicine & Biology

First measurement of radiation hardness

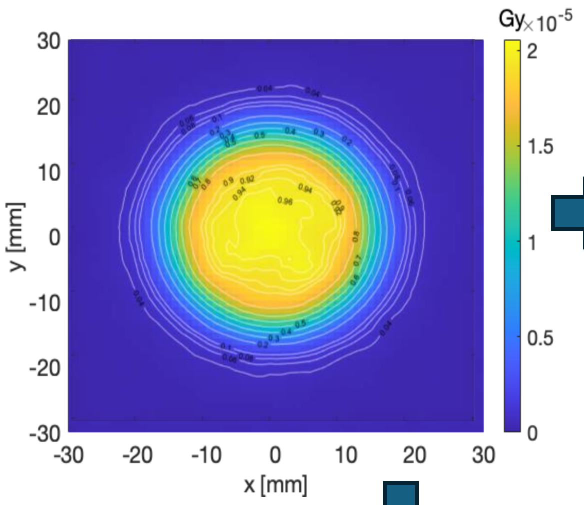


Experimental setup

- Detectors: 10x10, 5x5, 4.5 mm² 10 um thick SiC at the build-up
- Acquisition: Keithley electrometer
- Reference dosimeters: **Alanine dosimeters**



Dose distributions measurements with 1D/2D SiC systems



1D Array: **DREAM**

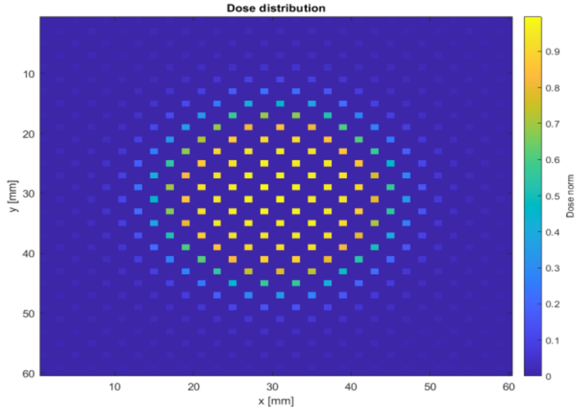
Detecto**R** for dose profil**E** me**A**sure**M**ents at FLASH regimes

Silicon carbide array **D**etecto**R** for dose profil**E** me**A**sure**M**ents at FLASH regimes

R4I Research for Innovation

2D matrix → **DALI'**

Development of **A**dvanced dosimetric techniques for u**L**tra-h**I**gh dose rate beams



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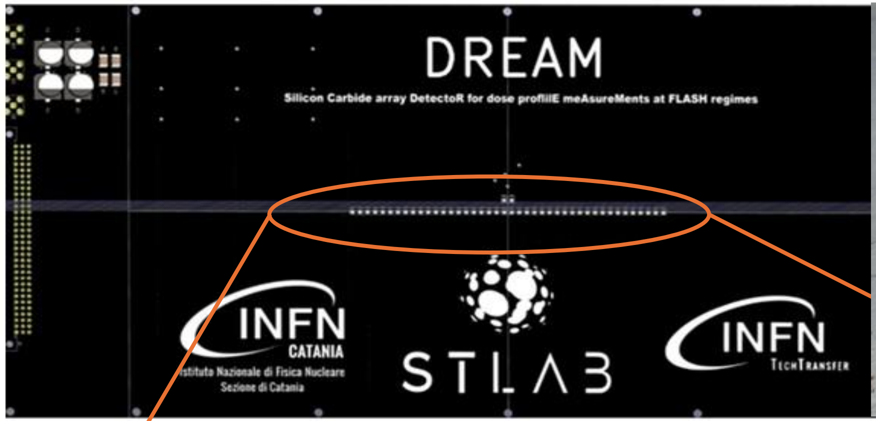
UNIVERSITÀ DEGLI STUDI DI PALERMO

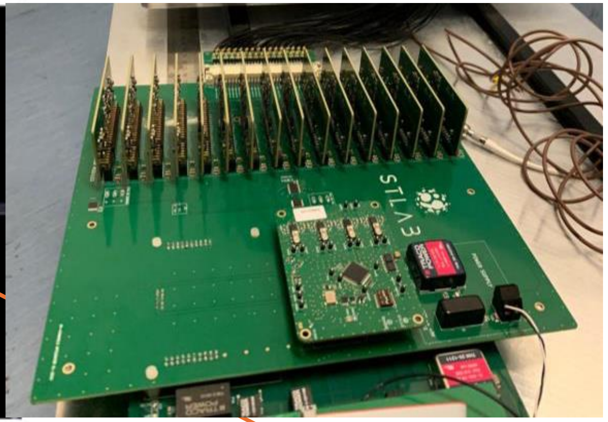
THE Tuscany Health Ecosystem

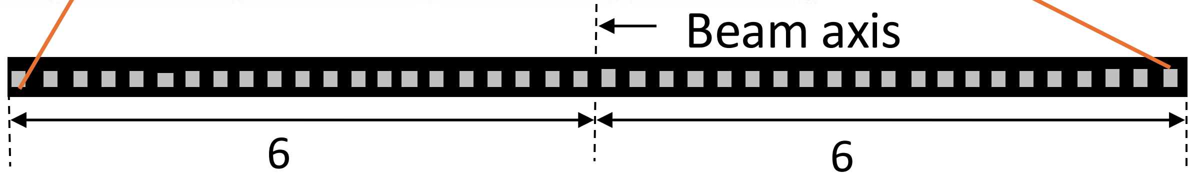
- Minimizing the number of detectors and the cost → optimized design and SiC displacement
- Support for the future clinical trial with UHDR e- beams @ CPFR

>60 small size (1 mm) SiC detectors mounted on a PCB



Analogic integrating readout electronics





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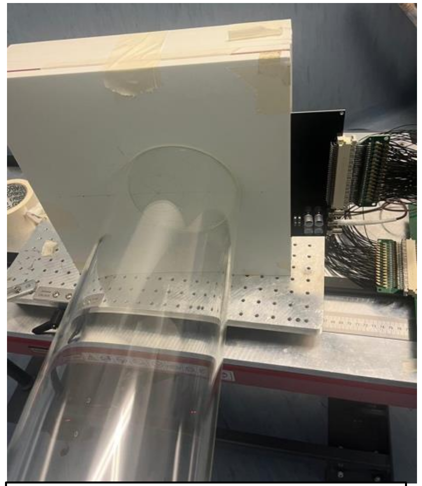
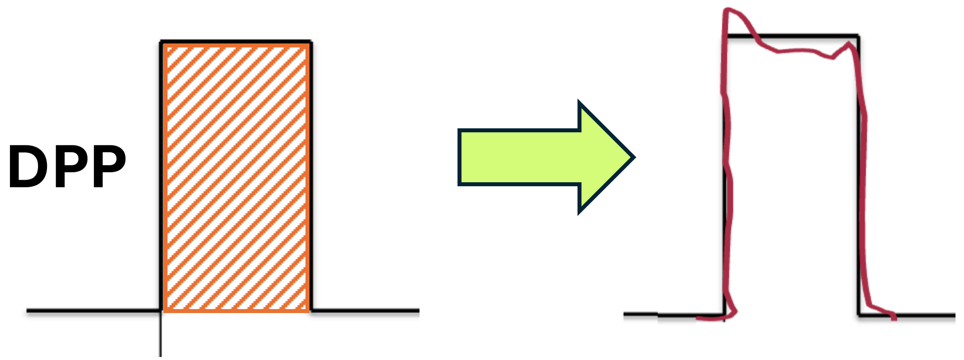
First test with UHDR electron beams



Patent submitted

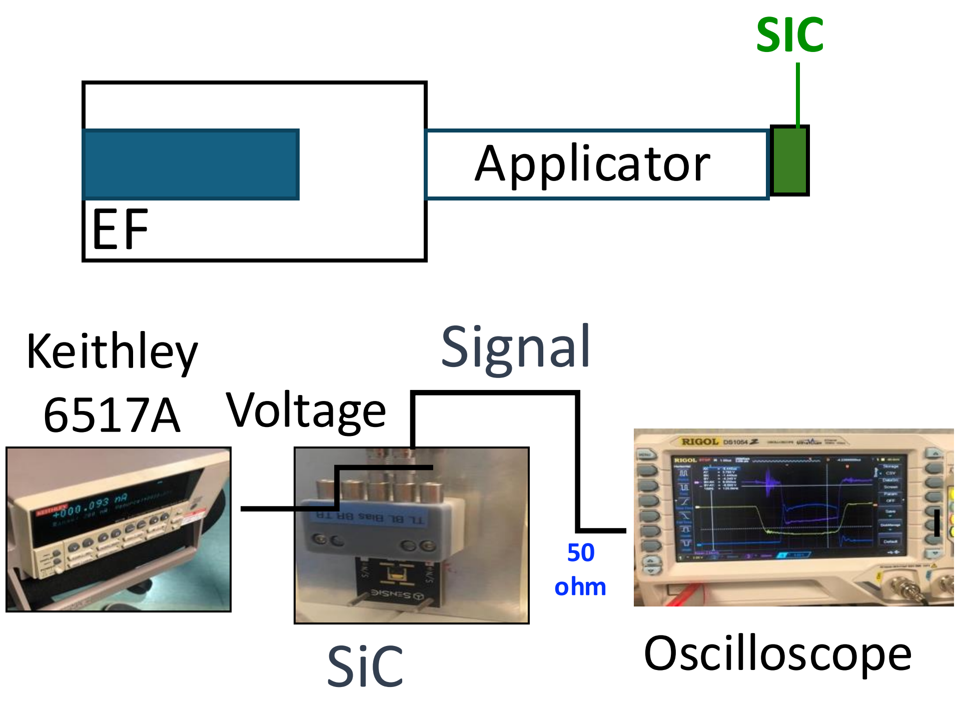
Real time monitoring of single pulse waveforms

FRIDA

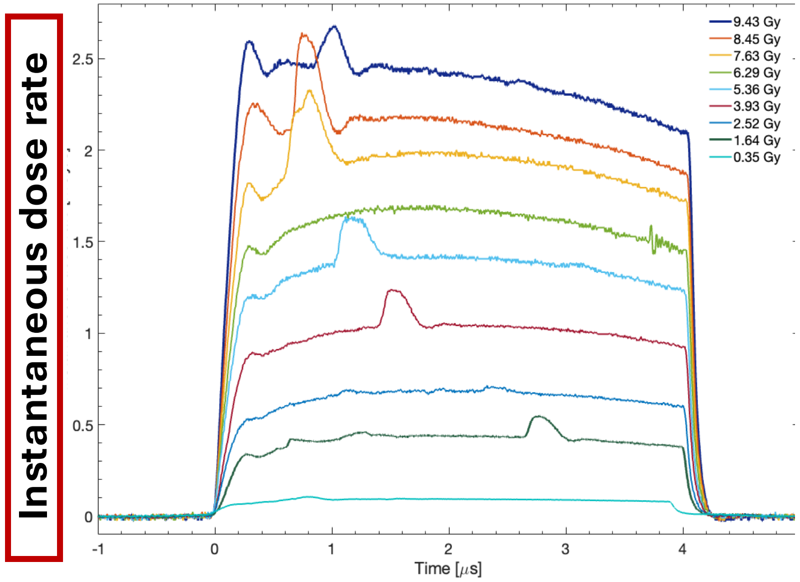


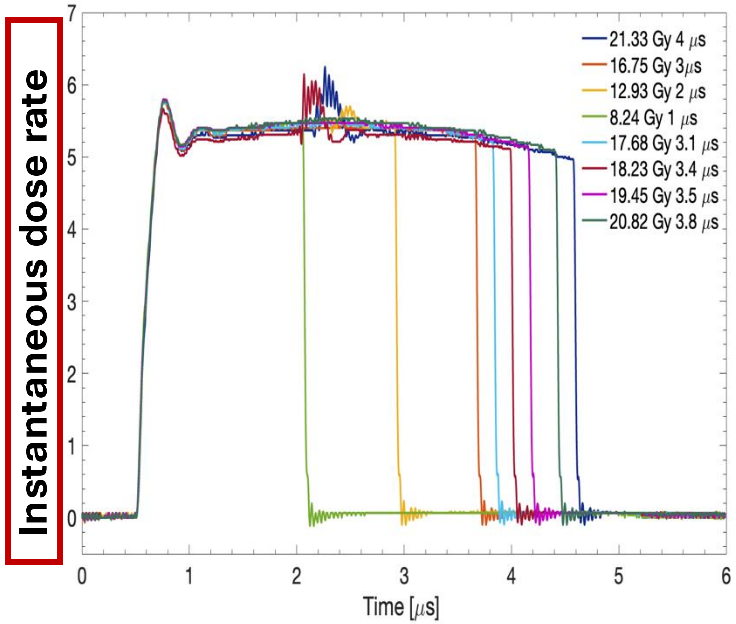
- **Time resolution** of the order of '10 ns to measure the small variation of the electron beam current within the pulse
- **Sensitivity** at different DPP
- **Measurement** of the pulse width

✓ Accurate measure of the DPP

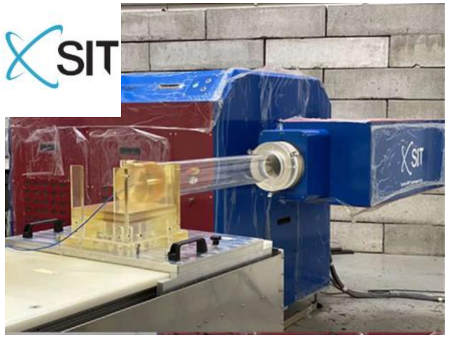


After applying the calibration factor in dose [Gy/nC]



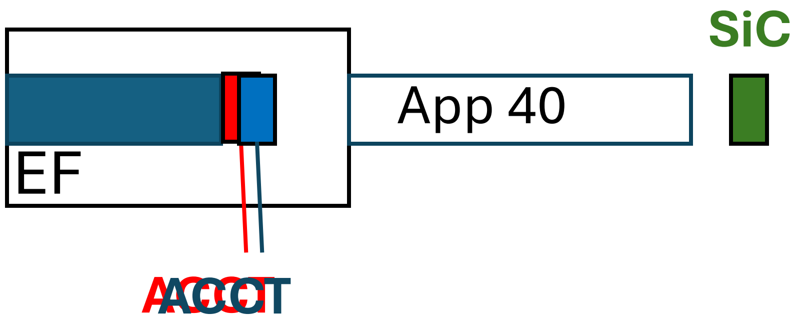


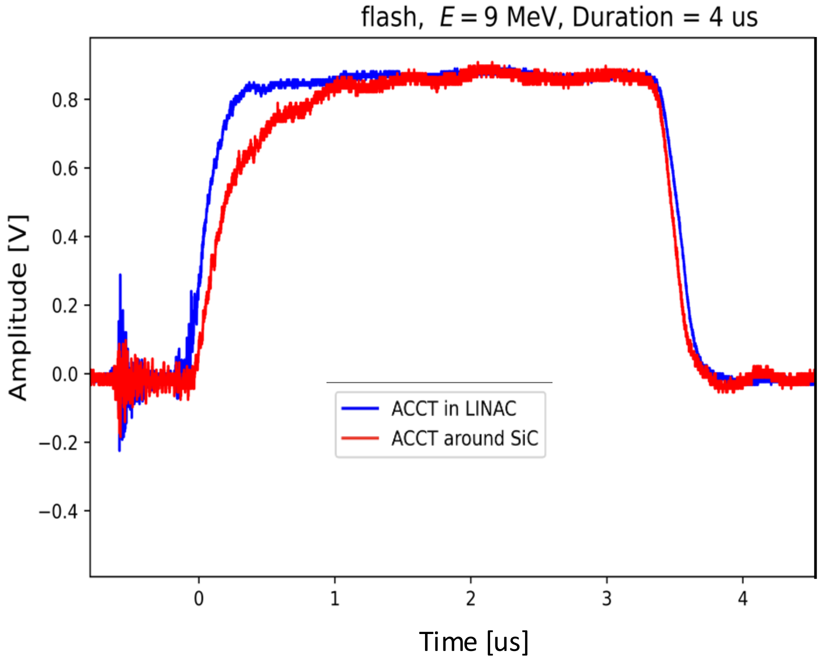
Real-time beam monitoring:
cross-comparison with reference beam monitoring detectors (ACCT)

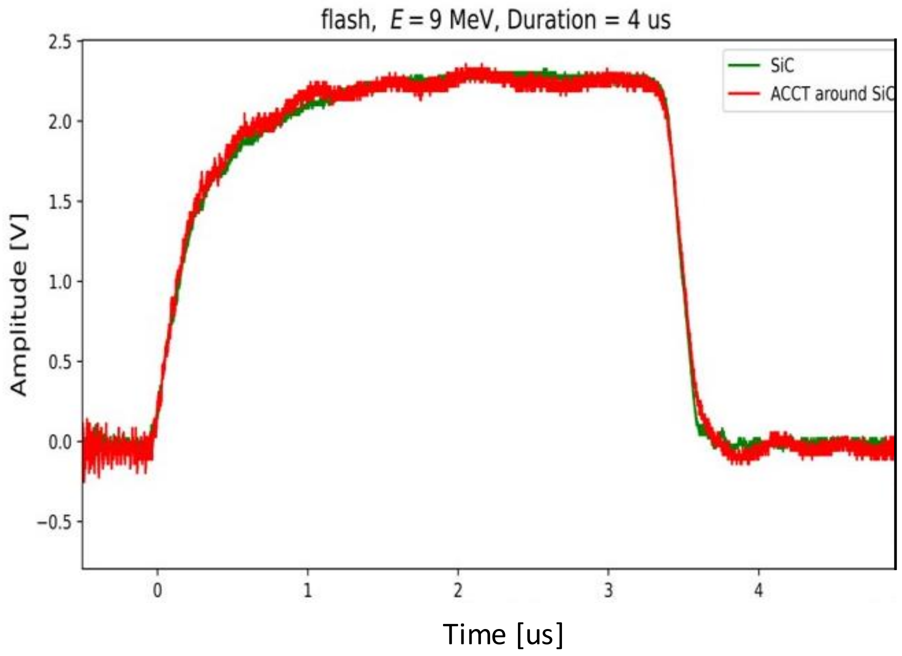


ACCT (AC current transformer)

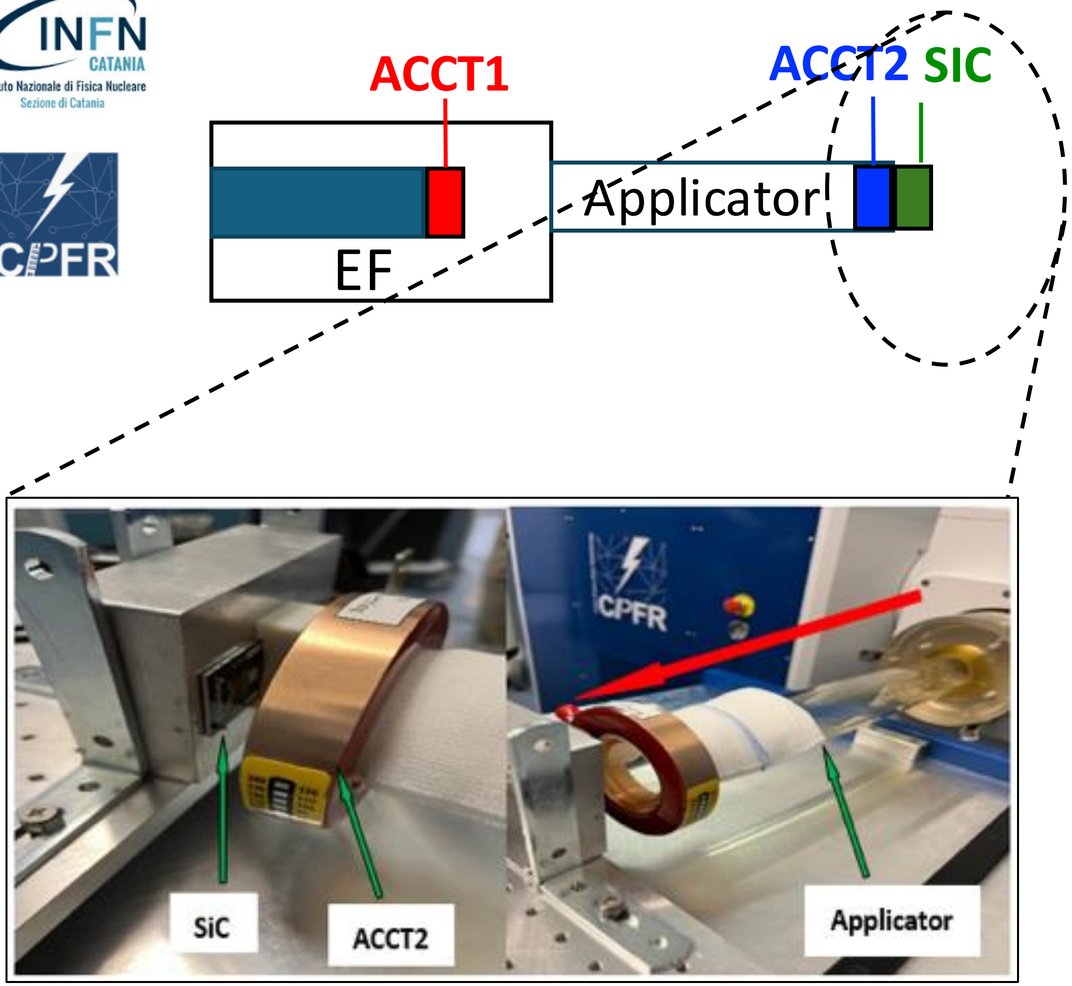
(no position sensitive)

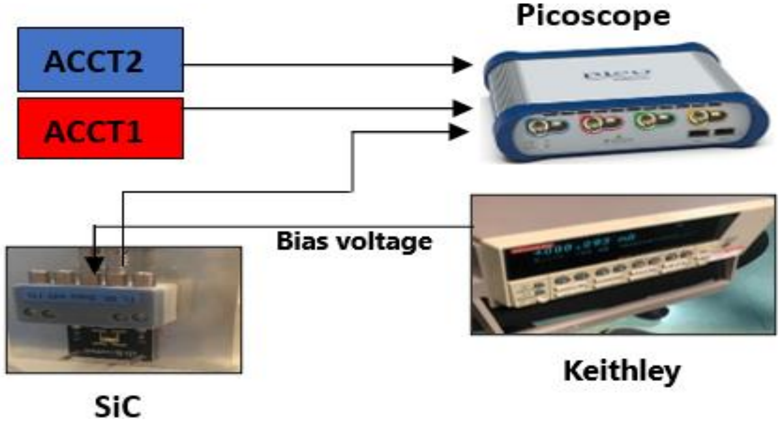






Systematic comparison of the ACCT and SiC signals in different conditions and experimental setups @ CPFR

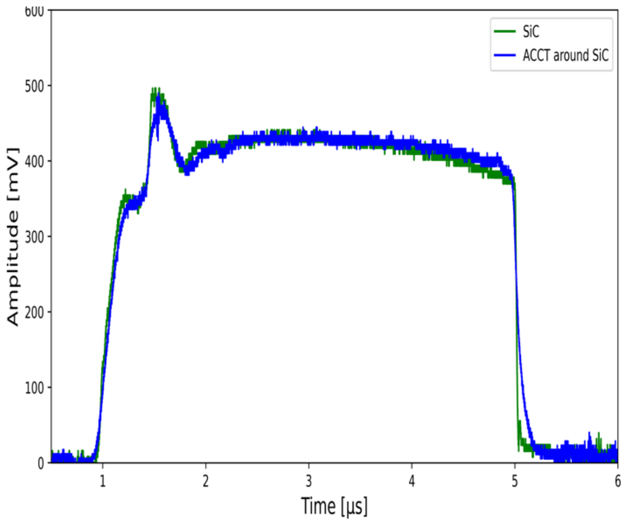


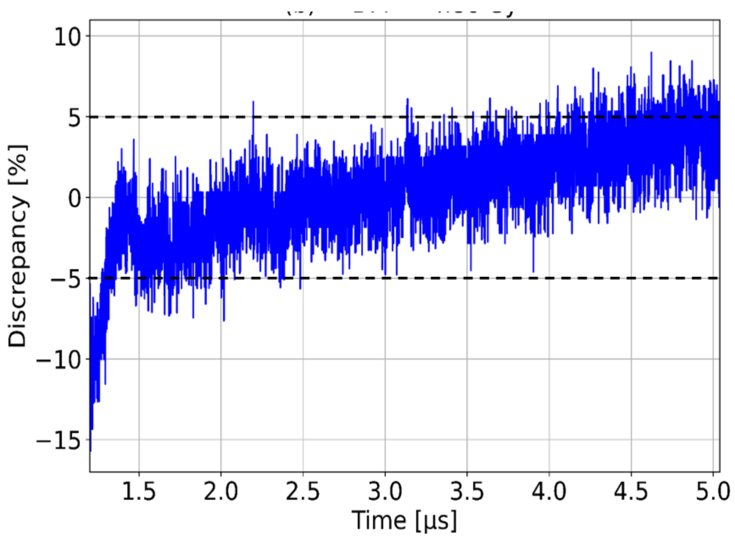


Experimental setup

- App 40 mm
- DPP=0.698-3.87 Gy/pulse
- ACCT1 (linac)
- ACCT2 (irr point)
- 4.5 mm2 diameter SiC
- 500 MHz Picoscope

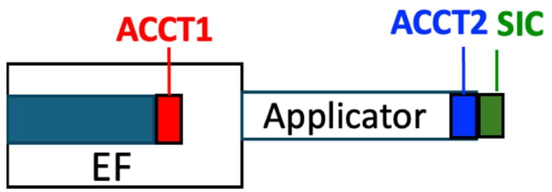
COMPARISON OF SIC-ACCT WAVEFORMS AT THE SAME POSITION





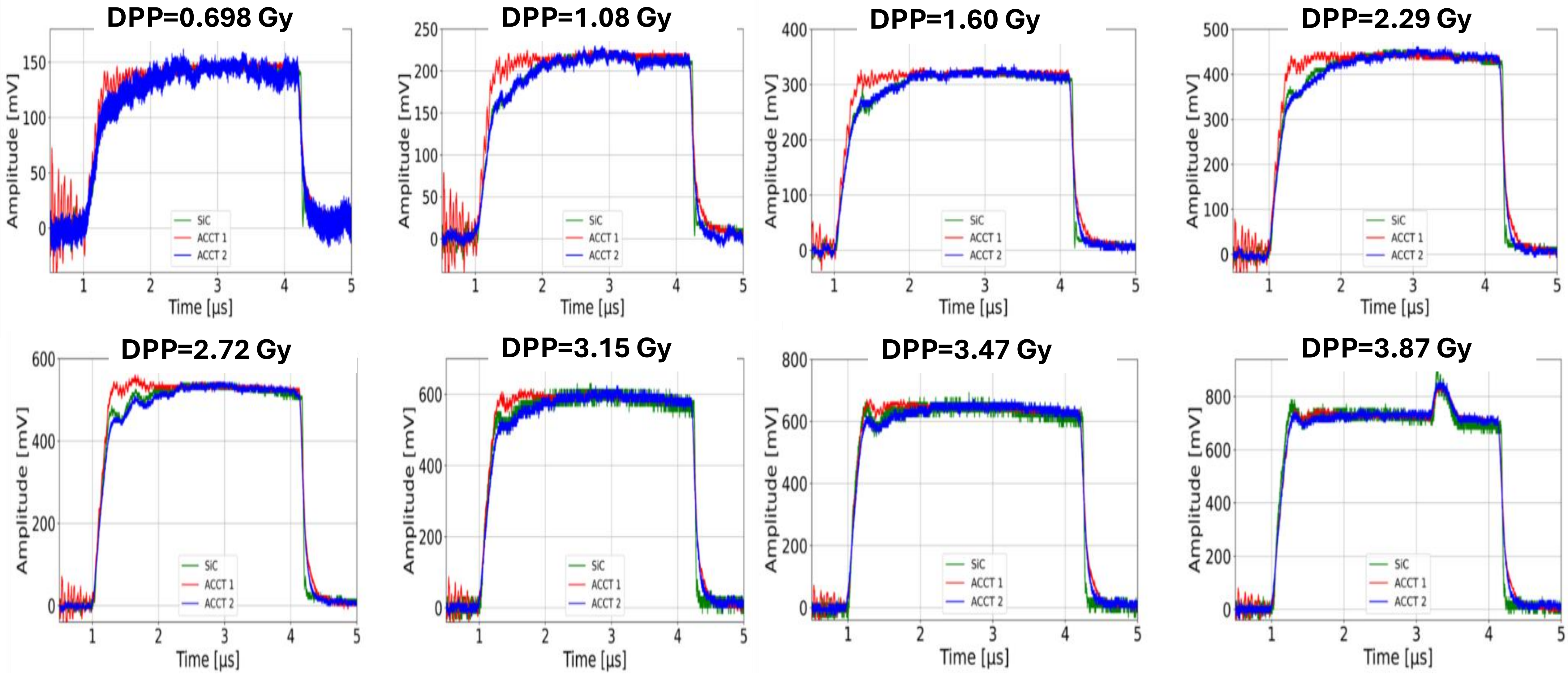
C. Okpuwe et al., Radiation Research (2025)

Comparison of ACCT1, ACCT2 and SiC waveformes



C. Okpuwe et al., Radiation Research (2025)

Dose per pulse (DPP)

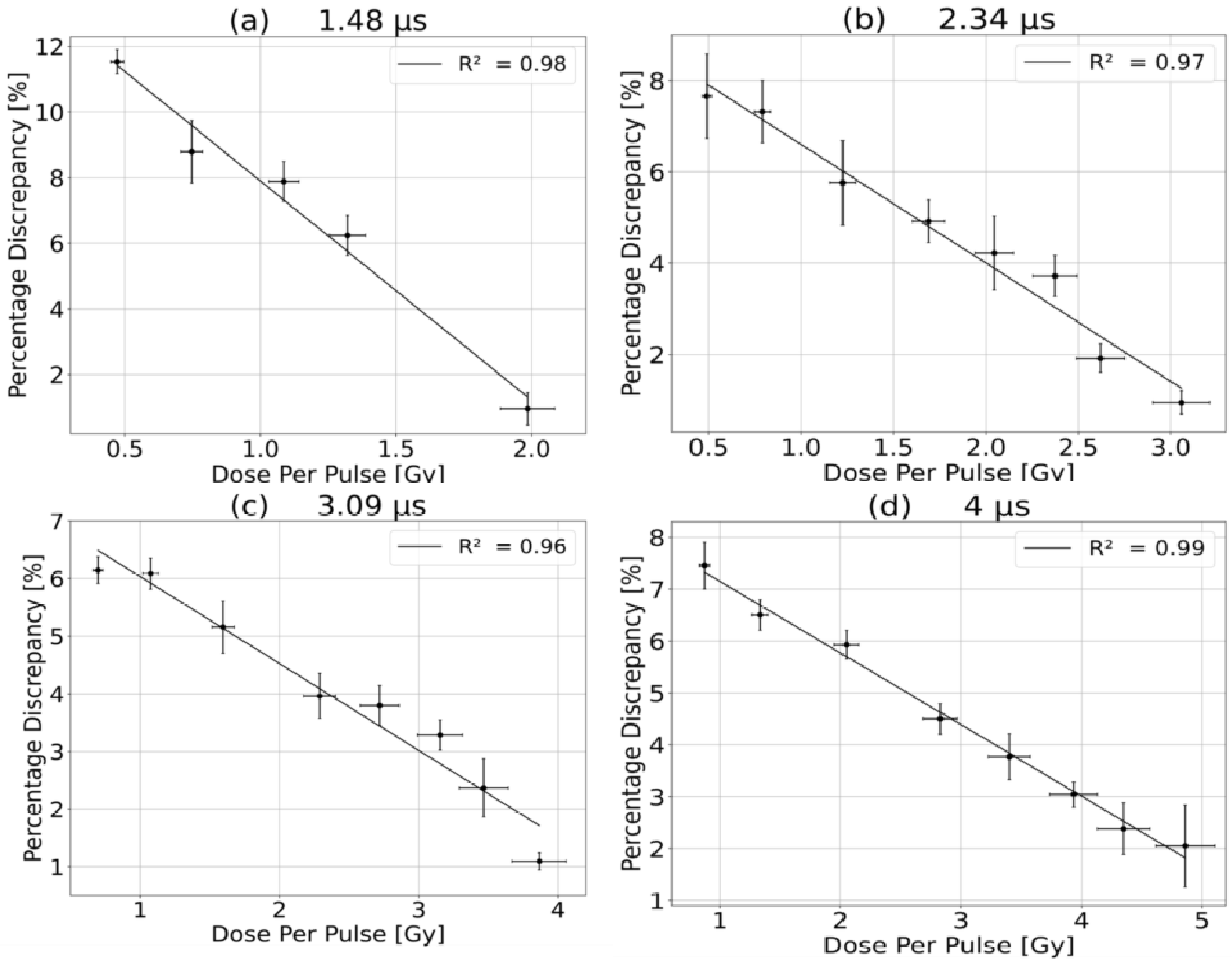


Quantitative analysis of the integral discrepancy between the ACCT1 and the SiC detector

Percentage discrepancy of the normalized integrals

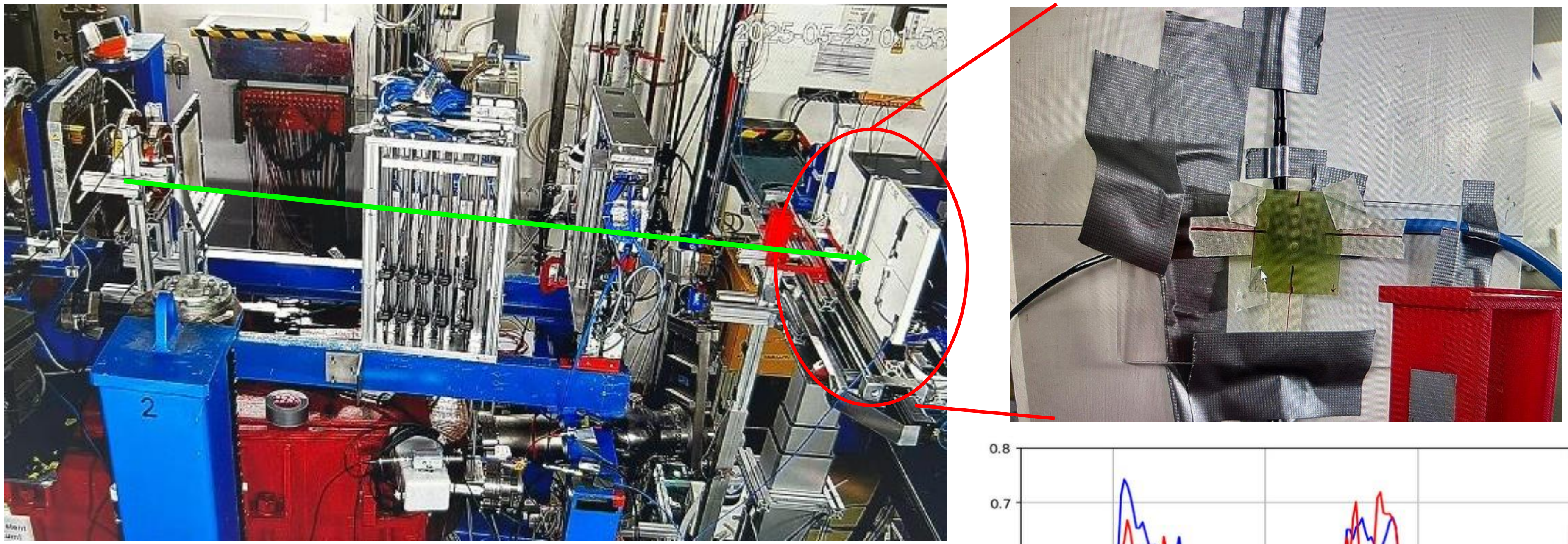
$$Dis = \left(\frac{Int\_ACCT1 - Int\_SiC}{Int\_ACCT1}\right) * 100\ [\%]$$

$$\Delta Dis = \frac{1}{Int\_ACCT1} * \left(\sqrt{(\Delta Int\_SiC) + \left(\frac{Int\_SiC}{Int\_ACCT1}\right)^2 (\Delta Int\_ACCT1)^2}\right) * 100\ [\%] \qquad (4)$$



C. Okpuwe et al., Radiation Research (2025)

Experiment with UHDR carbon ion beams@ GSI

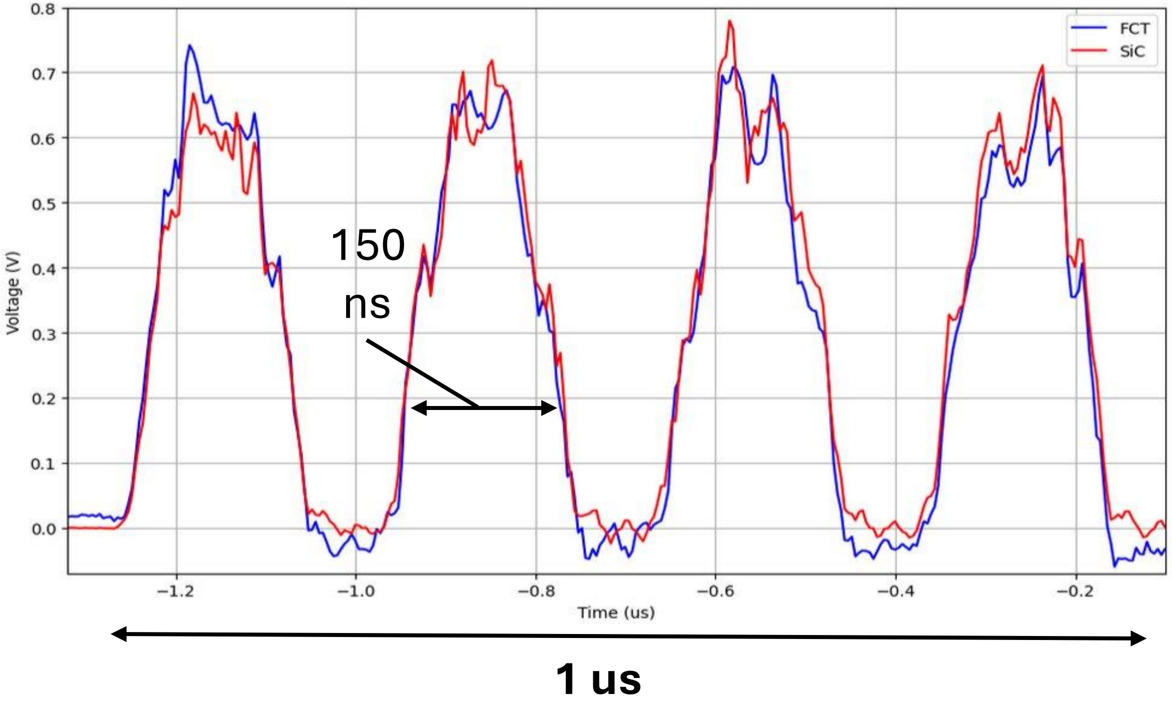


Daria Boscolo (GSI)
Weber Ulrich (GSI)

✓ Submitted proposal in collaboration with GSI researchers

Beam parameters
number of carbons: **10^9 carbons**
Energy = **240 MeV/u**
1 spill = **1 us**
Beam scatterer = 1mm thick **lead foil**

Detectors
Encapsulated SiC, flash diamond
Fast current transformer (**FCT**)



Conclusions and remarks

- ✓ Possibility to realize **different area and thickness** SiC detectors with different sentitivities
- ✓ Building **encapsulated SiC dosimeters** for reference dosimetry in water
- ✓ Linearity of charge response with the dose rate using different particle beams with different temporal profiles: from almost continuous proton beams to ultra high pulsed electron beams with dose per pulse and instantaneous dose-rate up to **20 Gy/pulse** and **5.5 MGy/s**
- ✓ Multiple SiC array and matrix for 1D/2D **spatial dose distribution (QA)** for FLASH radiotherapy
- ✓ **Temporal structure** of single electron pulses
- ✓ Validation and comparison with established toroids

→ Potentiality to be used in more extreme beam temporal structure , such as VHEE electron beams (10’s ps sub bunches)

Italian AIFM Working Group on FLASH Radiotherapy and SFRT (Spatially Fractionated Radiation Therapy)

ASSOCIAZIONE ITALIANA DI FISICA MEDICA

Coordinators:
F. Di Martino (AUOP, Pisa) and F. Romano (INFN Catania)

- 52 components
- Proposed and approved in July 2023
- Kick-off meeting (remote) in December 2023: objectives and activity plan presented
- Second practical meeting (remote) to define the activities and propose sub-groups in March 2024:

1. Dosimetric protocol for low energy UHDR e- bems
2. Report on available technologies for dosimetry for FLASH

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1) definition of reference conditions	S. Andreoli, A. Ciccotelli, F. Di Martino, L.Masturzo, G. Milluzzo, J. Pensavalle, F. Romano, A. Giuliano, **A. Soriani.**
2) Measurement of absolute dose in reference conditions	S. Andreoli, L. Barone Tonghi, A. Ciccotelli, F. Di Martino, S. Linsalata, M. Marrale, **L. Masturzo**, G. Milluzzo, J. Pensavalle, F. Romano, A. Soriani. I. Veronese, A. Giuliano
3) Measurement of the instantaneous dose rate and pulse shape	A.G. Amico, F. Di Martino, **G. Milluzzo**, J. Pensavalle, F. Romano.
4) Relative dosimetry	S. Andreoli, L.Barone Tonghi, F. Di Martino, S.Linsalata, M. Marrale, L.Masturzo, G. Milluzzo, **J. Pensavalle**, **L. Raffaele,** F. Romano, A. Soriani, A. Spinelli, C. Talamonti, I. Veronese.
5) Newly developed detectors and future applications	M. Bruzzi, E. Ciarrocchi, K. Kanxheri, F. Di Martino, G. Milluzzo, F. Romano, A.Spinelli, c. Talamonti, **A. Vignati**, I. Veronese, J. Pensavalle.

Support clinical trials at CPFR in Pisa in 2025 !

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Thank you for your attention

Anthem — AdvaNced Technologies for Human-centrEd Medicine

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