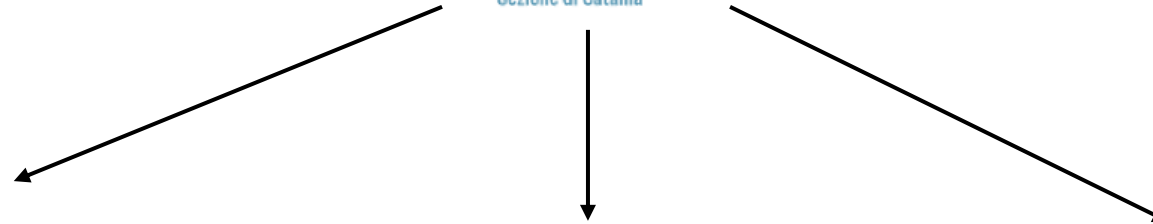




Activities on **Silicon carbide** dosimeters, graphite calorimeters and **alanine** pellets within the FRIDA project

G. Milluzzo, G. Arcidiacono, C. Okpuwe, S. Ahmed, G. Trovato, D. Zitelli, M. Marrale, M.C. D'Oca, L. Napoli, G. Pusateri, R. Guerrera, F. Romano

FRIDA general meeting, 4 Marzo 2026



Alanine pellets for reference absolute dosimetry



Silicon Carbide detectors for dosimetry and beam monitoring



Graphite calorimeter for dosimetry in reference conditions



Synergy with the PNRR-PNC ANTHEM project



Anthem
Advanced Technologies for Human-centred Medicine

Dosimetric characterization of the beams with reference dosimeters: alanine dosimeters

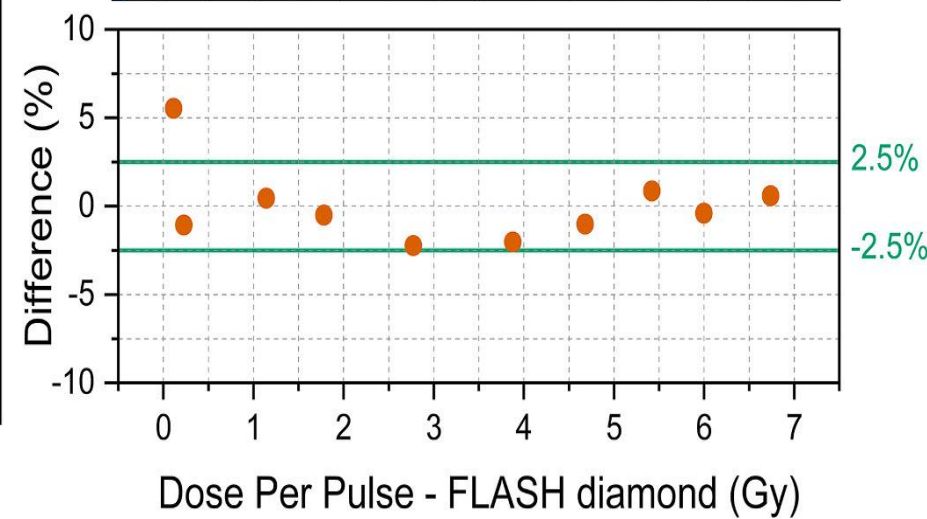
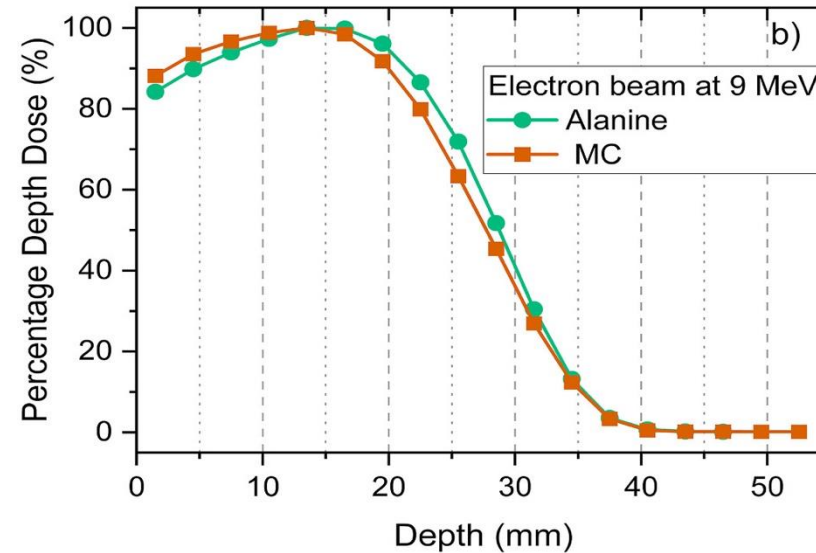
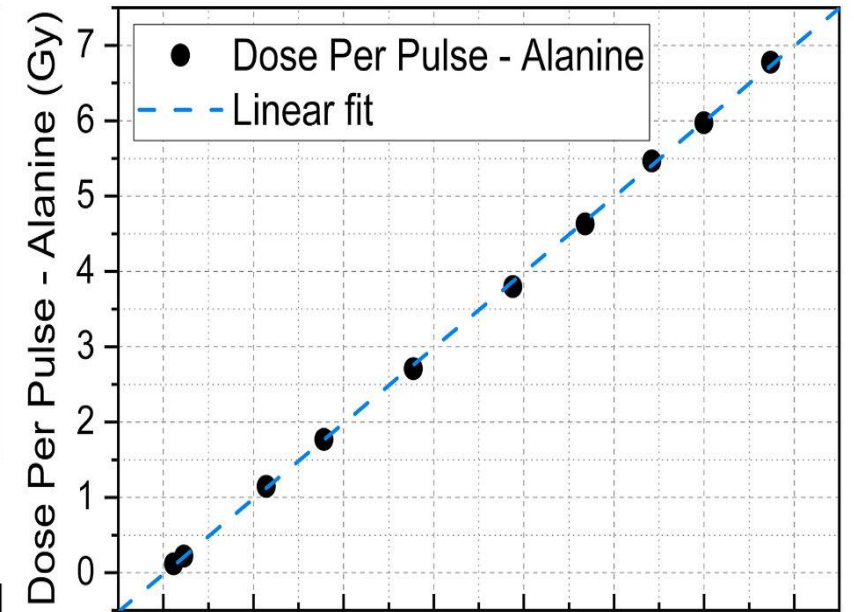
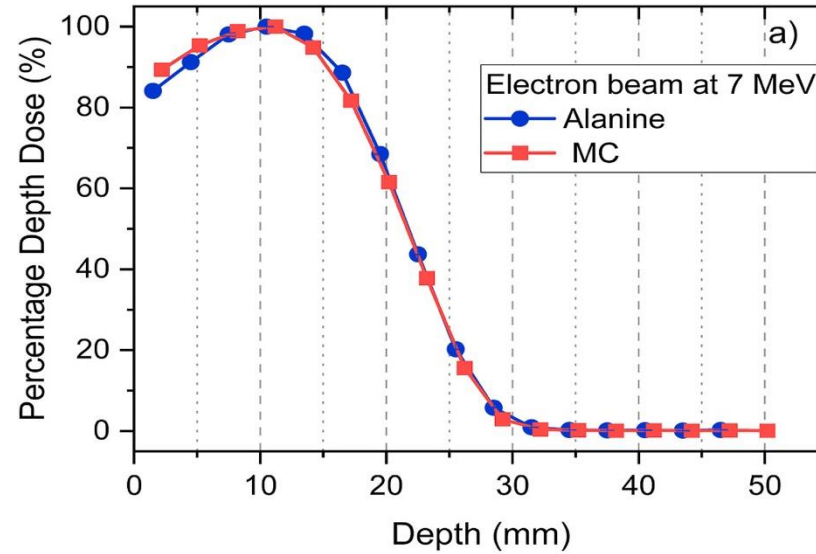
Alanine pellets



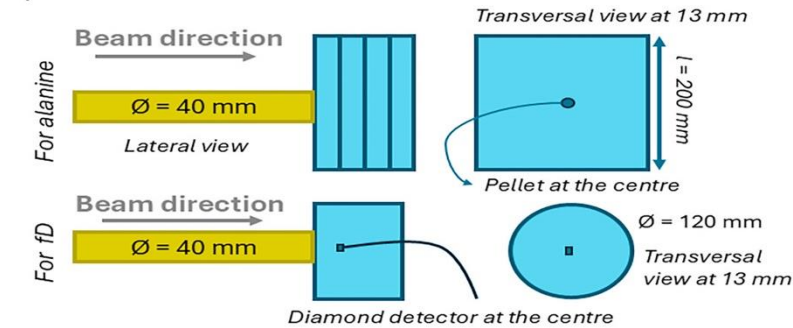
- Gamma-Service
- diameter 4.80 mm

Calibration

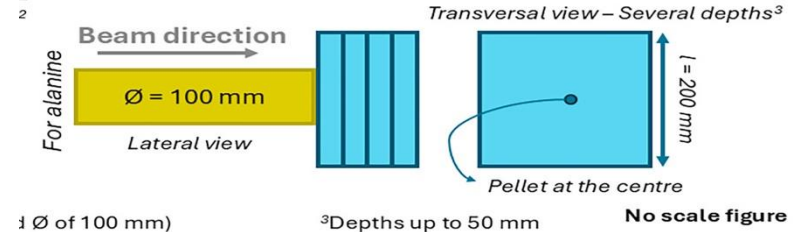
- Elekta Versa HD linear accelerator.
- Dose Range: 2.5 Gy to 20 Gy
- Photons: 9 MV



MEASUREMENTS OF DPP



MEASUREMENTS OF PDD

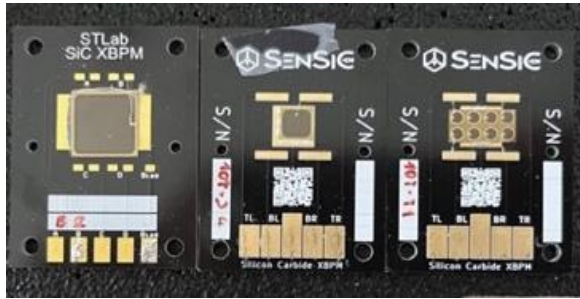


Silicon carbide detectors for dosimetry in radiotherapy

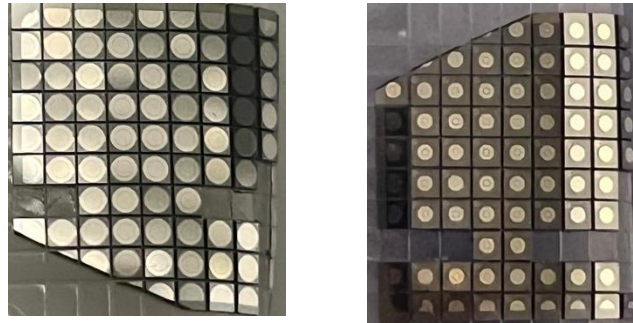


PiN diodes: 4-100 mm², 10 um thick

10x10 mm² 5x5 mm² 2x2 mm²



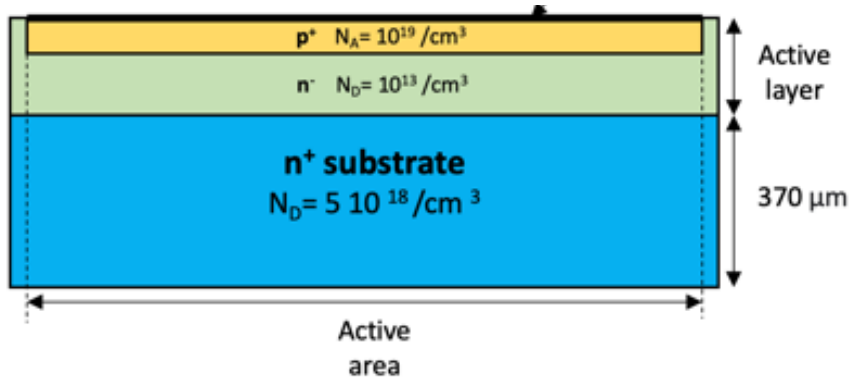
Schottky diodes: 300-800 um diameter, 22 um thick, Guard ring structure to reduce superficial leakage



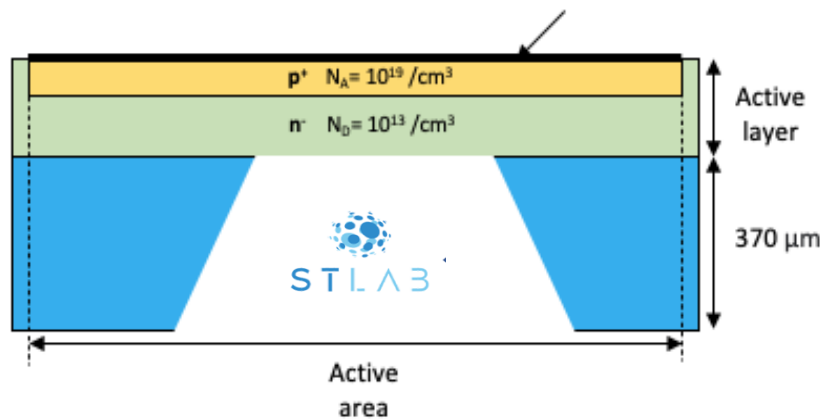
Waterproof encapsulated SiC detector for reference dosimetry



Standard configuration with thick bulk substrate

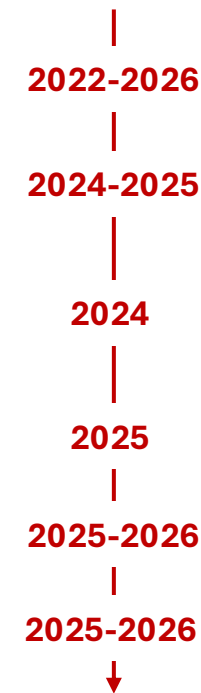


Free-standing membrane



Experiments and dosimetric characterization with UHDR beams

Facility	Accelerator	Particle type	Energy	Dose rate
CPFR	Electron flash linac	Pulsed (4 us) electrons	9 MeV	Conv-5 MGy/s
Trento Protontherapy Centre	Isocronus cyclotrons	Protons	228 MeV 180 MeV	Conv-500 Gy/s Clinical
Turin Linac	Modified Electa Versa 18 MV	Pulsed electrons (2 us)	10 MeV	1 MGy/s
GSI	Synchrotron	Pulsed (1 us) Carbon ions	240 MeV/u	10 ⁹ ions/spill
PTB	Linac	Pulsed (2 us) electrons	20 MeV	10 MGy/s
ALFA facility @ ELIbeamlines	LWFA 1KHz laser	Pulsed (10 fs) electrons	10-50 MeV	Average 6 Gy/min Inst dose rate >10 ¹⁰ Gy/s



Romano F, Milluzzo G, DiMartino F, et al., 2023 Appl Sci.

Milluzzo G, et al., 2024 Med Phys. ;1-12

Okpuwe C. et al., Journal of Instrumentation. 2024;19(3)

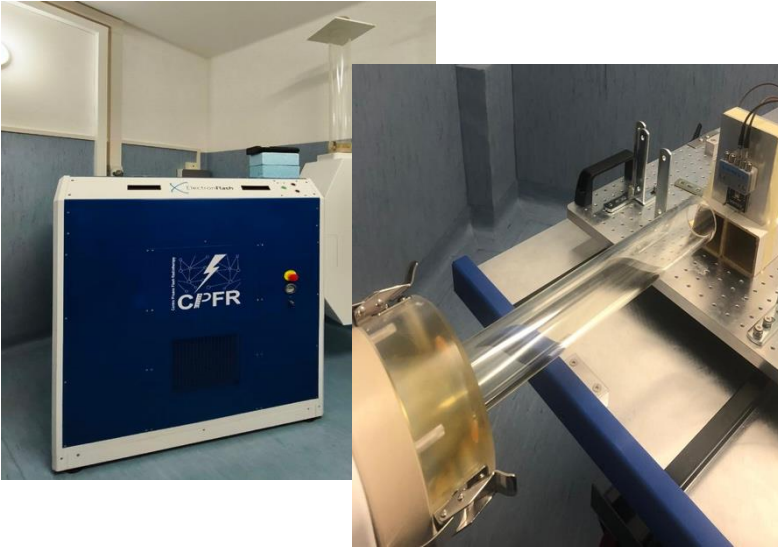
Milluzzo G, et al., 2025 Phys. Med. Biol. 70 205019

Okpuwe C. et al., Radiation Research 2025, 203(4), 236-245

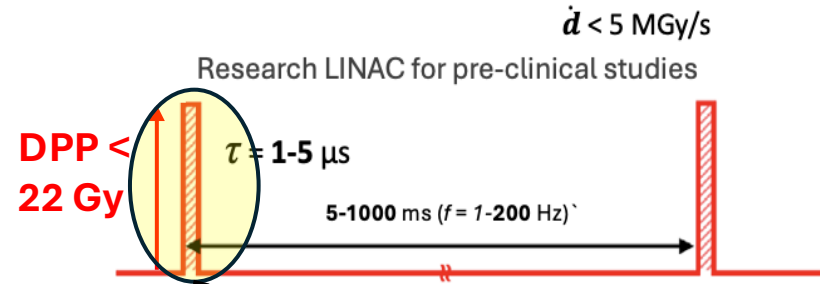
Trovato G. et al., accepted in Journal of Instrumentation 2026

Milluzzo G. et al., submitted in Nuovo Cimento 2026

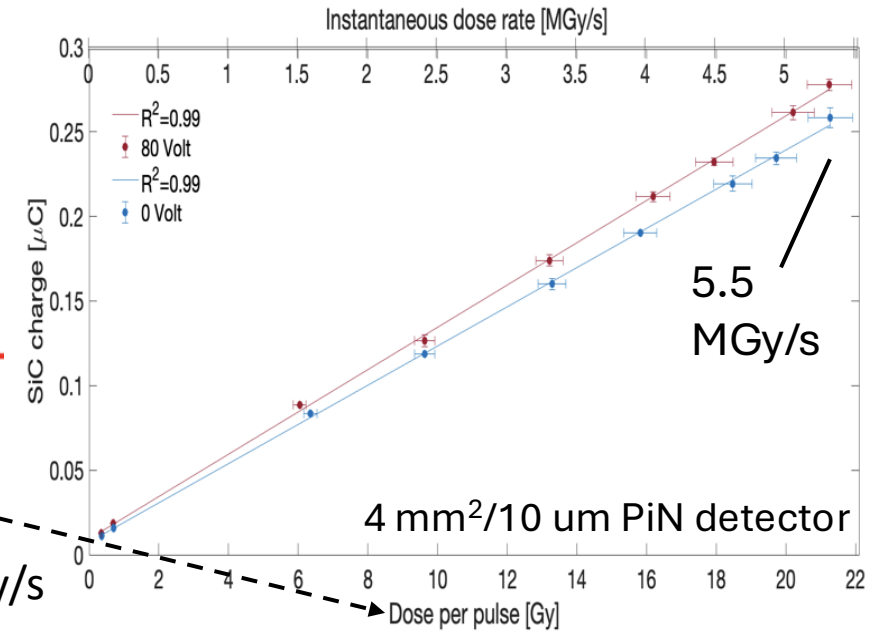
Pulsed electron beams @ CPFR



Temporal structure



- 9 MeV pulsed electron beams
- Single pulse duration: 0.5-4 μs
- Dose per pulse: from 0.1-20 Gy
- Instantaneous dose rates up to 5 MGy/s



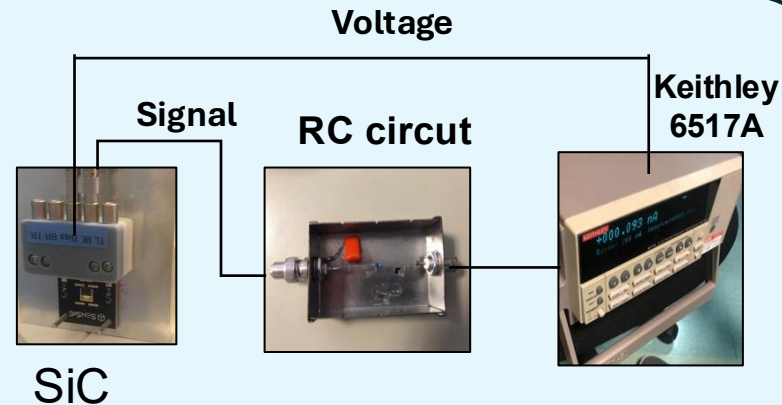
F. Romano et al., (2023), Appl Science

G. Milluzzo et al., (2024) Medical Physics

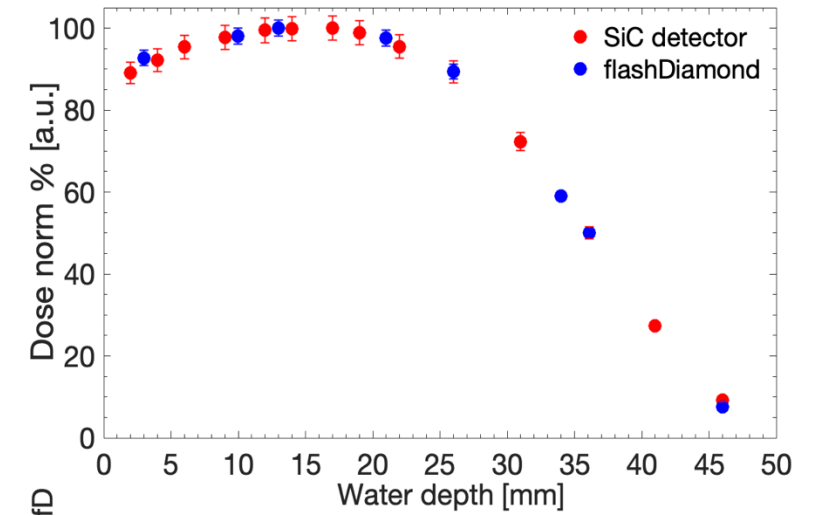
G. Milluzzo et al., (2025), Physics in Medicine & Biology

Experimental setup

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

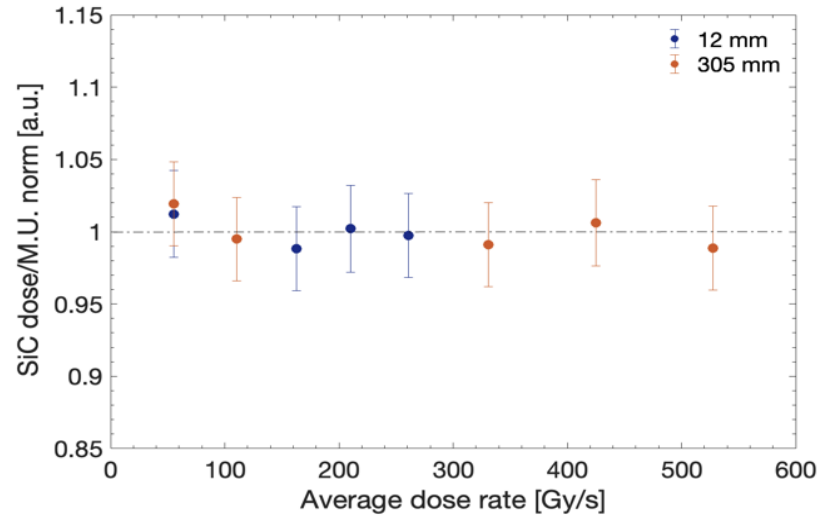


PDD measurement

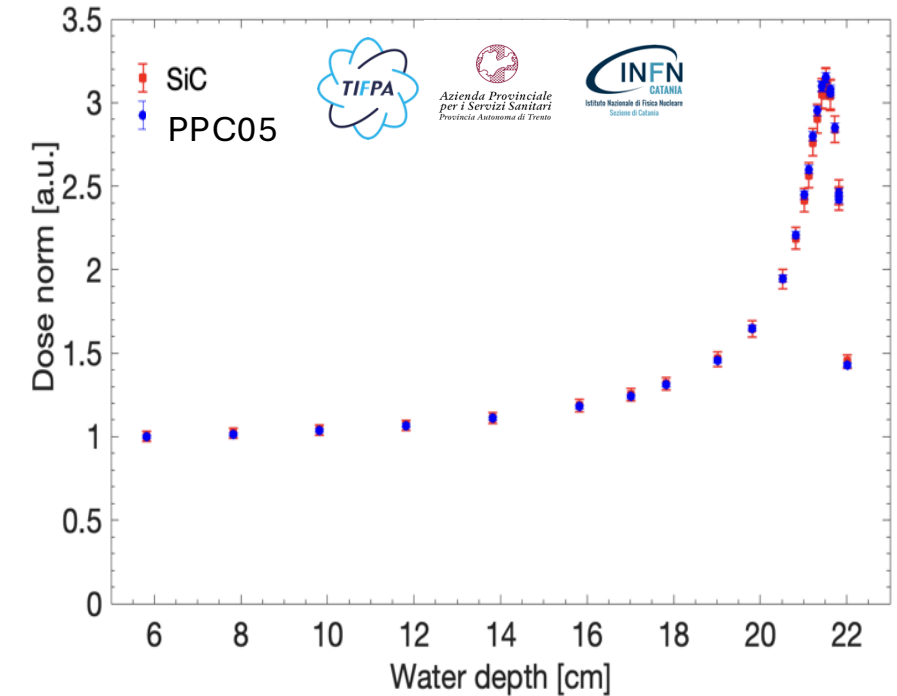
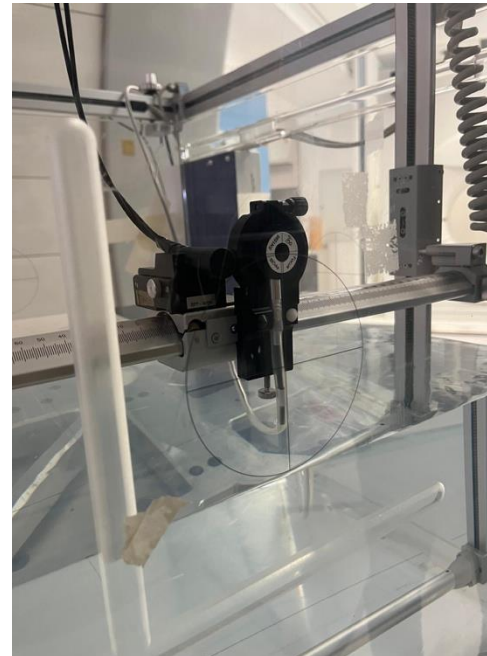


Silicon carbide dosimeters for UHDR protontherapy

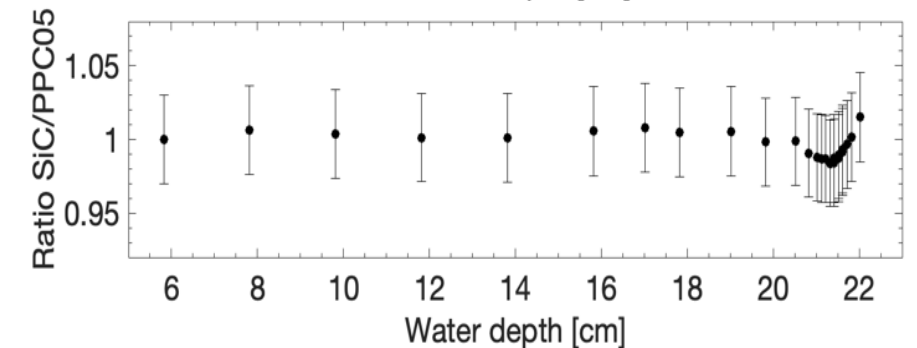
228 MeV **UHDR** proton beams



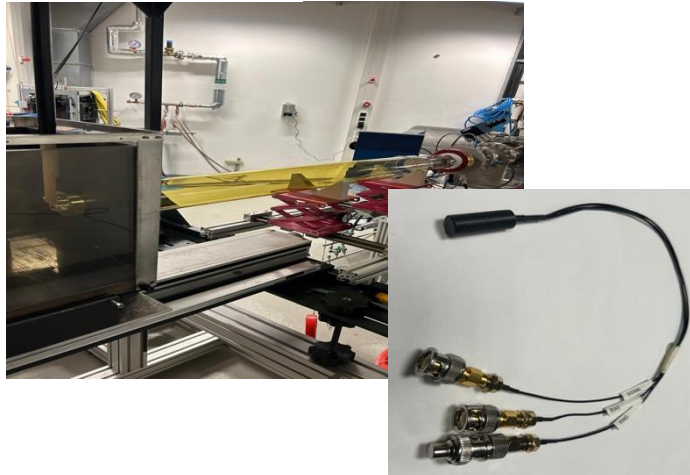
180 MeV **clinical** proton beams



Waterproof encapsulated SiC detector
for reference dosimetry in water



Characterization of the SiC dosimeter @ PTB

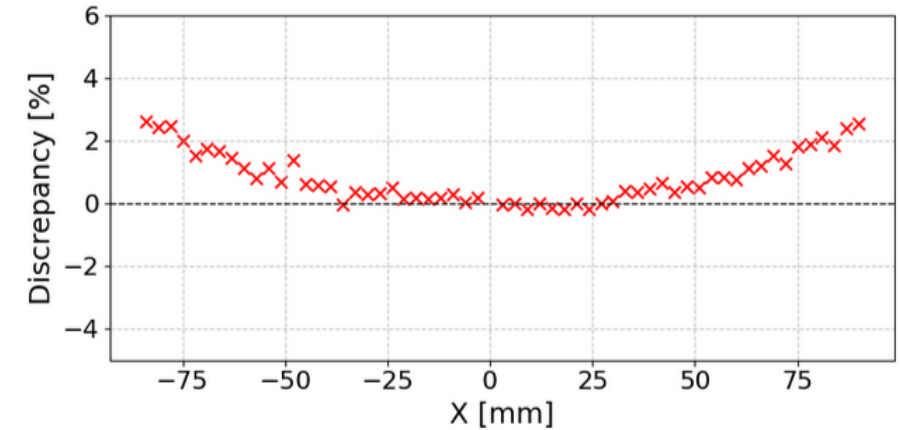
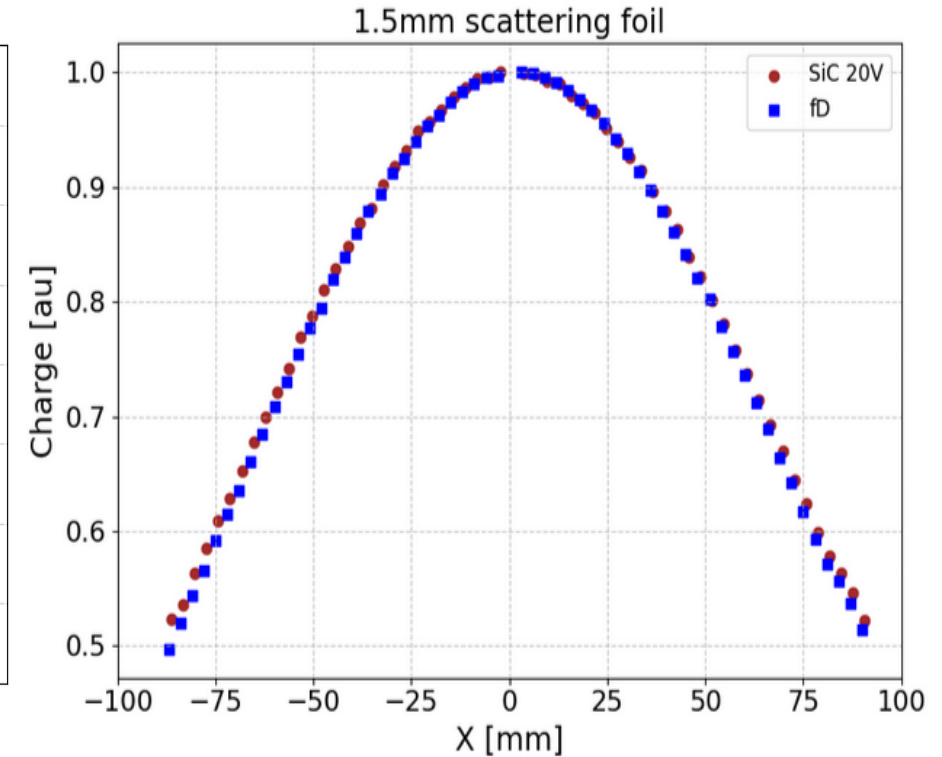
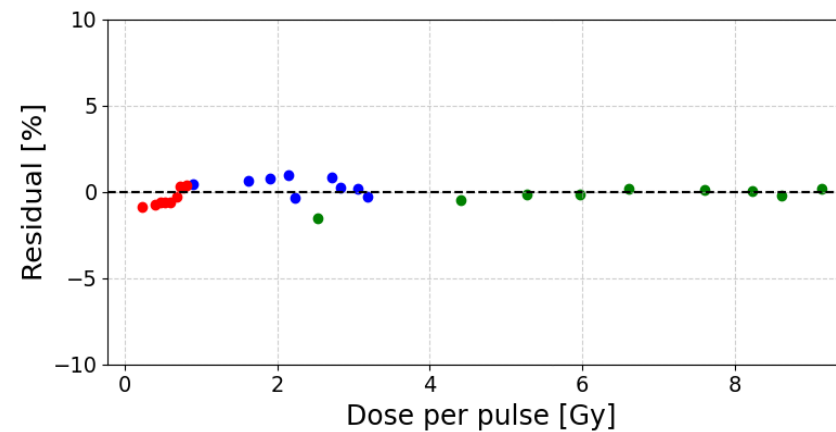
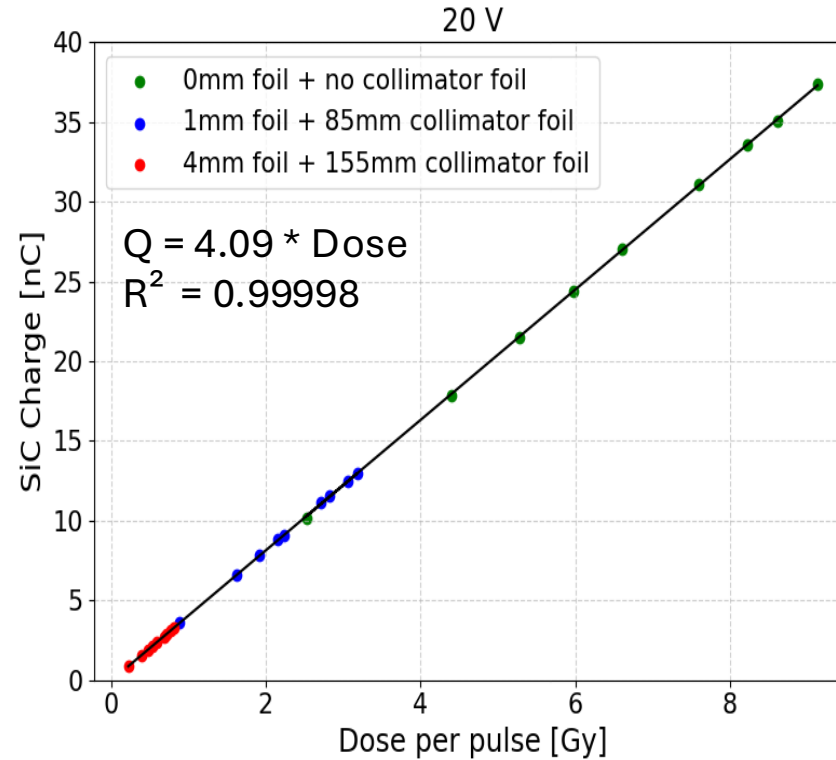


Beam at PTB

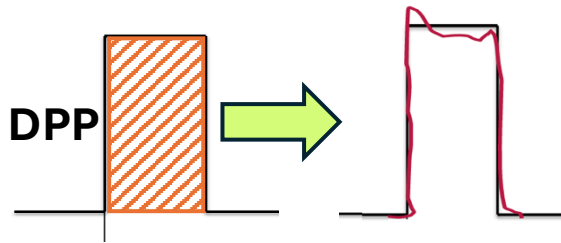
- Energy = **20 MeV**
- Pulse width = 1us, 2 us
- Pulse charge: up to around 275 nC

Dose per pulse (DPP) variation method

- 1) Including **Al scattering foil** of different thicknesses (4mm, 1mm, 1.5mm)
- 2) **Slit size** was adjusted from 2 mm – 20 mm to vary the DPP at the irradiation point.
- 3) Sometimes, including PMMA **collimator** (45 mm, 60 mm, 85 mm, 155 mm diameter)



Measuring the instantaneous dose rate in UHDR pulsed beams



- **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

Keithley 6517A



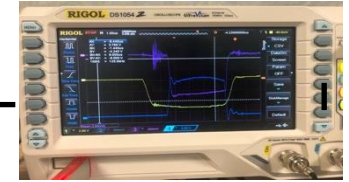
Voltage



SiC

Signal

50 ohm



Oscilloscope

Pulsed **electrons**



9 MeV 1-4 μ s



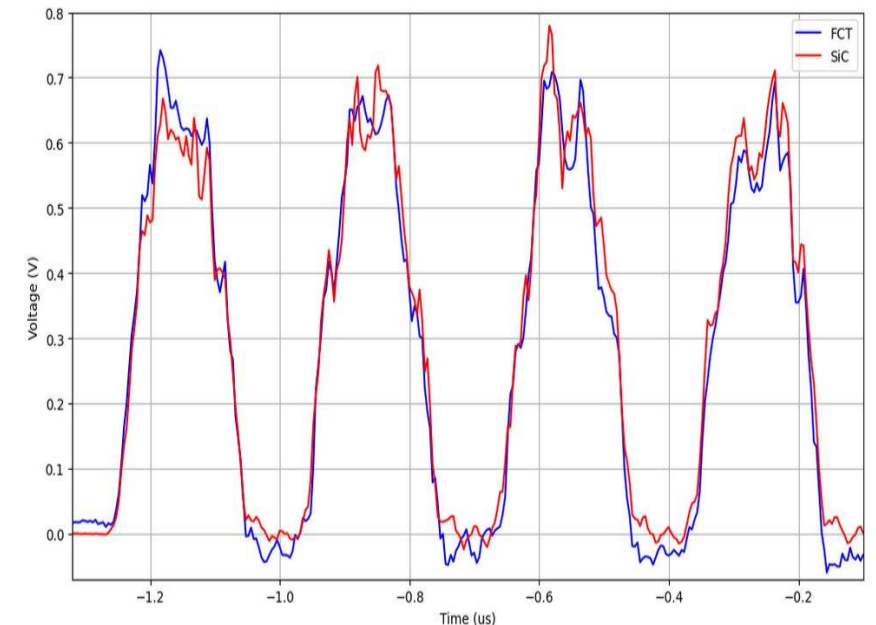
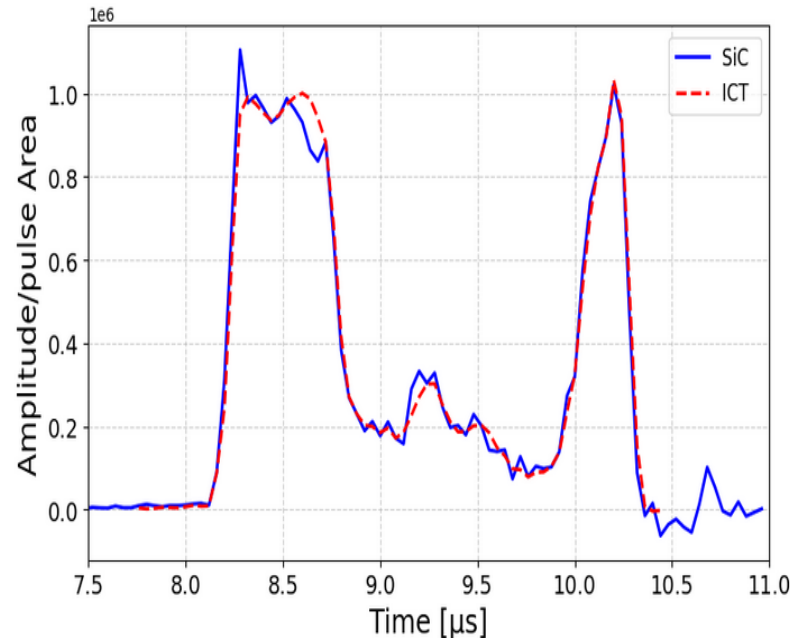
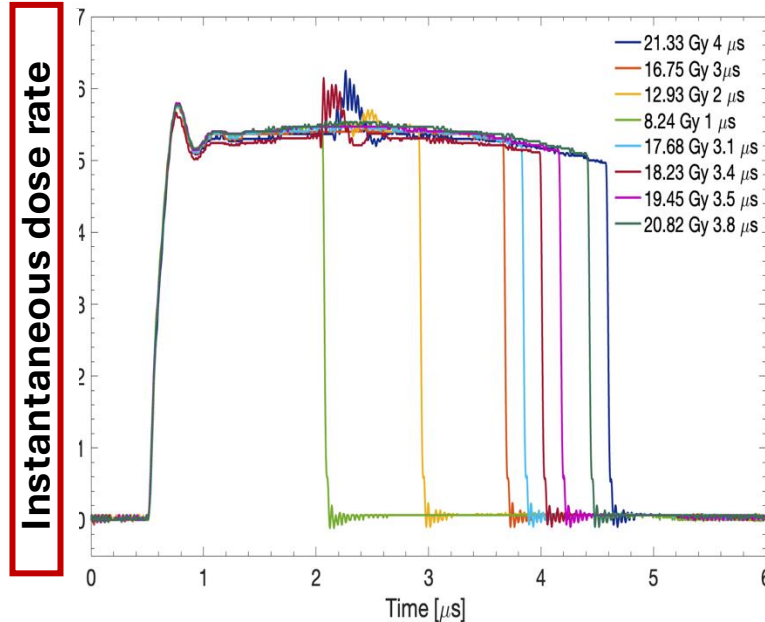
20 MeV 2 μ s

Pulsed **carbon** ions

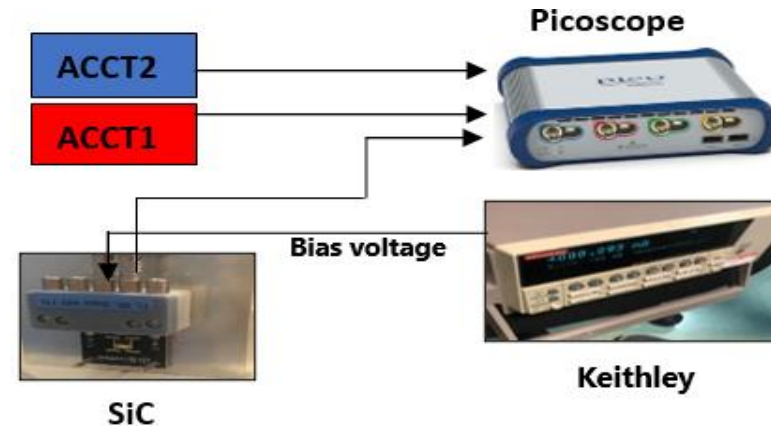
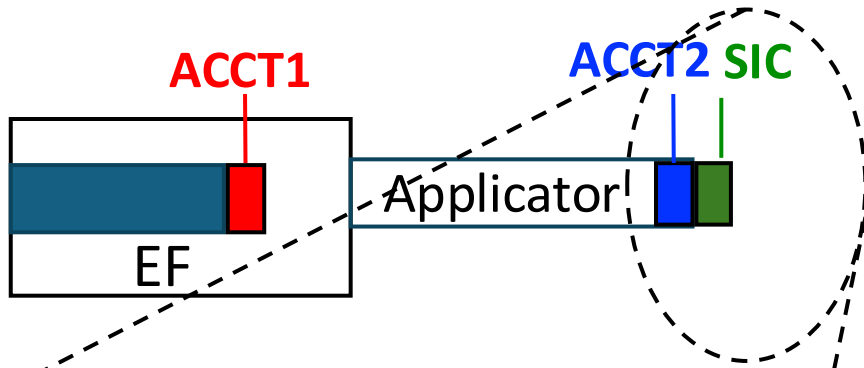


240 MeV/u

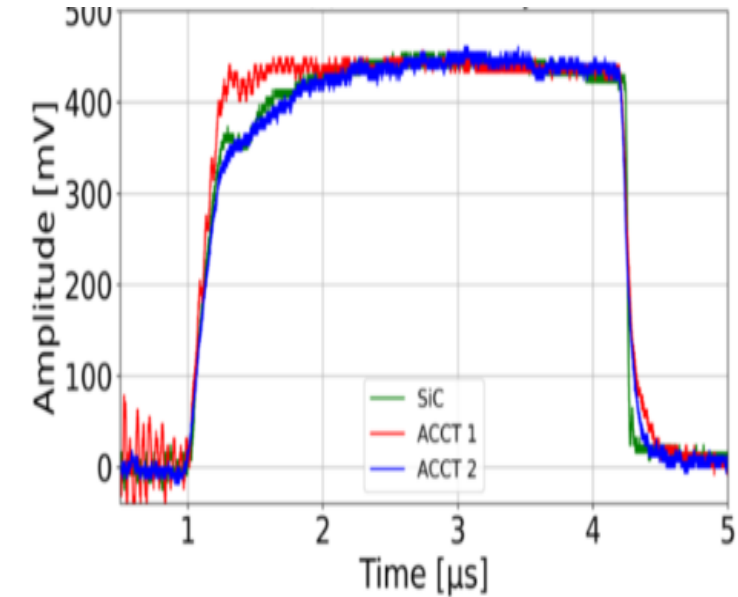
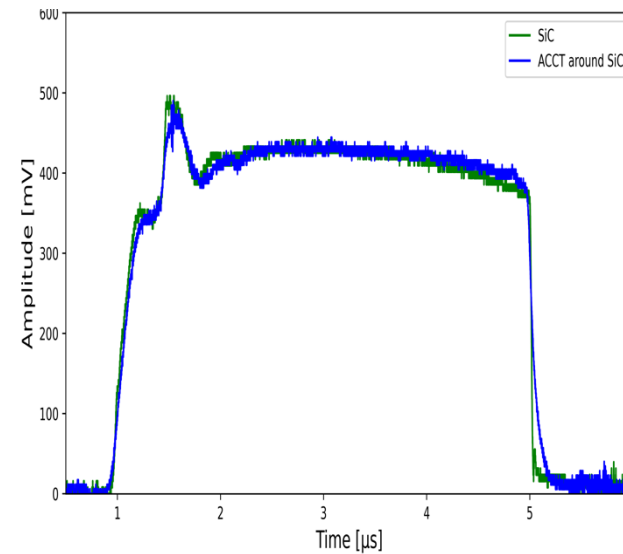
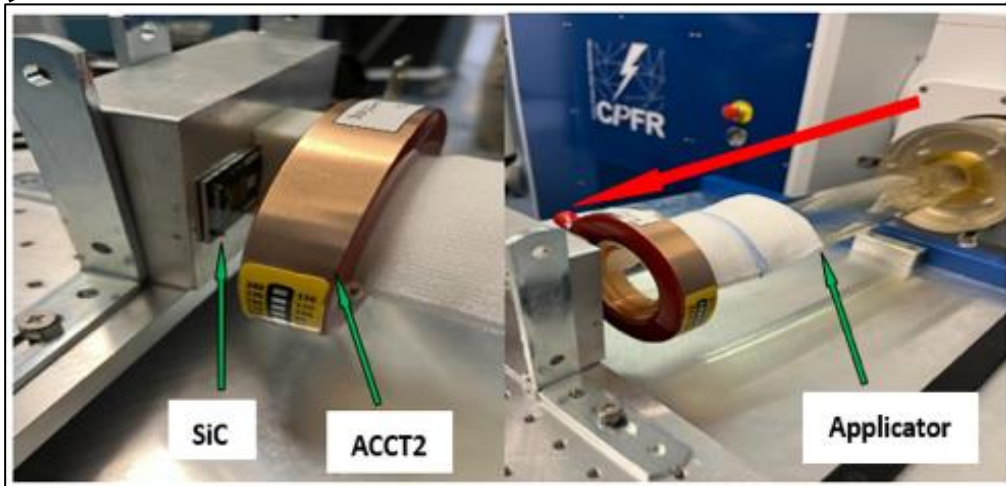
1 spill = 1 μ s



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



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



Intercomparisons and calibrations of the developed BMs and dosimeters

SiC-Si detector comparison with the TO-Linac

Beam Parameters

- Pulse width = 2 μ s
- Normal Field size: 25 x 25 cm²
- Energy = 10 MeV for FLASH
- PRF = 6 Hz (when needed)

Beam current setting

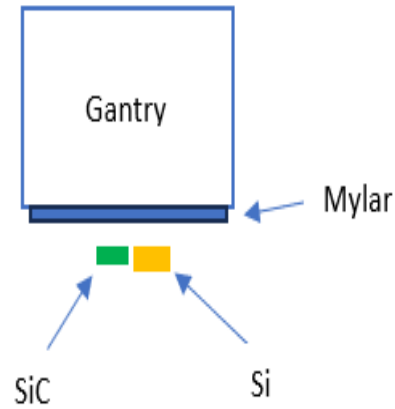
- High power
- Low power

Detectors

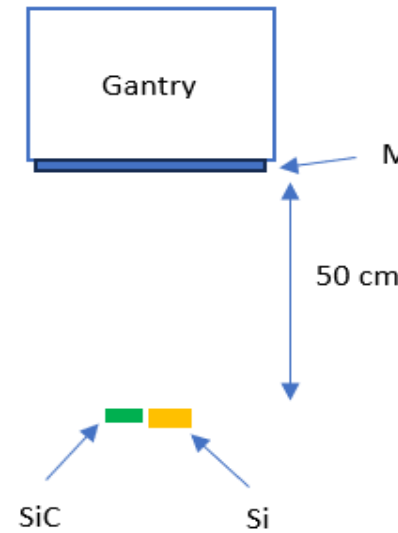
- SiC : 10 μ m , 4.5 mm² , bias V = 80 V
- Si: 45 μ m , 2 mm² , bias V=360 V
- SiC and Si were connected to the Oscilloscope (Teledyne Lecroy, 2.5 GHz, 40 GS/s)



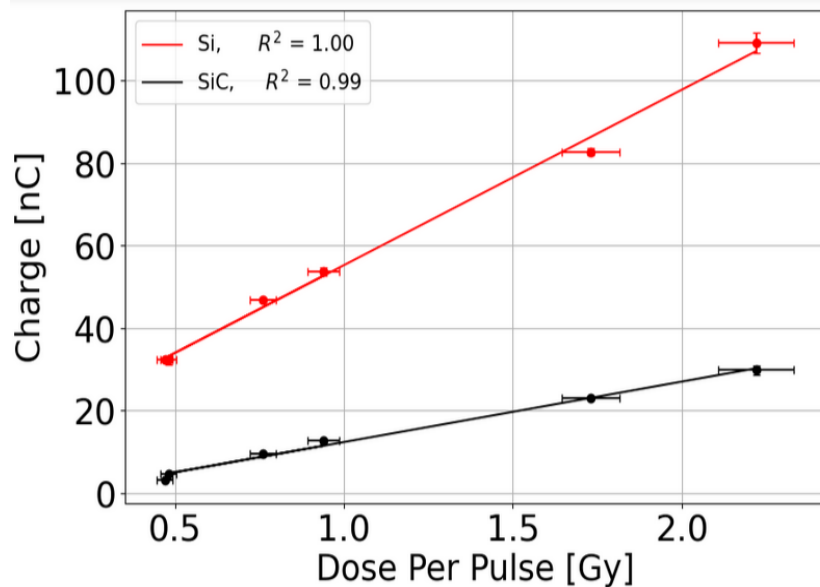
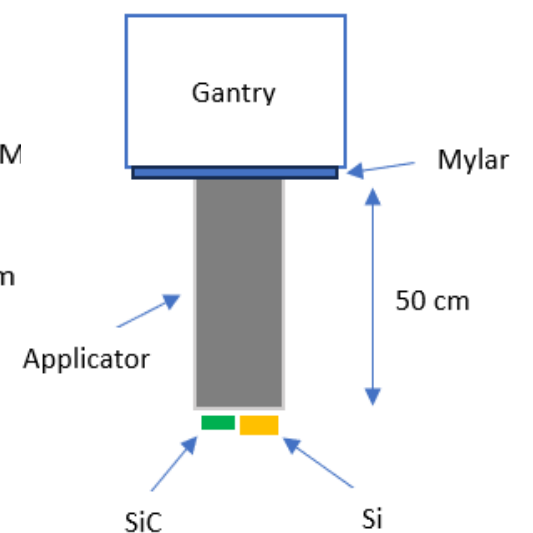
(1) Close to Mylar



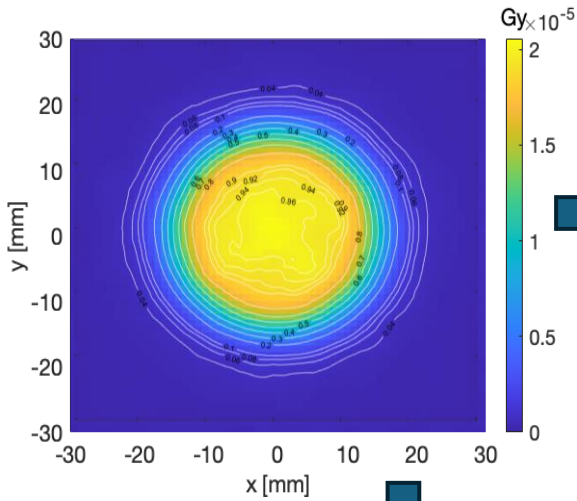
(2) Isocenter



(3) Isocenter + collimator



From FRIDA to DREAM: dose distributions measurements with 1D/2D SiC systems

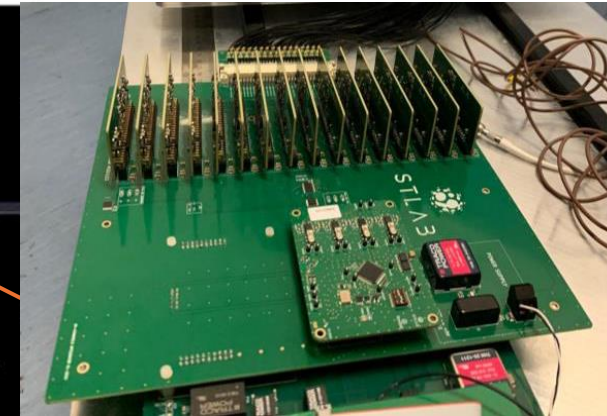
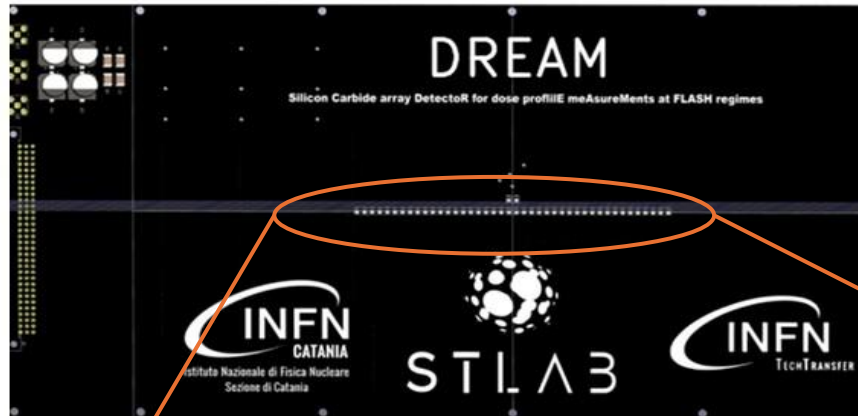


1D Array: **DREAM**
Silicon carbide array
Detector for dose
profilE meAsureMents
at FLASH regimes

R4I Research for Innovation

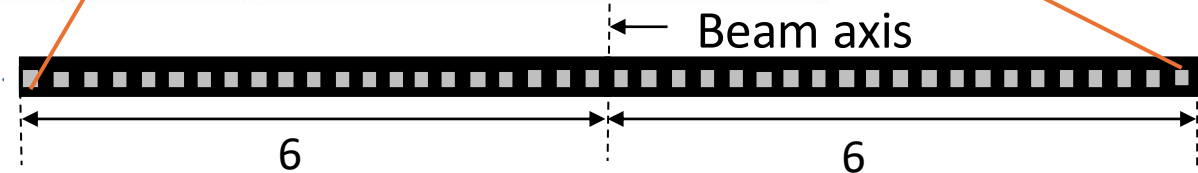
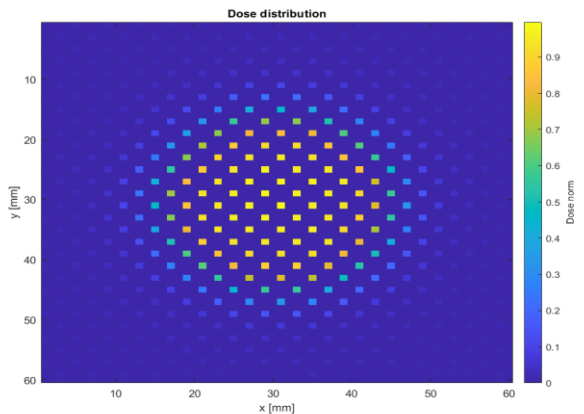
>60 small size (1 mm) SiC detectors mounted on a PCB

Analogic integrating readout electronics

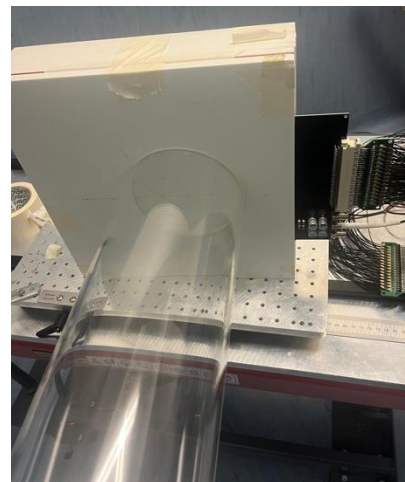


2D matrix → **DALI'**

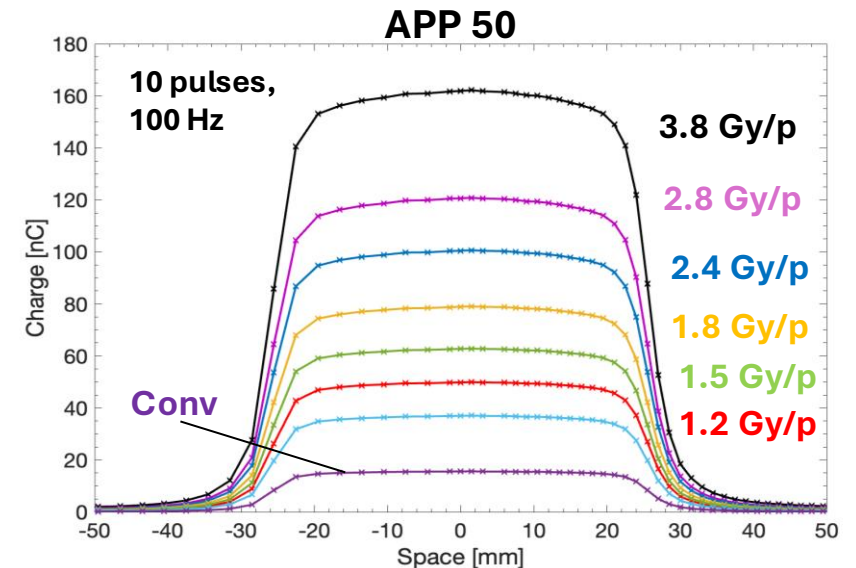
Development of **A**dvanced dosimetric techniques
for **u**ltra-**h**igh dose rate beams



First test with UHDR electron beams



Patent submitted

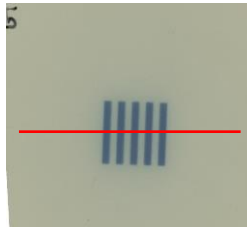
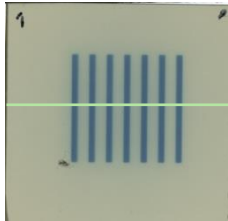
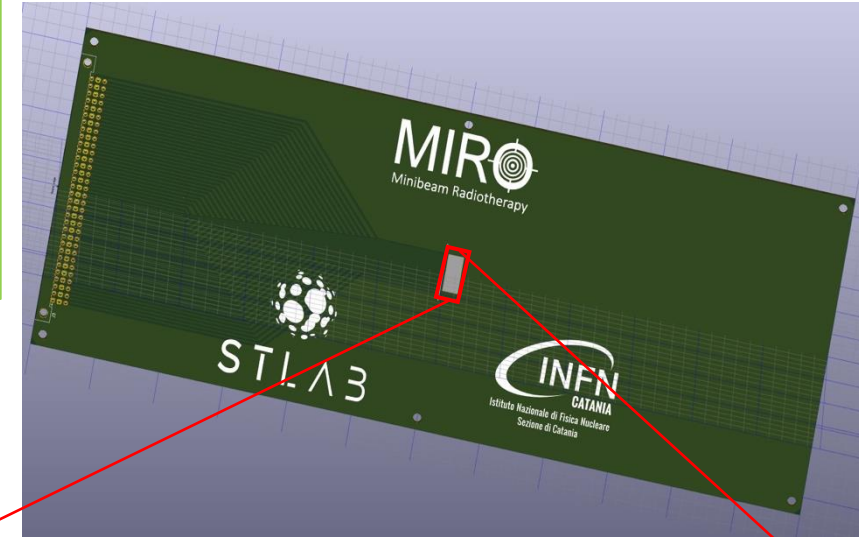
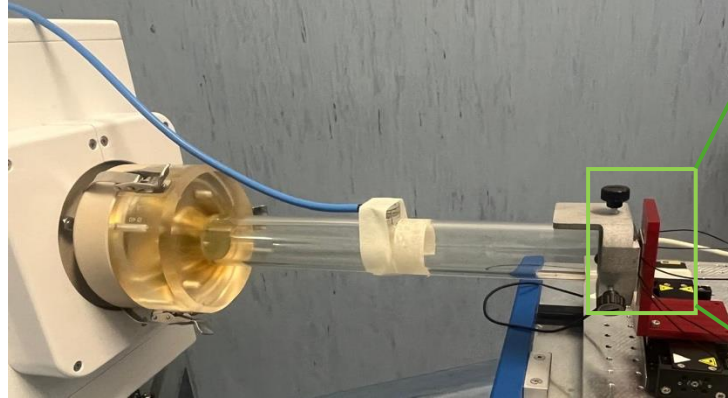


- Minimizing the number of detectors and the cost → optimized design and SiC displacement
- Support for the future clinical trial with UHDR e- beams @ CPFR

SiC detector: **300 μm** diameter, **22 μm** thick

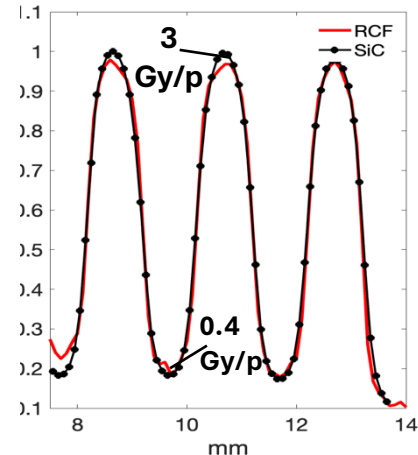
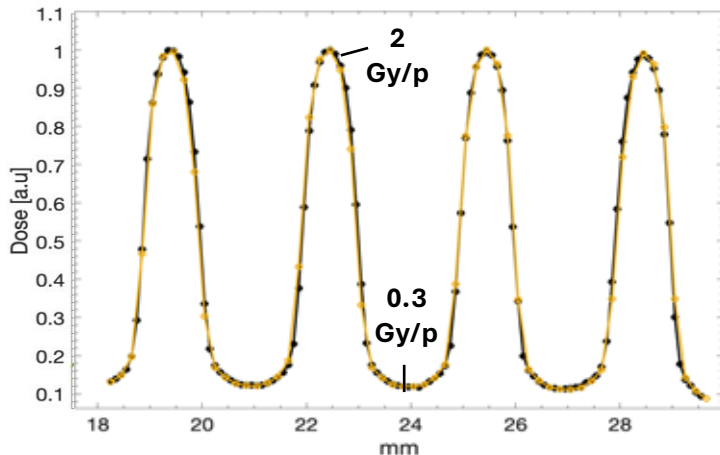
SiC array

- ✓ **Suitable** for UHDR beams
- ✓ **Dose rate independent**
- ✓ Radiation hard
- ✓ **Small size, high sensitivity** in valleys



FWHM=1 mm. **c-t-c=3 mm**
200 μm spatial resolution

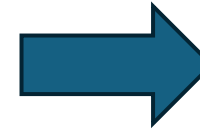
FWHM=1 mm, **c-t-c=2 mm**
100 μm spatial resolution



1 cm

100, 60x 60 μm SiC diodes, c-t-c 100 μm
Simultaneous real-time measurement of the charge along the minibeam pattern

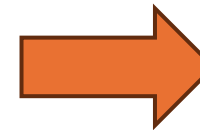
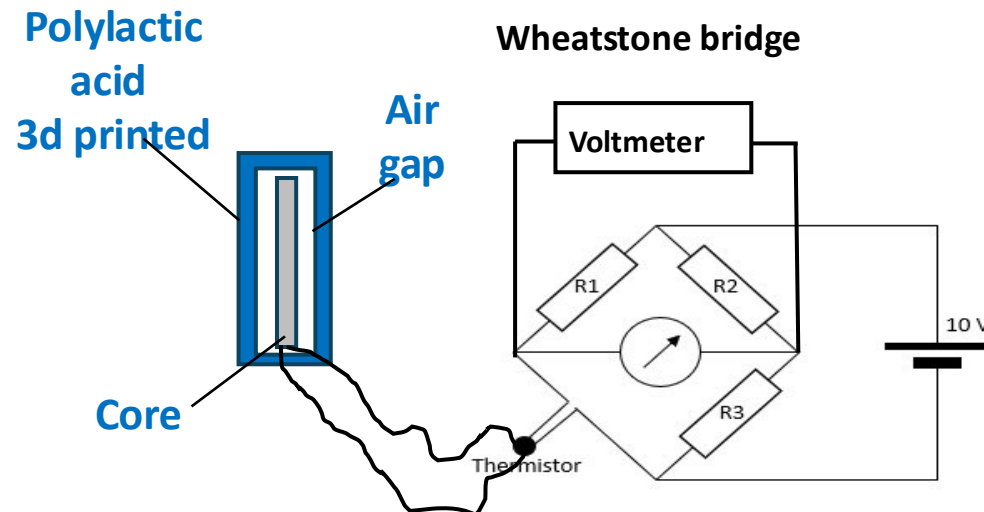
Portable graphite calorimeter prototype development and characterization with electrons/protons



Systematic experimental campaign for characterization with UHDR electron beams @ CPER varying all the beam parameters from conventional to UHDR

e-

The FRIDA-CALO



First preliminary test with UHDR proton beams @ TIFPA

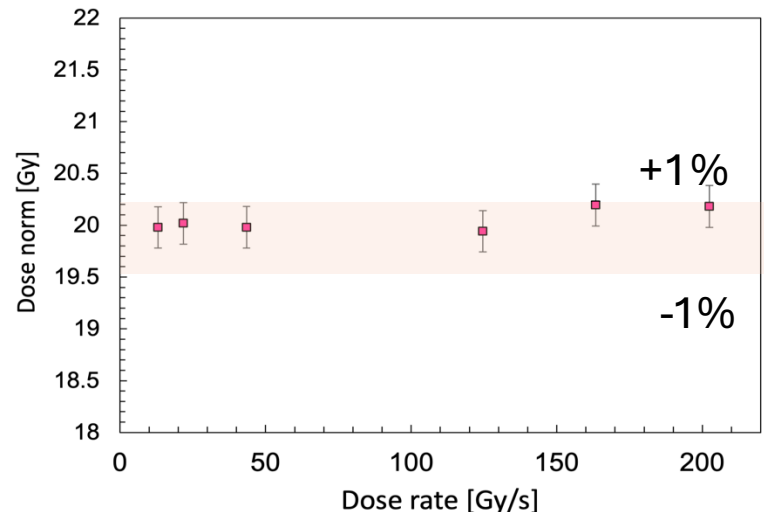
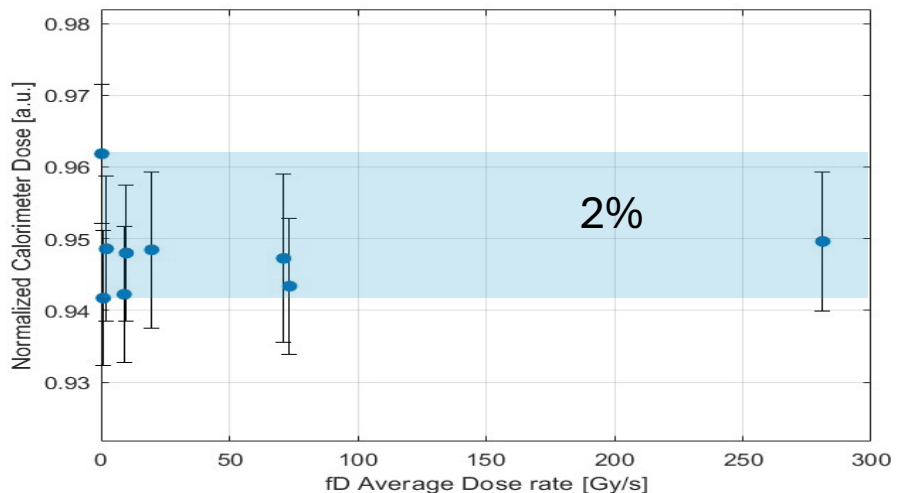
p+

Measurements with UHDR **electron** and **proton** beams

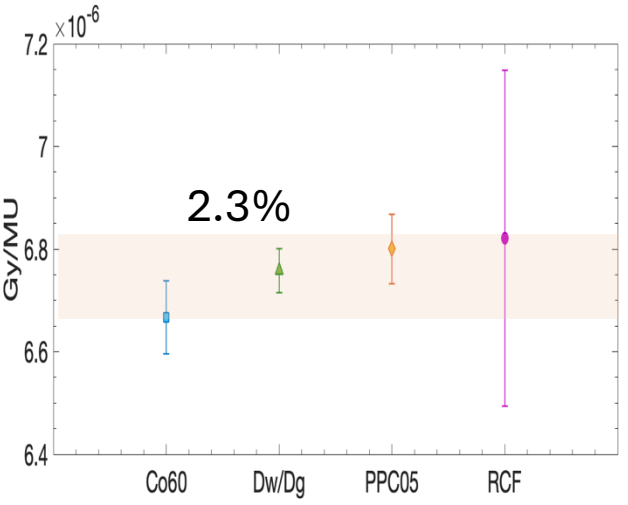
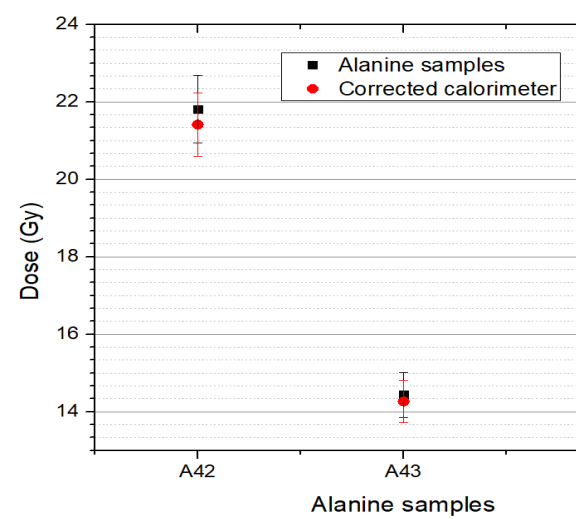
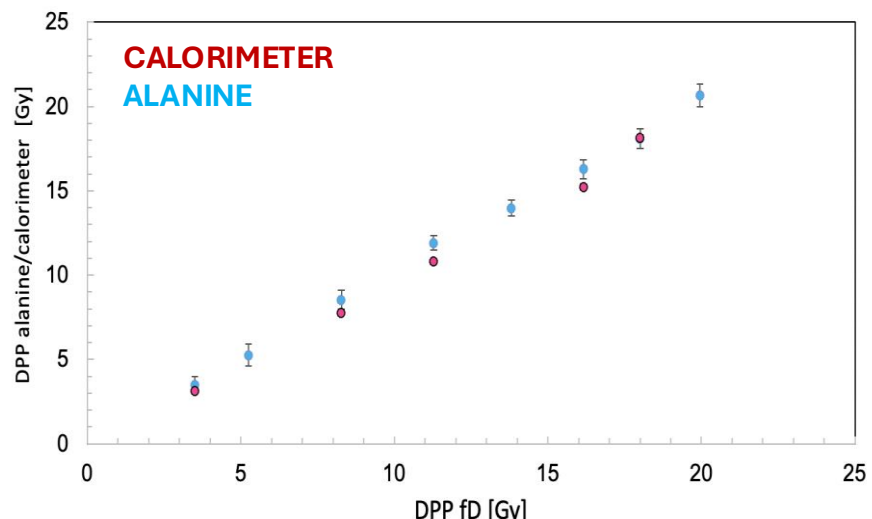
Measurements with UHDR electron beams @ CPFR

Measurements with UHDR proton beams @ Centro di Protonterapia di Trento

Response vs Average dose rate



Absolute dose: intercomparison with alanine pellets, RCF, ICs



Publications, talks in international conferences and products

10 papers published in Peer-reviewed journals

2 papers and reviews submitted in Peer-reviewed journals

21 invited talks in international conferences of the field (**FRPT (2), ESTRO (2), IWORID (2), AIFM (3), INFN WS (4), SIF (2), FATA (1), VHEE (1), INSIGHT (1), SSD (1), MMND-ITRO (1), ICDA (1)**)

11 Oral presentations in international conferences

3 Best abstract awards at the Flash Radiotherapy and Particle Therapy international conference (FRPT)

7 Master thesis

1 Master thesis in progress

3 PhD thesis in progress

Invited review and roadmaps in high IF peer-reviewed journals

F. Romano et al., Ultra-high dose rate dosimetry: Challenges and opportunities for FLASH radiation therapy. Med Phys. **2022**;1-21.

A. Subiel, F. Romano Recent developments in absolute dosimetry for FLASH radiotherapy. Br J Radiol (**2023**) 10.1259.

A. Petoukhova.... F. Romano, G. Milluzzo...et al., FLASH Radiotherapy for electrons and protons: roadmap towards the clinical introduction, submitted in Physics Med Biol

A. Vignati, F. Gomez, G. Milluzzo, Active systems for dosimetry and beam monitoring of UHDR beams, in prep for Nuovo Cimento

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



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

4th International Particle Minibeam Radiotherapy (PMBT) Workshop



Abstract submission: 6 March!

Pisa (Italy), 28-30 April 2026



Organizing Committee:

S. Capaccioli, A. Cavalieri, E. Ciarrocchi, F. Di Martino, M. Maffei, G. Milluzzo, F. Paiar, F. Romano (Chair), V. Tozzini

Scientific Committee:

Fabio Di Martino, Niels Bassler, Sam Flynn, Judith Reindl, Jolanda Prezado, Francesco Romano, Emanuele Scifoni, Joao Seco



SCUOLA SUPERIORE
DI FISICA IN MEDICINA
PIERO CALDIROLA

Direttore:
Nando Romeo

PISA

18-19 giugno 2026

W O R K S H O P

**ASPETTI TECNOLOGICI, DOSIMETRICI,
RADIOBIOLOGICI E ESPERIENZE E PROSPETTIVE
CLINICHE DELLA RADIOTERAPIA FLASH
E DELLA RADIOTERAPIA
SPAZIALMENTE FRAZIONATA (SFRT)**



Responsabili Scientifici: Fabio Di Martino, Francesco Romano

Coordinatori Scientifici: Simone Capaccioli, Marco Giannelli, Fabiola Paiar



Thank you for your attention