WP3- FLASH beam monitoring & dosimetry

INFN-CT activities

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Deliverables

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Deliver.	Short name	Description	When (M)
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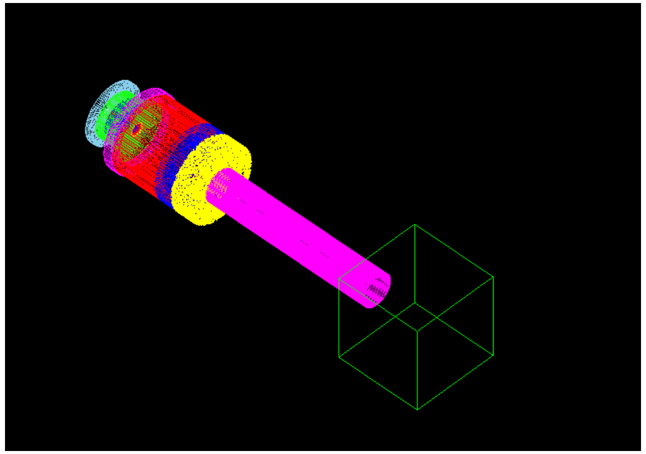
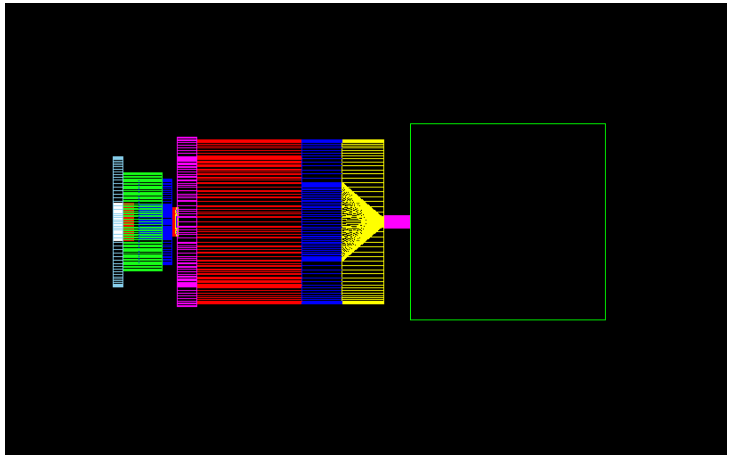
M3.3	Prototypes commissioning	BM and Dosimetric systems prototypes commissioning	36

Advanced example: eFLASH_radiotherapy

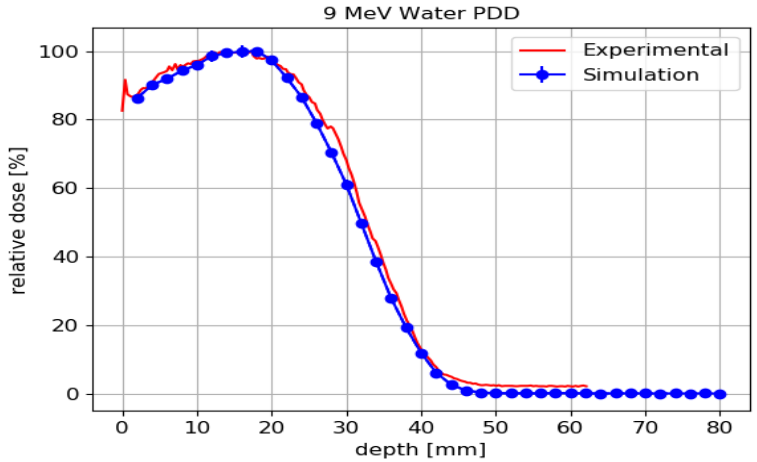
Current authors: J. Pensavalle (University of Pisa, Italy) G. Milluzzo (INFN Catania, Italy), F. Romano (INFN Catania, Italy)

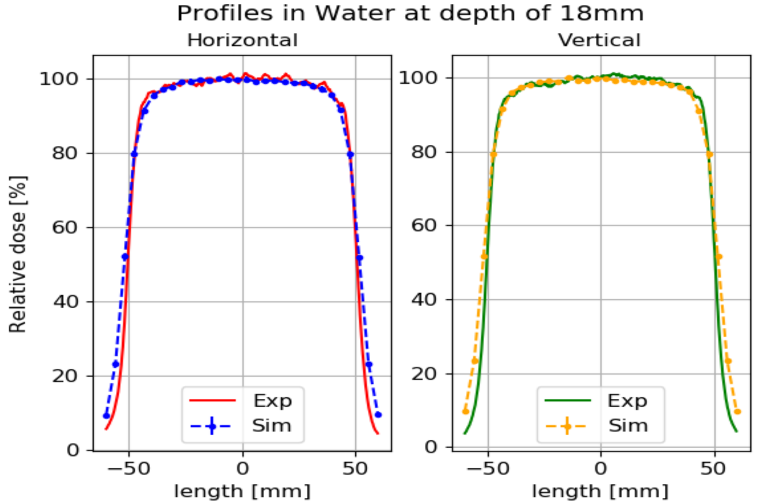
- We accurately replicated the most relevant components of the ElectronFlash LINAC at CPRF by following the manufacturing specifications provided by Sordina Iort Technologies S.p.A.
- Variable applicator dimensions for different dose per pulse set-up (diameter 1cm to 10cm).
- Simulation of a water phantom and detectors placed within the phantom to predict dose distributions and scattering
- From both the PDD and dose profiles, we can see a good agreement between simulation and validation.





Validation of PDD and beam profiles with RCF





WP3. Dosimetry

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D.3.3.1

Dosimetric characterization of the beams with reference dosimeters: ***alanine*** *dosimeters (M24)*

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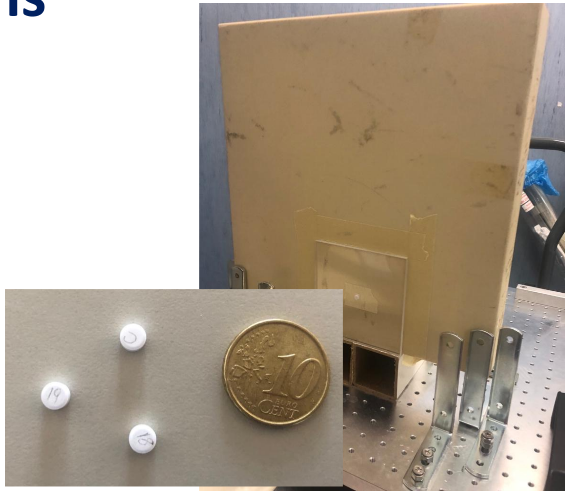
Experiment with Electron FLASH linac accelerator @ CPFR

Experimental conditions

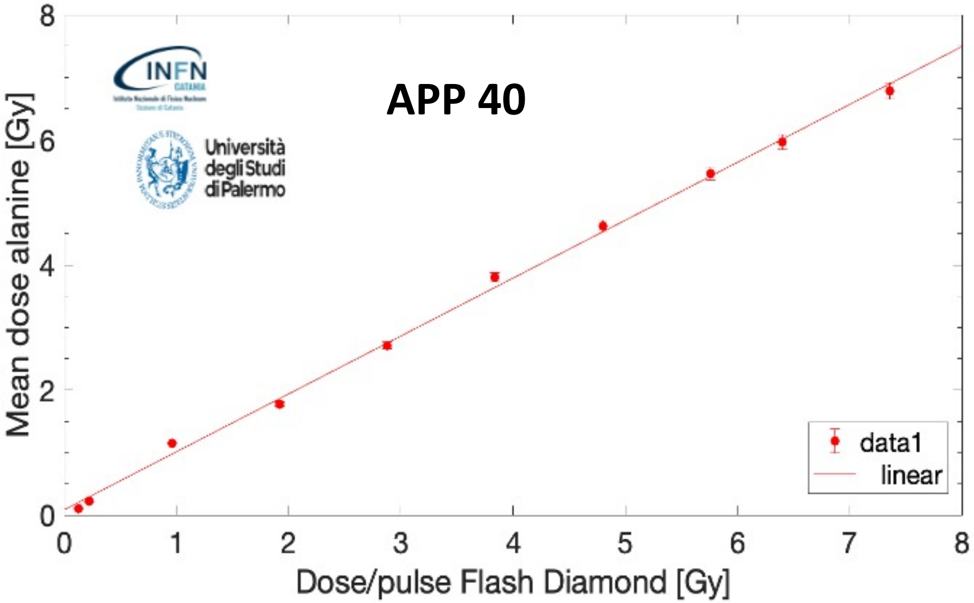
- E = 9 MeV
- Pulse duration: 0.5-4 us
- Dose per pulse: from 0.1-15 Gy
- Istantaneous dose rates up to MGy/s
- Single alanine detector
  placed in a phantom at the build-up
- 40-100 mm Applicator



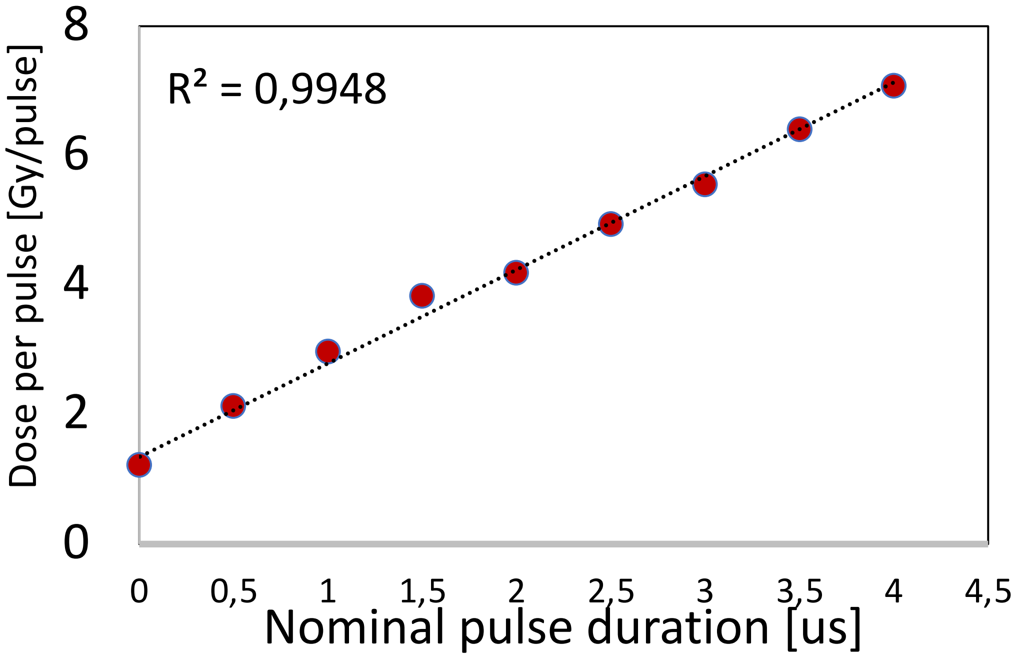
Measurements

- Comparison of alanine dose response with the reference dosimeter (Flash diamond) varying the DPP (working points) and pulse duration
- Intercomparison of alanine response with the metrology service of NPL

DPP comparison with FLASH diamond



DPP VS pulse length



WP3. Beam monitoring

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D.3.1.4

***SiC** detectors tests with UHDR electron/protons for beam monitoring (M16)*

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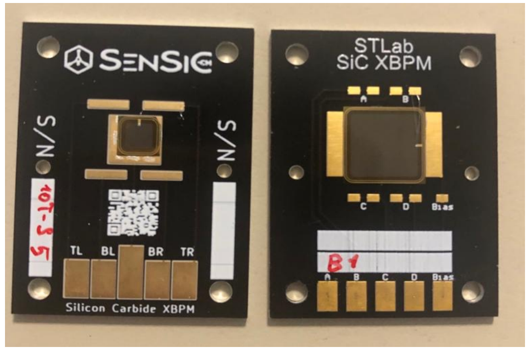
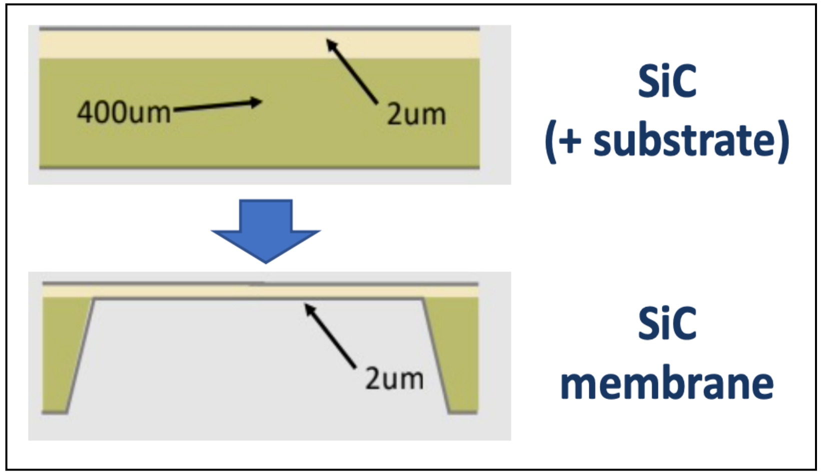
Silicon carbide detectors for beam monitoring and dosimetry

Silicon carbide (SiC) detectors have been realized at the STLab company. The devices are semiconductor PIN junctions: a thin p+, highly do
low doped layer on top of a n+ thick substrate. In case of the free-standing membranes the substrate n+ is removed by electrochemical etching

SiC with bulk

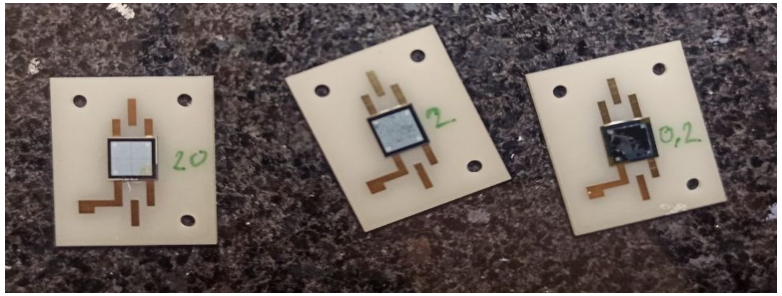
5x5 mm^2 **1x1 cm^2**





Freestanding membranes

20um **2um** **0.2um**



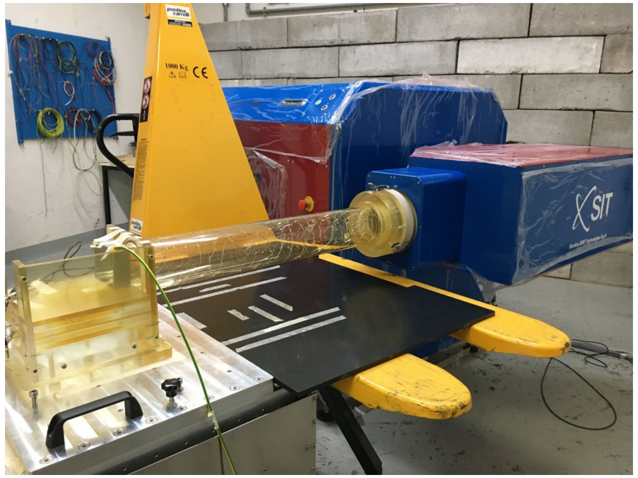
First characterization of SiC detectors with UHDR electrons @SiT Sordina Electron FLASH facility

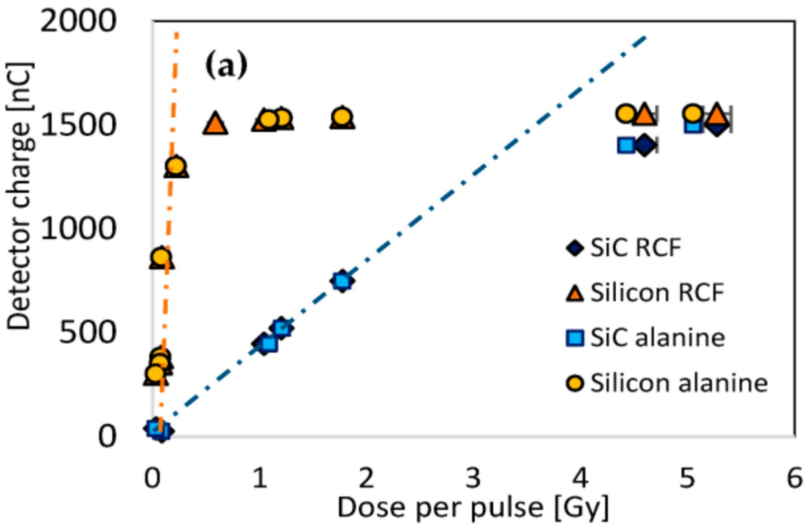
Accelerator parameters

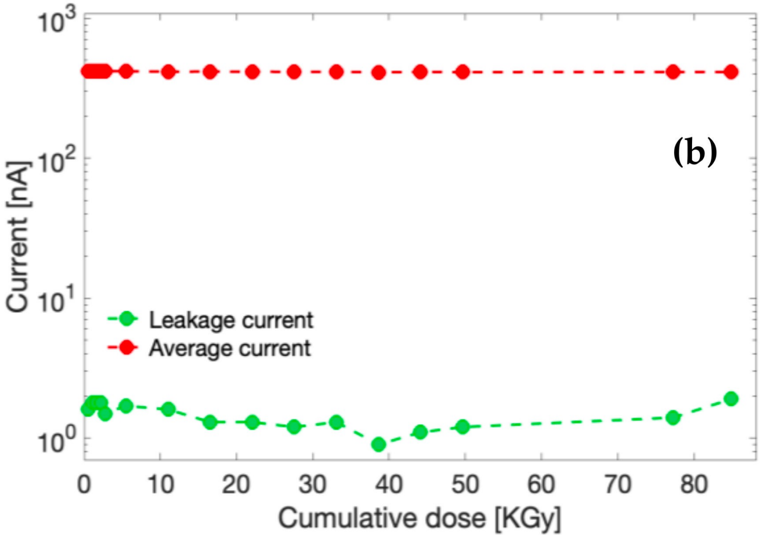
- SiT-Sordina Electron FLASH
- E = 7, 9 MeV
- Pulse duration: 1-4 us
- Dose per pulse: from 0.01-10 Gy
- Average dose rates up to few kGy/s

Measurements

- E = 9 MeV
- Pulse t = 2 us
- 10 um thick SiC
- V = 480 V
- D/p = 0.01 – 10 Gy
- 35 mm collimator
- Comparison with PTW diode
- Electrometer issues at larger doses per pulse





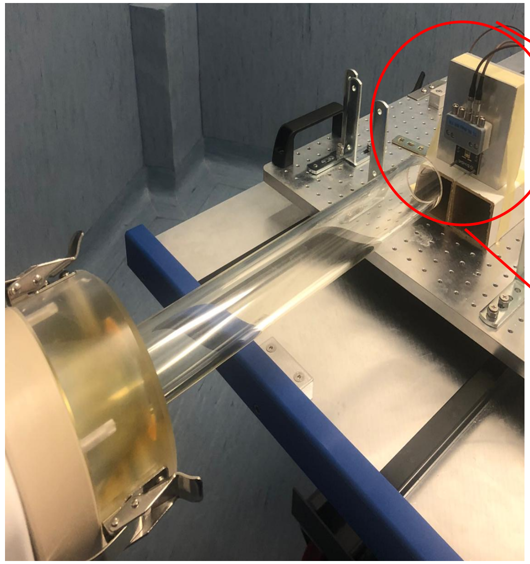


Romano, F.; Milluzzo, G et al. First Characterization of Novel Silicon Carbide Detectors with Ultra-High Dose Rate Electron Beams for FLASH Radiotherapy. Appl. Sci. 2023, 13, 2986.

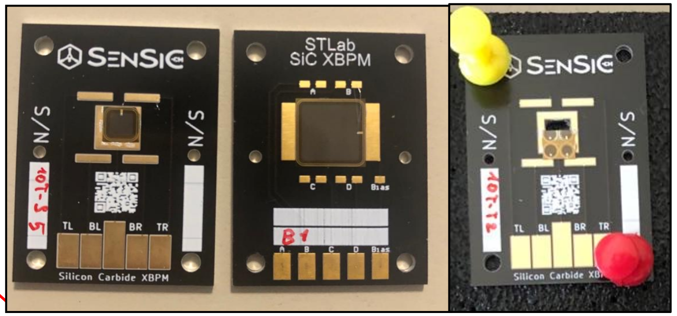
Characterization with Electron FLASH Linac accelerator @ CPFR

Experimental conditions

- E = 9 MeV
- **Pulse duration: 0-5-4 us**
- **Dose per pulse: from 0.1-20 Gy**
- Istantaneous dose rates up to **5 MGy/s**
- 10x10, 5x5, 2x2 mm^2 10 um thick SiC placed at the build-up connected to a Keithley electrometer
- Alanine dosimeters at the build-up
- **30,40,100 Applicator and Open Field**
- RC circuit connected to the detector to slow down the current acquisition in the electrometer

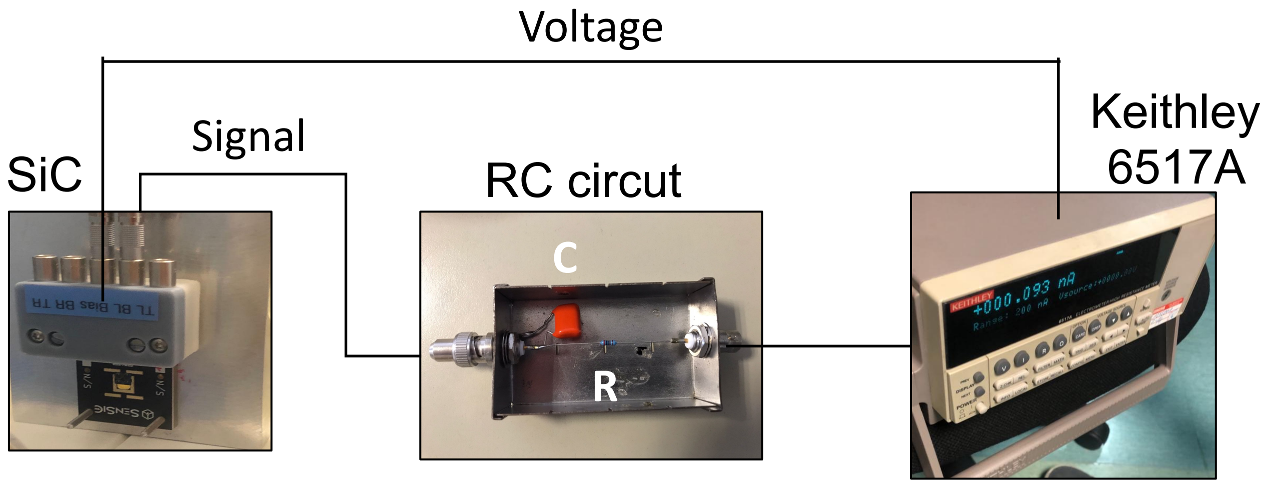


5x5 mm^2 10x10 mm^2 2x2 mm^2

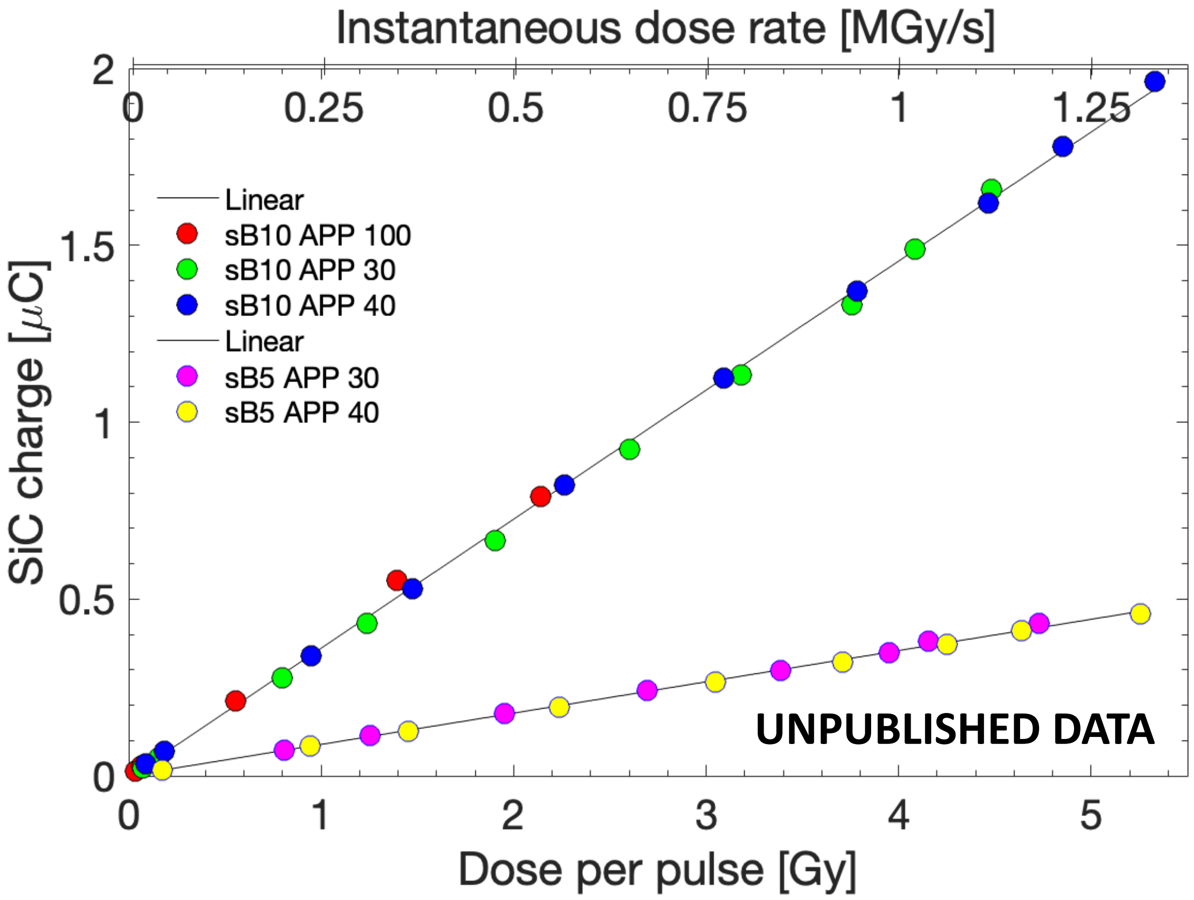


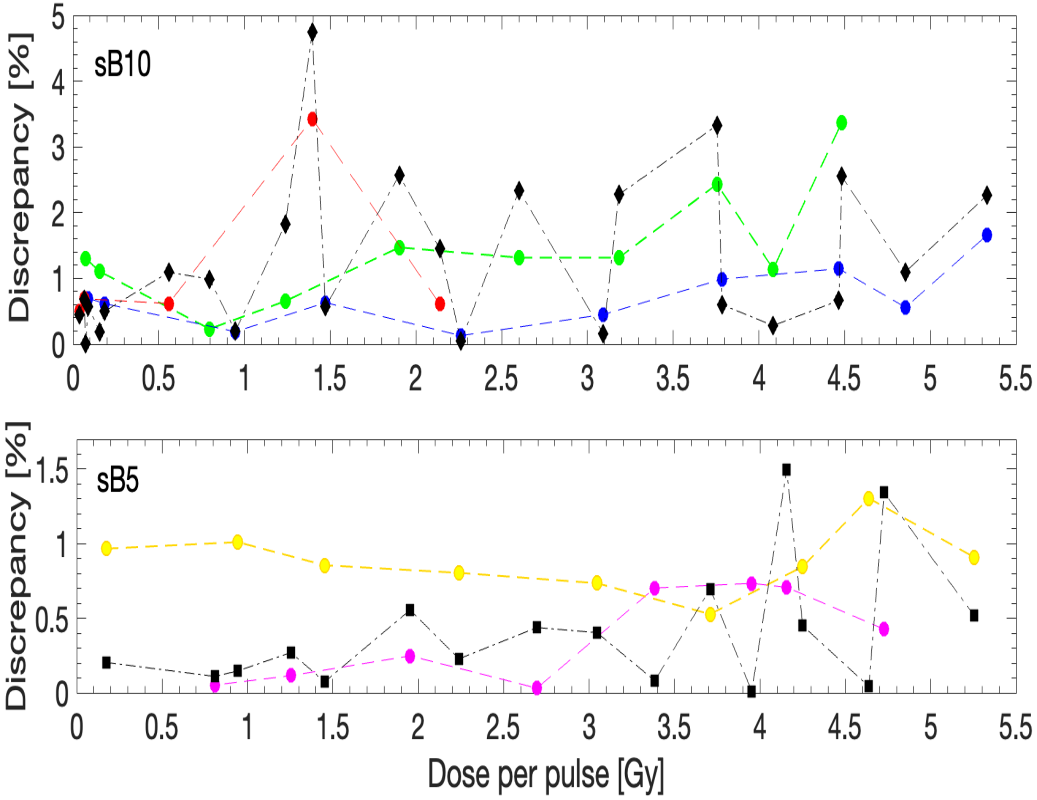
Measurements

- SiC response as a function of the BIAS voltage
- SiC response as a function of the dose per pulse to verify linearity in single pulse
- Comparison with alanine detectors
- **Intra pulse instantaneous dose-rate measurements**



SiC response in charge VS DPP-All applicators and SiC





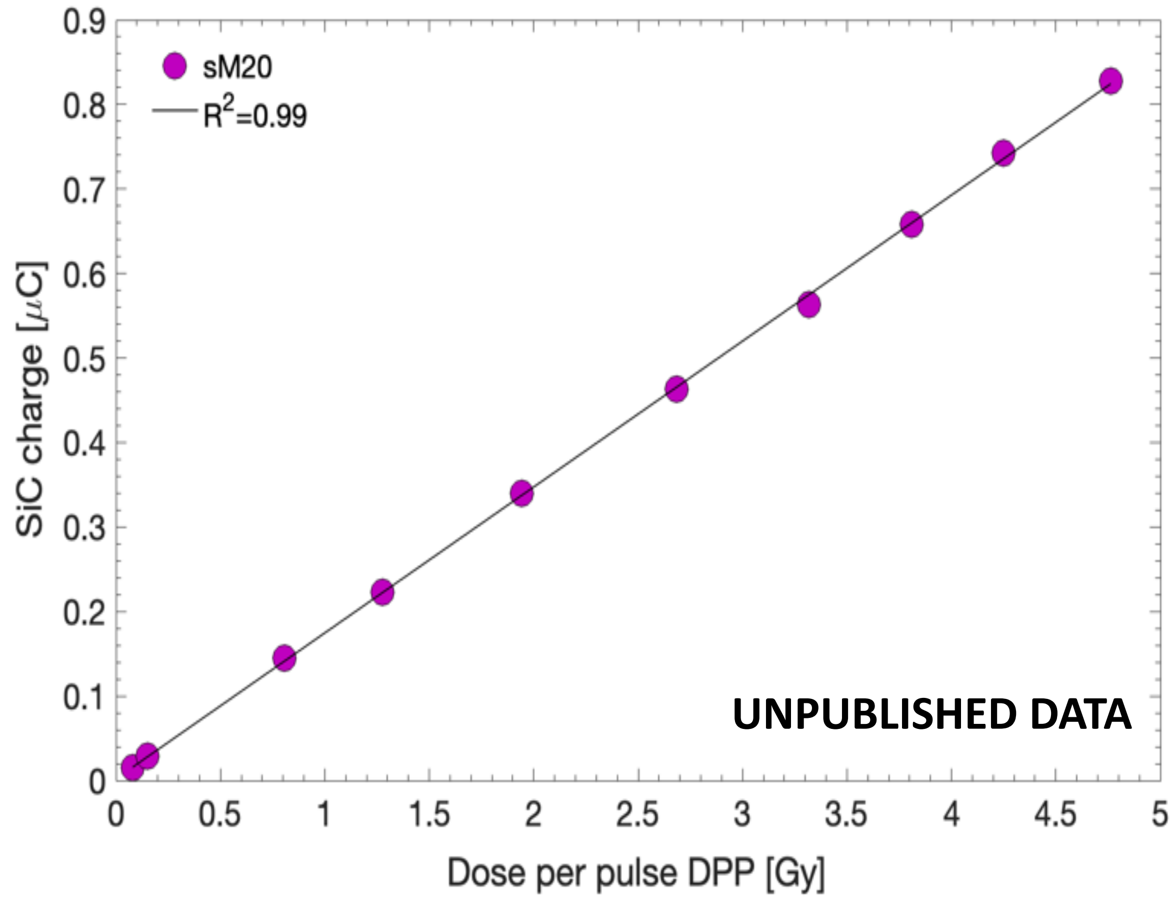
G. Milluzzo et al., in prep for Medical Physics

G. Milluzzo et al, talk accepted at ESTRO Congress

G. Milluzzo et al, talk accepted at **12° Congresso Nazionale AIFM**

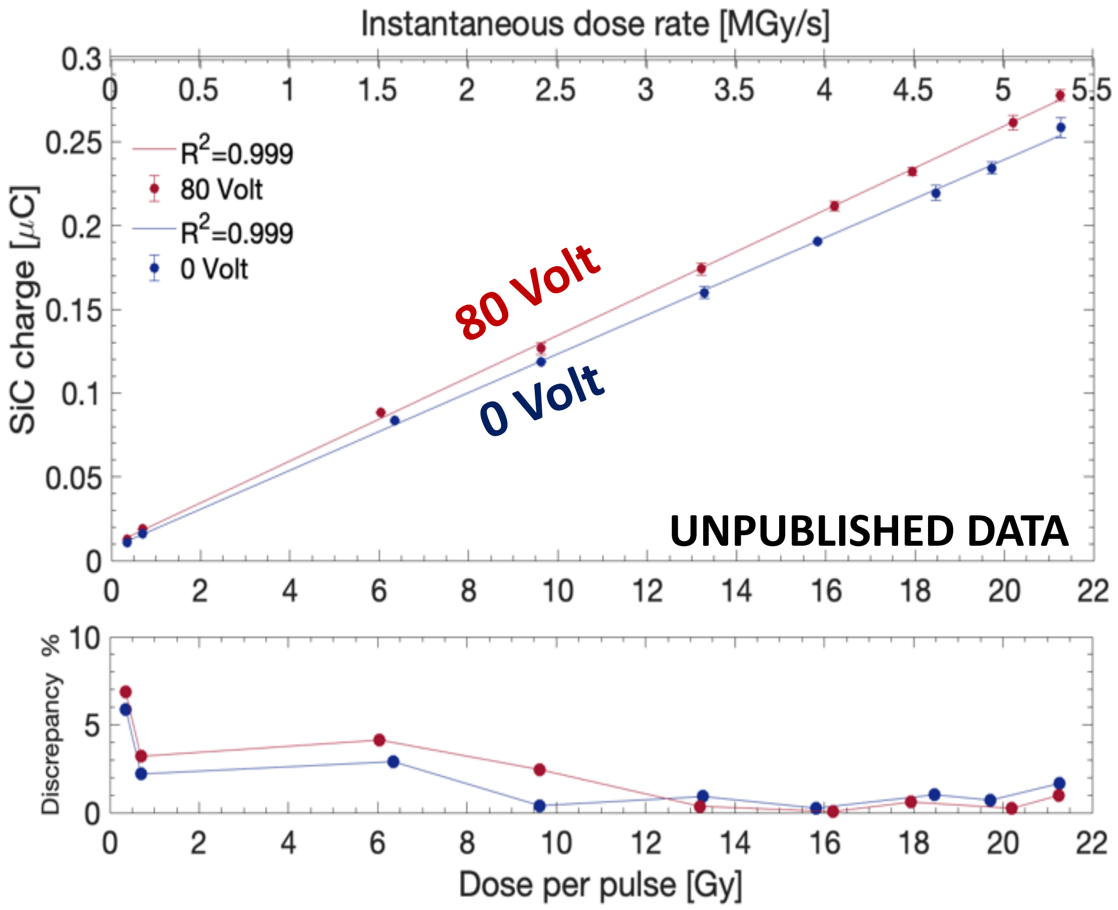
SiC response in charge VS DPP

SiC 20 um thick membrane-full detector irradiated



G. Milluzzo et al., in prep for Medical Physics

OPEN-FIELD NO APPLICATOR 3 mm² SiC detector



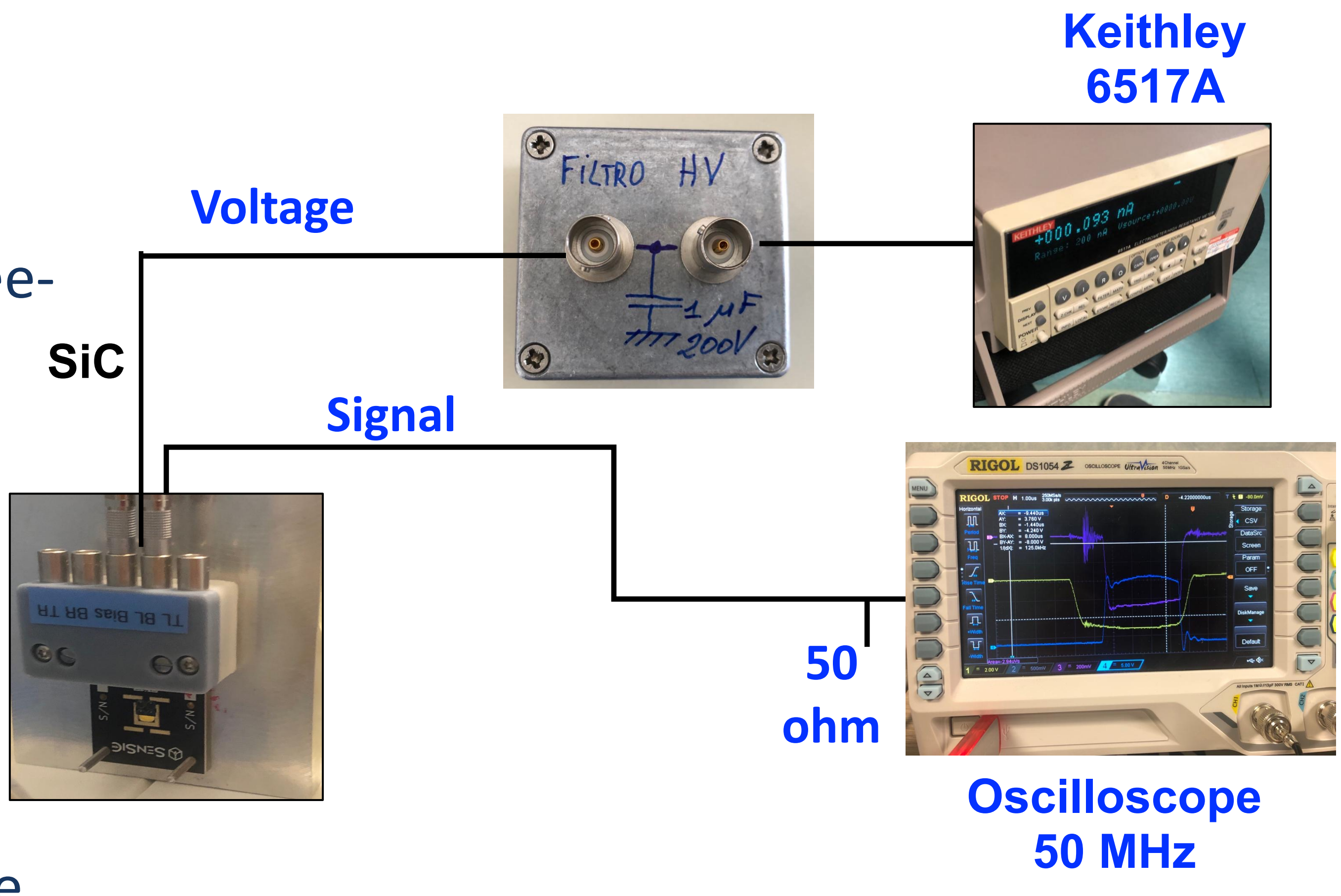
G. Milluzzo et al, talk accepted at ESTRO Congress

G. Milluzzo et al, talk accepted at **12° Congresso Nazionale AIFM**

Measurements with the oscilloscope of the intra-pulse instantaneous dose rate@CPFR

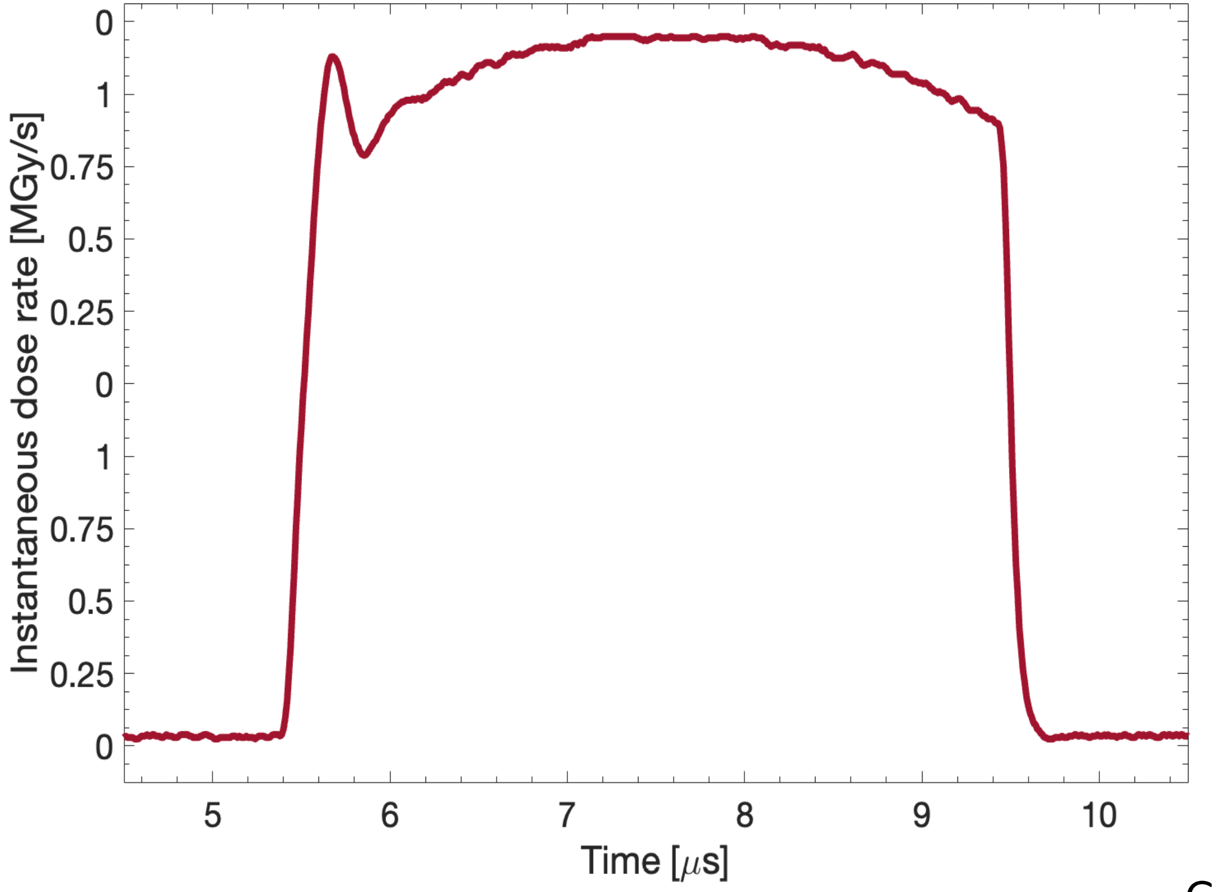
Experimental conditions

- E = 9 MeV
- Pulse duration: 0.1-4 us
- Dose per pulse: from 0.1-8 Gy
- 10x10, 5x5 10 um thick SiC & 20 um free-standing membrane
  placed at the build-up connected to a Keithley
  electrometer
- Alanine dosimeters at the build-up
- 30,40,100 mm Applicator
- RC circuit connected to the detector to slow down the current acquisition in the electrometer



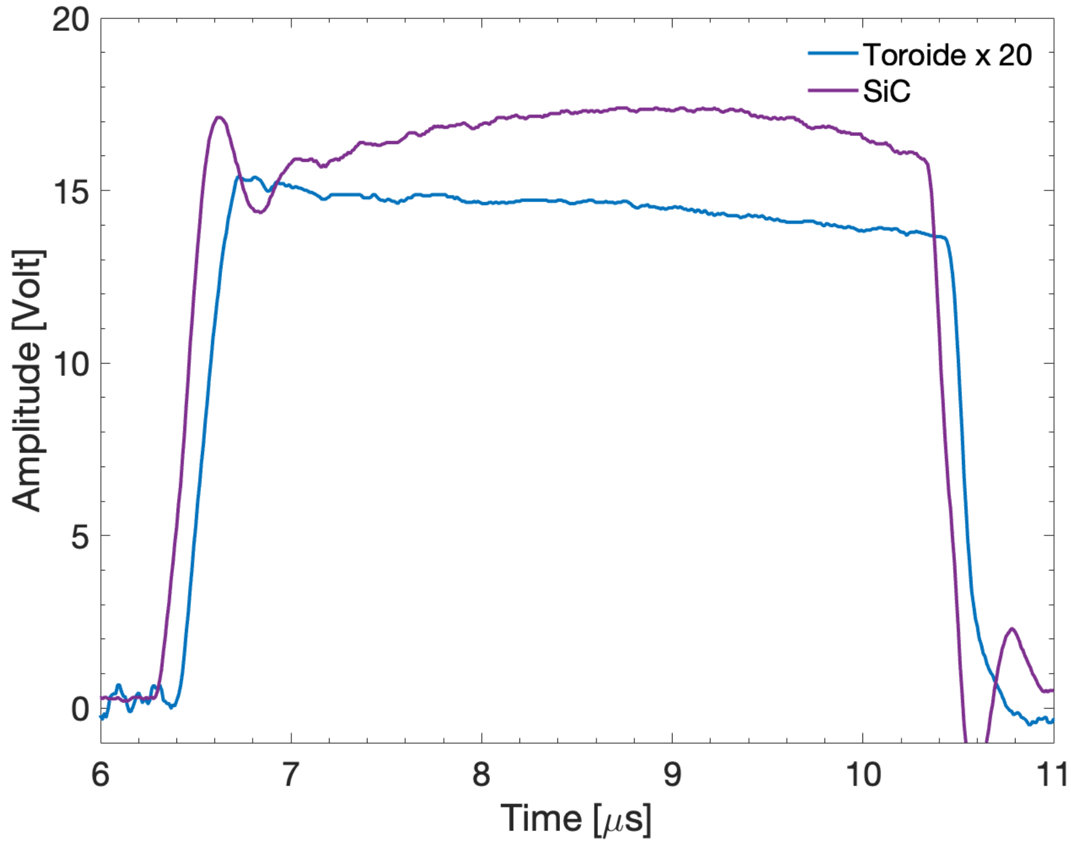
Intra-pulse instantaneous dose-rate measurements

Single pulse waveforms – different pulse lengths



Comparison with ACCT

=>> ACCT and SiC in different positions



G. Milluzzo et al, talk accepted at ESTRO Congress

G. Milluzzo et al, talk accepted at **12° Congresso Nazionale AIFM**

Planned activity for Silicon carbide detectors

- Comparison of the ACCT-SiC signals at the same position for instantaneous dose-rate monitoring

- Extend the linearity curve up to high DPP in the perspective of beam monitoring
- Design and realization of 2D array Silicon carbide for single shot beam profile monitoring

- Test with FLASH proton beams @ PARTREC-UMCG, TIFPA …

WP3. Beam monitoring

Activity of INFN Catania

D.3.1.4

Portable calorimeter prototype development and characterization with electrons/protons

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FRIDA general meeting Trento 29-30 Marzo 2023

Calorimetry for absolute dosimetry

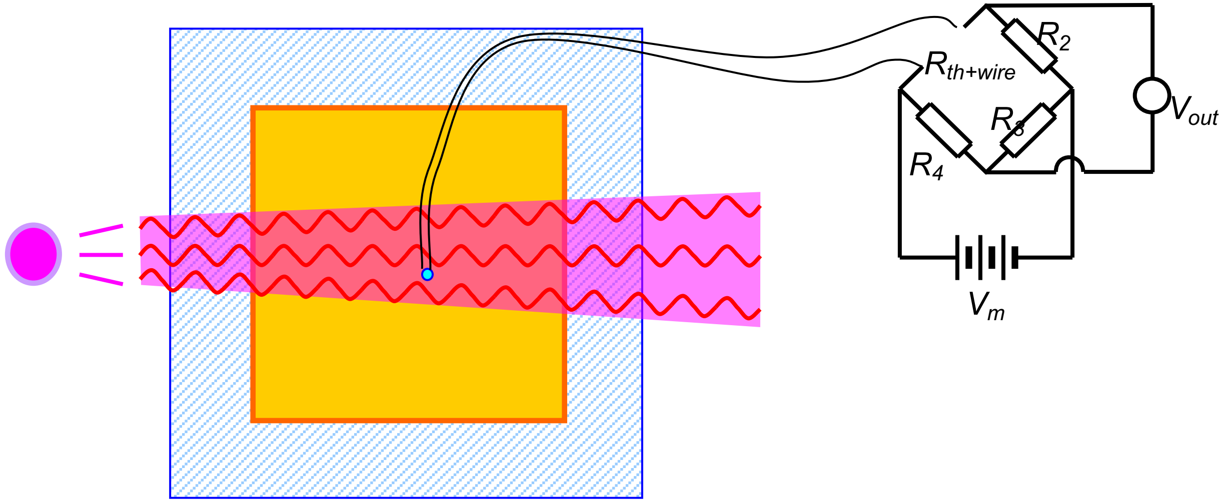
Charge liberated in the medium results in an energy cascade - the liberated energy ends up as heat → measured as a temperature rise

$$D_m = c_m \Delta T$$

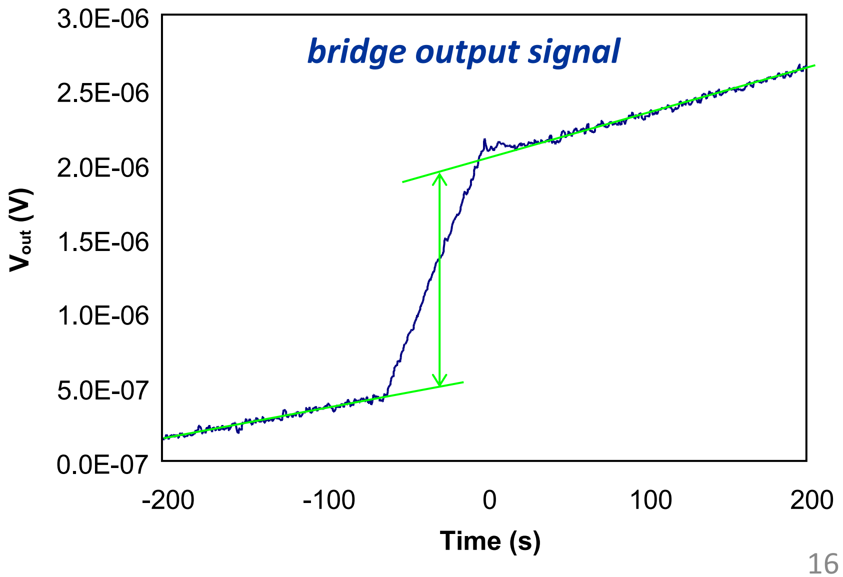
Where c_m stands for the specific heat capacity of the material and ΔT for the temperature rise.

- Water calorimeters: bulky systems typically used as a primary standard for metrology
- The temperature rise of water is **very small**:

$$\Delta T\ (water) = 2.4 \times 10^{-4}\ \text{K/Gy}$$



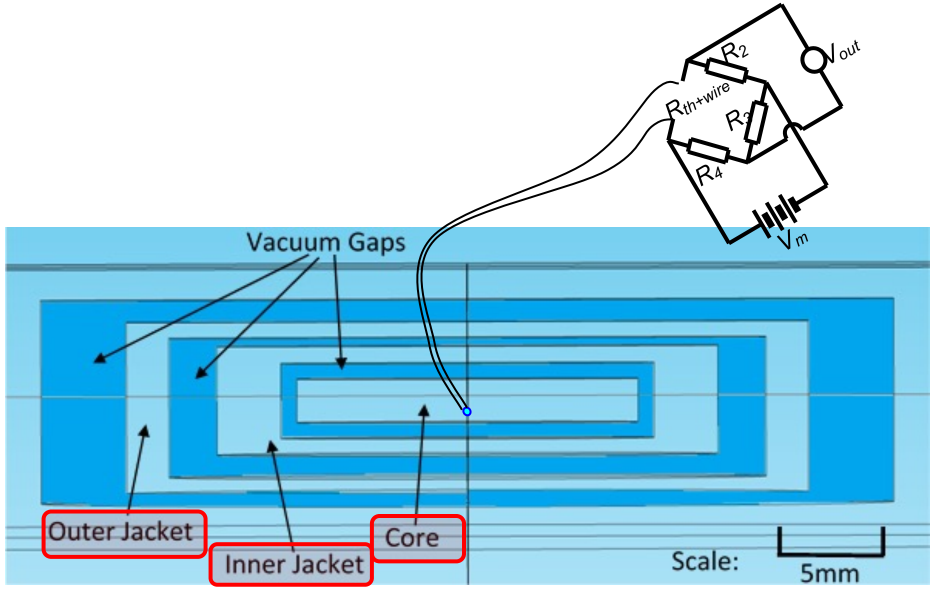
Independent on dose rate!



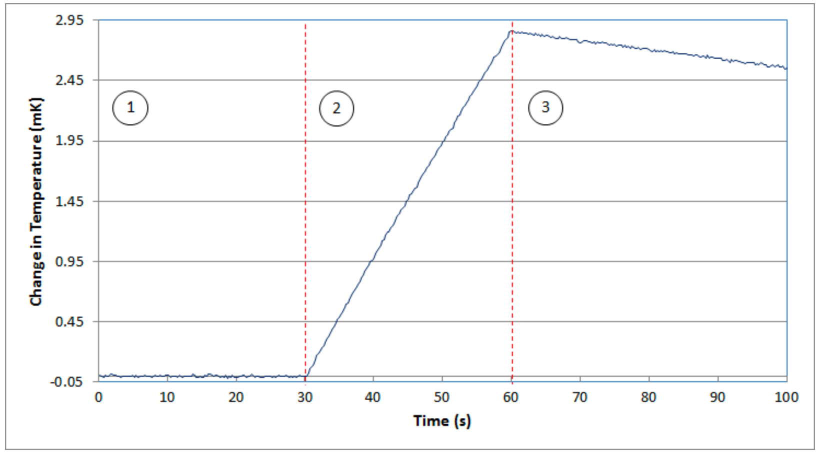
Graphite calorimeters: operational modes

Main common operation modes for graphite calorimeters:

- **Isothermal mode**:
  - temperature of all the components is kept constant
  - electrical energy is supplied to heat the components and keep them at a chosen constant temperature
  - during irradiation the beam will heat the components → the electrical energy supplied drops to maintain a constant temperature.
  - *the drop in electrical energy supplied will be equal to the radiation energy supplied to the calorimeter*



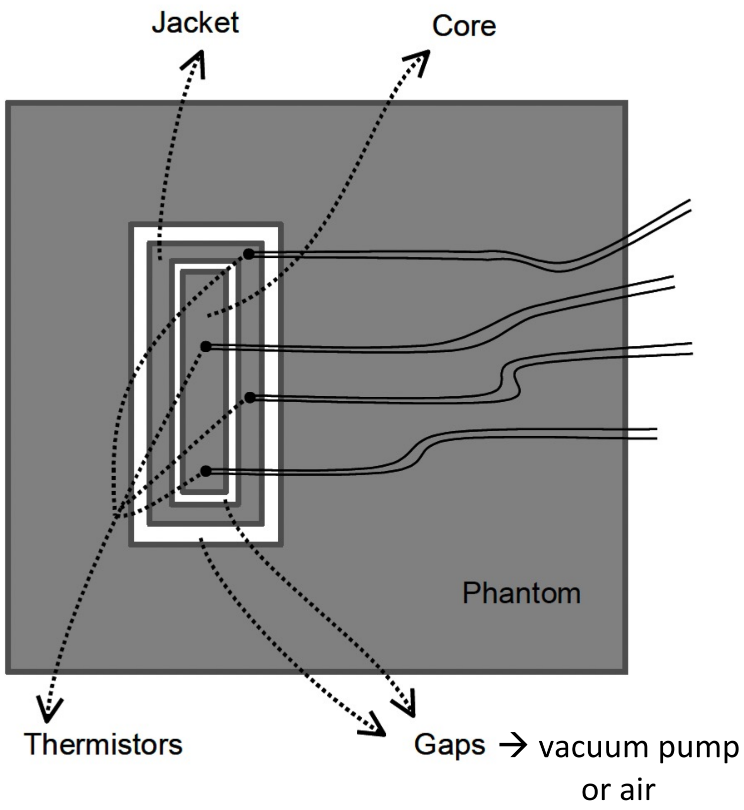
- **Adiabatic mode**
  - the temperature in all components is allowed to drift
  - any energy deposited in the calorimeter by the radiation presents as a rise in the temperature of the components.
  - no electrical heating involved
  - only measuring of temperatures using the sensing thermistors



- **Quasi-adiabatic mode**
  - If room temperature is not stable → it is difficult to see radiation induced temperature rises
  - the temperature of the outer jacket is fixed, but the core and inner jacket are allowed to drift
  - provides an environment with greater stability for the inner components

Graphite calorimeters

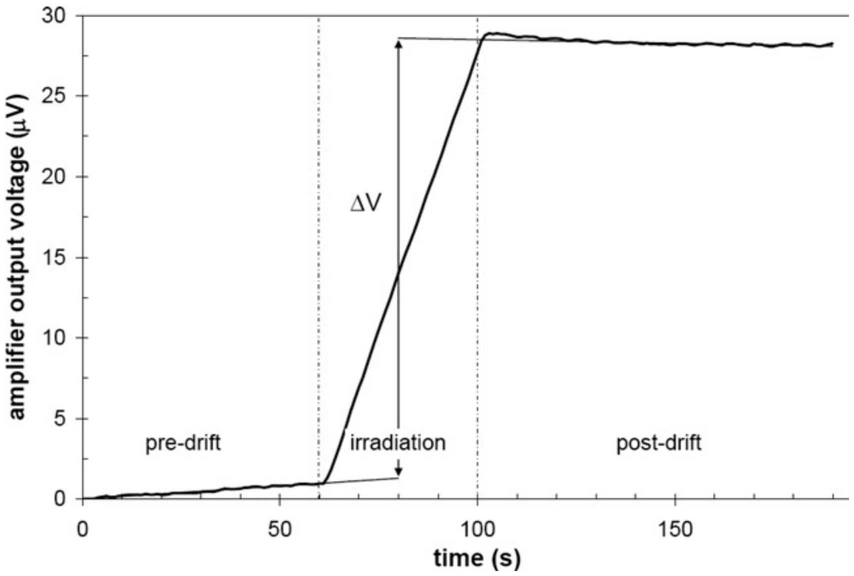
- Higher temperature rise as respect water for same dose
  → Developed much earlier than water calorimeters
- lattice impurities and chemical reactions
  → assumed to be negligible (confirmed by experiments)
- High thermal diffusivity:
  heat deposited in a graphite volume distributes within the volume in ∽ ms
  → *no possibility to measure T rise at point of measurement inside the phantom*
- A **core** needs to be thermally isolated from the surrounding graphite by one or more air or vacuum gaps → **nested configuration**
- Conversion factor from dose-to-graphite to dose-to-water required through *Monte Carlo* simulations (larger uncertainties)
- Correction factor to be applied:
  - for the effect of gaps (vacuum or air)
  - Volume average correction factor due to the finite size of the core
  - heat transfers
  - pre- post- drift extrapolation

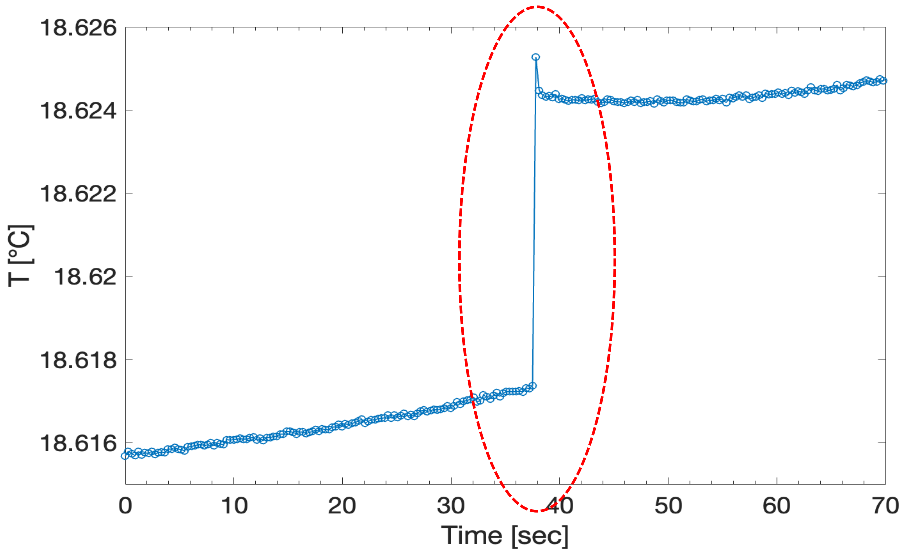


	c ($J \cdot kg^{-1} \cdot K^{-1}$)	$\Delta T/D$ ($mK \cdot Gy^{-1}$)
water	4180	0.24
graphite	710	1.41

Calorimeters for UHDR beams? Yes, but portable and as secondary standard

Slow delivery of the dose= temperature rise in the order of minutes





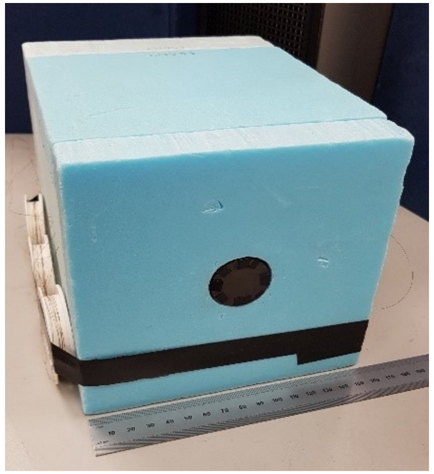
Instantaneous delivery of the dose= instantaneous temperature rise

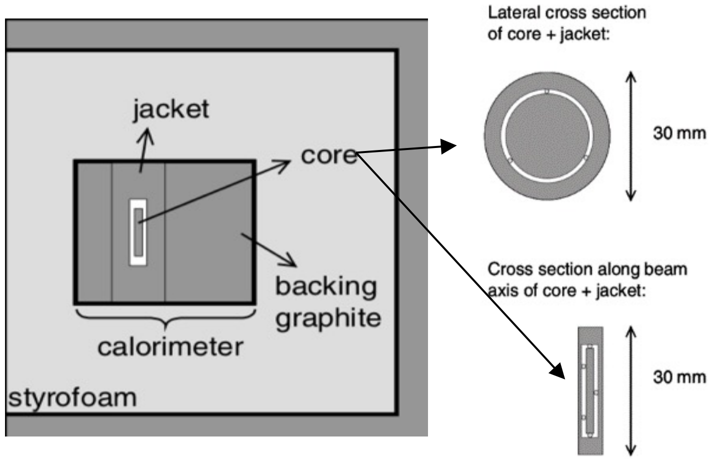
Conventional Radiotherapy

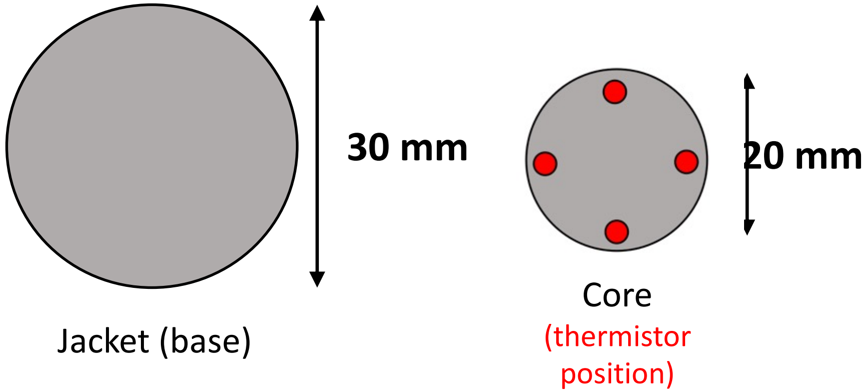
FLASH Radiotherapy

Development of a small portable graphite calorimeter

- Requirement: small, portable, easy-to-use
  - ***thin-walled calorimeter*** *in order to minimize divergence/absorption of the beam*
  - **No vacuum pump (air gaps)** → not an issue for high T rise gradients due to UHDRs
  - **Cylindrical** shape (core nested in a jacket + additional graphite slabs)
  - **Four thermistors connected to the core**
  - **Two thermistors connected to the jacket:** i) enabling jacket **temperature measurement** (more accurate assessment of the core-jacket heat transfer); ii) providing capability to operate in a **constant temperature mode** (further improving isolation)
  - One thermistor for **monitoring the ambient temperature**

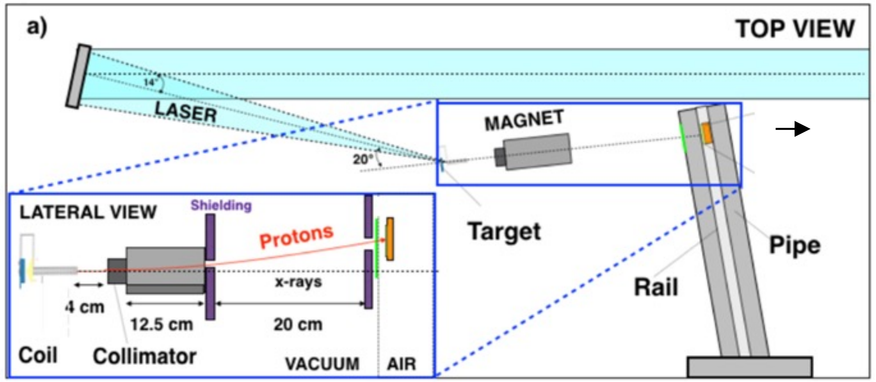


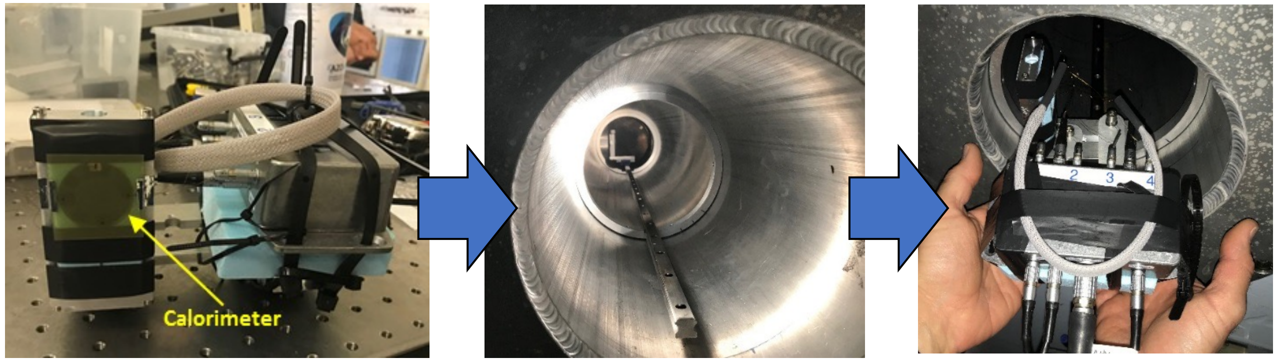




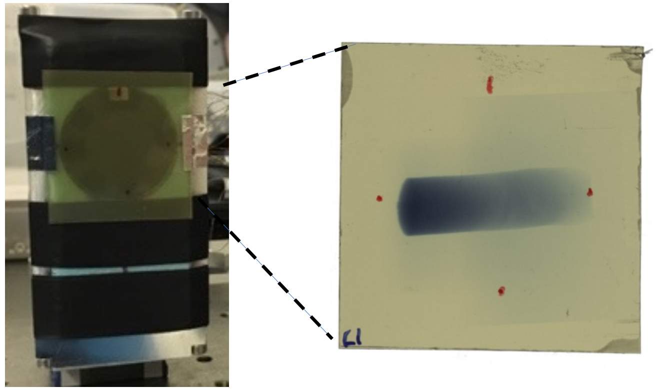
Calorimetry for UHDR laser-driven protons

- **First ever recorded absorbed dose measurement using calorimetry → proof-of-principle test with laser-driven protons at RAL (Rutherford Appleton Laboratory, UK) using VULCAN PW laser of CLF**

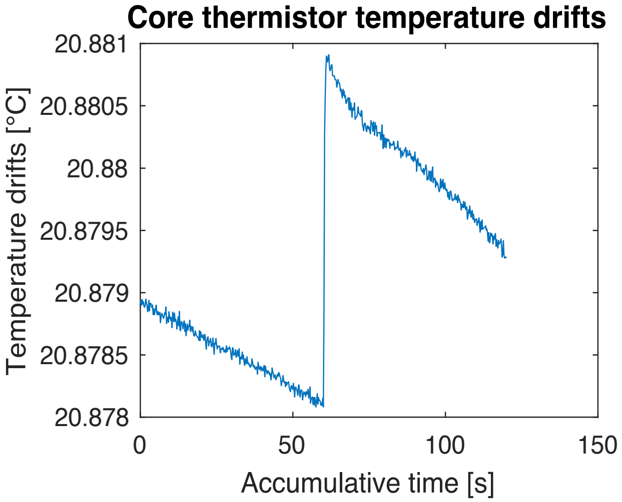




- **VULCAN PW** pulses of energy **600 J** and **~500 fs** durations
- focused to intensities > $\mathbf{10^{20}}$ $\mathbf{W/cm^2}$ onto **15 μm Au** targets
- Protons produced in the range **20– 45 MeV**
- High-energy component separated using a **0.9 T** dipole magnet
- Doses between **1-3 Gy in one single pulse**
- Instantaneous dose rate exceeding 10^9 Gy/s

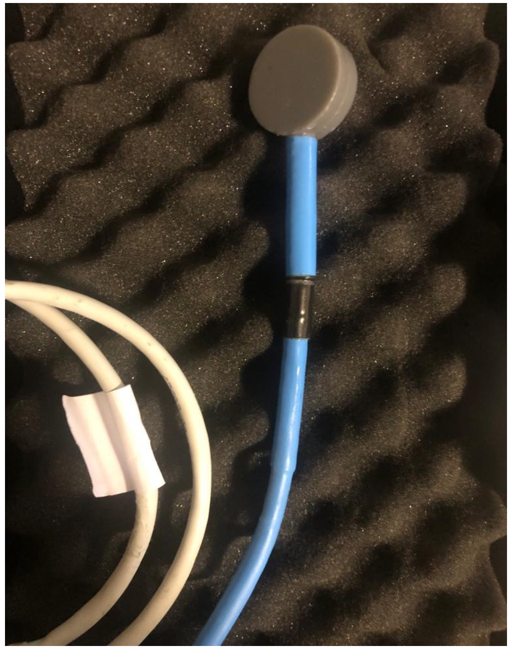


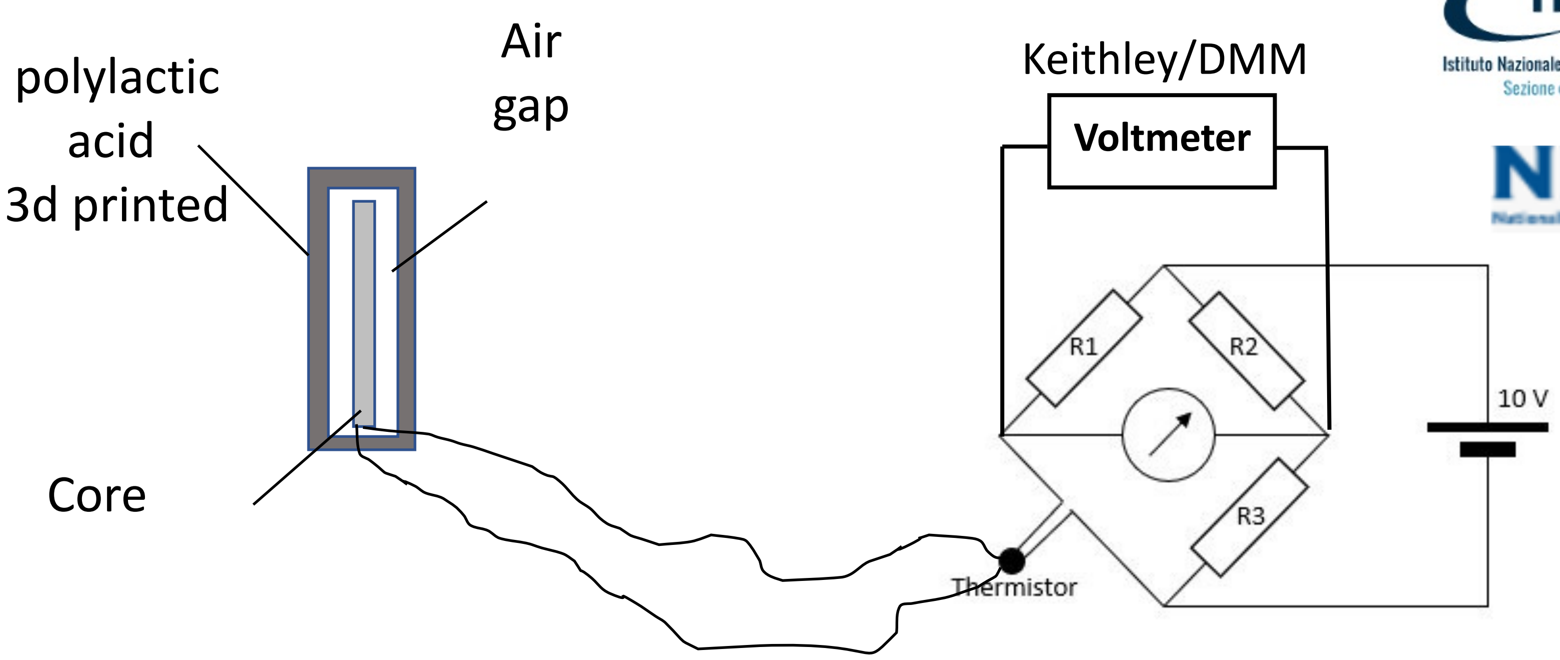
- Protection from EMP → Discrete components strategically positioned to protect the circuitry



F. Romano et al., Journal of Physics (2020)

Secondary standard graphite calorimeter for reference dosimetry with UHDR beams
The "FRIDA-CALO"





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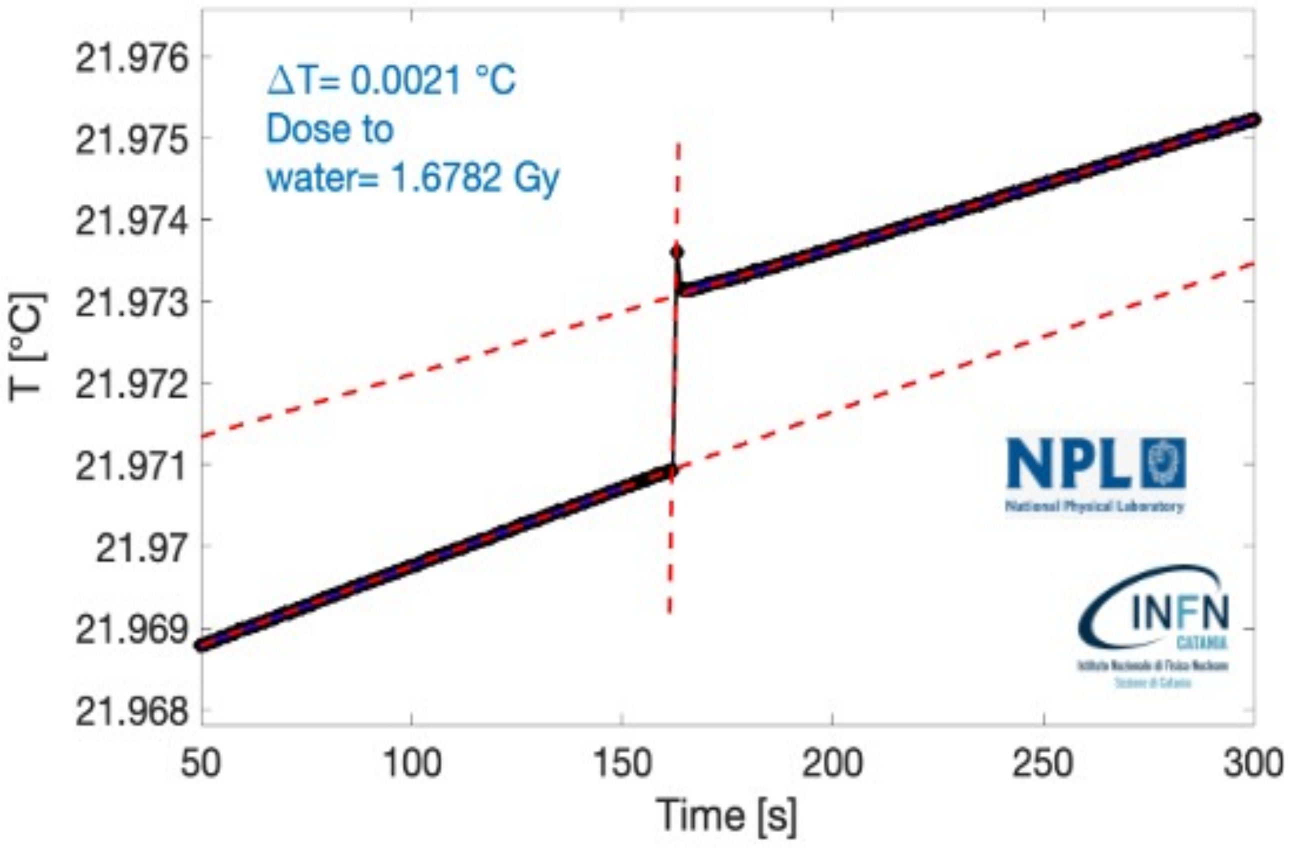
NPL

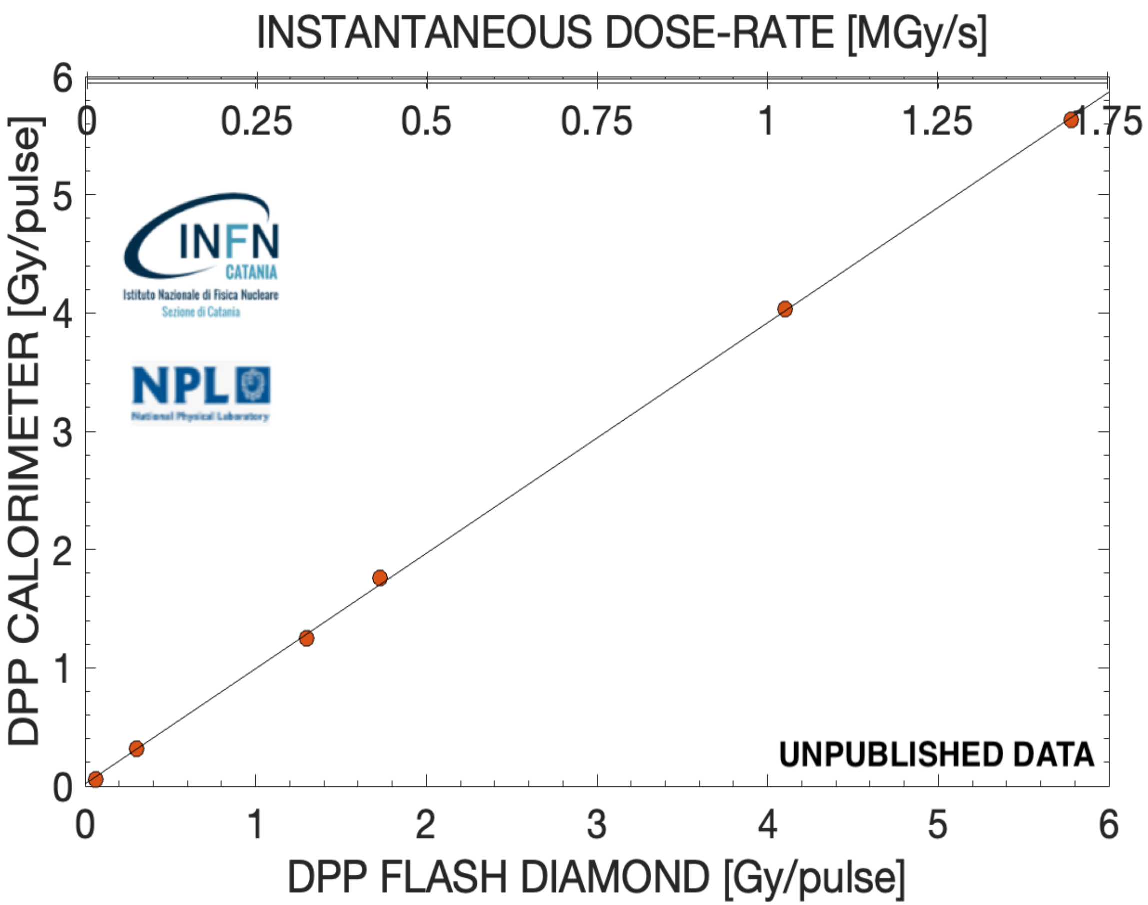
- High accuracy **reference** dosimetry (*active dosimeter*)
- Simple usage and low cost
- 2 mm graphite core
- 1 single termistor connected to the Wheatstone bridge to measure the temperature increase during the irradiation
- IBA PPC05 ion chamber geometry (same holders)

First test with UHDR beams @ CPFR

SINGLE PULSE TEMPERATURE RISE



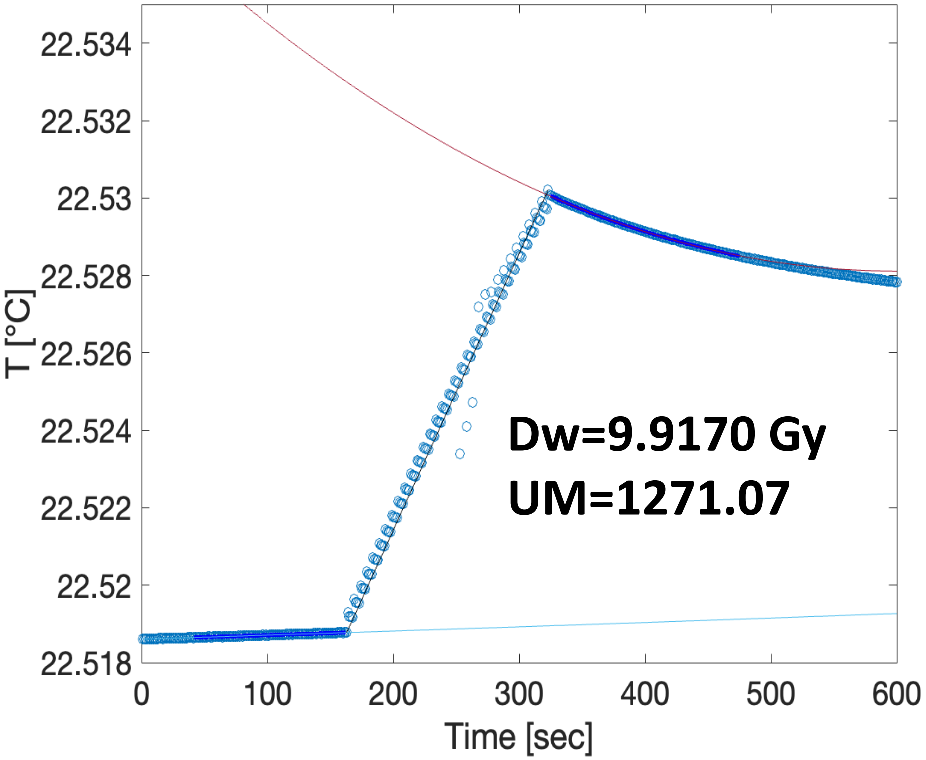
App 100-40, pulse length= 4 us



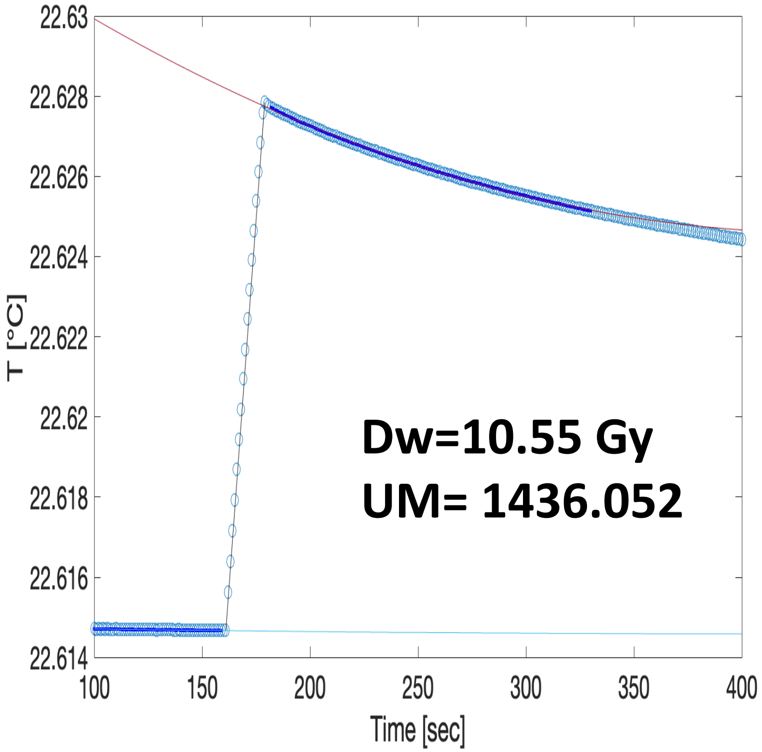
F. Romano et al, talk accepted at **12° Congresso Nazionale AIFM**

First test with UHDR beams @ CPFR

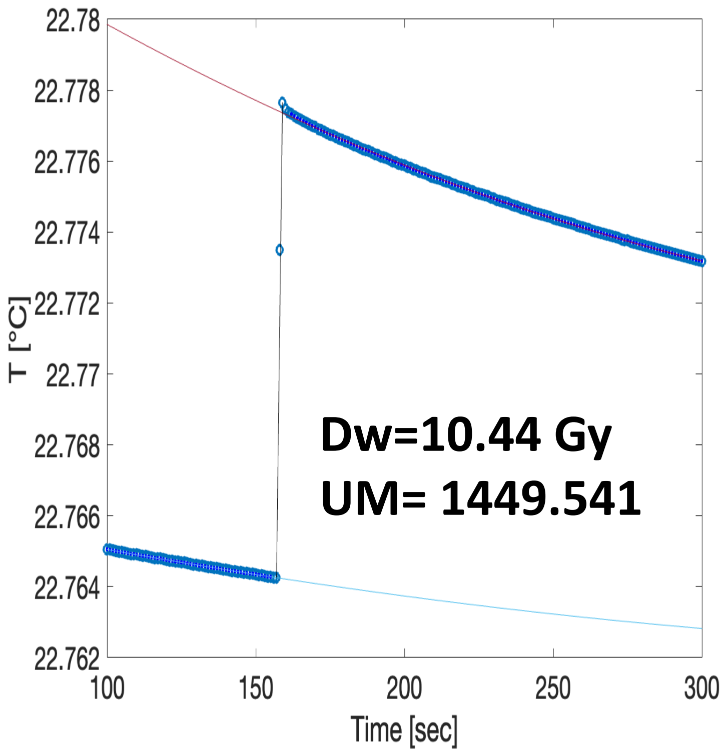
0.289 Gy/pulse 35 pulses 1 Hz→
40 s irradiation time
Conventional

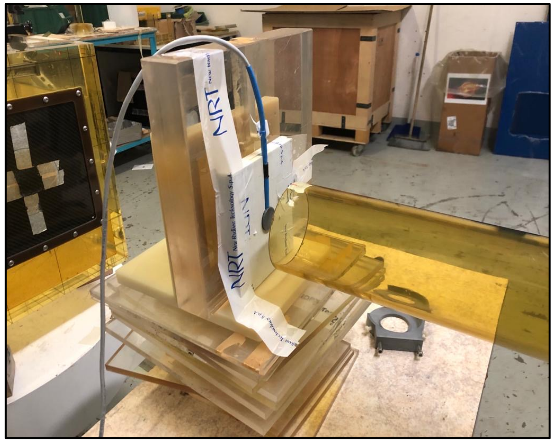


0.289 Gy/pulse 35 pulses 10 Hz→
4 s irradiation time



0.289 Gy/pulse 35 pulses 245 Hz→
0.15 s irradiation time
FLASH



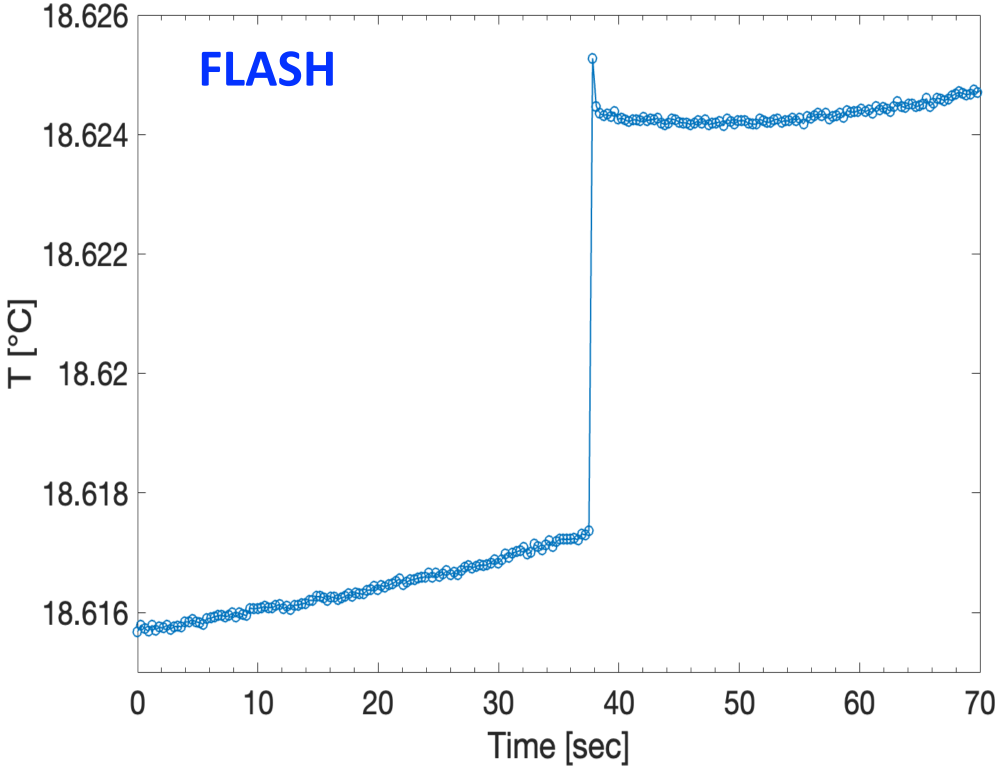


TEST @SIT APRILIA

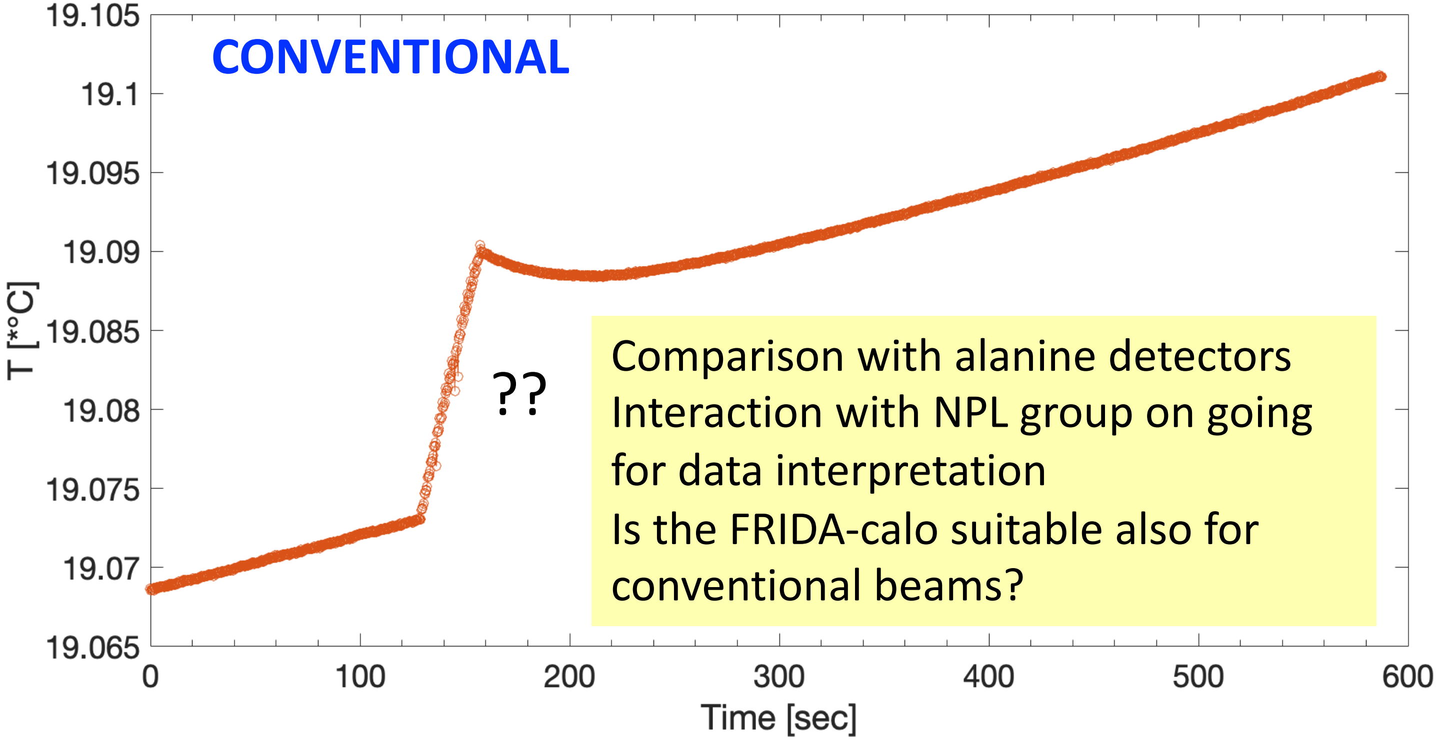
EXP CONDITIONS

- Reference dosimetry with alanine detector
- Only two modalities (beam currents) of irradiation FLASH/CONV

3 pulses – about 3 Gy/pulse t=5 us -10 Hz
Total dose=10 Gy Irrad. Time=0.3 s



50 pulses-0.2 Gy/pulse-2 Hz
Total dose=10 Gy Irrad. Time=30 sec



Comparison with alanine detectors
Interaction with NPL group on going for data interpretation
Is the FRIDA-calo suitable also for conventional beams?

Consuntivi 2022

TALK

1. G. Milluzzo ,, "Characterization of novel ultra-thin Silicon Carbide detectors with ultra-high dose rate electron beams for FLASH radiotherapy", Flash Radiotherapy and Particle Therapy (FPRT), Barcellona, 30 Novembre-2 Dicembre 2022 (Poster presentation)
2. F. Romano : " Flash and mini beams effects: towards a combined approach?", Flash Radiotherapy and Particle Therapy (FPRT), Barcellona, 30 Novembre-2 Dicembre 2022 (Poster presentation)
3. M. Marrale: "Dosimetric characterization of an ultra-high dose rate beam for flash radiotherapy through alanine epr dosimetry " , Flash Radiotherapy and Particle Therapy (FPRT), Barcellona, 30 Novembre-2 Dicembre 2022 (Poster presentation)
4. G. Milluzzo : "Challenges and opportunities of ultra-high dose rate dosimetry for FLASH radiotherapy", 47th Annual meeting of the European Radiation Research Society (ERRS), 21-24 Settembre 2022 (Poster presentation)
5. F. Romano "Dosimetry for FLASH radiotherapy: challenges and recent developments " invited talk ERSS
6. M. Marrale et al., "Could alanine/EPR dosimetry be useful for ultra-high dose rate beams used for FLASH radiotherapy? ", EPRBioDose conference, 2022.
7. F. Romano " " , Scuola Caldirola Pisa Settembre 2022
8. M. D'OCA Alanine/EPR dosimetry for ultra-high dose rate beams used for FLASH radiotherapy , CVIII Congresso Nazionale della Società Italiana di Fisica, September 12th-16th 2022, Milano (Italy) (2022).
9. M. MARRALE,, Dosimetric characterization of an ultra-high dose rate beam for flash radiotherapy through alanine epr dosimetry, EPRBiodose2022 Virtual event 28th-30th March 2022 (2022b).

PUBLICAZIONI

1. Romano, F.; Milluzzo, G.;Di Martino, F.; D'Oca, M.C.; Felici, G.; Galante, F.; Gasparini, A.; Mariani, G.; Marrale, M.; Medina, E.; et al. First Characterization of Novel Silicon Carbide Detectors with Ultra-High Dose Rate Electron Beams for FLASH Radiotherapy. Appl. Sci. 2023, 13, 2986.
2. Medina E.; Sangregorio E.; Crnjac A.; Romano F.; Milluzzo G.; Vignati A.; Jakšic M.; Calcagno L.; Camarda M. Radiation hardness study of Silicon Carbide sensors under high temperature proton beam irradiations. Micromachines 2022, 1, 0.
3. Romano, F.; Bailat, C.; Jorge, P.G.; Lerch, M.L.F.; Darafsheh, A. Ultra-high dose rate dosimetry: Challenges and opportunities for FLASH radiation therapy. Med. Phys. 2022, 49, 4912–4932.

TESI

Elettra Castronovo, "Dosimetria tramite Risonanza Paramagnetica Elettronica per fasci di Radioterapia FLASH", Relatori: Prof. Maurizio Marrale, Dr. Francesco Romano, Dott.ssa Giuliana Milluzzo, A.A. 2021/2022 Università degli Studi di Palermo