Calorimetry techniques for absolute dosimetry of proton beams with ultra-high pulse dose rates

Francesco Romano

francesco.romano@ct.infn.it

Istituto Nazionale di Fisica Nucleare

Sezione di Catania, Italy

National Physical Laboratory

CMES – Medical Radiation Science, Teddington, UK

PTCOG 2020 Online, 13-14 September 2020

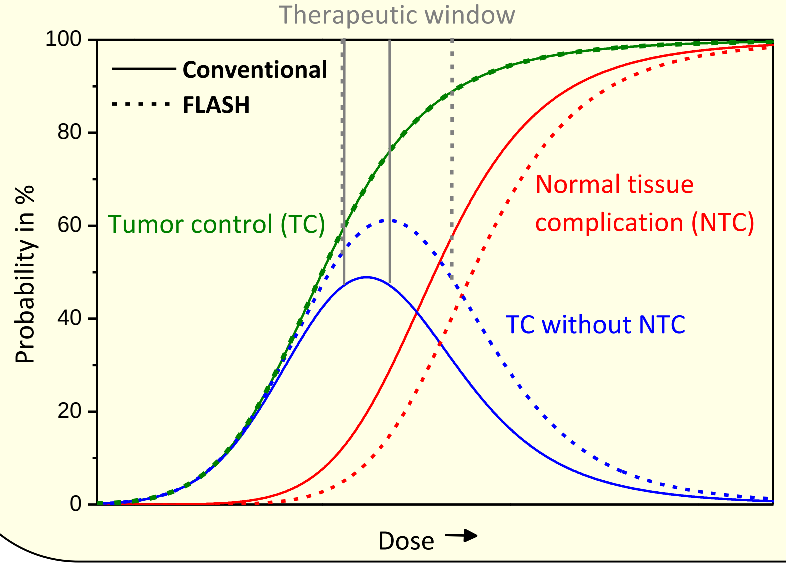
Beams with ultra-high pulse dose rates

- Improved the 3D dose conformation thanks to major advances in technologies.
  - therapeutic resistance to radiation can cause local disease progression
  - maximum deliverable radiation dose limited by normal tissue toxicities

→ ***New radiotherapy strategies required***

- Advances in proton accelerators (synchrocyclotrons and laser-based accelerators) has led to the use of irradiation modalities characterized by ultra-high pulse dose-rates (UHPDR).

The use of almost "instantaneous" delivery of radiation dose decreases undesired effects to healthy tissues still preserving the required tumour control → ***FLASH effect***



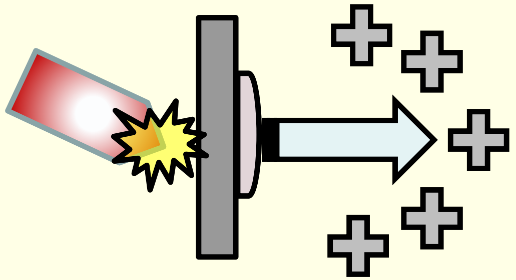
Favaudon et al., Sci Transl Med 6 (2014)

Durante et al., Br J Radiol 91 (2018)

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

Bourhis et al., Radioth. Oncol. (2019)

Even higher dose-rate per pulses produced by ***laser-matter interaction*** → *promising as particles are produced in compact "plasma accelerator"*



Ultrashort durations (~ 10 fs)
Ultra-high dose rate per pulse (10^9 Gy/min)

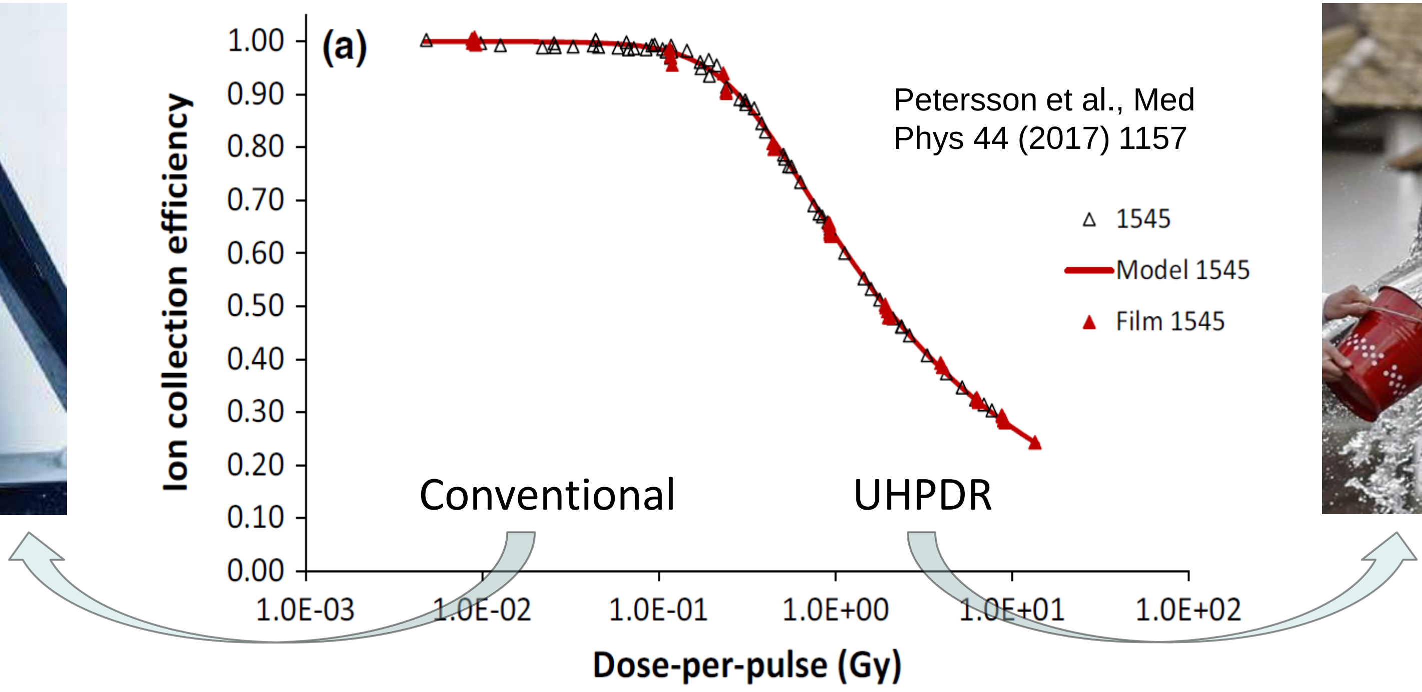
Protons produced through laser-target interaction (TNSA mechanism)

S.V. Bulanov *et al*, Phys. Lett. A, (2002)

E. Fourkal et al, Med Phys., (2003)

V. Malka, *et al*, Med. Phys., (2004)

Challenges for dosimetry of UHPDR beams



- Accurate dosimetry of high dose-rate particle beams is challenging
- Response of established active detectors influenced by high dose rates
- Generation of large electromagnetic pulse during laser-matter interaction (for laser systems)

UHDpulse EMPIRE project

EMPIR Call:	2018 / Health (JRP)
Coordinator:	Andreas Schüller (PTB)
Duration:	2019-2022
Start:	1. Sept. 2019
Funding:	2.1 M €

Topic: tools for traceable dose measurements for:

- FLASH radiotherapy
- VHEE radiotherapy
- laser driven medical accelerators

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

https://www.euramet.org/research-innovation/search-research-projects/details/project/metrology-for-advanced-radiotherapy-using-particle-beams-with-ultra-high-pulse-dose-rates/

***UHDpulse**: Metrology for advanced radiotherapy using particle beams with ultra-high pulse dose rates*

5 National Metrology Institutes
leading in the field of dosimetry

2 academic hospitals
pioneers in FLASH-RT

3 universities
experts in detector development
pioneer in laser-driven beams

3 national research institutes
pioneer in detector development
pioneer in laser-driven beams
dosimetry expert

1 European research institute
laser-driven beam research

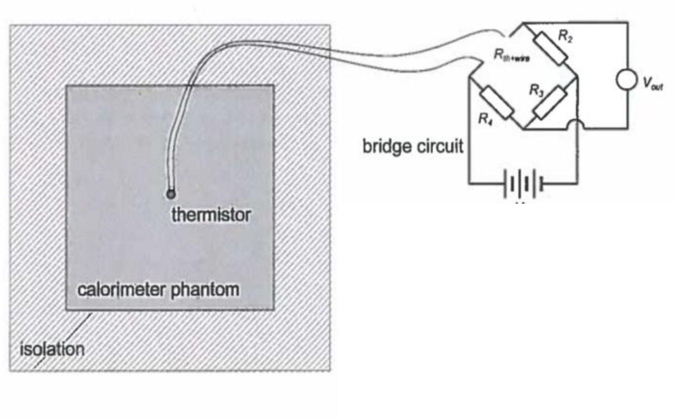
2 companies
expert in detector development

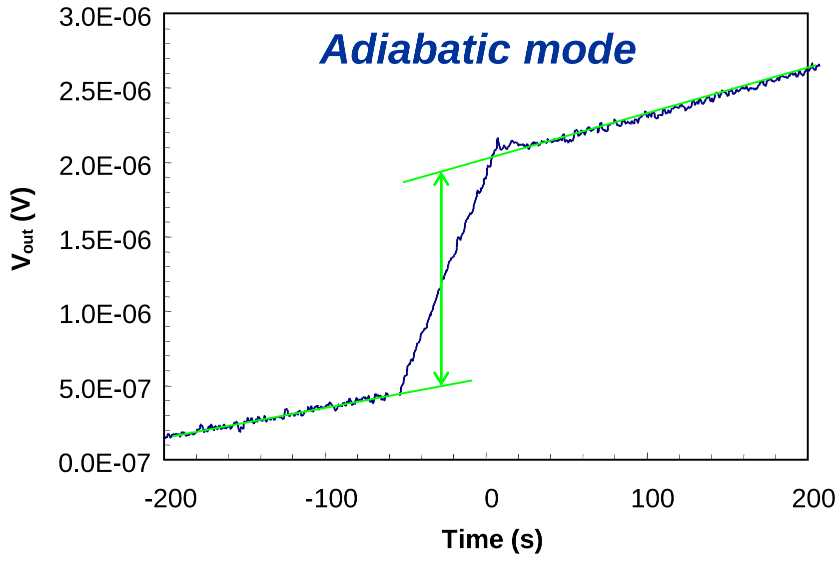
NMI's		Irradiation facility provider		Radiation detector developer	
PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin	WP6 (coordin.)	CHUV Centre hospitalier universitaire vaudois	WP3	ADVACAM Imaging the Unseen	WP4
NPL National Physical Laboratory	WP1	institut Curie		CSIC cnm	
METAS	WP2	eli beamlines		USC Universidade de Santiago de Compostela	
CMI Czech Metrology Institute	WP5 (impact)	Nuclear Physics Institute of the CAS public research institution		Politecnico Milano 1863	
Central Office of Measures		Queen's University Belfast		PTW The Dosimetry Company	
		HZDR Helmholtz Zentrum Dresden Rossendorf			

Calorimetry for proton dosimetry

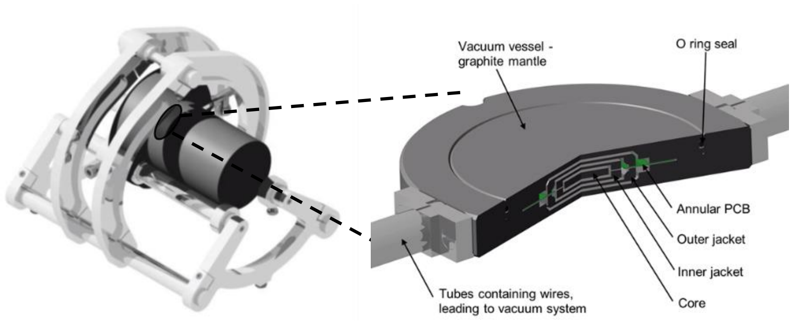
- Novel approach proposed by NPL never exploited so far for laser-driven beams based on **calorimeters**

- Water and graphite calorimeters have been demonstrated with p beams
- **Graphite calorimetry** at NPL (higher sensitivity)



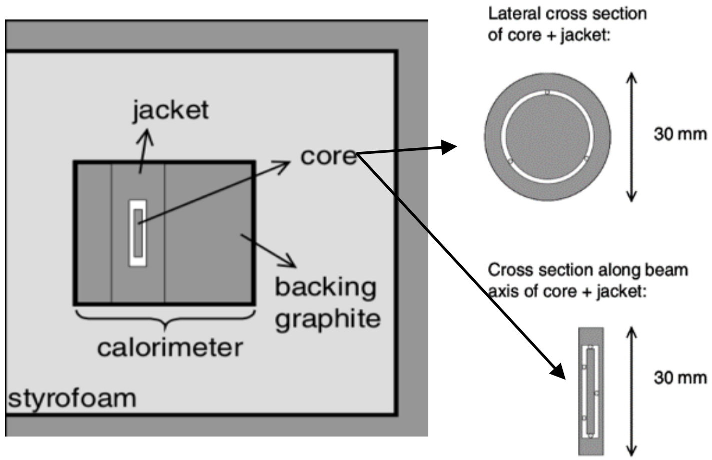


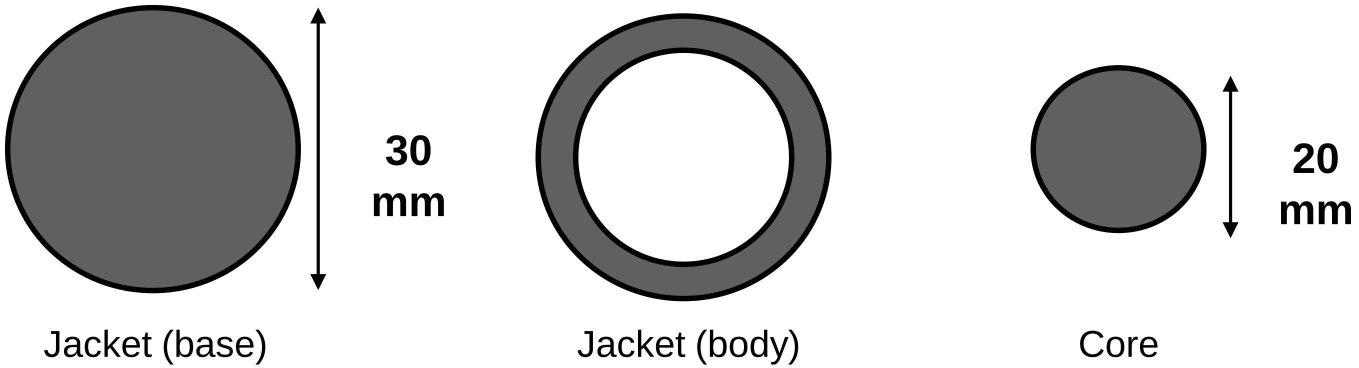
- **primary standard graphite calorimeter for absorbed dose in clinical proton beams**
- New IPEM UK code of practice to deliver an uncertainty on reference dosimetry for protons of approximately 2% (at 95% CL)



Development of a small portable graphite calorimeter

- Requirement: laser-driven proton energies of 15-60 MeV (→ WE range about 3-30 mm)
  - ***thin-walled calorimeter*** *in order to minimize divergence/absorption of the beam*
- A small portable graphite calorimeter (SPGC) originally developed for conventional low energy proton beams up to 60 MeV (Palmans *et al.* PMB **49** 2004) completely **refurbished** at NPL
  - **Cylindrical** shape (core nested in a three-piece jacket + additional graphite slabs)
  - Operated in **adiabatic mode**
  - **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**
- Functional tests successfully performed at NPL using conventional photon beams

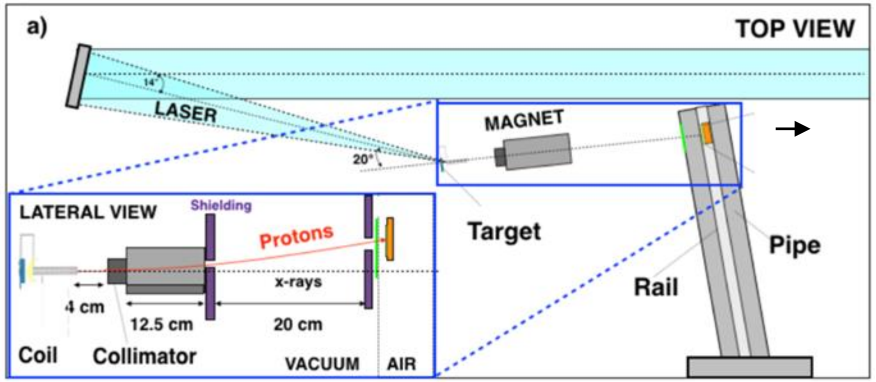




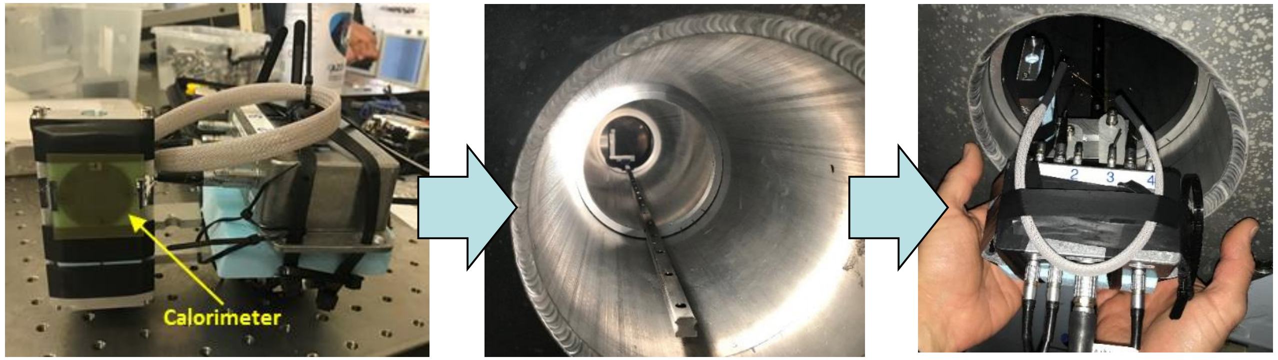
Calorimetry for laser-driven proton beams

- **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**

- Protection from EMP → Discrete components strategically positioned to protect the circuitry
- Monte Carlo simulations (with the Topas/Geant4 code) → SPGC and laser-driven beams parameters simulated to predict dose per shot at the core position



- **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**

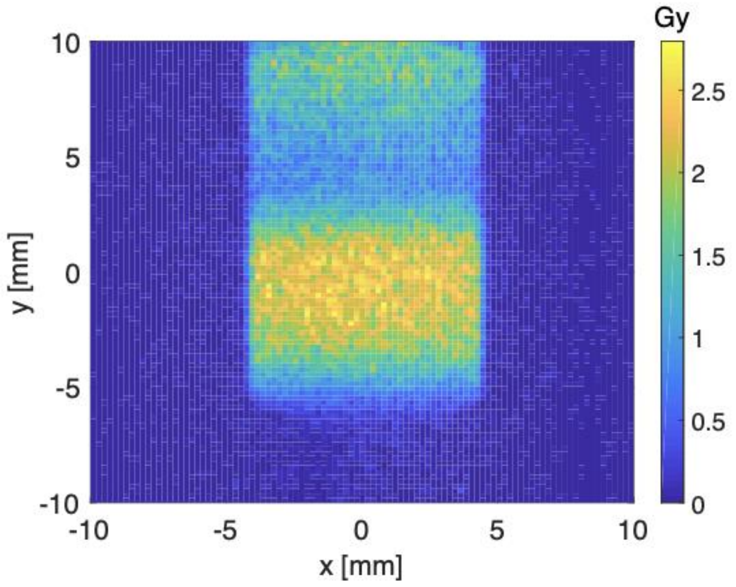


- **Design** and **realization** of the **holder** to be placed inside the pipe
- **RCF** to measure the **dose distribution** at the calorimeter entrance

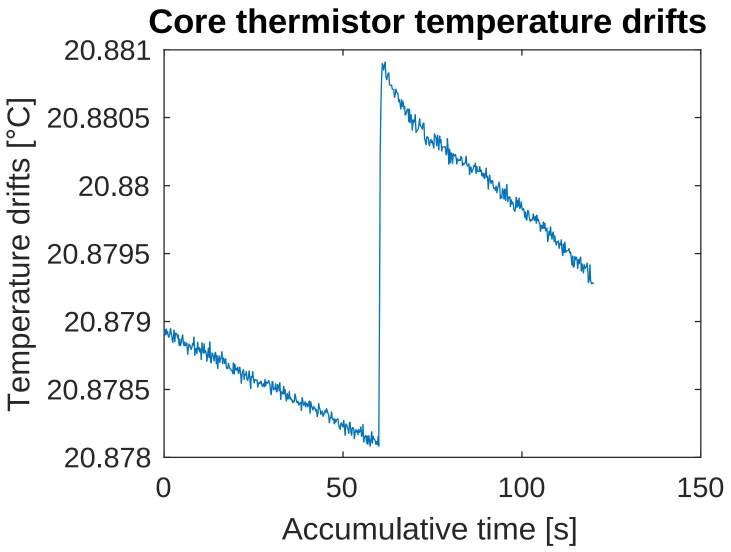
Proof of principle measurement at RAL

Total of **five** shots performed with this setup

- Four at full power (~600 J) directly onto calorimeter
- One with calorimeter taken from re-entrance pipe (assess EMP)



Expected dose map obtained from Monte Carlo simulations



Radiation induced temperature rises of one of the core thermistors for first laser shot

Analyzing the temperature drifts for each shot, and converting to absorbed dose: 1) **2.2 Gy**, 2) **1.2 Gy**, 3) **1.7 Gy**, 4) **0.4 Gy**

Feasibility of calorimetry in a laser environment demonstrated

Summary and future perspectives

- UHPDR/laser-driven beams offer potential benefits for applications
- Challenges associated with dosimetry at these high dose rates
- EMPIR project UHDpulse aiming at addressing these challenges
- Alternative approach through calorimetry of laser-driven beams demonstrated
- Dedicated campaign for calorimetry measurements of laser-driven protons carried out
- First calorimetry measurements with FLASH proton beams performed and further experimental campaigns planned
- Metrological and validated tools will be provided to support accurate preclinical studies and to enable future clinical applications of these emerging techniques

Thank you

Acknowledgements:

A. Subiel, N. D. Lee, H. Palmans, R. Thomas

National Physical Laboratory; CMES - Medical Radiation Science, Teddington TW11 0LW, Middlesex, UK;

S. McCallum, A. McIlvenny, H. Ahmed, G. Milluzzo, M. Borghesi

Centre for Plasma Physics, Queen's University Belfast, BT7 1NN;

A. Schueller

Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin, Bundesallee 100, 38116 Braunschweig;

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

This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.