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Development and characterization of GUM portable primary standards for absorbed dose to water

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Świętokrzyskie
Centrum
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Uniwersytet
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w Kielcach

IAEA TRS No. 398
Code of Practice for high energy photon beams

$$D_{w,Q} = M_Q \cdot k_{TP} \cdot (k_h)_Q \cdot (k_{elec})_Q \cdot \left(k_{pol}\right)_Q \cdot (k_s)_Q \cdot \frac{N_{D,w,Q_0}}{\left(k_{pol}\right)_{Q_0} \cdot (k_s)_{Q_0}} \cdot k_{Q,Q_0}$$

[TRS 398, 2000]

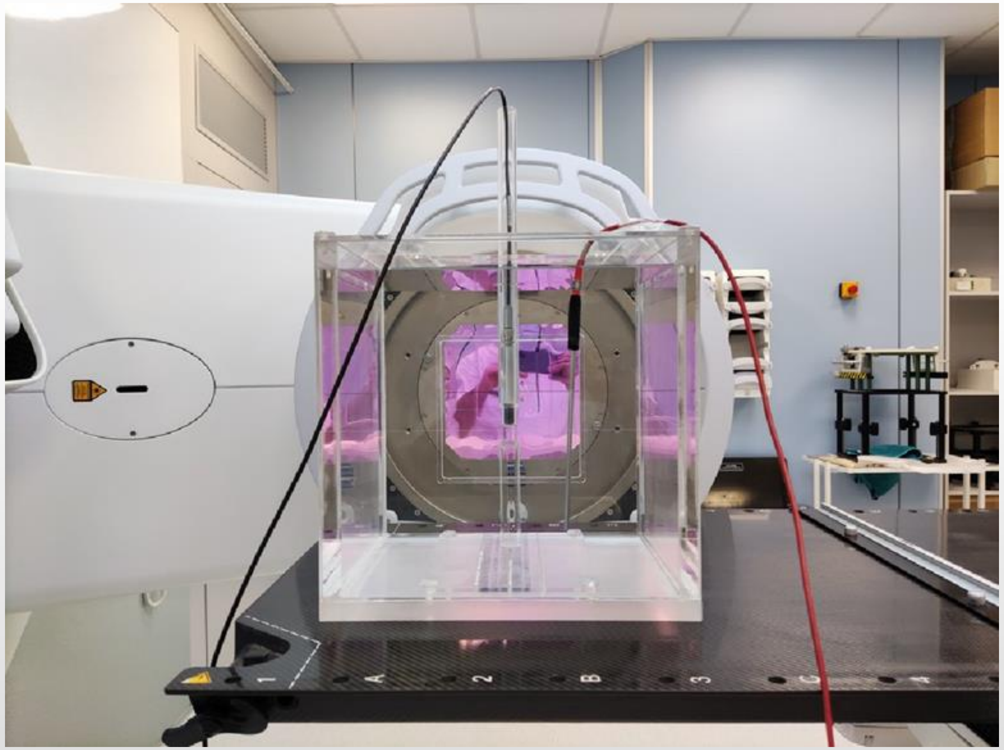
Dose accuracy limiting factors

k_{pol}

k_s

k_{Q,Q_0}

Portable primary standards

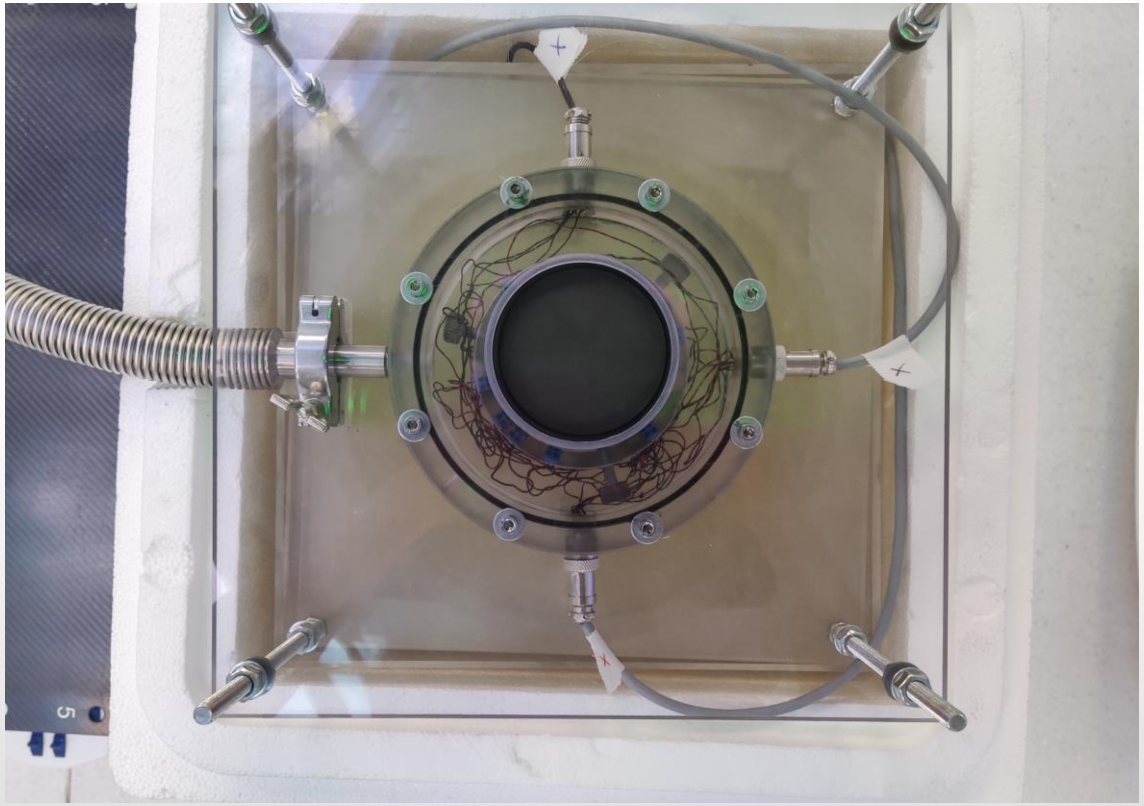


The GUM-DW3 graphite ionization chamber.

The GUM graphite calorimeter.

GUM portable primary standards

The GUM-DW3 graphite ionization chamber.

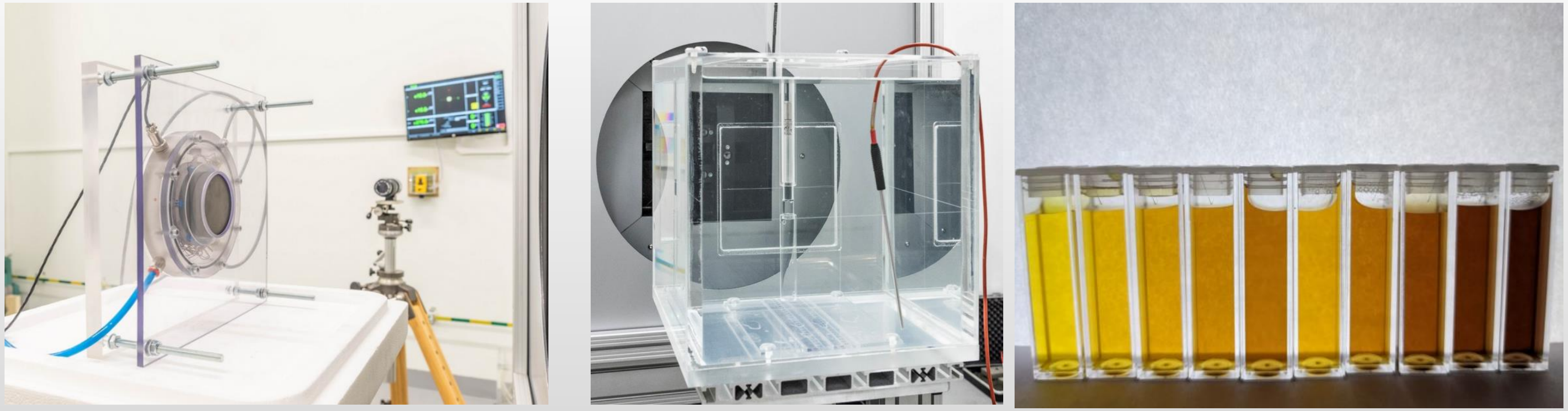


The GUM graphite calorimeter.

Absolute primary standards

- Calorimetry has the highest accuracy - it does not require a characterized field of ionizing radiation as a reference
- Ionometry method relies on W_{air}
- Fricke dosimetry relies on $G(Fe^{3+})$

[Seuntjens et al., 2009]



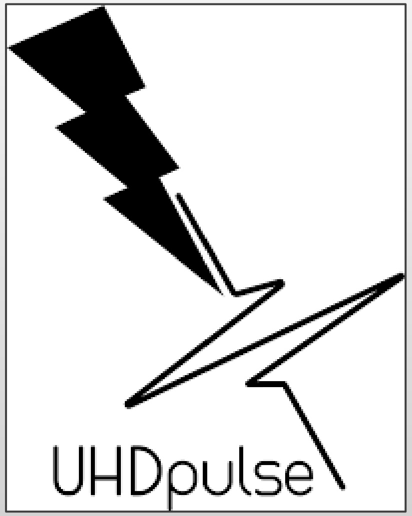
Absolute dosimeters. From left: calorimeter, ionization chamber and Fricke chemical dosimeter.

Potential reference for new RT modalities

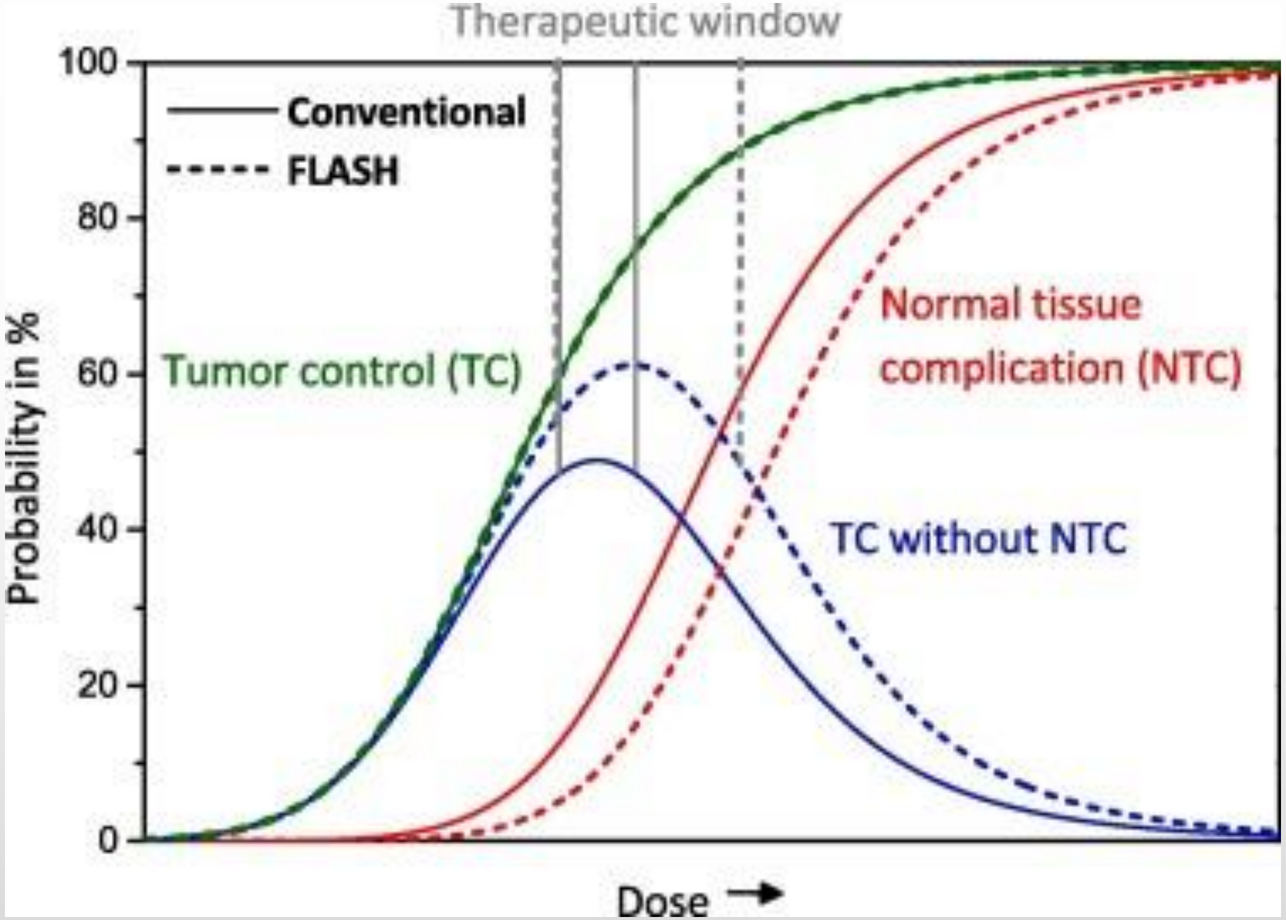
Conventional radiotherapy
0.1 Gy/s

Ultra **H**igh **D**ose **R**ate radiotherapy
(FLASH) **> 40 Gy/s**

Ultra **H**igh **D**ose **P**ulse **R**ate beams
(UHDPR)



[18HLT04 UHDpulse, 2021]



[Schüller et al., 2020]

Principle of calorimetric measurements

$$D = \frac{E}{m} = c \cdot \Delta T$$

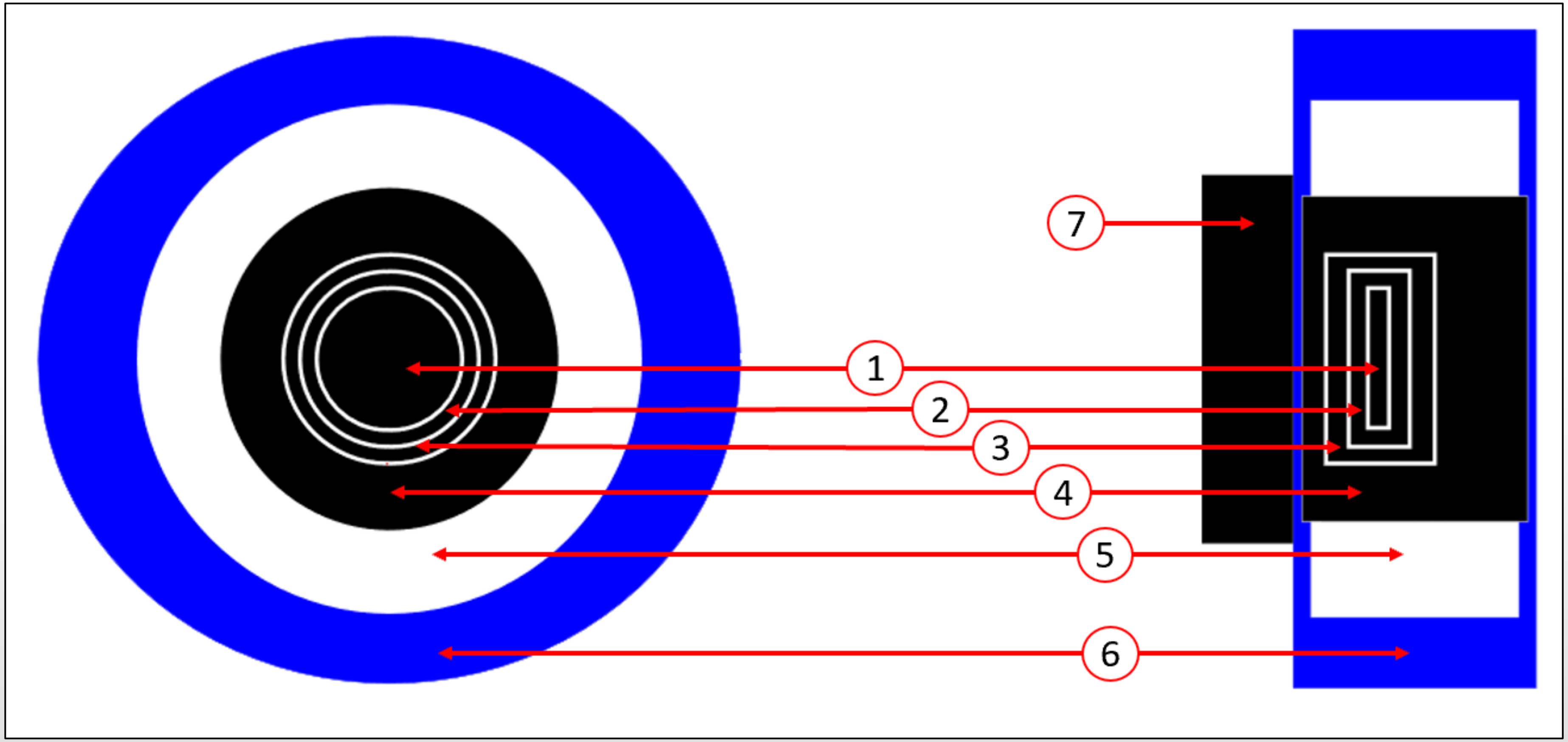
- c – specific heat capacity
- ΔT – temperature increase

Graphite versus water calorimetry

Graphite calorimetry	Water calorimetry
$f_{w,g}$ (MC simulation)	$f_{w,w} = 1$
c = 706.9 J K^{-1} kg^{-1} 1 Gy ⟶ **ΔT = 1,4 mK**	c = 4184 J K^{-1} kg^{-1} 1 Gy ⟶ **ΔT = 0,24 mK**
Heat defect negligible	Heat defect
Stabilisation time > 2-3 h	Stabilisation time > 20 h

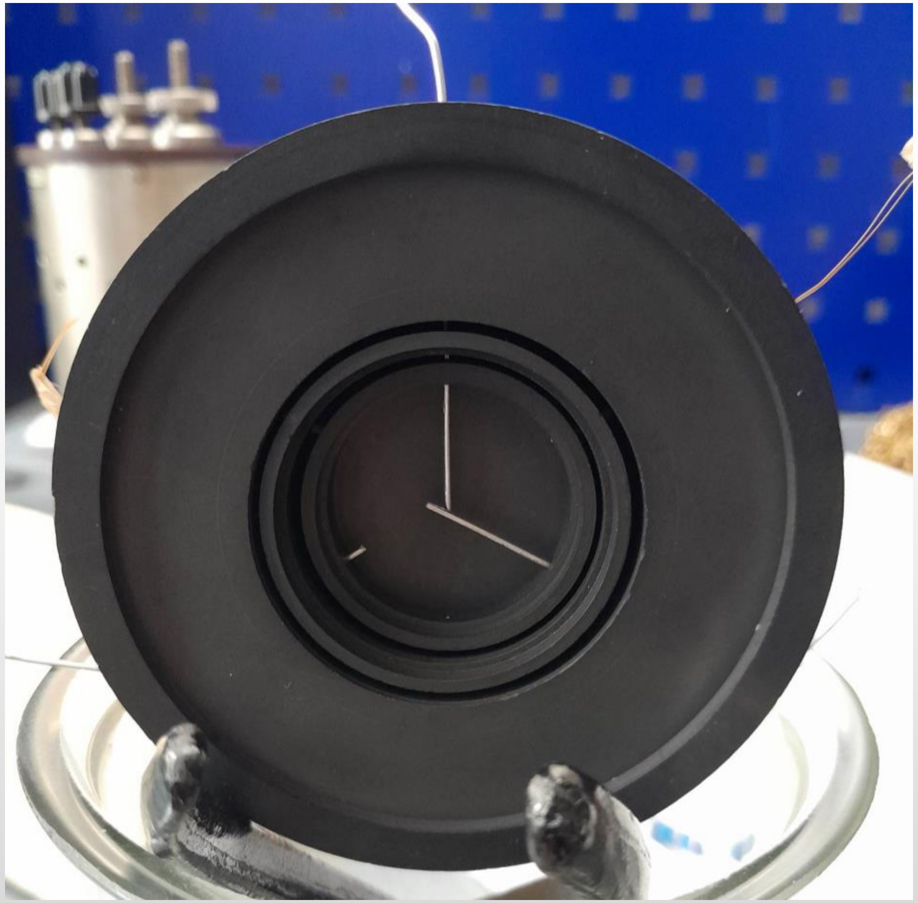
[Picard et al., 2006]

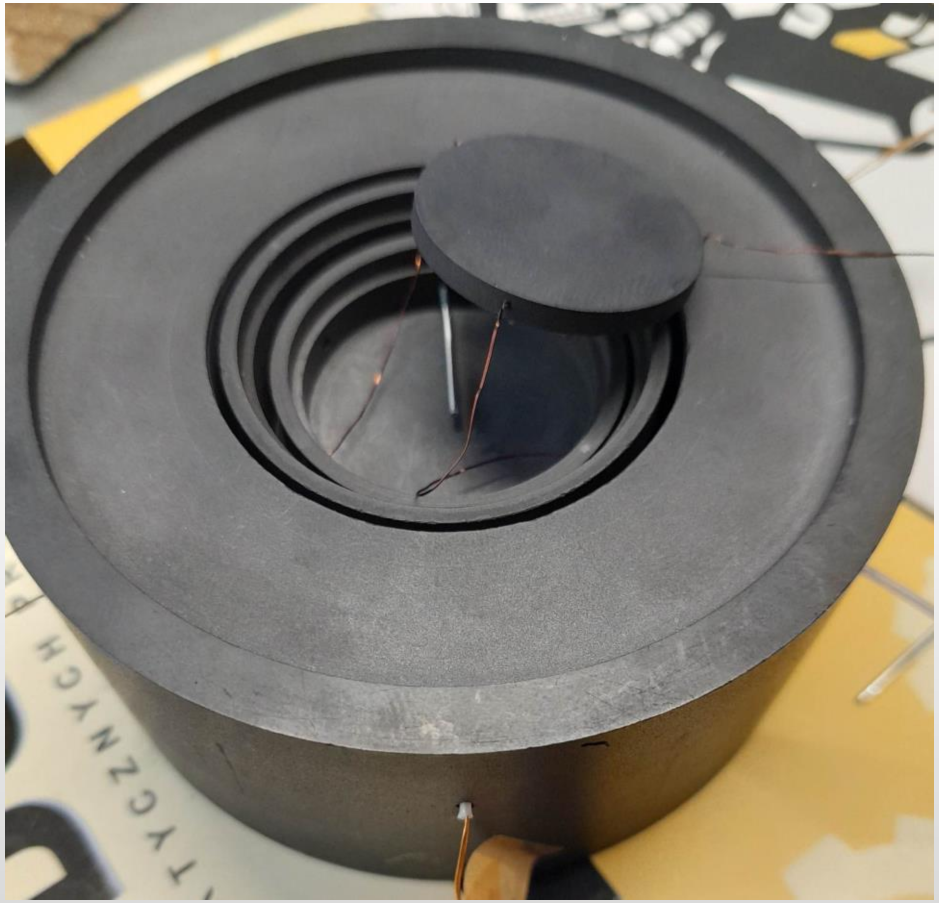
Calorimeter construction

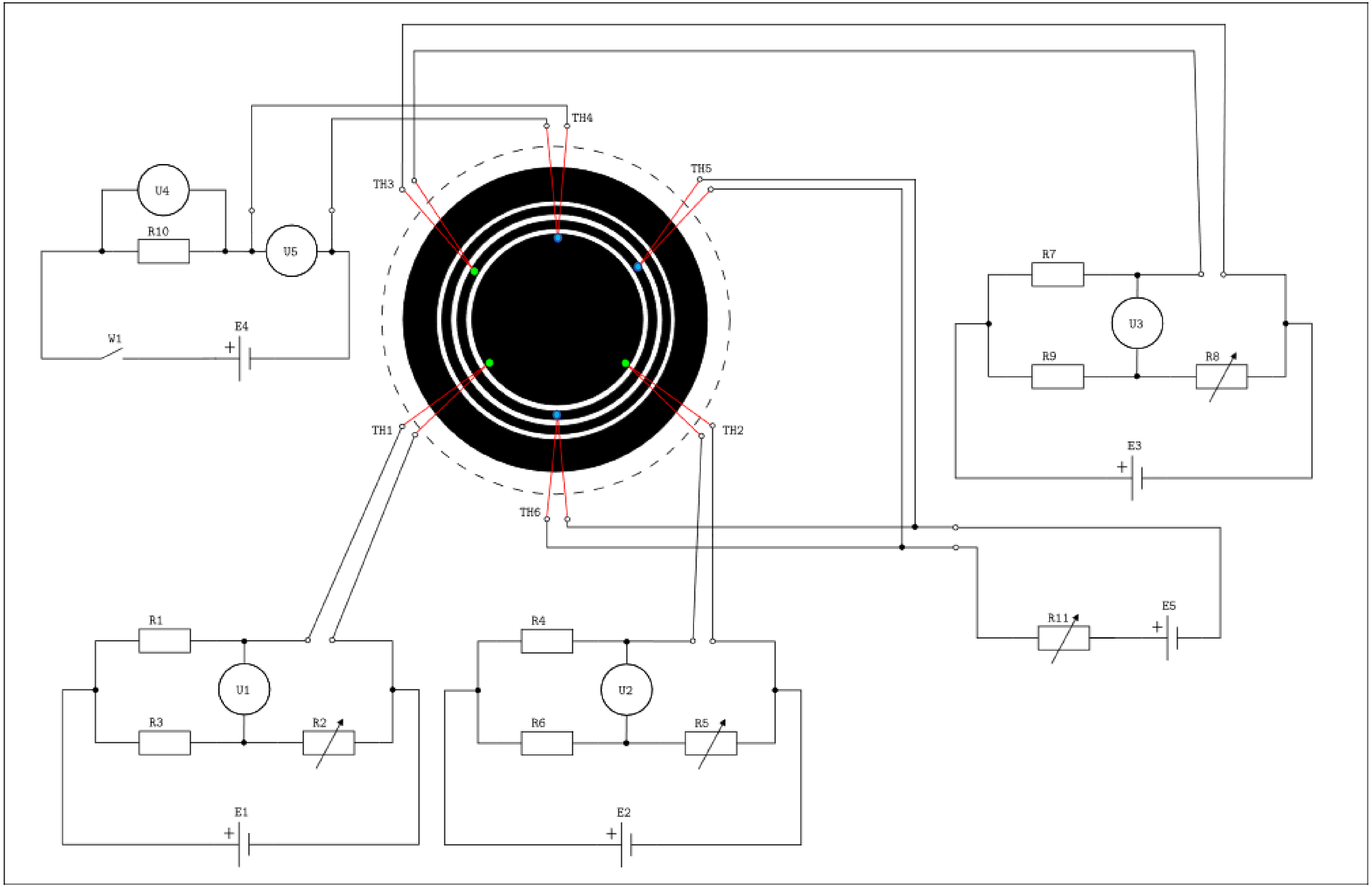


Scheme of graphite calorimeter construction: 1. core, 2. inner jacket, 3. outer jacket, 4. body, 5. vacuum gap, 6. vacuum shield, 7. compensation (build-up) block.

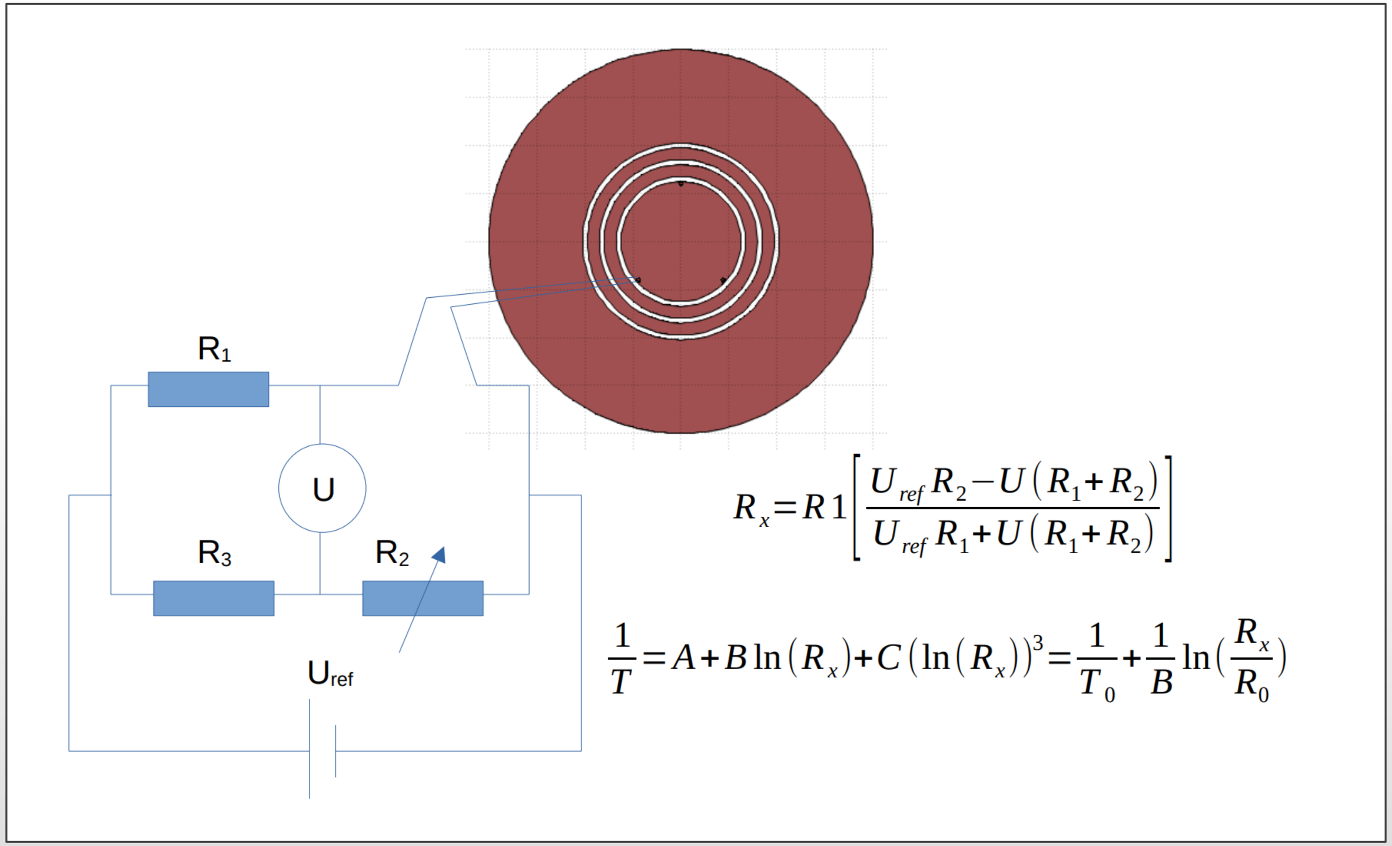
Calorimeter construction






U4
R10
U5
W1
E4
+
TH4
TH3
TH5
TH1
TH2
TH6
R7
U3
R9
R8
E3
+
R11
E5
+
R1
U1
R3
R2
E1
+
R4
U2
R6
R5
E2
+

DC Wheatstone bridge

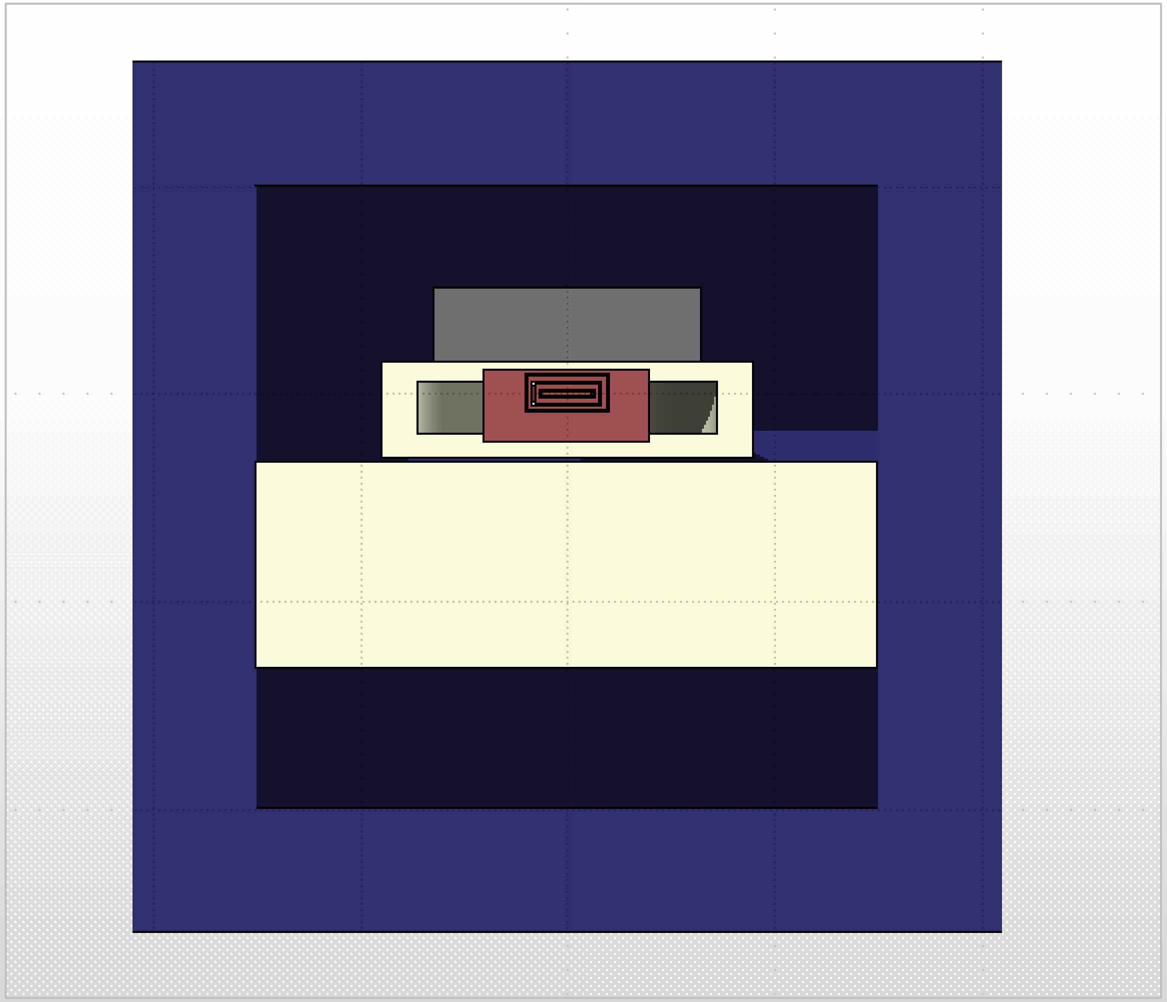


$$R_x = R1\left[\frac{U_{ref}R_2 - U(R_1+R_2)}{U_{ref}R_1 + U(R_1+R_2)}\right]$$

$$\frac{1}{T} = A + B\ln(R_x) + C(\ln(R_x))^3 = \frac{1}{T_0} + \frac{1}{B}\ln\left(\frac{R_x}{R_0}\right)$$

Determination of the temperature of the core based on the Steinhart–Hart equation.

MONTE CARLO model



In preparation for this work, we used the resources of the Center for Computation and Computational Modelling of the Faculty of Exact and Natural Sciences of the Jan Kochanowski University in Kielce.

- High energy photon beams: WFF 6 MV, 10 MV 15 MV
- Ecut 512 keV, Pcut 1 keV
- Styrofoam casing

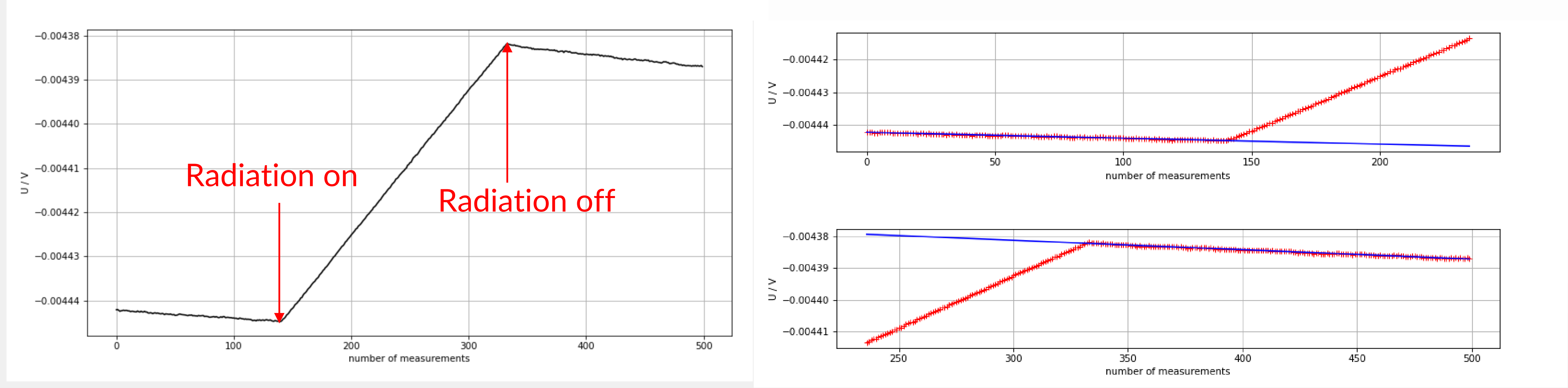
The GUM calorimeter model in FLUKA.

MONTE CARLO: Determination of correction factors

$$D_w = \boxed{k_{gap} \cdot k_{eq} \cdot k_{imp} \cdot f_{w,g} \cdot k_{rn}} \cdot D_g$$

- k_{gap} - gap correction accounting vacuum gaps
- k_{eq} - correction for equilibrium deviations
- k_{imp} - impurity correction factor
- $f_{w,g}$ - ratio of absorbed dose to water and to the graphite core
- k_{rn} - correction for radial non-uniformity in water

Quasi-adiabatic mode



Example quasi-adiabatic run. Screenshots from calorimeter control software.

Quasi-adiabatic versus isothermal mode

Operational mode	Measurand	Primary expression
Quasi-adiabatic with radiation	$\frac{E_{rad}}{m_{core}}$	$c_g \Delta T$
Quasi-adiabatic electrical calibration	$c_g \Delta T$	$\frac{\Delta E_{elec}}{m_{core}}$
Isothermal	$\frac{E_{rad}}{m_{core}}$	$-\frac{\Delta E_{elec}}{m_{core}}$

[Seuntjens et al., 2009]

Specific heat capacity

- Measurement during electrical calibration

$$c_g = \frac{E}{\Delta T \cdot m}$$

Mean value obtained in 6-month stability control: c_g = 747.481 ± 0.010 JK^{-1} kg^{-1}

- Empirical model adapted to GUM calorimeter

$$c_g = 706.9 + 3 \cdot (\bar{T} - 295.15) + 33.67$$

$\bar{T}$ - mean temperature during measurements with radiation

Calorimeter measurements

PTB
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Ultra-high dose pulse rate (UHDPR) electron beams

ŚCO
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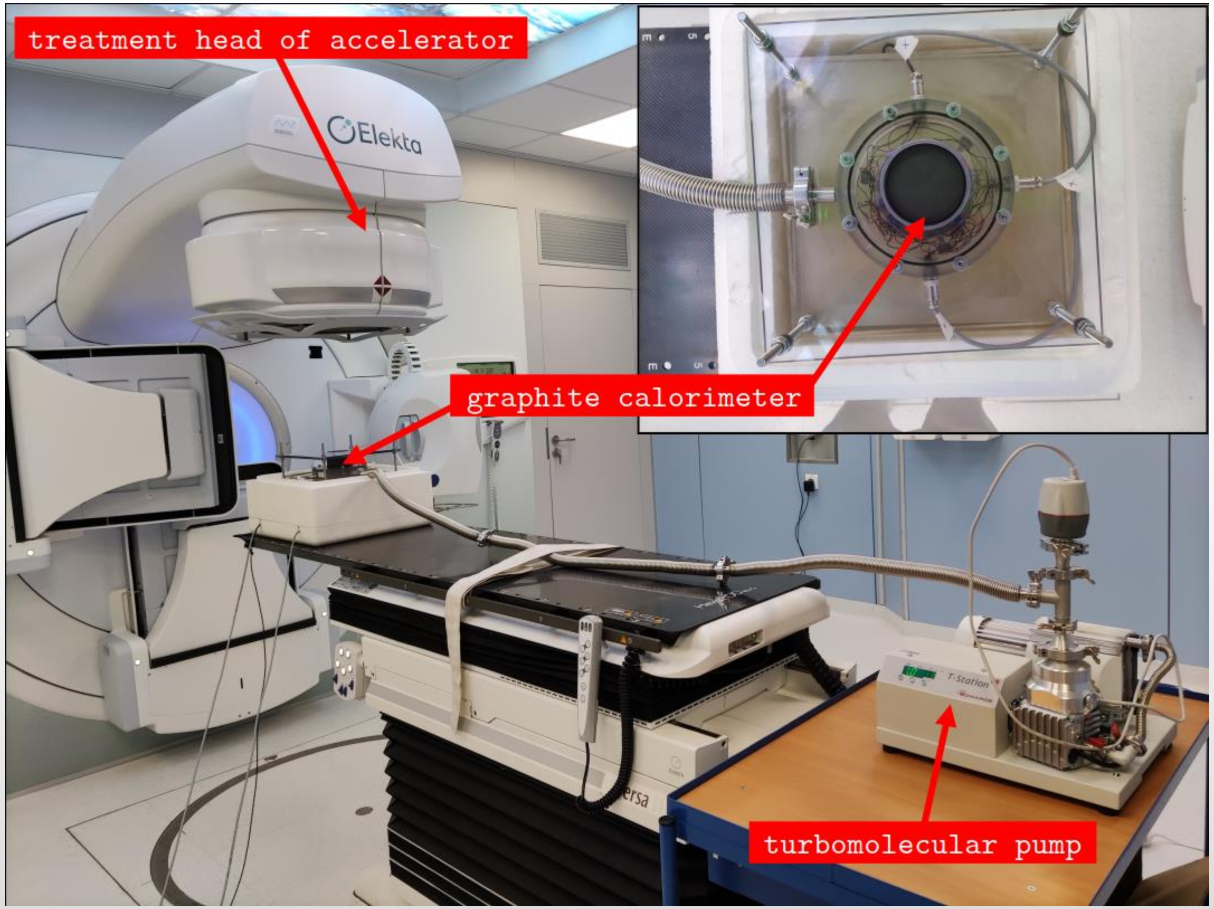
High energy photon beams

IFJ
Cyclotron Centre
Bronowice
CCB

- conventional proton beams 225 MeV
- FLASH protons: scanning and pencil beams

IC calibration in high energy photon beams

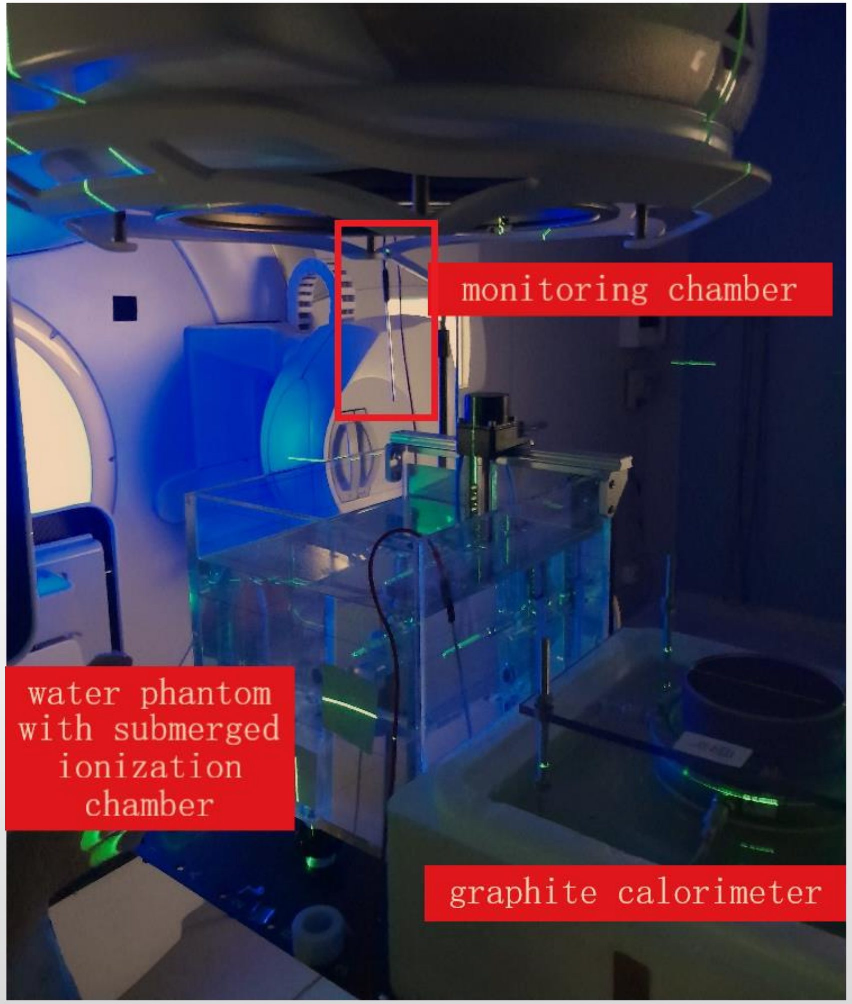
- Core positioned at 10 g/cm^{-2} reference depth in water
- Core-source distance 100 cm



Portable graphite calorimeter during measurements in the Holy Cross Cancer Center.

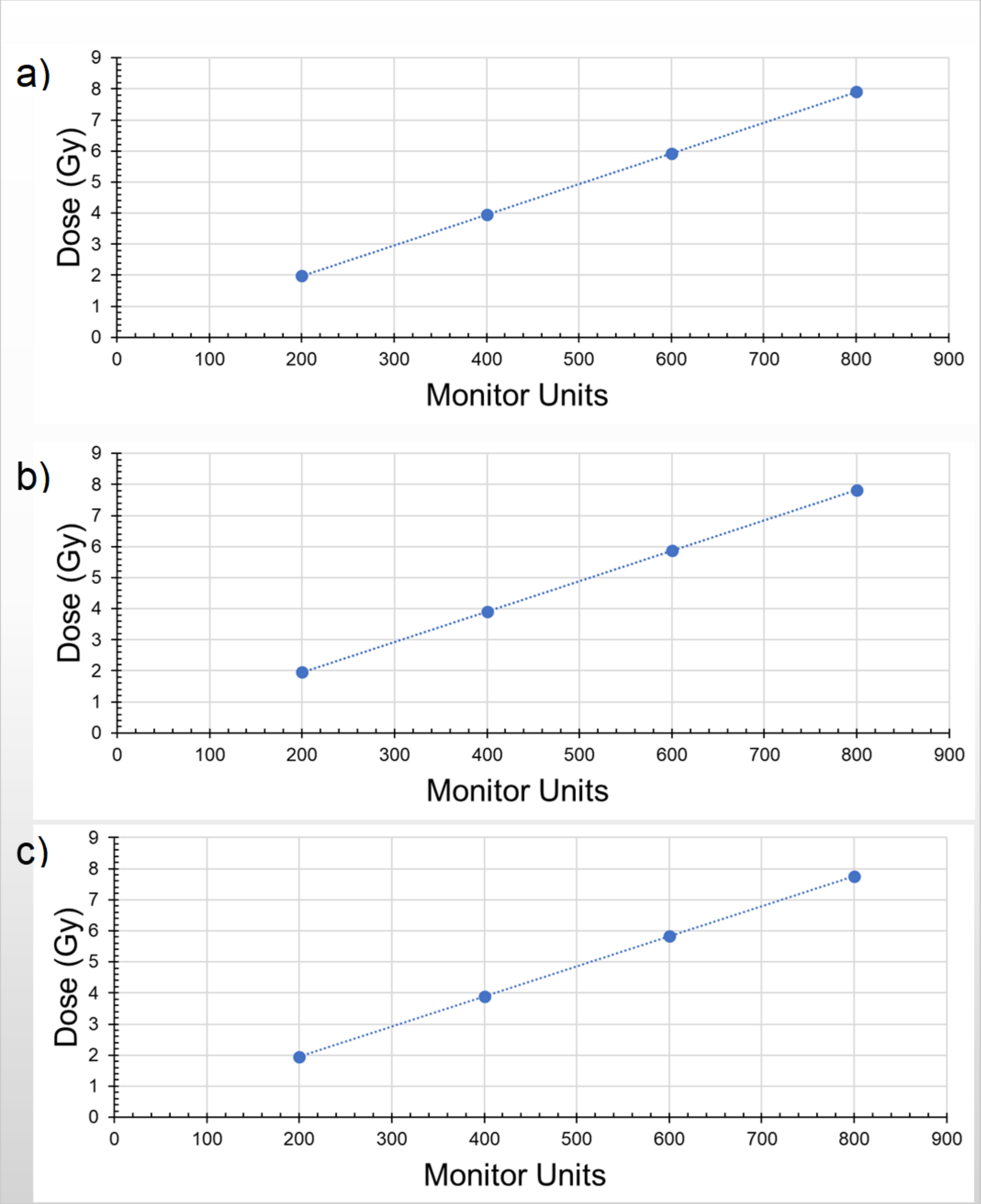
IC calibration in high energy photon beams

- Calibrated chambers: type PTW 30013 with UNIDOS electrometers
- Polarising potential 400 V
- Source-to-surface distance (SSD) 90 cm



Instrument setup during calibration.

MU versus measured doses



Dose per monitor units plots for three different accelerator photon beams:

a) 6 MV,
b) 10 MV,
c) 15 MV.

The linear fit is described by the following equations:

a) y = 0,0099x + 0,0008,
b) y = 0,0098x - 0,0081,
c) y = 0,0097x + 0,0114.

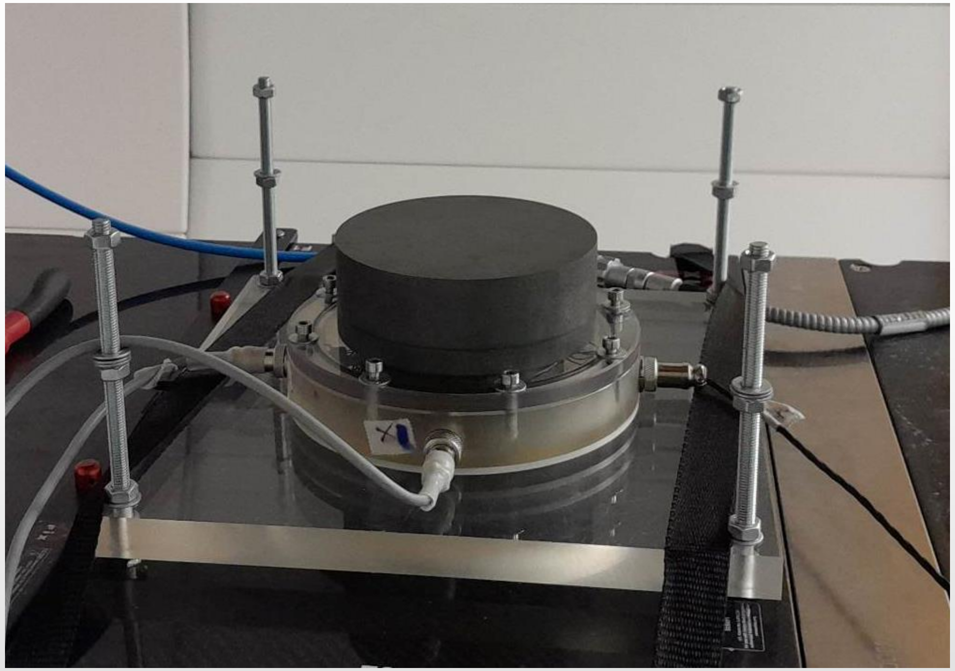
Calibration coefficients

$$N_{Dw} = \frac{D_w / Q_{corr-cal}}{M_{corr} / Q_{corr-IC}}$$

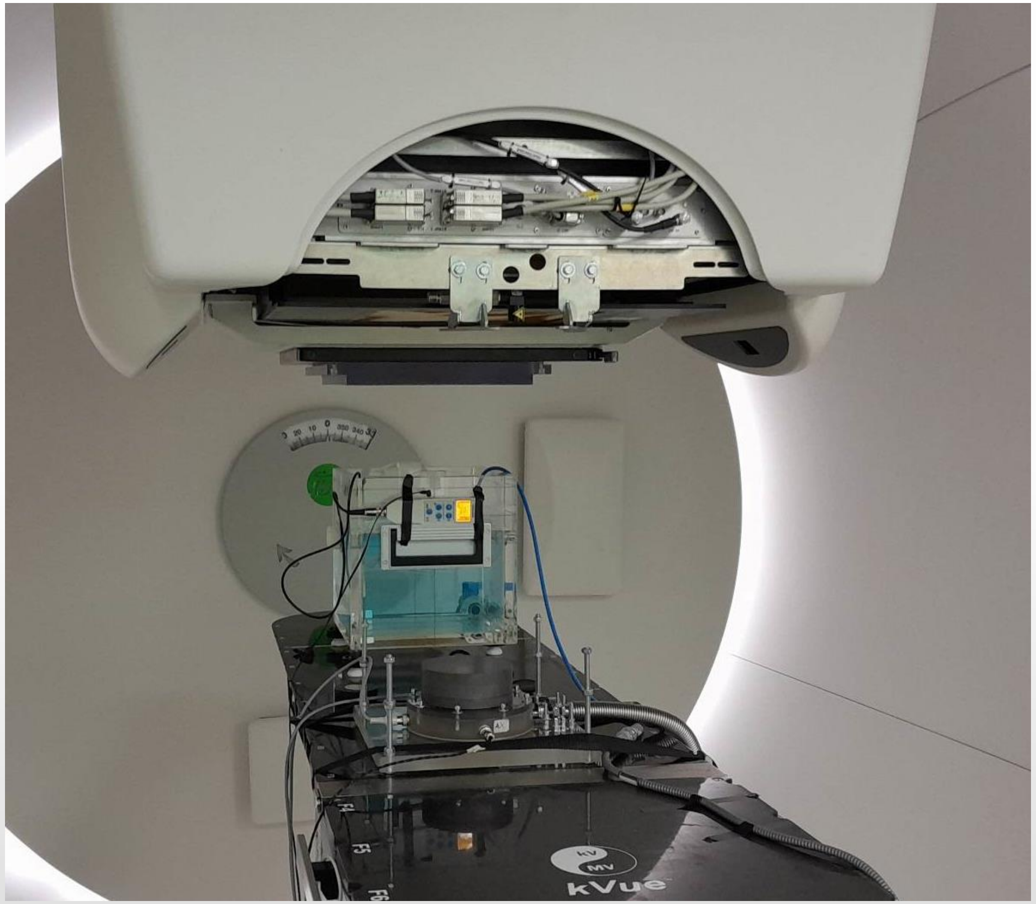
Photon beam energy	N_{Dw} (Gy·µC^{-1})		
	SN 9967	**SN 12858**	**SN 2947**
6 MV	53.46	53.06	53.10
10 MV	52.50	52.55	52.36
15 MV	52.29	52.14	52.15

Photon beam energy	Relative standard uncertainty (%)		
	SN 9967	**SN 12858**	**SN 2947**
6 MV	0.51	0.68	0.87
10 MV	0.43	0.56	0.45
15 MV	0.46	0.55	0.39

Measurements in conventional proton beams



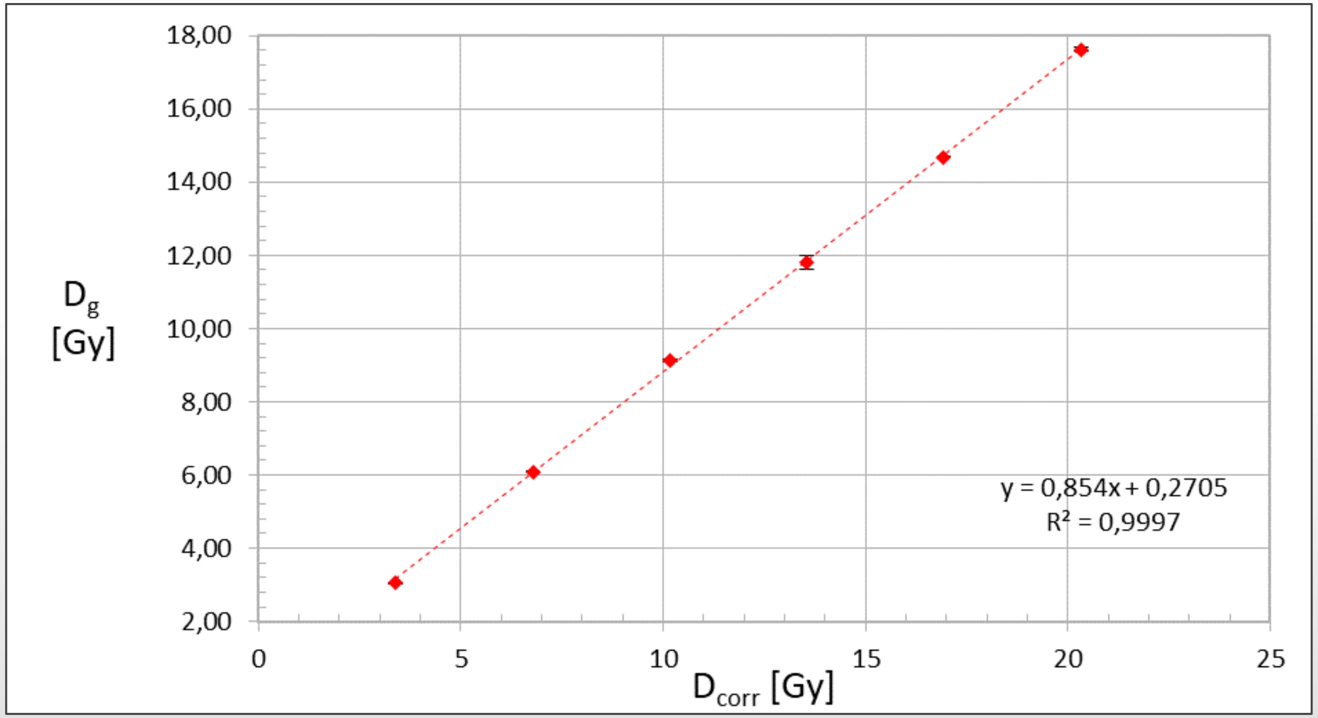
Graphite calorimeter with buildup material.



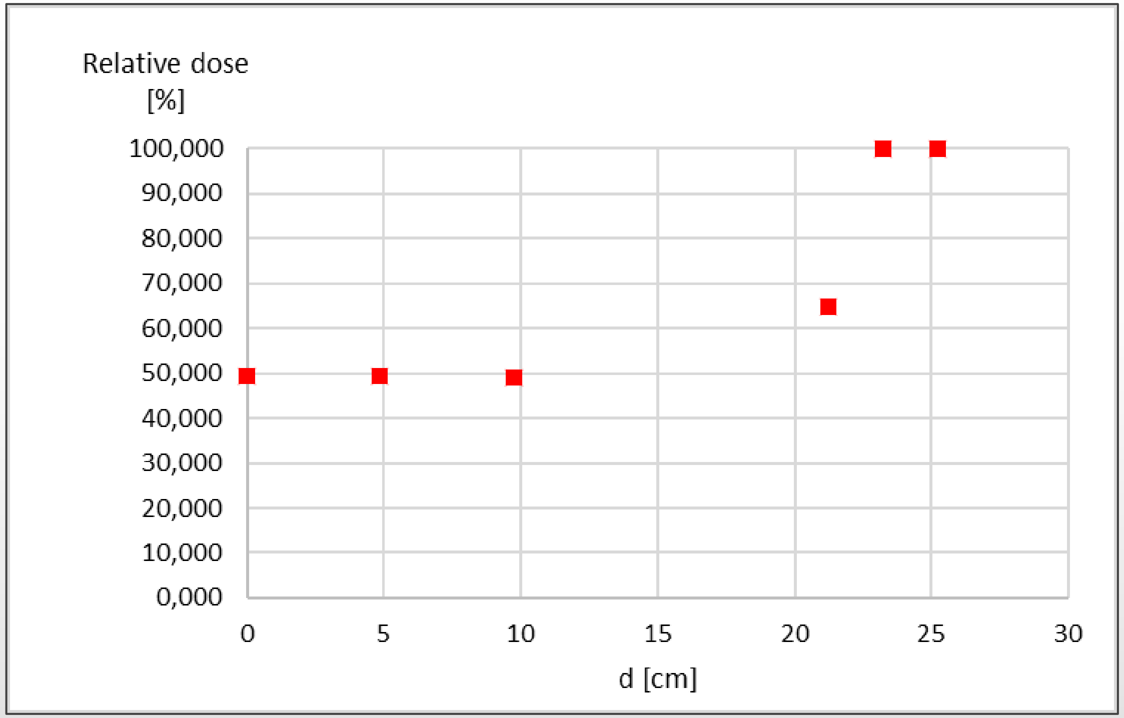
Measurements with calorimeter in the Cyclotron Centre Bronowice with proton beams.

Measurements in conventional proton beams

Główny Urząd Miar



Dose* measured with calorimeter per corrected dose measured by monitoring chamber.

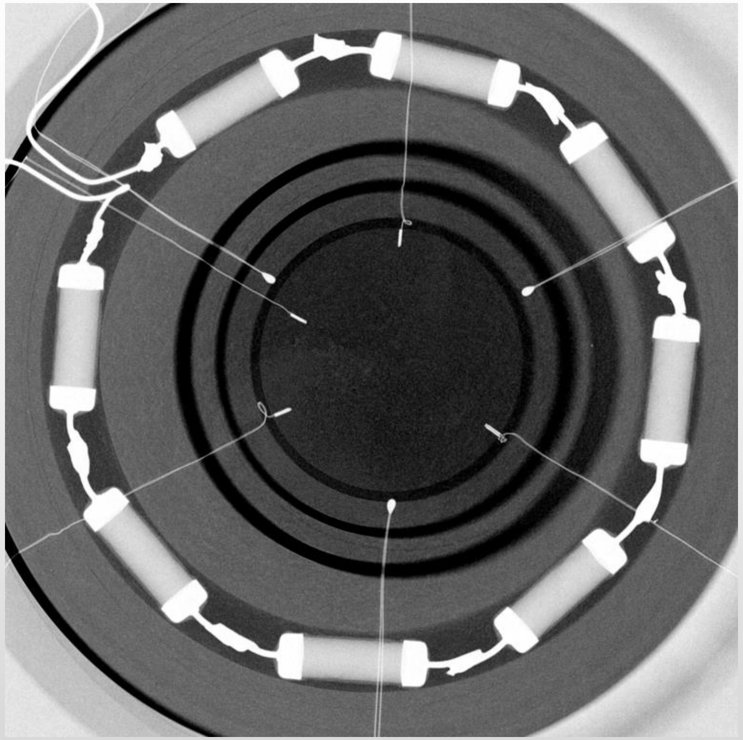


Proton Bragg curve*.

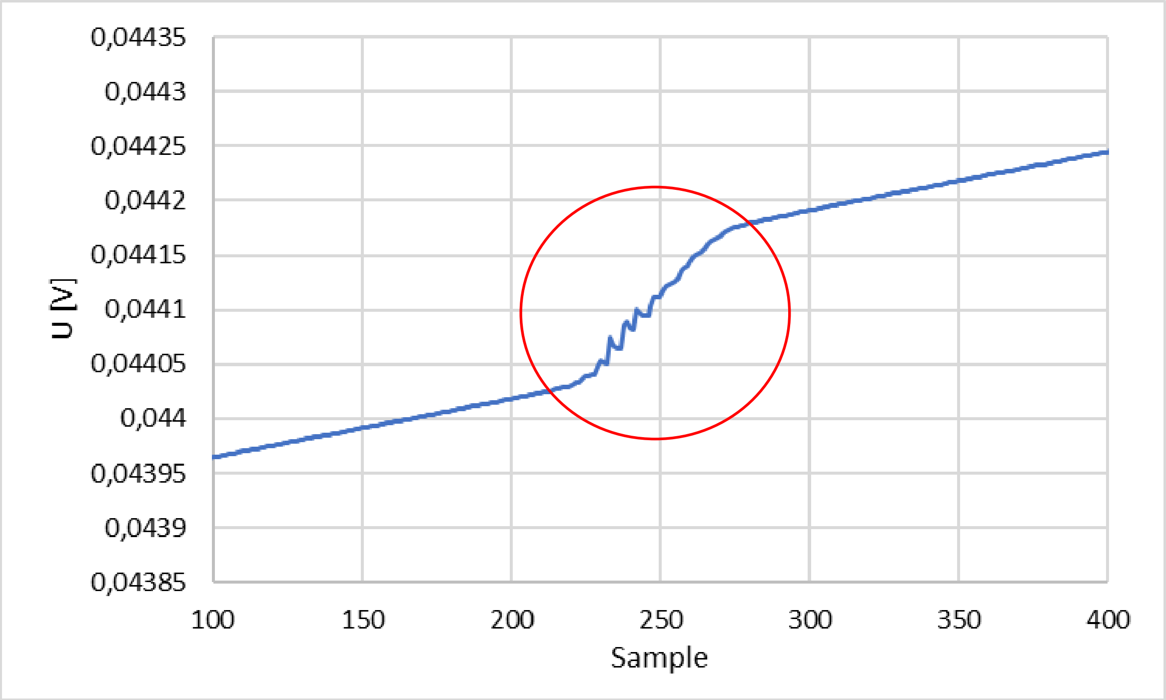
*** Without MC corrections!**

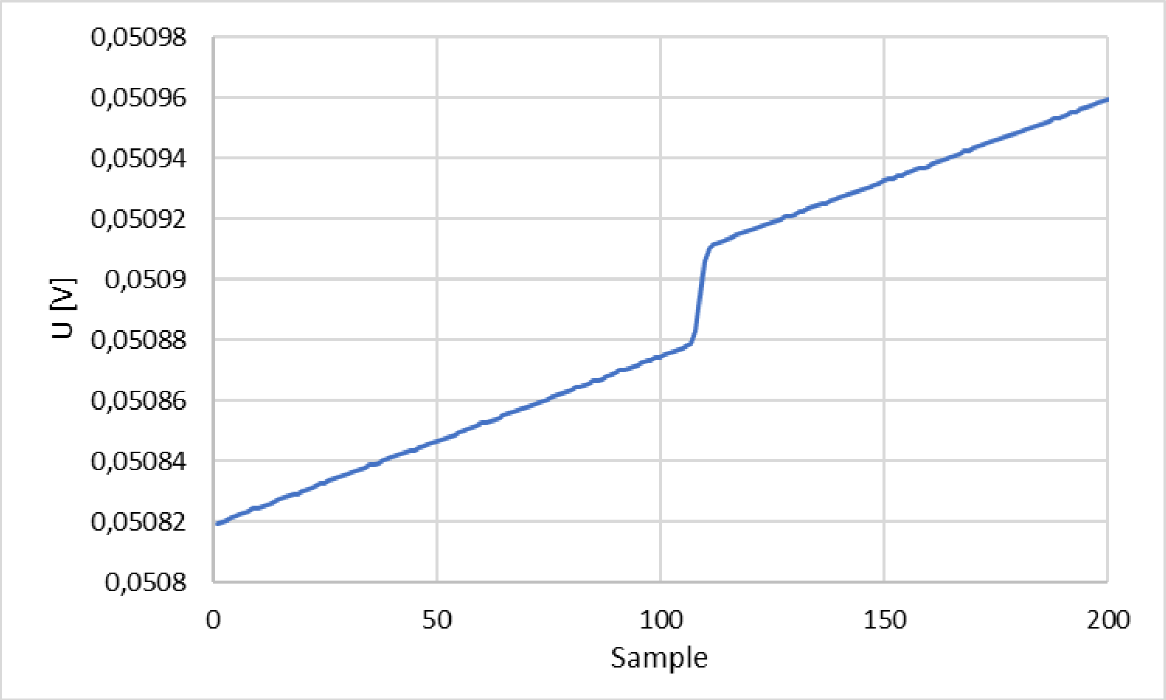
Alternative calorimeter design

A second version of the calorimeter has been built with smaller epoxy coated NTC thermistors.



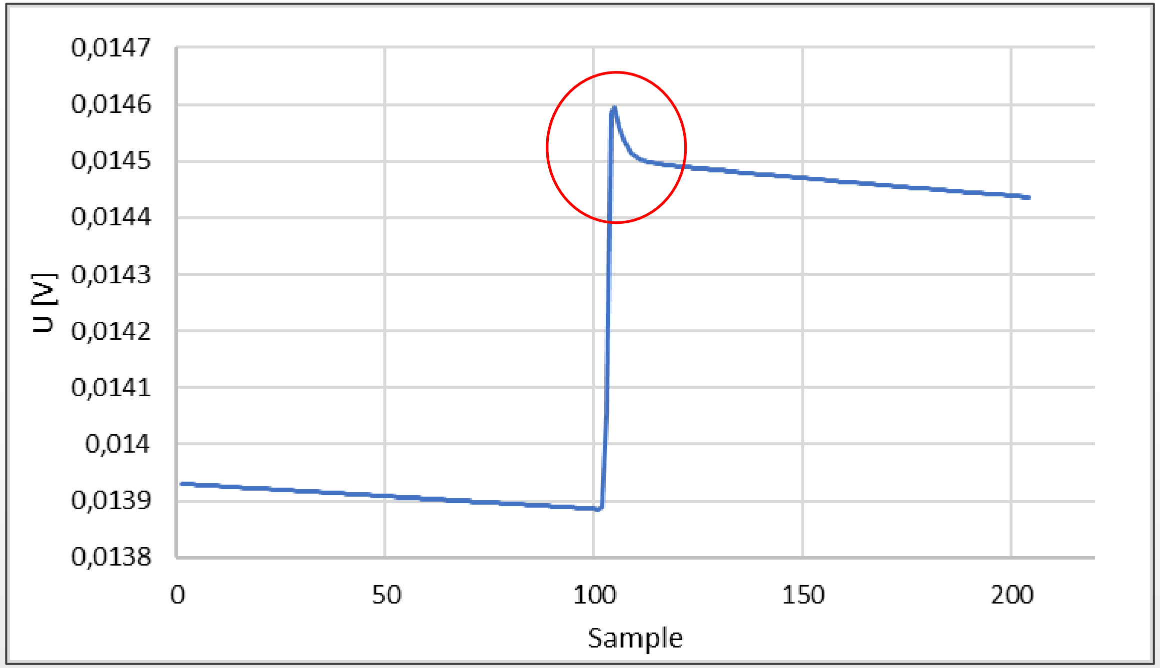
Sensitivity of the calorimeter

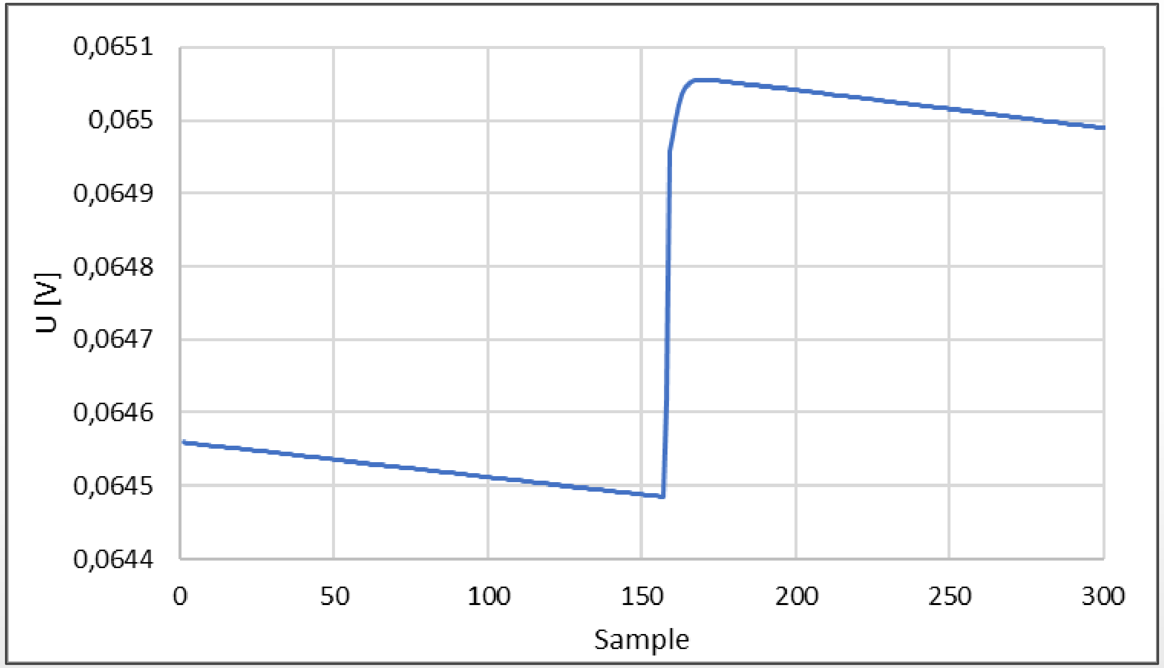




Single runs of the alternative calorimeter: on the left showing the sensitivity to the scanning beam position changes, on the right without peaks thanks to using a smaller field.

Measurements in FLASH proton beams

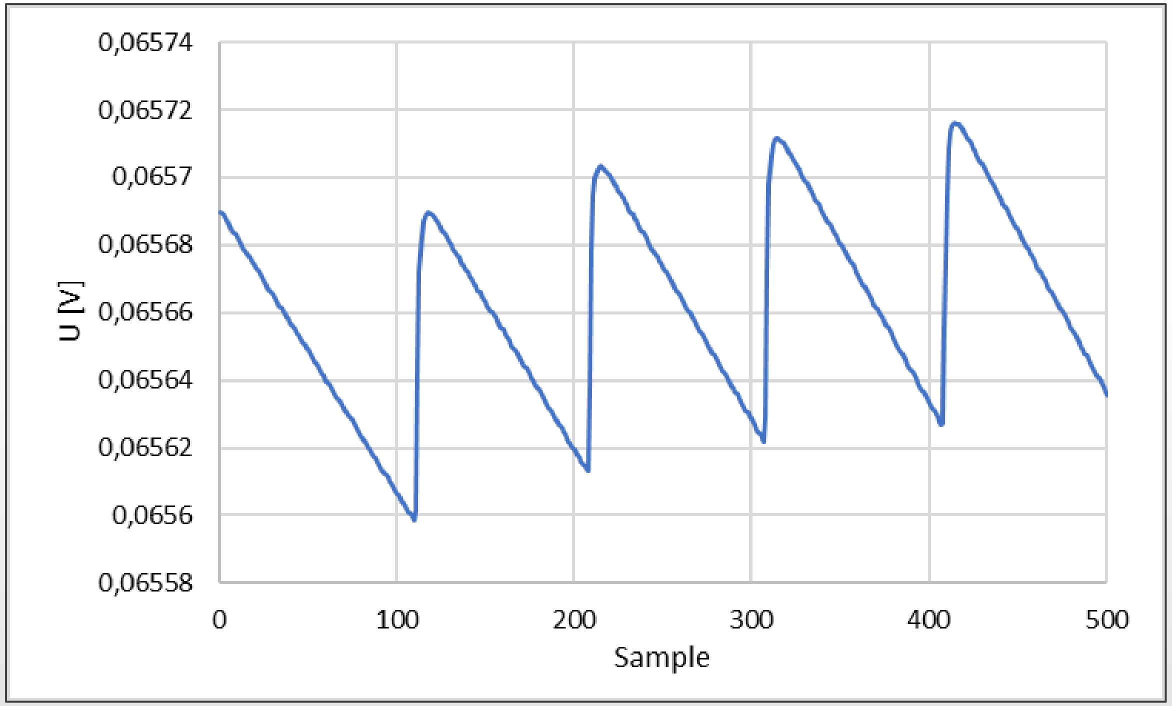




Single runs of the alternative calorimeter: on the left the first calorimeter version with a heat-defect peak caused by the thermistors glass coating, on the right the second version of the calorimeter.

Conclusion

- GUM portable calorimeters have been successfully tested in a range of therapeutic beams.
- They can be used for calibrations of reference dosimeters in hospital conditions for high energy photon-beams.
- Further work is intended for proton and FLASH beams.



Measurement series with 5 FLASH beam irridiations.

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