Current Status of Dosimetry in FLASH Radiotherapy: suitable dosimeters to use in UHDR irradiations

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Outline

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- Accuracy in RT
- Dosimetry for UHDR beams
  - Passive detectors
  - Active detectors
    - Calorimeters
    - Ionization chambers
- Summary and Conclusions

Requirement on Accuracy in RT

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- The ICRU Rep.24 (1976) states:

An uncertainty of 5% is tolerable in the delivery of absorbed dose to the target volume

- Currently, the recommended accuracy of dose delivery is generally **5-7% (k=2)**

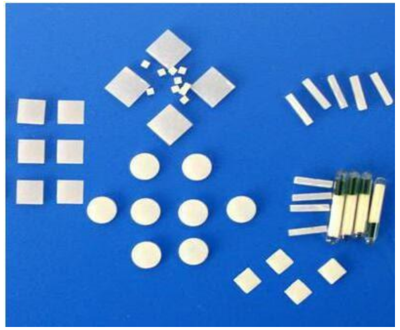
Given the size of the error in the biological contribution, it is important that the physical errors are minimized

Dosimetry for UHDR beams

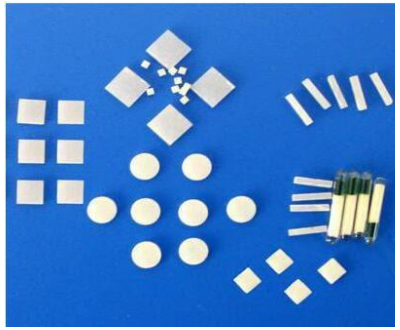
Passive dosimeters

- Alanine
- Radiochromic films
- TLDs
- Methyl viologen

dose rate independent



Dosimetry for UHDR beams



Passive dosimeters

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dose rate independent

- linear relationship with the dose rate – dose rate independence
- water equivalence
- can be used for small fields measurements (TLDs, films, alanine)

- Complex and time-consuming evaluation process and post-irradiation processing
- Require calibration for each batch, which can be time consuming
- Large uncertainties **IF** the evaluation process not well established

Dosimetry for UHDR beams

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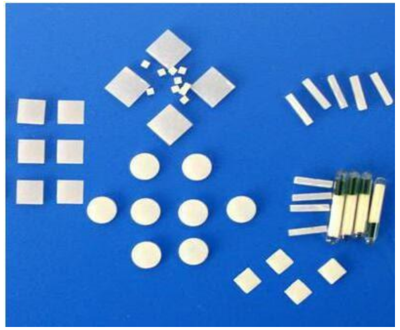

Example of proposed solution to reduce processing time

- Fast alanine dosimetry for FLASH RT by optimization of reading parameters
- The total reading time for the three measurements was 7.8 min with ±2% (k=1) uncert. (for doses above 10 Gy)
- To measure dose below 5Gy with uncert. below 5% (k=1) the reading time increased to 13 min

Gondré Rad.Res. 194:6 (2020)

Dosimetry for UHDR beams

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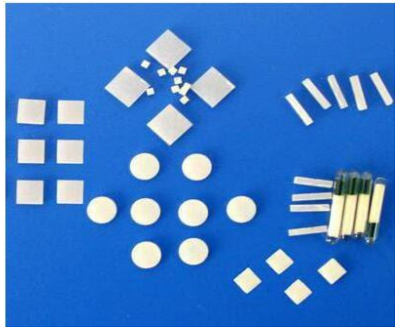


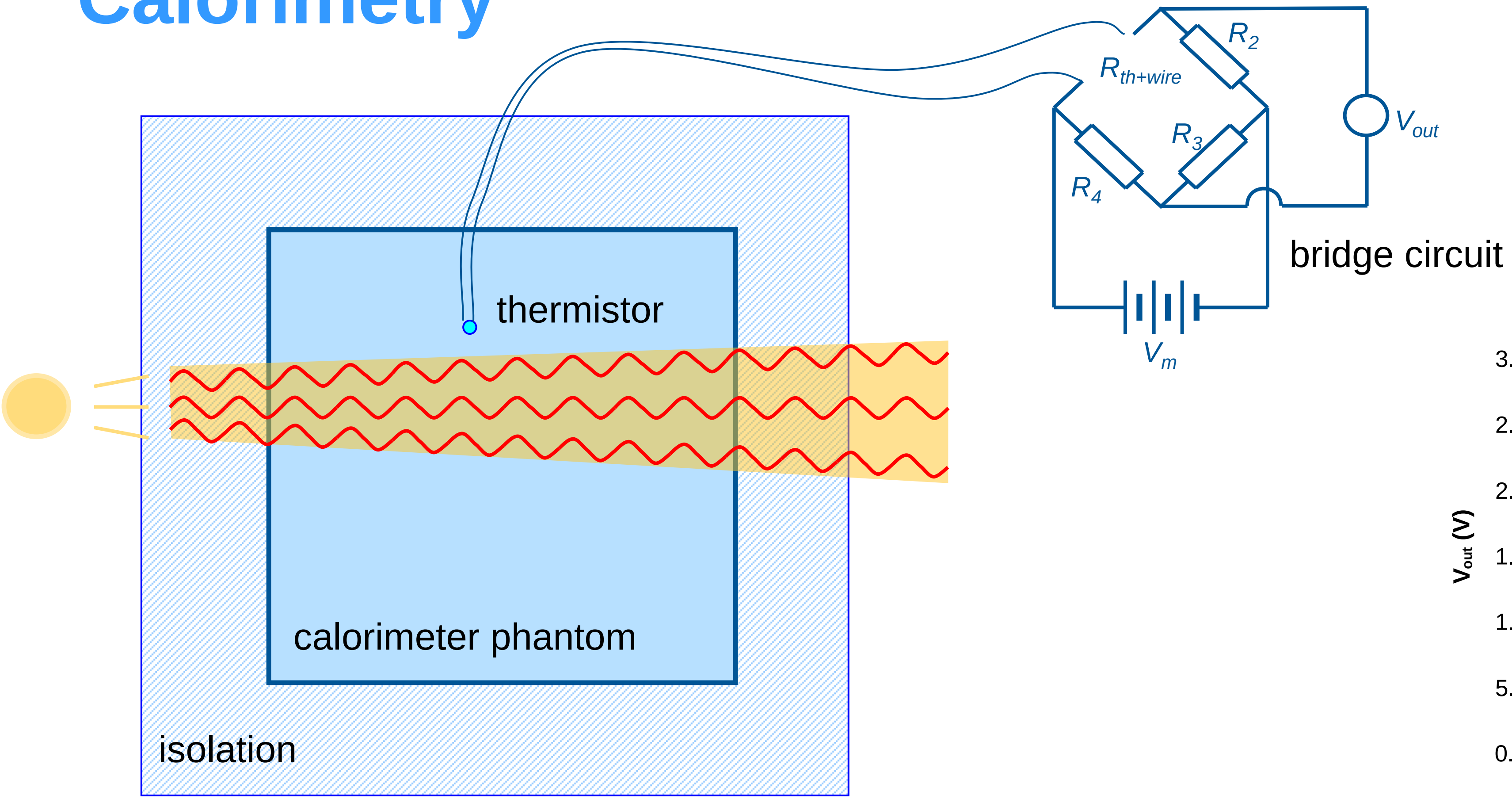
Active (online) **detectors**

- Calorimeters
- Ionization chambers } dependence as a function of DPP

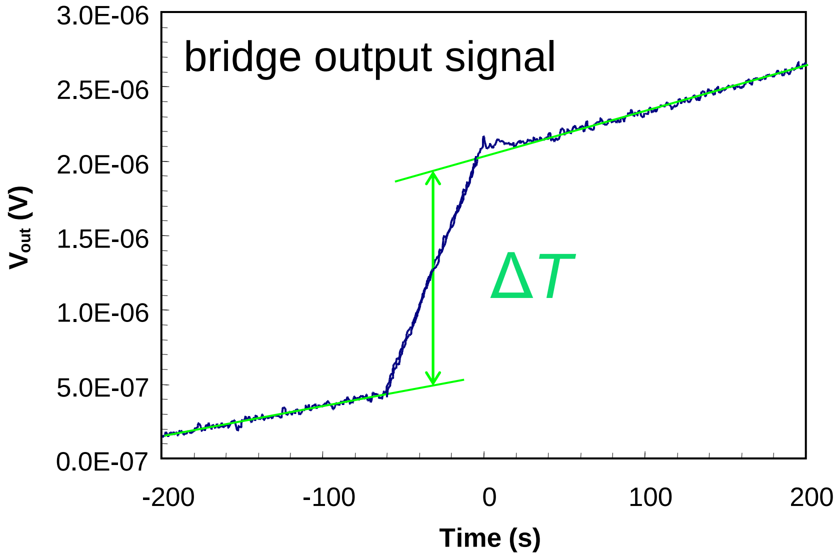


Calorimeters

Calorimetry



$$D=c\cdot\Delta T$$



ADVANTAGES

- independent of dose-rate
- linear with dose in UHDR range
- independent of pulse structure
- real-time readout

Calorimetry in UHDR beams

NPL primary standard graphite calorimeter

- Originally developed for use with conventional proton beams, the control and analysis software was reconfigured to enable it to be used with UHDR particle beams
- Consists of graphite discs arranged in a nested construction, maintained under vacuum
- Operated in quasi-adiabatic mode, thermistors detect changes in temperature of the graphite created by energy absorbed from the radiation beam allowing derivation of absorbed dose
- 250 MeV (Varian ProBeam® operating in research mode) at ~65 Gy/s
- The core of the calorimeter was positioned at the isocentre with graphite plates placed in front to position the core at a WET of 5 gcm^{-2}

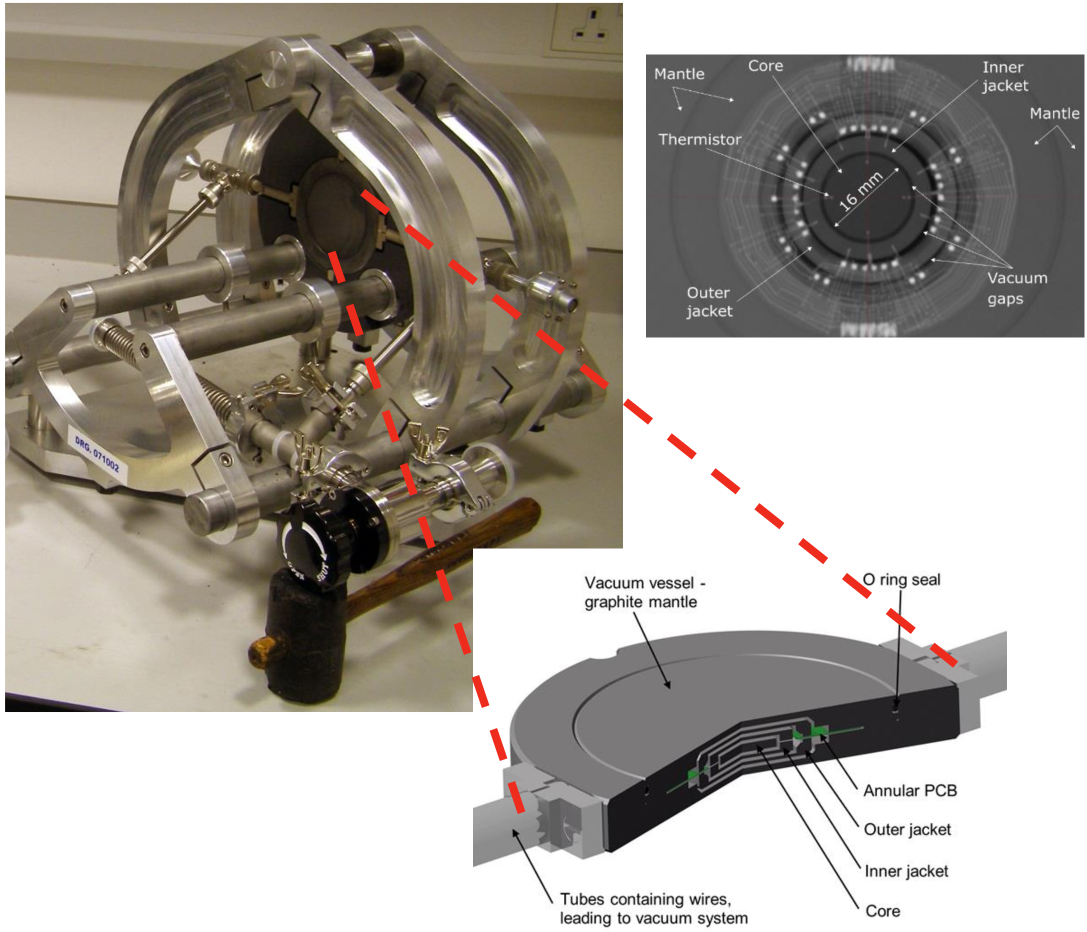


Fig. NPL's primary standard graphite calorimeter.

Calorimetry in UHDR proton beam

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EURAMET

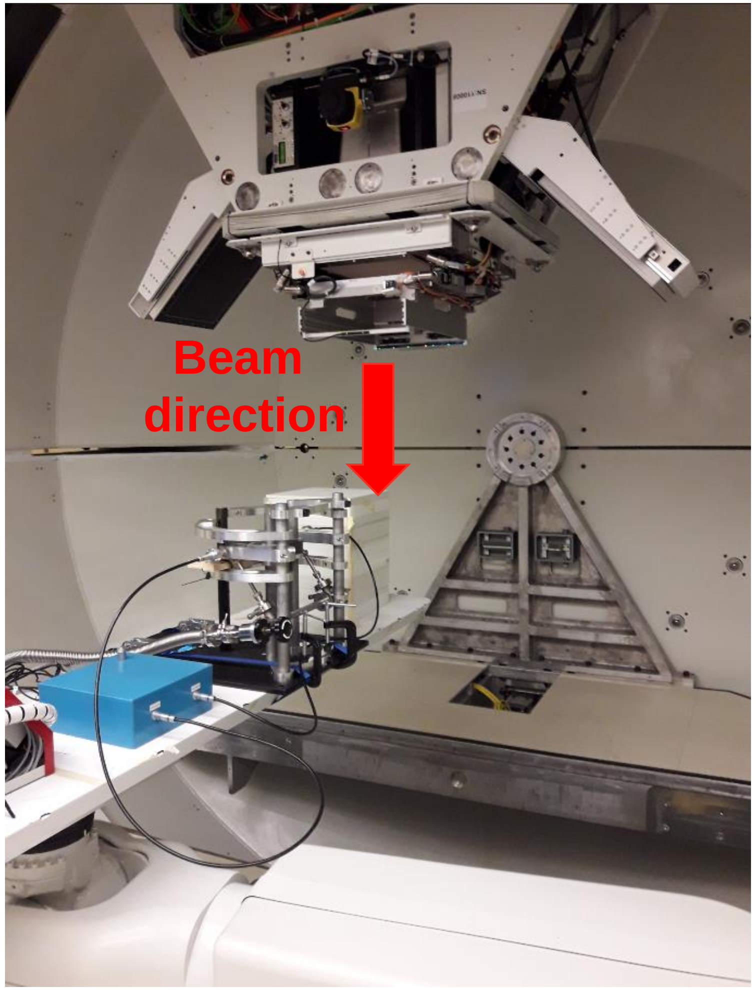

Fig. Experimental setup

Lee, Med.Phys.(2022), 1–12.

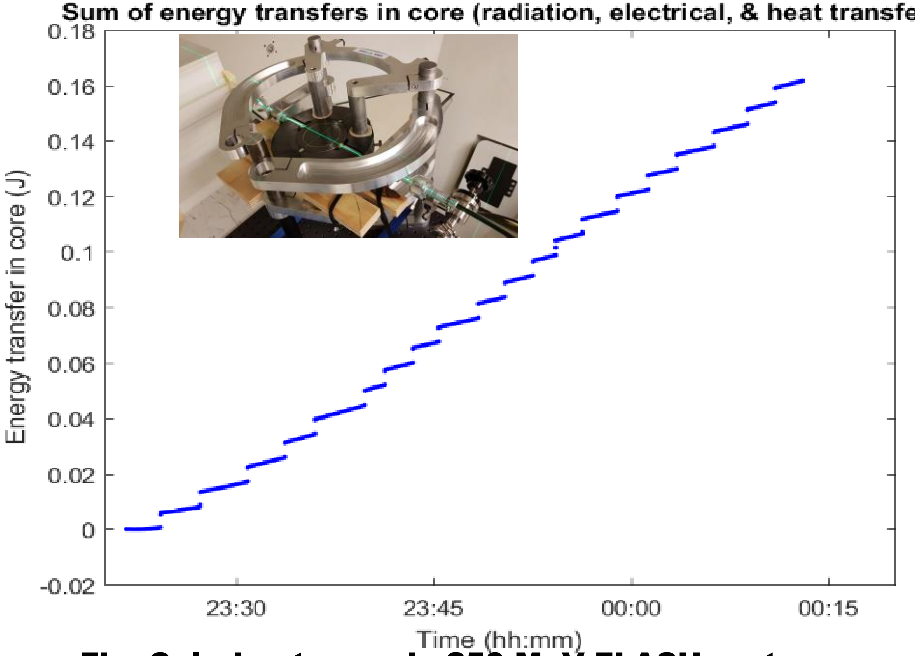

Fig. Calorimetry run in 250 MeV FLASH proton beam

Parameter	Value
c (J·kg^{-1}·K^{-1})	651.57+2.74· (T-273.15)
k_{imp}	1.0016
k_{gap}	1.0029
$s_{w,g}$	1.1210
k_{fl}	0.9713
$k_{z,cal}$	1.0000

Sources of uncertainties (%)	Type A	Type B
Physical dimensions	<0.01	0.09
Electrical calibrations	0.20	0.06
Specific heat capacity	0.08	0.26
k_{imp}. k_{gap}	0.01	0.11
$s_{w,g}$. k_{fl}	0.07	0.71
$k_{z,cal}$	-	0.10
Positioning on beam axis and reference depth	0.06	0.13
PCB	-	0.25
Calorimeter measurements and analysis	0.04	0.15
Total	0.24	0.84
Overall (1σ)	0.9	

Lourenço *et al. Sci.Rep.* under review

	Proton calorimeter				dose to water	
Field size, cm	5 x 6	5 x 8	5 x 10	5 x 12	6 x 5	12 x 5
Mean Dose, Gy	**7.654**	**7.690**	**7.726**	**7.736**	**7.666**	**7.741**
SDOM, %	0.04%	0.04%	0.04%	0.04%	0.04%	0.03%

Small Portable Graphite Calorimeter (SPGC)

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- Originally developed for use with the Clatterbridge ocular proton beam (Palmans et al. 2002). The device was refurbished and integrated with the current control and analysis software developed for UHDR particle beams
- Thermistors are embedded around the circumference of both graphite components
- Operates only in quasi-adiabatic mode
- The core of the calorimeter was positioned at the isocentre with graphite plates placed in front to position the core at a WET of 5 gcm^{-2}

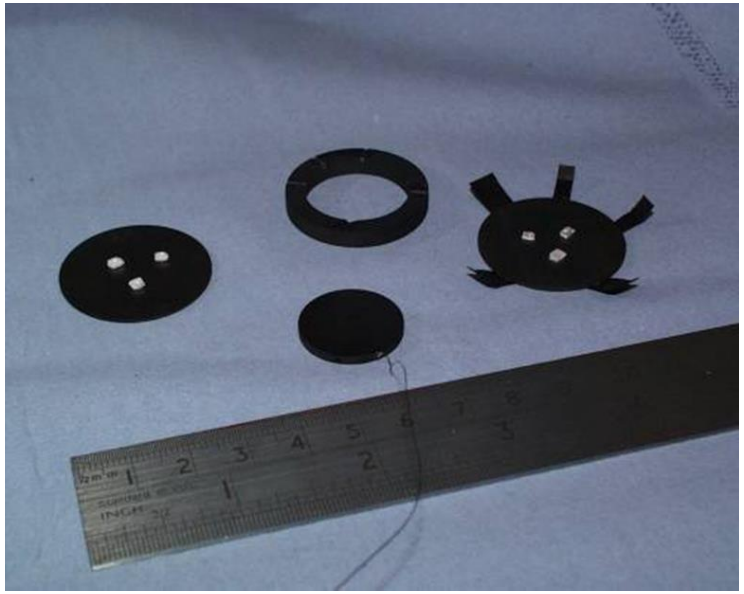
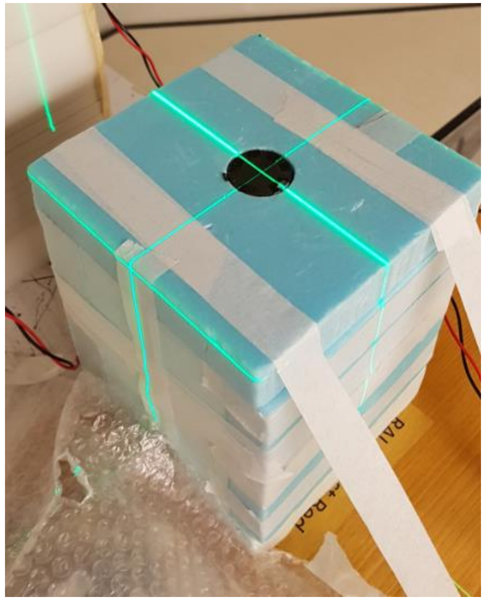


Fig. SPGC



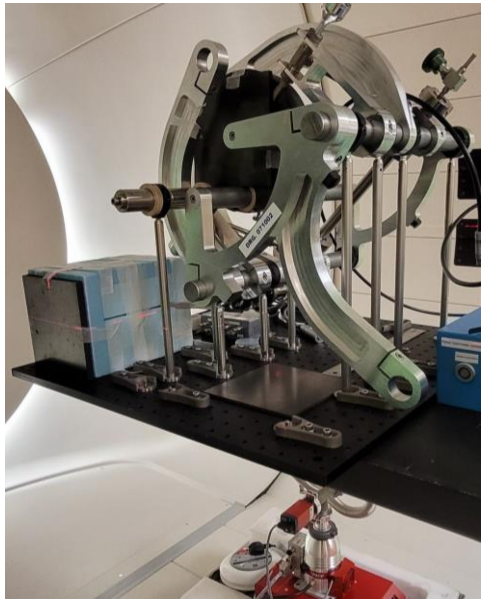


Fig. Experimental setup

Cincinnati Children's

	SPGC - provisional dose to water
Field size, cm	5 x 6
Mean Dose, Gy	**7.657**
SDOM, %	0.27%
Type B Uncertainty, %	1.50
Combined Standard Uncertainty, %	1.50
Overall Expanded uncertainty, *k* =1 %	1.50

[UNPUBLISHED – please, do not distribute]

Al calorimeter

Linear dose response with varying DPP is equivalent to alanine

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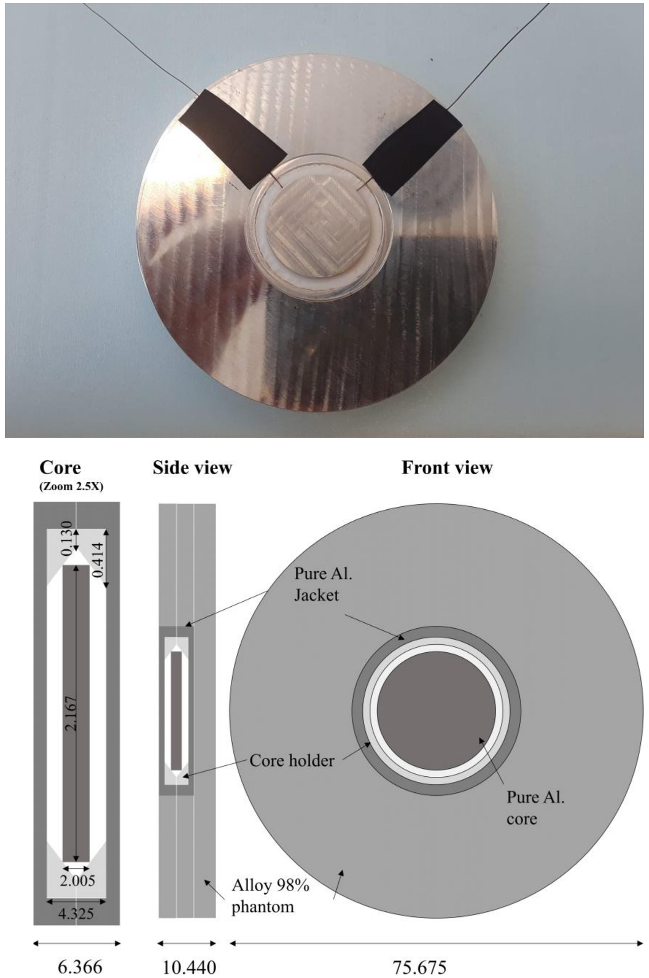
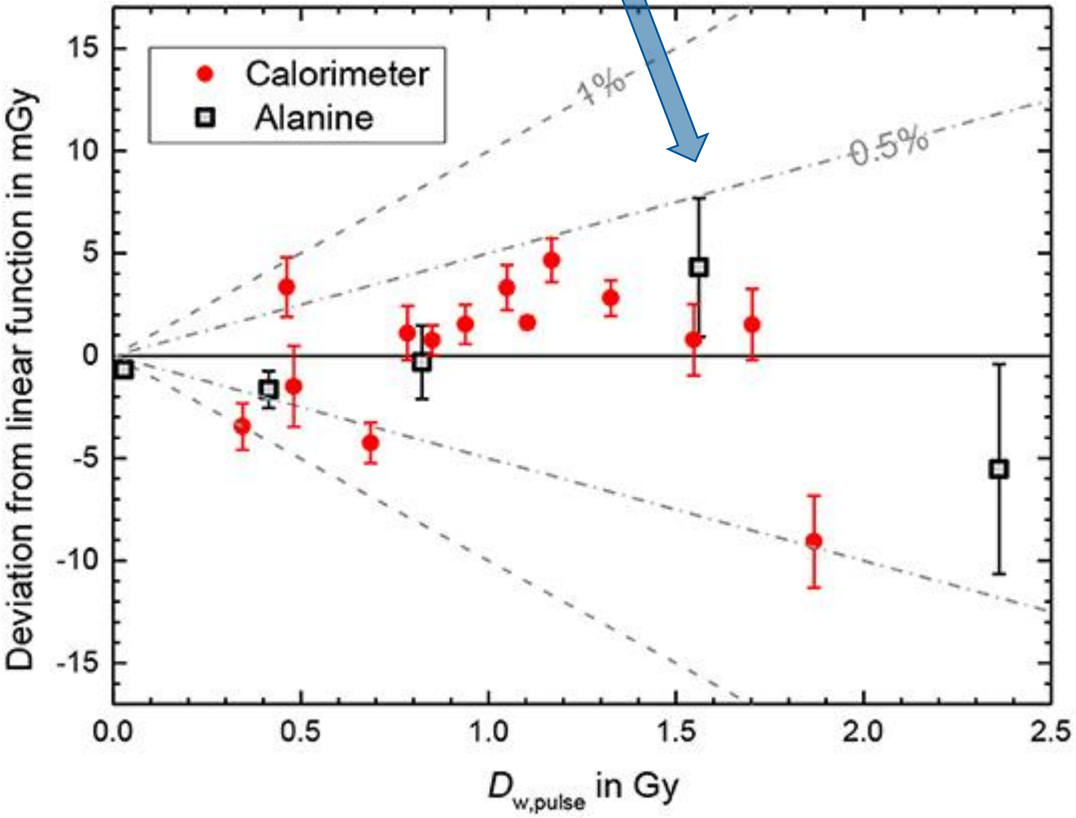


Fig. Construction of Al calorimeter



Average deviation was 0.25%

Measured dose deviation from linearity (in mGy) as a function of measured DPP

Courtesy of A. Bourgouin

Bourgouin et al., *Front.in Phys.*, Vol.8, 567340 (2020)

Aerrow – a probe-type graphite calorimeter

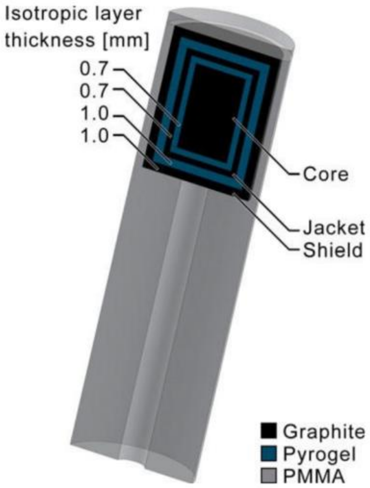


Fig. Aerrow detector

Renaud *et al. Med. Phys*. 45 (1) (2018)

- Developed at McGill
- Made by Sun Nuclear
- Designed for in clinic measurements
- Operating in quasi-adiabatic mode

READING SYSYEM

- Thermistor ready by high stability DMM Agilent

Dose conversion factor

Temp.change

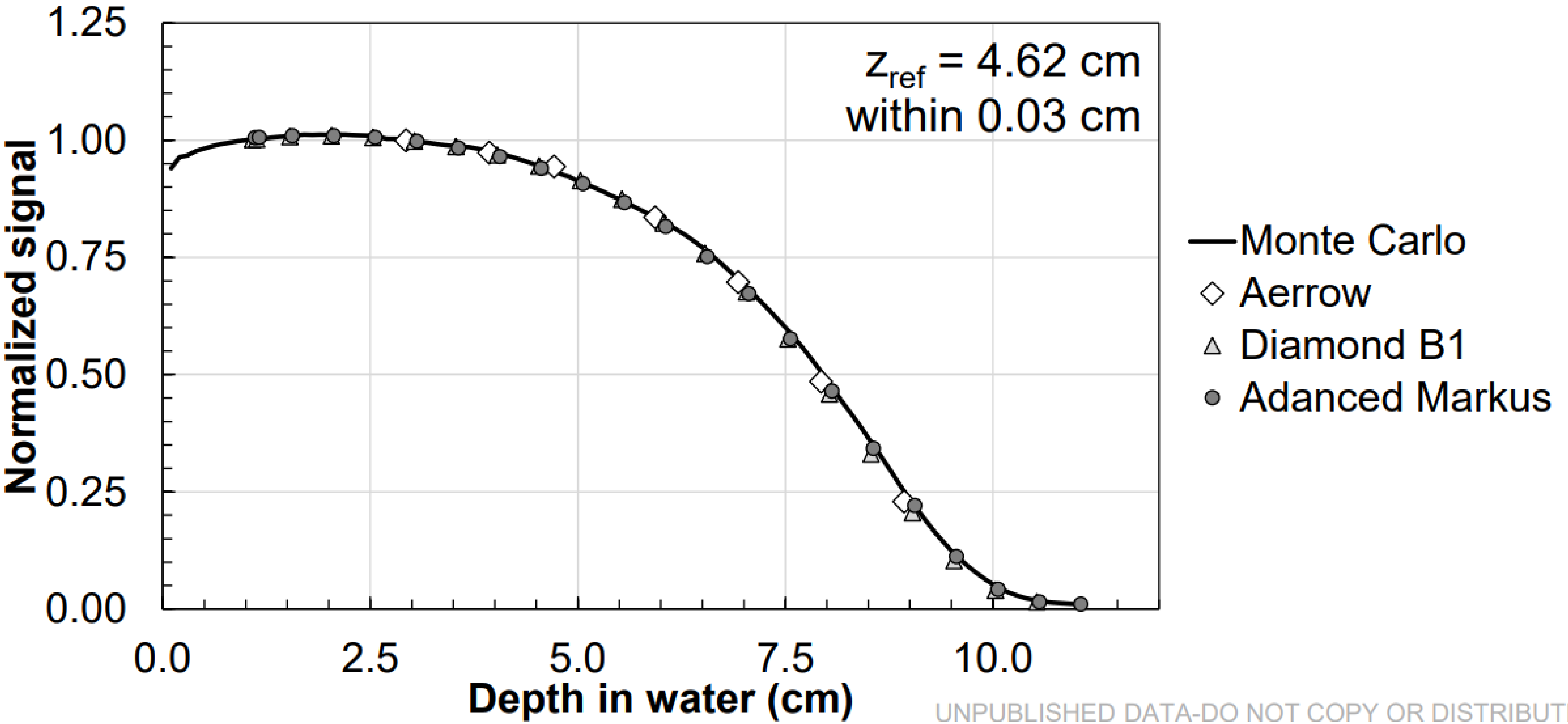
Dose-to-water

$$D_w = c_{gr} \cdot \Delta T \cdot K_{\mathrm{ht}} \cdot \left(\frac{D_{\mathrm{w}}}{D_{\mathrm{gr}}}\right)_{MC}$$

spec.heat capacity

Heat loss corr.

Depth-dose curve



Source: http://uhdpulse-empir.eu/wp-content/uploads/FRPT_Bourgouin_Calorimetry-presentation.pdf

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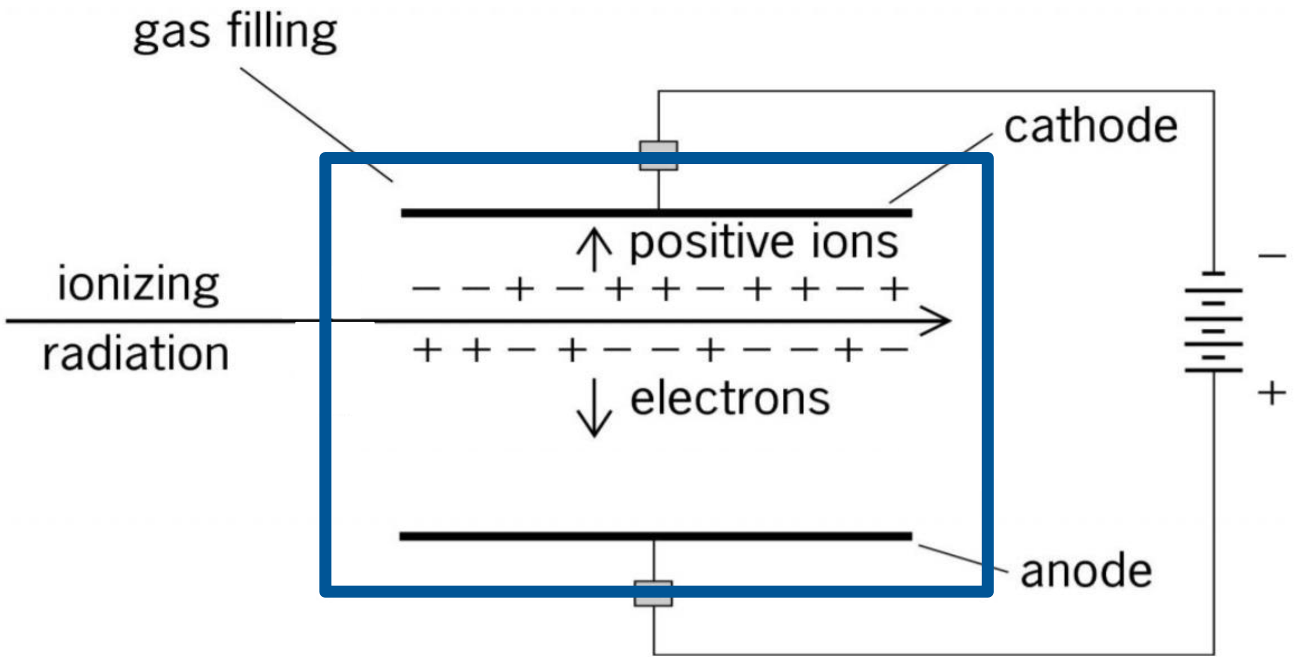
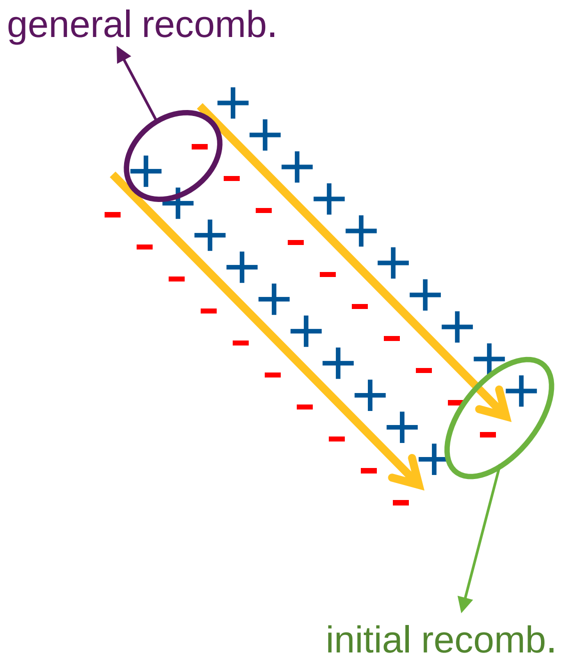
Ionization chambers

Ionization chamber





Initial Recombination

- Recombination along a single charged particle track.
- **Independent of dose and dose-rate**.
- More pronounced in highly ionising particles such as alpha-particles.

General Recombination

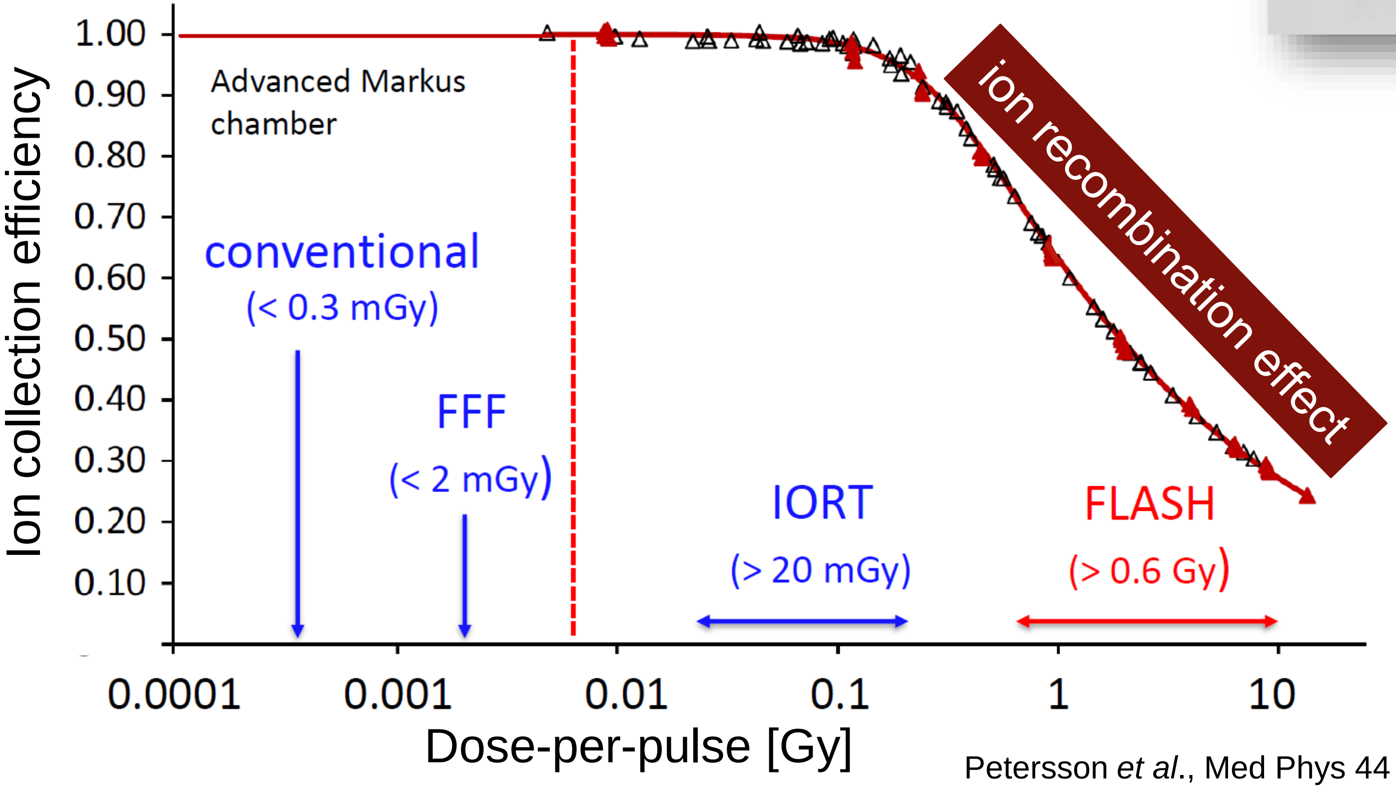
- Recombination between separate charged particle tracks.
- Directly dependent on charge density i.e the number of ions produced per unit volume.
- **Dose-rate dependent.**

General recombination is likely to play a much larger role in recombination effect in UHDR pulsed beams

Di Martino, et al. Med Phys. 32(7) (2005)

IC: Metrological challenges of dosimetry at UHDR

Typical behaviour of IC at FLASH dose rates



Petersson *et al.*, Med Phys 44 (2017) 1157

PTW Advanced Markus (1 mm electrode separation)

$$k_s = \left(1 + \left(\frac{DPP[mGy]}{U[V]}\right)^{\alpha}\right)^{\beta}$$

no physical meaning

IC: Metrological challenges of dosimetry at UHDR

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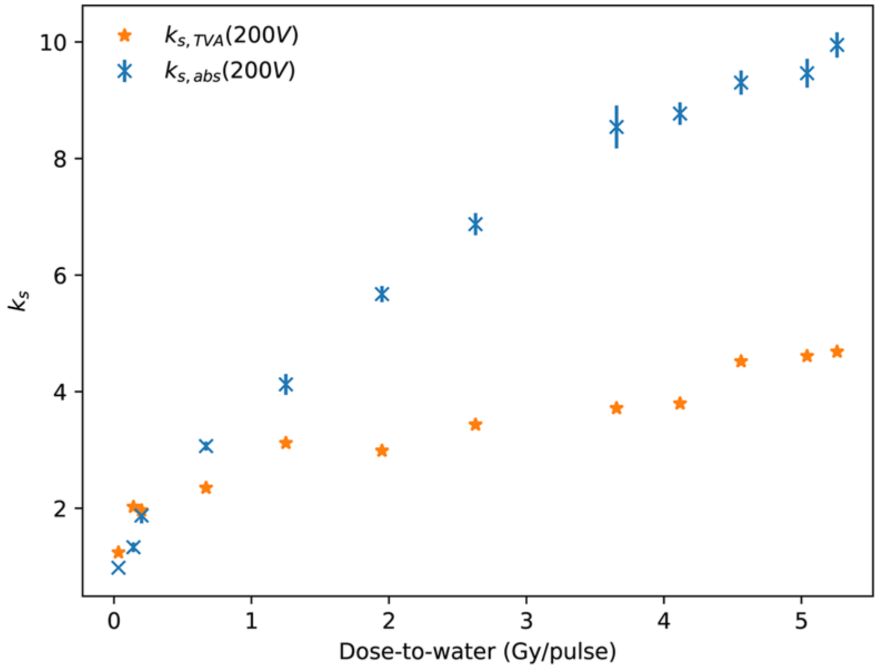
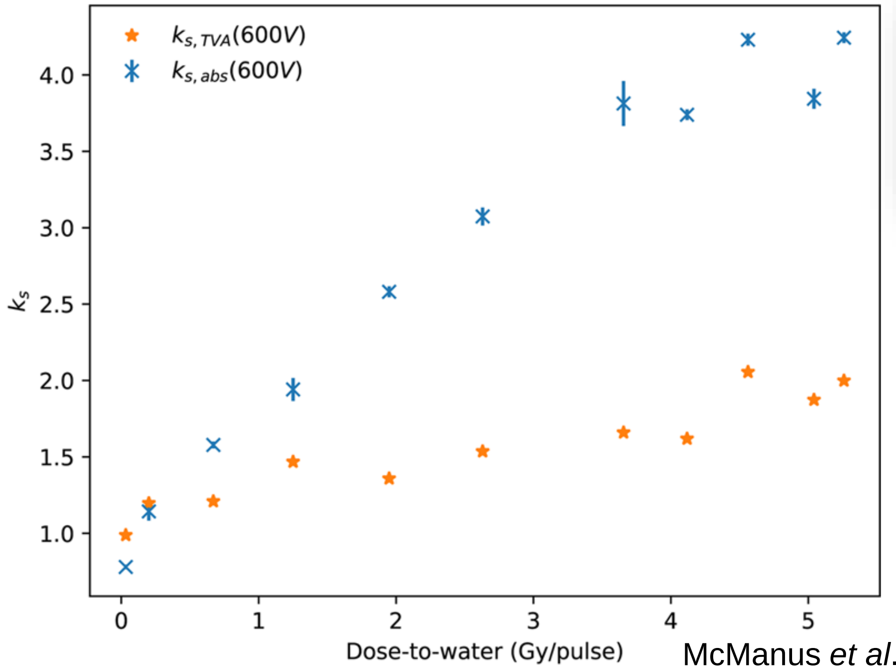




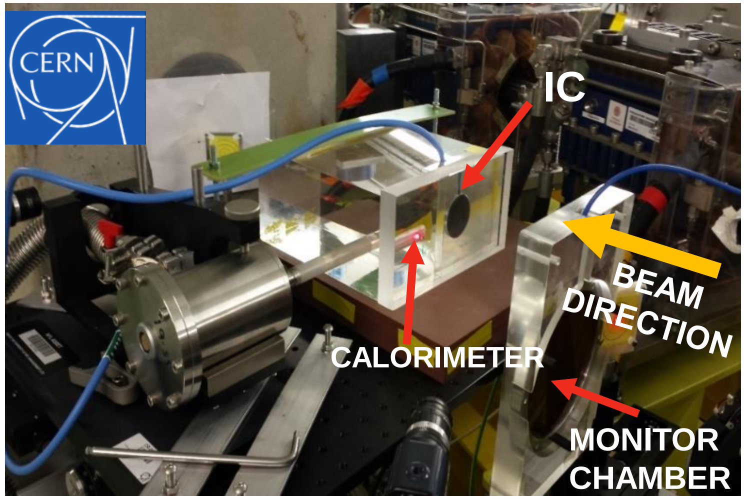
PTW Roos (2 mm electrode separation)

- 200 MeV VHEE beam
- DPP: 0.03 – 5.3 Gy/pulse
- Graphite calorimeter employed as reference detector

$$k_{s,abs} = \frac{D_{w,cal}}{M k_{pol} k_{TP} k_{Q,Q_0} N_{D,w,Q_0}}$$

McManus *et al*., Sci. Rep. (2020)

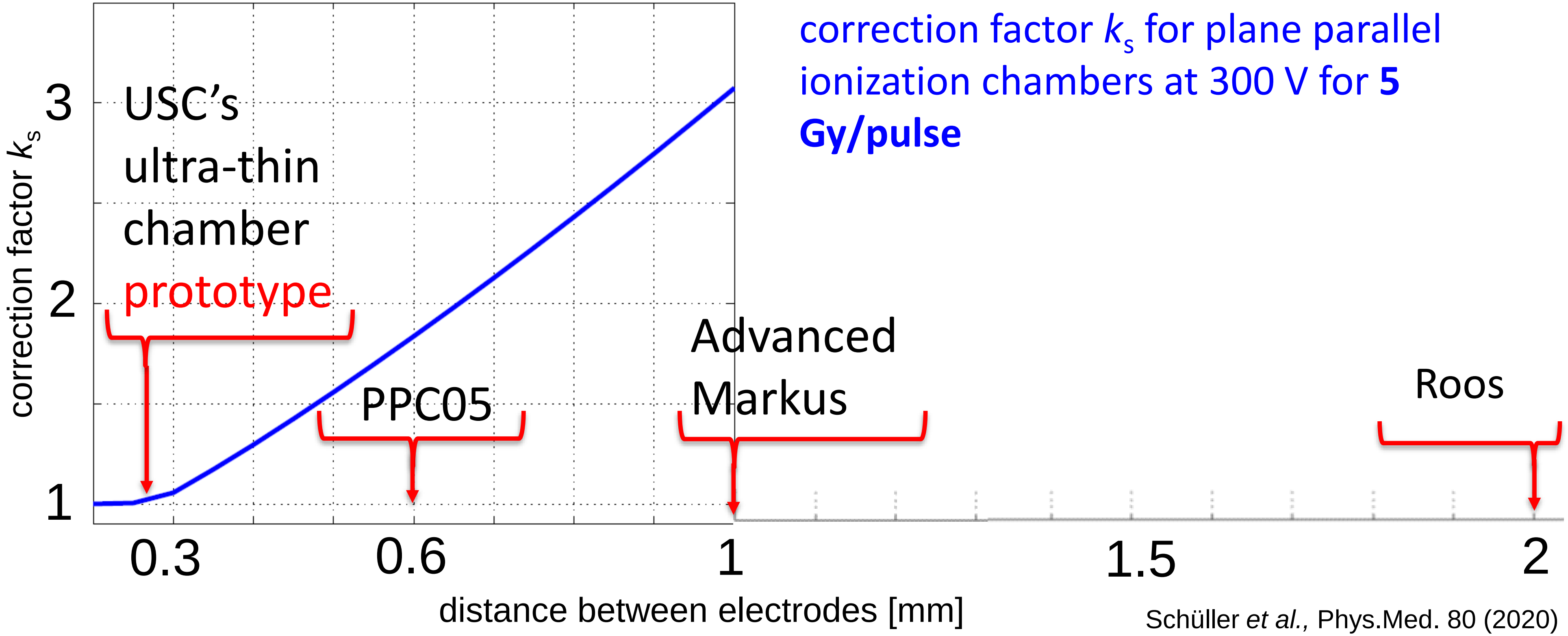
- k_s up to 10 (V = 200 V) → **collection eff. 10%**
- k_s up to 4 (V = 600 V) → **collection eff. 25%**
- $k_{s,abs}$ compared with $k_{s,TVA}$ (two-voltage method)
- Available **analytical ion recombination models cannot predict chamber behaviour** for such a high DPP



Possible solution for UHDR beams

USC's prototype ionization chambers for ultra-high DPP

Fig. Ionization chamber prototype (0.27 mm)



Simulated ion recombination correction factor k_s for plane parallel ionization chambers at 300 V for **5 Gy/pulse**

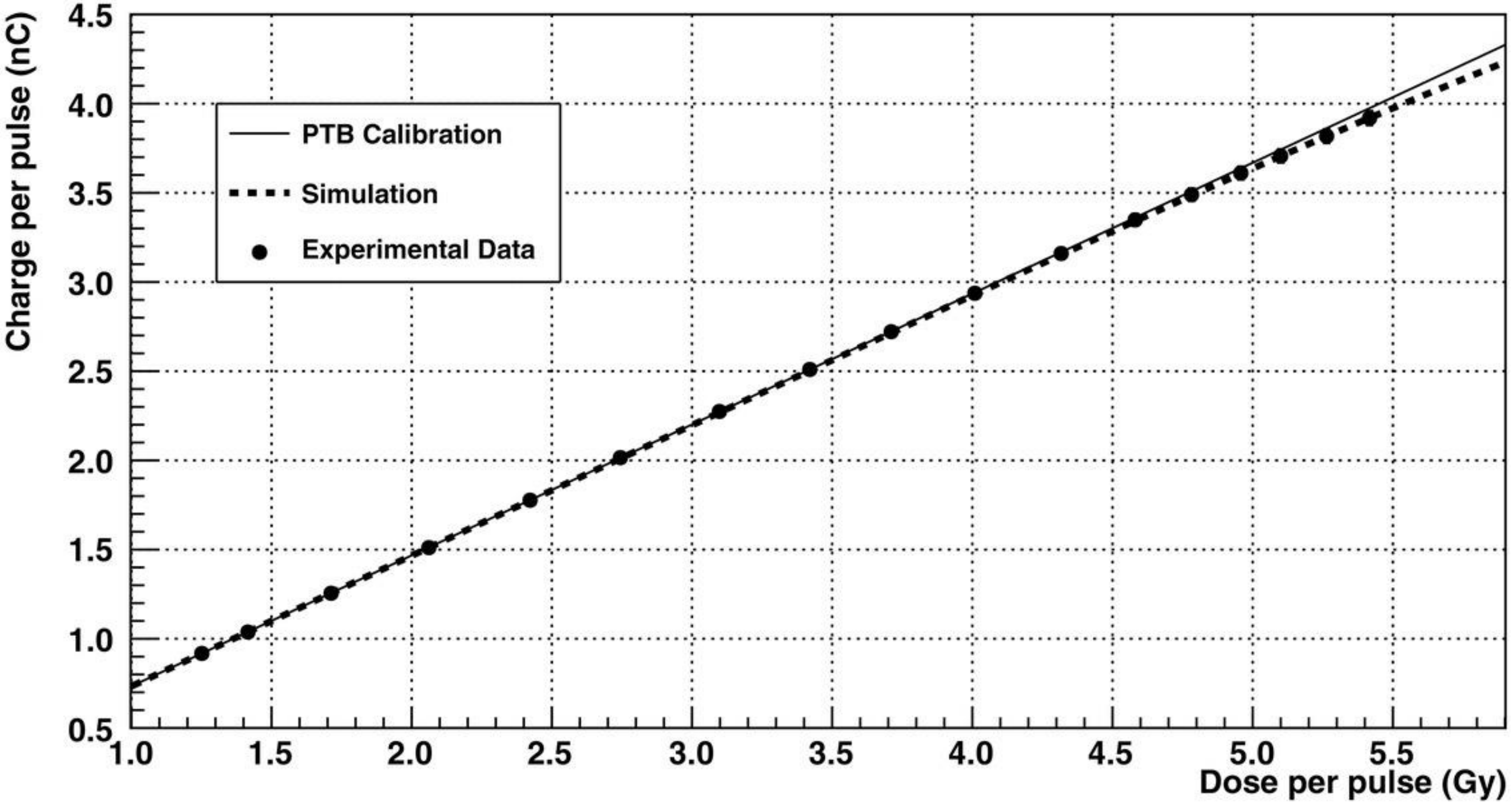
Schüller *et al.*, Phys.Med. 80 (2020)

Courtesy of Faustino Gomez

Possible solution for UHDR beams

USC's prototype ionization chambers for ultra-high DPP

Fig. Ionization chamber prototype (0.27 mm)



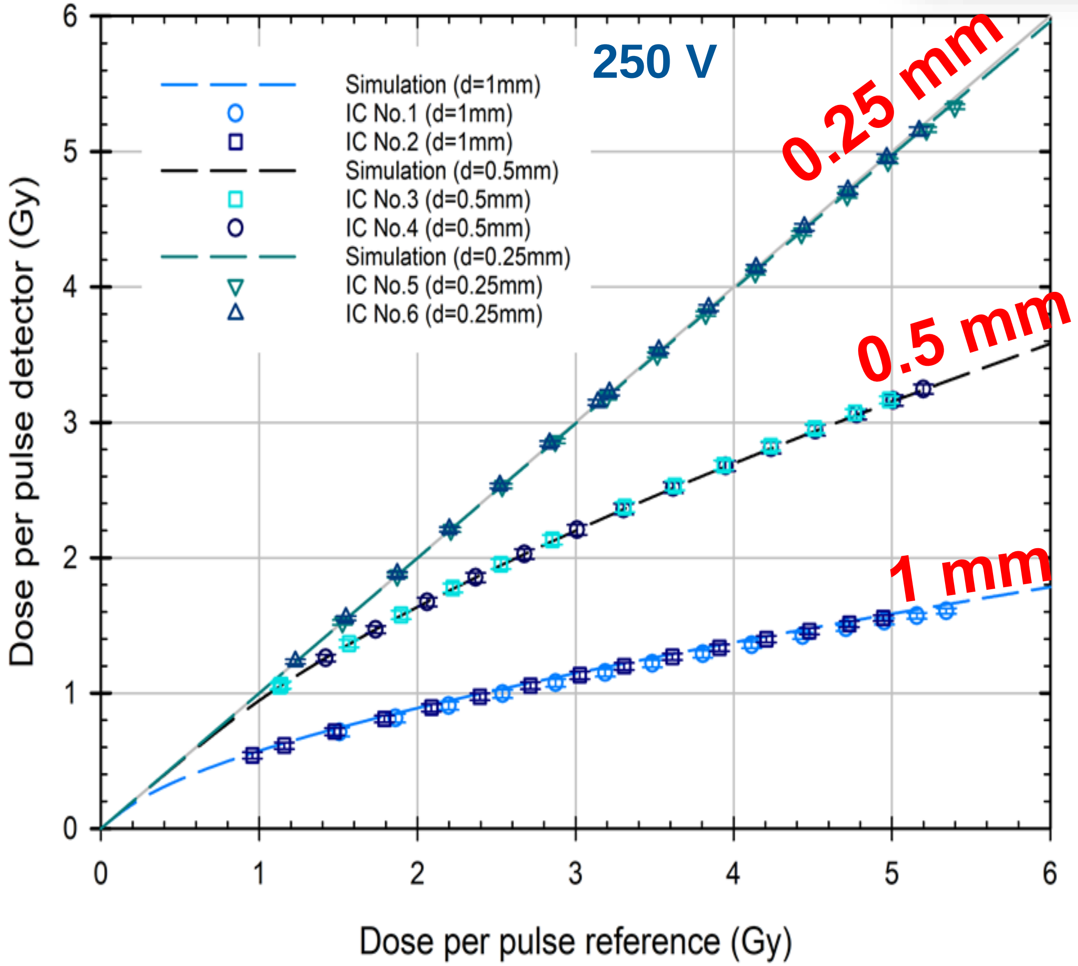
Courtesy of Faustino Gomez

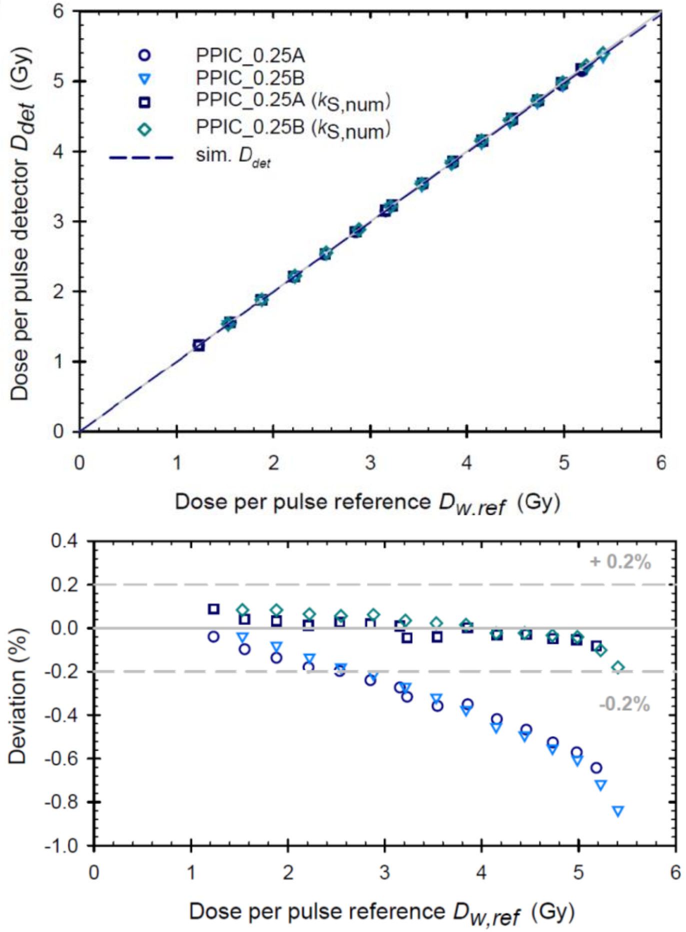
Gomez *et al.*, Med.Phys.1-10 (2022)

Possible solution for UHDR beams

PTW's prototype ionization chambers for ultra-high DPP

Fig. PTW IC prototype (0.25 mm)





Courtesy of R. Kranzer

Kranzer *et al.*, Phys. Medica under review

Conclusions

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- FLASH RT requires several developments before safe implementation to clinics
- Passive detectors (alanine, film, TLDs) are dose-rate independent, but require post-irradiation processing (not desirable for routine clinical use)
- Calorimetry-based detectors could become potential dosimetry devices in UHDR beams, but their operation need to be simplified to allow clinical implementation
- Commercially available ionization chambers show large deviations at ultra-high dose per pulse (DPP) due to ion recombination.
- Prototypes of parallel plate ionization chambers with very small electrode gap separation are promising candidates for future secondary standard devices for UHDR beams, however their full characterization still needs to be carried out

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Thank you

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