Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Dosimetry for UHDR electron beams for FLASH radiotherapy

Dr. Andreas Schüller
Department 6.21 “Dosimetry for Radiotherapy”

13th MT ARD ST3 Meeting, Pre-workshop "medical applications“
25.6.25, DESY (Zeuthen)

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Dosimetry for UHDR electron beams for FLASH radiotherapy

Contents

- Introduction PTB dept. “Dosimetry for Radiotherapy”
- UHDR electron beams for FLASH RT
- Dosimetry for conventional clinical electron beams
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Introduction PTB dept. "Dosimetry for Radiotherapy"

Primary standard of the unit Gy for absorbed dose to water

$$\boxed{D_w = d\varepsilon/dm}$$

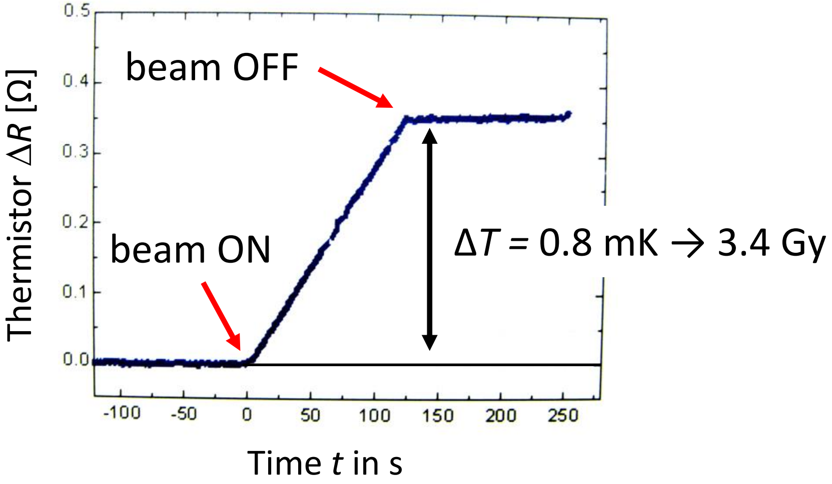
1 Gy = 1 J/Kg

ε: energy deposit in medium, *m:* mass of medium (water)

$$\boxed{D_w = c_p \cdot \Delta T \cdot \Pi k_i}$$

$\Delta T = 0.24$ mK/Gy

c_p: Heat capacity of water, ΔT: Radiation-induced temperature rise
Πk_i: corrections for perturbations (heat transport, etc.)

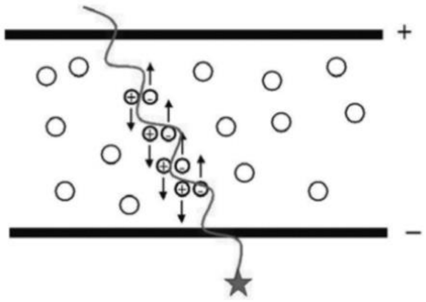


Clinical beams: 4 - 22 MeV, 2 - 4 µs pulse duration, PRF 100 – 400 Hz, mean dose rate < 5 Gy/min

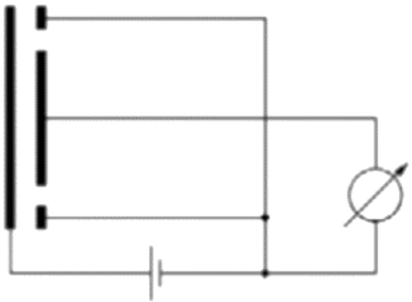
PTB's primary standard water calorimeter at a medical LINAC at PTB

Introduction PTB dept. “Dosimetry for Radiotherapy”

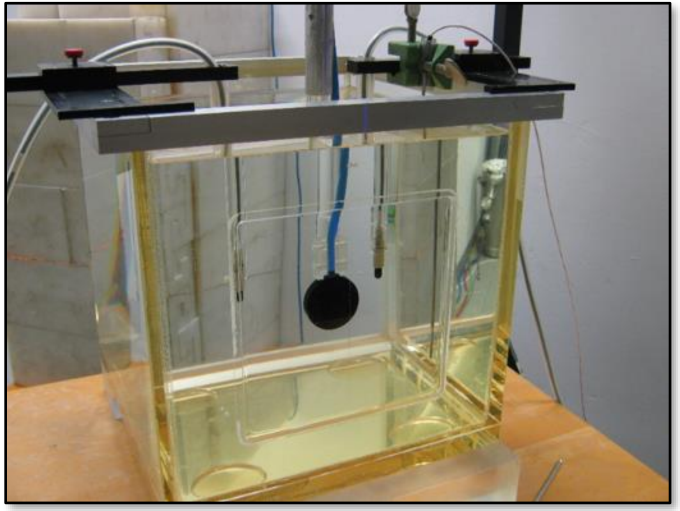
Ionization chambers: standard detector for reference dosimetry in radiation therapy



ionizing radiation creates ion pairs



high voltage   current



Plane-parallel ionization chamber in a water phantom

$$\boxed{D_w = M\,N\,\Pi k}$$

M	chamber reading [C]
$\boldsymbol{N}$	**calibration coefficient [Gy/C]**
k	correction factors

Introduction PTB dept. “Dosimetry for Radiotherapy”

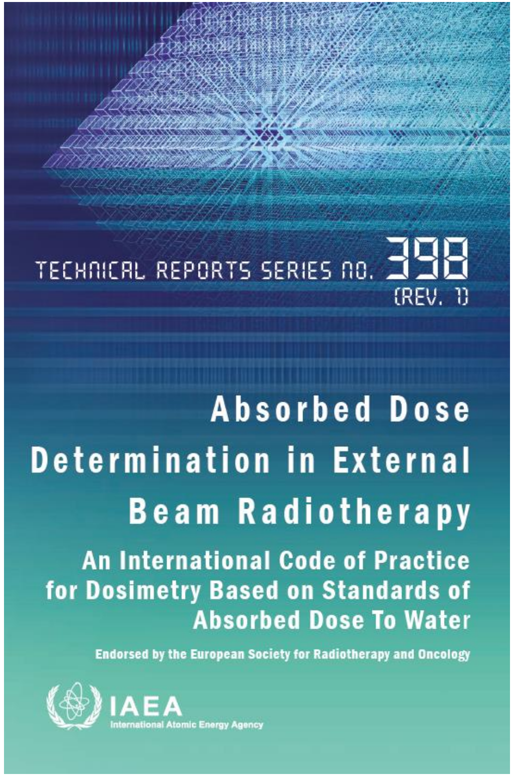
Ionization chambers: standard detector for reference dosimetry in radiation therapy

Formalism for clinical reference dosimetry (Codes of Practice):

- IAEA’s TRS 398 (PTB co-author)
- DIN 6800-2 (PTB lead)
- DIN 19454 „Dosimetry for ultra-high dose rates (FLASH)“ (PTB lead)

$$\boxed{D_w = M\,N\,\Pi k}$$

M	chamber reading [C]
$\boldsymbol{N}$	**calibration coefficient [Gy/C]**
k	correction factors

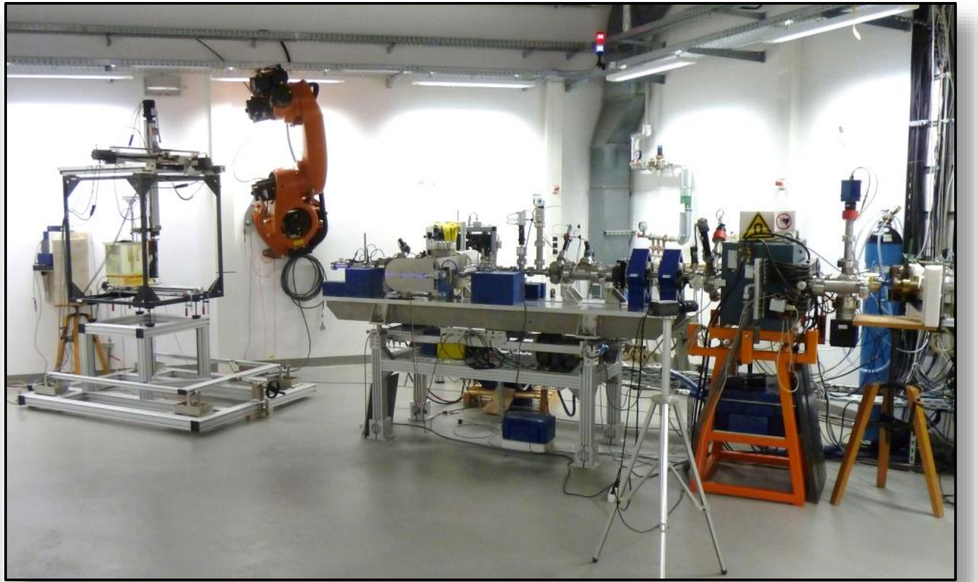


Introduction PTB dept. “Dosimetry for Radiotherapy”

Ultra-high pulse dose rate reference electron beam

PTB’s Research electron accelerator

E = 0.5 – 50 MeV, t_{pulse} = 0.3 – 3 us



Beam line with water phantom

up to **30 Gy per pulse** (SSD 0.5 m, 20 MeV, t_{pulse} = 2 us)

A. Bourgouin *et al*. *Phys. Med. Biol.* **67** (2022) 085013.
https://doi.org/10.1088/1361-6560/ac5de8

EU funded Joint Research Projects

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

UHDpulse

http://uhdpulse-empir.eu

EURAMET

The European Association of National Metrology Institutes

Duration:	Sep/2019-Feb/2023
Funding:	2.1 M €
Coordinator:	Andreas Schüller (PTB)
Topic:	**dosimetry for**
	- FLASH radiotherapy
	- VHEE radiotherapy
	- laser driven beams
Output:	47 papers (peer reviewed, open access)
	44 other publications
	91 oral conference presentations
	1 patent

A. Subiel et al Phys. Med. Biol. 69 (2024) 14TR01
https://doi.org/10.1088/1361-6560/ad539d

A. Schüller et al., Physica Medica 80 (2020) 134-150
https://doi.org/10.1016/j.ejmp.2020.09.020

EU funded Joint Research Projects

FLASH-DOSE "Traceable dosimetry for FLASH radiotherapy"

FLASH-DOSE

https://flash-dose.eu/

Duration: Jun/2025-May/2028

Funding: 1.3 M €

Coordinator: Jacco de Pooter (VSL)

Topic: **dosimetry for**

- FLASH radiotherapy

PTB will lead: ***WP4 "Reference dosimetry in clinical UHDPP electron beams"***

EURAMET

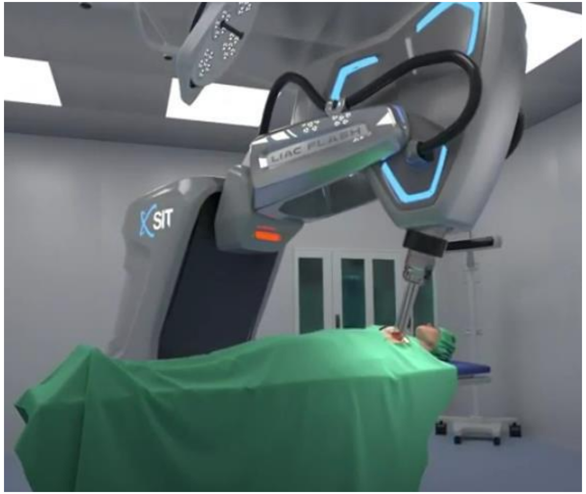
The European Association of National Metrology Institutes

UHDR electron beams for FLASH RT

Commercially available clinical FLASH electron accelerators

IntraOp Mobetron
With FLASH-IQ™

PMB ALCEN
FLASHKNiFE:



LIAC FLASH: life changing IOeRT FLASH device.
SIT Sordina IORT Technologies

UHDR electron beams for FLASH RT

Commercially available clinical FLASH electron accelerators

varian
A Siemens Healthineers Company

FlashEffects™ Program

FLEX Research Products

Welcome to the future of Flash research

Introducing the expanded FLEX™ product line. From treatment planning to delivery, FLEX empowers you to efficiently perform cutting-edge non-clinical research in the growing field of Flash therapy.

Be a Leader in Flash Research

- Uncover the science behind this new frontier in cancer research
- Save time on planning, set up, and calibration so you can focus on publishing results
- Pave the way for the future of Flash Therapy

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Convert your existing Varian linear accelerator to enable Flash delivery for research and training purposes.

- Deliver Flash via a familiar and reliable system
- High energy electron Flash for optimal flexibility to conduct a wide range of biological studies

UHDR electron beams for FLASH RT

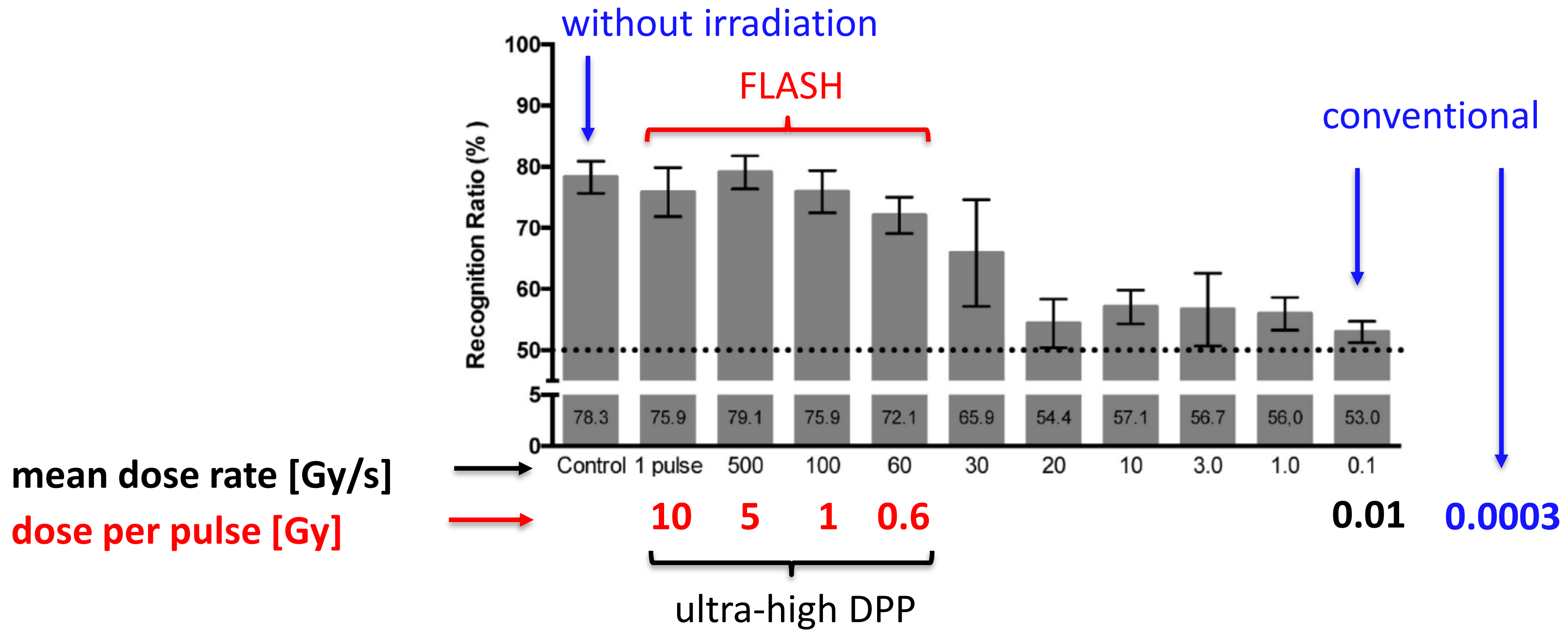
Comparison FLASH vs. conventional irradiation

	FLASH	conventional
Mean dose rate	**> 40 Gy/s**	**5 Gy/min**
Total delivery time	< 300 ms	4 min
Pulse duration	1 - 5 µs	4 µs
Pulse repetition frequency	10 - 100 Hz	100 - 400 Hz
Dose rate within the pulse	~ MGy/s	< 100 Gy/s
Dose per pulse (DPP)	0.6 – 10 Gy	0.3 mGy

ultra-high dose per pulse

UHDR electron beams for FLASH RT

Example: 10 Gy brain irradiation of mice

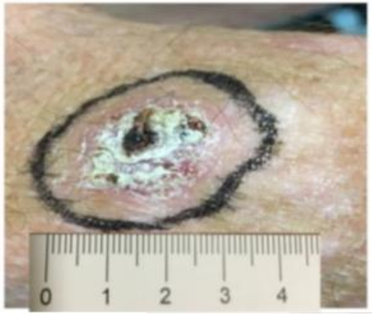


Montay-Gruel *et al.*, Radiother. Oncol. 124 (2017) 365
http://dx.doi.org/10.1016/j.radonc.2017.05.003

UHDR electron beams for FLASH RT

Example: FLASH RT of a human (lymphoma on skin)

- 10 pulses (of 1 μs duration)
- Total delivery time: 90 ms
- **Dose per pulse: 1.5 Gy**



day 0

3 weeks

5 months

Bourhis et al., Radiother. Oncol. 139 (2019) 18
http://dx.doi.org/10.1016/j.radonc.2019.06.019

UHDR electron beams for FLASH RT

Example: cancer treatment at dogs

- < 16 pulses
- Mean dose rates: > 400 Gy/s
- Pulse dose rates: ~0.7 MGy/s
- Delivery time: < 75 ms
- **Dose per pulse: 2 Gy**

treatment of the leg with in vivo dose measurements by radiochromic film

Konradsson et al., Front. Oncol. (2021) 11:658004
https://doi.org/10.3389/fonc.2021.658004

Dosimetry for conventional electron beams

Ionization chambers: standard detector for reference dosimetry in radiation therapy

Advanced Markus®
Chamber
Type 34045

Well-guarded plane-parallel chamber for the dosimetry of high-energy electron beams, especially for high dose per pulse values

Ion collection efficiency at nominal voltage	
Ion collection time	22 µs
Max. dose rate for	
≥ 99.5 % saturation	187 Gy/s
≥ 99.0 % saturation	375 Gy/s
Max. dose per pulse for	
≥ 99.5 % saturation	2.78 mGy
≥ 99.0 % saturation	5.56 mGy

Ranges of use	
Chamber voltage	± (50 ... 300) V
Radiation quality	(2 ... 45) MeV electrons

conventional: 0.3 mGy per pulse

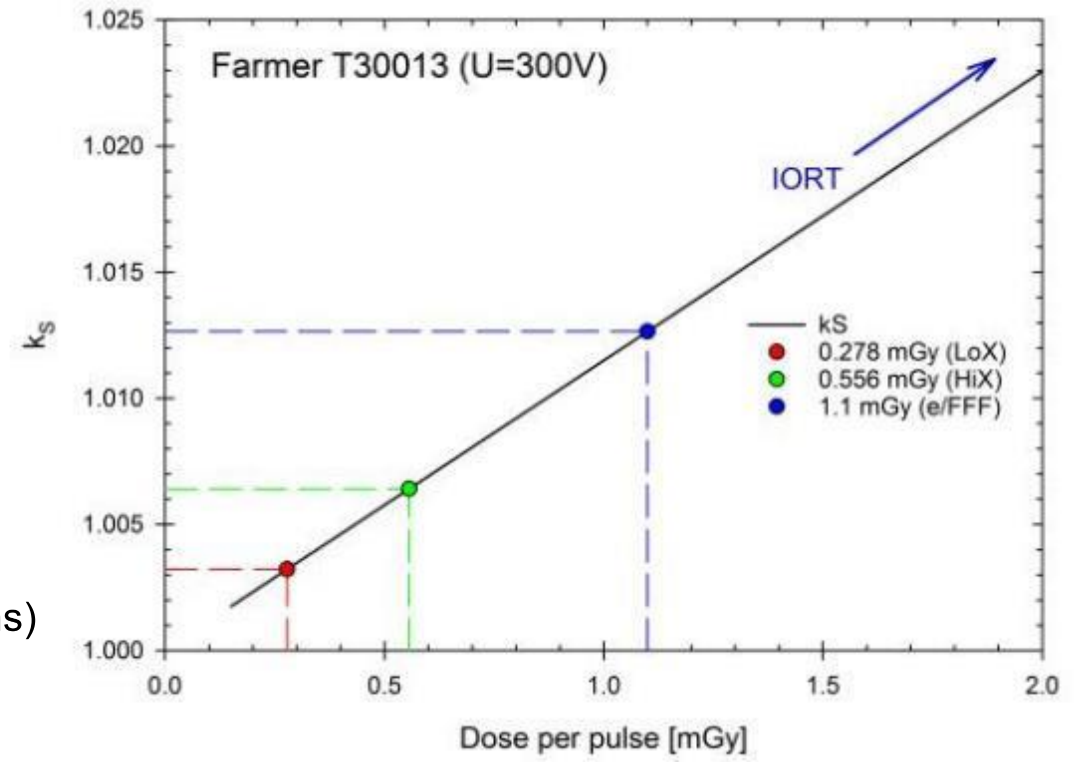
electron FLASH:
ultra-high dose per pulse = 0.6 – 10 Gy per pulse

Dosimetry for conventional electron beams

Ion recombination correction

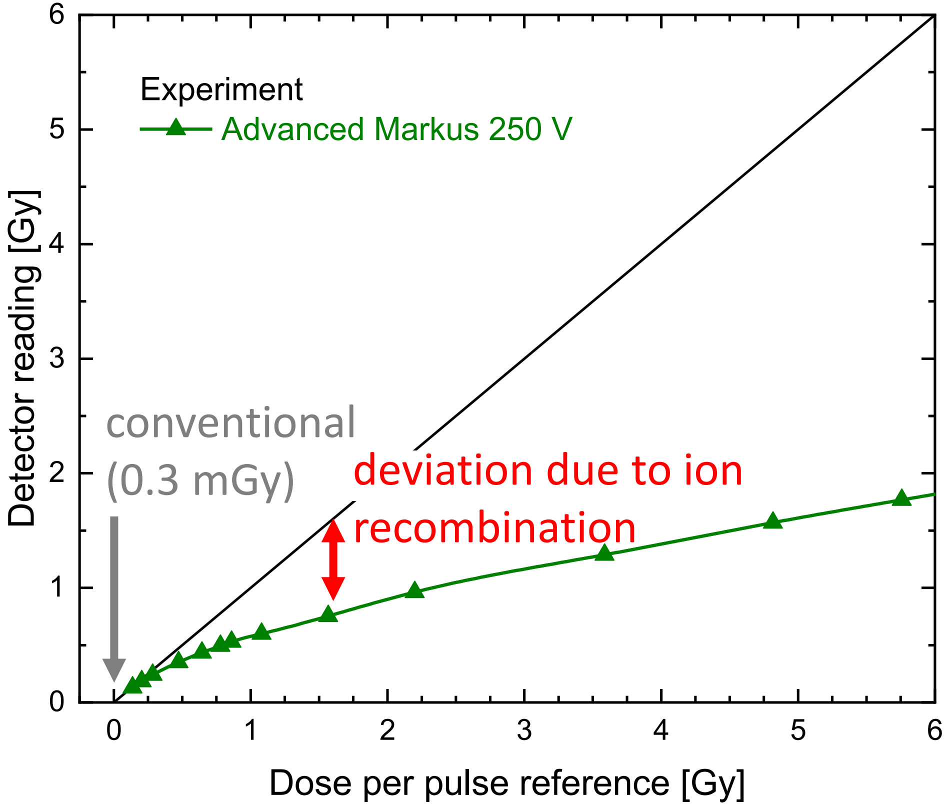
$$D_W = M\, N\, k_\rho k_Q \boldsymbol{k_s}\, \Pi k$$

D_W	absorbed dose to water [Gy] at $\boldsymbol{z_{ref}(R_{50})}$
M	chamber reading [C]
$\boldsymbol{N}$	**calibration coefficient [Gy/C]**
	correction due to
k_ρ	air density
$\boldsymbol{k_Q(R_{50})}$	**radiation quality** (x MeV electrons vs. Co-60 photons)
$\boldsymbol{k_s(D_P)}$	**ion recombination**



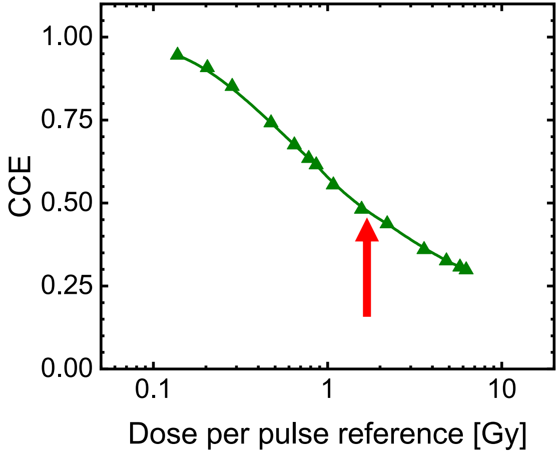
Dosimetry for UHDR electron beams

Ion recombination correction

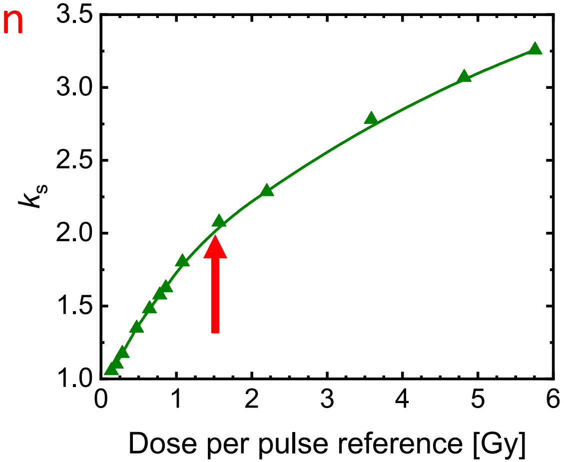


Charge Collection Efficiency

$$\boxed{CCE = k_s^{-1}}$$

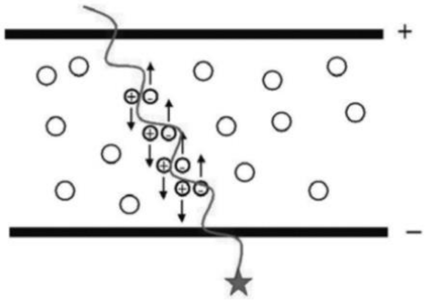


recombination correction



Dosimetry for UHDR electron beams

Ion recombination



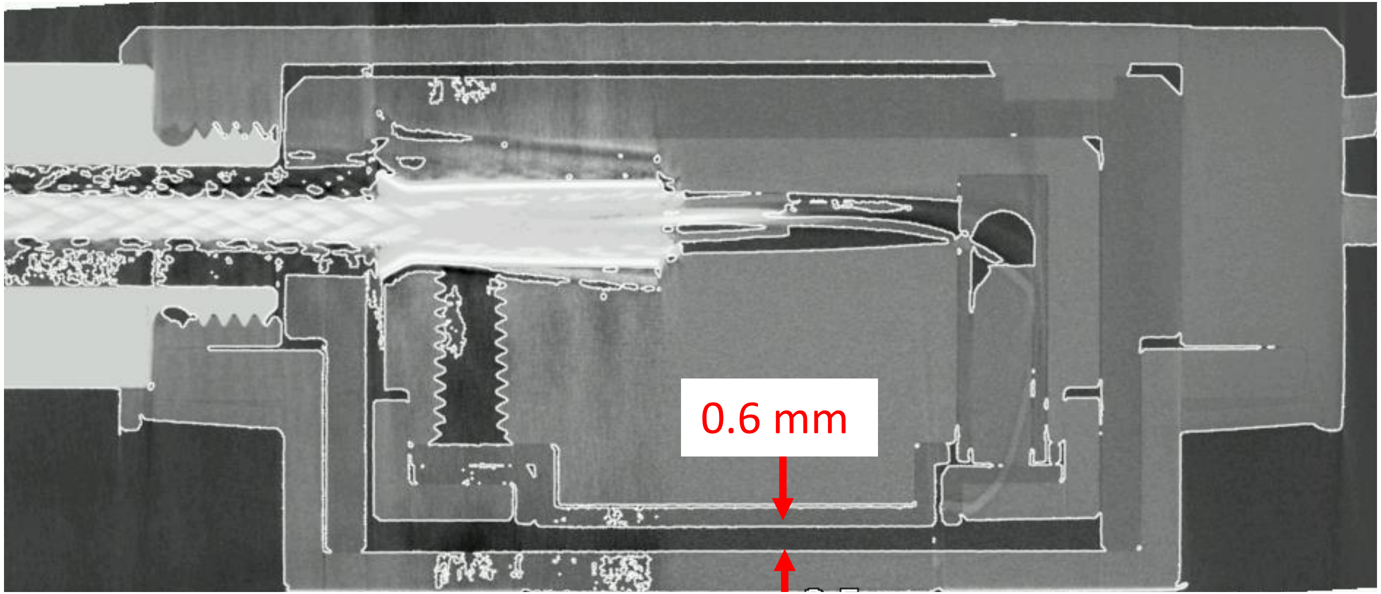
ionizing radiation creates ion pairs

<u>ion recombination depends on:</u>

- ion density → dose per pulse
- gas
  - mobility of ions
  - recombination coefficient
- electric field strength
  - voltage
  - electrode distance

Dosimetry for UHDR electron beams

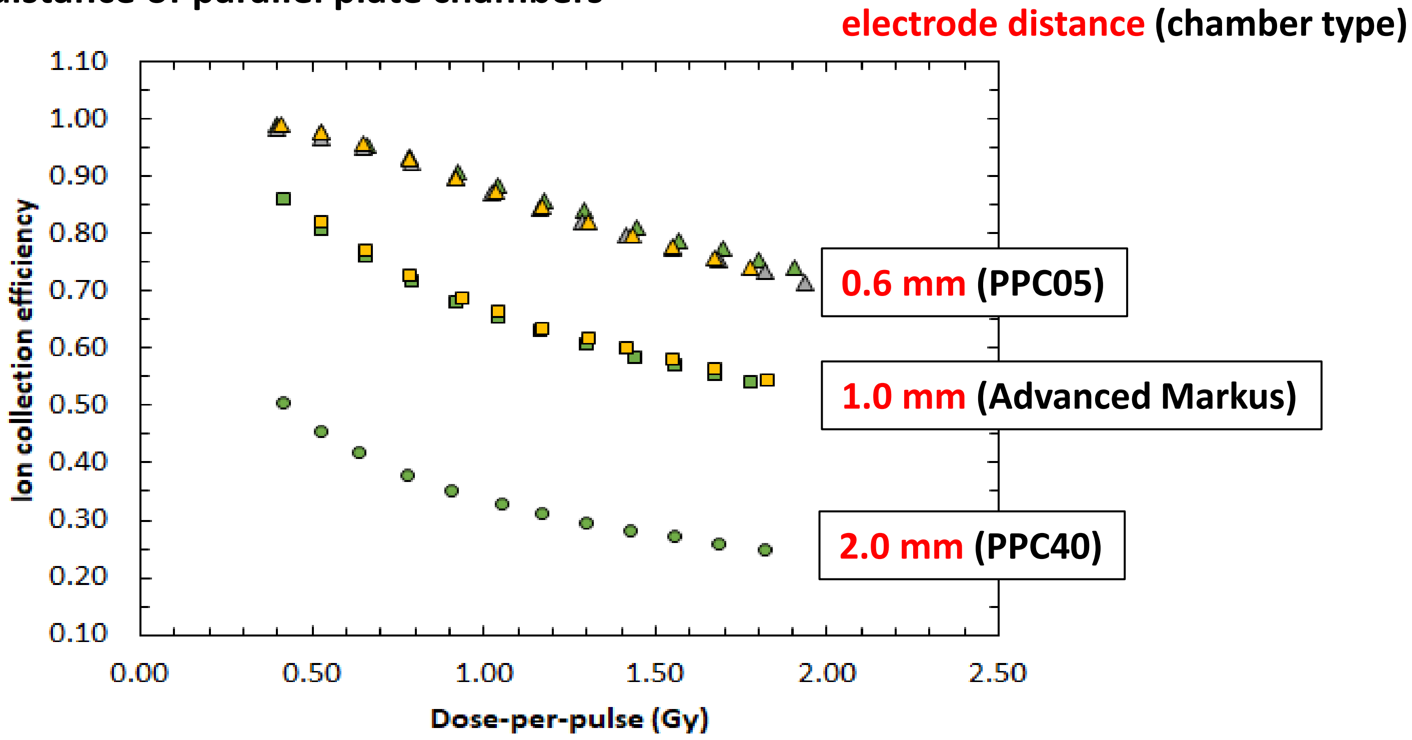
Electrode distance of parallel plate chambers



microCT image of IBA PPC05 ionization chamber

Dosimetry for UHDR electron beams

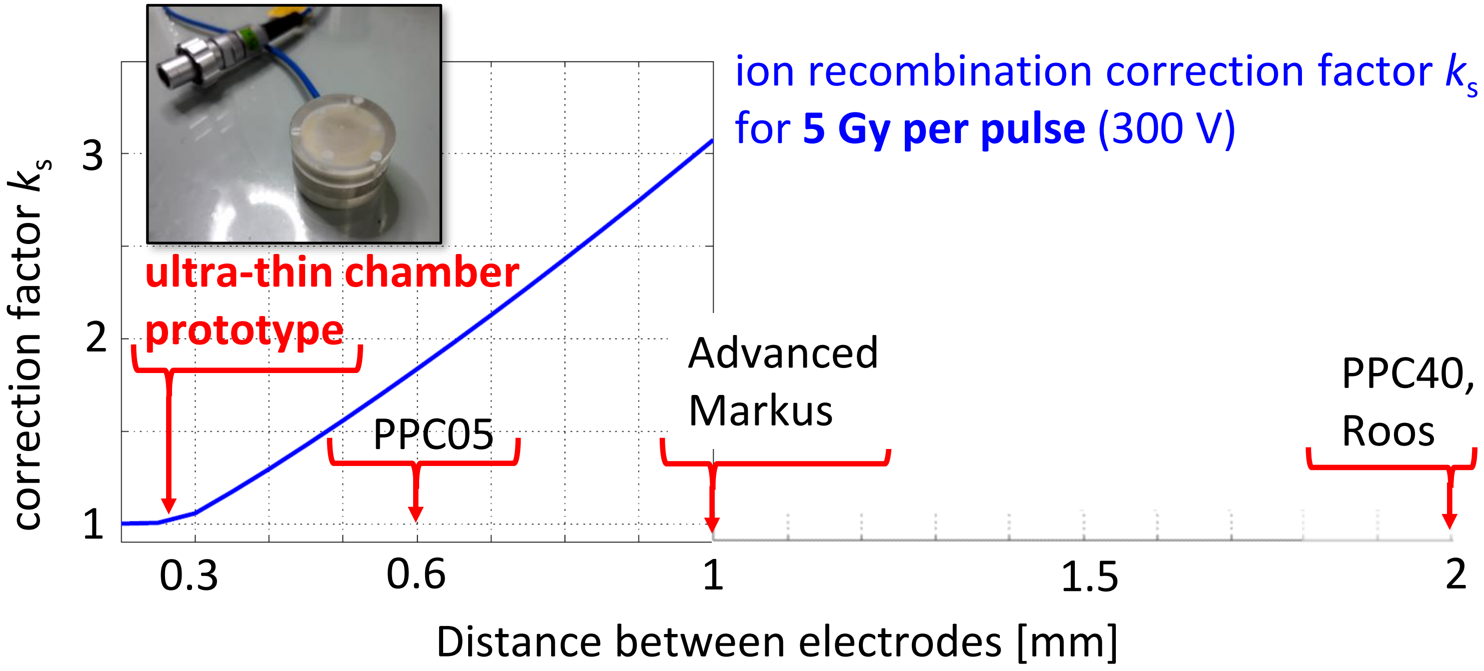
CCE vs. electrode distance of parallel plate chambers



A. Bourgouin *et al. Phys. Med. Biol.* **68** (2023) 235002
https://doi.org/10.1088/1361-6560/ad0a58

Dosimetry for UHDR electron beams

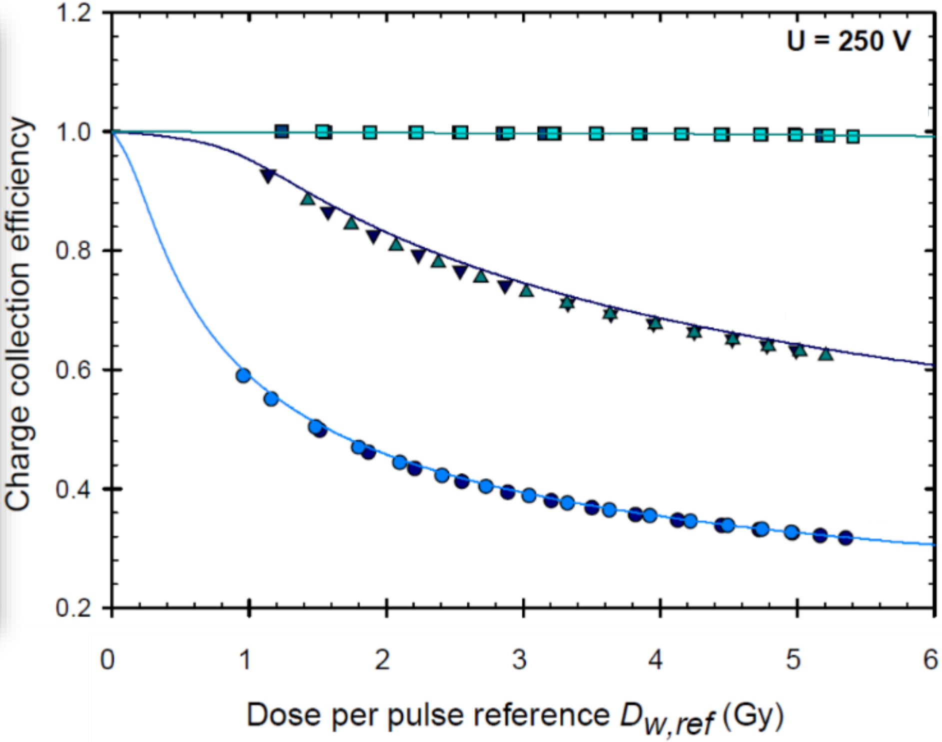
CCE vs. electrode distance of parallel plate chambers



F. Gomez *et al.* Med Phys. **49** (2022) 4705.
https://doi.org/10.1002/mp.15668

Dosimetry for UHDR electron beams

CCE vs. electrode distance of parallel plate chambers



electrode distance

0.25 mm (ultra-thin)

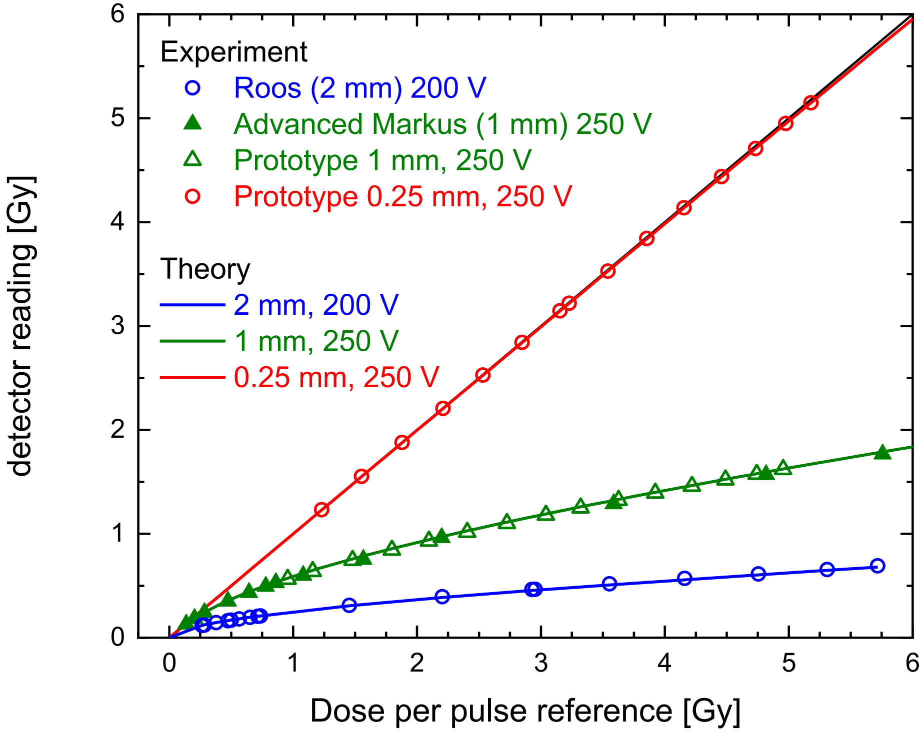
0.5 mm

1 mm

R. Kranzer, A. Schüller *et al.,* Phys. Med. **104** (2022) 10.
https://doi.org/10.1016/j.ejmp.2022.10.021

Dosimetry for UHDR electron beams

CCE vs. electrode distance of parallel plate chambers



PTW ultra-thin chamber

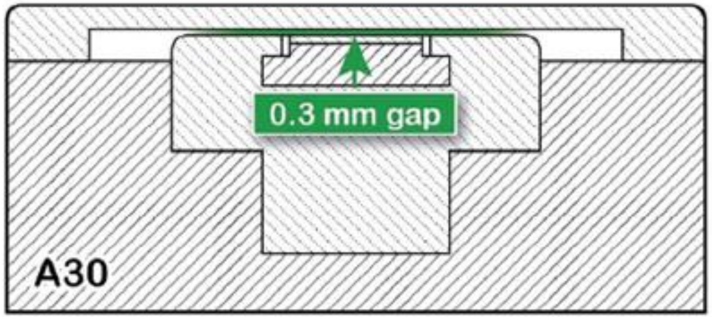
Advanced Markus

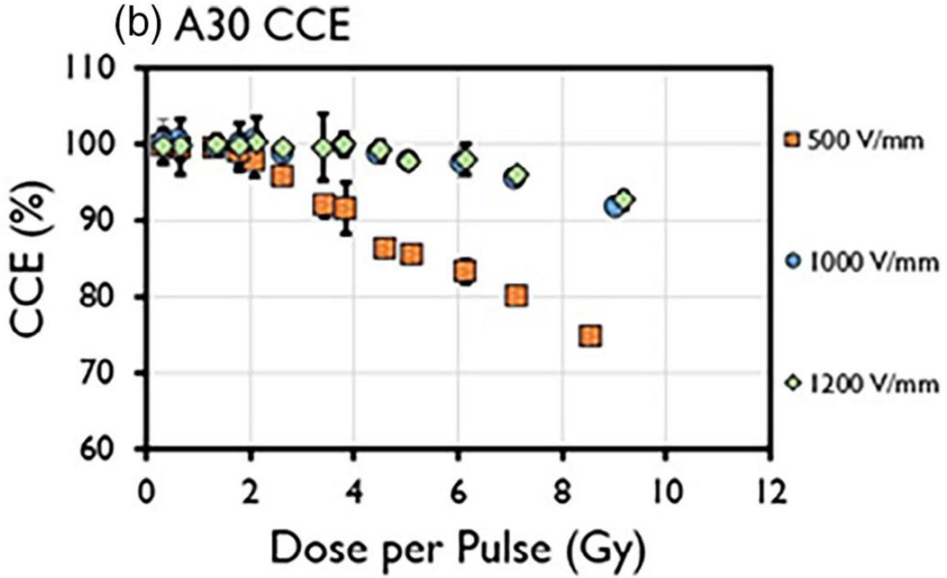
Roos

Dosimetry for UHDR electron beams

CCE vs. electrode distance of parallel plate chambers

Standard Imaging Exradin A30
(commercially available end of 2025)





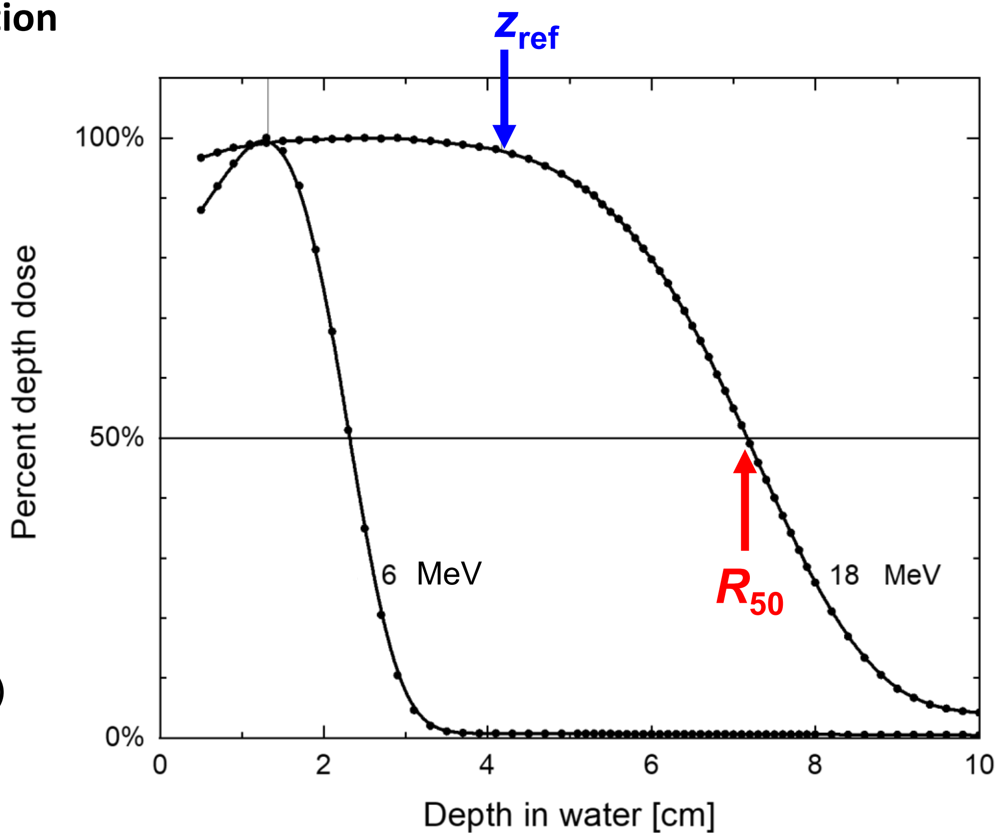
Liu et al. Development of novel ionization chambers for reference dosimetry in electron flash radiotherapy. Med Phys. 2024;51:9275–9289.
https://doi.org/10.1002/mp.17425

Dosimetry for conventional electron beams

Reference depth and radiation quality correction

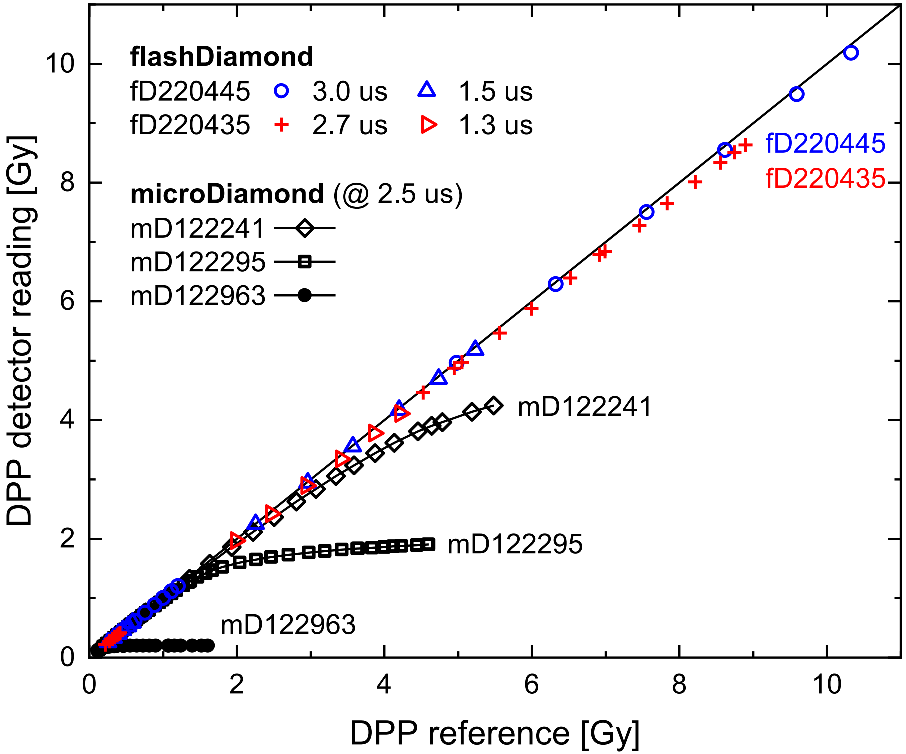
$$\boxed{D_W = M\, N\, k_\rho \boldsymbol{k_Q} k_s\, \Pi k}$$

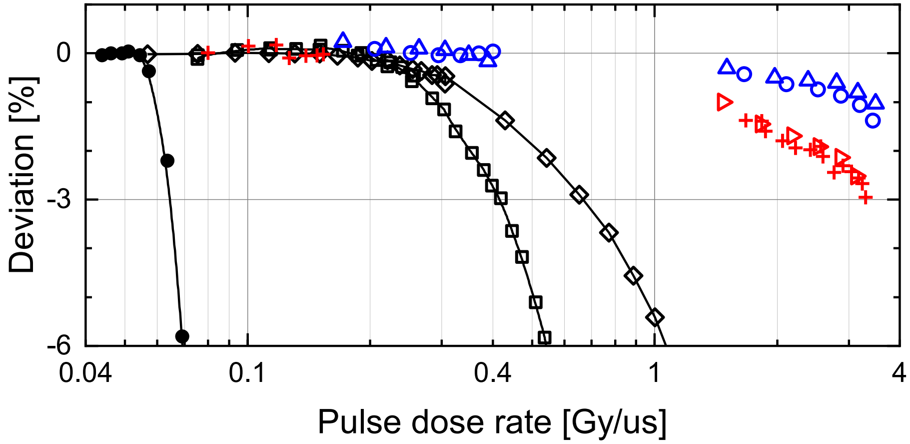
D_W	absorbed dose to water [Gy]
	at z_{ref} **= 0.6** R_{50} **– 0.1 cm**
M	chamber reading [C]
N	calibration coefficient [Gy/C]
	correction due to
k_ρ	air density
$\boldsymbol{k_Q}(R_{50})$	**radiation quality**
	(x MeV electrons vs. Co-60 photons)
$k_s(D_P)$	ion recombination



Dosimetry for UHDR electron beams

flashDiamond





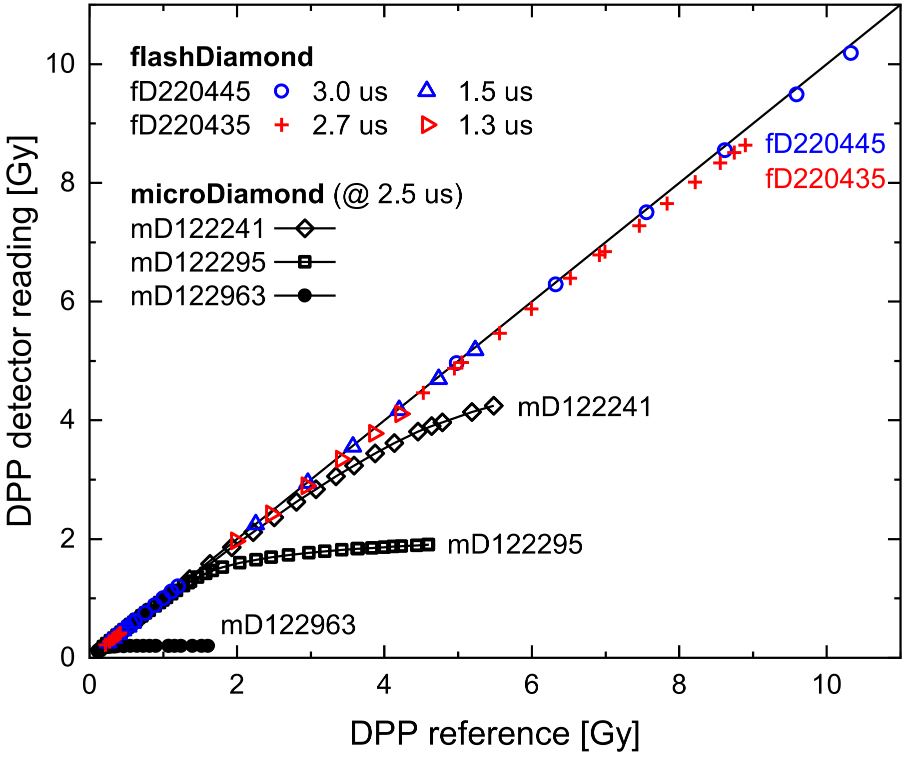
R. Kranzer *et al.* Phys. Med. Biol. **67** (2022) 075002.
https://doi.org/10.1088/1361-6560/ac594e

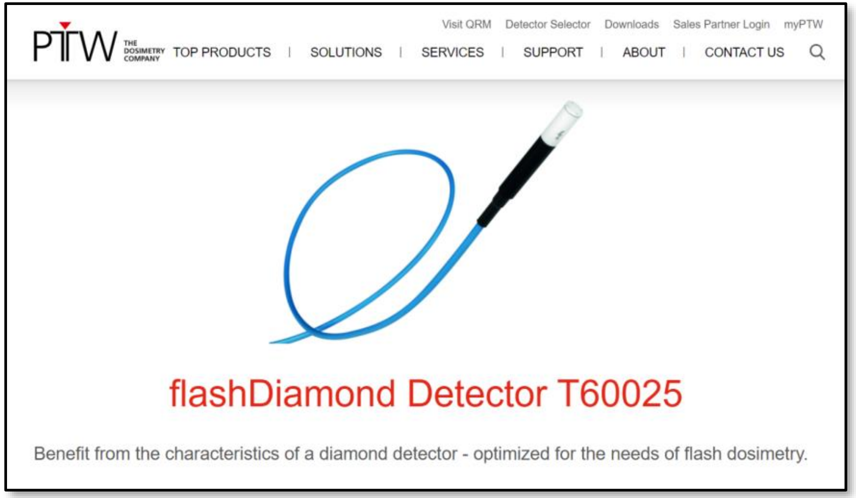
G. Verona Rinati et al. Med. Phys. **49** (2022) 5513.
https://doi.org/10.1002/mp.15782

A. Subiel et al Phys. Med. Biol. 69 (2024) 14TR01
https://doi.org/10.1088/1361-6560/ad539d

Dosimetry for UHDR electron beams

flashDiamond



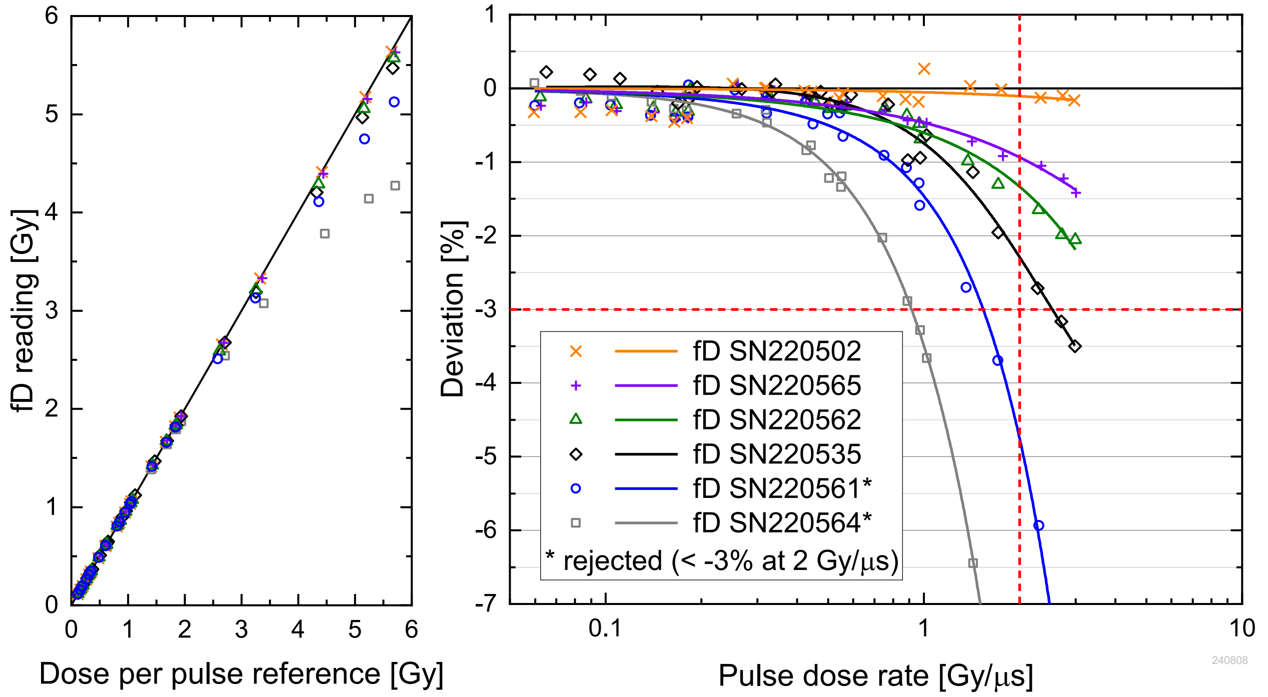


https://www.ptwdosimetry.com/en/products/flashdiamond-detector/

commercially available since 2023

Dosimetry for UHDR electron beams

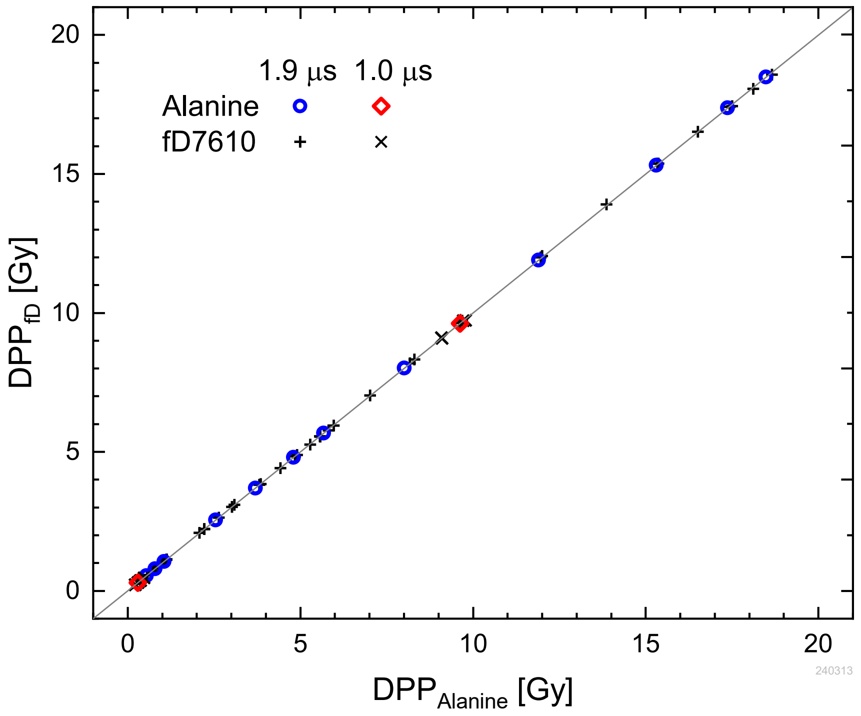
flashDiamond

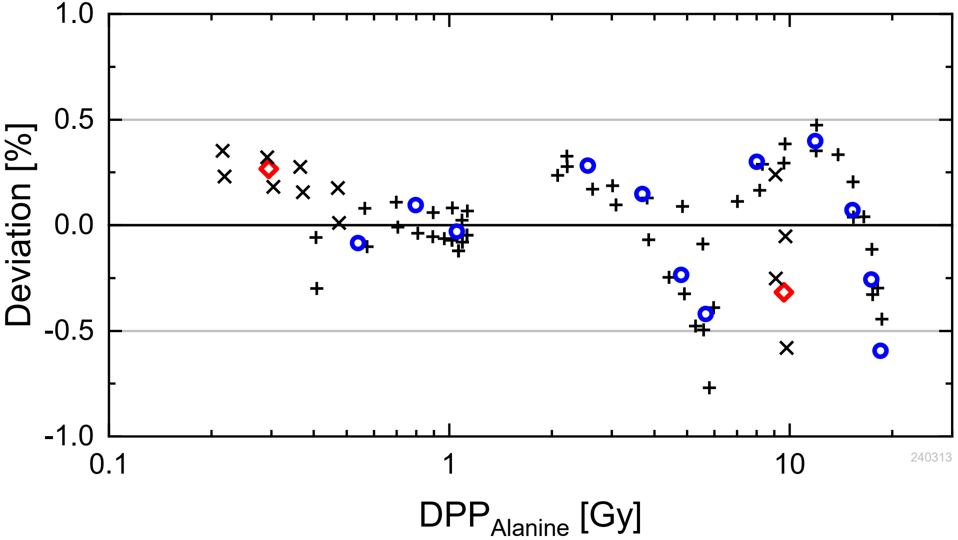


PTB tests on behalf of PTW every single flashDiamond before delivery, ensuring that the deviation from linear response is less than 3% up to 2 Gy/µs

Dosimetry for UHDR electron beams

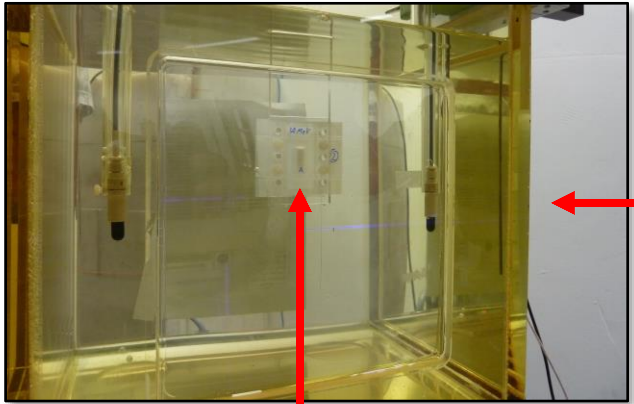
flashDiamond vs. Alanine

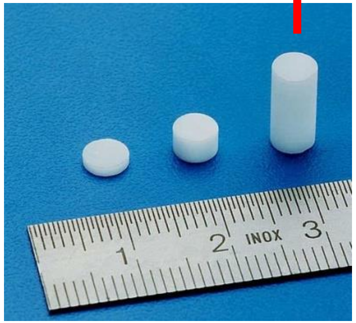


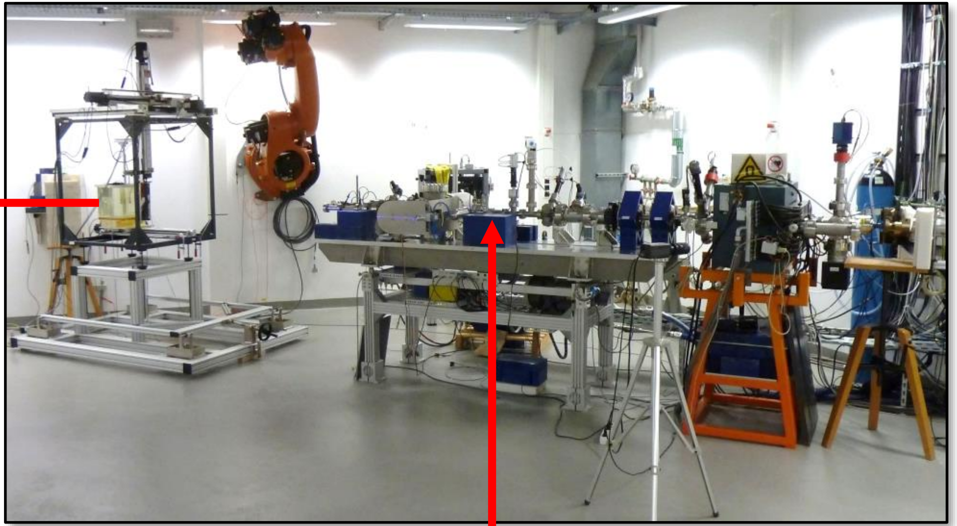


Dosimetry for UHDR electron beams

PTB's Alanine dosimetry system as reference







Alanine pellets at reference depth in water phantom

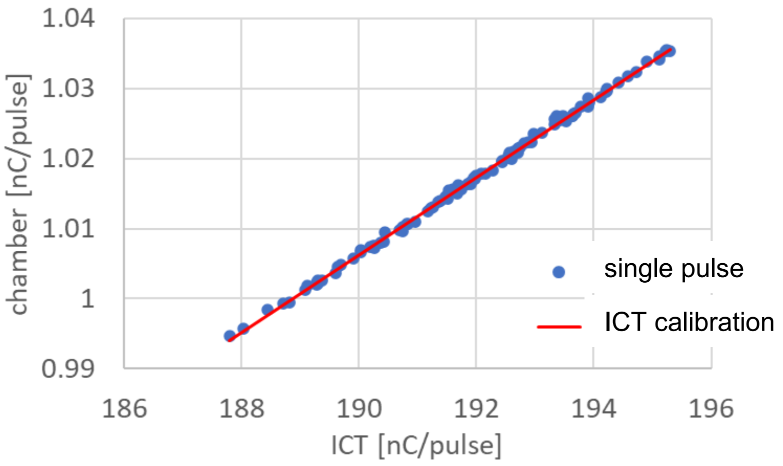
Dose traceable to PTB's primary standard, independent of dose rate (uncertainty < 0.5 %)

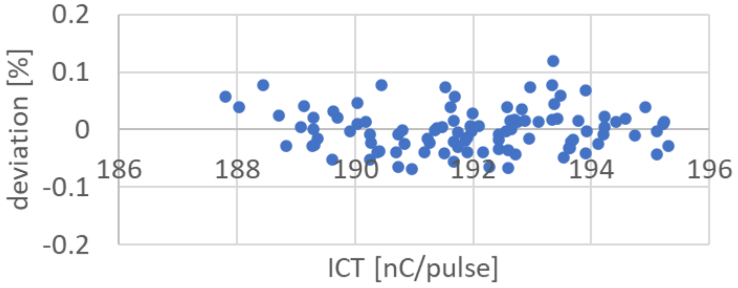
Current transformer (Bergoz ICT): Non-destructive absolute beam pulse charge measurement (uncertainty < 0.1 %)

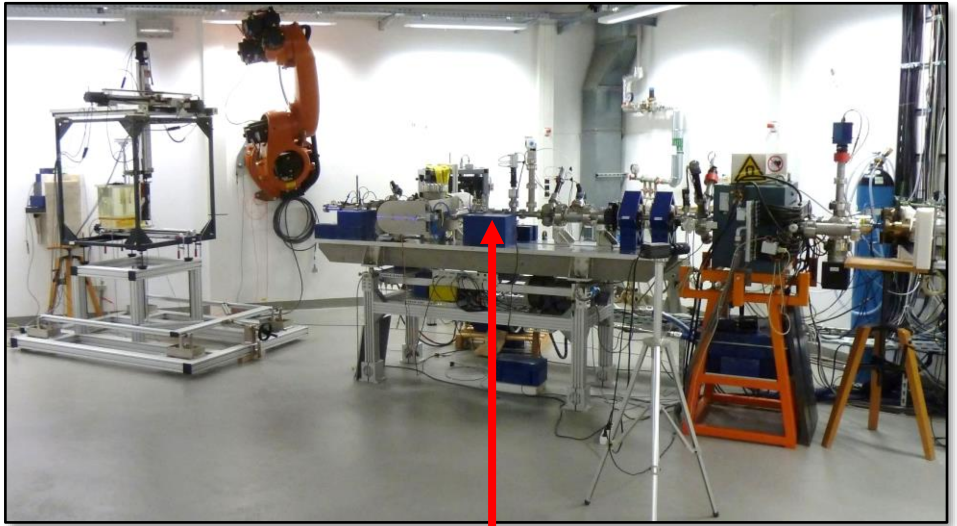
A. Bourgouin *et al.* Phys. Med. Biol. **67** (2022) 205011
https://doi.org/10.1088/1361-6560/ac950b

Dosimetry for UHDR electron beams

Beam monitor







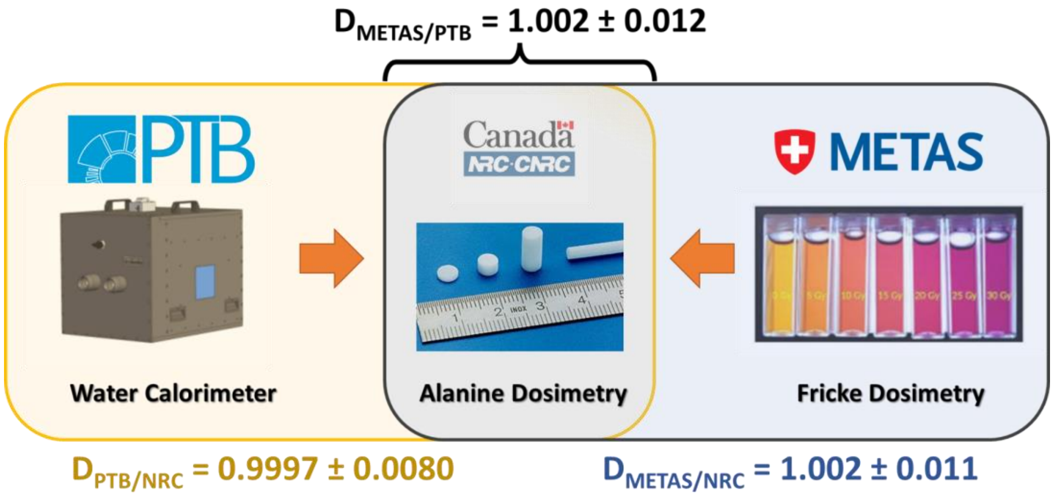
Current transformer (Bergoz ICT): Non-destructive absolute beam pulse charge measurement (uncertainty < 0.1 %)

A. Bourgouin *et al.* Phys. Med. Biol. **67** (2022) 205011
https://doi.org/10.1088/1361-6560/ac950b

Dosimetry for UHDR electron beams

Comparison of primary standards for ultra-high pulse dose rate electron beams

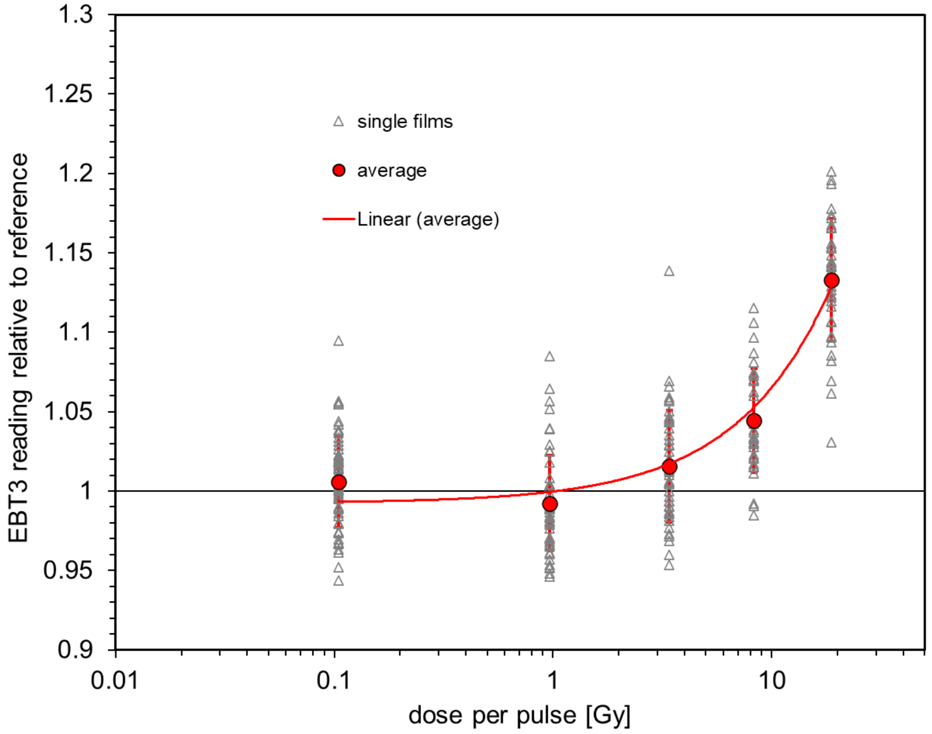
PTB's primary standard water calorimeter in ultra-high pulse dose rate electron beam



Alexandra Bourgouin *et al.* Phys. Med. Biol. **68** (2023) 115016
https://doi.org/10.1088/1361-6560/acce1d

Dosimetry for UHDR electron beams

radiochromic film

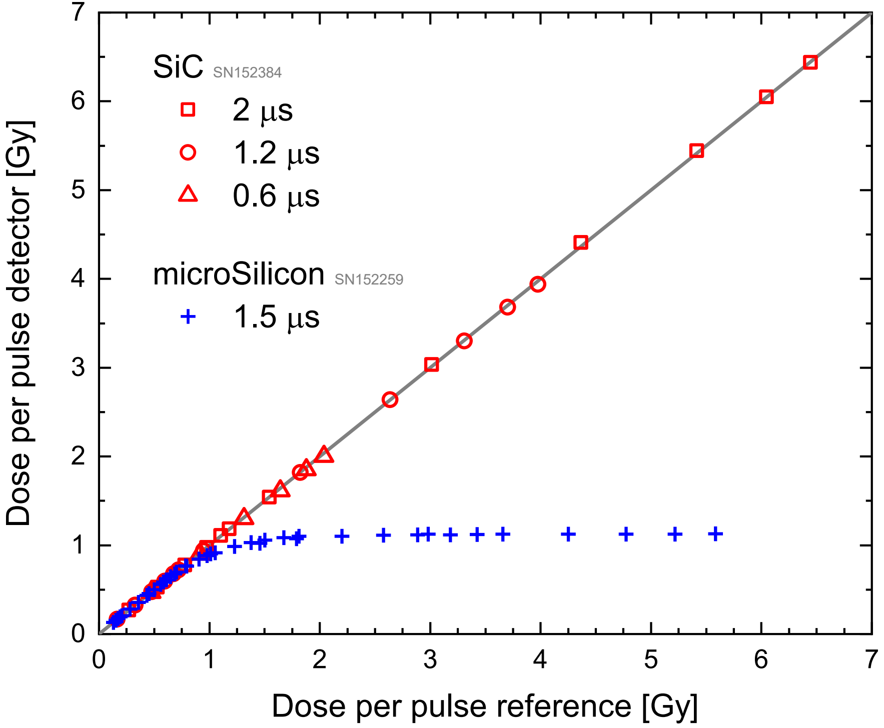


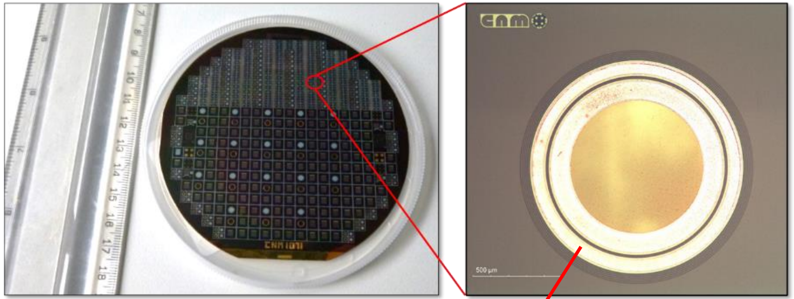
For DPP > 4 Gy per pulse (> 2 MGy/s) significant overresponse is observed

F. Horst *et al.* Physica Medica 125S1 (2024) S307
https://doi.org/10.1016/j.ejmp.2024.103901

Dosimetry for UHDR electron beams

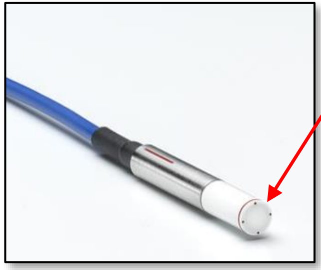
SiC diode dosimeter





4" SiC wafer

1 mm diode



Encapsulation by PTW (microSilicon housing)

Celeste Fleta *et al.*, Phys. Med. Biol. **69** (2024) 095013
https://doi.org/10.1088/1361-6560/ad37eb

Summary

- Conventional ionization chambers show large deviations in UHDR electron beams due to ion recombination at ultra-high DPP

- Current Codes of Practice do not address UHDR beams

- Ultra-thin ionization chambers were developed for UHDR electron beams. Standard Imagin A30 will be commercially available soon.

- flashDiamond detector is commercially available and can be used for absolute dosimetry of UHDR electron beams

- independent comparisons with suitable passive dosimeters are mandatory

Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
Bundesallee 100
38116 Braunschweig

Dr. Andreas Schüller
Telefon: 0531 592-6209
E-Mail: andreas.schueller@ptb.de
www.ptb.de

Stand: 6/2025