Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Dosimetry of electron beams – challenges and possible solutions for VHEE and FLASH

UHDpulse

Andreas Schüller
Department 6.2 “Dosimetry for Radiation Therapy and Diagnostic Radiology”

VHEE’2020 Workshop
5.-7.October 2020, CERN (virtual)

Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Dosimetry of electron beams – challenges and possible solutions for VHEE and FLASH

UHDpulse

Contents

- Dosimetry for conventional clinical electron beams
- Dosimetric challenges at FLASH and VHEE
- The UHDpulse project
- Possible solutions for VHEE and FLASH dosimetry

Dosimetry for conventional clinical electron beams

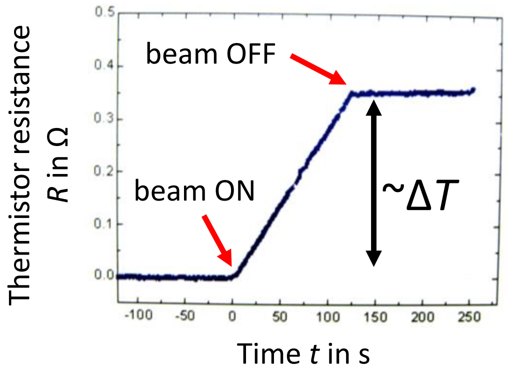
Primary standard of the unit Gy for absorbed dose to water

$D_w = d\varepsilon/dm$ 1 Gy = 1 J/Kg

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

$D_w = c_p \cdot \Delta T \cdot \Pi k_i$ $\Delta T = 0.24$ mK/Gy

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

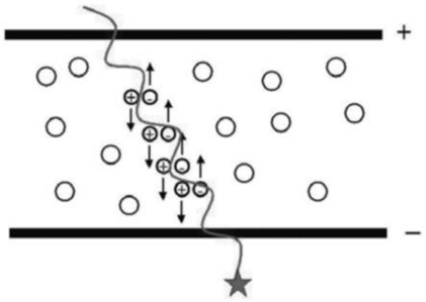


Clinical beams: 4 – 22 MeV, 100 – 400 Hz,
1 - 4 µs macropulse, mean dose rate < 5 Gy/min

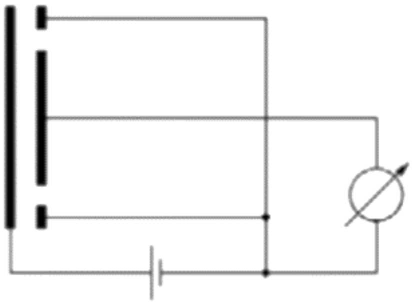
PTB water calorimeter at a medical LINAC

Dosimetry for conventional clinical electron beams

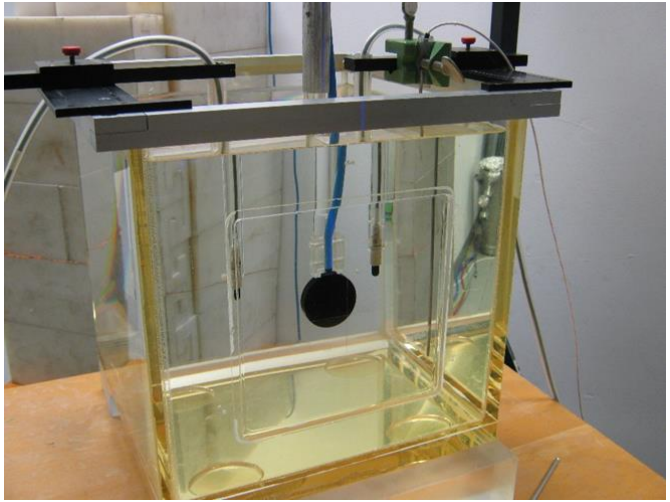
Ionization chambers: the standard for reference dosimetry in conventional radiotherapy



ionizing radiation creates ion pairs



high voltage current



Plane-parallel ionization chamber in a water phantom (recommended for electron beams)

Codes of Practice:
Formalism for clinical reference dosimetry of high-energy electron beams (3 – 50 MeV)

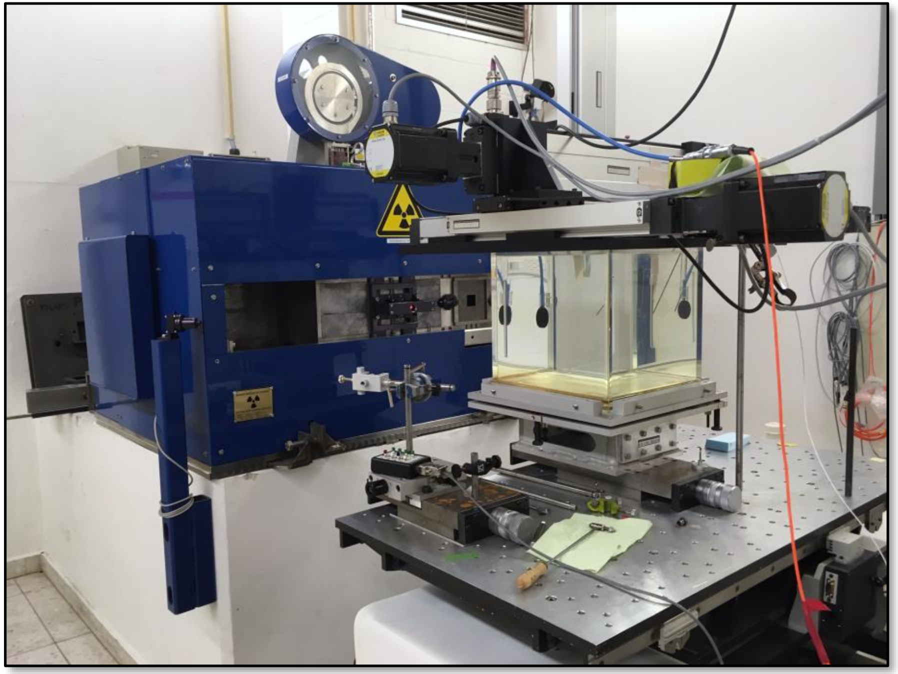
→ IAEA's TRS 398, AAPM's TG-51, DIN 6800-2

Dosimetry for conventional clinical electron beams

Formalism for electrons up to 50 MeV

$$D = (M - M_0)\, N\, k_\rho k_h k_s k_p k_E$$

D absorbed dose (at $\boldsymbol{z}_{\mathbf{ref}}$)
M reading
M_0 zero reading
N calibration coefficient (Co-60)
<u>*correction due to*</u>
k_ρ air density
k_h humidity
k_s ion recombination
k_p polarity
k_E radiation quality (electrons)



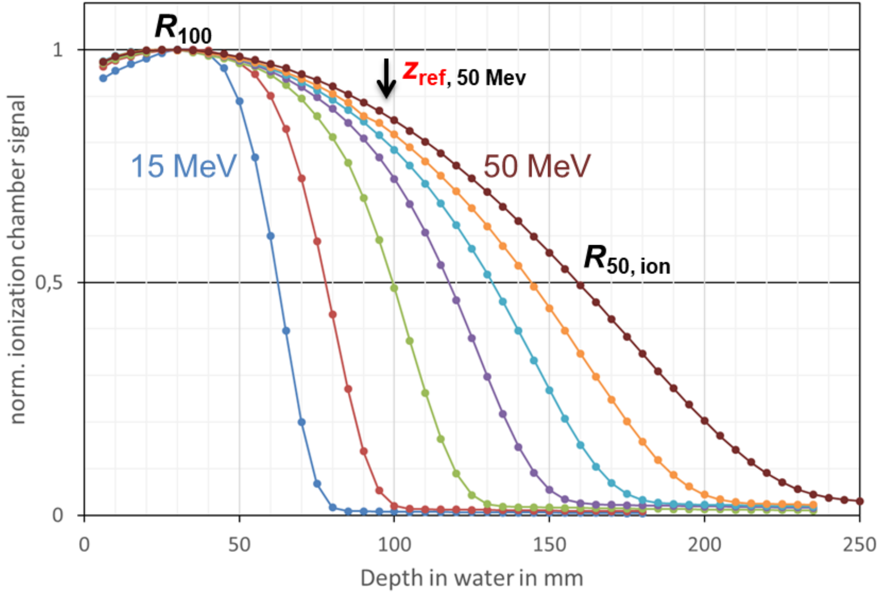
^{60}Co Source of PTB's calibration service
(dose rate determined by means of water calorimeter)

Dosimetry for conventional clinical electron beams

Formalism for electrons up to 50 MeV

$$D = (M - M_0)\, N\, k_\rho k_h k_s k_p k_E$$

D	absorbed dose (at z_{ref})
M	reading
M_0	zero reading
$\mathbf{N}$	**calibration factor (Co-60)**
	correction due to
k_ρ	air density
k_h	humidity
$\mathbf{k_s}$	**ion recombination**
k_p	polarity
$\mathbf{k_E}$	**radiation quality (electrons)**



Reference depth: $z_{ref} = 0.6\, R_{50} - 0.1$ (in cm)

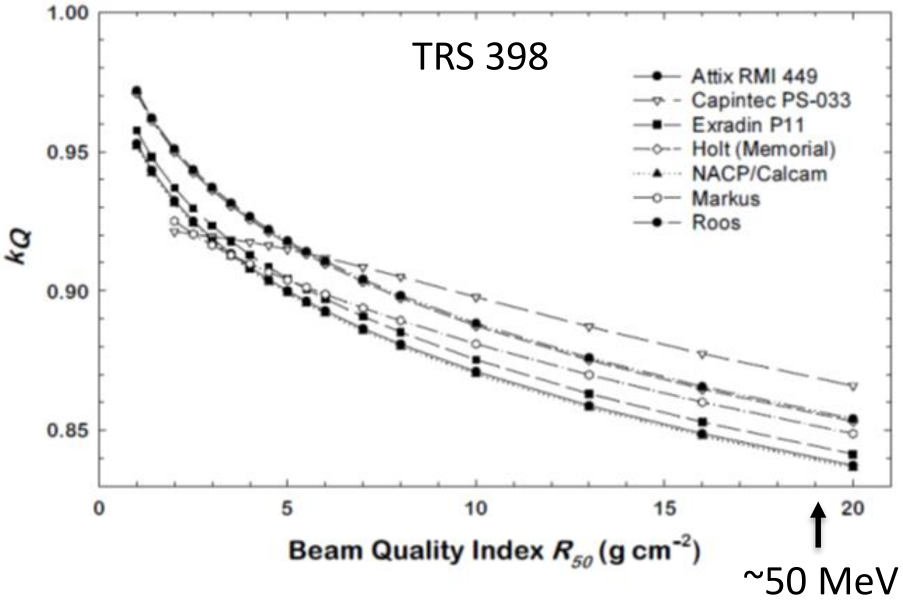
$R_{50} = 1.059\, R_{50,\,ion} - 0.37$ cm ($R_{50,\,ion} > 10$ cm)

Dosimetry for conventional clinical electron beams

Formalism for electrons up to 50 MeV

$$D = (M - M_0)\, N\, k_\rho k_h k_s k_p k_E$$

D	absorbed dose (at $\boldsymbol{z}_{\mathbf{ref}}$)
M	reading
M_0	zero reading
$\boldsymbol{N}$	**calibration factor (Co-60)**
	correction due to
k_ρ	air density
k_h	humidity
$\boldsymbol{k_s}$	**ion recombination**
k_p	polarity
$\boldsymbol{k_E}$	**radiation quality (electrons)**



$k_E = k_Q = -\,0.1312\,(R_{50})^{0.214}\, k_E$“

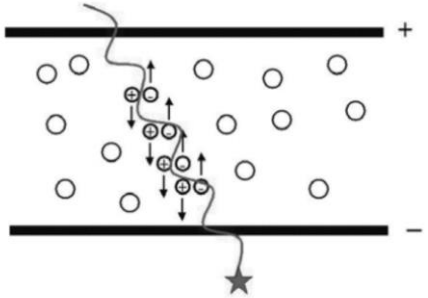
k_E“(Advanced Markus)=0.985

Dosimetry for conventional clinical electron beams

Formalism for electrons up to 50 MeV

$$D = (M - M_0)\ N\ k_\rho k_h k_s k_p k_E$$

D	absorbed dose (at $\boldsymbol{z}_{\mathbf{ref}}$)
M	reading
M_0	zero reading
$\boldsymbol{N}$	**calibration factor (Co-60)**
	correction due to
k_ρ	air density
k_h	humidity
$\boldsymbol{k_s}$	**ion recombination**
k_p	polarity
$\boldsymbol{k_E}$	**radiation quality (electrons)**



high dose per beam pulse
→ high density of ion pairs
→ ion recombination
→ deviation from linear response

For conventional beams (< 0.3 mGy/pulse)
$\boldsymbol{k_s}$ amounts to a few 0.1%

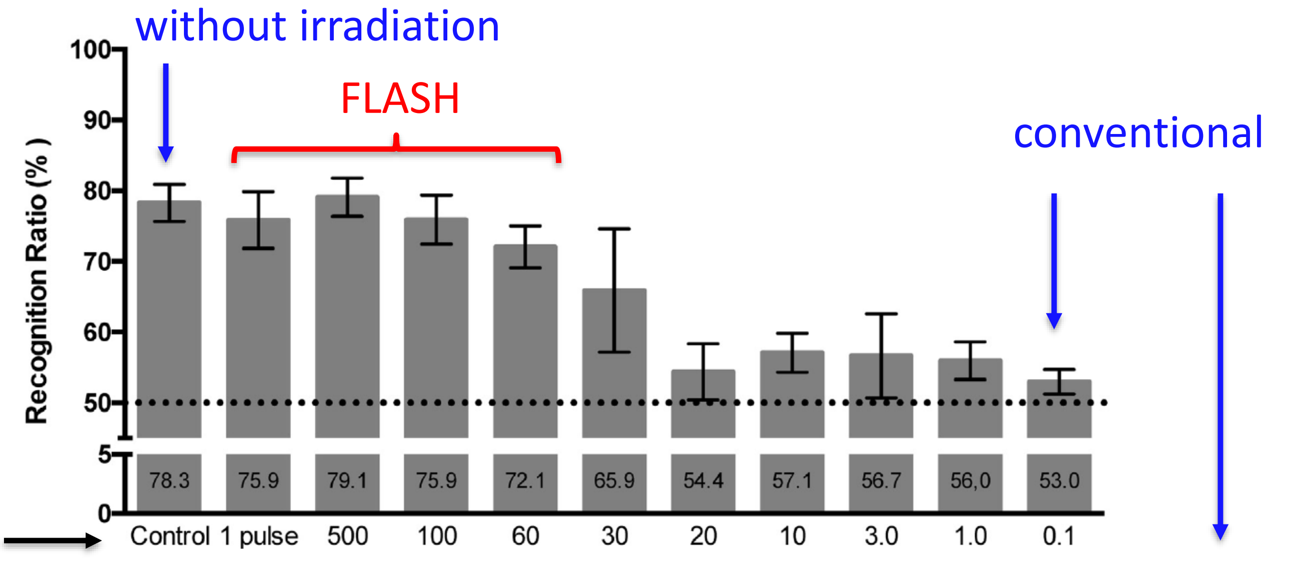
Dosimetric challenges at FLASH

Example: FLASH irradiation of mice

institutCurie

CHUV Centre hospitalier universitaire vaudois

whole brain irradiation with 10 Gy



Mean dose rate [Gy/s] →

Dose per pulse [Gy] → 10 5 1 0.6 0.01 0.0003

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

Dosimetric challenges at FLASH

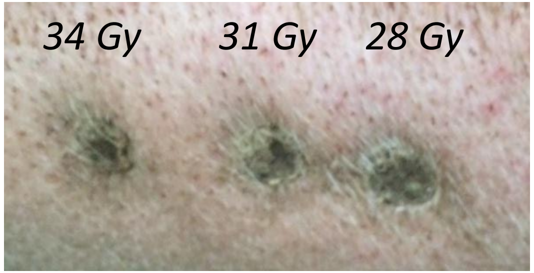
Example: FLASH irradiation of pig skin

Centre hospitalier universitaire vaudois

Conventional and FLASH Irradiation (with same total dose)

36 weeks post-RT

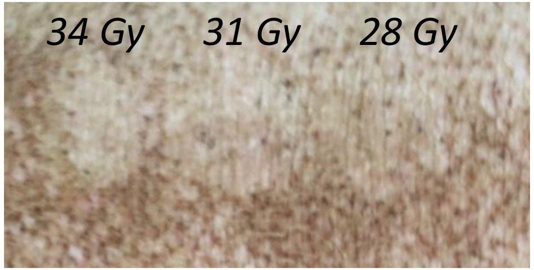
Conventional (5 Gy/min)



necrotic lesions

FLASH (300 Gy/s)

3 Gy/pulse



normal appearance of skin

Vozenin *et al.*, Clin Cancer Res 25 (2019) 35
http://dx.doi.org/10.1158/1078-0432.CCR-17-3375

Dosimetric challenges at FLASH

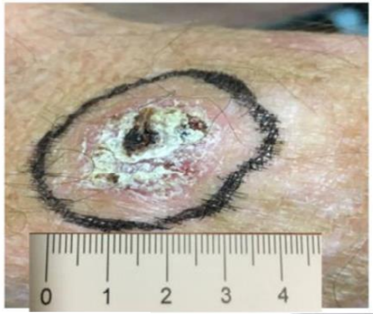
Example: Treatment of the first human patient with FLASH-RT

Centre hospitalier universitaire vaudois

<u>Disease:</u>
lymphoma on skin

<u>conventional RT:</u>
20 Gy in 6 - 10 fractions
high grade acute skin reactions
takes >3 months to heal

<u>FLASH-RT:</u>
10 pulses (of 1 μs duration) in 90 ms
with **1.5 Gy/pulse**



Day 0

after 3 weeks

(max. of skin reactions)

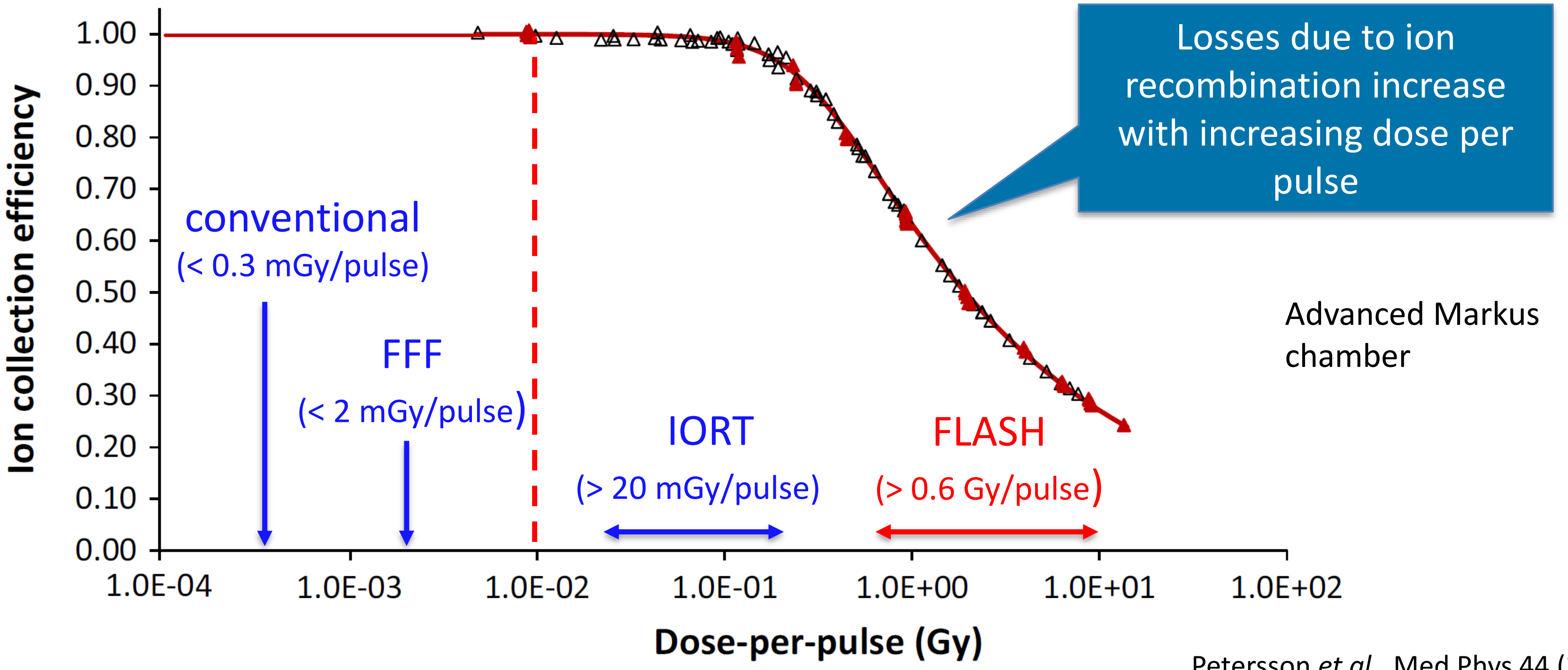
after 5 months

Bourhis *et al.*, Radiother. Oncol. (2019)

DOI: 10.1016/j.radonc.2019.06.019

Dosimetric challenges at FLASH

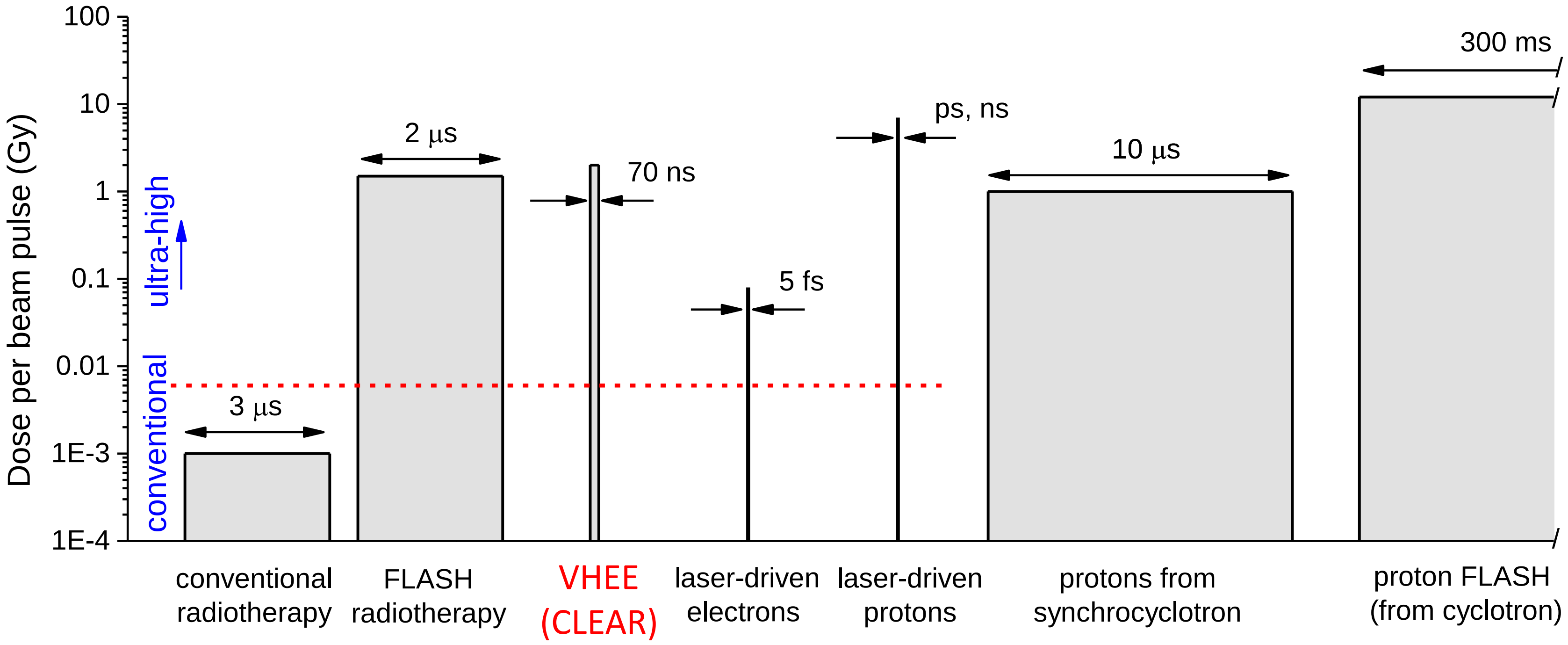
Typical performance of an ionization chamber



Petersson *et al.*, Med Phys 44 (2017) 1157
https://doi.org/10.1002/mp.12111

Dosimetric challenges at FLASH and VHEE

Limit for ionization chambers



Dosimetric challenges at FLASH and VHEE

Crucial point dosimetry

If an error is made in dosimetry, the difference in tissue response between conventional irradiation and ultra-high dose rate irradiation at apparently the same total dose may be due to this error and not due to the FLASH effect.

Tools and methods established in dosimetry for conventional RT are not suitable for FLASH-RT or VHEE-RT

no active dosimeters for real time dosimetry

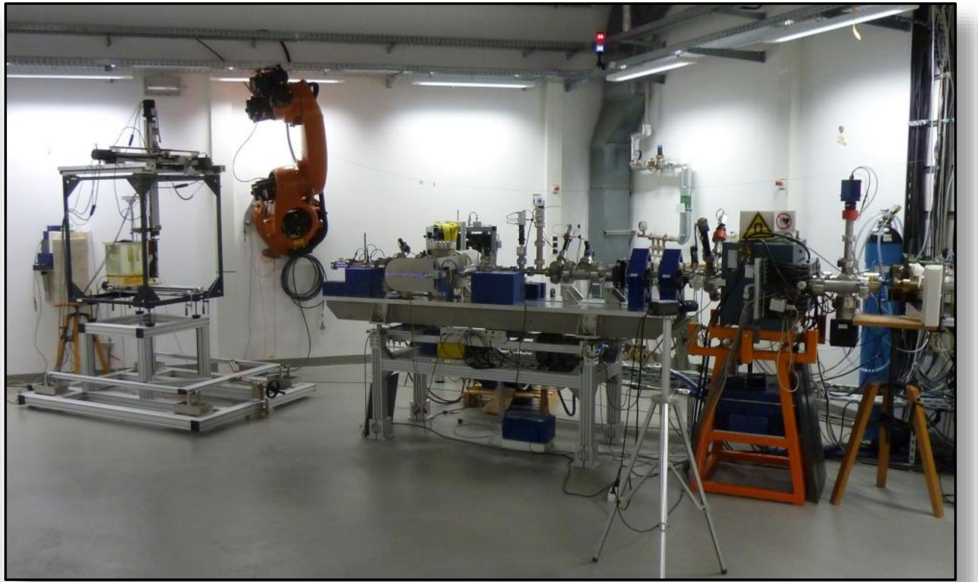
no formalism (Codes of Practice) for reference dosimetry

no corresponding primary standard

Dosimetric challenges at FLASH and VHEE

Ultra-high dose per pulse and energies which exceed the clinical range at PTB

PTB's Research electron accelerator

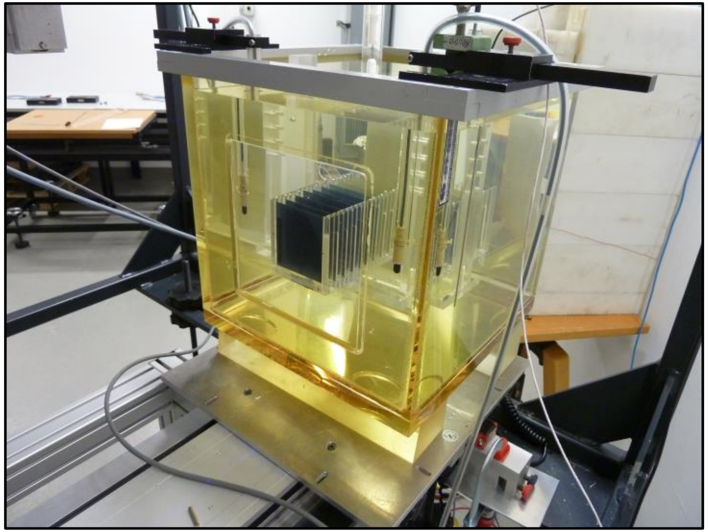


Beam line with water phantom

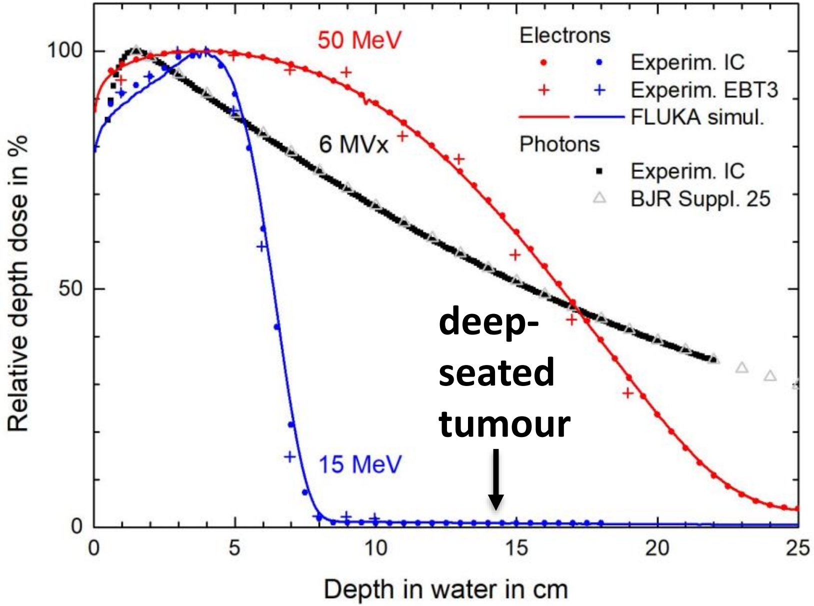
E = 0.5 – 50 MeV, up to 3 Gy/pulse (@ 0.7 m)

Dosimetric challenges at VHEE

Verification of energy independence of passive dosimeters up to 50 MeV



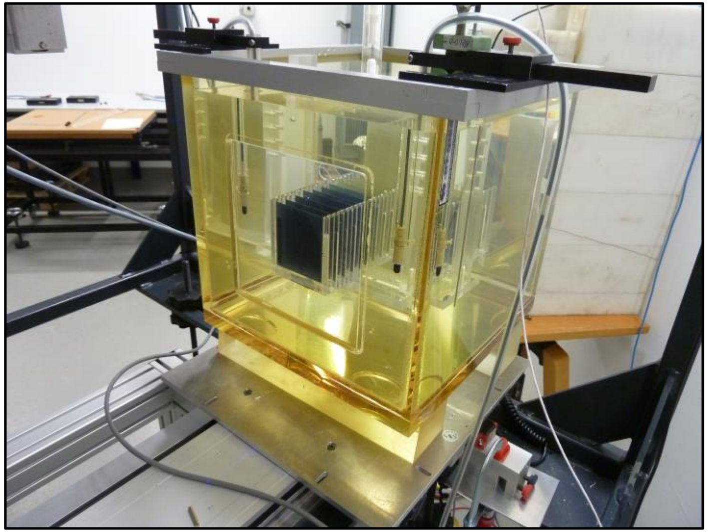
Stack of equispaced EBT3 films after exposure to 50 MeV electron beam



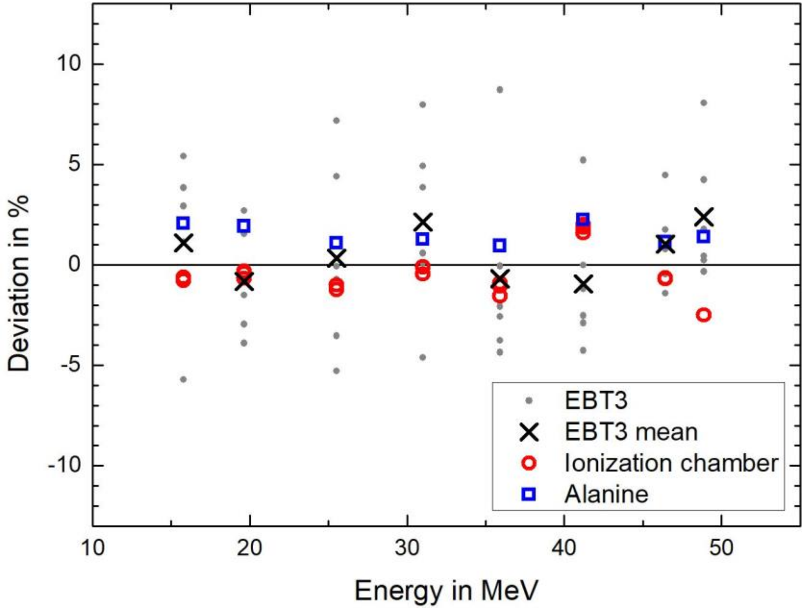
Karolina Kokurewicz, A. Schüller *et al.,* Dosimetry for new radiation therapy approaches using high energy electron accelerators, Frontiers in Physics (2020, accepted)
https://doi.org/10.3389/fphy.2020.568302

Dosimetric challenges at VHEE

Verification of energy independence of passive dosimeters up to 50 MeV



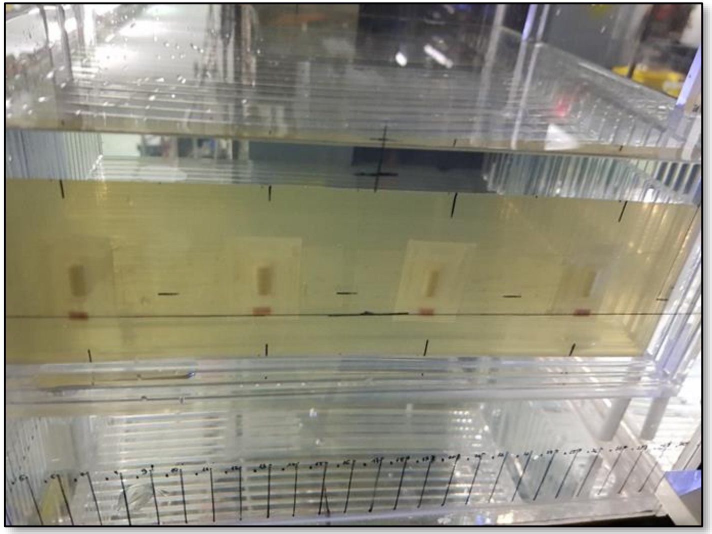
Stack of equispaced EBT3 films after exposure to 50 MeV electron beam



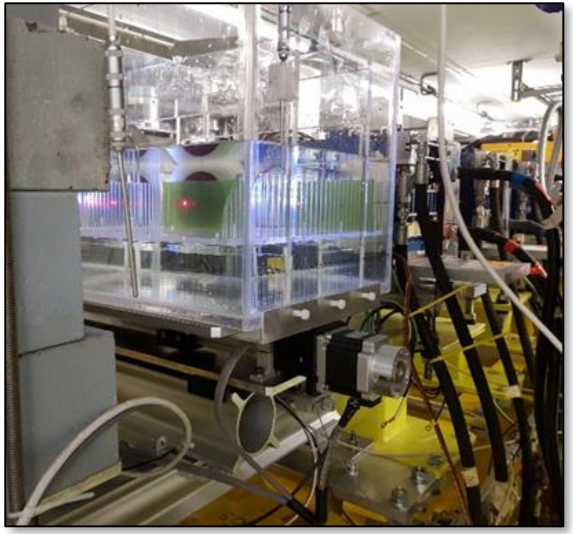
Karolina Kokurewicz, A. Schüller *et al.,* Dosimetry for new radiation therapy approaches using high energy electron accelerators, Frontiers in Physics (2020, accepted)
https://doi.org/10.3389/fphy.2020.568302

Dosimetric challenges at VHEE

Verification of energy independence of passive dosimeters at VHEE



Alanine samples glued on EBT3 film in a water phantom



Setup at CLEAR facility

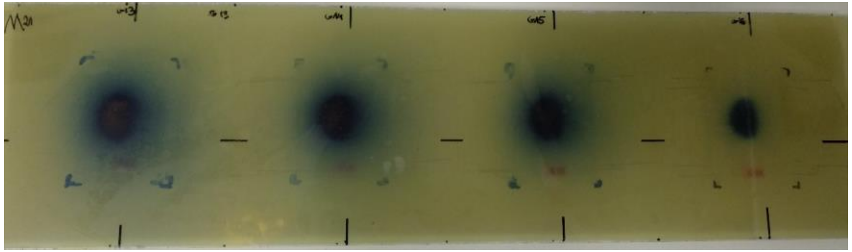
Karolina Kokurewicz, Investigation of focused Very High Energy Electrons (VHEEs) as a new radiotherapy method, PhD thesis (2020)

Dosimetric challenges at VHEE

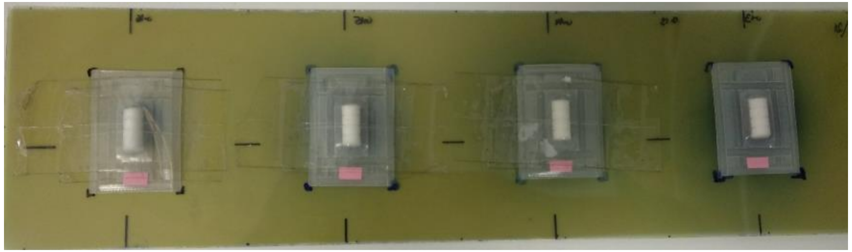
Verification of energy independence of passive dosimeters at VHEE

requested dose: 20 Gy 15 Gy 10 Gy 1 Gy

151 MeV



irradiated EBT3 film front side



4 stacks of 4 alanine pellets on the rear face of the EBT3 films

<u>dose range limits</u>

EBT3:
< 40 Gy

PTB Alanine
dosimetry system:
< 25 Gy

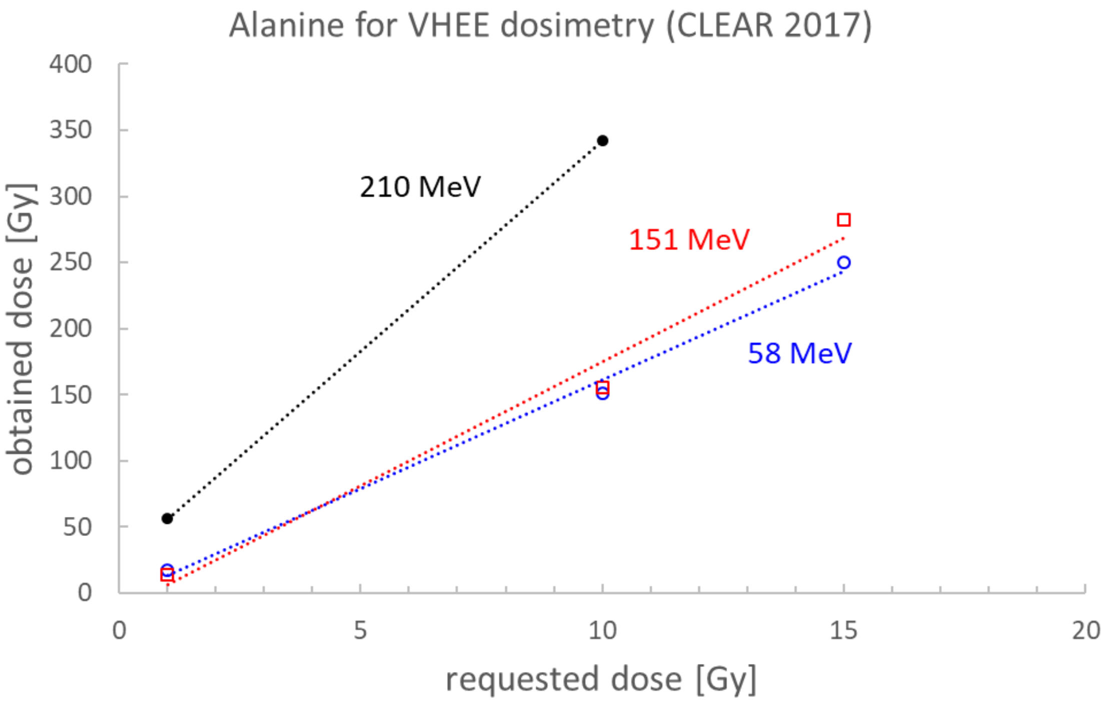
Dosimetric challenges at VHEE

Verification of energy independence of passive dosimeters at VHEE

dose range limits

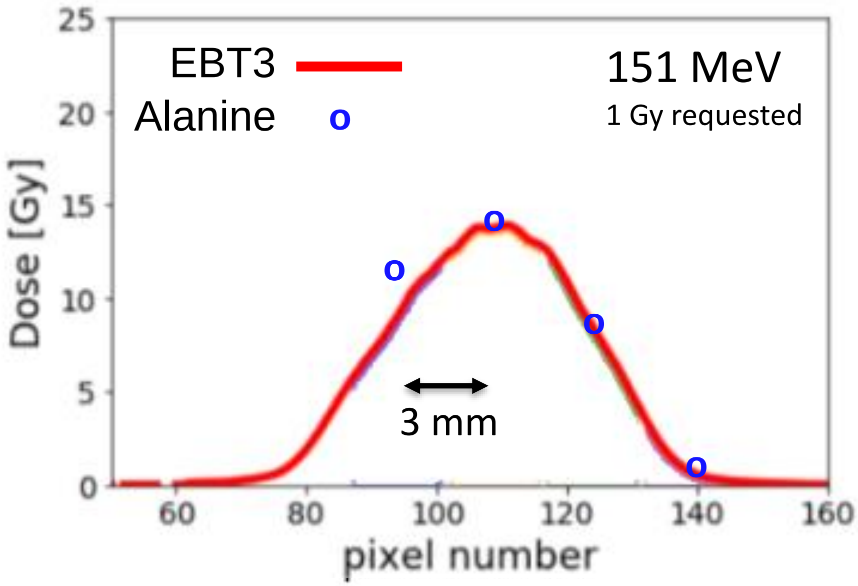
EBT3:
< 40 Gy

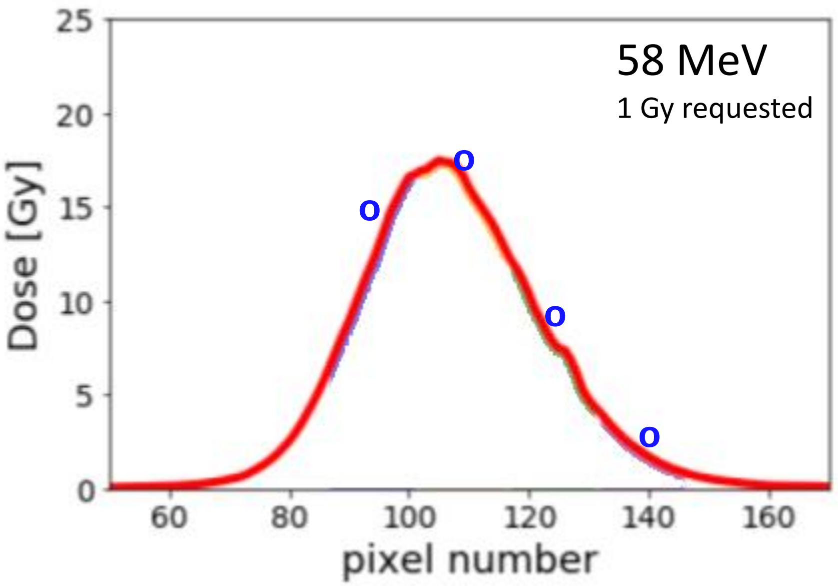
PTB Alanine
dosimetry system:
< 25 Gy



Dosimetric challenges at VHEE

Verification of energy independence of passive dosimeters at VHEE





Karolina Kokurewicz, Investigation of focused Very High Energy Electrons (VHEEs) as a new radiotherapy method, PhD thesis (2020)

EMPIR project „UHDpulse“

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

Type: Joint Research Project

Duration: 2019-2023

Start: 1. Sept. 2019

Funding: 2.1 M €

Coordinator: Andreas Schüller (PTB)

Topic: Tools for traceable dose measurements for:

- **FLASH radiotherapy**
- **VHEE radiotherapy**
- **Laser driven accelerators**

http://uhdpulse-empir.eu/

UHDpulse

EMPIR EURAMET

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

The European Metrology Programme for Innovation and Research (EMPIR):

- metrology-focused programme of coordinated R&D
- enables European metrology institutes, industrial and medical organisations, and academia to collaborate

UHDpulse

UHDpulse Partners and Collaborators

Metrology Institutes

PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

Central Office of Measures

NPL National Physical Laboratory

CMI Czech Metrology Institute

METAS

NRC·CNRC Canadä

6 Metrology institutes
3 Hospitals
5 Universities
5 Research institutes
6 Companies
+ Proton therapy network

Irradiation facility provider

CHUV Centre hospitalier universitaire vaudois

Queen's University Belfast

institut Curie

HZDR Helmholtz Zentrum Dresden Rossendorf

eli beamlines

InspireProject

ujf Nuclear Physics Institute of the CAS public research institution

MedAustron

SIT

Radiation detector developer

ADVACAM Imaging the Unseen

Carl von Ossietzky Universität Oldenburg

CSIC CNM

Sun Nuclear corporation

USC Universidade de Santiago de Compostela

varian

Politecnico Milano 1863

lpc caen laboratoire de physique corpusculaire

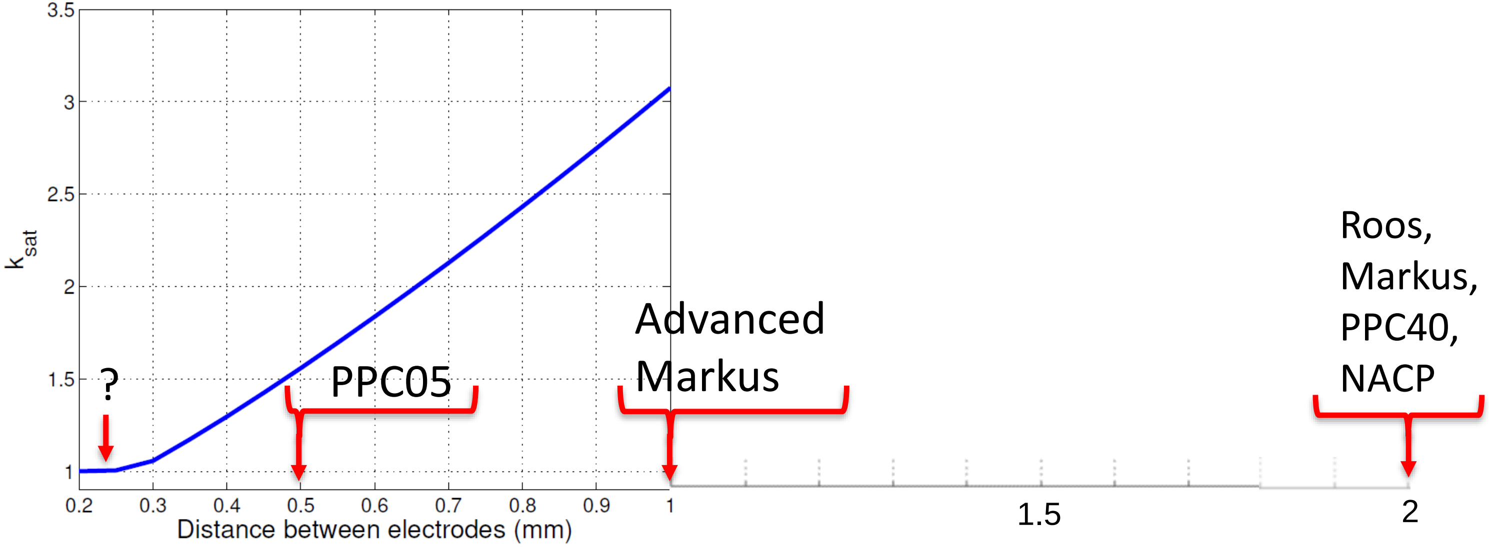
PTW The Dosimetry Company

iba Dosimetry Protect, Enhance and Save Lives

Université Laval

Possible solutions for VHEE and FLASH dosimetry

New designed ionization chamber with smaller gap

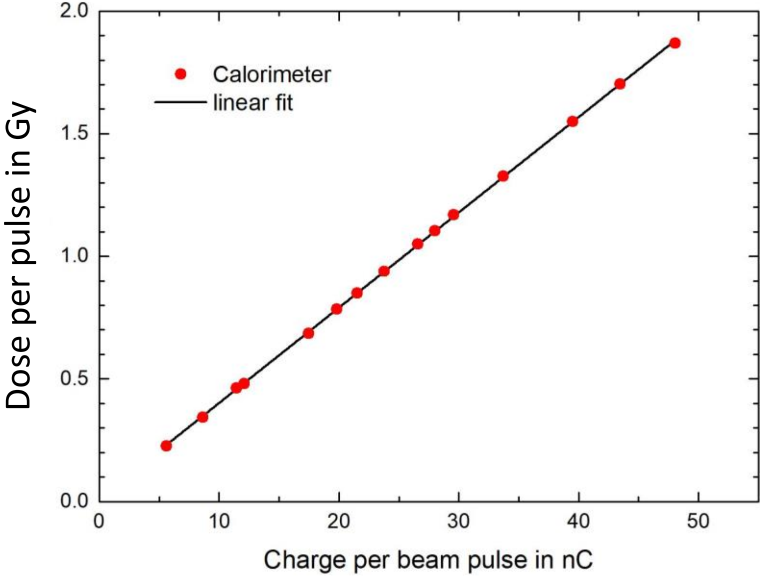


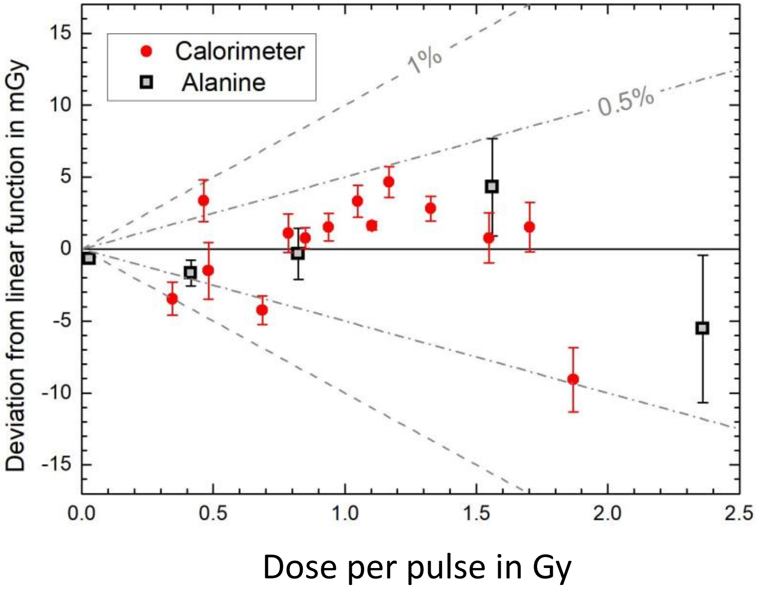
Simulated ion recombination correction factor for a plane parallel ionization chamber at 300 V for 5 Gy/pulse

A. Schüller, ..., Faustino Gomez *et al.,* The European Joint Research Project UHDpulse, Physica Medica (2020, accepted)

Possible solutions for VHEE and FLASH dosimetry

Al-calorimeter





A. Bourgouin, A. Schüller *et al.,* Calorimeter for real-time dosimetry of pulsed ultra-high dose rate electron beams, Frontiers in Physics (2020, accepted)
https://doi.org/10.3389/fphy.2020.567340

Possible solutions for VHEE and FLASH dosimetry

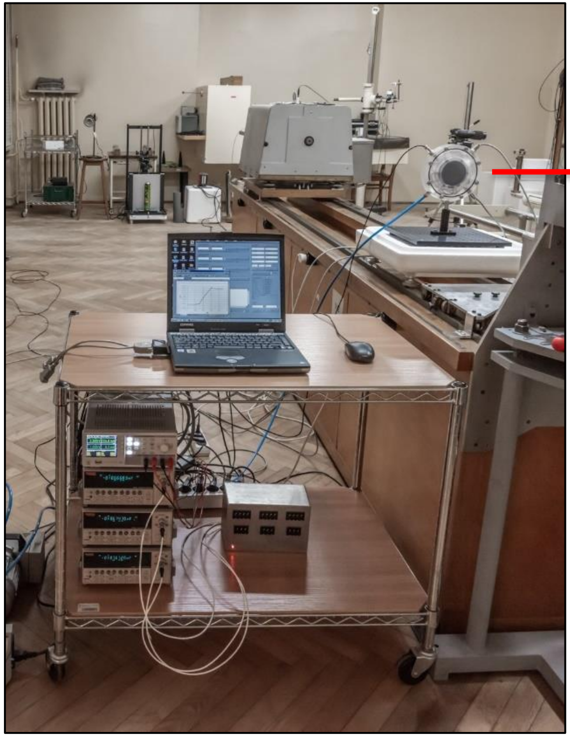
Portable graphite calorimeter

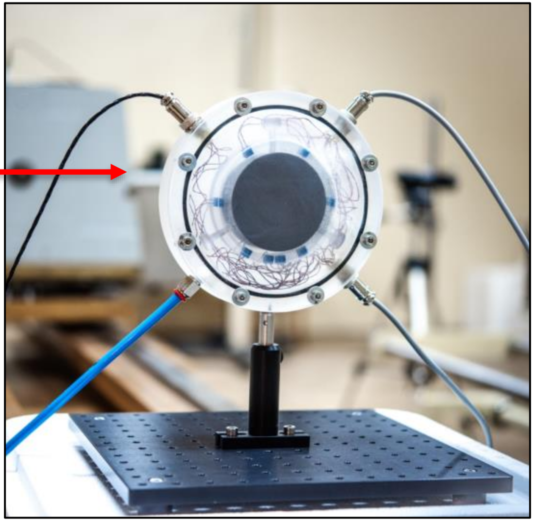
UHDpulse

Central Office of Measures

NPL National Physical Laboratory

PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin



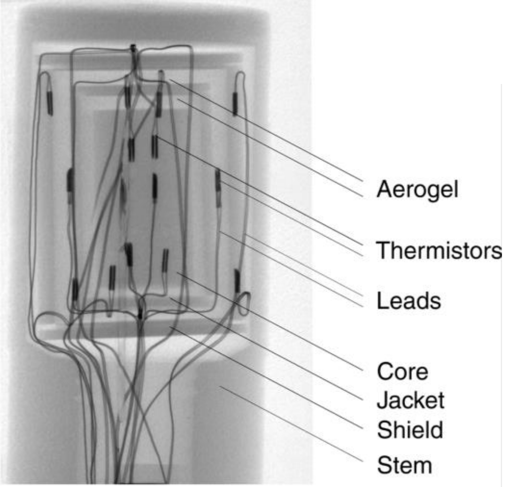


A. Schüller, ..., Adrian Knyziak *et al.*, The European Joint Research Project UHDpulse, Physica Medica (2020, accepted)

Possible solutions for VHEE and FLASH dosimetry

Graphite probe calorimeter “Aerrow”

A prototype without its waterproof housing, next to a SNC 600c Farmer chamber



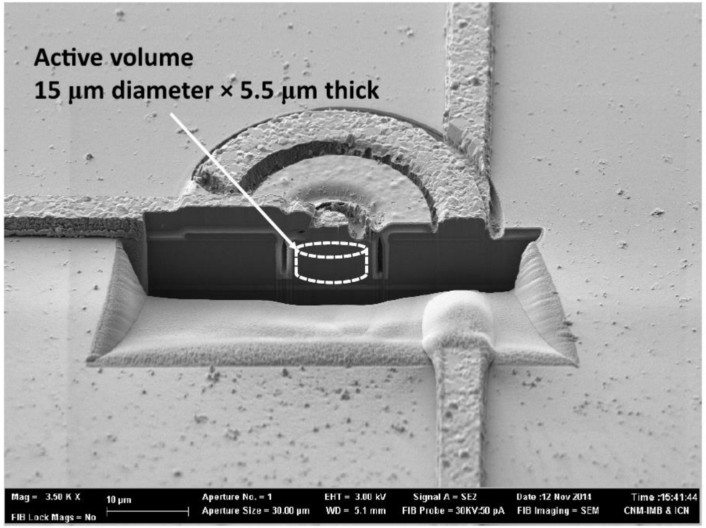
micro-CT scan of the prototype calorimeter

A. Schüller, ..., A. Schönfeld *et al.*, The European Joint Research Project UHDpulse, Physica Medica (2020, accepted)

J. Renaud *et al.*, Med. Phys. 45 (2018) 414
https://doi.org/10.1002/mp.12669

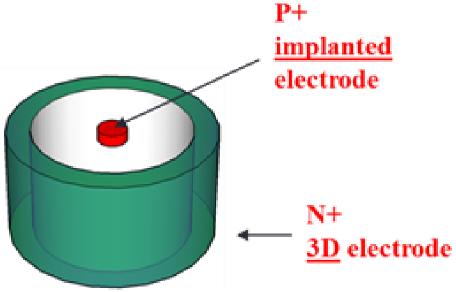
Possible solutions for VHEE and FLASH dosimetry

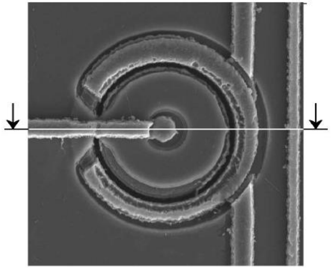
Si-microdosimeter



SEM image of a section of the Si-microdosimeter.

A. Schüller, ..., Celeste Fleta et al., The European Joint Research Project UHDpulse, Physica Medica (2020, accepted)





J. Prieto-Pena *et al.*,
Phys. Med. Biol. 65 (2020) 175004
https://doi.org/10.1088/1361-6560/ab87fa

Possible solutions for VHEE and FLASH dosimetry

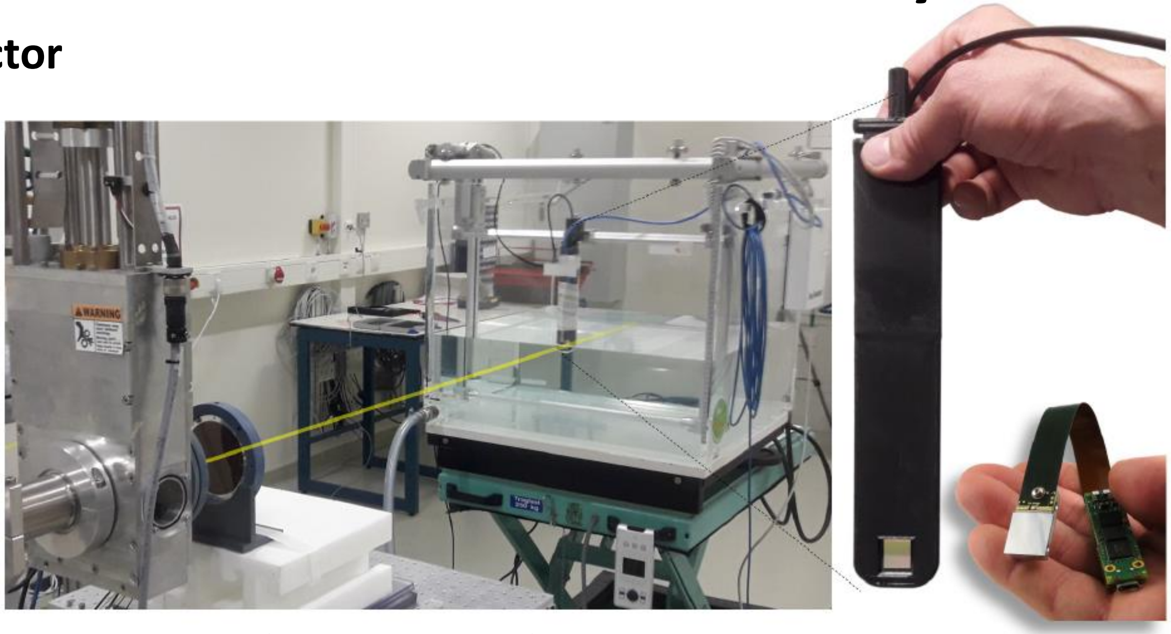
Utilization of Timepix3 detector

UHDpulse

ADVACAM
Imaging the Unseen

CZECH METROLOGY INSTITUTE

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF



MiniPIX TPX3 Flex in a water phantom in an ultra-high dose rate proton beam

A. Schüller, ..., Jan Jakubek *et al.,* The European Joint Research Project UHDpulse, Physica Medica (2020, accepted)

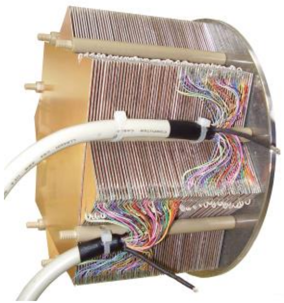
Possible solutions for VHEE and FLASH dosimetry

Multi-Leaf Faraday Cup for determination of energy + pulse charge

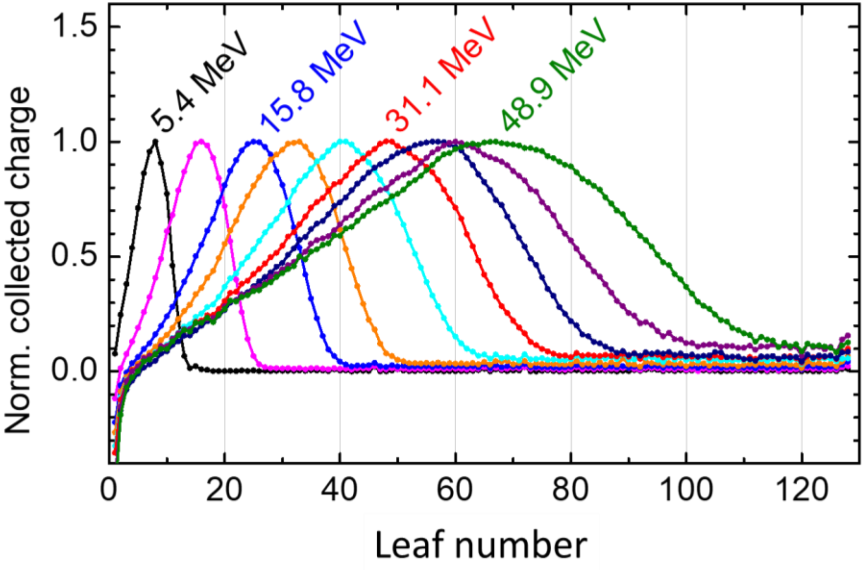
UHDpulse

PTB
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

MedAustron



128 Al leaves



C. Makowski, A. Schüller, Development and Calibration of a Multi-Leaf Faraday Cup for the Determination of the Beam Energy of a 50 MeV Electron LINAC in Real-Time
https://doi.org/10.18429/JACoW-IBIC2019-MOPP004

UHDpulse

http://uhdpulse-empir.eu/

Interested institutes that want to contribute to the goals of the project may join as collaborator.

contact:
andreas.schueller@ptb.de

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.