Reference dosimetry in PBS proton beams

Séverine Rossomme[1] and Carles Gomà[2,3]

[1] Université catholique de Louvain, Belgium
[2] KU Leuven, Belgium
[3] University Hospitals Leuven, Belgium

severine.rossomme@uclouvain.be
carles.goma@kuleuven.be

Outline

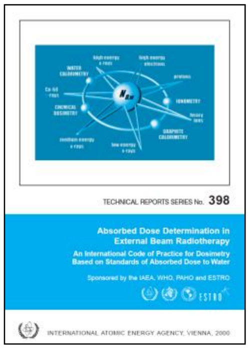
PART 1:

- State-of-the-art
  - International dosimetry protocols
  - Reference dosimetry in PBS beams
- Beam quality correction factors (Monte Carlo calculation)

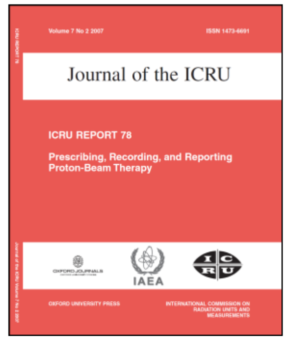
PART 2:

- Calorimetry
- Ion recombination

International Codes of Practice

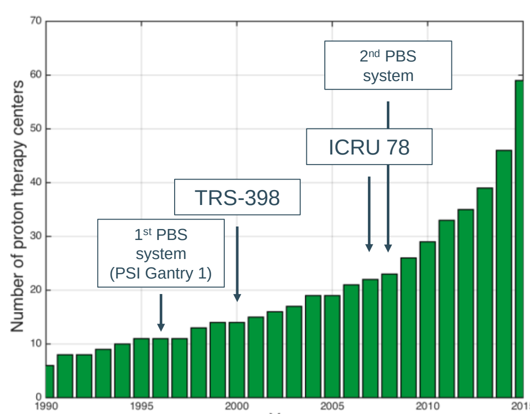


Published in 2000



Published in 2007

Historical perspective



Source: www.ptcog.ch (April 2015)

IAEA TRS-398 reference conditions

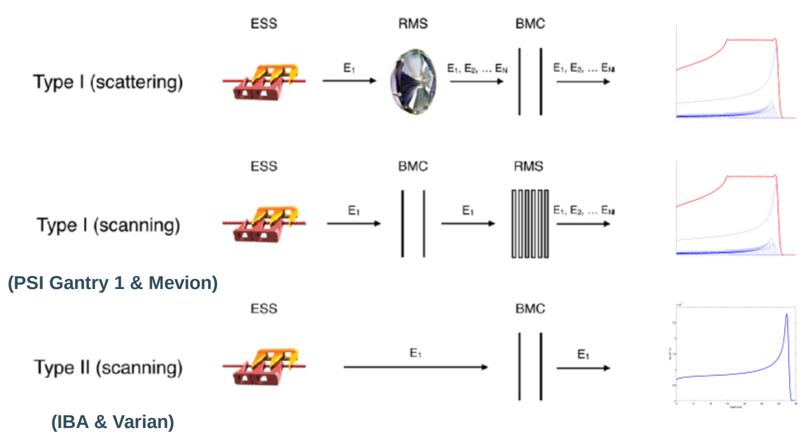
TABLE 30. REFERENCE CONDITIONS FOR THE DETERMINATION OF ABSORBED DOSE IN PROTON BEAMS

Influence quantity	Reference value or reference characteristics
Phantom material	Water
Chamber type	For $R_{res} \geq 0.5$ g/cm², cylindrical and plane parallel For $R_{res} < 0.5$ g/cm², plane parallel
Measurement depth z_{ref}	Middle of the SOBP[a]
Reference point of the chamber	For plane-parallel chambers, on the inner surface of the window at its centre For cylindrical chambers, on the central axis at the centre of the cavity volume
Position of the reference point of the chamber	For plane-parallel and cylindrical chambers, at the point of measurement depth z_{ref}
SSD	Clinical treatment distance
Field size at the phantom surface	10 cm × 10 cm, or that used for normalization of the output factors whichever is larger. For small field applications (i.e. eye treatments), 10 cm × 10 cm or the largest field clinically available

[a] The reference depth can be chosen in the 'plateau region', at a depth of 3 g/cm², for clinical applications with a monoenergetic proton beam (e.g. for plateau irradiations).

Department of Oncology, Laboratory of Experimental Radiotherapy
KU LEUVEN

How to deliver a SOBP?



Gomà et al PMB 2016 **61** 6594

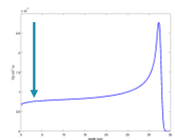
Department of Oncology, Laboratory of Experimental Radiotherapy
KU LEUVEN

IAEA TRS-398 reference conditions

TABLE 30. REFERENCE CONDITIONS FOR THE DETERMINATION OF ABSORBED DOSE IN PROTON BEAMS

Influence quantity	Reference value or reference characteristics
Phantom material	Water
Chamber type	For $R_{res} \geq 0.5$ g/cm², cylindrical and plane parallel For $R_{res} < 0.5$ g/cm², plane parallel
Measurement depth z_{ref}	Middle of the SOBP[a]
Reference point of the chamber	For plane-parallel chambers, on the inner surface of the window at its centre For cylindrical chambers, on the central axis at the centre of the cavity volume
Position of the reference point of the chamber	For plane-parallel and cylindrical chambers, at the point of measurement depth z_{ref}
SSD	Clinical treatment distance
Field size at the phantom surface	10 cm × 10 cm, or that used for normalization of the output factors whichever is larger. For small field applications (i.e. eye treatments), 10 cm × 10 cm or the largest field clinically available

[a] The reference depth can be chosen in the 'plateau region', at a depth of 3 g/cm², for clinical applications with a monoenergetic proton beam (e.g. for plateau irradiations).



7

Department of Oncology, Laboratory of Experimental Radiotherapy

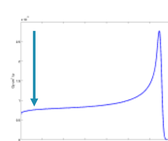
KU LEUVEN

IAEA TRS-398 reference conditions

TABLE 30. REFERENCE CONDITIONS FOR THE DETERMINATION OF ABSORBED DOSE IN PROTON BEAMS

Influence quantity	Reference value or reference characteristics
Phantom material	Water
Chamber type	For $R_{res} \geq 0.5$ g/cm², cylindrical and plane parallel For $R_{res} < 0.5$ g/cm², plane parallel
Measurement depth z_{ref}	Middle of the SOBP[a]
Reference point of the chamber	For plane-parallel chambers, on the inner surface of the window at its centre For cylindrical chambers, on the central axis at the centre of the cavity volume
Position of the reference point of the chamber	For plane-parallel and cylindrical chambers, at the point of measurement depth z_{ref}
SSD	Clinical treatment distance
Field size at the phantom surface	10 cm × 10 cm, or that used for normalization of the output factors whichever is larger. For small field applications (i.e. eye treatments), 10 cm × 10 cm or the largest field clinically available

[a] The reference depth can be chosen in the 'plateau region', at a depth of 3 g/cm², for clinical applications with a monoenergetic proton beam (e.g. for plateau irradiations).

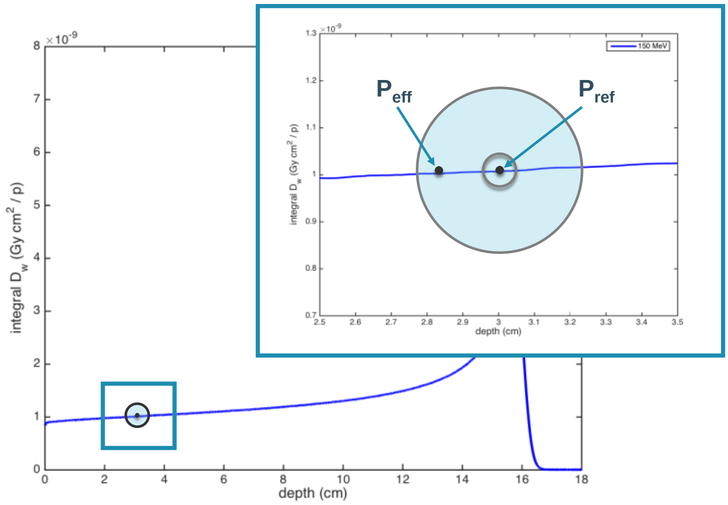


8

Department of Oncology, Laboratory of Experimental Radiotherapy

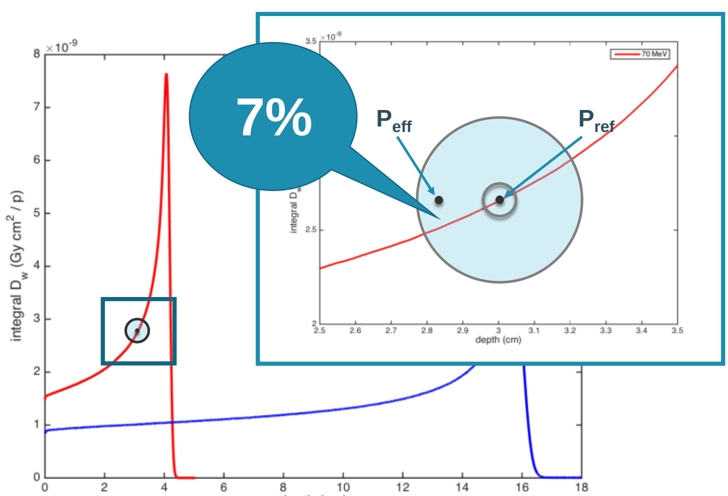
KU LEUVEN

Cylindrical chambers



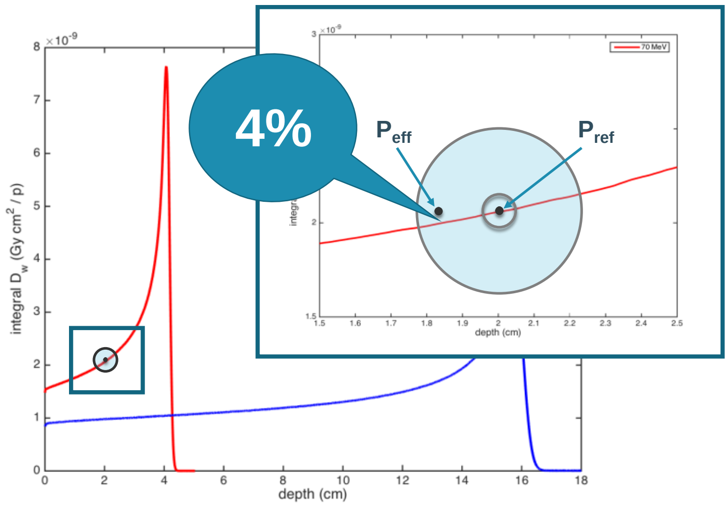
Department of Oncology, Laboratory of Experimental Radiotherapy
KU LEUVEN

Cylindrical chambers

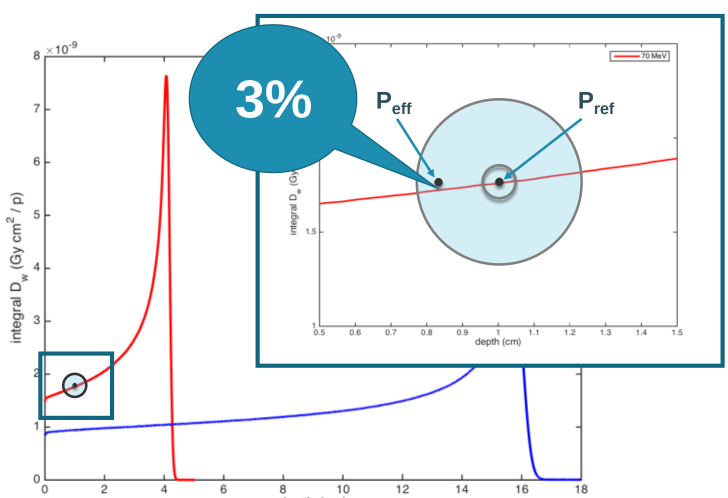


Department of Oncology, Laboratory of Experimental Radiotherapy
KU LEUVEN

Cylindrical chambers



Cylindrical chambers



Can we use TRS-398?

TABLE 30. REFERENCE CONDITIONS FOR THE DETERMINATION OF ABSORBED DOSE IN PROTON BEAMS

Influence quantity	Reference value or reference characteristics	Type I	Type II
Phantom material	Water	✓	✓
Chamber type	For $R_{res} \geq 0.5$ g/cm², [illegible] plane parallel For $R_{res} < 0.5$ g/cm², plane parallel	✓ ✓	
Measurement depth z_{ref}	[illegible]	✓	
Reference point of the chamber	For plane-parallel chambers, on the inner surface of the window at its centre [illegible]	✓	✓
Position of the reference point of the chamber	For plane-parallel [illegible], at the point of measurement depth z_{ref}	✓	
SSD	Clinical treatment distance	✓	✓
Field size at the phantom surface	10 cm × 10 cm, or that used for normalization of the output factors whichever is larger. For small field applications (i.e. eye treatments), 10 cm × 10 cm or the largest field clinically available	✓	✓

[a] The reference depth can be chosen in the 'plateau region' [illegible] for clinical applications with a monoenergetic proton beam (e.g. for plateau irradiations). ←

minimize dose gradient

Department of Oncology, Laboratory of Experimental Radiotherapy

KU LEUVEN

Dose determination

$$D_{w,Q} = M_Q N_{D,w,Q_0} k_{Q,Q_0}$$

$$M_Q = M'_Q k_{TP} k_h k_{elec} k_{pol} k_s$$

Department of Oncology, Laboratory of Experimental Radiotherapy

KU LEUVEN

Beam quality correction factors

Monte Carlo calculated

Literature review

Mono-energetic beams

IOP Publishing | Institute of Physics and Engineering in Medicine — Physics in Medicine & Biology

Phys. Med. Biol. 61 (2016) 2389–2406 — doi:10.1088/0031-9155/61/6/2389

Monte Carlo calculation of beam quality correction factors in proton beams using detailed simulation of ionization chambers

Carles Gomà[1], Pedro Andreo[2] and Josep Sempau[3]

[1] Department of Physics, Swiss Federal Institute of Technology Zurich, Zurich, Switzerland
[2] Department of Medical Physics, Karolinska University Hospital, Stockholm, Sweden
[3] Institut de Tècniques Energètiques, Universitat Politècnica de Catalunya, Barcelona, Spain

Gomà et al PMB 2016 **61** 2389

SOBP

Consistency in quality correction factors for ionization chamber dosimetry in scanned proton beam therapy

Jefferson Sorriaux[a)]
Center of Molecular Imaging, Radiotherapy and Oncology, Institut de Recherche Expérimentale et Clinique, Université catholique de Louvain, Avenue Hippocrate 54, 1200 Brussels, Belgium
ICTEAM Institute, Université catholique de Louvain, Chemin du Cyclotron 6, 1348 Louvain-la-Neuve, Belgium

Mauro Testa
Department of Radiation Convergence Engineering, Yonsei University, Wonju 220-710, Korea

Harald Paganetti
Department of Radiation Oncology, Massachusetts General Hospital Harvard Medical School, Boston, MA 02114, USA

Damien Bertrand
Ion Beam Applications S.A, Chemin du Cyclotron 3, 1348 Louvain-la-Neuve, Belgium

John Aldo Lee
Center of Molecular Imaging, Radiotherapy and Oncology, Institut de Recherche Expérimentale et Clinique, Université catholique de Louvain, Avenue Hippocrate 54, 1200 Brussels, Belgium
ICTEAM Institute, Université catholique de Louvain, Chemin du Cyclotron 6, 1348 Louvain-la-Neuve, Belgium

Hugo Palmans
Medical Physics Department, EBG MedAustron GmbH, Wiener Neustadt A-2700, Austria
Acoustics and Ionising Radiation Division, National Physical Laboratory, Teddington TW11 0LW, UK

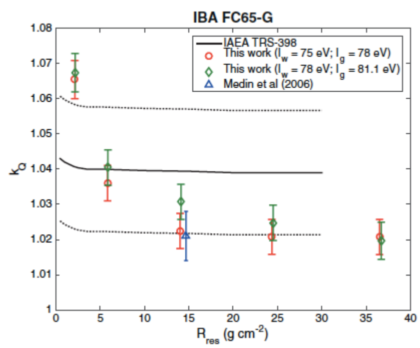
Stefaan Vynckier
Département de Radiothérapie, Cliniques Universitaires Saint-Luc, Avenue Hippocrate 54, 1200 Brussels, Belgium

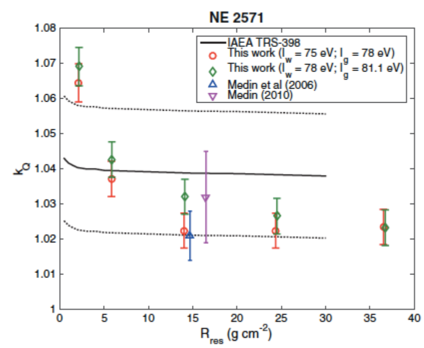
Edmond Sterpin
Center of Molecular Imaging, Radiotherapy and Oncology, Institut de Recherche Expérimentale et Clinique, Université catholique de Louvain, Avenue Hippocrate 54, 1200 Brussels, Belgium
Department of Oncology, Laboratory of Experimental Radiotherapy, Katholieke Universiteit Leuven, O&N Herestraat 49 – box 818, 3000 Leuven, Belgium

Sorriaux et al *Med Phys* 2017 **44** 4919

MC-calculated k_Q factors

Cylindrical chambers





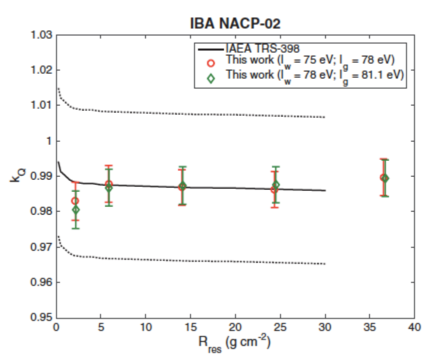
Gomà et al PMB 2016 **61** 2389

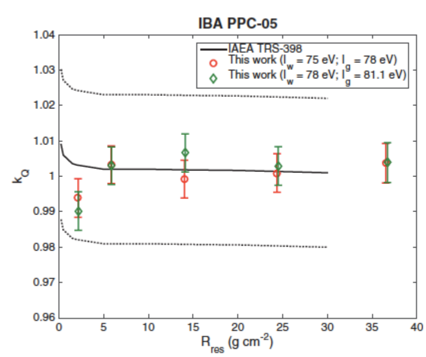
Department of Oncology, Laboratory of Experimental Radiotherapy

KU LEUVEN

MC-calculated k_Q factors

Plane-parallel chambers





Gomà et al PMB 2016 **61** 2389

Department of Oncology, Laboratory of Experimental Radiotherapy

KU LEUVEN

RTNORM

RTNORM

RADIOTHERAPY NORMATIVE

EMPIR EURAMET

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

www.rtnorm.eu

Department of Oncology, Laboratory of Experimental Radiotherapy

KU LEUVEN

Reference dosimetry in PBS proton beams

Part 2 : calorimetry/ionometry

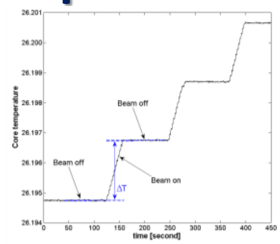
miro

Calorimetry: principle

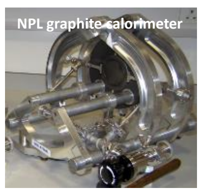
A **calorimeter** determines **the absorbed dose** from its definition

$$D_m = c_{p,m}\,\Delta T\,k$$

$c_{p,m}$: specific heat capacity
k: corrections
ΔT : temperature rise



Graphite calorimeter or water calorimeter ?



	$c_{p,m}$ [J/K kg]	$\Delta T/D_m$			
water	4180	0.24 mK sensitivity	1.44 . 10^{-7}	0.96-1.02 heat defect	Dose-to-water
graphite	710	1.41 mK	0.80 . 10^{-7}	1.000	Dose-to-graphite conversion

Water or Graphite calorimetry

Graphite calorimetry: dose conversion

$$D_w = D_g\ s_{w,g}\ k_{fl}$$

- $s_{w,g}$: water-to-graphite stopping power ratio
- k_{fl} : fluence correction factor (nuclear interaction cross sections)

Palmans et al., PMB (2013) 58(10): 3481 *Rossomme et al., PMB (2013) 58(16): 5363*

Water calorimetry: chemical heat defect

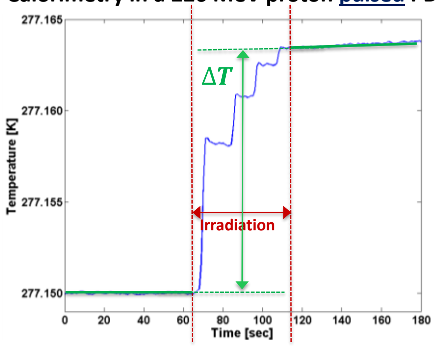
- cause: chemical reactions induced by ionizing radiation
- consequence: loss/gain of temperature
- solution: pure water saturated

heat transfers

- cause: conduction and convection
- consequence: loss/gain of temperature
- solution:
  - Convection: temperature of calorimeter ~ **4 °C** (the volumetric expansion coefficient of water is zero)
  - Conduction: numerical simulations

Direct comparison between our water calorimeter and ionisation chambers

Calorimetry in a 226 MeV proton pulsed PBS



First IBA Proteus®ONE (S2C2) at Centre Antoine Lacassagne, in Nice (France)

Accelerator: IBA superconducting synchrocyclotron

- Pulse frequency of the accelerator = 1 kHz
- Typical pulse length ~ 4-6 μsec

Beam characterisations

- 10 x 10 cm² mono-energetic beams (mono-layer)
- Clinical dose rate
- Depth of measurement: 3.1 g/cm² in water

Calorimetry: take home messages

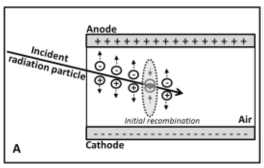
- Positive preliminary results demonstrate the **feasability of water calorimetry in pulsed PBS proton beams**.
- Due to the gradient of the depth-dose distribution, a depth inferior to 3.1 cm would be more suitable for the lowest energy to minimise the uncertainty in positioning.
- **Ionometry** has to be carried out with care, in particular the determination of **ion recombination correction factors**

Ionometry - recombination

$$D_{w,Q_0}^{\text{IC}} = M_{Q_0} N_{D,w,Q_0} k_{Q_0,Q_0}$$

- M_Q: corrected response of the ionization chamber for air temperature and pressure, ion recombination and polarity
- **Ion recombination correction factors**

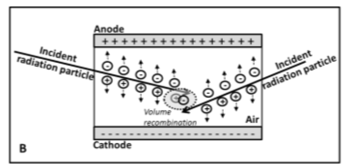
Initial recombination



- ions created in the **same** ionisation track
- independent of the dose rate
- depends on the **ion density** within the track

Jaffé's theory

Volume recombination



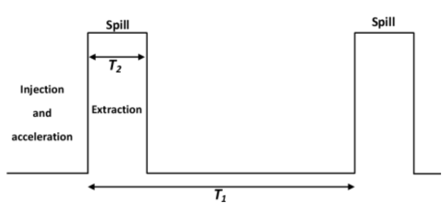
- ions created in **different** ionisation tracks
- depends on the **dose rate**
- Independent of the ion density within the track

Boag's theory

General model for particle beams

$$k_s^{\text{tot}} = k_s^{\text{ini}} \, k_s^{\text{vol}}$$

- **Volume recombination: Boag's models**



Pulsed beams: $T_2 \ll \tau_c \ll T_1$

$$k_s^{\text{vol, pulsed}} = 1 + \frac{\alpha \, I_{sat}}{V}$$

voltage

Continuous beams

$$k_s^{\text{vol, cont}} = 1 + \frac{\beta \, I_{sat}}{V^2}$$

- **Initial recombination: Jaffé's model**

$$k_s^{\text{ini}} = \left(\frac{e^{-1/g}}{g \frac{\bar{q}}{V}} \left(li\left(e^{\frac{1}{g} + \ln\left(1 + \frac{\bar{q}}{V}\right)} \right) - li\left(e^{1/g}\right) \right) \right)^{-1}$$

with $\bar{q} = \frac{2 \, d^2 \, D}{k \, b^2}$ and $g = \frac{\alpha \, N}{8 \, \pi \, D}$ (ion density)

$$k_s^{\text{ini}} \sim \log\left(\frac{1}{V}\right) \sim 1 + \frac{1}{V}$$ *(Taylor development)*

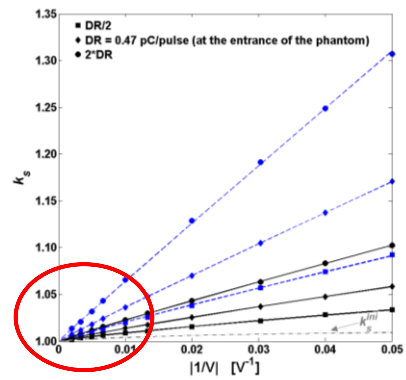
Experimental k_s-values

Plane-parallel ionisation chamber: IBA PPC40

symbols : experimental k_s-values
lines : theoretical k_s-values

96.17 MeV pulsed PBS proton beam

Black: 3.1 cm Blue: peak (~7 cm)

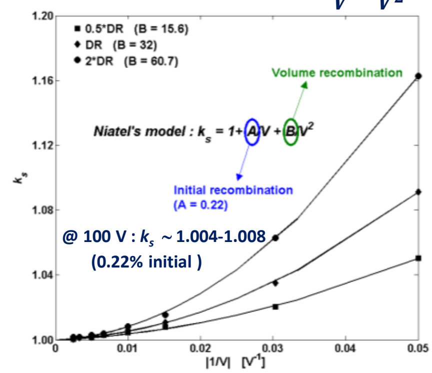


Rossomme et al., PMB (2017) 62:5365

100 MeV PBS proton beam

(depth: plateau)

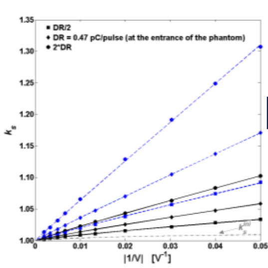
Niatel (1967): $k_s = 1 + \frac{A}{V} + \frac{B}{V^2}$



27

Use of 2V-method in PBS proton beams

Plane-parallel ionisation chamber: IBA PPC40

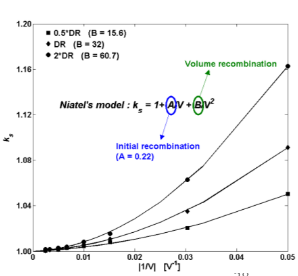


96.17 MeV pulsed PBS proton beam

(plateau)	2V-method (ratio:3)	Boag/Jaffé	Difference
300 V	1.0053/1.0067/1.0094	1.0035/1.0052/1.0081	**0.2%/0.2%/0.1%**
100 V	1.0083/1.0128/1.0214	1.0090/1.0139/1.0227	**0.1%/0.1%/0.1%**

100 MeV PBS proton beam

	2V-method (ratio:3)	Niatel	Difference
300 V	1.0008/1.0006/1.0007	1.0014/1.0011/1.0009	**0.1%/0.1%/0.0%**
100 V	1.0068/1.0036/1.0020	1.0083/1.0054/1.0038	**0.1%/0.2%/0.2%**



28

Recombination: take home messages

For plane-parallel ionisation chambers (IBA PPC40)

- ***k_s* cannot be neglected in scanned proton beams**.
- Excellent agreement between experimental and theoretical values.
- The solution to minimise k_s is to use the chamber at high voltage. However, that brings a risk to observe charge multiplication in the chamber.
- For the chamber tested (PPC40): **300 V can be safely used**.
- Initial recombination contribution $\Rightarrow$ **the two-voltage method as detailed currently in dosimetry protocols has to be used with care**

29

THANK YOU FOR YOUR ATTENTION

severine.rossomme@uclouvain.be
carles.goma@kuleuven.be

miro

30