Absolute and Relative Dosimetry of Proton Beams

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Overview

Absolute dosimetry

- Primary standards: calorimetry, Faraday cup,…
- Reference dosimetry: ionisation chambers

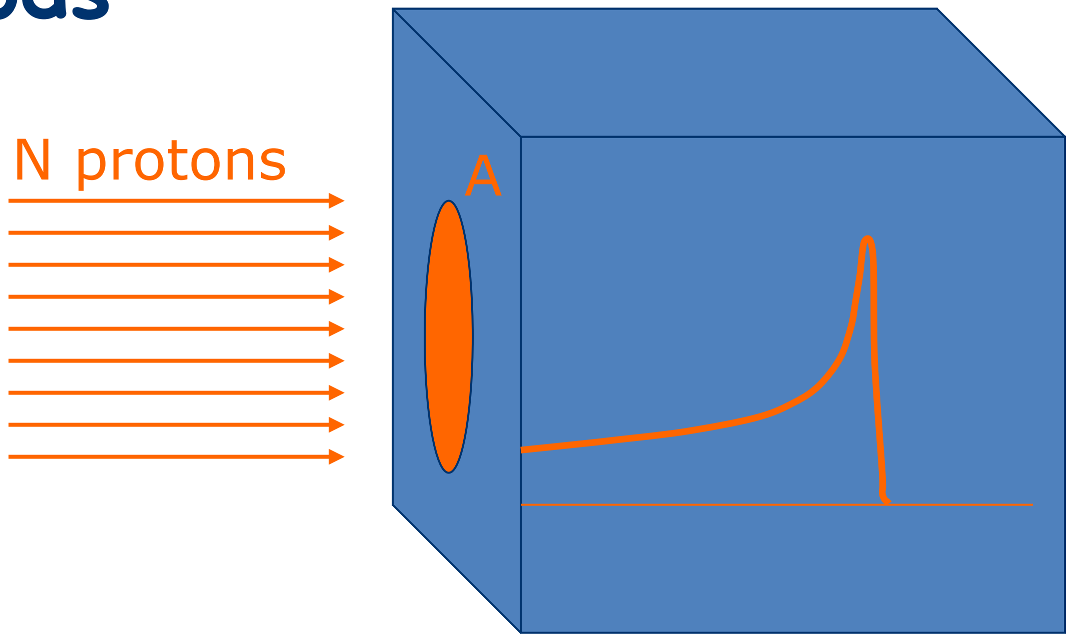
Relative dosimetry

- Depth dose measurements; quenching
- Lateral measurements, position sensitive detection

Examples from literature and NPL

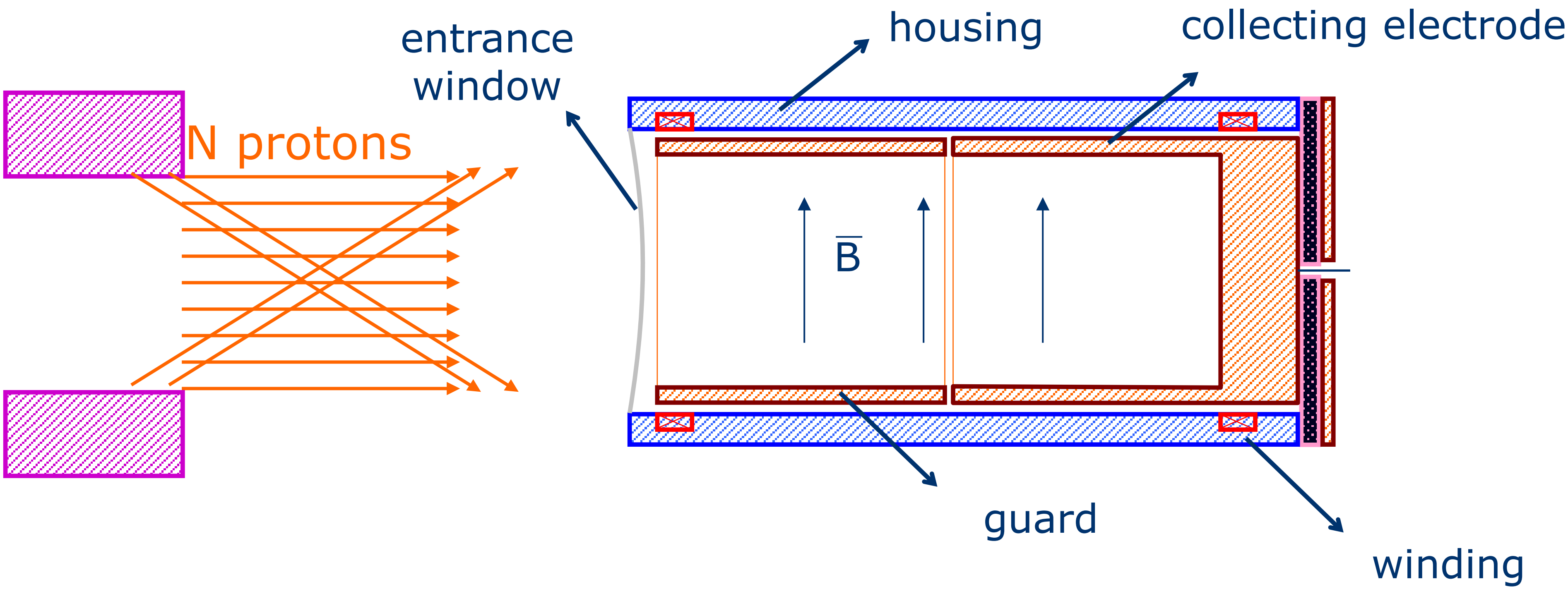
Specific issues scanned beams

Absolute dosimetry – Fluence based methods



$$D_{med} = \boldsymbol{\Phi} \left(\frac{S}{\rho}\right)_{med} \approx \frac{N}{A} \left(\frac{S}{\rho}\right)_{med}$$

Faraday cup – collimator scatter



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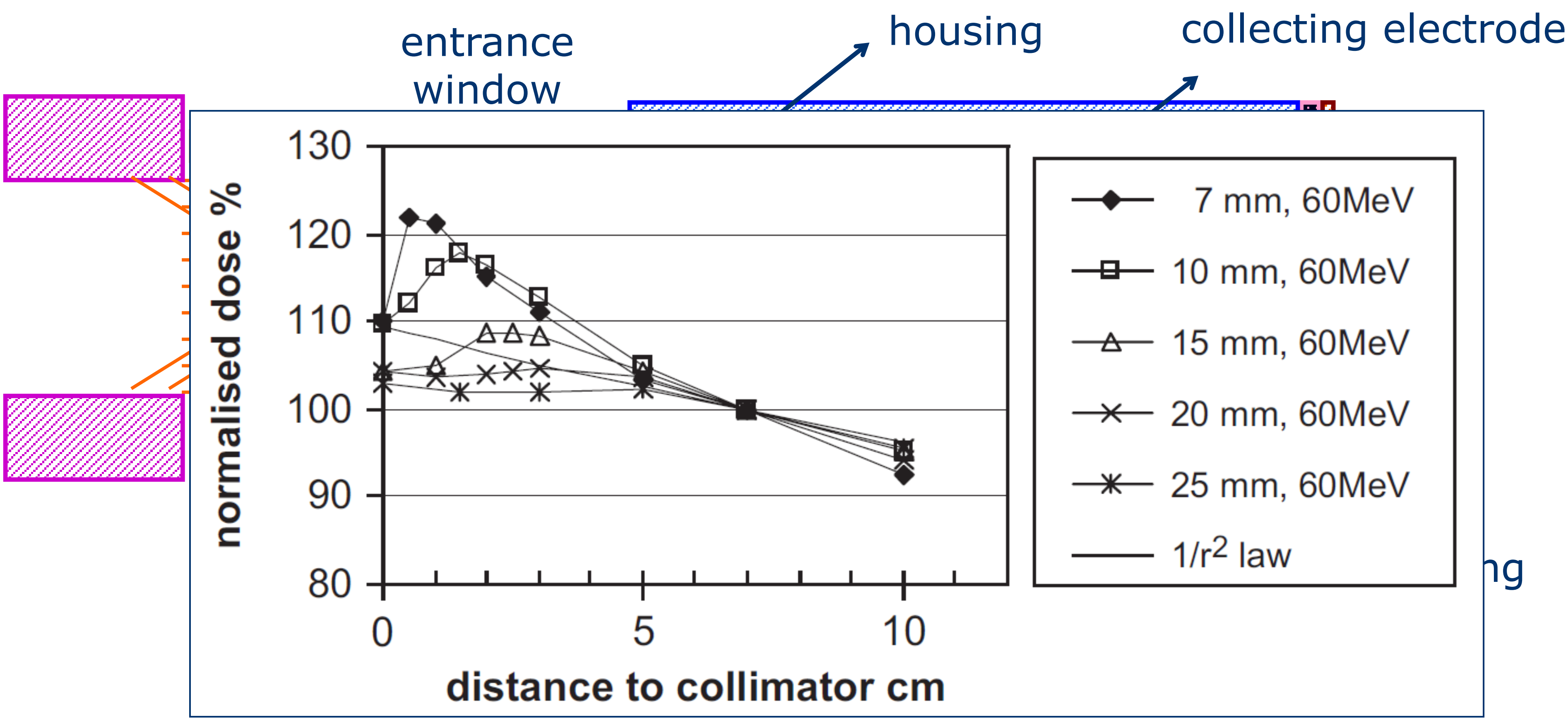
Faraday cup – collimator scatter

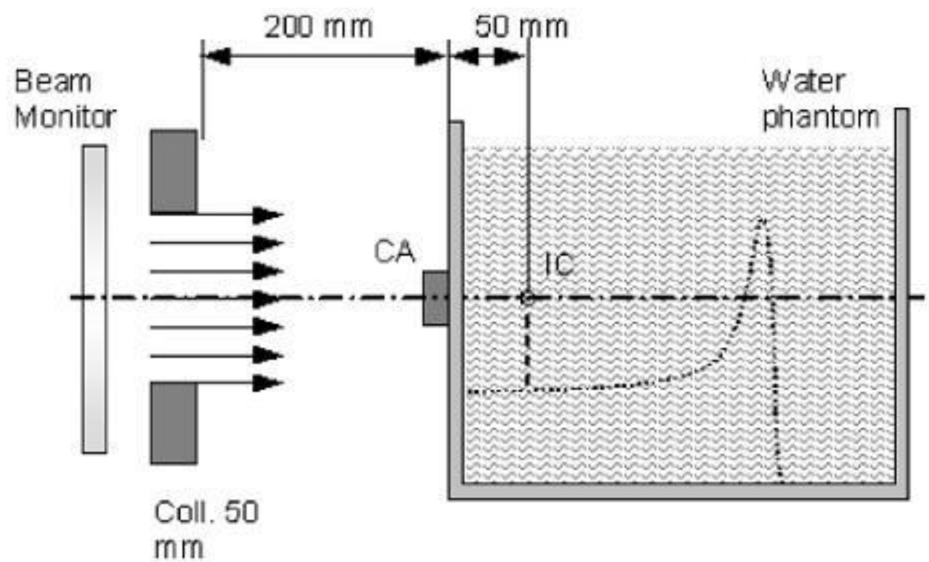


Kacperek (2009) Appl. Rad. Isot. 67:378-86

Absolute dosimetry – Activation measurement

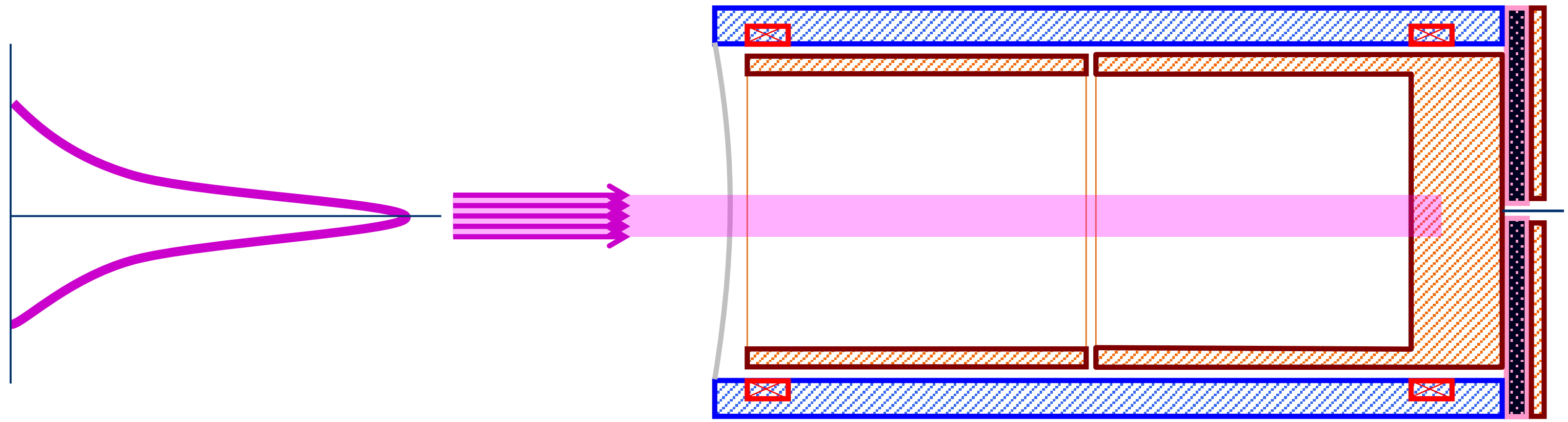
$^{12}C(p,pn)^{11}C$ reaction

4π $\beta\gamma$-coincidence counting



(Nichoporov 2003, Med Phys 30:972-8)

Faraday cup - scanned beams



Large area ion chamber: pdd(z)

Faraday cup: N/MU

S/ρ: DAP(z_{ref})

Integrate lateral dose profiles over all spots

Calorimetry

Absorbed dose = energy imparted per unit of mass

Calorimetry directly determines energy imparted by either

- Comparing with electrical energy dissipation
- Measuring temperature rise

Assumes medium doesn't change its physical or chemical state

Accounts with contributions/absorptions from nuclear reactions

± no particle type dependence

Calorimetry - principle

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

	c (J·kg^{-1}·K^{-1})	$\Delta T/D$ (mK·Gy^{-1})	α (m^2·s^{-1})
water	4180	0.24	1.44×10^{-7}
graphite	710	1.41	0.80×10^{-4}

Calorimetry for proton beams

At least 15 papers in the past 20 years so it's a proven technique

No primary standards

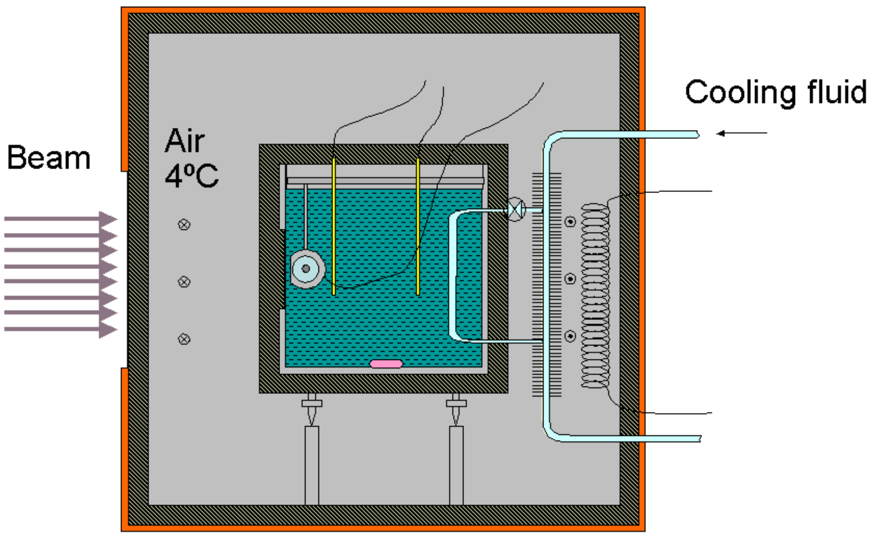
- Lack of interest/demand
- No beams in NMI

Not much in scanned beams

- Relatively new modality
- Calibration methods not established/standardised

Water calorimetry - chemical heat defect

Experiment

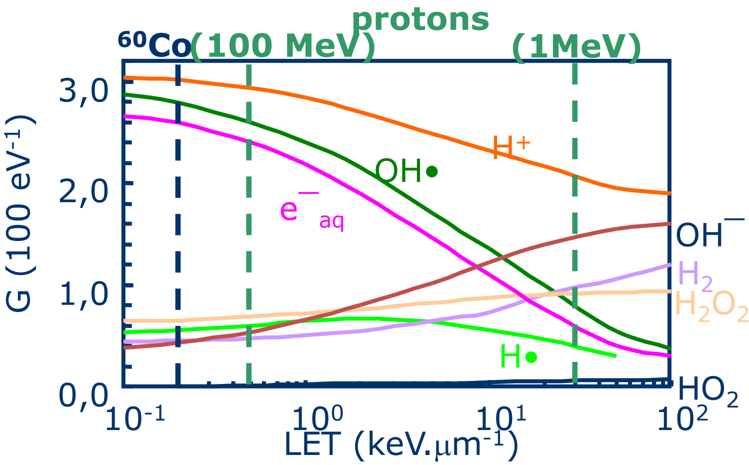


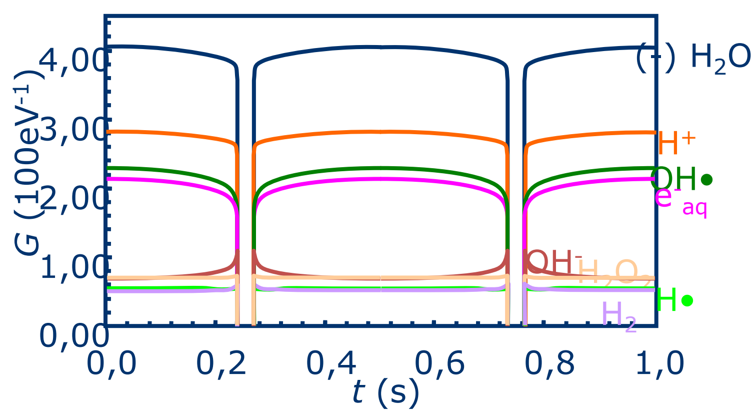
H_2O/Ar

H_2O/H_2

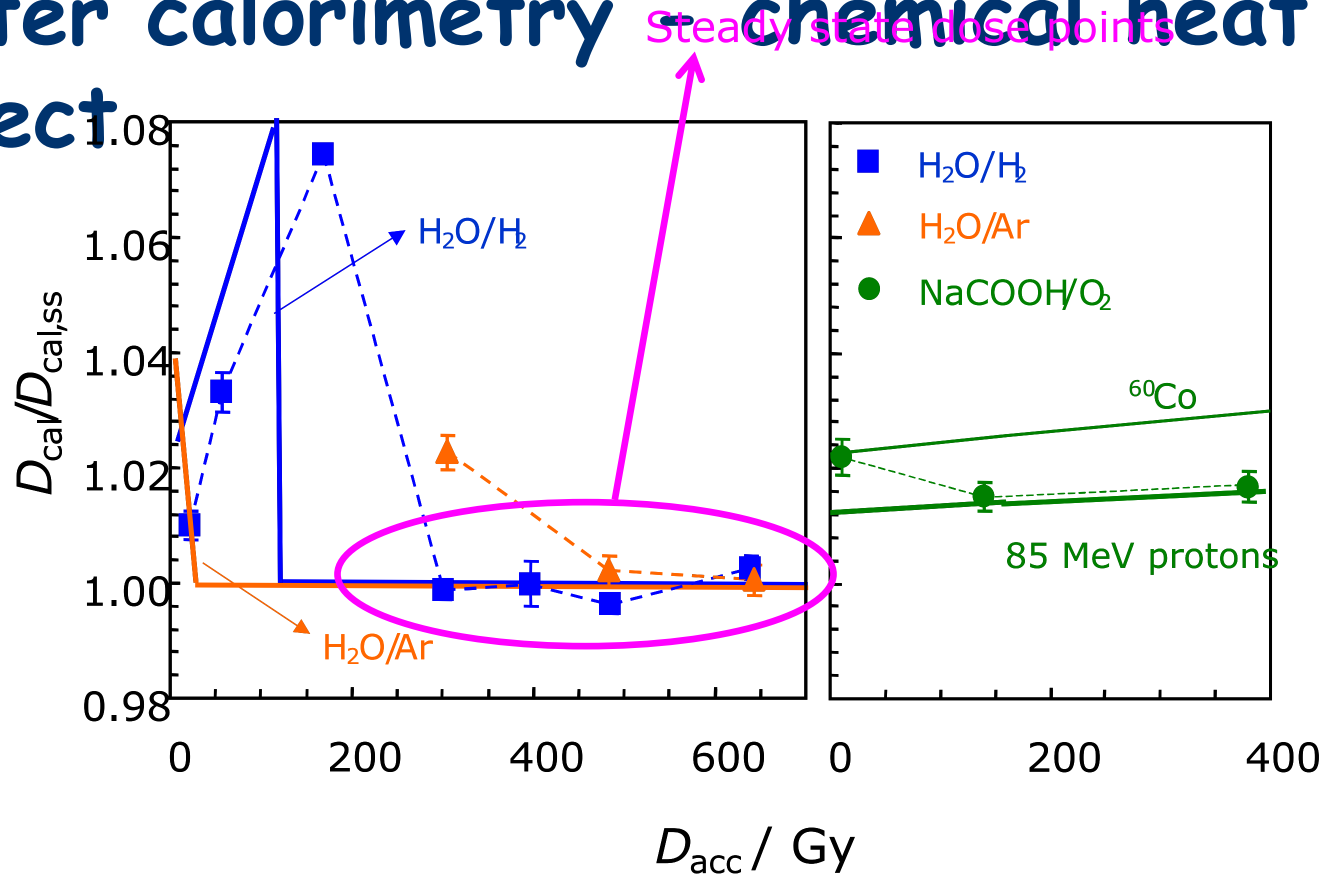
$H_2O+NaCOOH/O_2$

Simulations



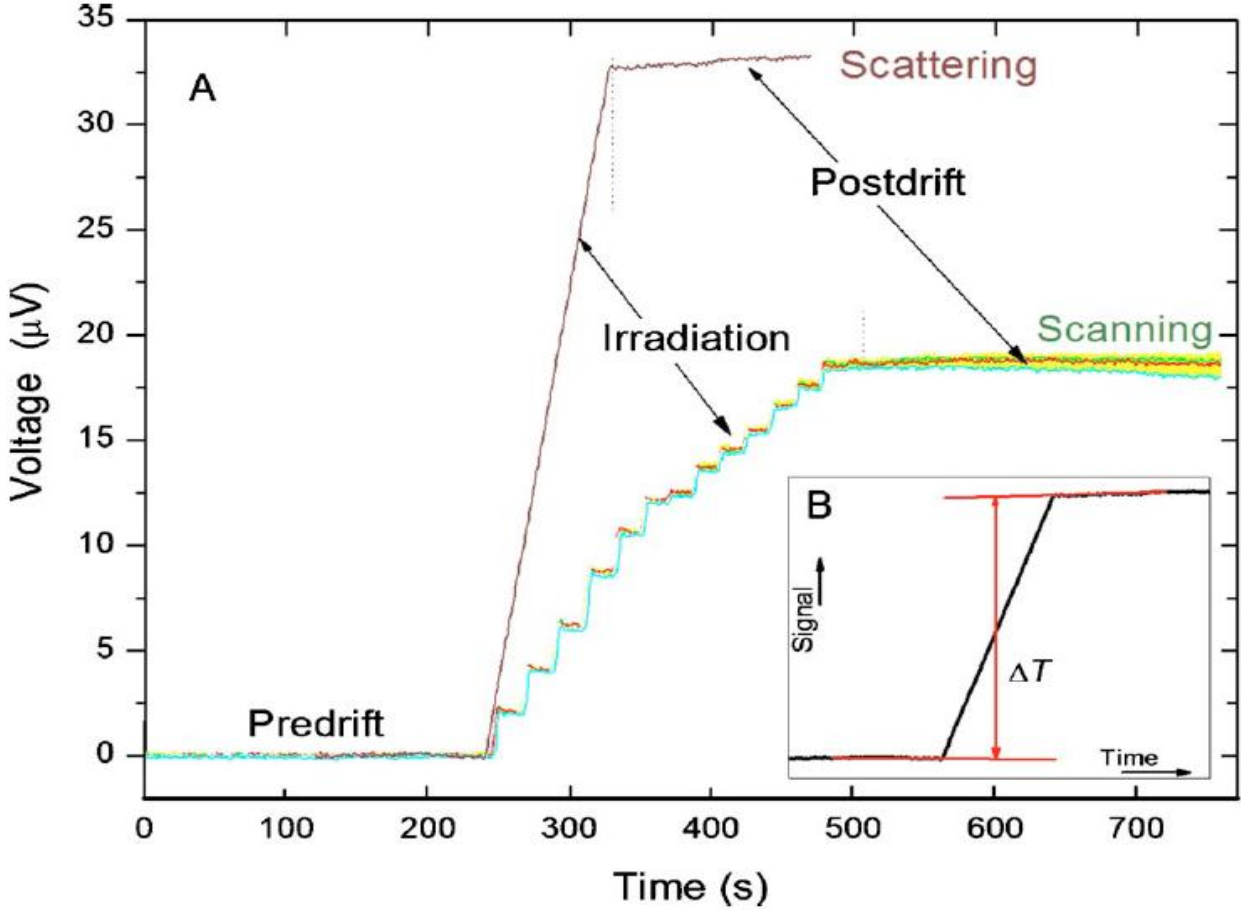


Water calorimetry – chemical heat defect



Palmans et al (1996) Med. Phys. 23:643-50

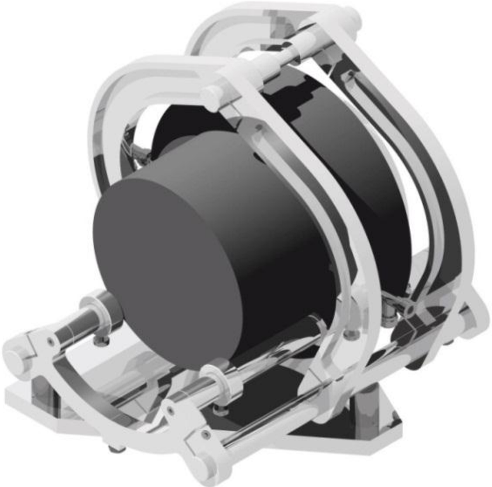
Water calorimetry - heat conduction

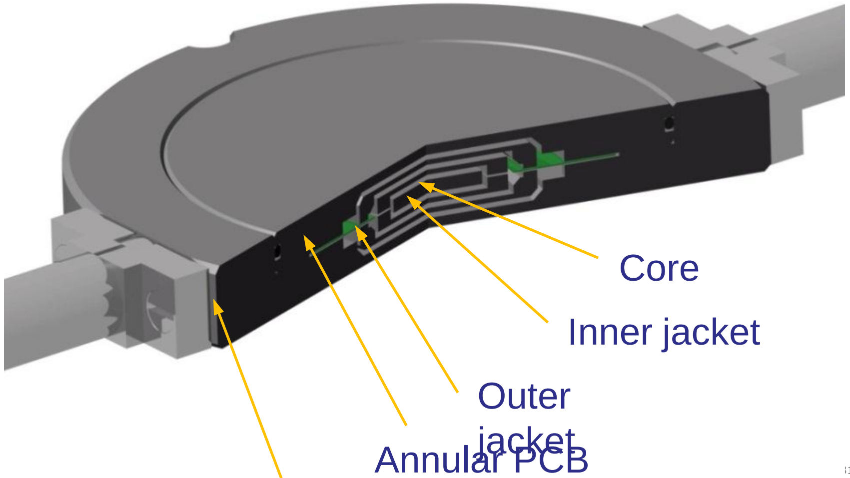


Sarfehnia et al (2010) Med. Phys. 37:3541-50 13

Graphite calorimetry

Palmans et al (2004)
Phys Med Biol 49:3737



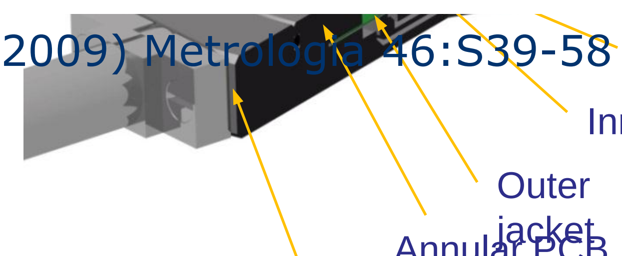


Graphite calorimetry

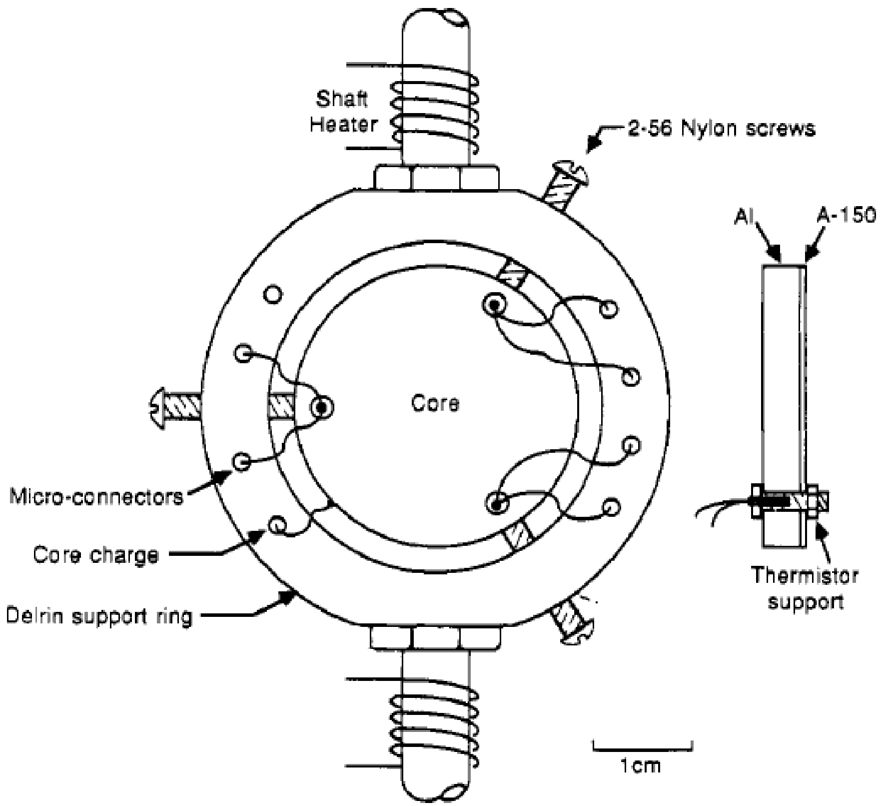
Palmans et al (2004)
Phys Med Biol 49:3737

Operational mode	Measurand	Primary expression	Corrections
Quasi-adiabatic radiation	$\frac{E_{\text{rad}}}{m_{\text{core}}}$	$= c_p \Delta T_{\text{core}}$	$-\frac{\Delta E_{\text{transfer}}}{m_{\text{core}}}$
Quasi-adiabatic electrical	$c_p \Delta T_{\text{core}}$	$= \frac{\Delta E_{\text{elec}}}{m_{\text{core}}}$	$+\frac{\Delta E_{\text{transfer}}}{m_{\text{core}}}$
Isothermal	$\frac{E_{\text{rad}}}{m_{\text{core}}}$	$= -\frac{\Delta E_{\text{elec}}}{m_{\text{core}}}$	$+c_p \Delta T_{\text{core}} - \frac{\Delta E_{\text{transfer}}}{m_{\text{core}}}$

Seuntjens and Duane (2009) Metrologia 46:S39-58



Graphite – heat defect?



graphite:

$k_{HD} = 1.004 \pm 0.003$

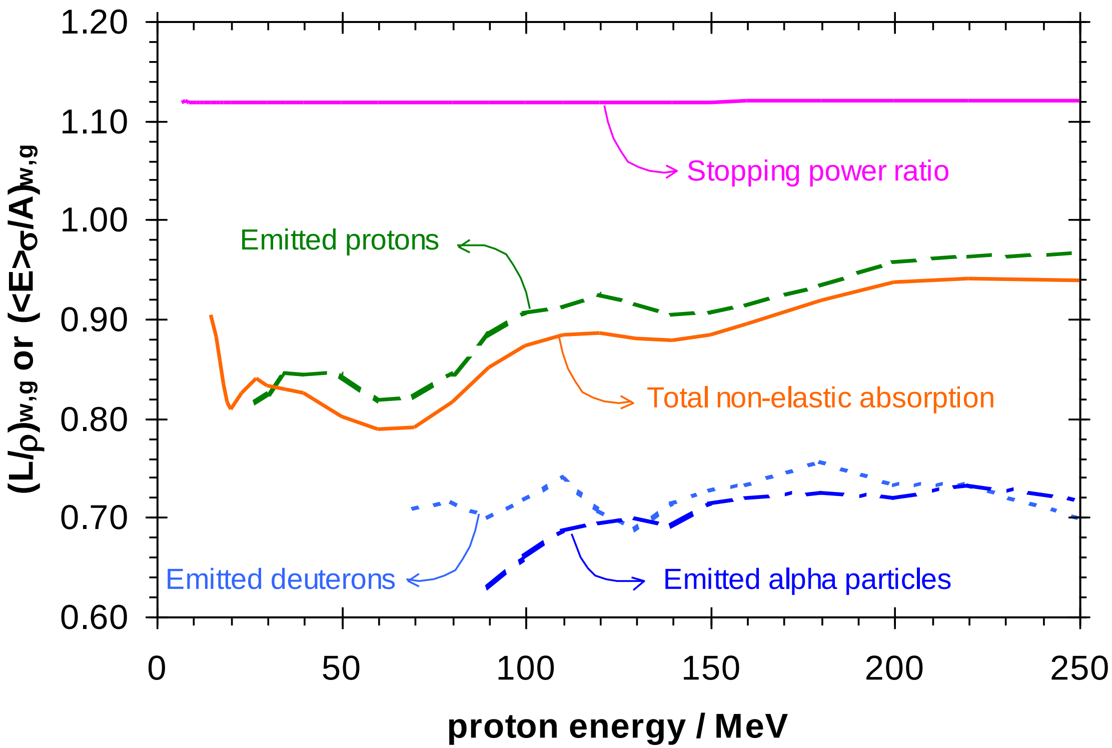
A150:

$k_{HD} = 1.042 \pm 0.004$

Schulz et al (1990) Phys. Med. Biol. 35:1563-74

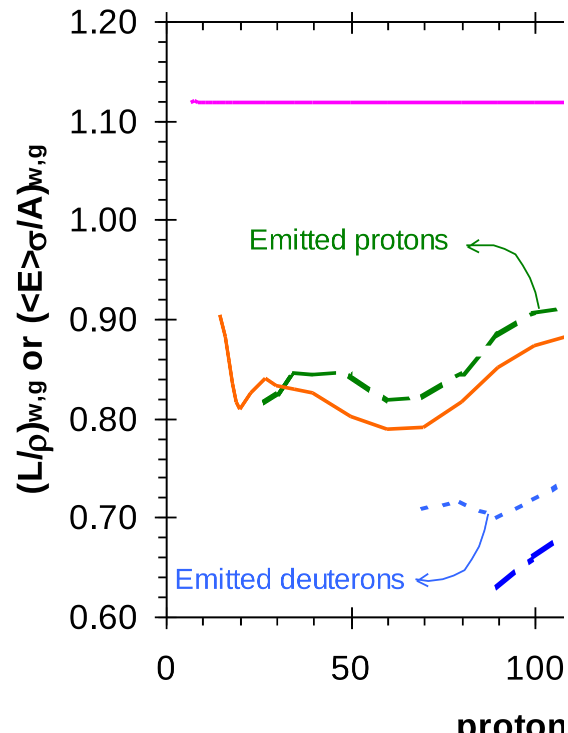
Dose conversion graphite calorimetry

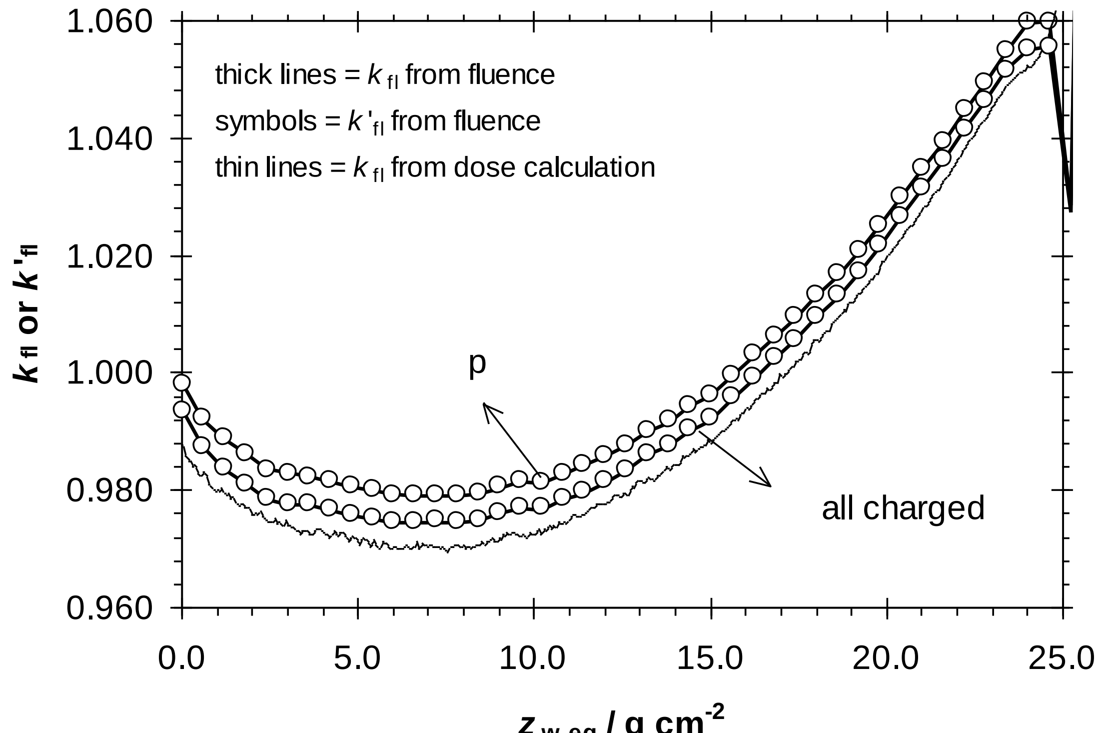
$$D_w(z_w) = D_g(z_g) \cdot \left(\frac{S}{\rho}\right)_g^w \quad ?$$



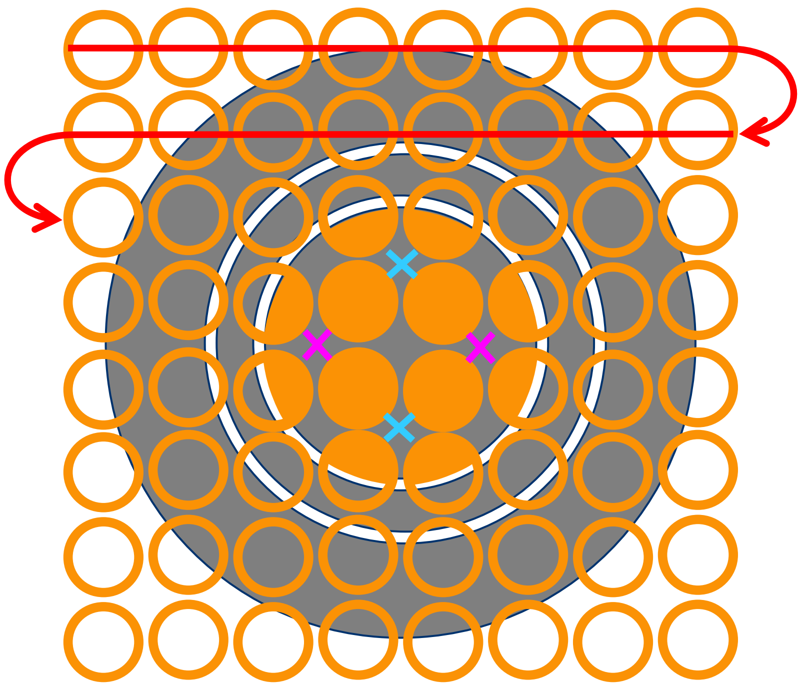
Dose conversion graphite calorimetry

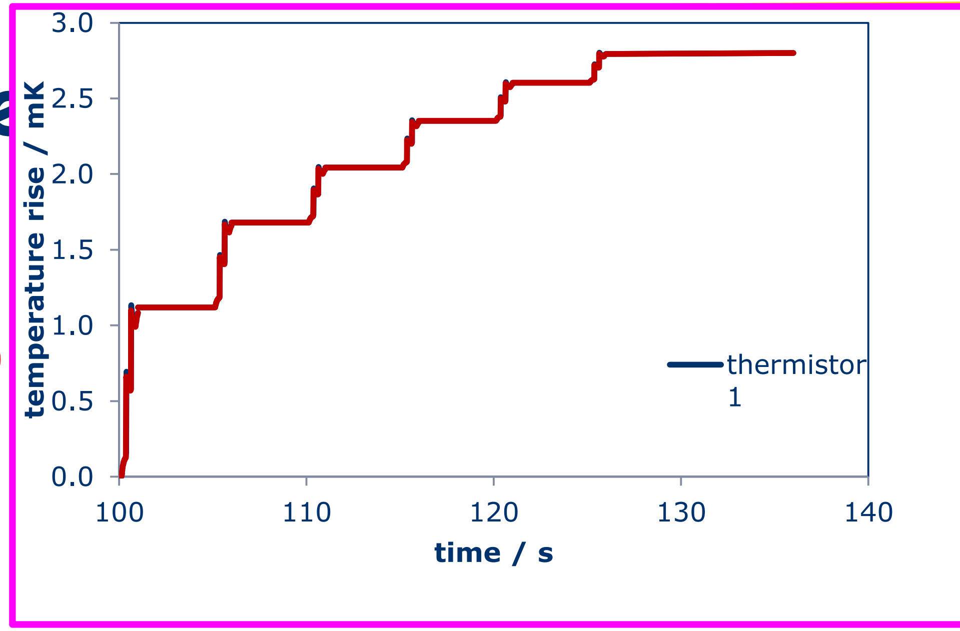
$$D_w(z_w) = D_g(z_g) \cdot \left(\frac{S}{\rho}\right)_g^w \quad ?$$

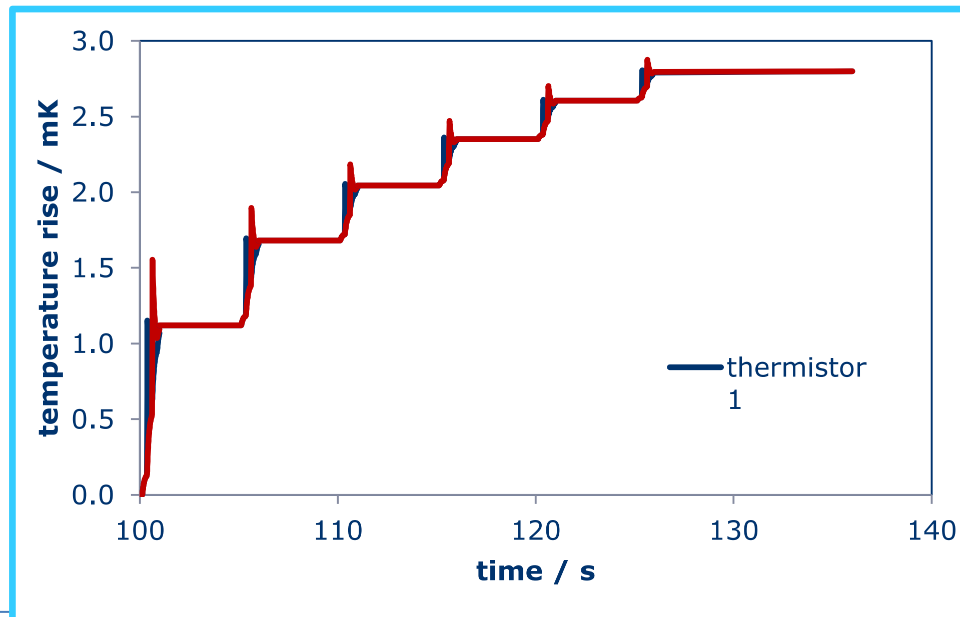




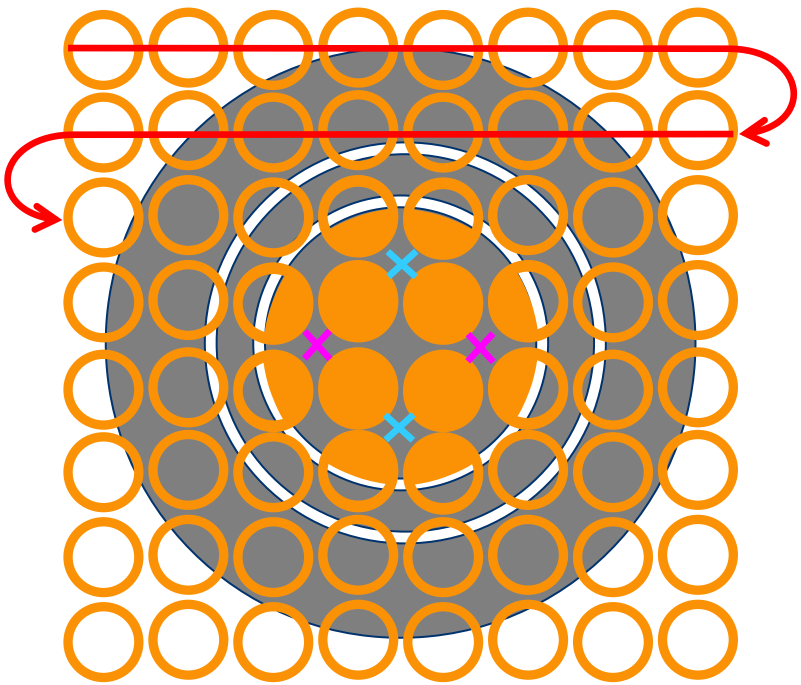
Graphite calorimeter within core

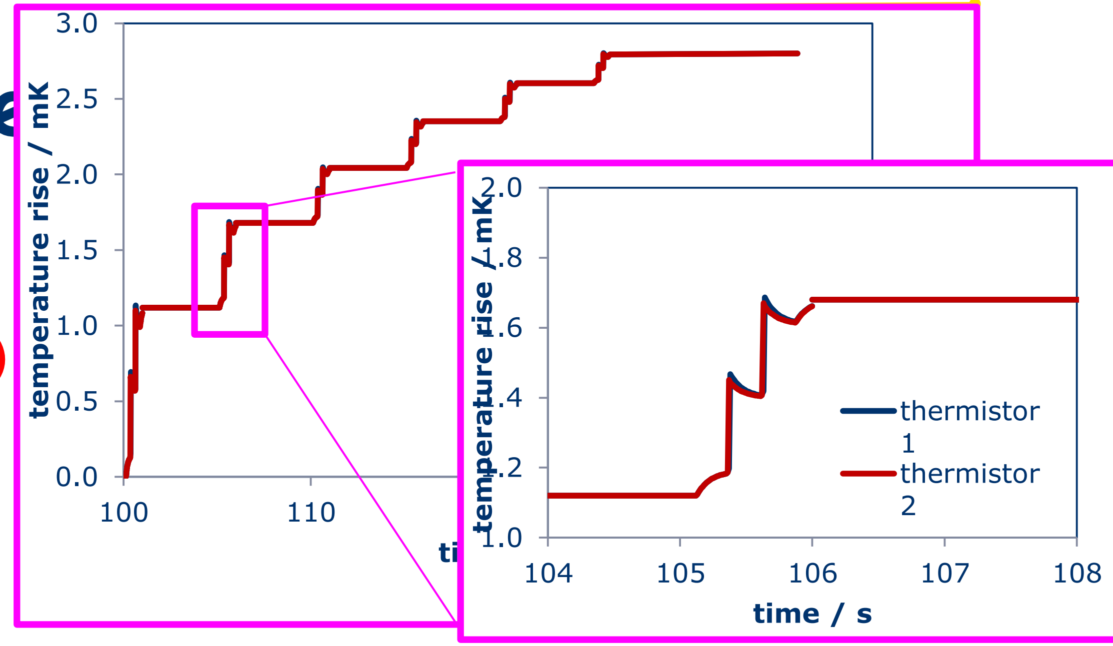


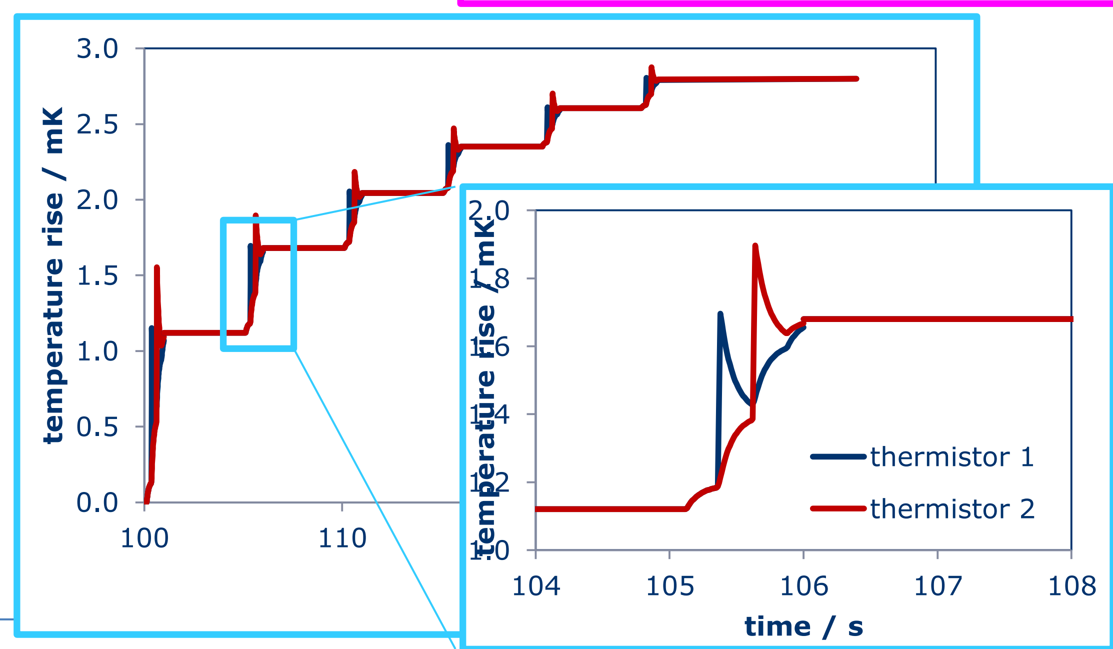




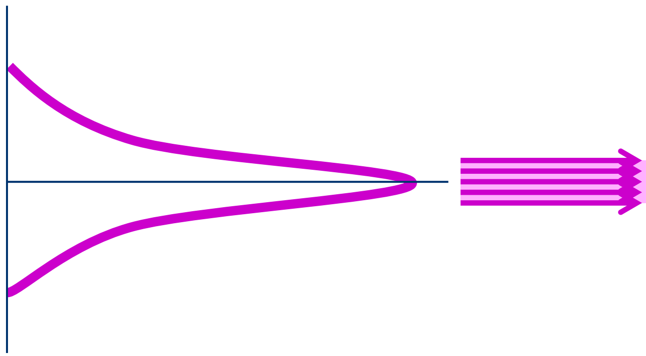
Graphite calorime
within core

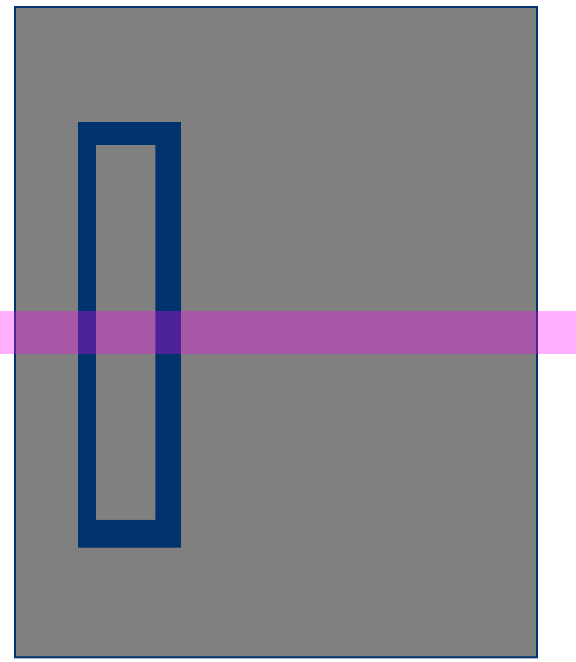






Graphite calorimetry – dose-area-product





Calorimeter: DAP(z_{ref})

Large area ion chamber: pdd(z)

Faraday cup: N/MU

S/ρ: DAP(z_0 or z_{ref})

Integrate lateral dose profiles over all spots

Reference dosimetry with ion chambers

TRS-398

ICRU report 78

$$D_{w,Q} = M_{corr,Q} N_{D,w} k_Q$$

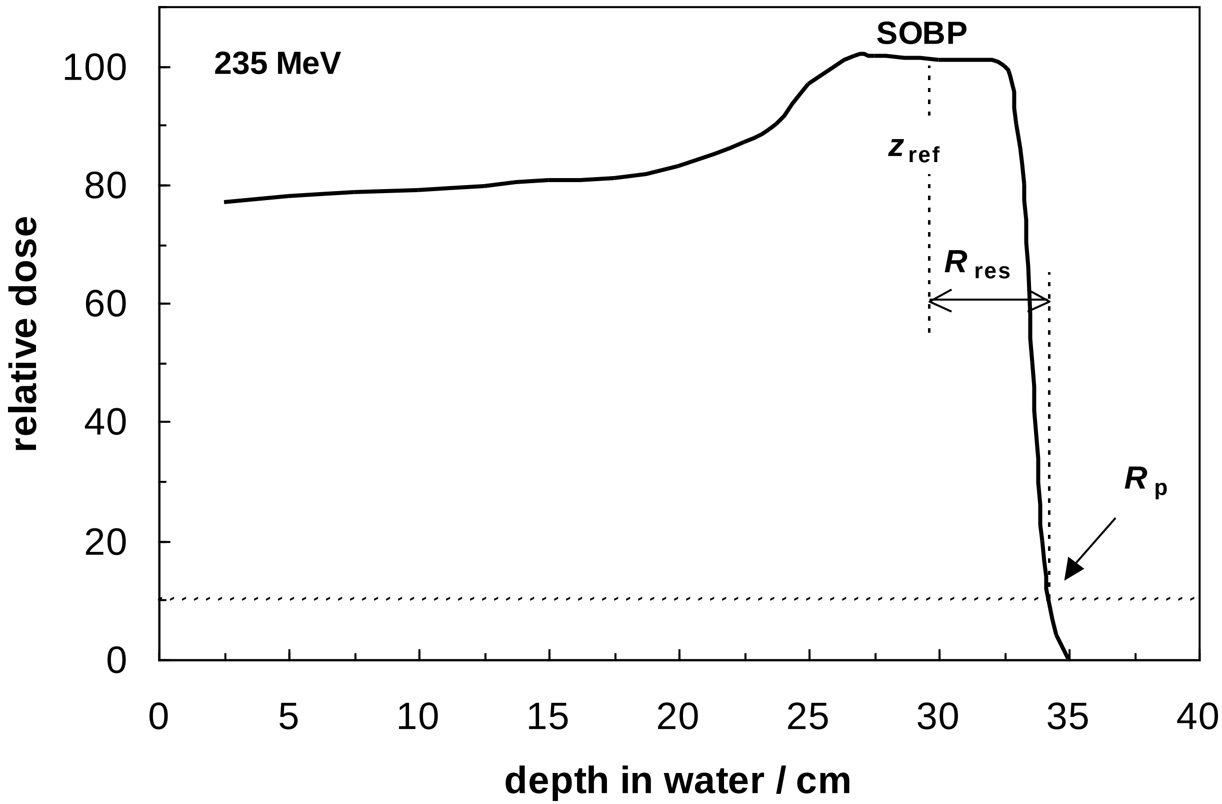
$$k_Q = \frac{\left[w_{air} \cdot \left(\frac{\bar{L}}{\rho} \right)_{air}^{w} \cdot P_{wall} P_{cel} P_{repl} \right]_p}{\left[W_{air} \cdot \left(\frac{\bar{L}}{\rho} \right)_{air}^{w} \cdot P_{wall} P_{cel} P_{repl} \right]_{calibr}}$$

$(w_{air})_p$ = 34.2 J/C based mainly on calorimetry data

$\left[\left(\frac{\bar{L}}{\rho} \right)_{air}^{w} \right]_p$ from Medin and Andreo 1997, Phys Med Biol 42:89

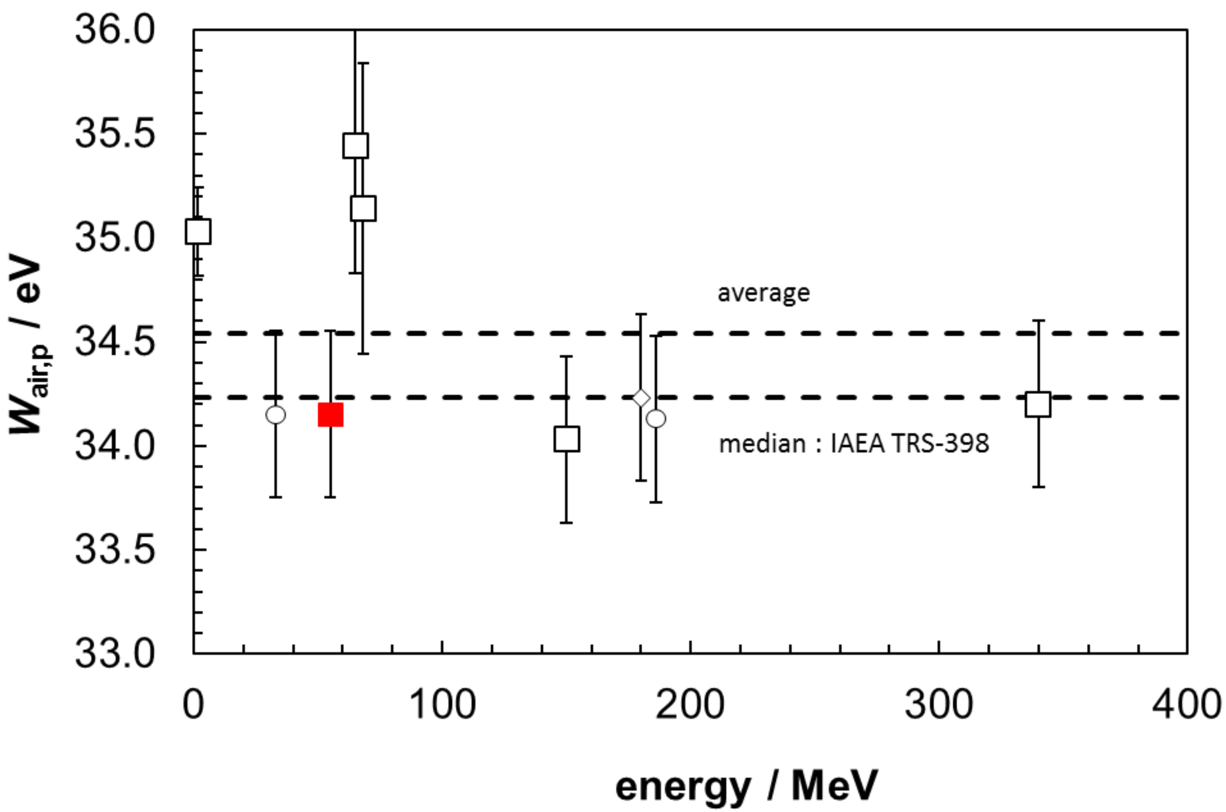
$[P_{wall} P_{cel} P_{repl}]_p = 1$

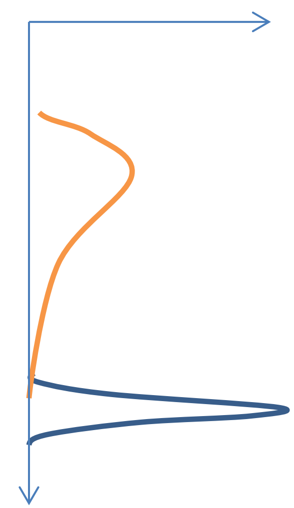
Residual range – beam quality for protons



W_{air} / protons

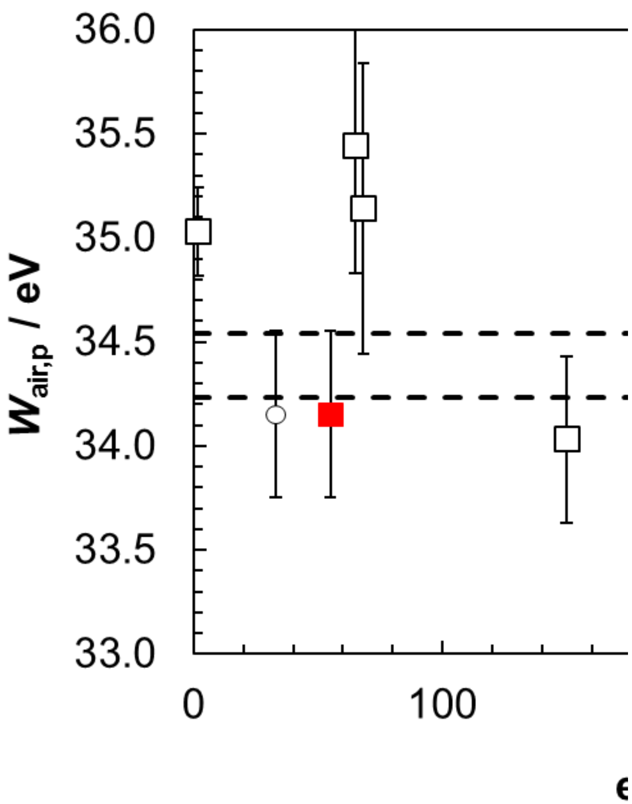
TRS-398



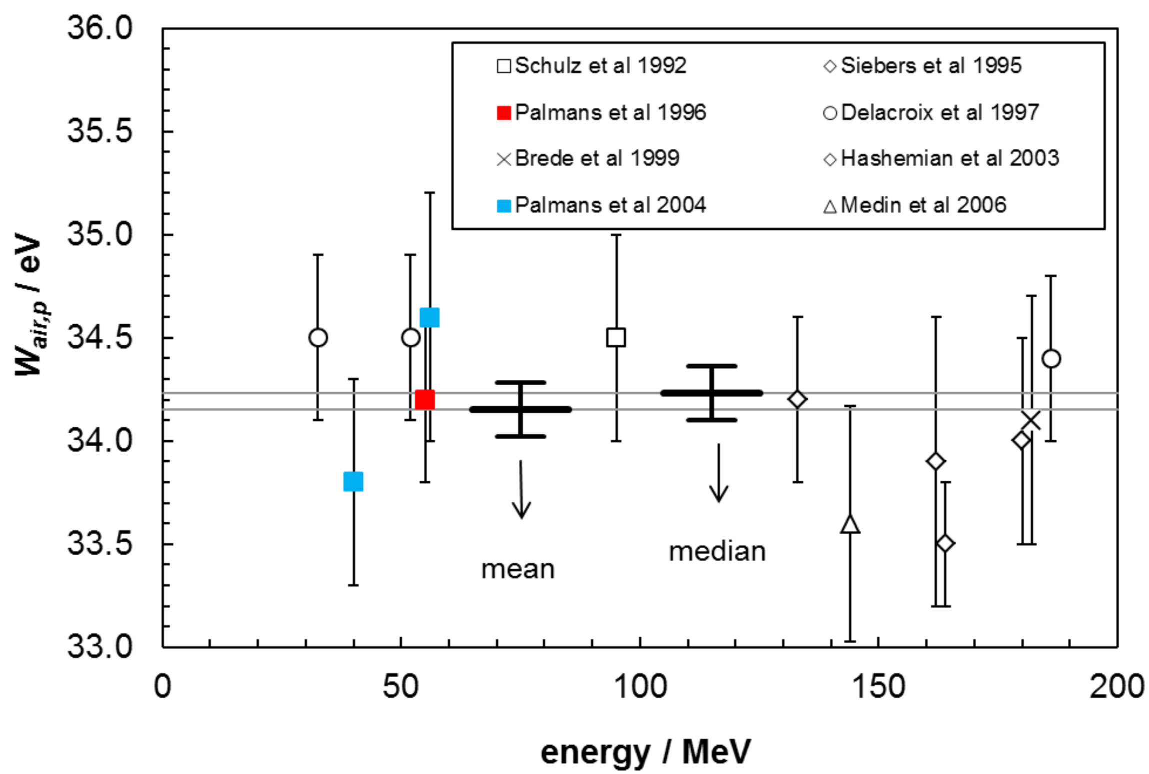


W_{air} / protons

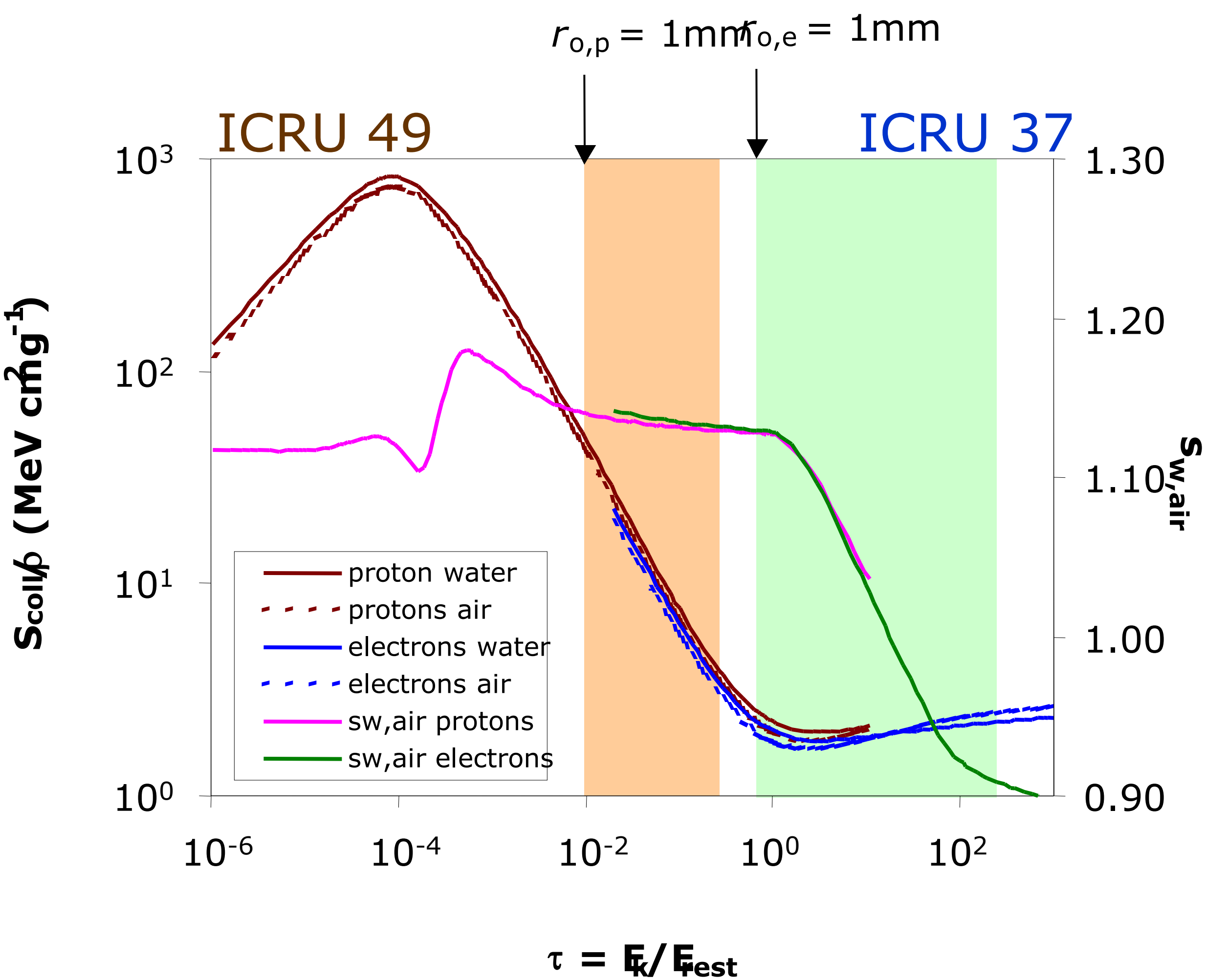
TRS-398



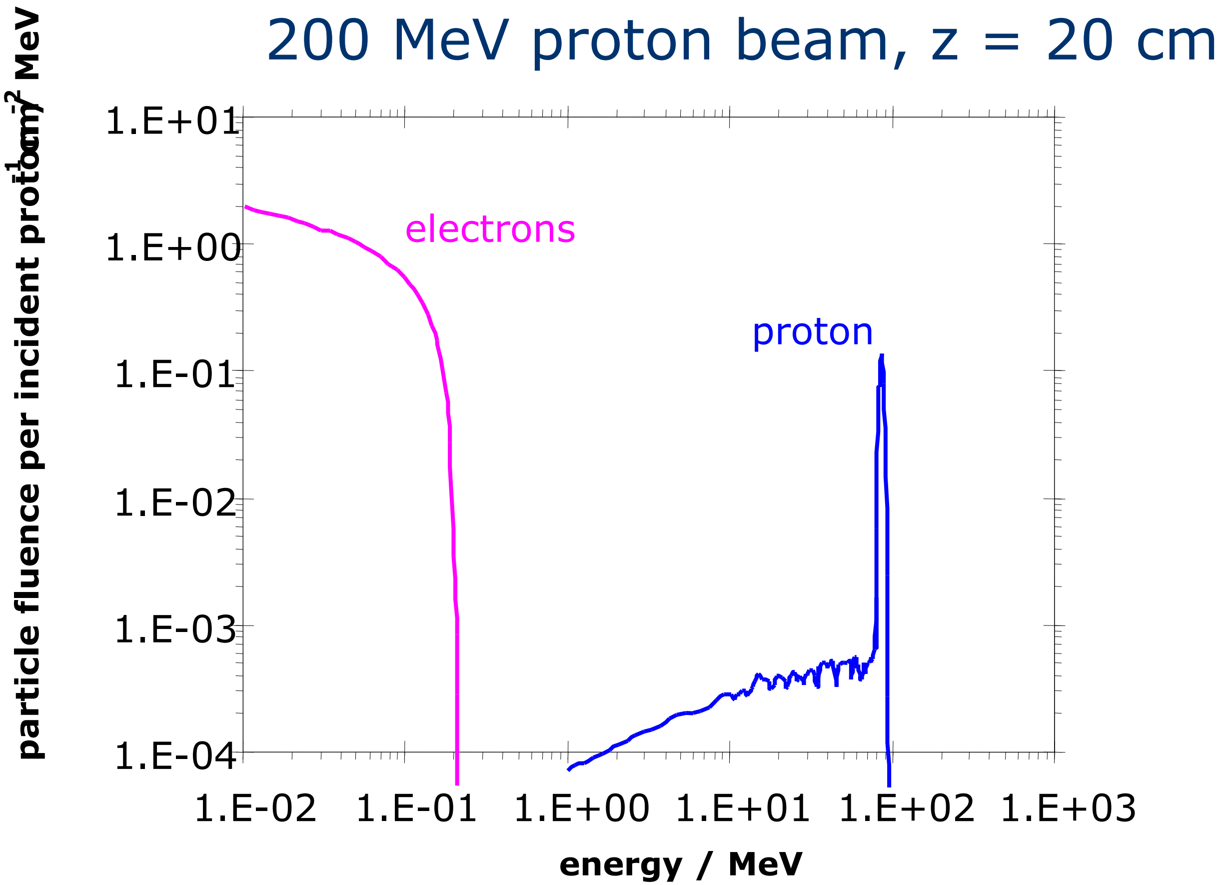
Jones 2006 RPC 75:541



Stopping powers – protons versus electrons



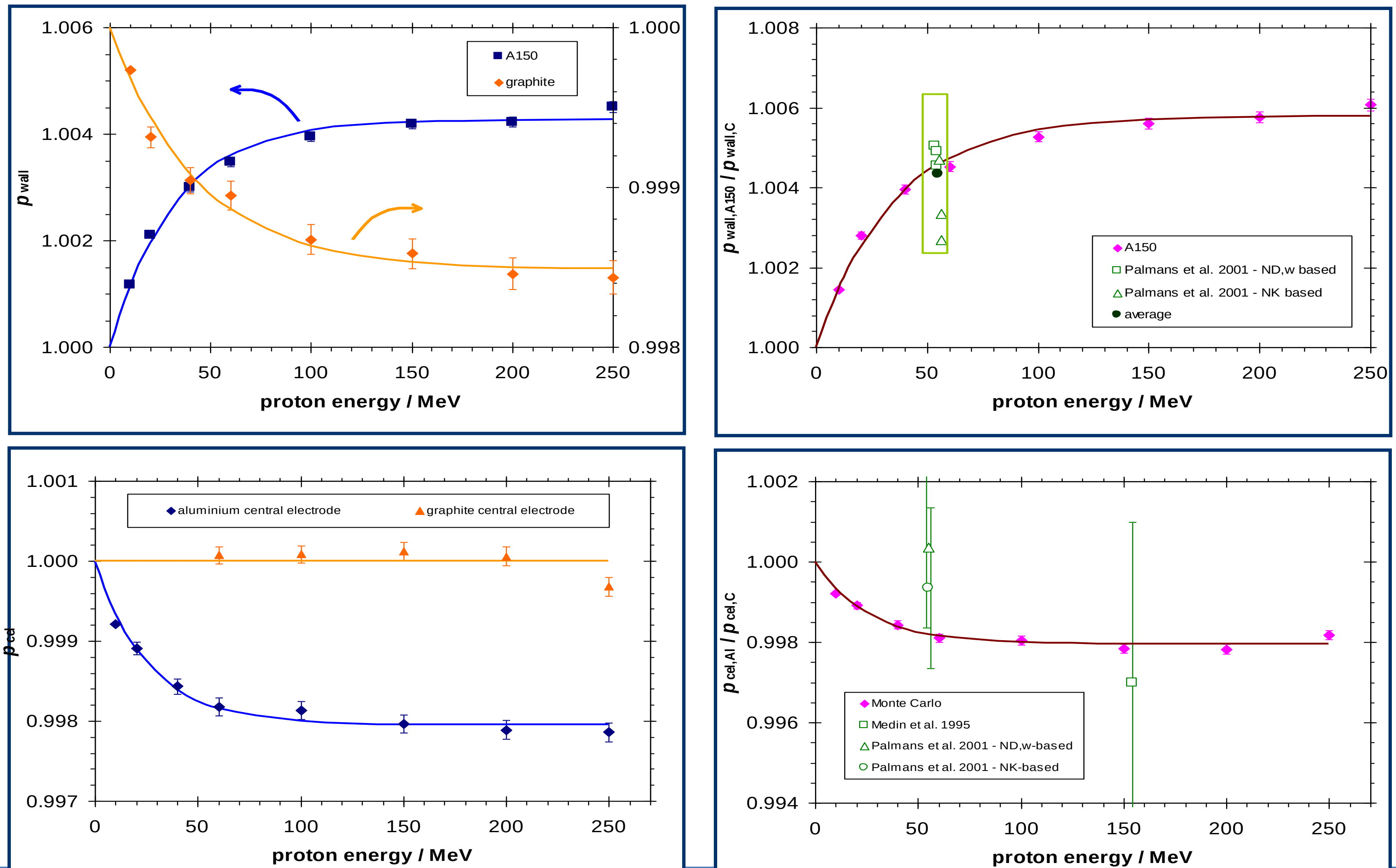
Electron slowing down spectrum



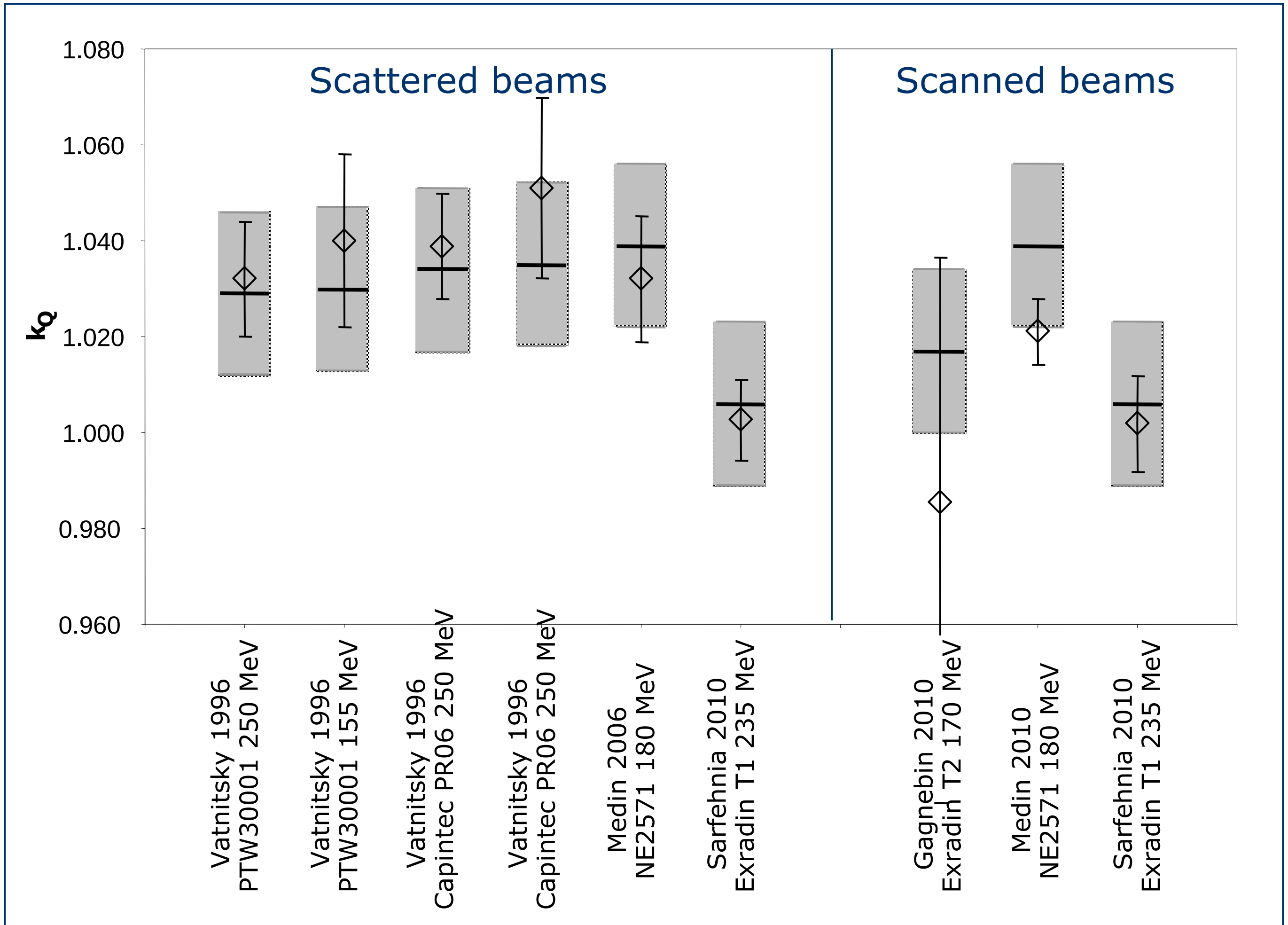
(Medin and Andreo 1997, Phys Med Biol 42:89-105)

Secondary electron perturbations

Palmans et al. (2011) Proc IDOS, IAEA-CN182-230

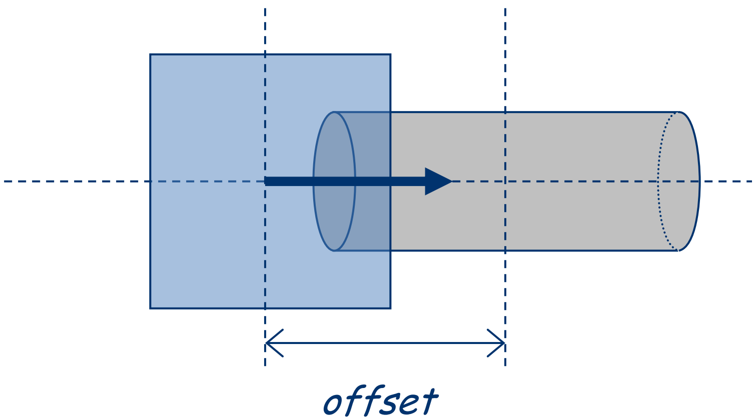


Ion chamber dosimetry of scanned beams

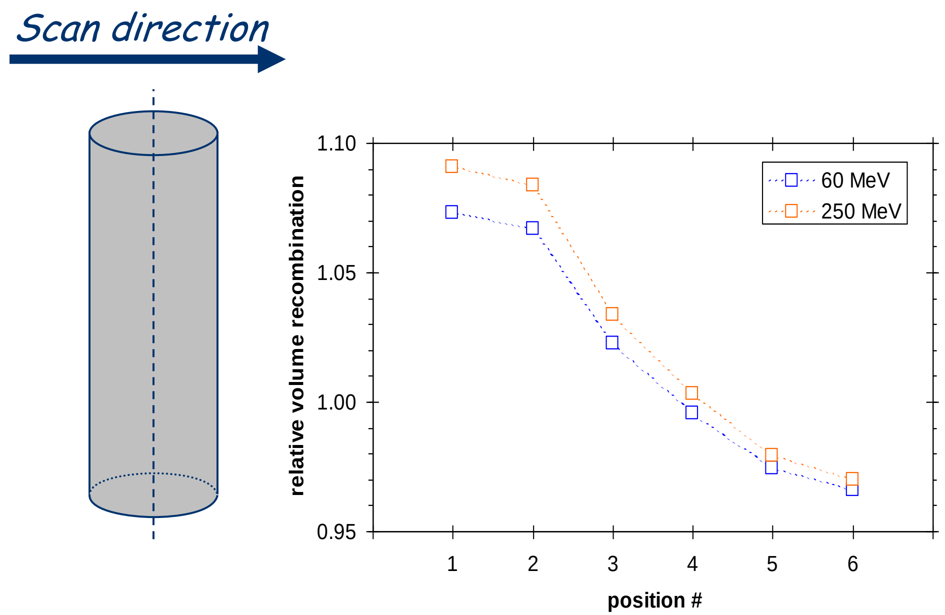


Ion recombination I

$$P_{ion} \approx 1 + \frac{A}{V} + \frac{B}{V^2} \frac{\iint i_{sat}^2 dxdt}{\iint i_{sat} dxdt}$$



	Rectangle	Gauss
60 MeV	1.006	1.015
250 MeV	1.009	1.024



Analogy IMRT beams: Palmans et al. 2010 Med. Phys. 37 2876-2889

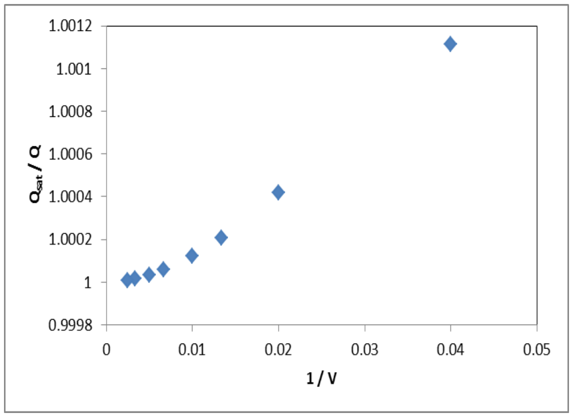
NPL MedAustron

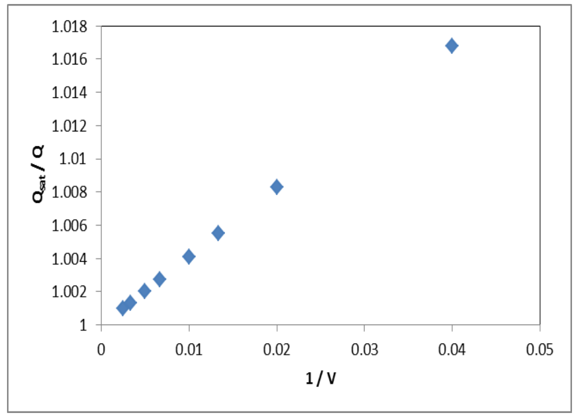
Ion recombination II

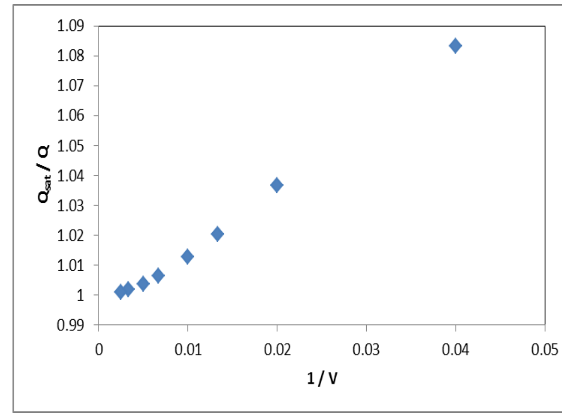
Continuous

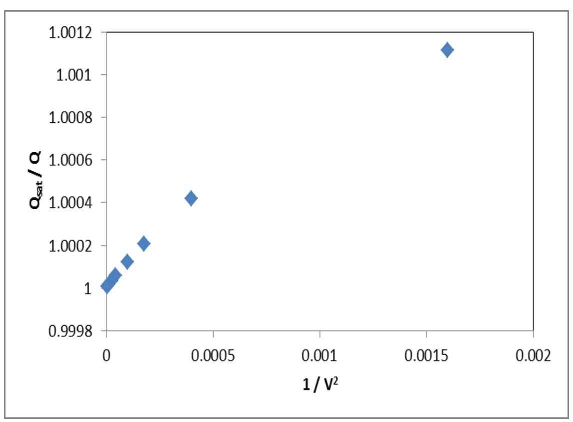
Pulsed

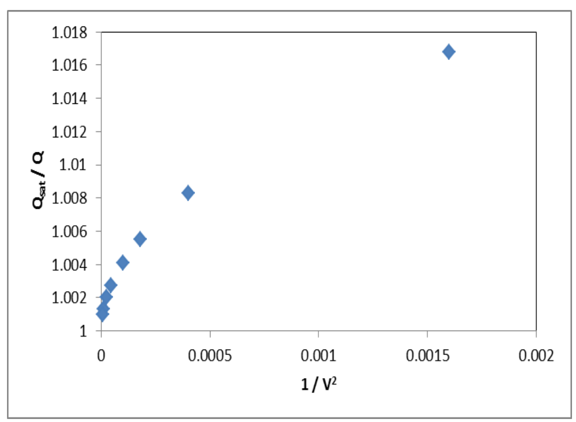
PBS

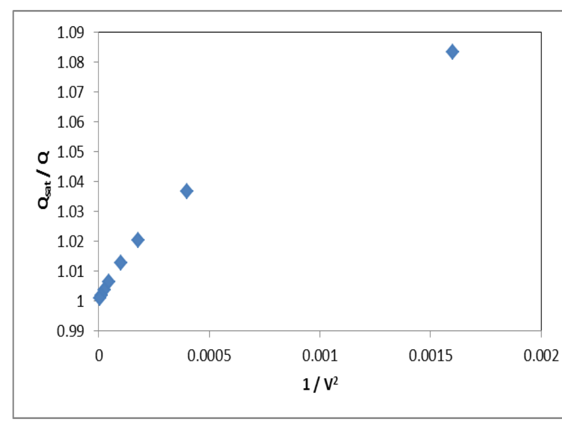






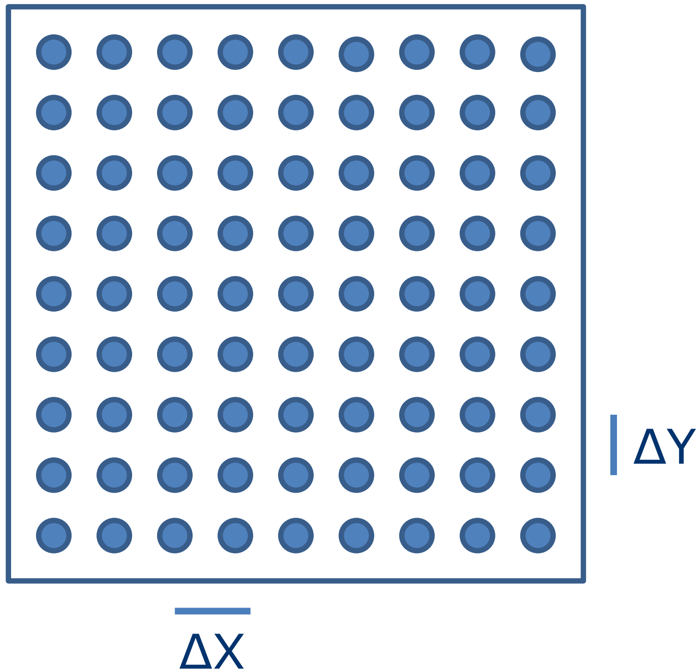






Reference dosimetry scanned beams

Jaekel 2004

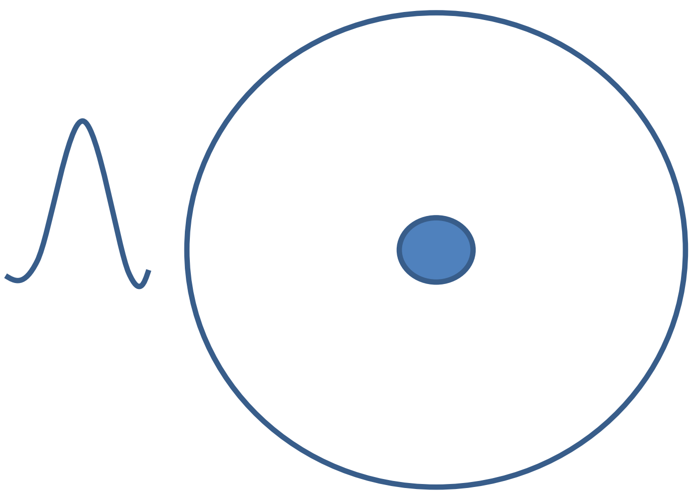


$$D_{w,Q}^{cyl} = M_Q^{cyl} N_{D,w,Q_0}^{cyl} k_{Q,Q_0}^{cyl}$$

$$N = \frac{D_{w,Q}^{cyl} \Delta X \Delta Y}{(S/\rho)_w}$$

Reference dosimetry scanned beams

Gillin 2010



$$DAP_{w,Q}^{BP} = M_{Q}^{BP} N_{DAP,w,Q_0}^{BP} \kappa_{Q,Q_0}^{BP}$$

$$N = \frac{DAP_{w,Q}^{BP}}{(S/\rho)_w}$$

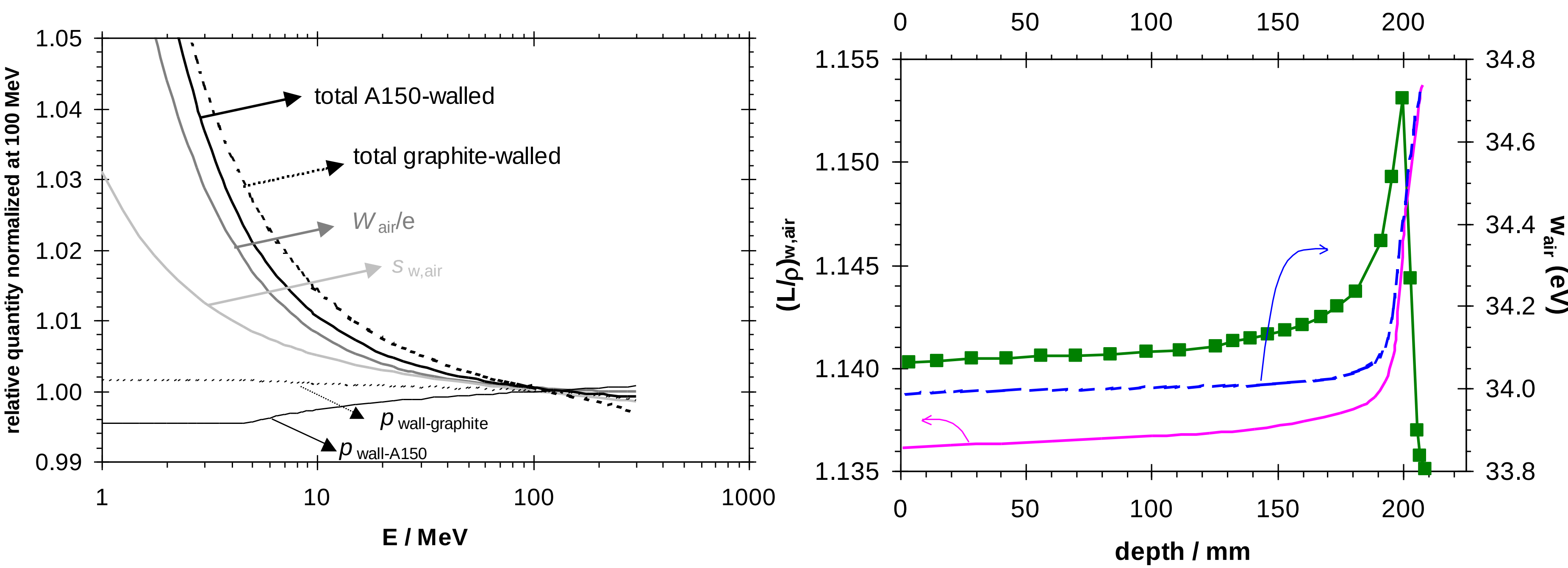
Relative dosimetry

Lateral profiles in general not problematic (except for volume averaging in small fields)

Depth dose profiles: LET dependence! Resulting in an under response in the Bragg peak

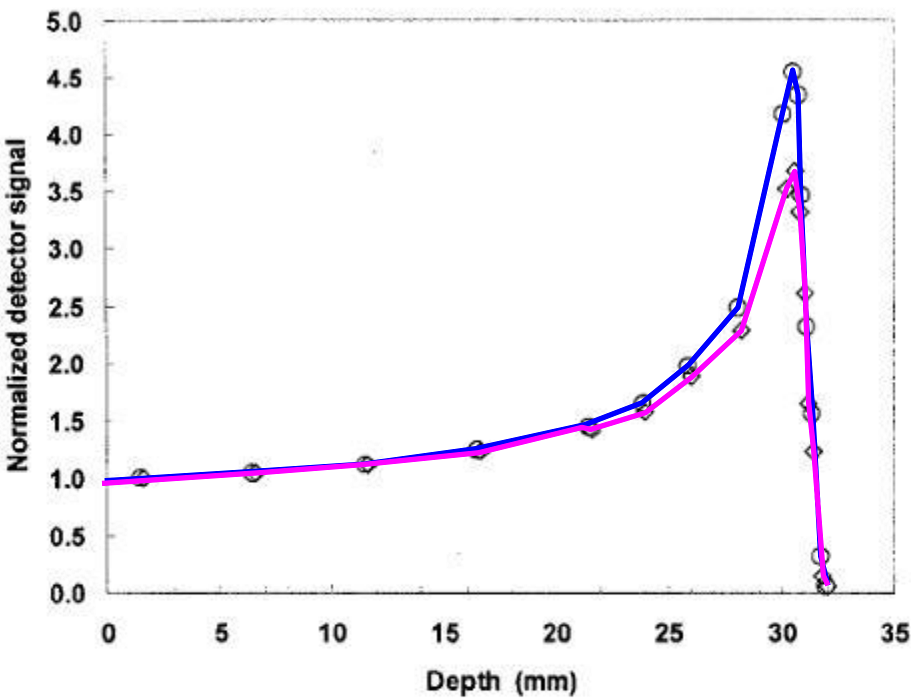
- Single hit theory (saturation of the sensitive site with one ionisation), e.g. alanine, film
- Inter-radical recombination, e.g gel dosimeters
- More complex models including charge transport, e.g. TLD

Relative dosimetry – ion chambers



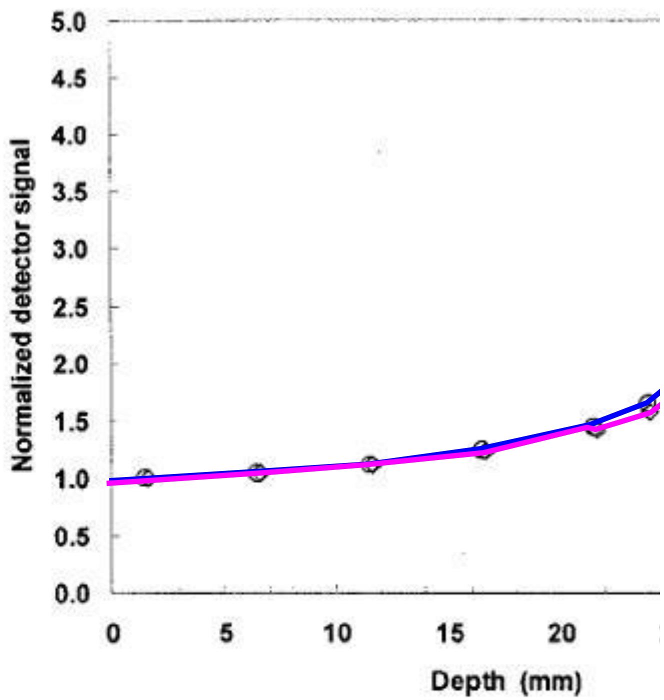
Palmans, Dosimetry, in : Proton Therapy Physics, Ed Paganetti

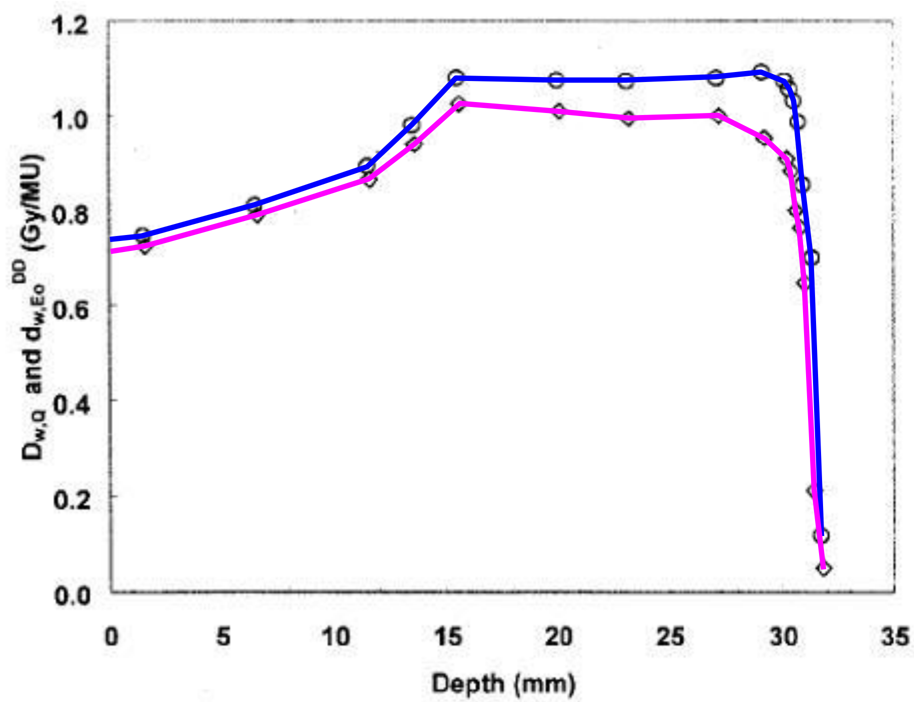
Relative dosimetry – Solid state detectors : diamond



(Fidanzio et al 2002, Med Phys 29:669-675)

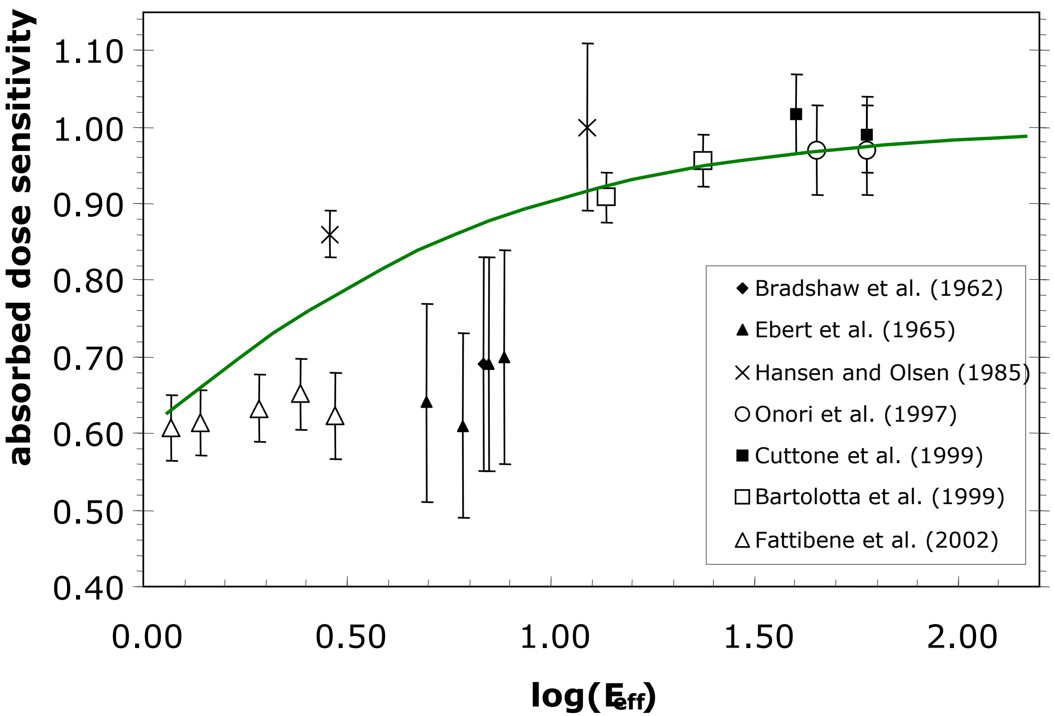
Relative dosimetry – Solid state detectors : diamond





(Fidanzio et al 2002, Med Phys 29:669-675)

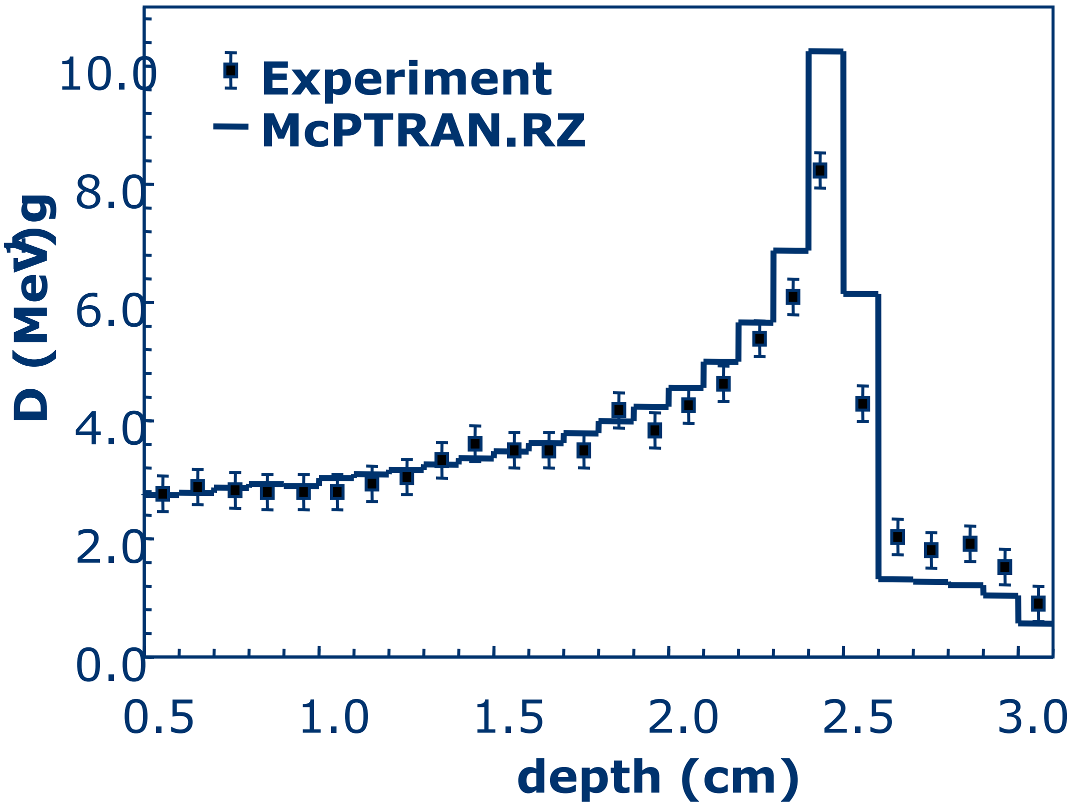
Relative dosimetry – Solid state detectors : alanine/ESR

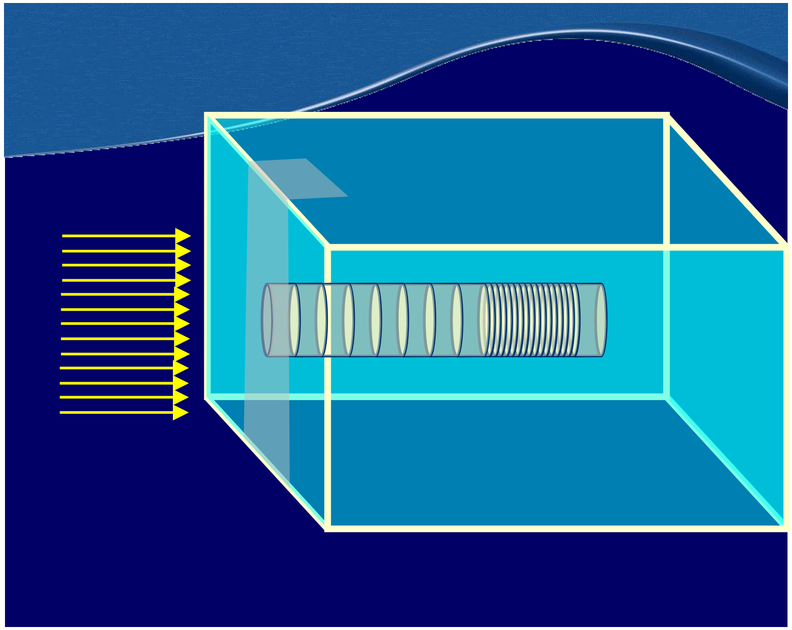


(Palmans 2003, Technol Cancer Res Treat. 2:579-86)

Alanine – stack in PMMA

(Palmans 2003 Technol Cancer Res Treat. 2:579) experimental data from Onori et al 1997 Med. Phys. 24:447





Alanine for protons and ions

Bassler et al. 2008

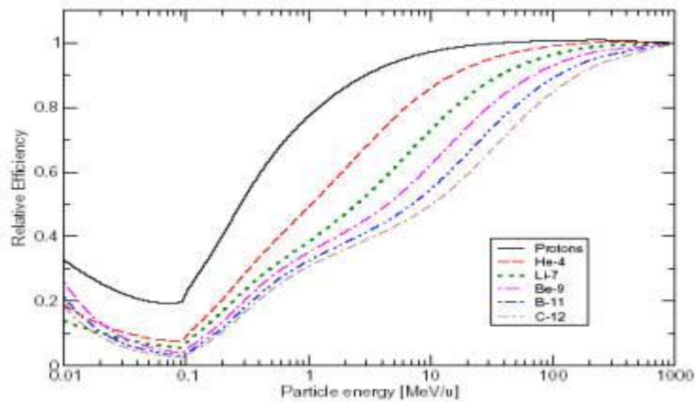
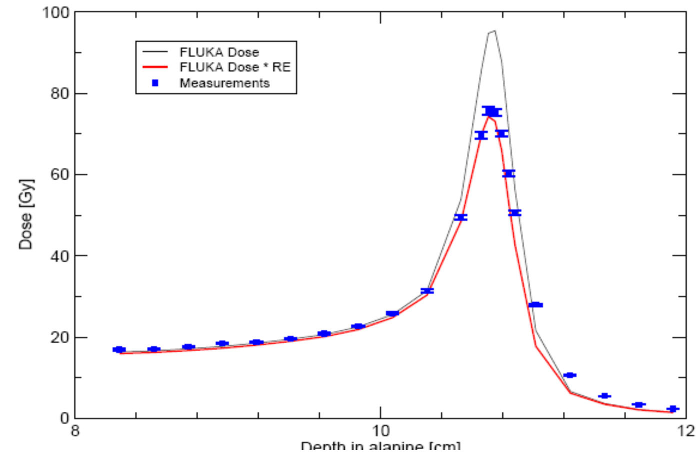
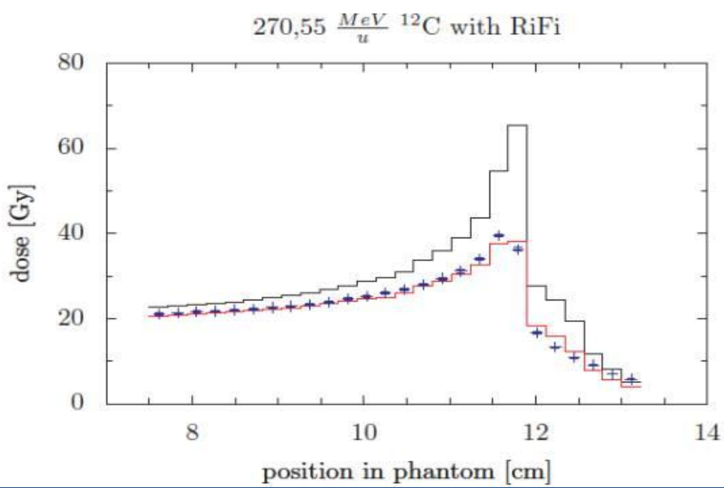


Fig. 1. Calculated relative efficiencies for infinitesimal thin detectors, without fading effects.

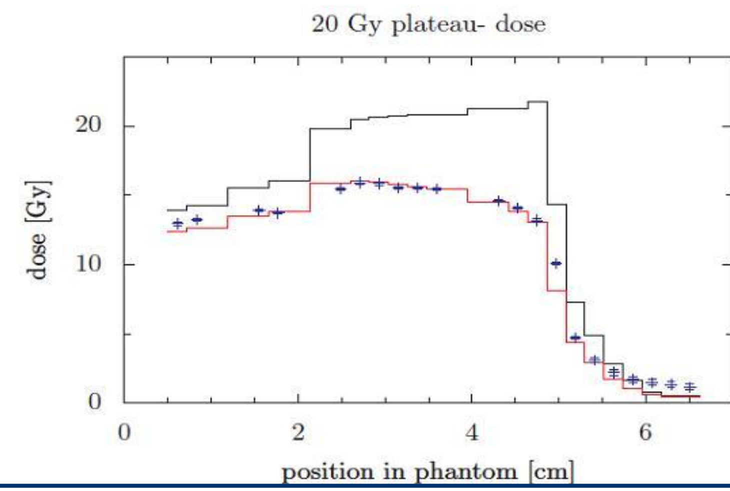
CERN anti-proton beam



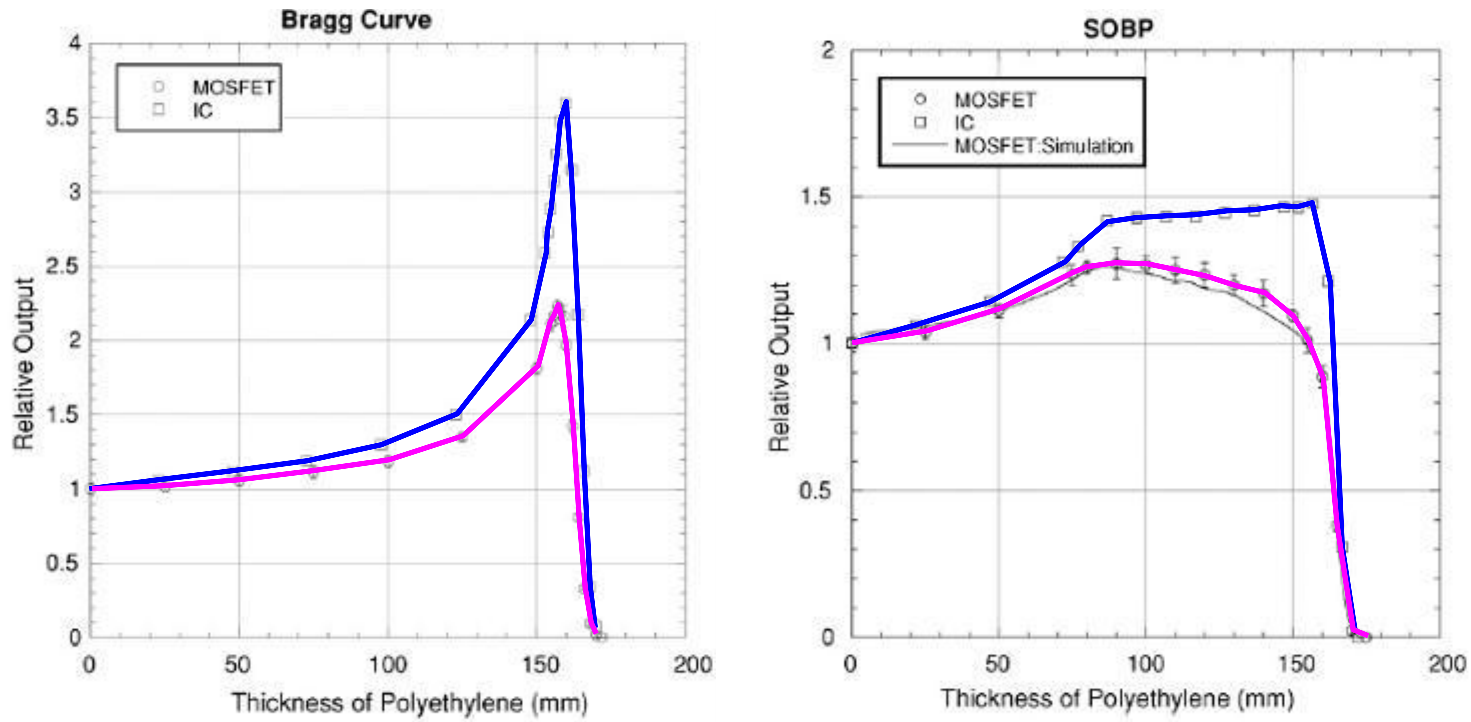
Herrmann et al. 2011



GSI ^{12}C ion beam

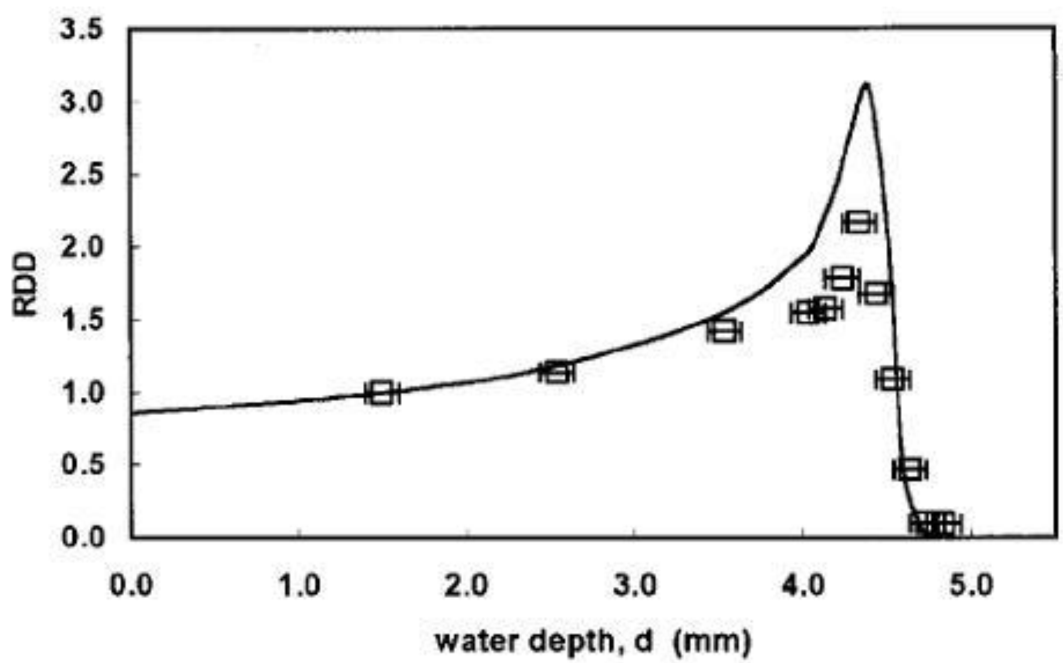


Relative dosimetry – Solid state detectors : mosfet



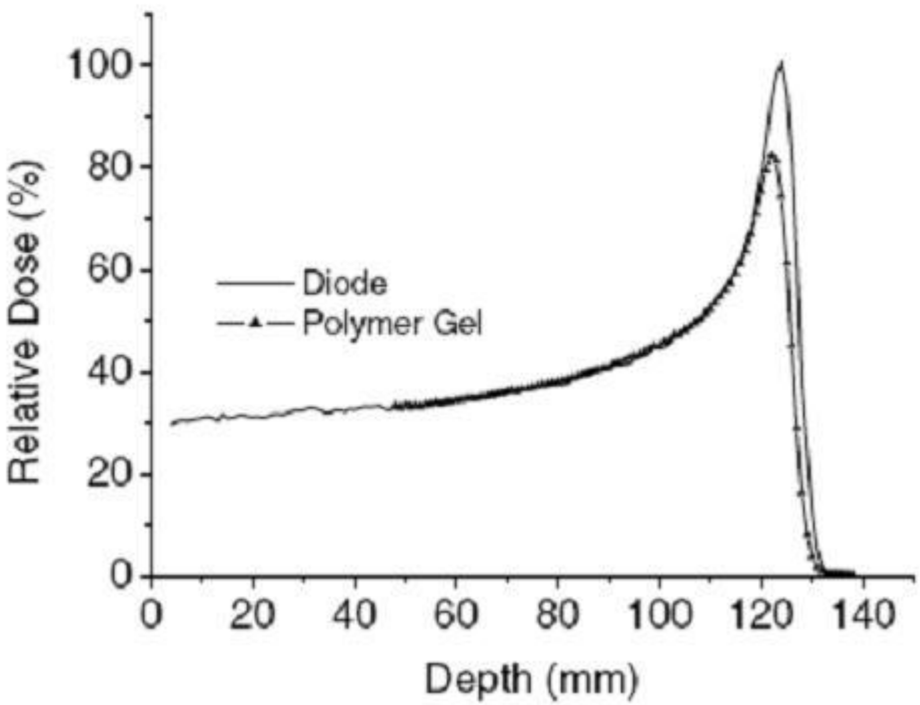
(Kohno et al 2006, Phys Med Biol 51:6077-86)

Relative dosimetry – Radiochromic film



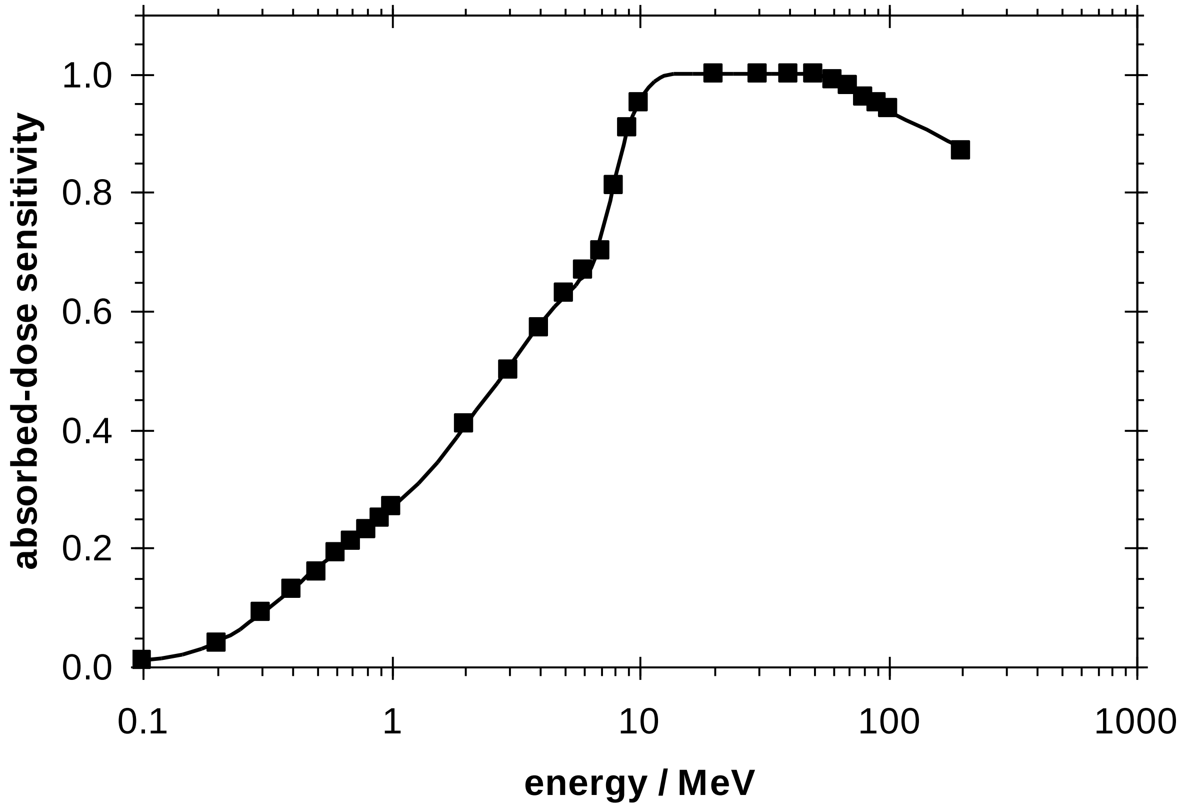
(Piermattei et al 2000,Med Phys 27:1655-60)

Relative dosimetry – Gel dosimetry



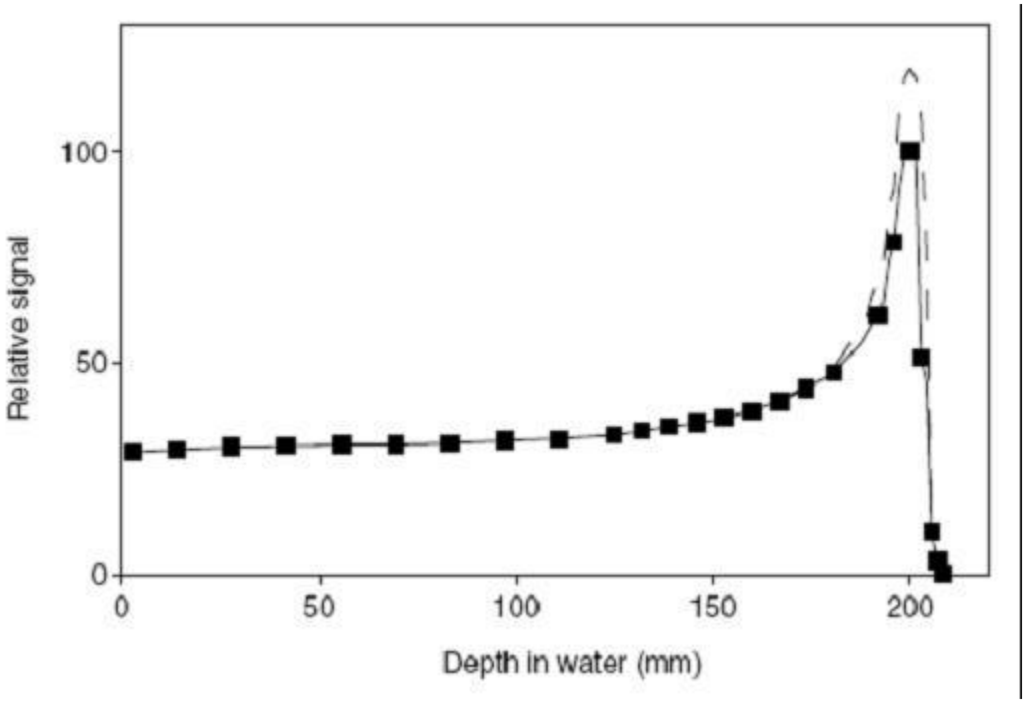
(Gustavsson et al. 2004 Phys. Med. Biol. 49:3847-55)

Relative dosimetry – TLD



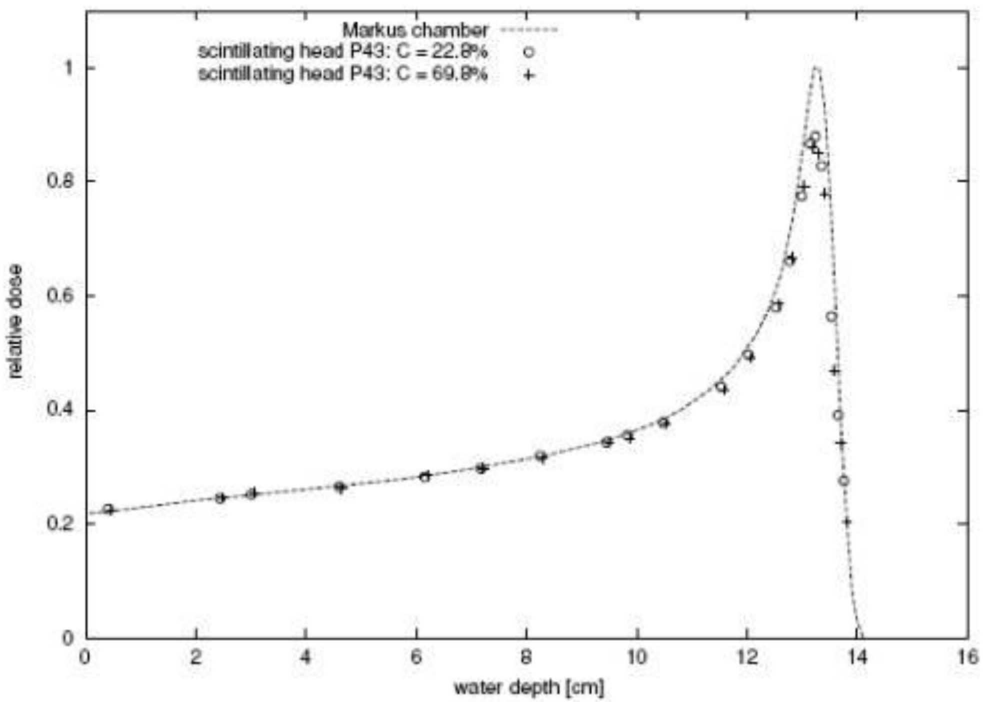
(Besserer et al 2001 Phys. Med. Biol. 46:473-85)

Relative dosimetry – Solid state detectors : diode



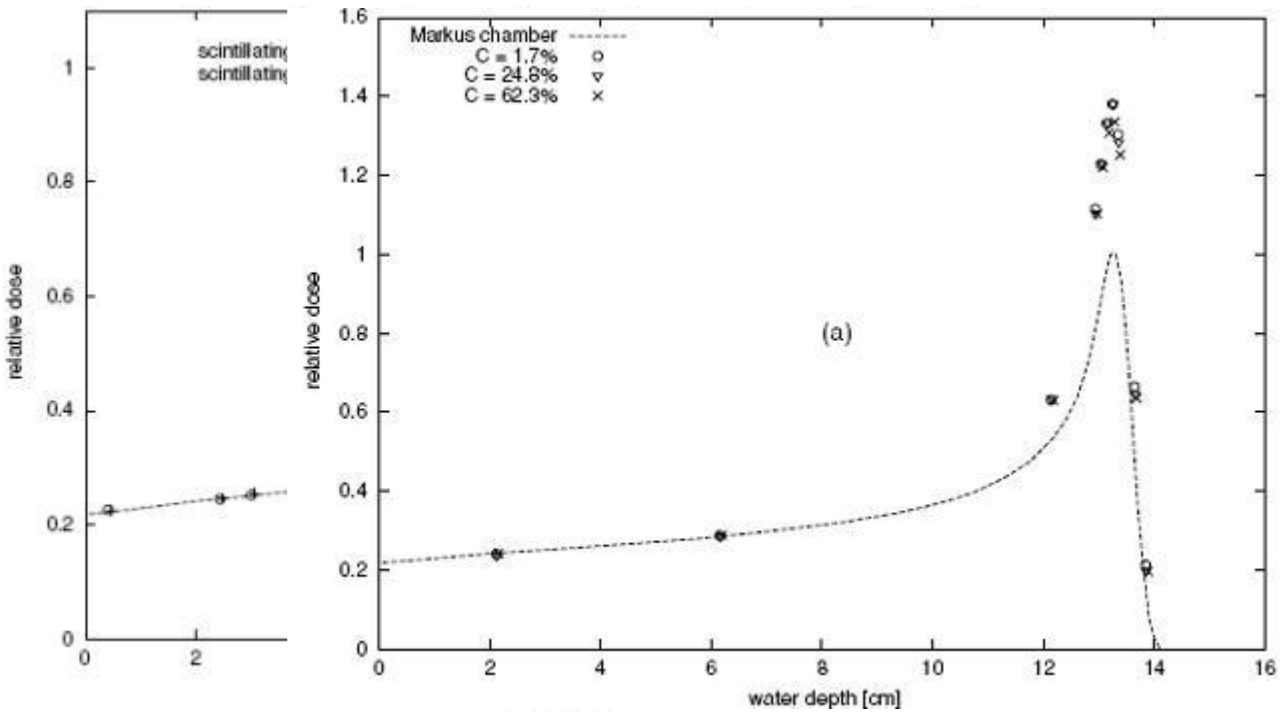
(Grusell and Medin 2000 Phys. Med. Biol. 45:2573-82)

Relative dosimetry – Plastic scintillator



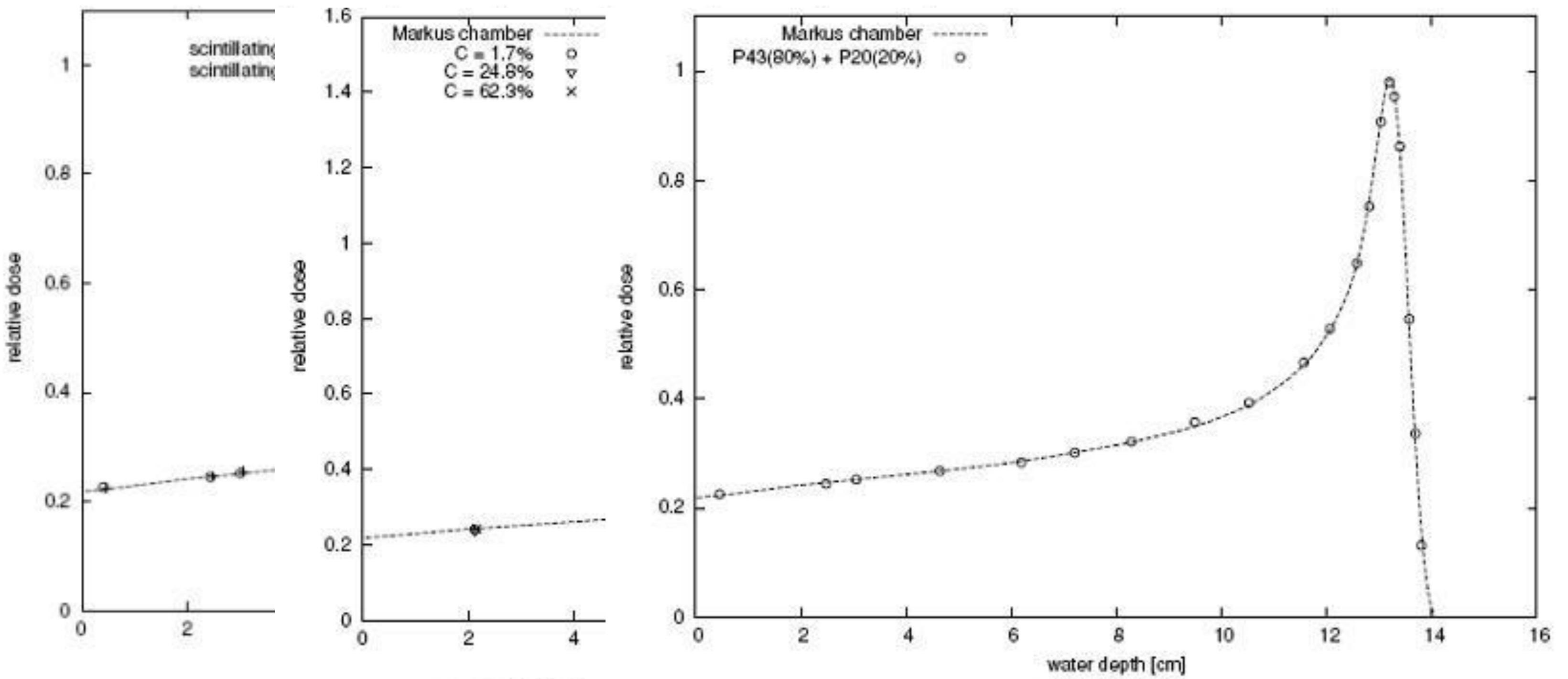
(Safai et al. 2004 Phys. Med. Biol. 49:4637-55)

Relative dosimetry – Plastic scintillator



(Safai et al. 2004 Phys. Med. Biol. 49:4637-55)

Relative dosimetry – Plastic scintillator



(Safai et al. 2004 Phys. Med. Biol. 49:4637-55)

Reading

C. P. Karger, O. Jäkel, H. Palmans and T. Kanai, "Dosimetry for Ion Beam Radiotherapy," Phys. Med. Biol. 55(21) R193-R234, 2010

H. Palmans, A. Kacperek and O. Jäkel, "Hadron dosimetry" In: Clinical Dosimetry Measurements in Radiotherapy (AAPM 2009 Summer School), Ed. D. W. O. Rogers and J. Cygler, (Madison WI, USA: Medical Physics Publishing), 2009, pp. 669-722

H. Palmans, "Dosimetry," In: Proton Therapy Physics, Ed. H. Paganetti (London: Taylor & Francis), 2011, pp. 191-219

H. Palmans, "Monte Carlo for proton and ion beam dosimetry," In: Monte Carlo Applications in Radiation Therapy, Ed. F. Verhaegen and J Seco, (London: Taylor & Francis), 2013, pp. 185-199

IAEA TRS-398

ICRU Reports 59 and 78