Hadron dosimetry

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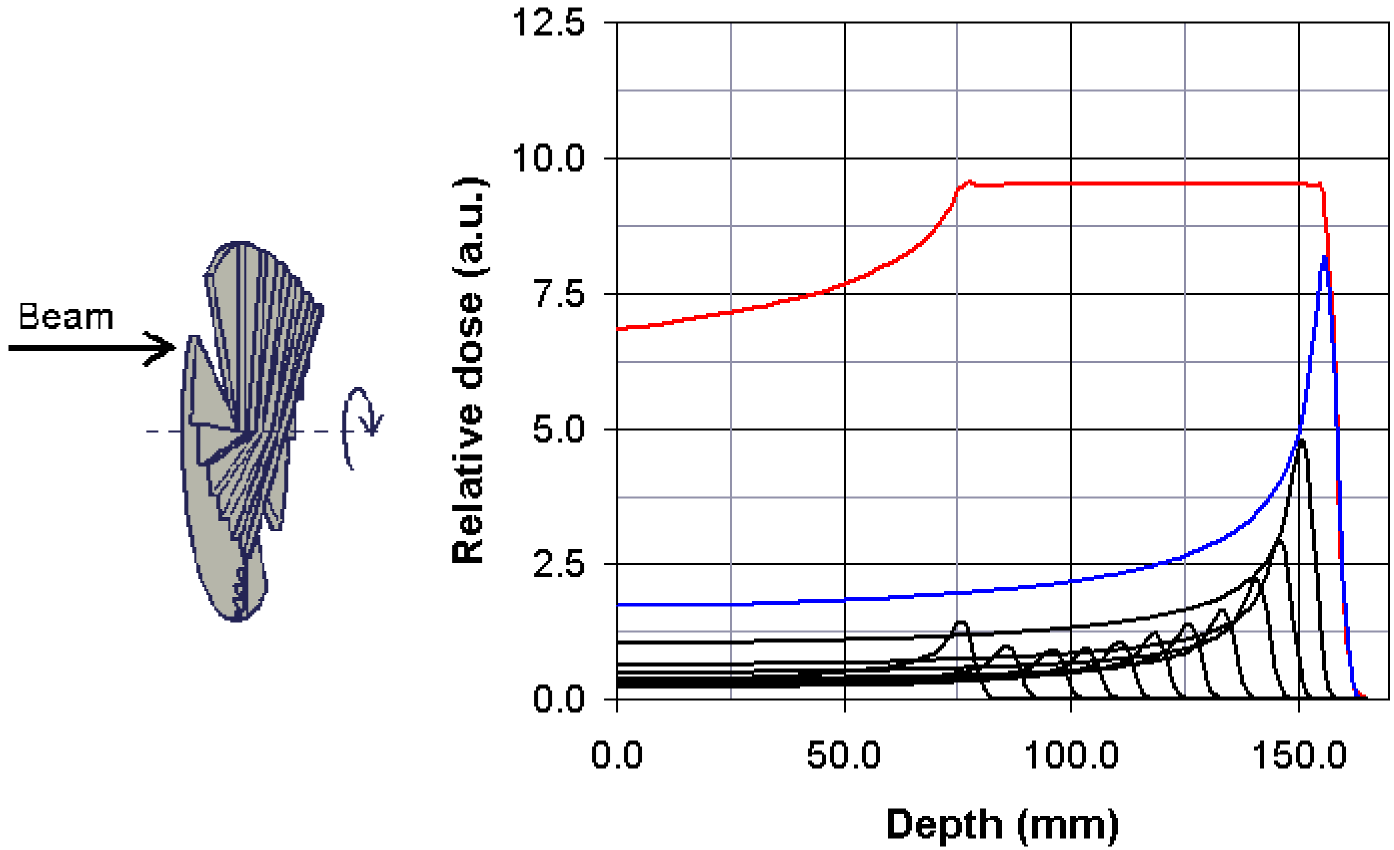
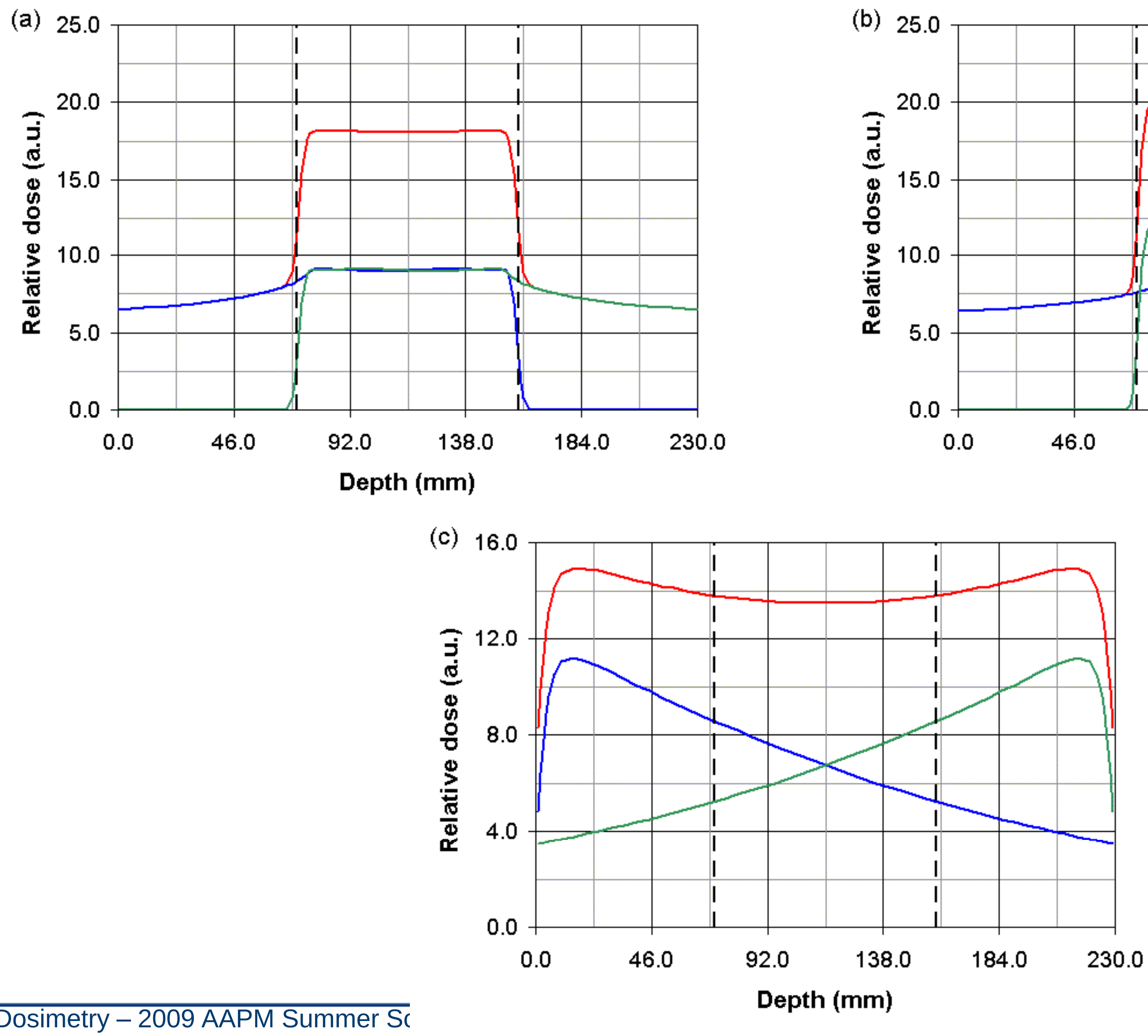
Overview

- Dosimetry: similarities and differences with photon and electron beams
- Absolute dosimetry:
  - Calorimetry, fluence based measurements, ion chambers
- Relative dosimetry:
  - Ionization chambers, solid state detectors, film, alanine

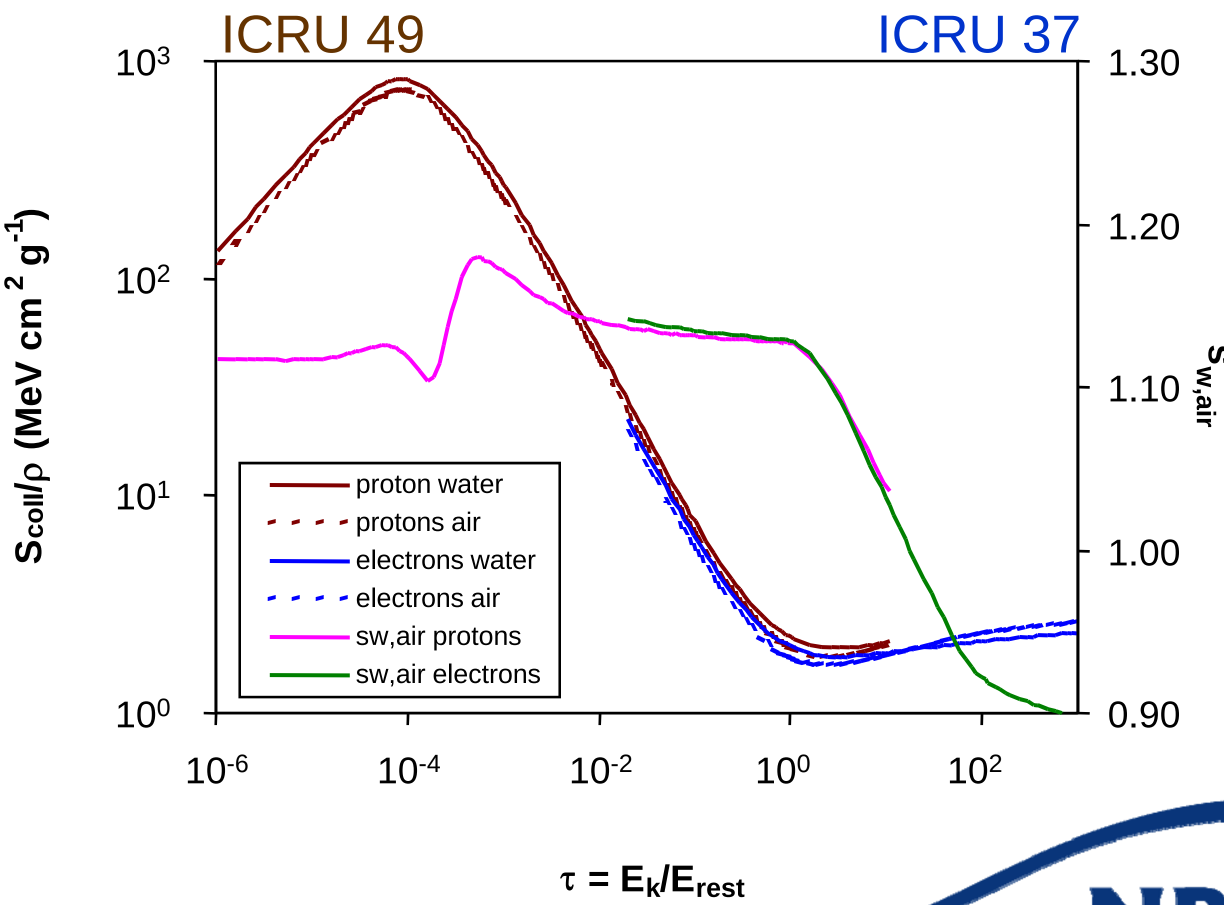
Protons and ions – the advantages



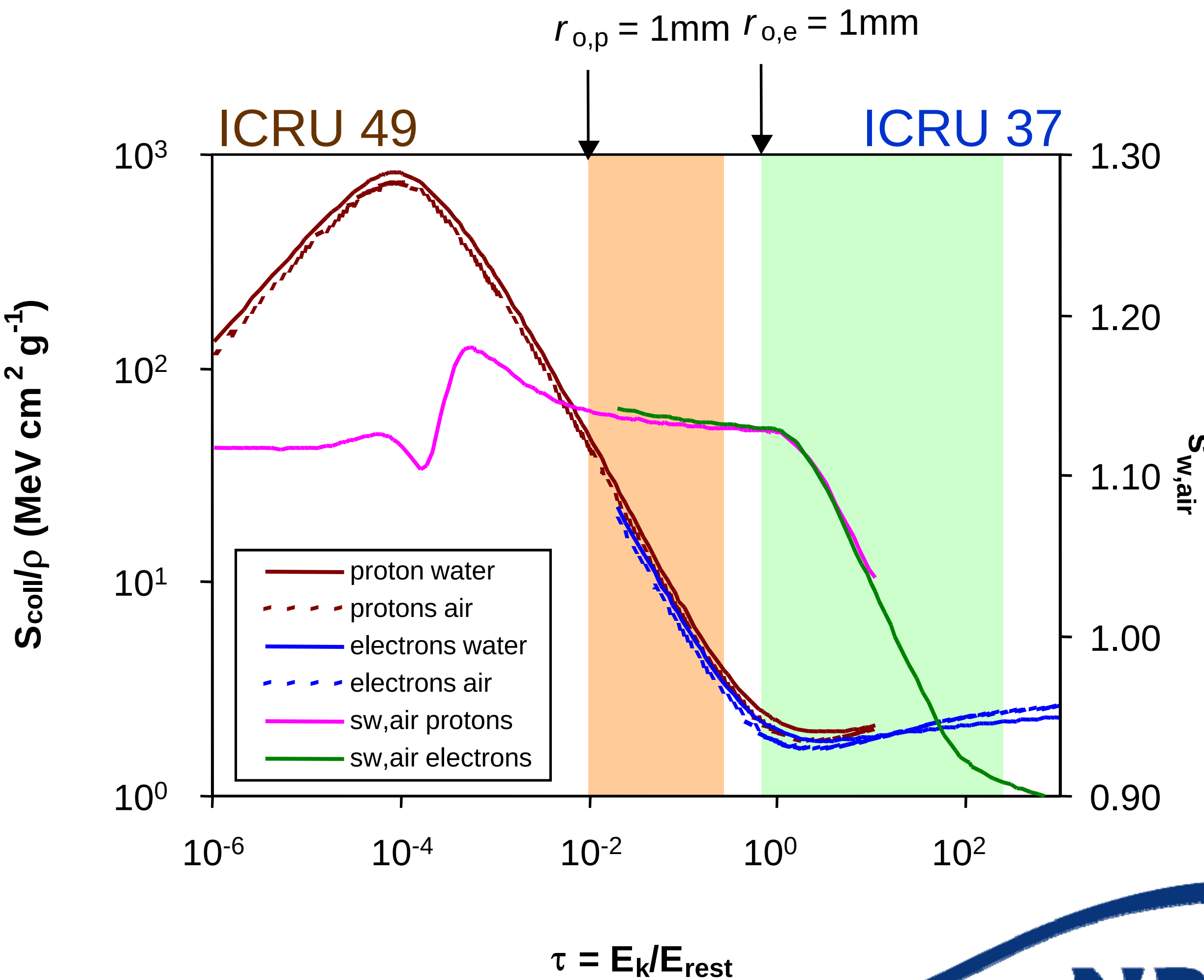
Protons and ions – the advantages



Stopping powers – protons versus electrons



Stopping powers – protons versus electrons



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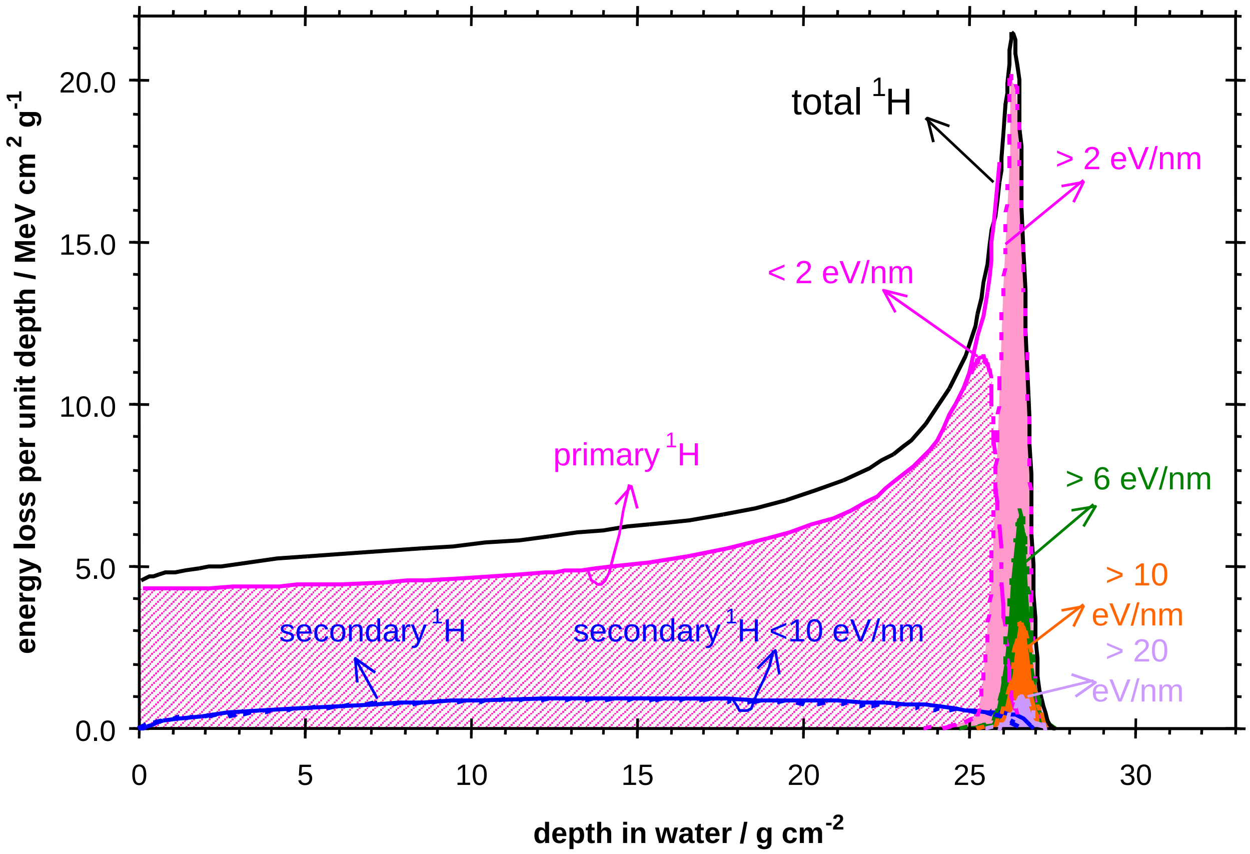
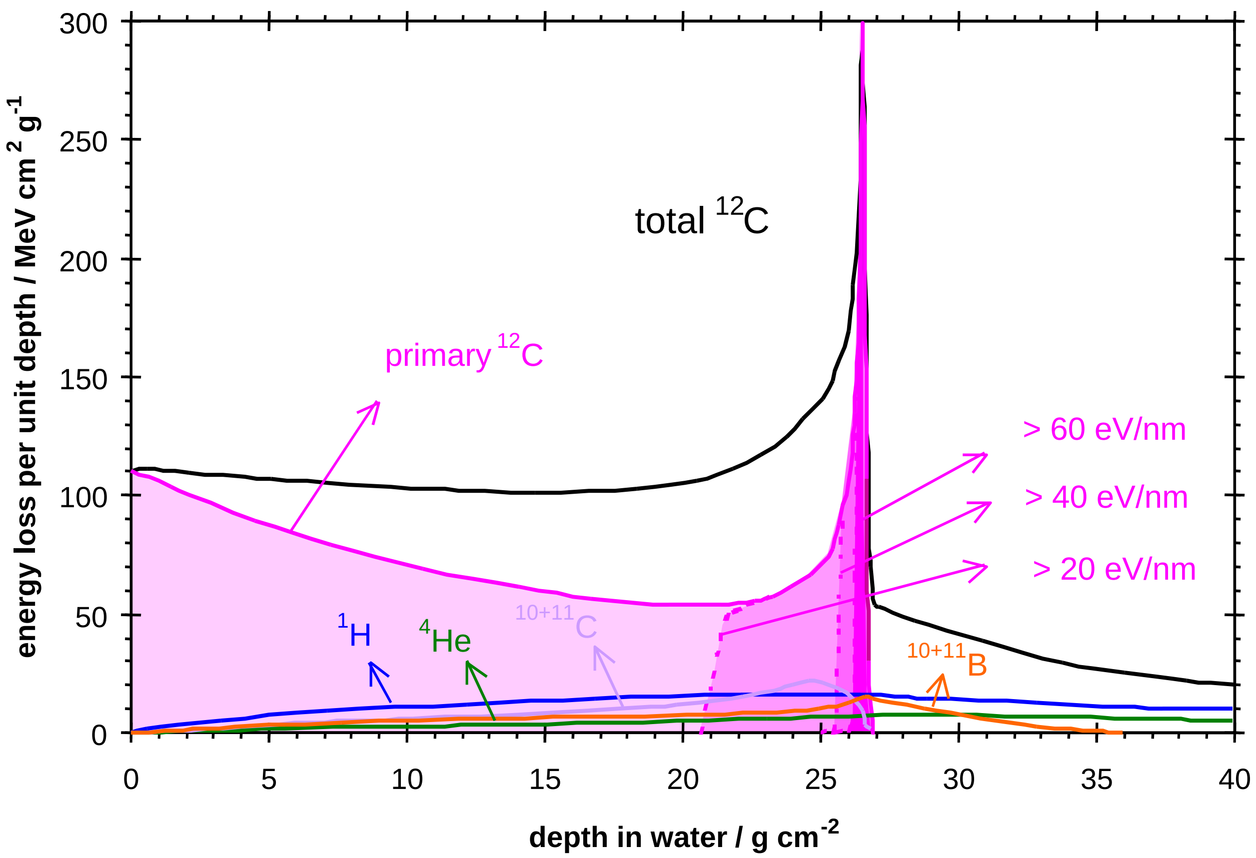
High-LET component: protons



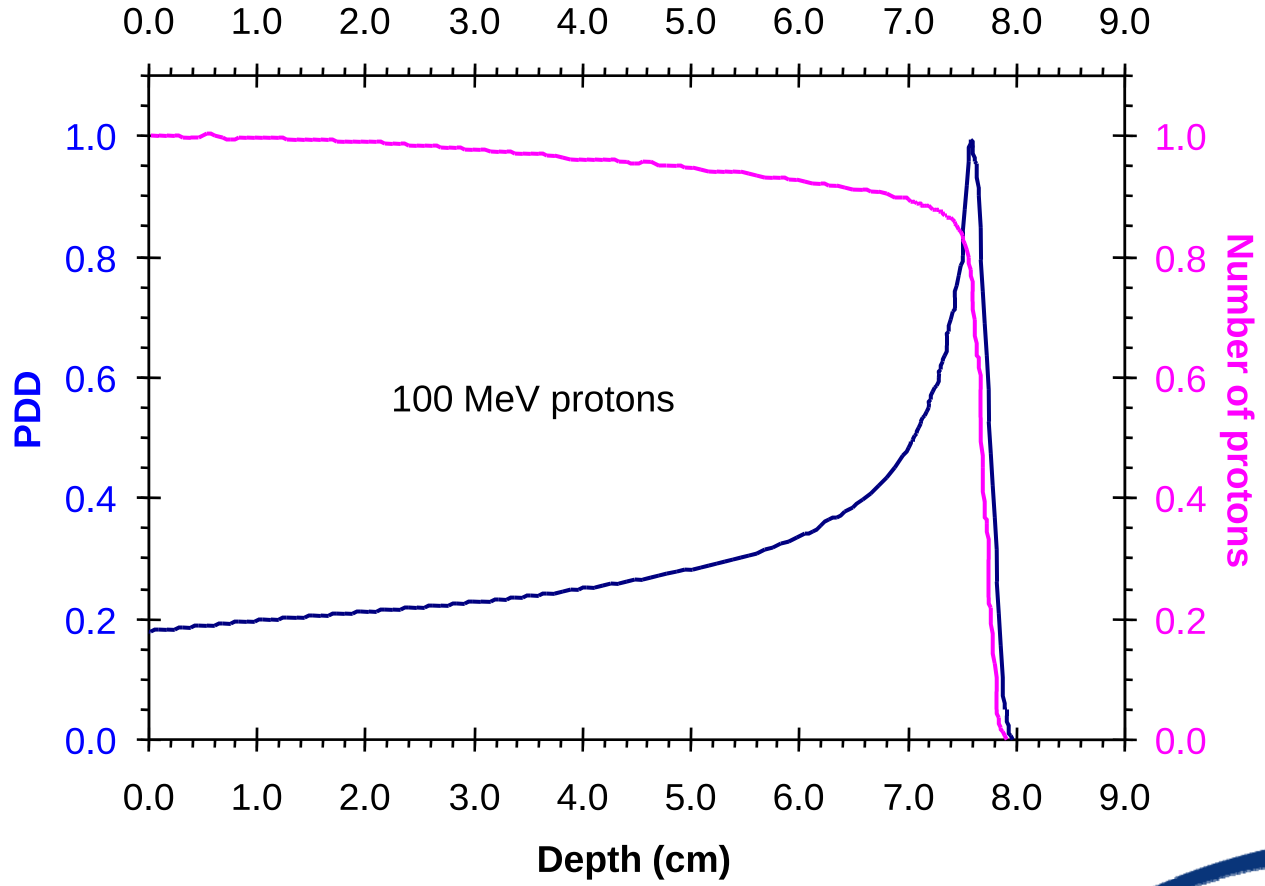
Kempe et al. (2007) *Med. Phys.* 34:183-92

High-LET component: carbon ions

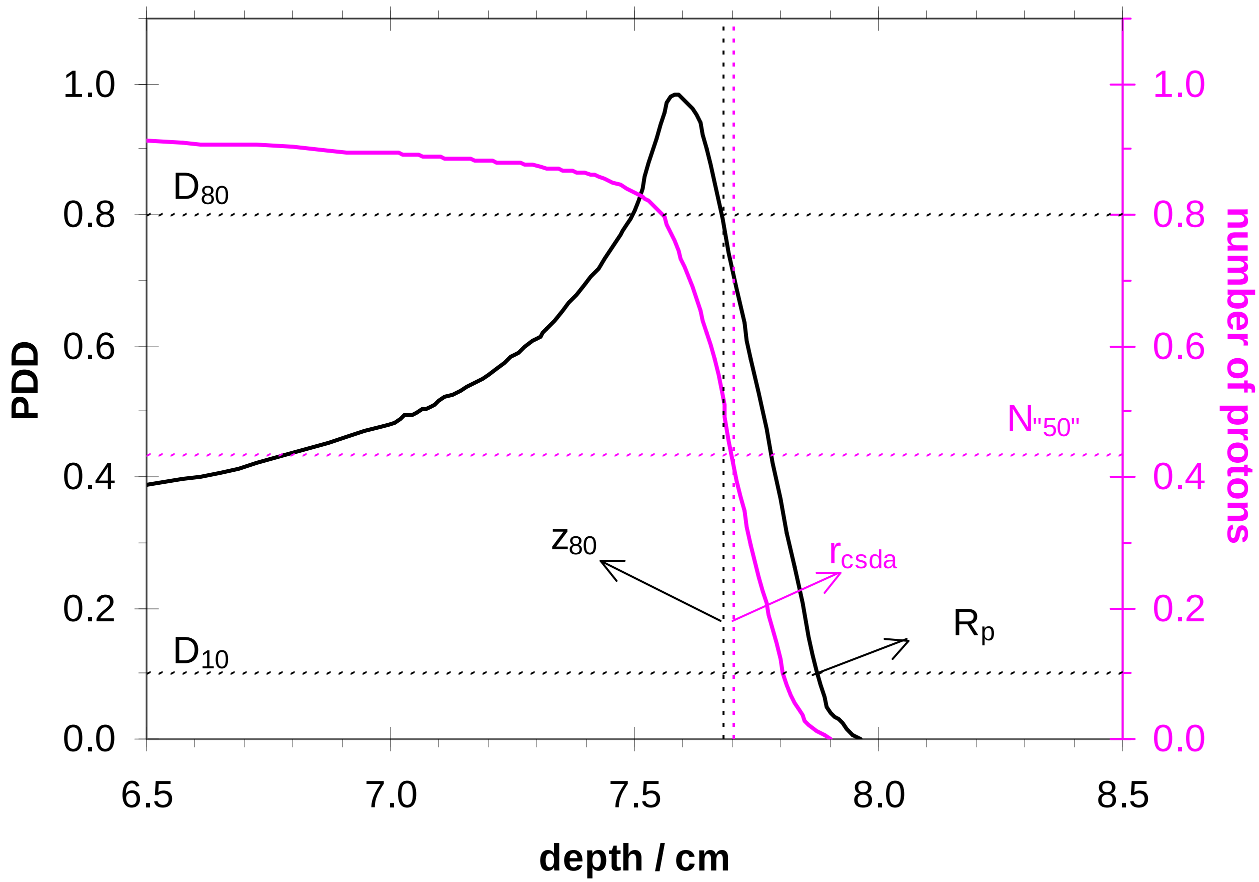


Kempe et al. (2007) *Med. Phys.* 34:183-92

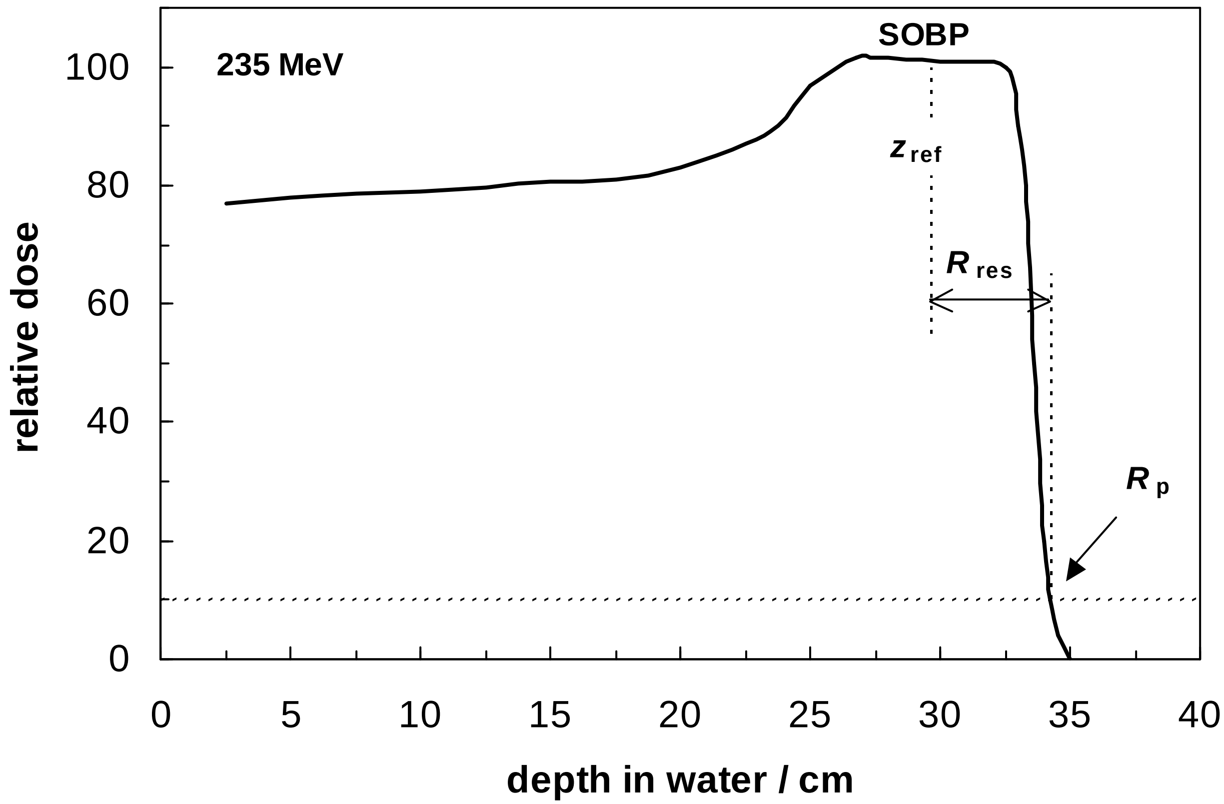
Attenuation – Nonelastic nuclear interactions



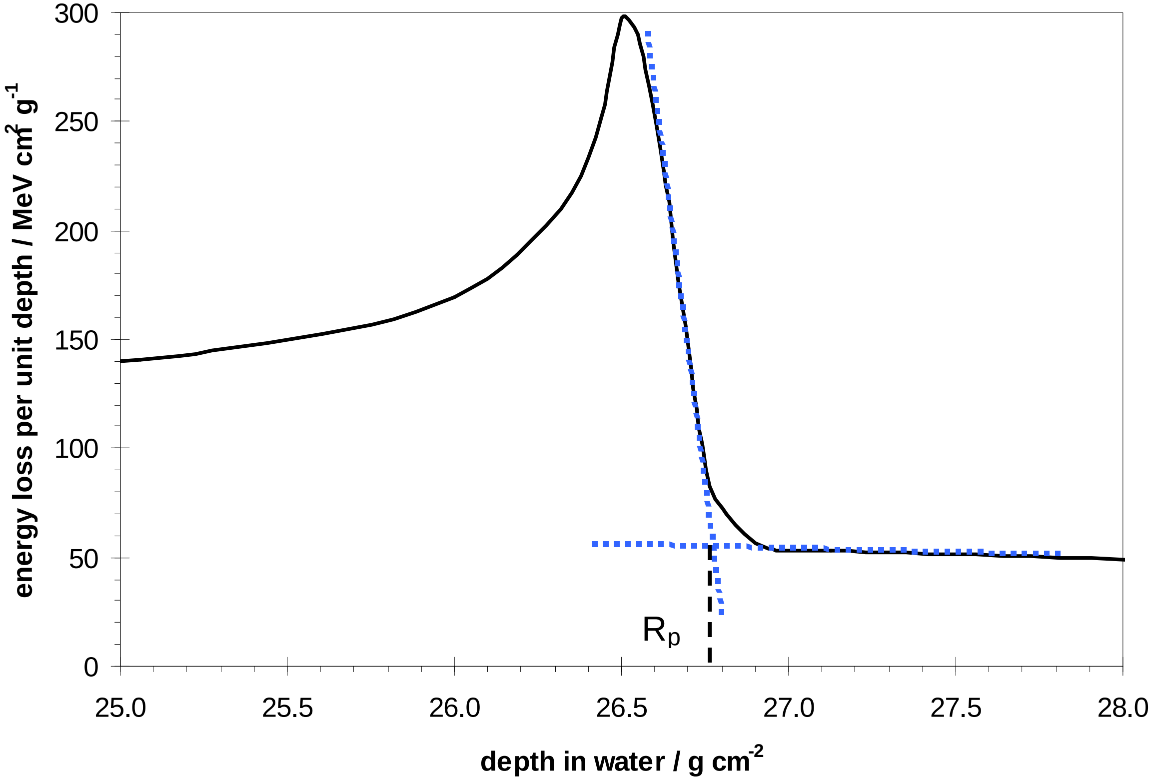
Definition of range parameters



Residual range – beam quality for protons



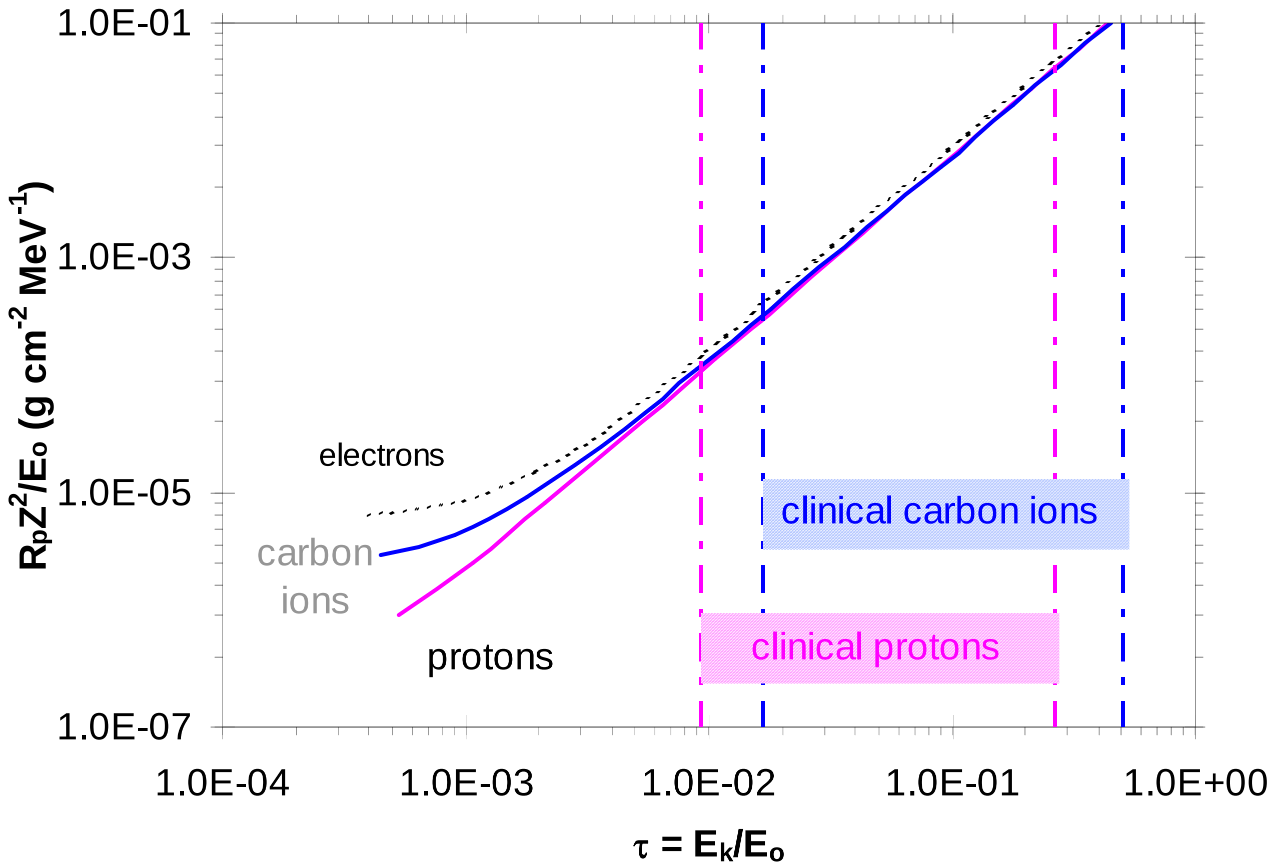
Practical range for carbon ions



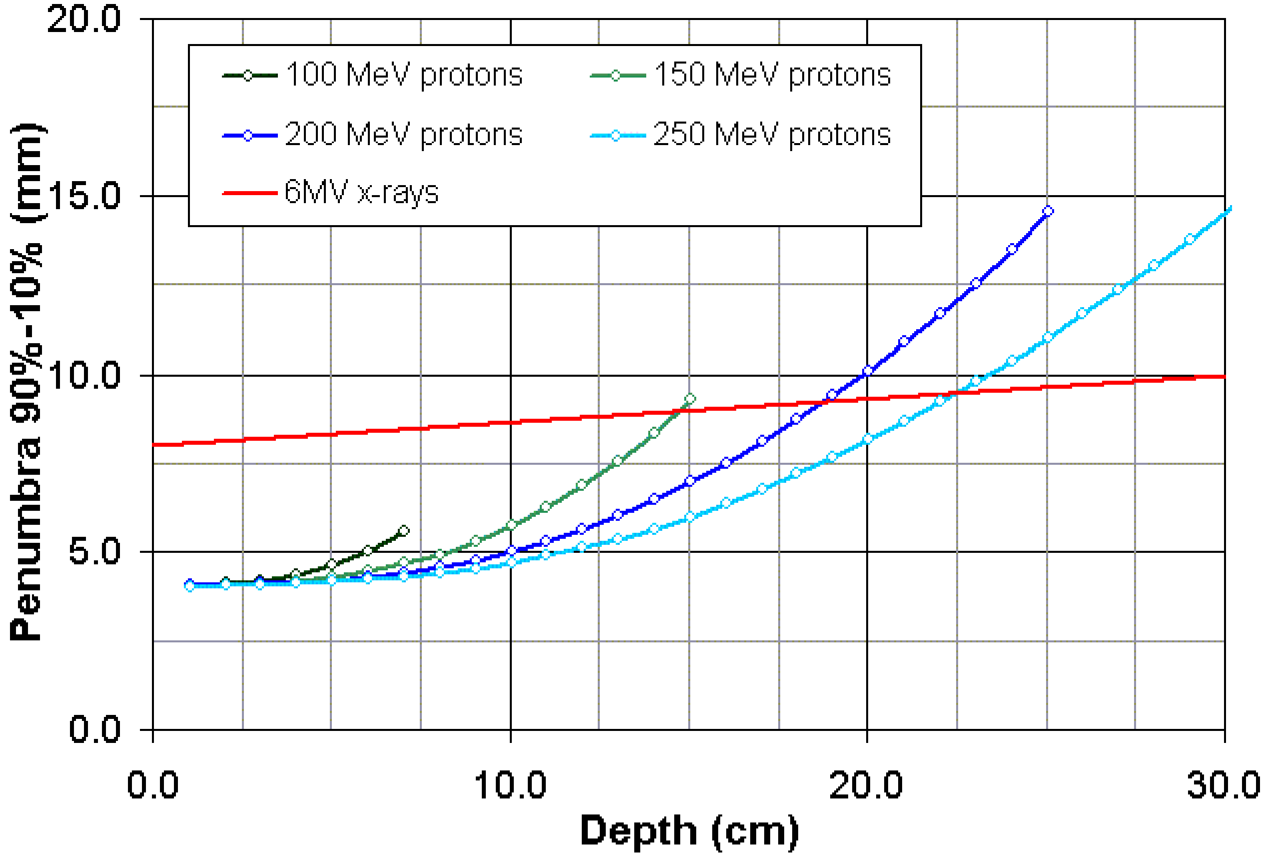
Kempe and Brahme (2008) *Med. Phys.* 35:159-70

$$R_p = C \cdot E_p{}^k + R_\Delta$$

Practical-range scaling



Scattering – protons versus photons



(Palmans 2006, Scope 15:5-12)

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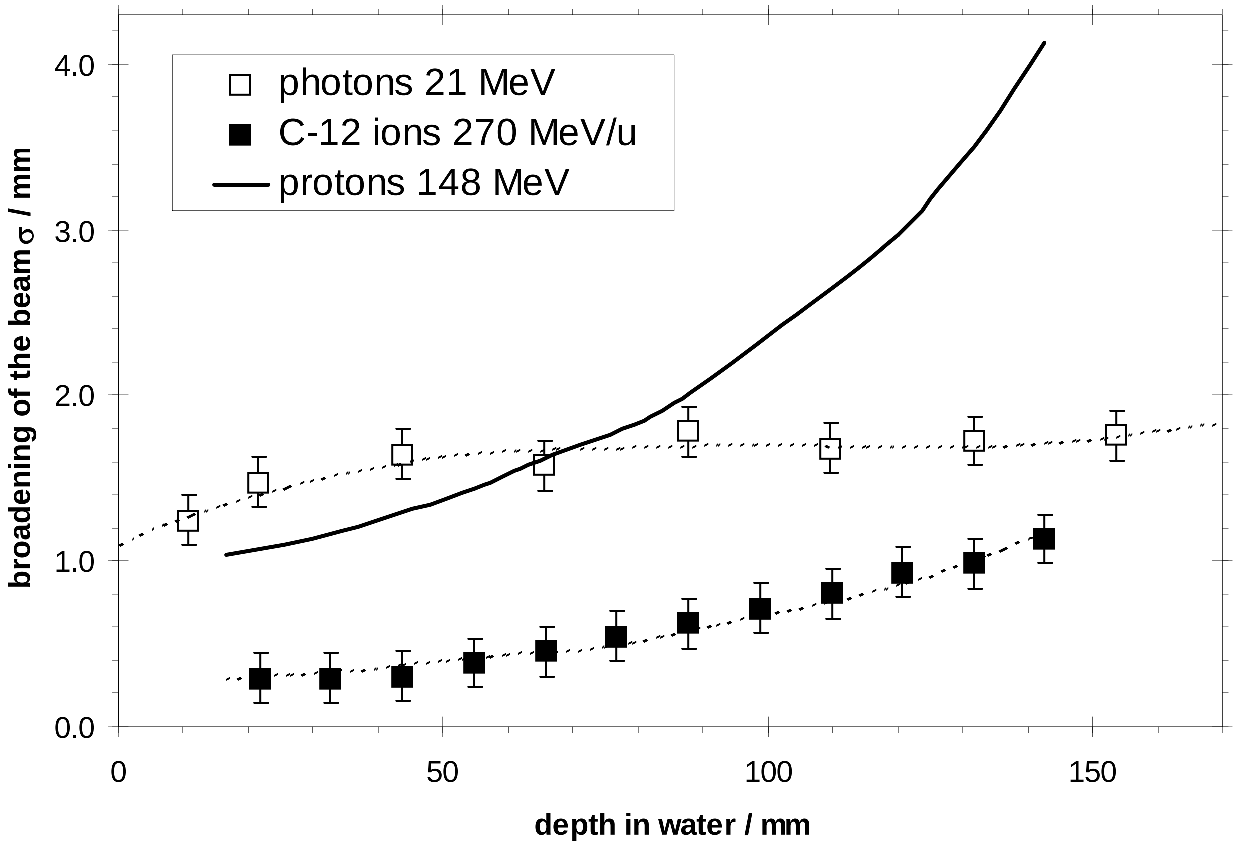
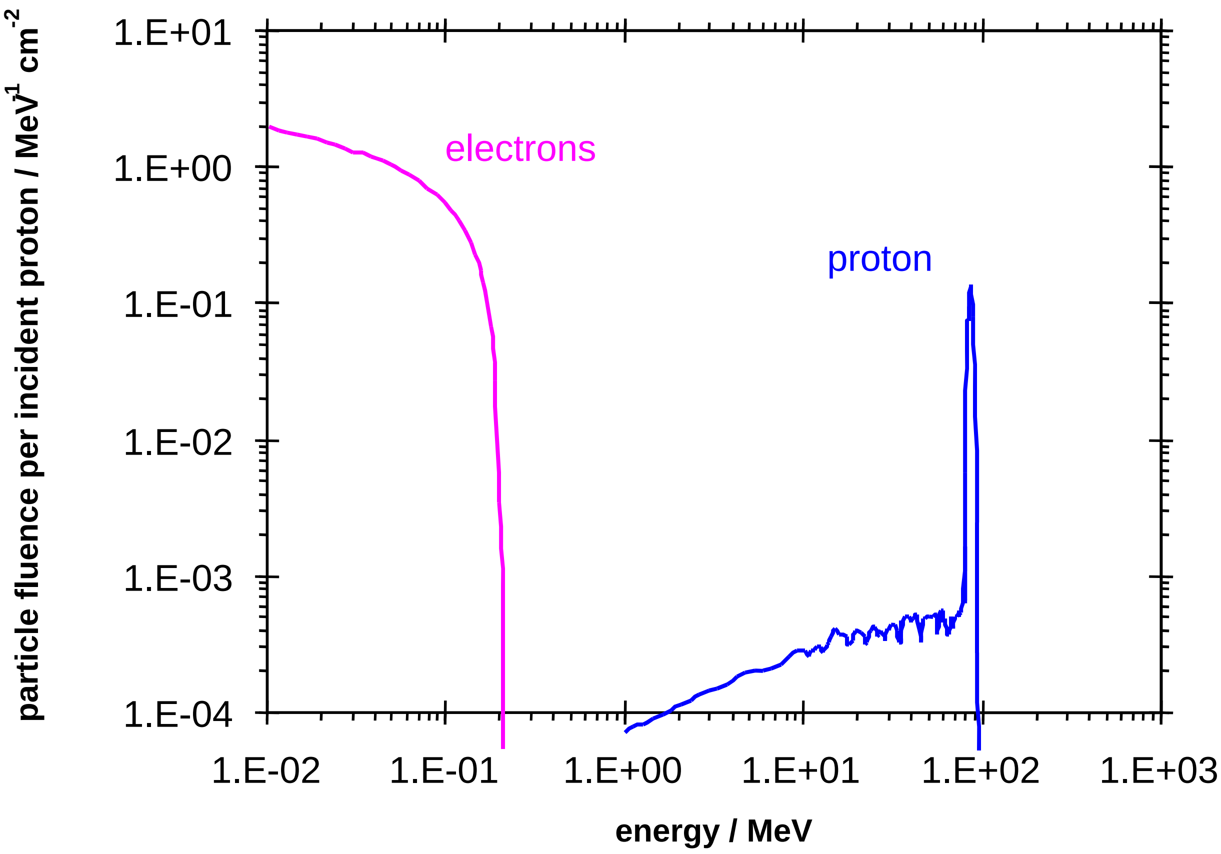
Scattering – carbon ions versus protons



Electron slowing down spectrum

200 MeV proton beam, z = 20 cm



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

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Absolute dosimetry

- Absorbed dose calorimetry
  - Water calorimetry
  - Graphite calorimetry
- Fluence based methods
  - Faraday cups
  - Activation measurement
- Calibrated ion chambers
- Alanine

Absolute dosimetry – Calorimetry

- Remember:

$$D = c.\Delta T.k_h$$

	C ($j.kg^{-1}.k^{-1}$)	α ($m^2.s^{-1}$)	$\Delta T/D$ ($mk.Gy^{-1}$)	k_h
water	4182	1.44×10^{-7}	0.24	0.96-1.02
graphite	704	0.80×10^{-4}	1.42	1.000 (?)

- Main problem in water: chemical heat defect
- Main problem in graphite: thermal diffusivity + dose conversion graphite to water

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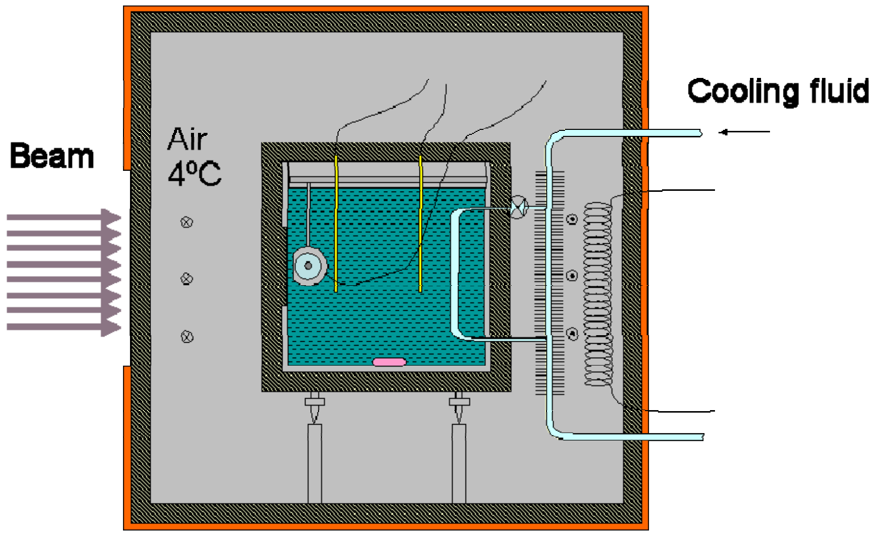
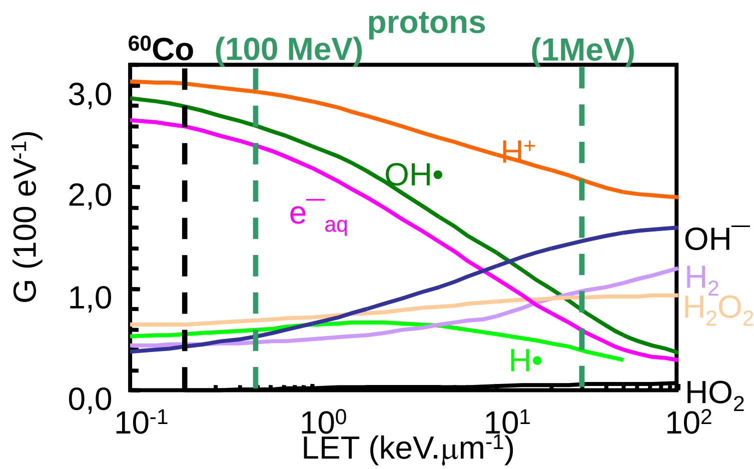
Water calorimetry / chemical heat defect protons

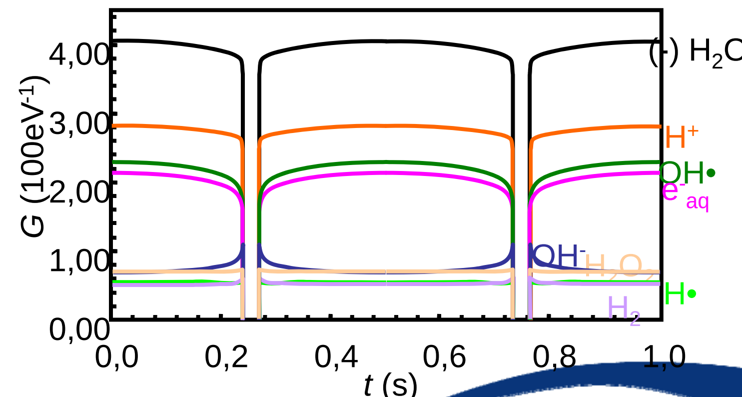
Experiment



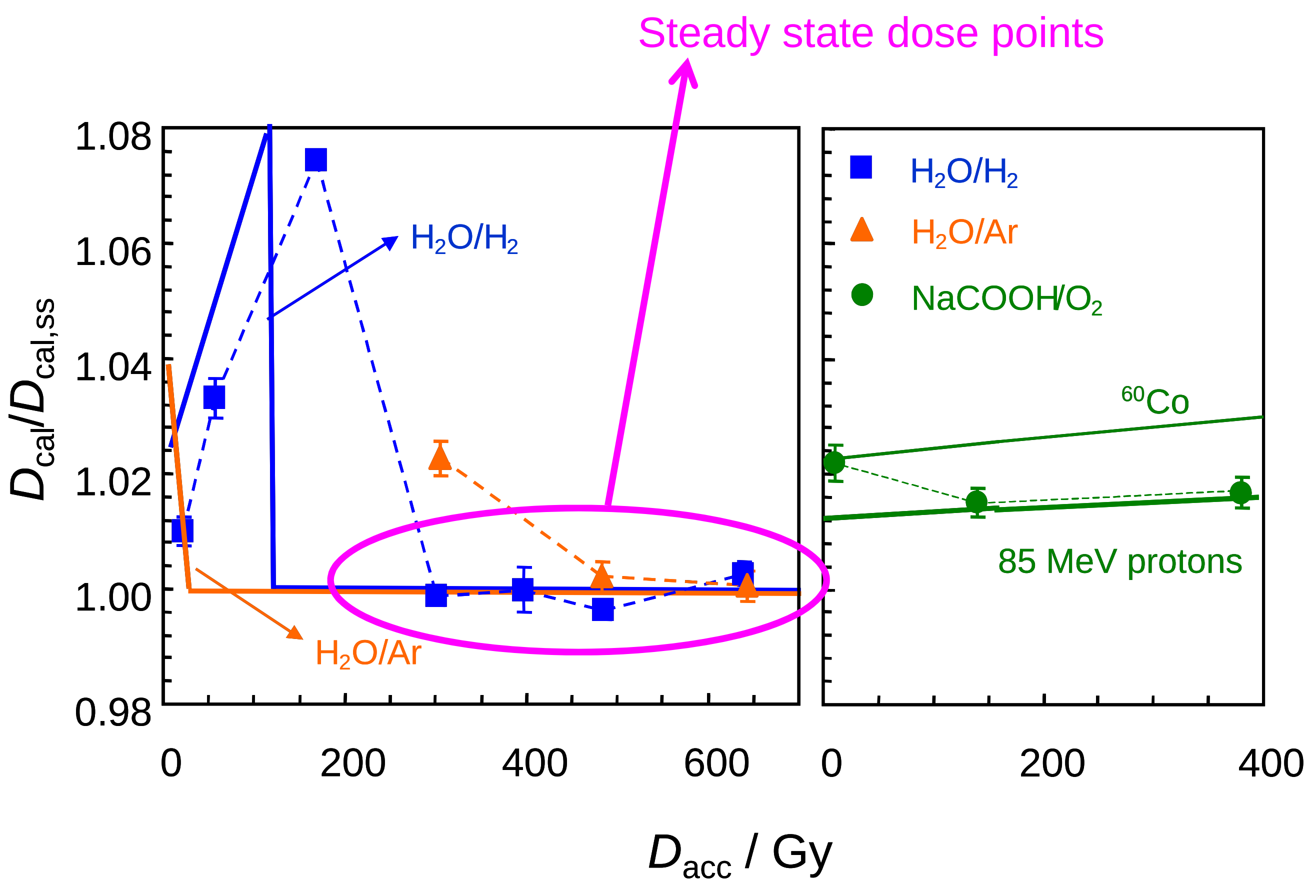
- H_20/Ar
- H_20/H_2
- $H_20+NaCOOH/O_2$

Simulations



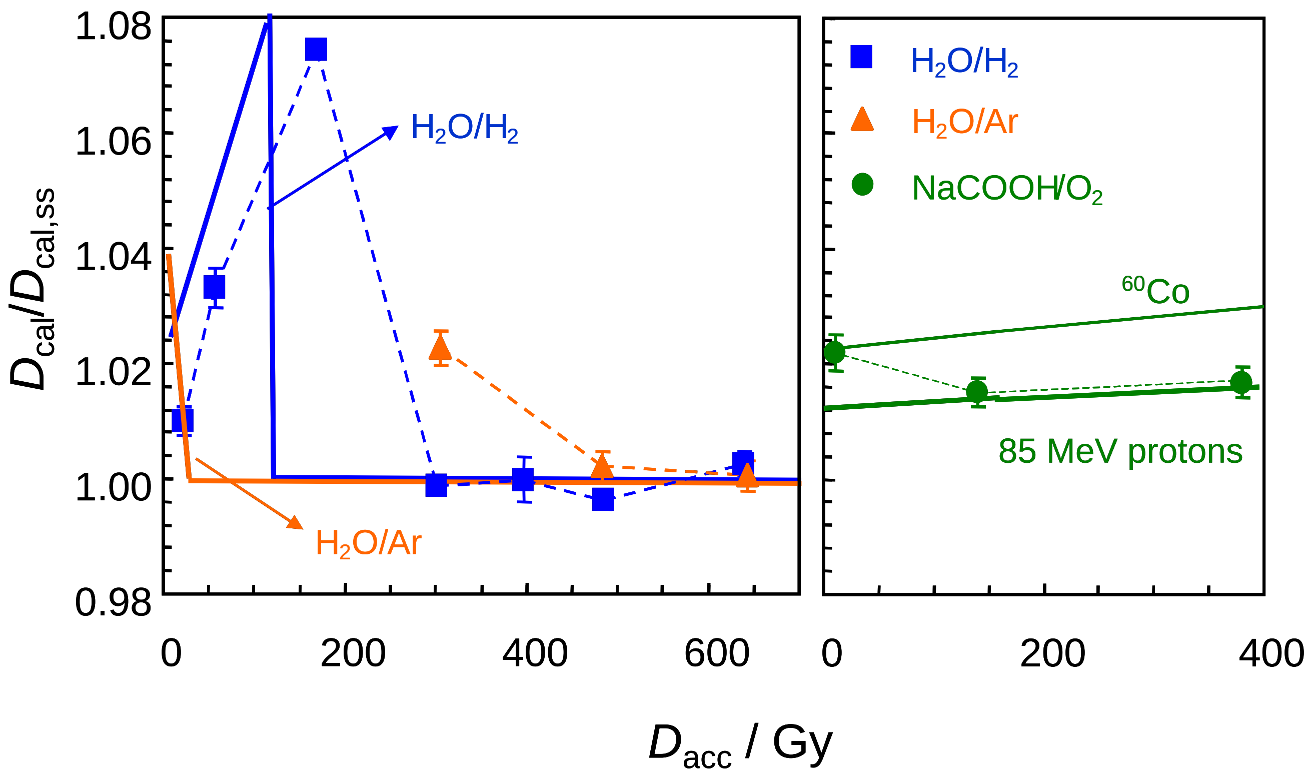


Water calorimetry / chemical heat defect protons



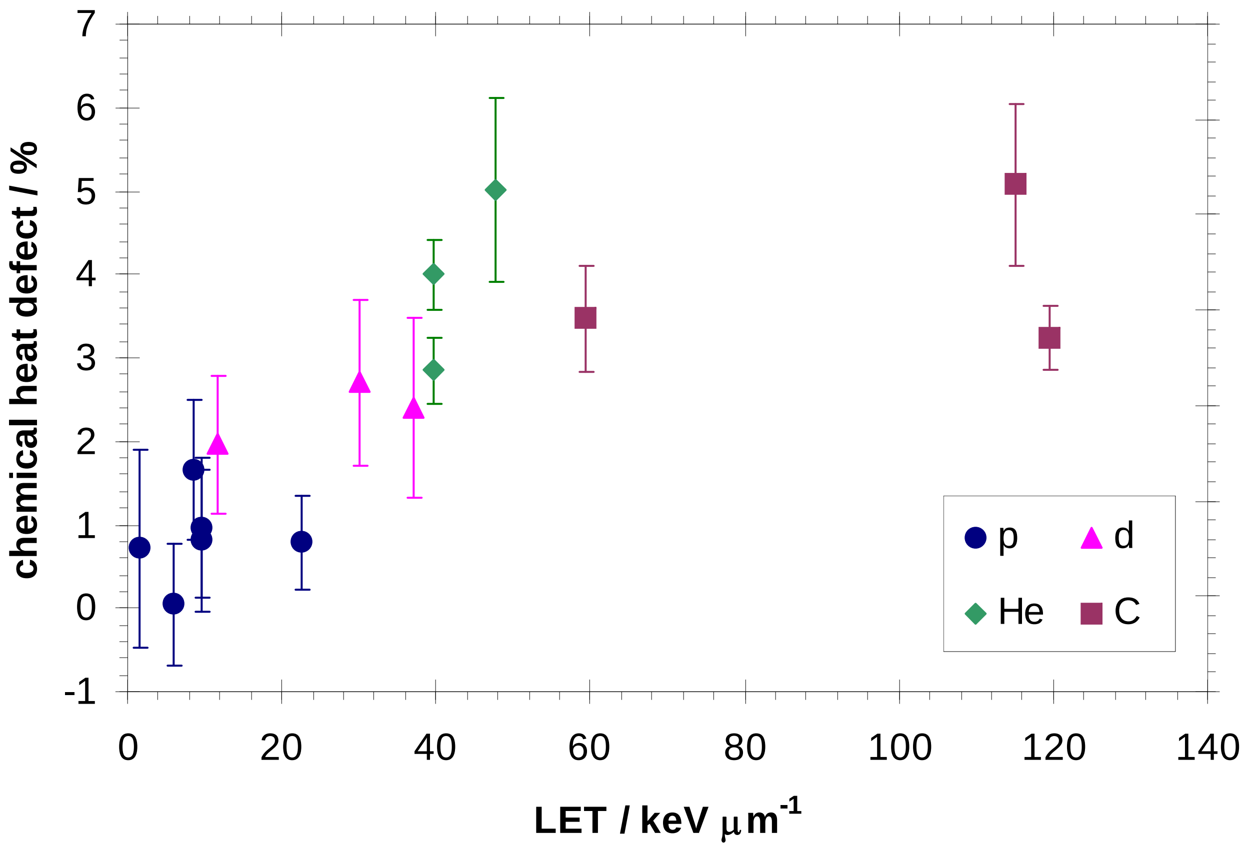
Palmans et al (1996) Med. Phys. 23:643-50

Water calorimetry / chemical heat defect protons



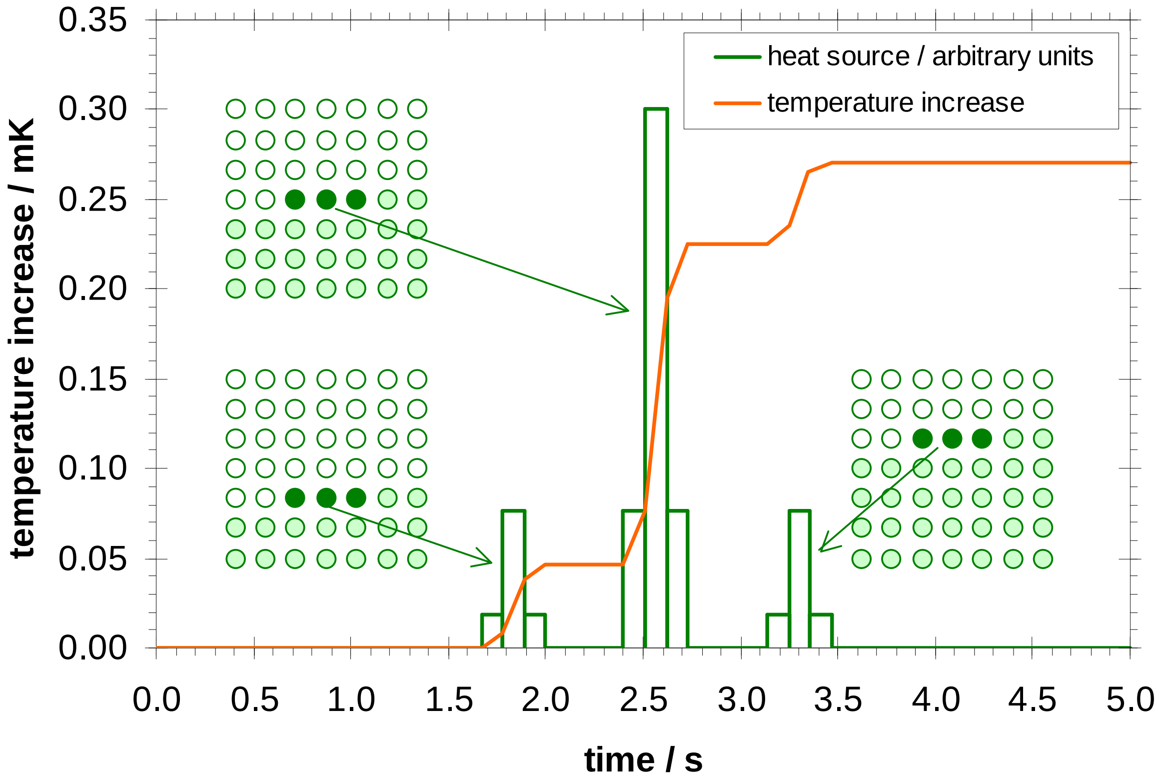
Palmans et al (1996) Med. Phys. 23:643-50

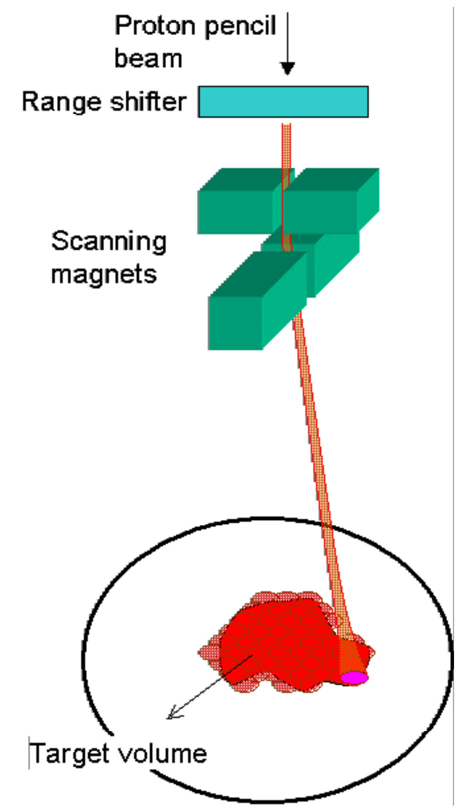
Water calorimetry / chemical heat defect ions



Brede et al. 2006 Phys. Med. Biol. 51:3667-82

Water calorimetry in spot-scanned protons

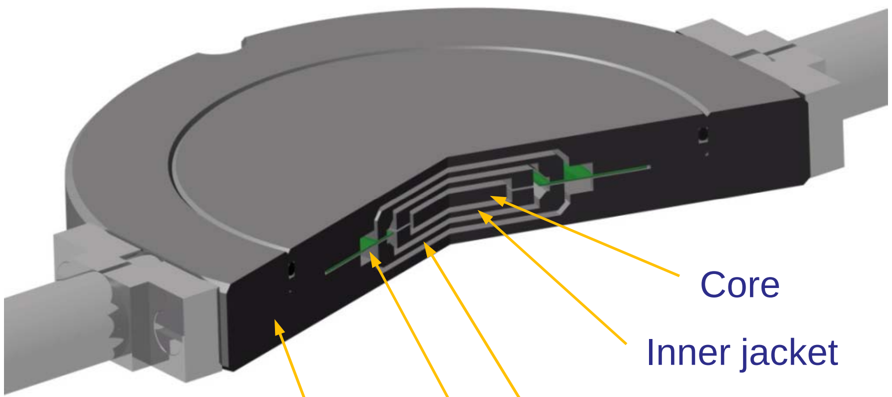




Sassowsky and Pedroni (2005) *Phys Med Biol.* 50:5381-400

Graphite calorimetry

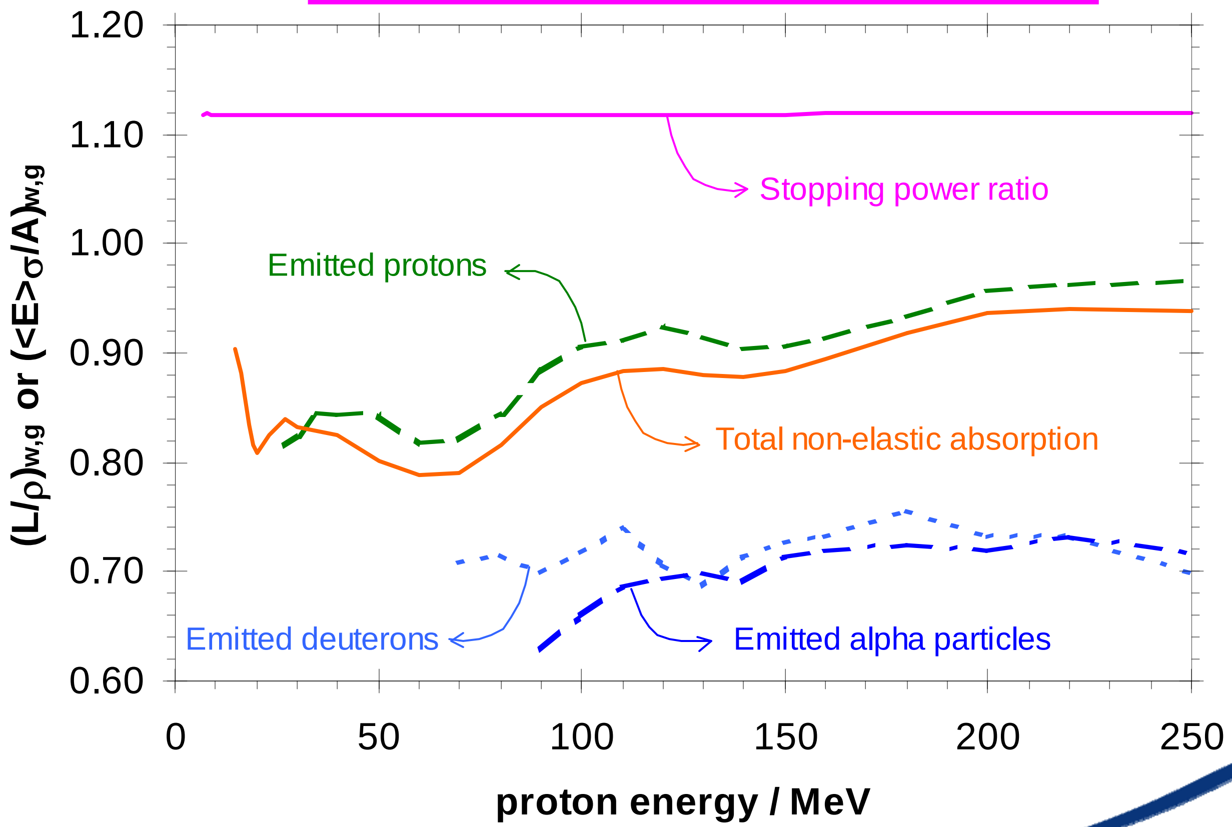
NPL primary standard level proton calorimeter under development:



Graphite calorimetry: water equivalence

interaction cross sections (ICRU49 & ICRU63)

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



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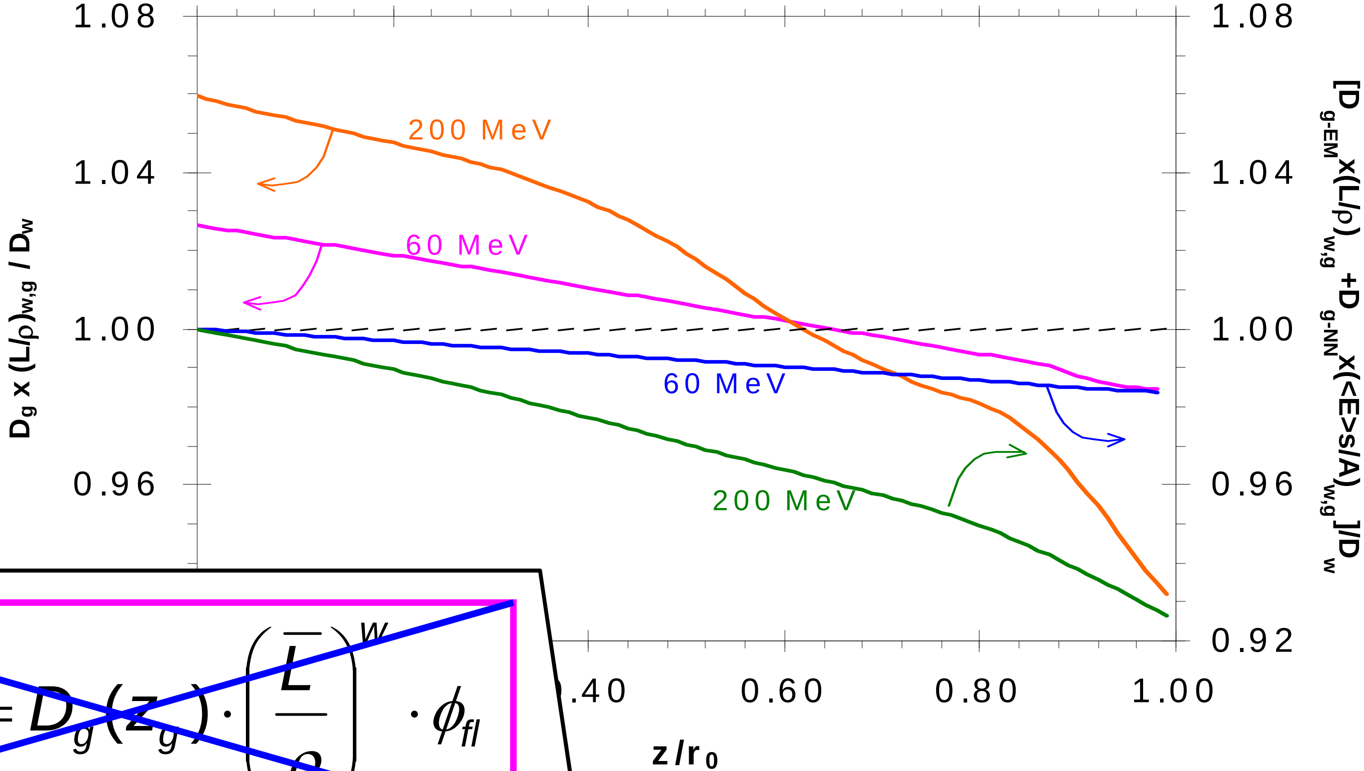
Graphite calorimetry: water equivalence

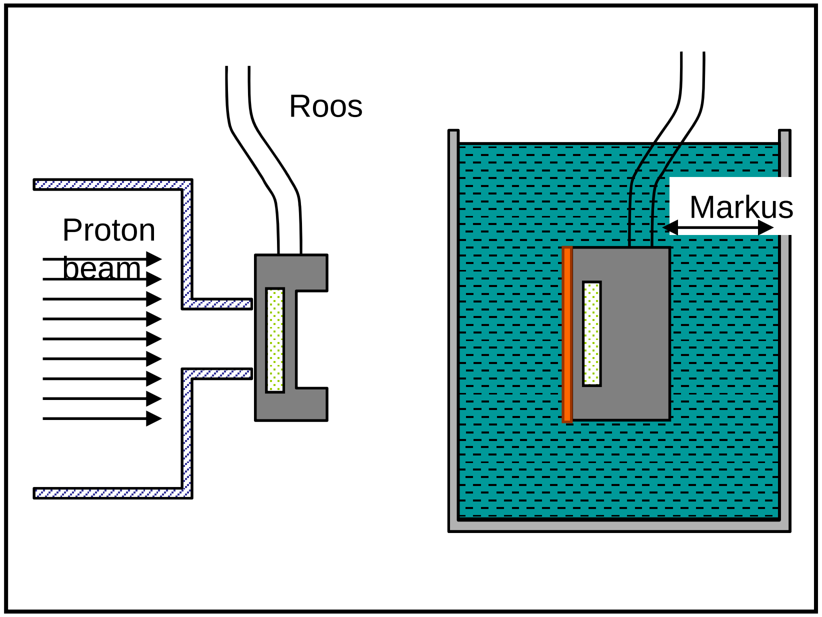
interaction cross sections (ICRU49 & ICRU63)

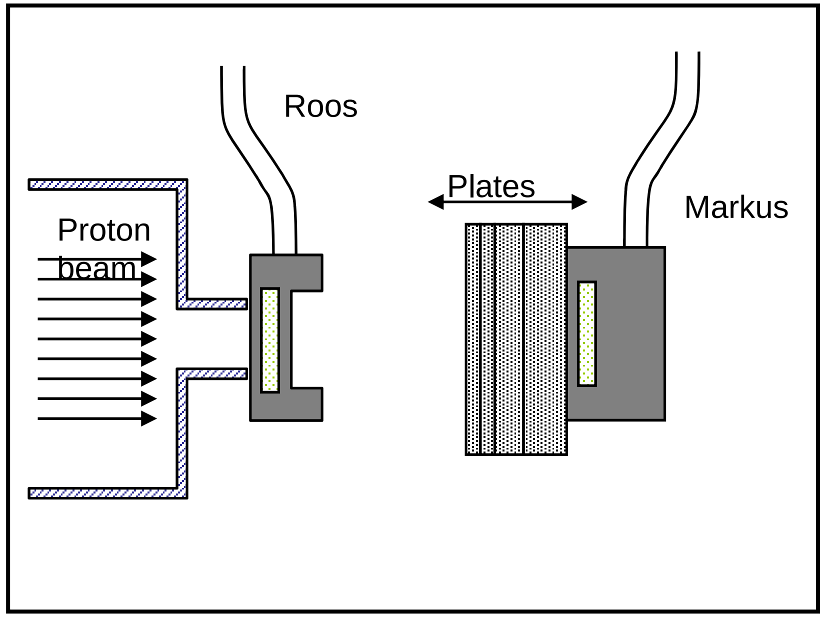


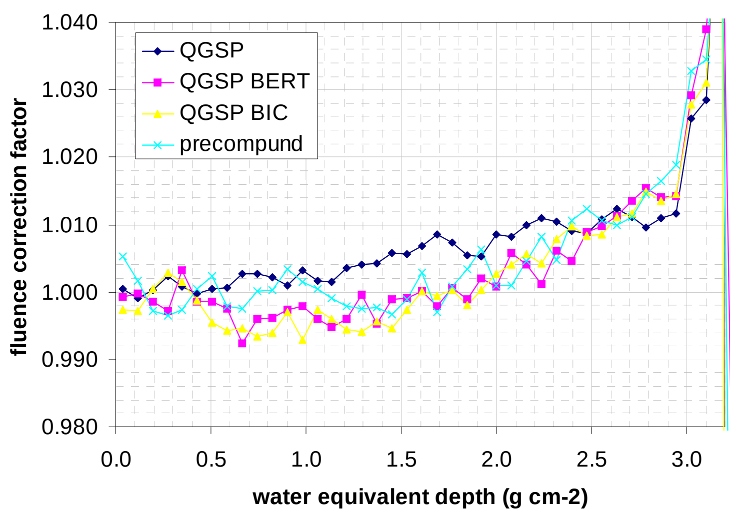
$$D_w(z_w) = D_g(z_g) \cdot \left(\frac{\overline{L}}{\rho}\right)_g^w \cdot \phi_{fl}$$

$$D_w(z_w) = \left[D_{g-EM}(z_g) \cdot \left(\frac{\overline{L}}{\rho}\right)_g^w + D_{g-NN}(z_g) \cdot \left(< E > \cdot \frac{\sigma}{A} \right)_g^w \right] \cdot \phi_{fl}$$

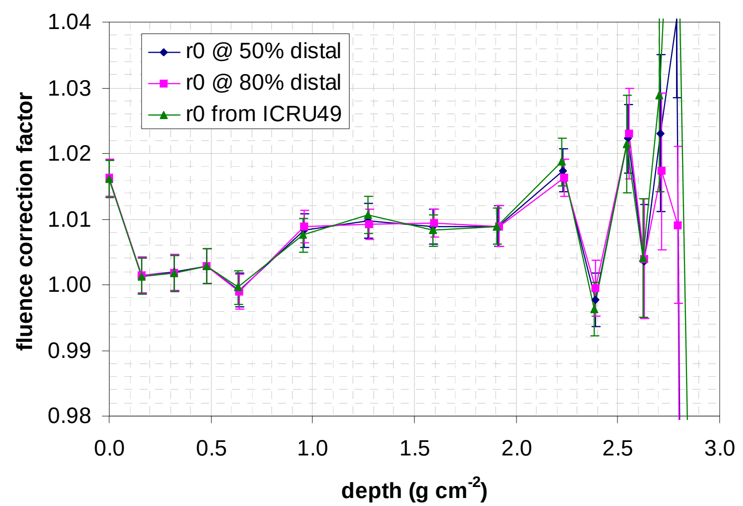
Graphite calorimetry: water equivalence





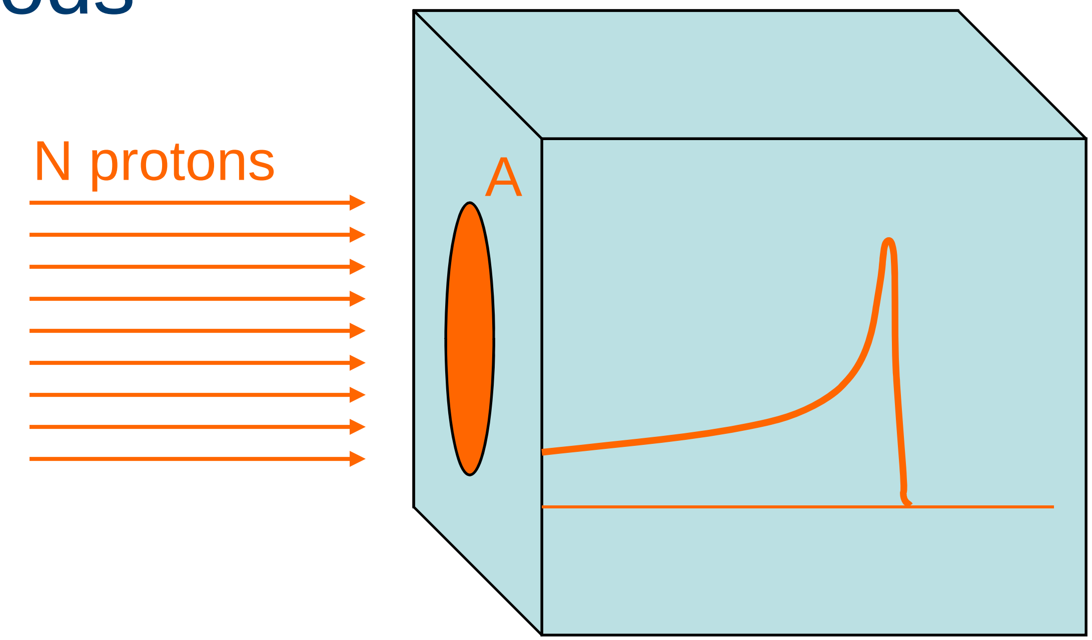


simulation



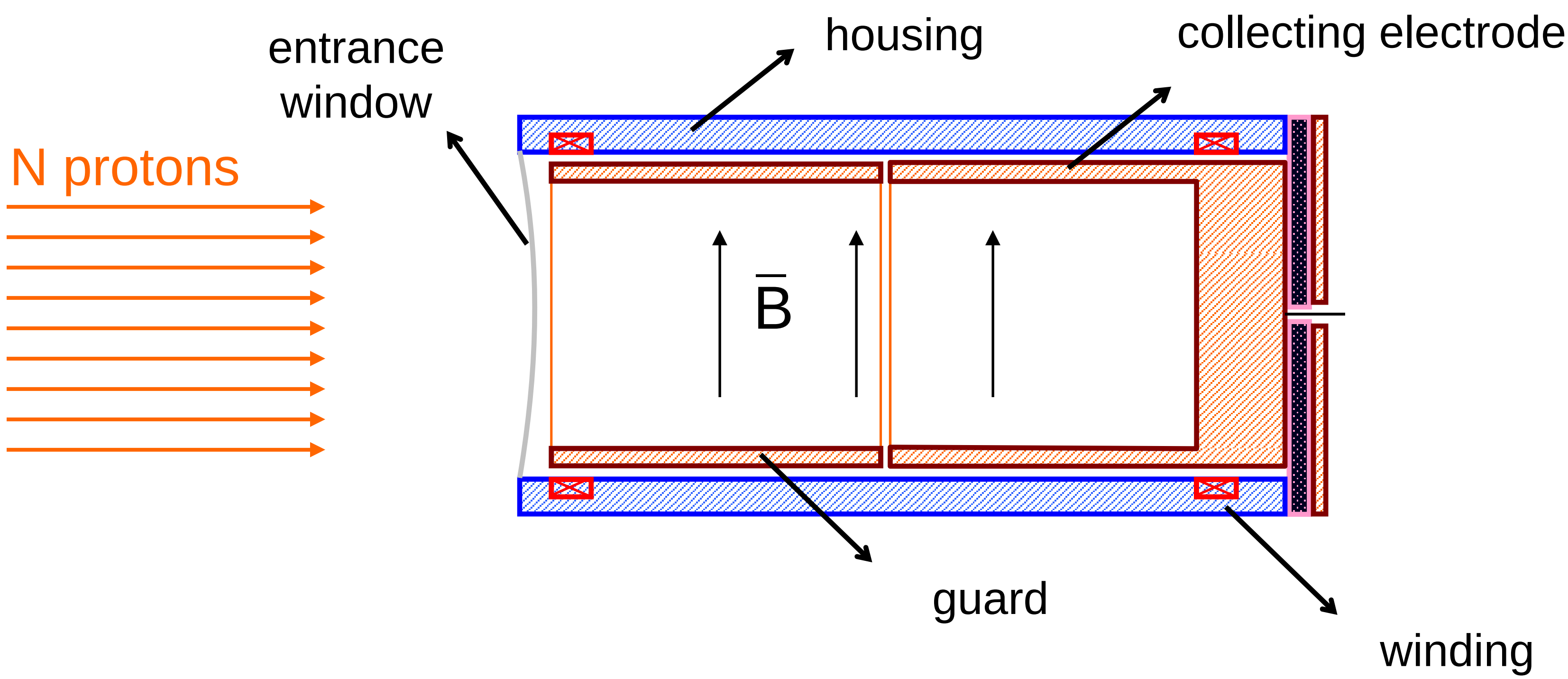
measurement

Absolute dosimetry – Fluence based methods



$$D_{med} = \frac{N}{A} \cdot \left[\frac{S}{\rho} \right]_{med}$$

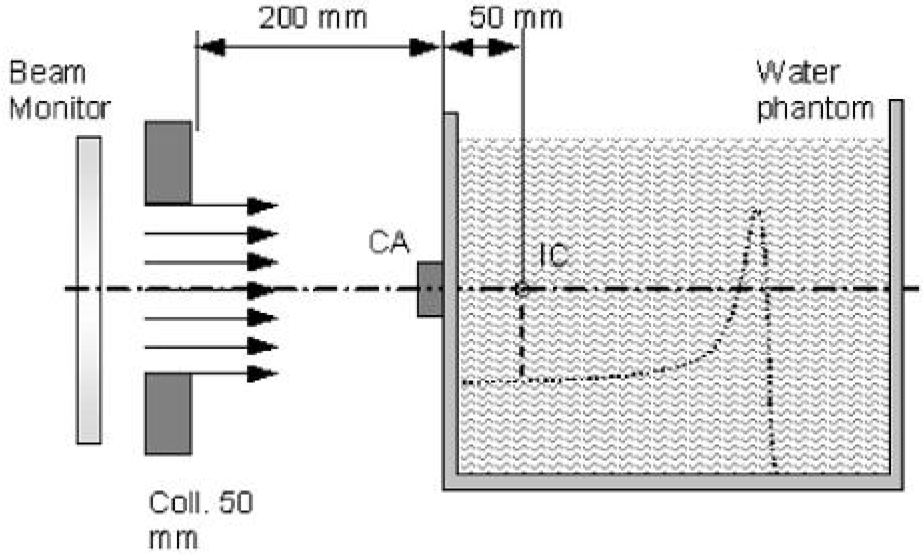
Absolute dosimetry – Faraday cup



(e.g. Pedroni et al 2005, Phys Med Biol 50:541-61,
Grusell et al 1995, Phys Med Biol 40:1831-40)

Absolute dosimetry – Activation measurement

- $^{12}C(p,pn)^{11}C$ reaction
- 4π $\beta\gamma$-coincidence counting



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

Absolute dosimetry – Ion chambers

- TRS-398
- ICRU report 78

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

$$k_Q = \frac{\left[w_{air} \cdot \left(\frac{\bar{L}}{\rho}\right)_{air}^{w} \cdot P_{wall} P_{cel} P_{repl} \right]_p}{\left[W_{air} \cdot \left(\frac{\bar{L}}{\rho}\right)_{air}^{w} \cdot P_{wall} P_{cel} P_{repl} \right]_{^{60}Co}}$$

- $(w_{air})_p$ = 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
- $[P_{wall} P_{cel} P_{repl}]_p = 1$

Ion chambers : w_{air} values from calorimetry

$$k_Q = \frac{N_{D,w,p}}{N_{D,w,c}} = \frac{D_{w,cal,p}/M_p}{N_{D,w,c}} = \frac{\left[w_{air} \cdot \left(\frac{\bar{L}}{\rho} \right)_{air}^{w} \cdot P_{wall} P_{cel} P_{repl} \right]_p}{\left[W_{air} \cdot \left(\frac{\bar{L}}{\rho} \right)_{air}^{w} \cdot P_{wall} P_{cel} P_{repl} \right]_{^{60}Co}}$$

$$(w_{air})_p = \frac{D_{w,cal,p}}{M_p} \cdot \frac{\left[W_{air} \cdot \left(\frac{\bar{L}}{\rho} \right)_{air}^{w} \cdot P_{wall} P_{cel} P_{repl} \right]_{^{60}Co}}{N_{D,w,^{60}Co} \cdot \left[\left(\frac{\bar{L}}{\rho} \right)_{air}^{w} \cdot P_{wall} P_{cel} P_{repl} \right]_p}$$

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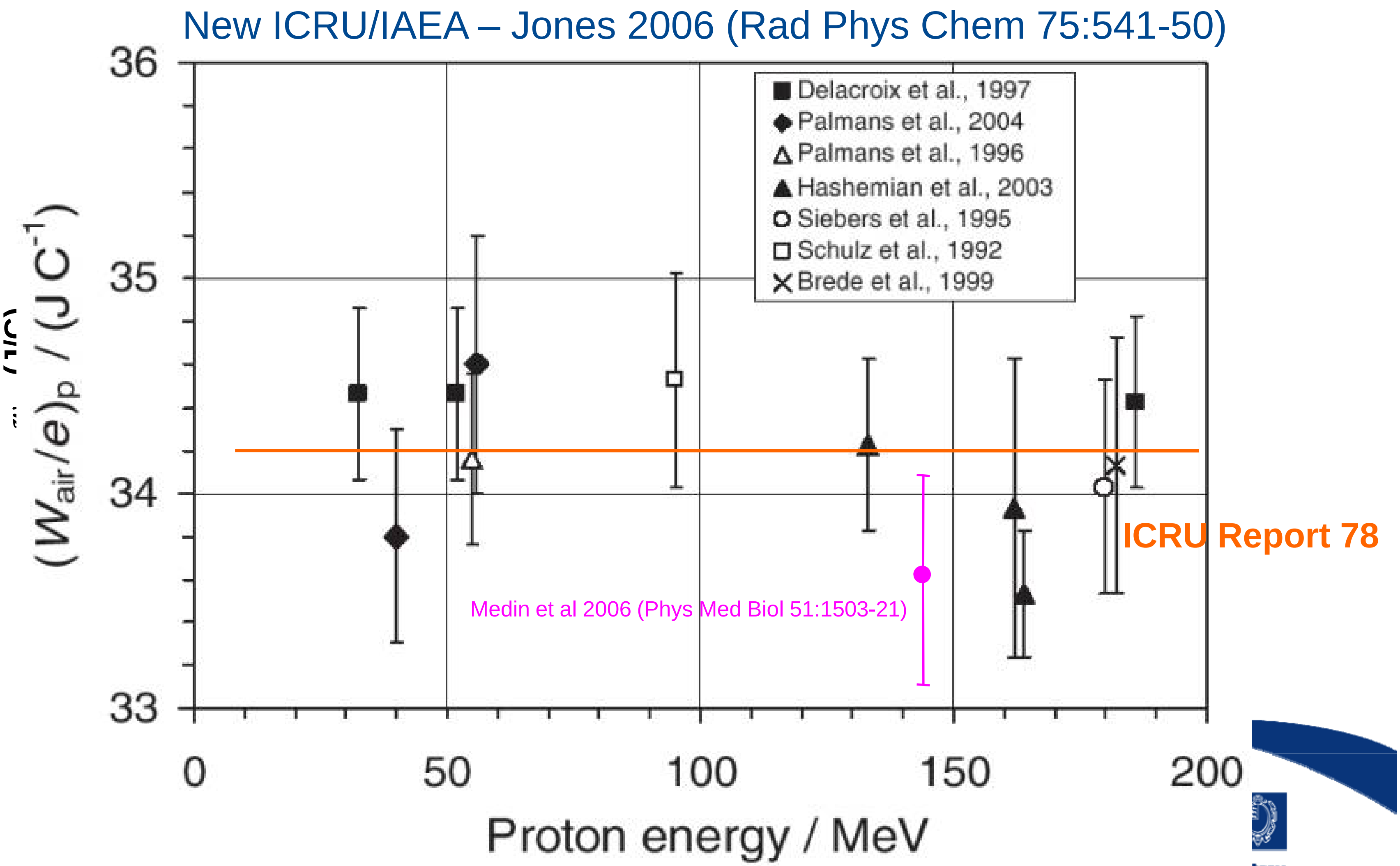
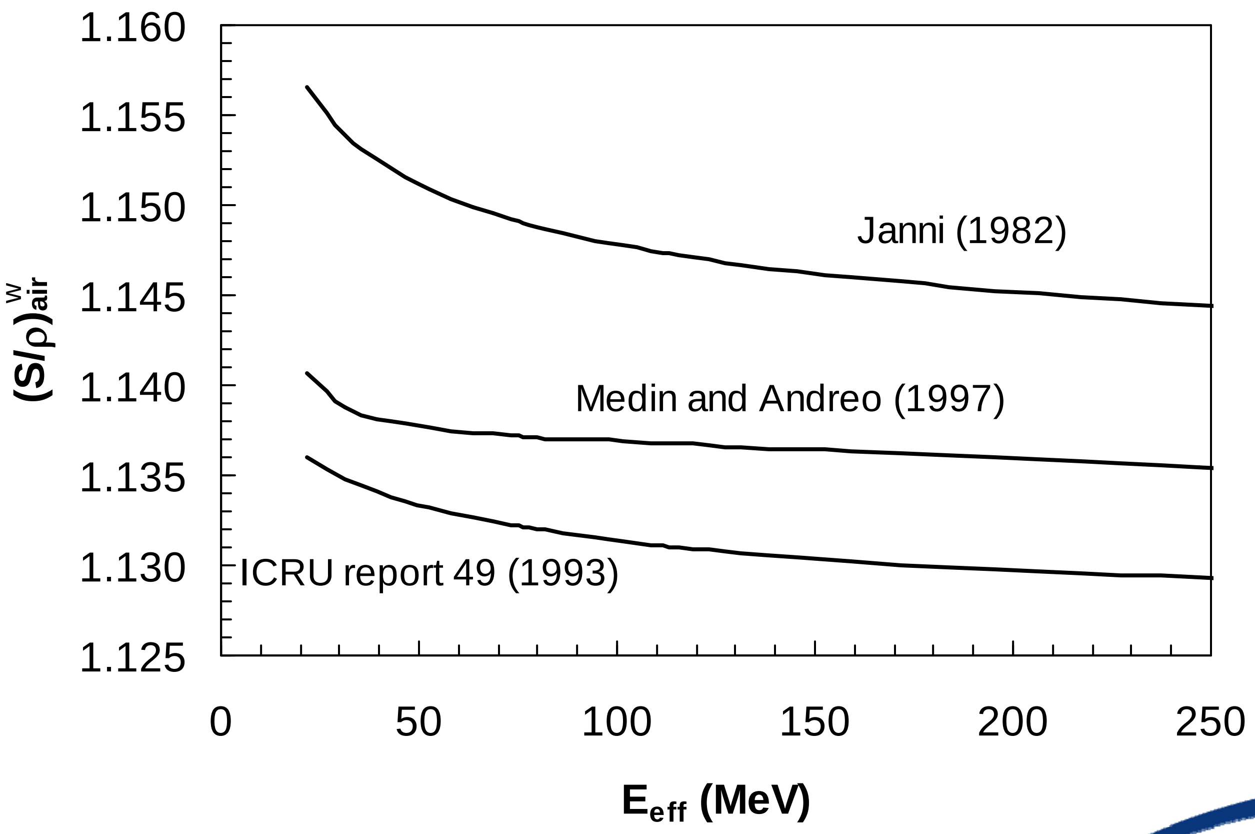
Ion chambers : w_{air} values from calorimetry



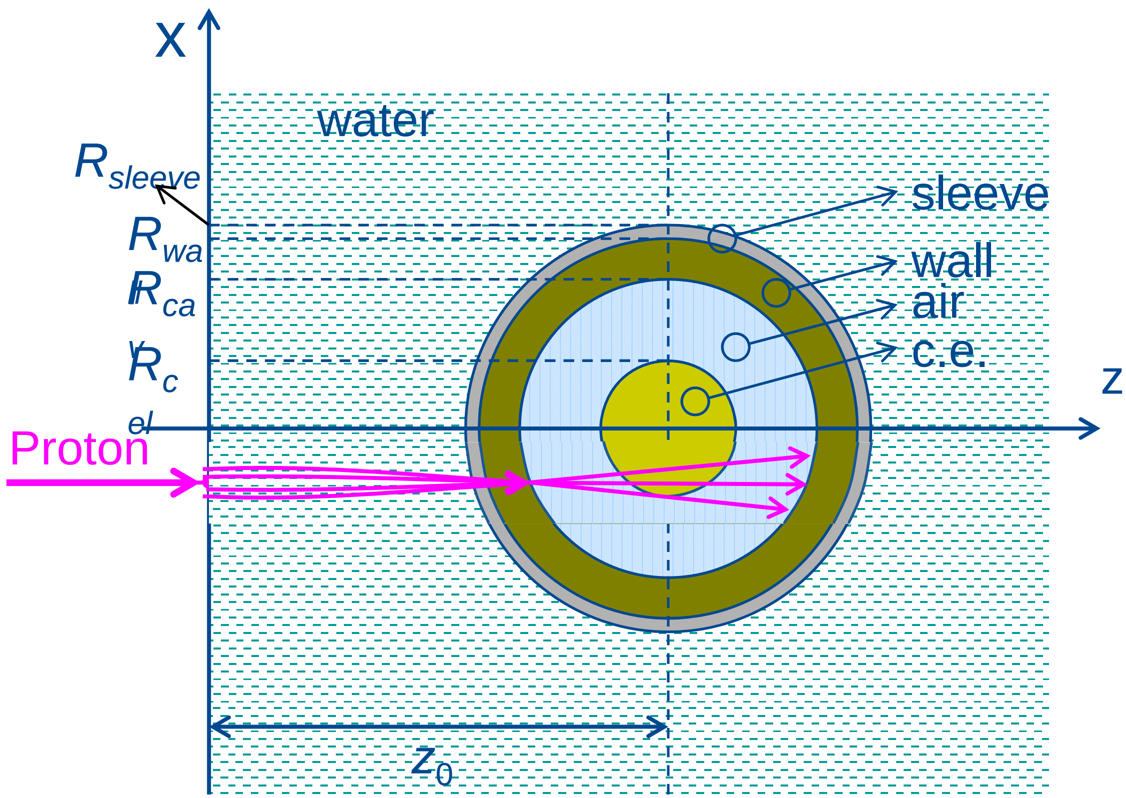
Ion chambers : water to air stopping power ratio



Ion chambers – perturbation correction factors

- Gradient correction factors
- Secondary electron correction factors

Ion chambers – analytical
Integrating the depth dose curve

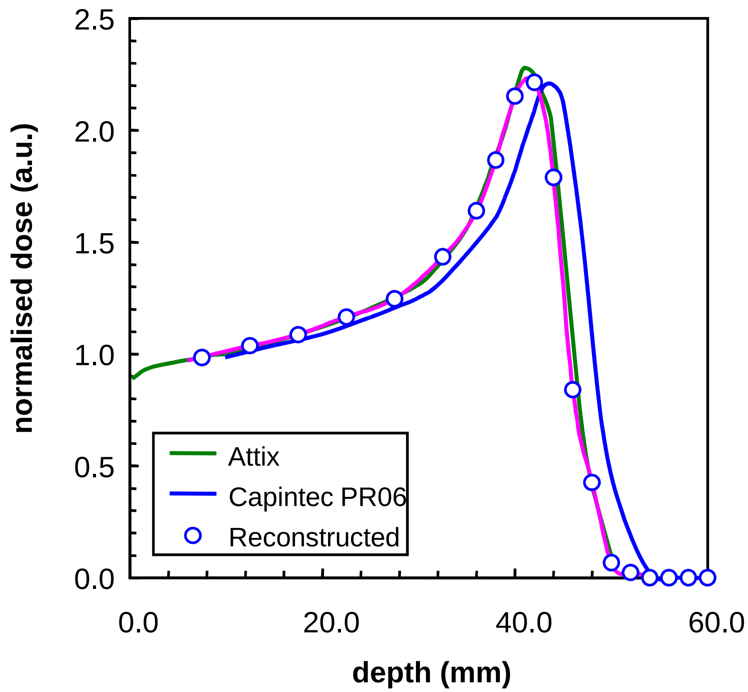


(Palmans 2006, Phys Med Biol. 51:3483-501
& Palmans 2006 NPL report DQL-RD-002)

Ion chambers – Comparison with experiment PDD's

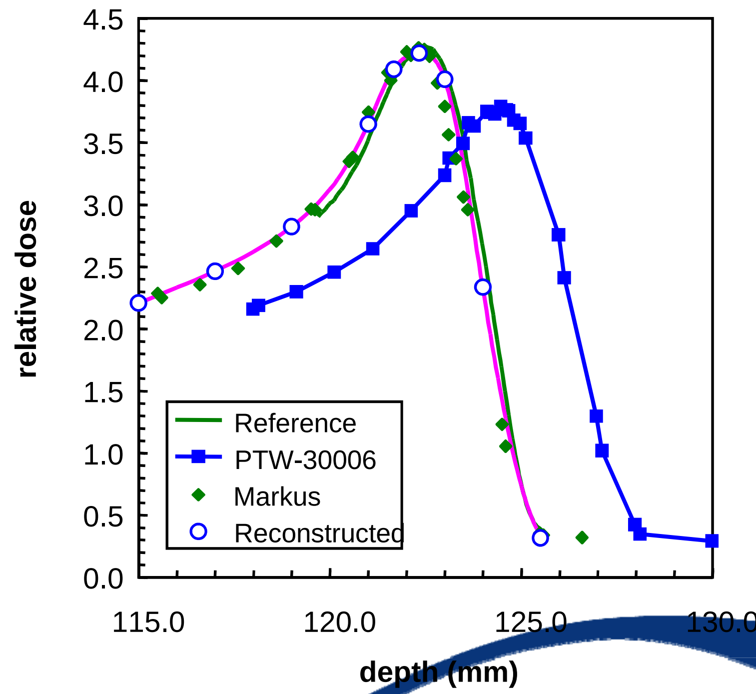
Mobit et al. 2000 *Med. Phys.* 27:2780-2787

78 MeV protons

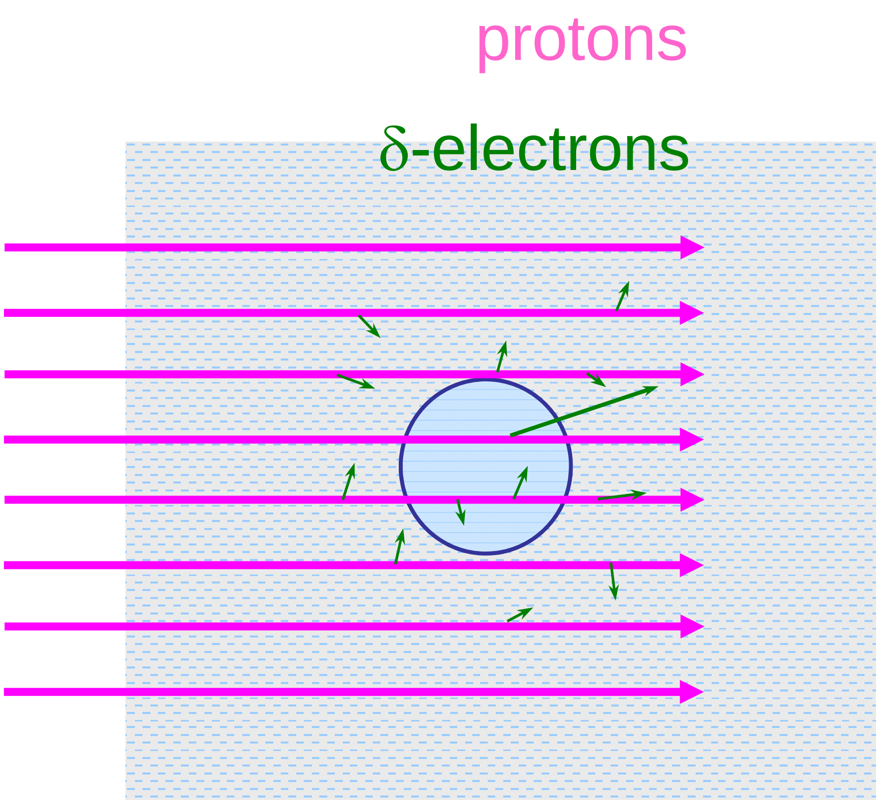


Jäkel et al. 2000 *Phys. Med. Biol.* 45:599-607

3 GeV ^{12}C



Ion chambers – cavity theory for p_{cav}



$$D_{med} = D_{air} \cdot \left(\frac{S^{SA}}{\rho}\right)_{air}^{med}$$

$$= D_{air} \cdot \left(\frac{S}{\rho}\right)_{air}^{med} \cdot p_{cav,e}$$

$$p_{cav,e} = \left(\frac{S^{SA}}{\rho}\right)_{air}^{med} \Big/ \left(\frac{S}{\rho}\right)_{air}^{med}$$

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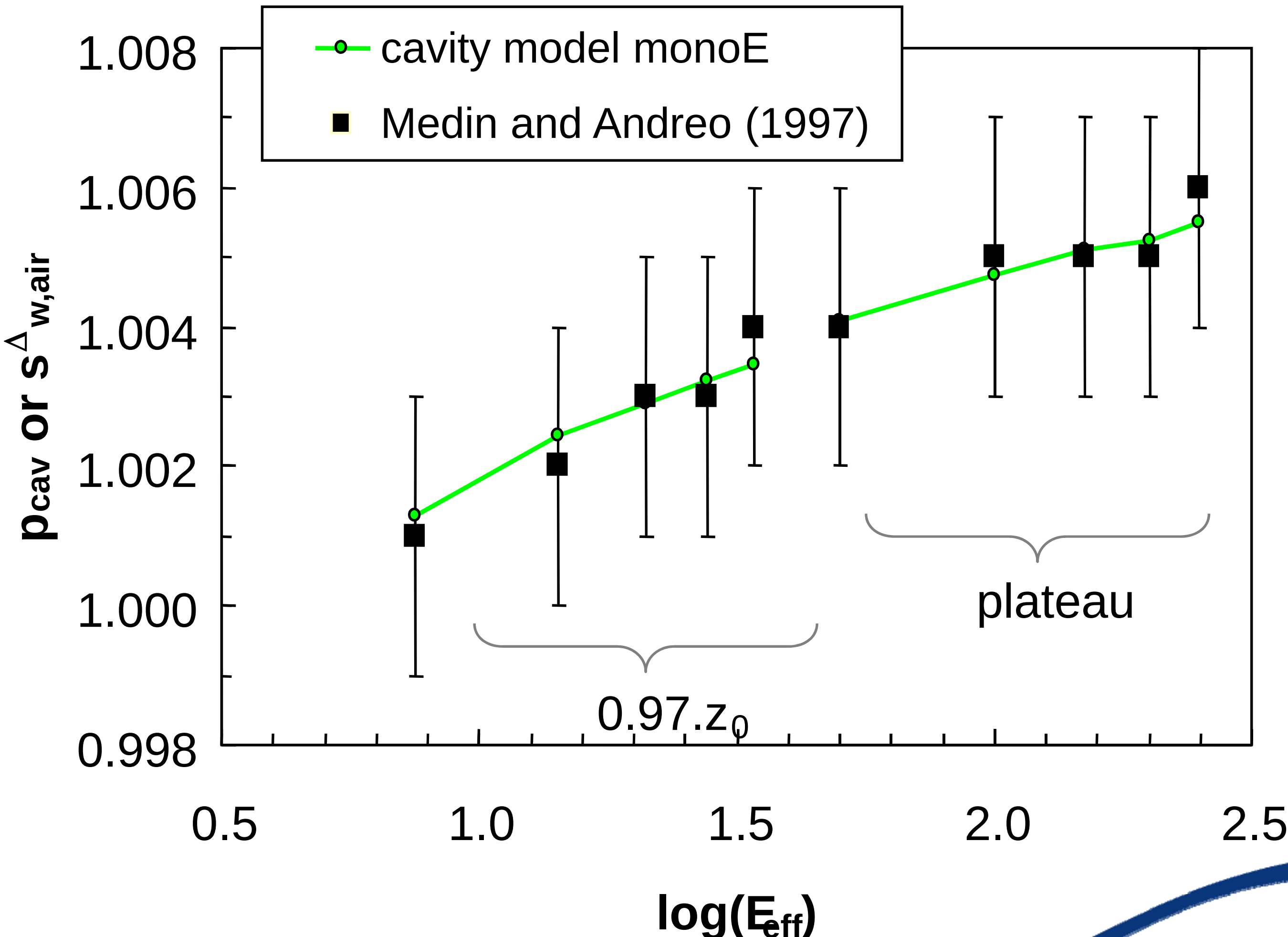
Calculation of (S^{Δ}/ρ) from ICRU49

$$\left(\frac{S_{col}^{\Delta}}{\rho}\right) = \frac{cst}{\beta^2}\cdot\frac{Z}{A}\cdot\left[\frac{1}{2}\ln\left(\frac{2mc^2\cdot\beta^2\cdot\Delta}{(1-\beta^2)\cdot I^2}\right) - \beta^2 + SDBB\right]$$

$cst = 0.307075\ MeV.cm^2.g^{-1}$

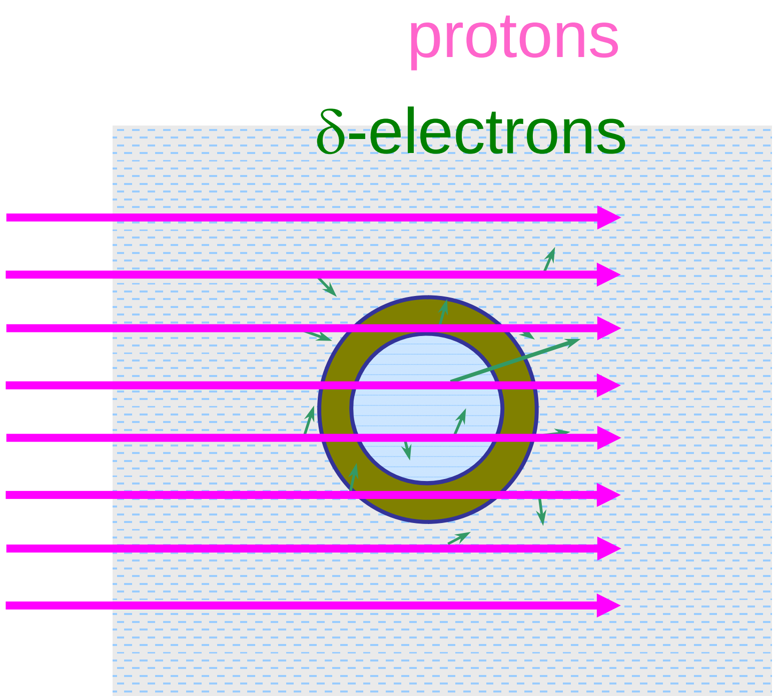
$$\left(\frac{S_{col}^{\Delta}}{\rho}\right)\Big/\left(\frac{S_{col}}{\rho}\right) = 1 - \left[\frac{cst}{2\beta^2}\cdot\frac{Z}{A}\cdot\ln\frac{W_{max}}{\Delta}\right]\Big/\left(\frac{S_{col}}{\rho}\right)$$

Compared with Medin and Andreo (1997)



Ion chambers – cavity theory for p_{wall}

(cfr. Nahum, in Dosimetry in Radiotherapy. Vienna: IAEA, 1988: for electron beams.)



$$D_{med} = D_{air} \cdot \left[\frac{S^{SA}}{\rho}\right]_{air}^{wall} \cdot \left[\frac{S}{\rho}\right]_{wall}^{med}$$

$$= D_{air} \cdot \left[\frac{S^{SA}}{\rho}\right]_{air}^{med} \cdot p_{wall,e}$$

$$p_{wall,e} = \left[\frac{S}{\rho}\right]_{wall}^{med} \cdot \left[\frac{S^{SA}}{\rho}\right]_{air}^{wall} \Big/ \left[\frac{S^{SA}}{\rho}\right]_{air}^{med}$$

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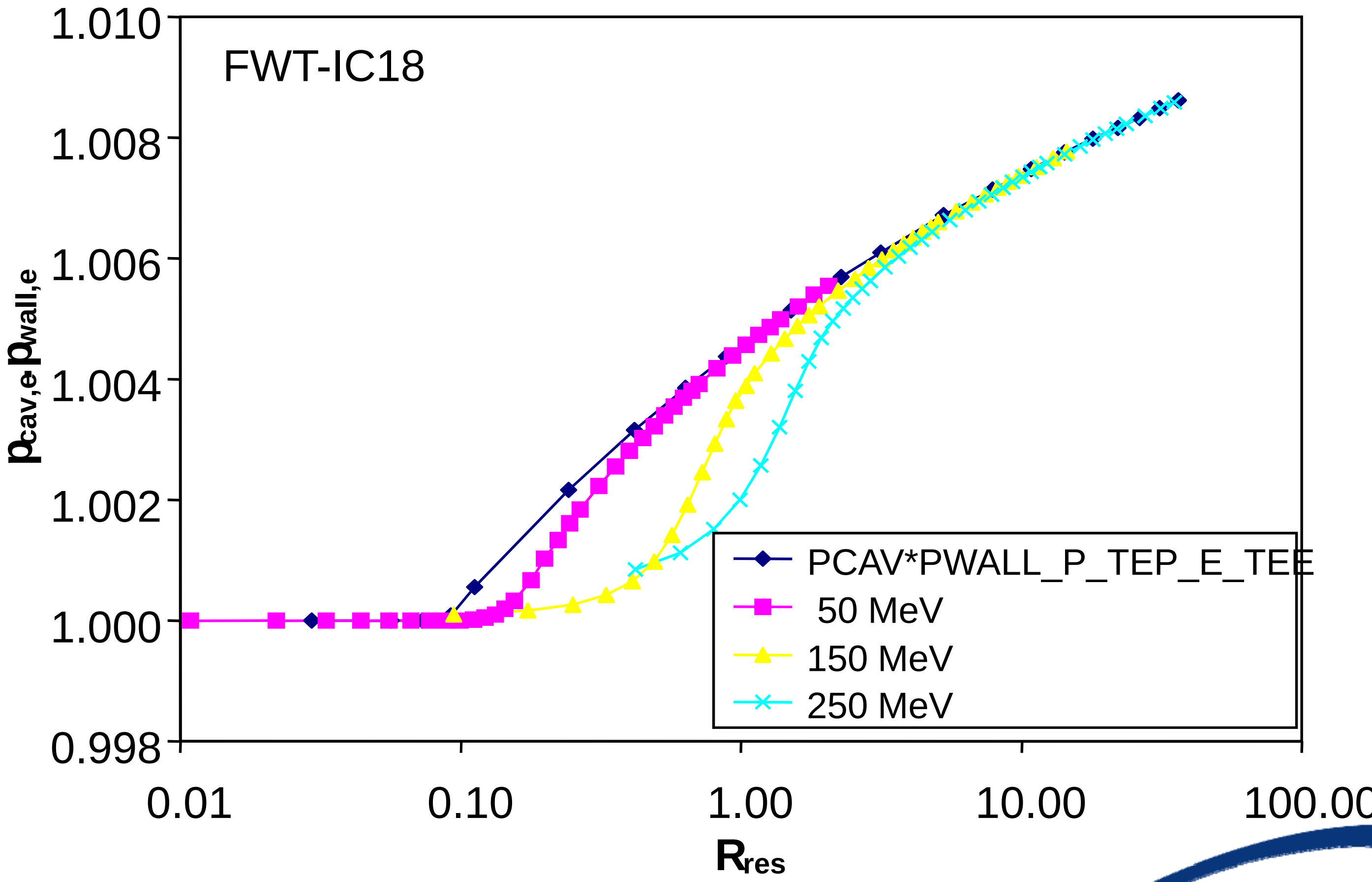
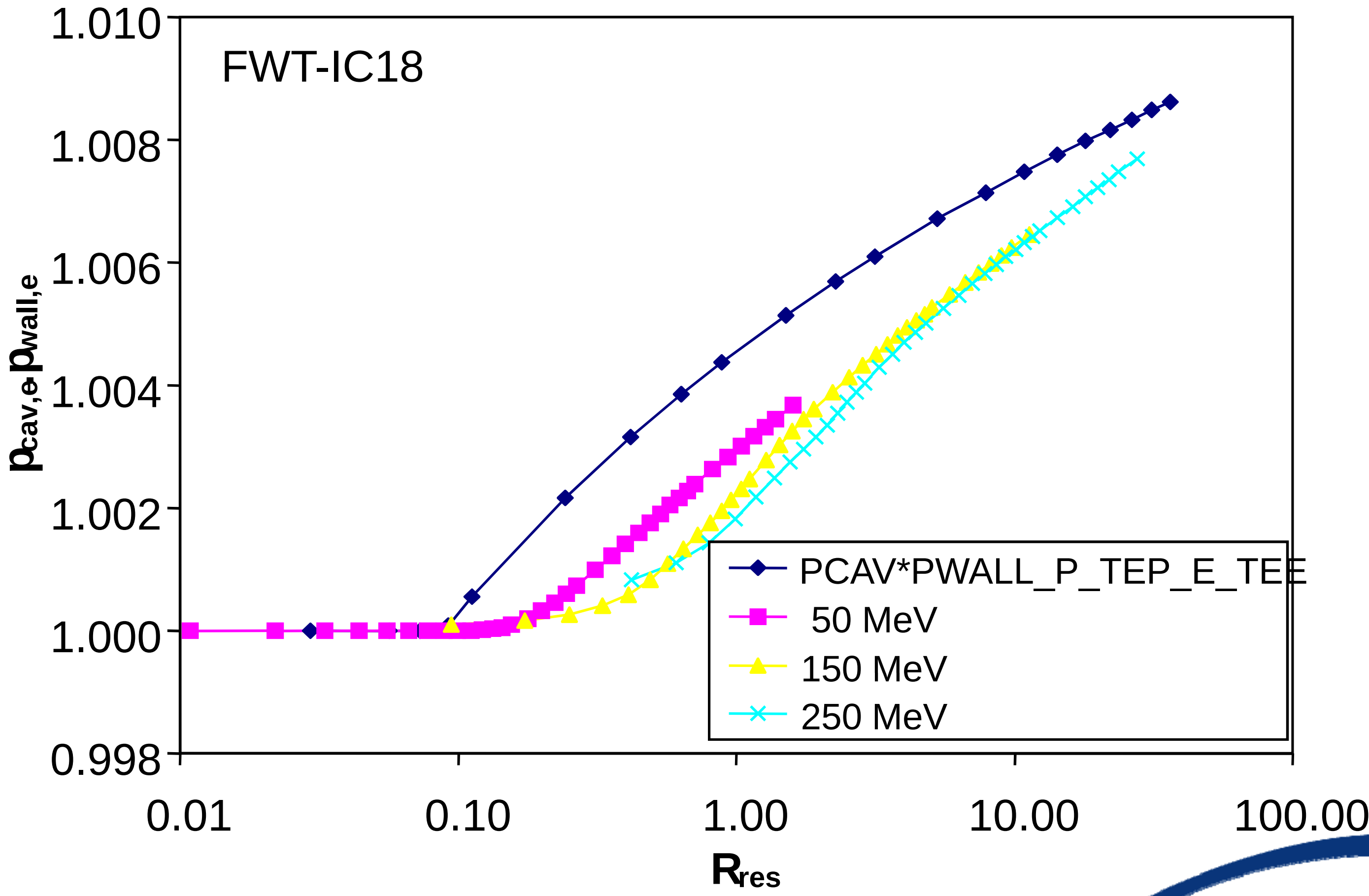
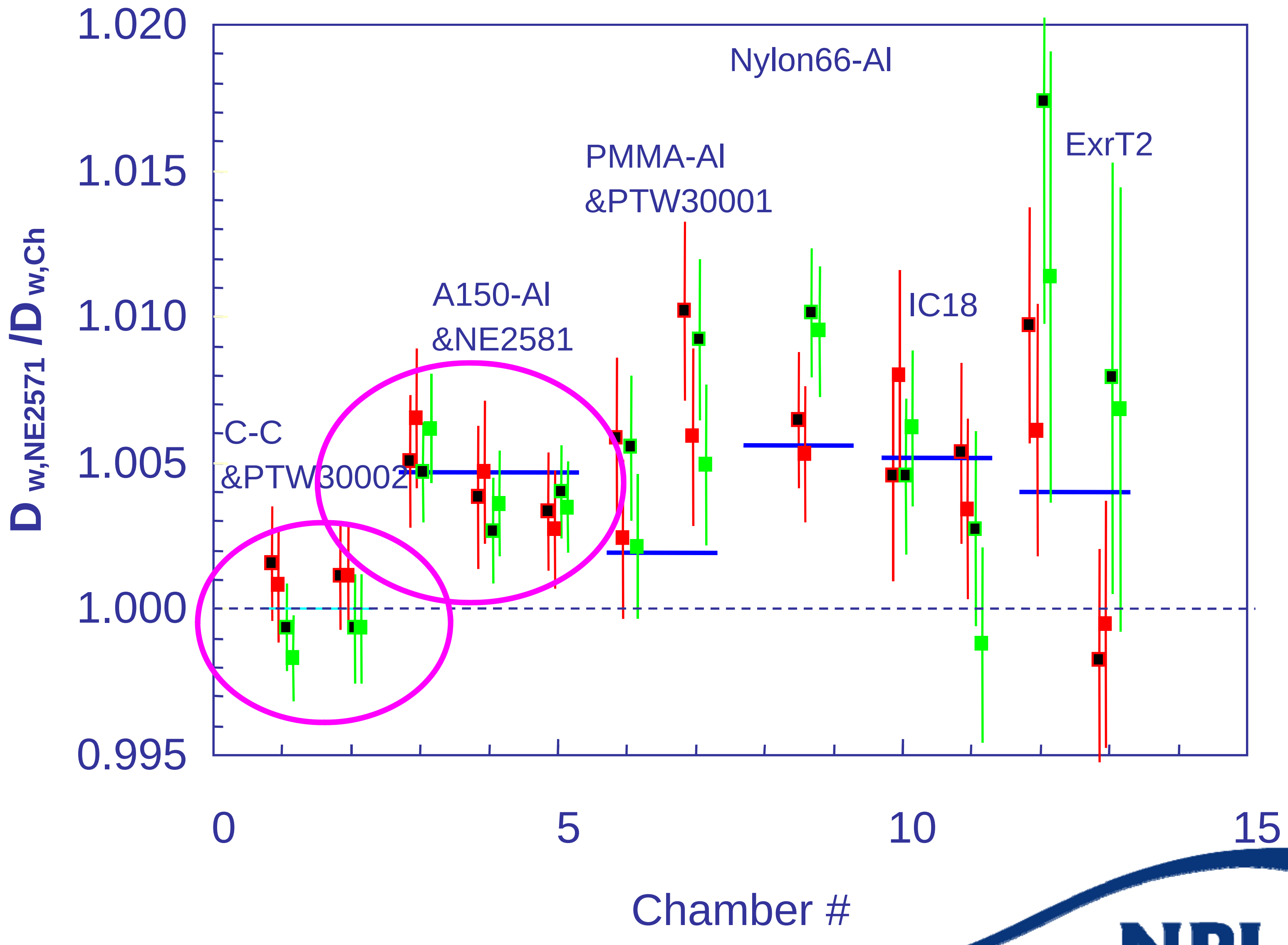
Ion chambers – cavity theory mono-energetic protons



Ion chambers – cavity theory modulated protons



Comparison with experiment perturbations



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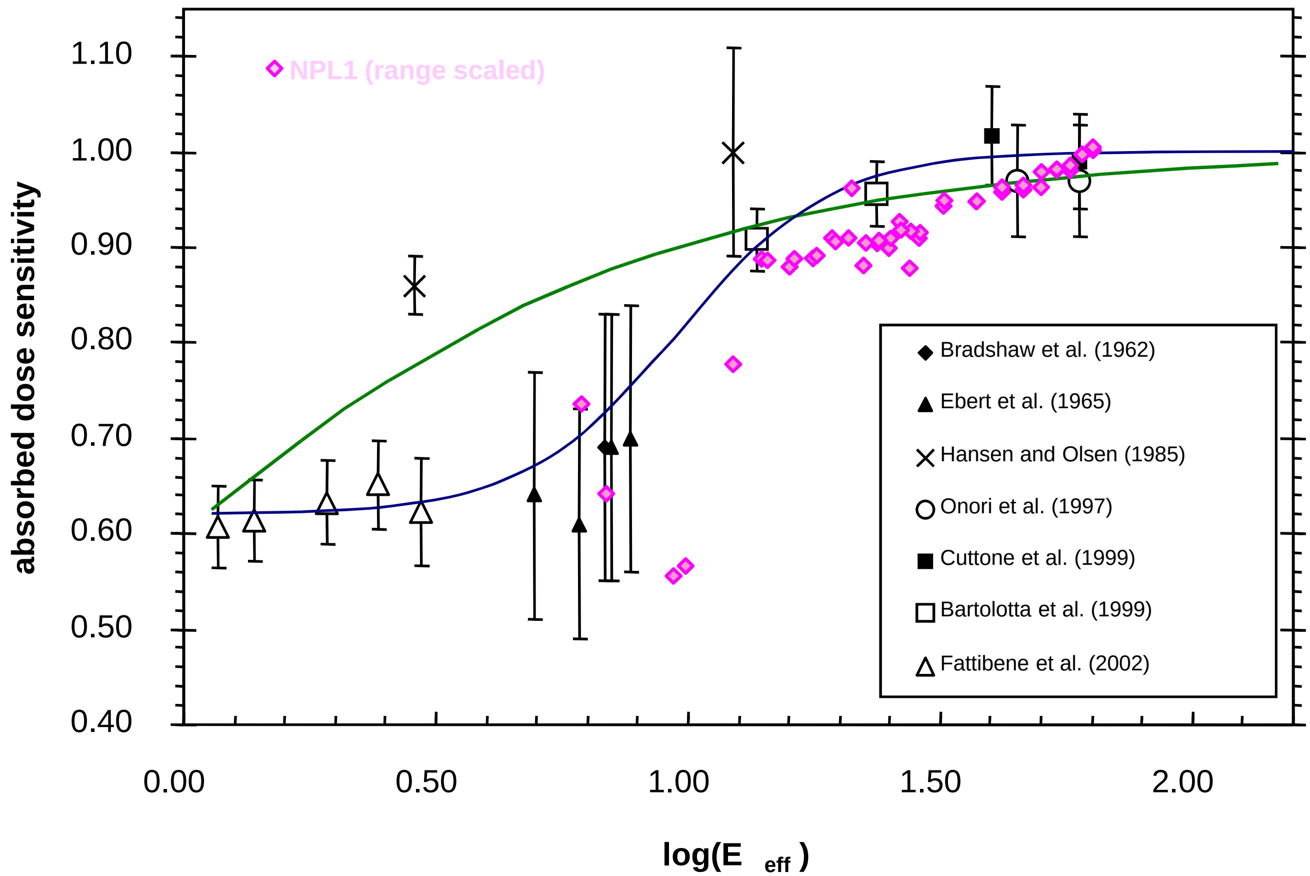
Alanine dosimetry



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

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

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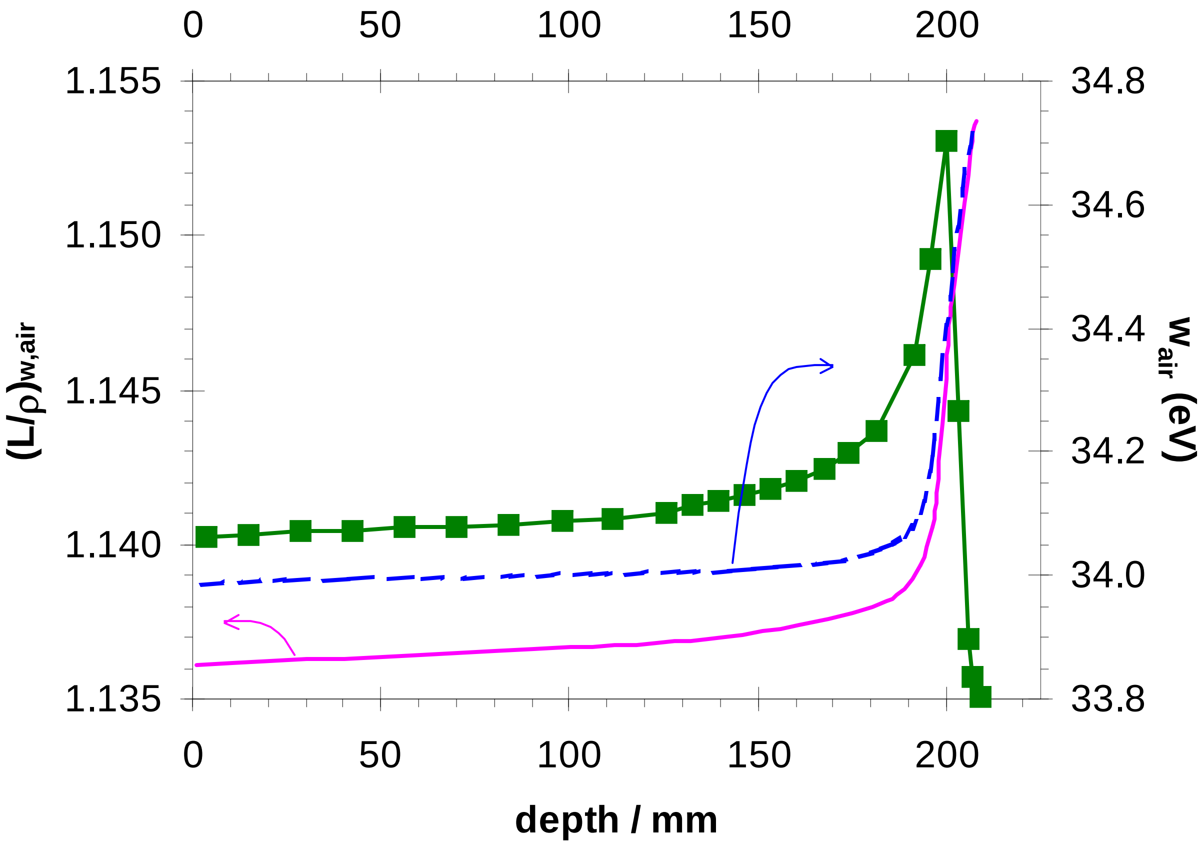
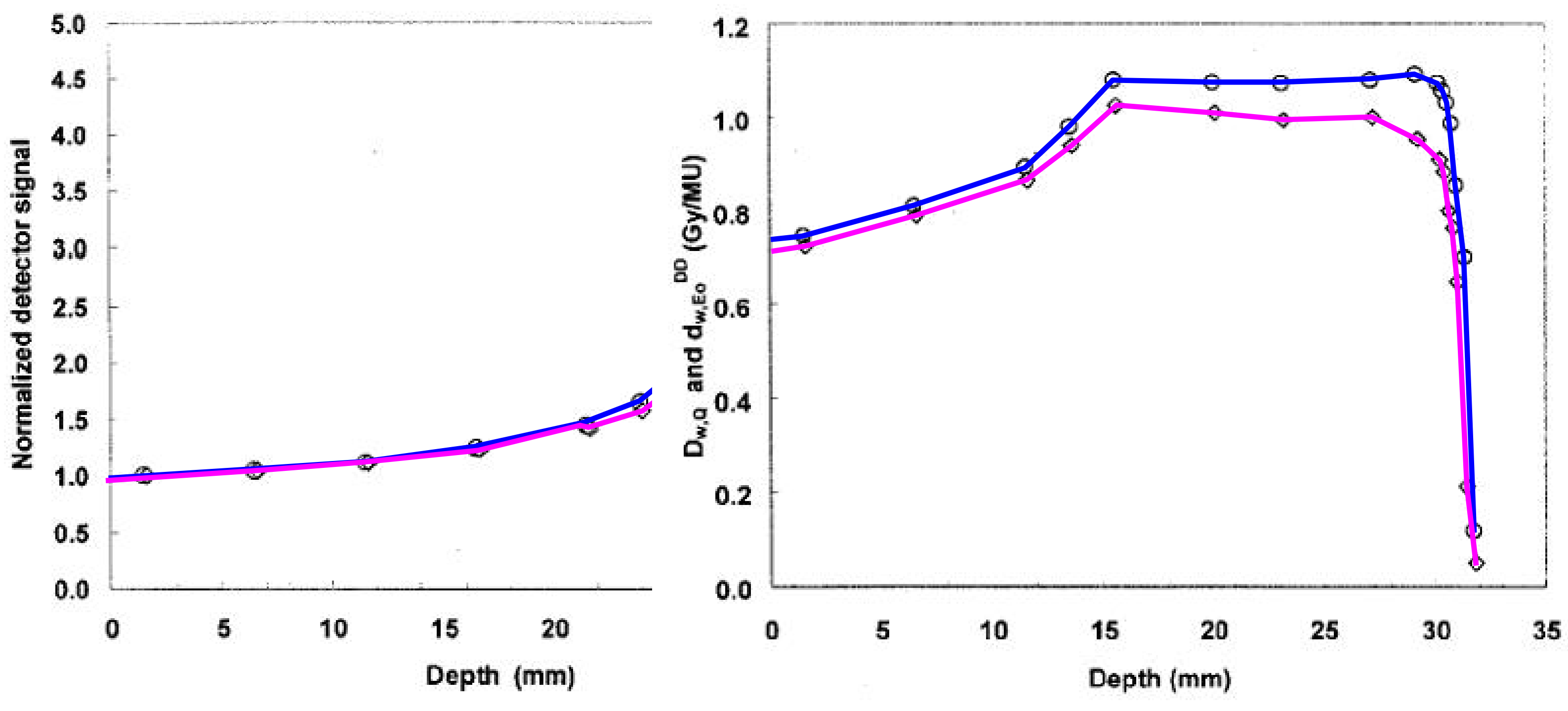
Relative dosimetry – ion chambers

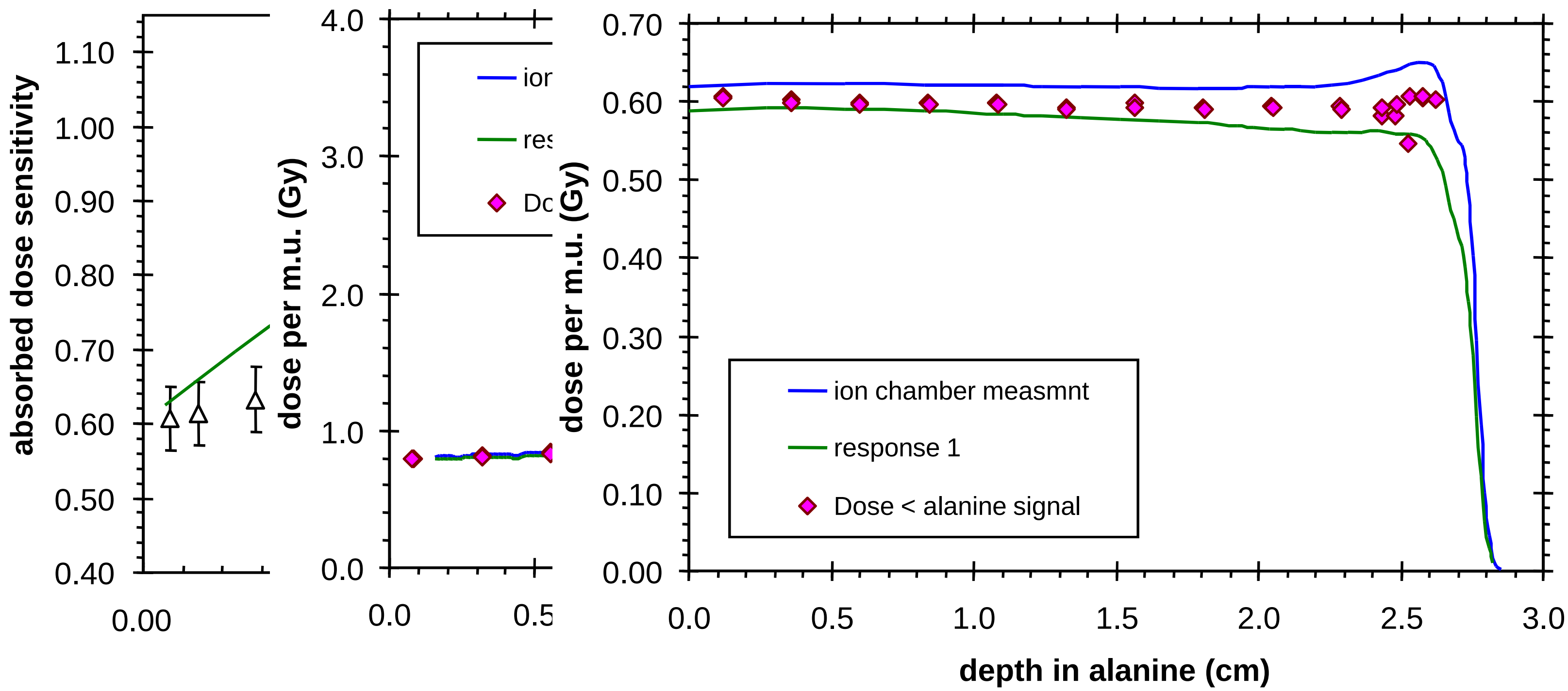


Relative dosimetry – Solid state detectors : diamond



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

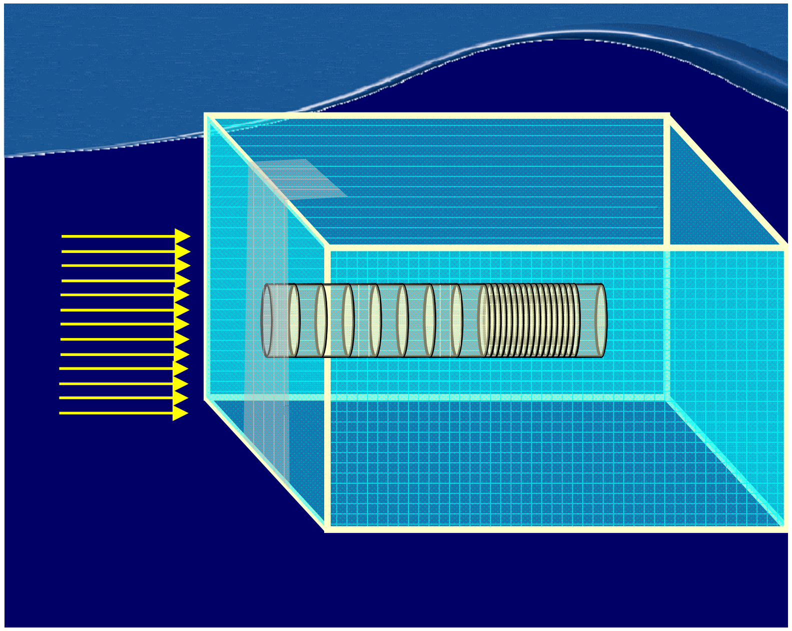
Relative dosimetry – Solid state detectors : alanine/ESR

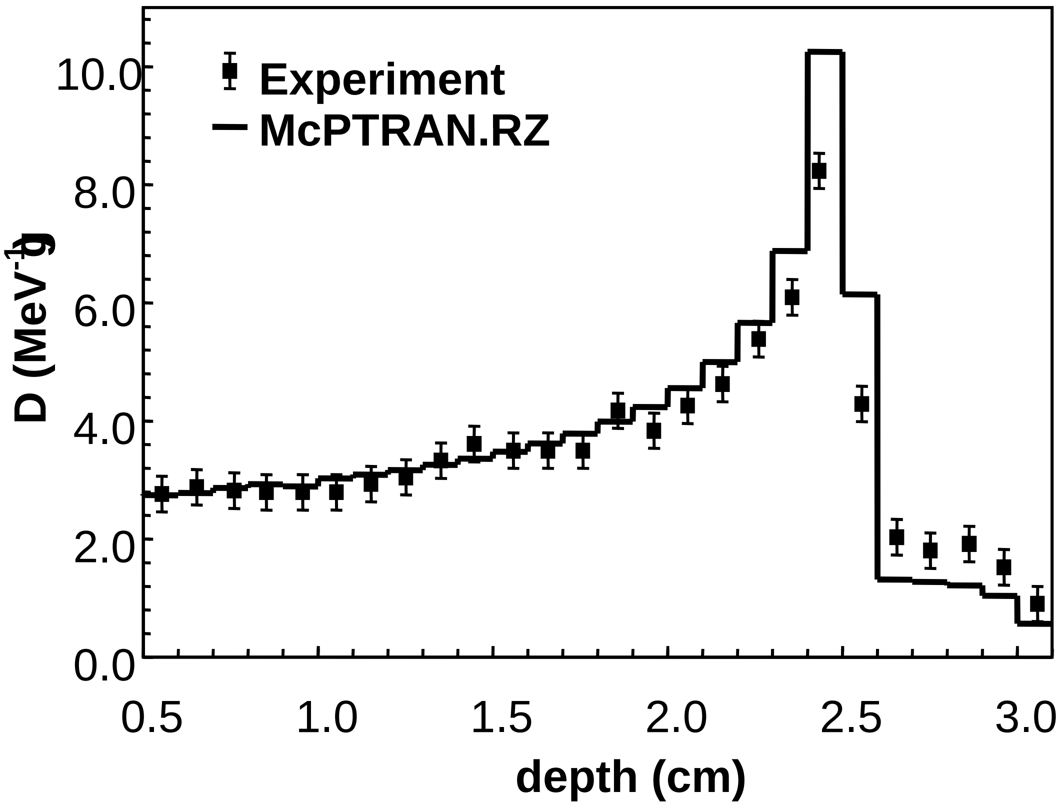


(P (Palmans et al 2009, unpublished data)

Alanine – stack in PMMA

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





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Alanine in anti-protons

N. Bassler, et al, Nucl. Instr. Meth. B 266 929-936, 2008

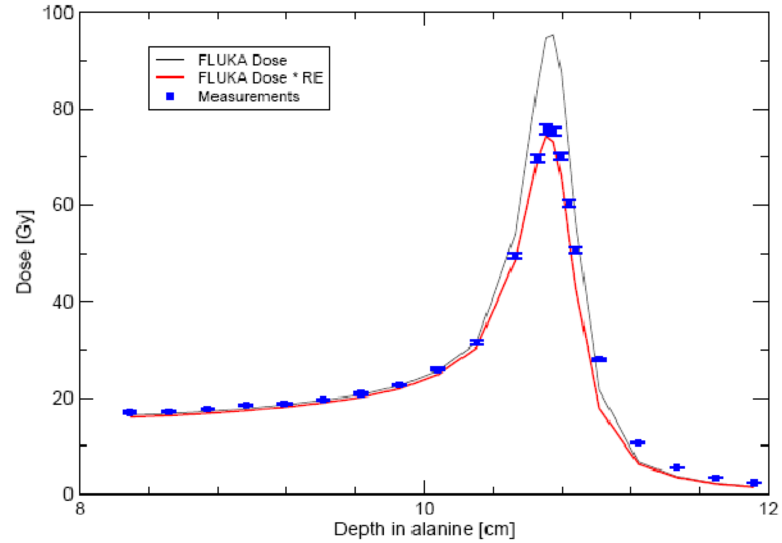

Fig. 3. Results for stack #2 plotted in the same fashion as figure 2. No shift along the x-axis needed to be applied here.

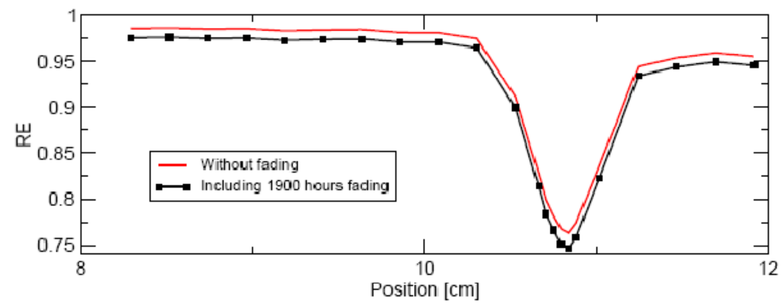

Fig. 4. Calculated relative effectiveness for stack #2 as a function of depth in phantom. The relative effectiveness drops off in the peak region due to the slowing down of antiprotons and the annihilation products with higher LET. The calculation is done twice, including and excluding fading effects.

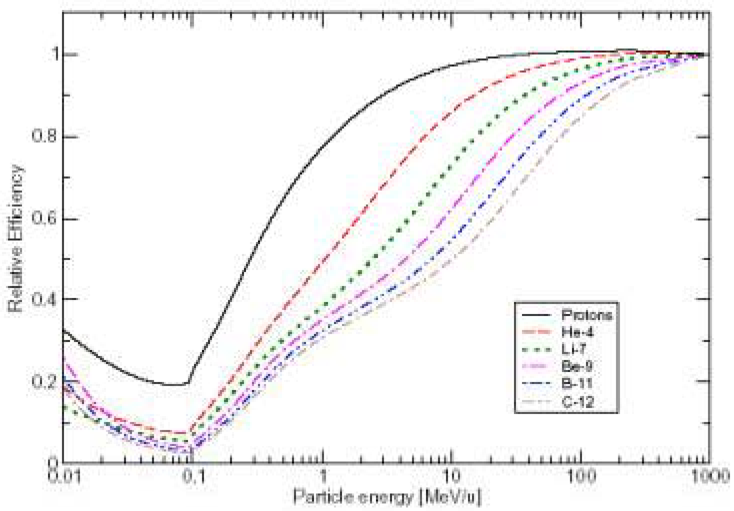

Fig. 1. Calculated relative efficiencies for infinitesimal thin detectors, without fading effects.

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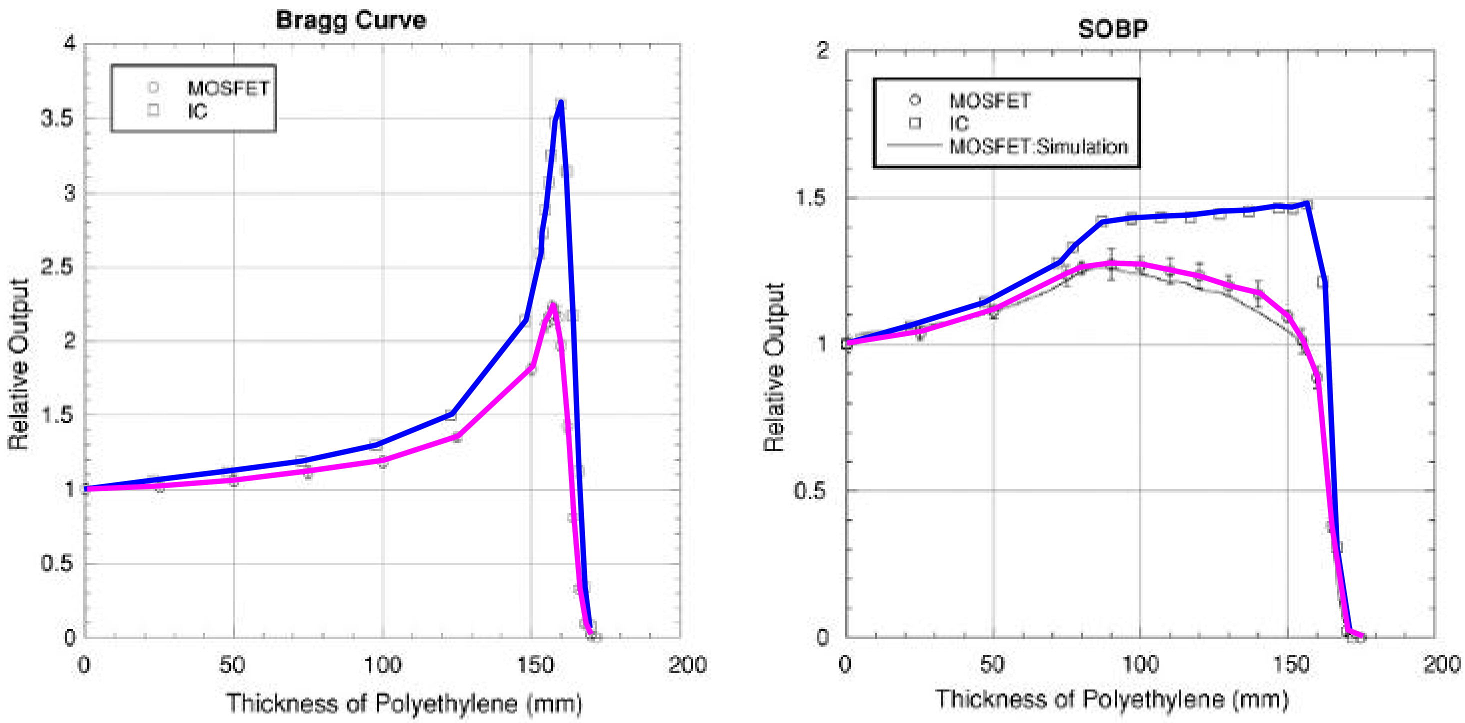
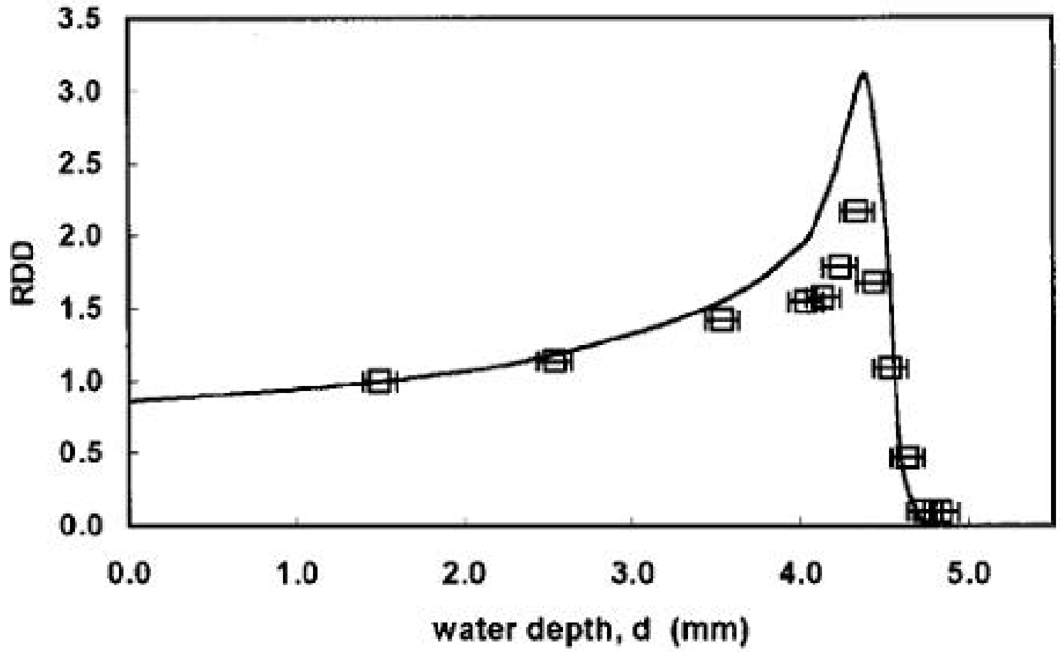
Relative dosimetry – Solid state detectors : mosfet



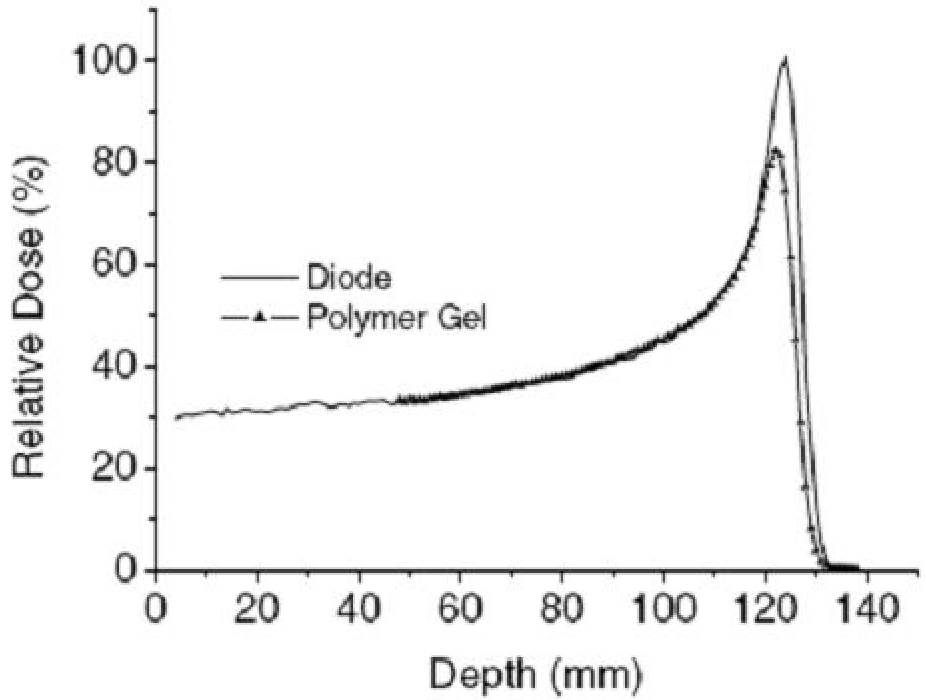
(Kohno et al 2006, Phys Med Biol 51:6077-86)

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)

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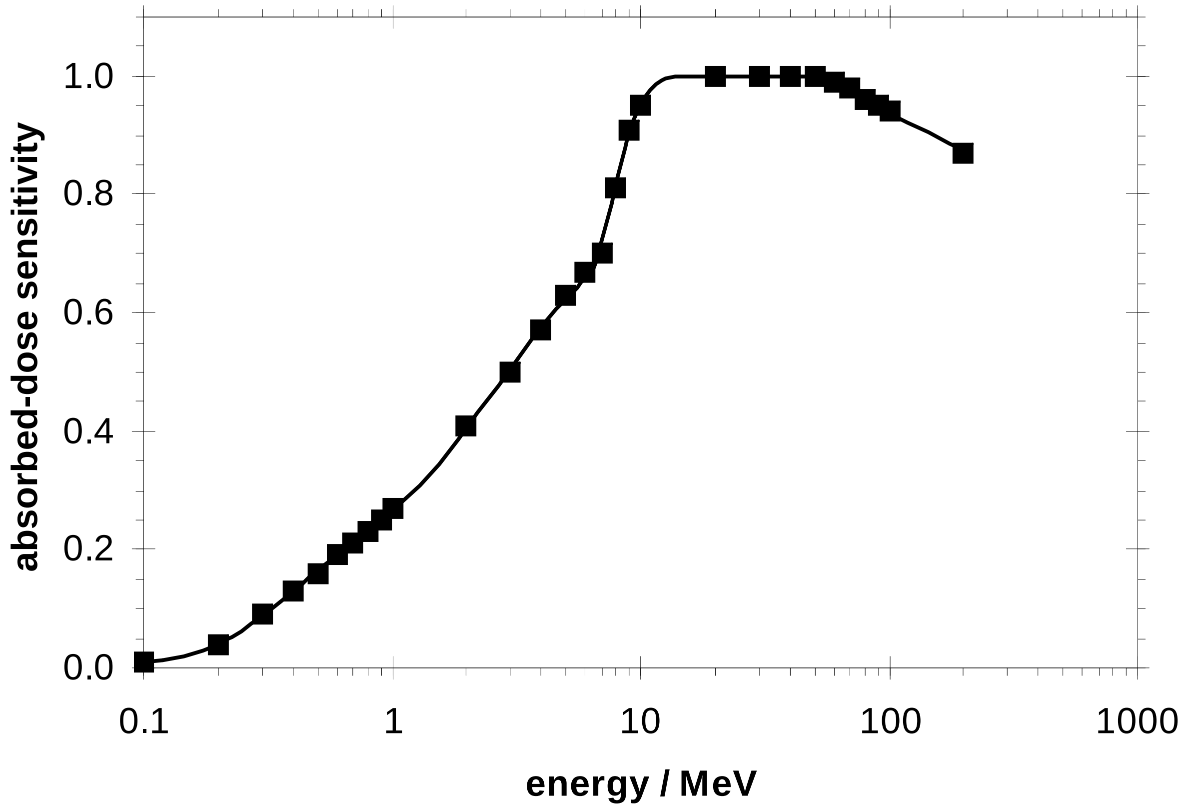
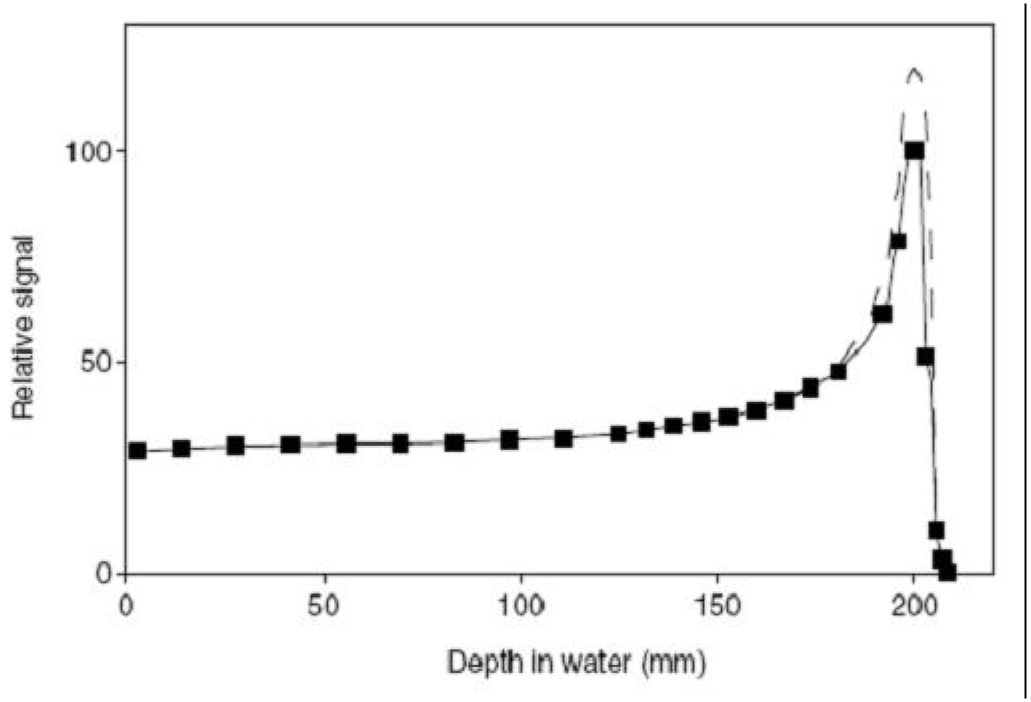
Relative dosimetry – TLD



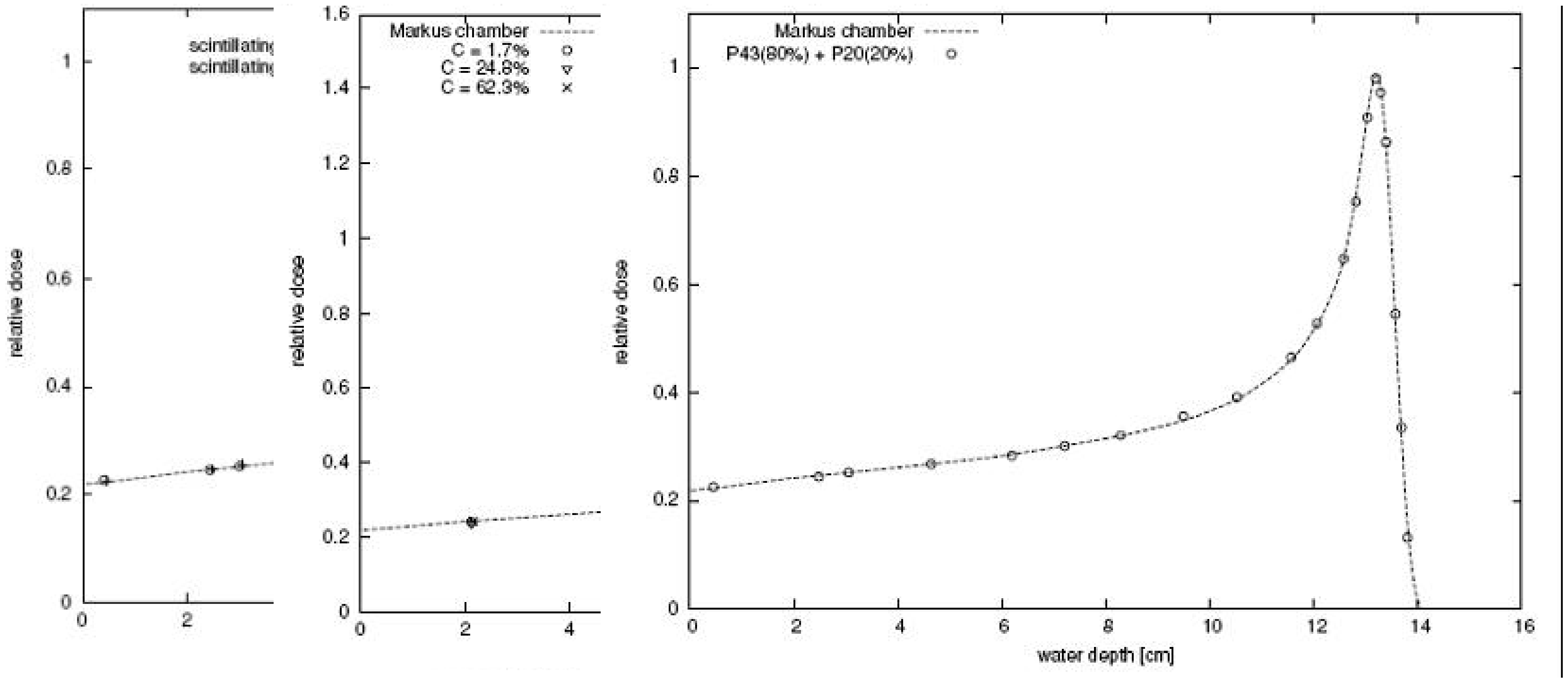
(Besserer et al 2001 Phys. Med. Biol. 46:473-85)

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)

Conclusion

- Absolute dosimetry
  - Calorimeters developed as primary instruments
  - Faraday cups, activation
  - Ion chambers for clinical reference dosimetry
- Relative dosimetry
  - Ion chambers for PDD as well as other detectors (but LET dependence!!)

Thank you