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NPL's progress towards absorbed dose standards for proton beams

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Overview

- Proton therapy and to a lesser extent ion therapy are treatment modalities of increasing importance
- Dosimetry has not been as well established as in high-energy x-ray beams
- NPL's activities in improving proton and ion dosimetry:
  - SR project 2002-2004
  - Graphite calorimetry
  - Interaction data
  - Alanine dosimetry
  - Monte Carlo simulation of perturbation correction factors

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Topics discussed in this talk

- Calorimetry
  - Graphite calorimetry in CCO beam
  - Development of a primary standard level graphite calorimeter for light-ions
- Interaction/basic data
  - $(w_{air})_p$ value
  - Stopping powers
  - Non-elastic nuclear interaction cross sections
- Correction factors for ionization chambers related to:
  - Recombination
  - Dose gradients
  - Secondary electrons
  - Non-elastic nuclear interactions

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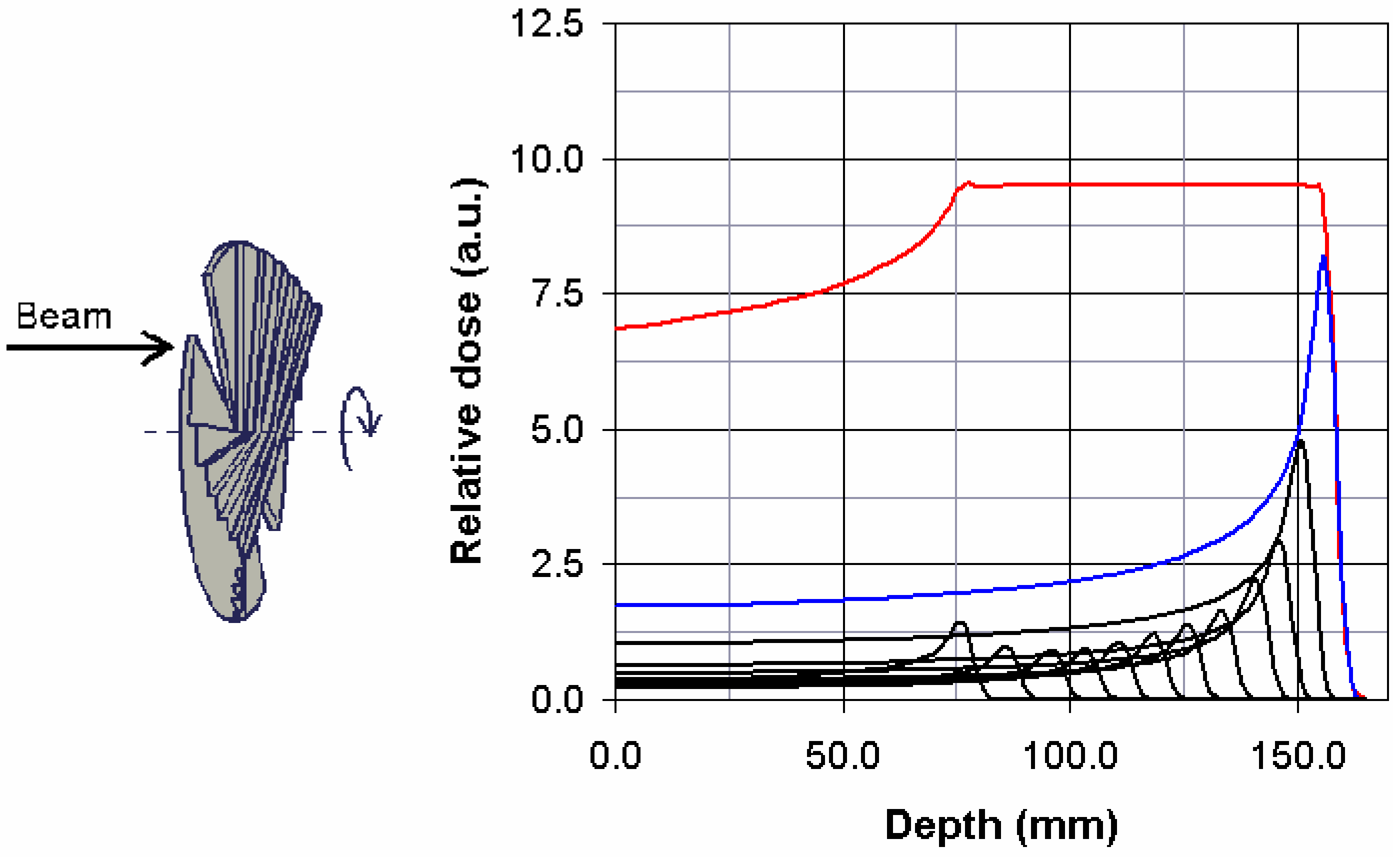
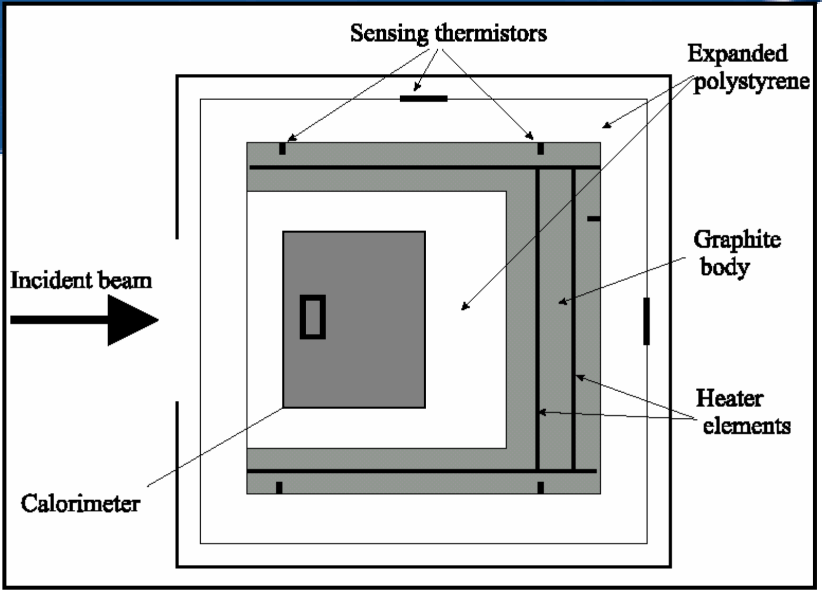
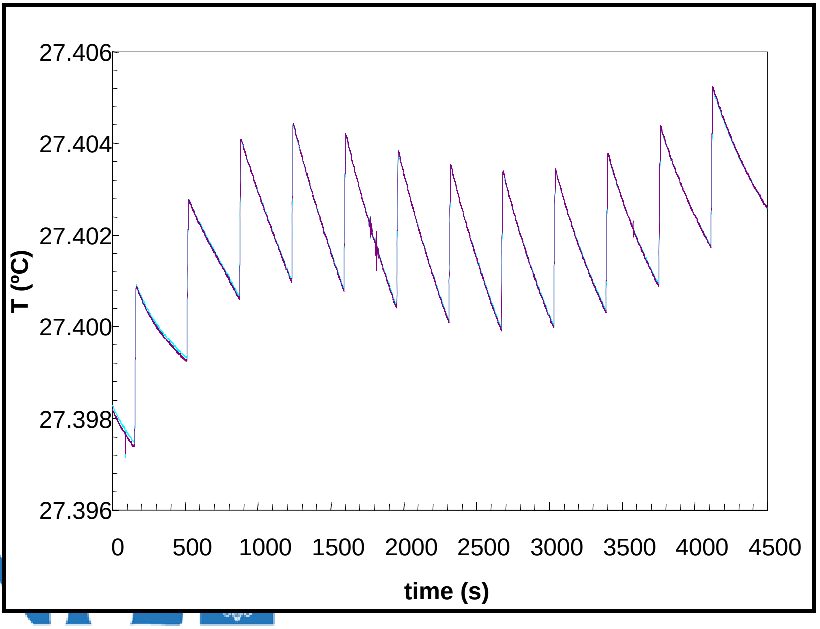
Why protons?

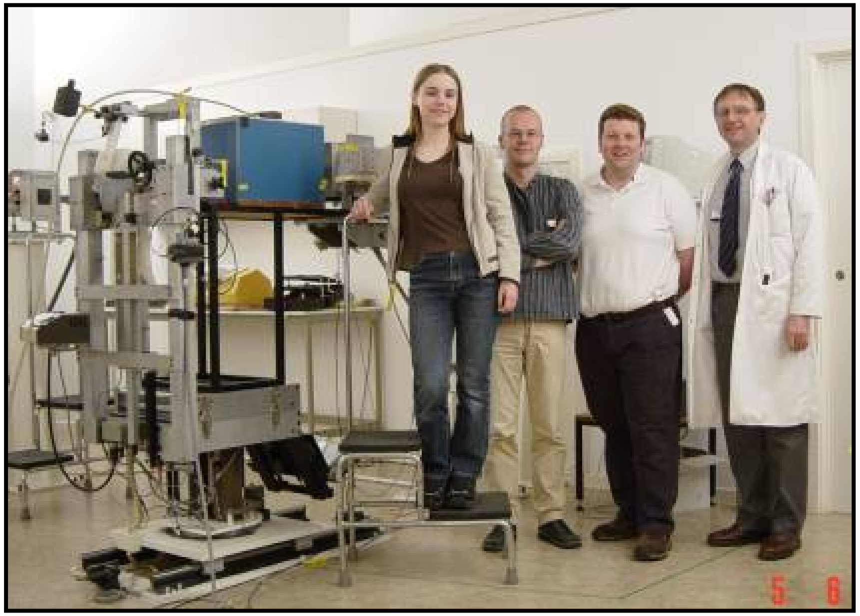

Beam
12.5
10.0
7.5
5.0
2.5
0.0
Relative dose (a.u.)
0.0
50.0
100.0
150.0
Depth (mm)

Graphite calorimetry for protons CCO

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



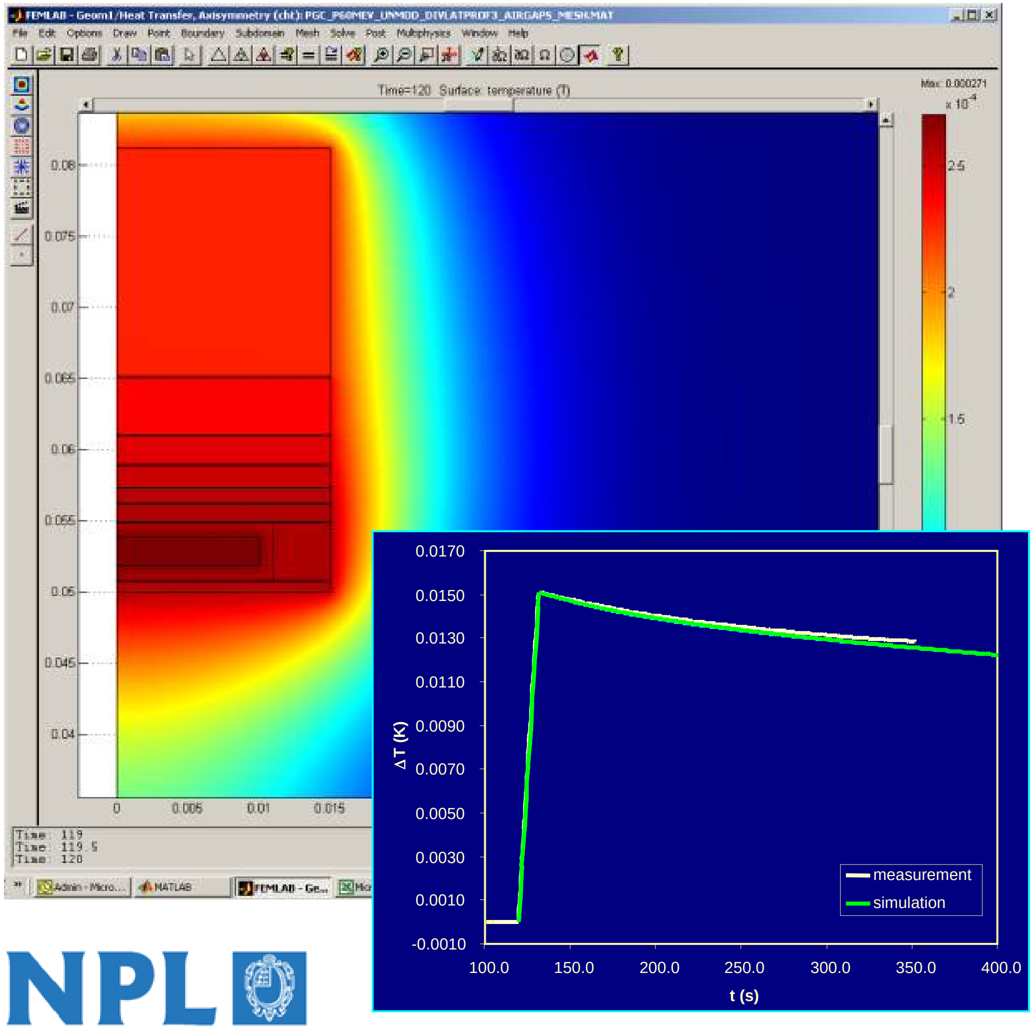




Graphite calorimetry for protons CCO

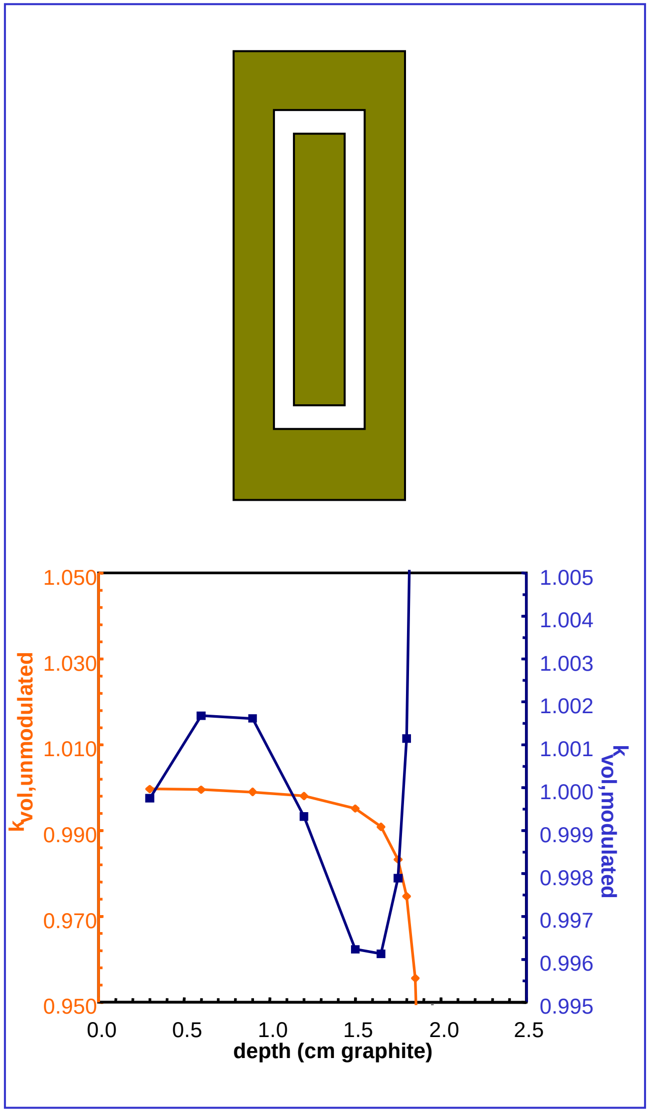
(Palmans et al 2004, Phys Med Biol 49:3737-49)

Heat transfer: FE (Comsol)

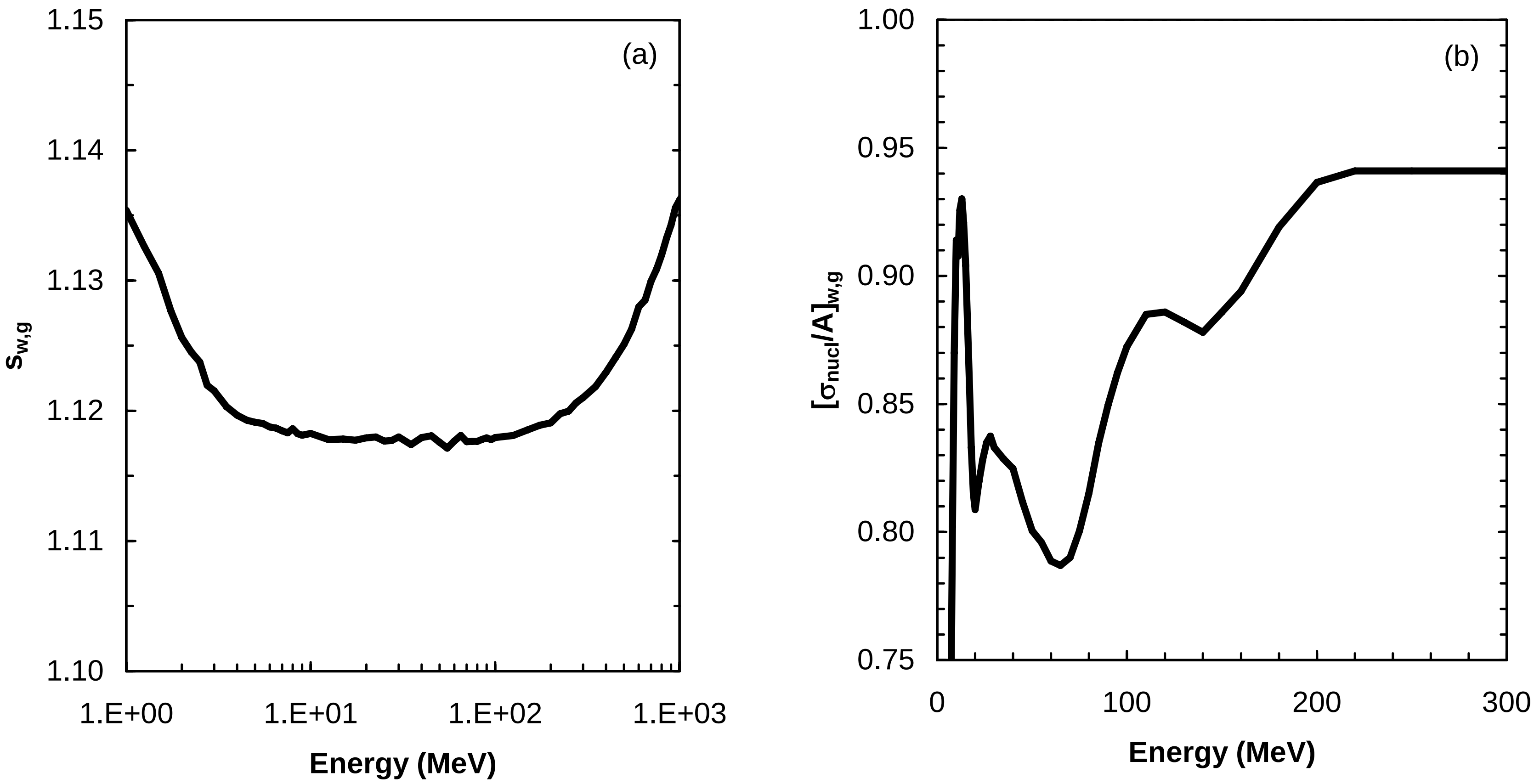


Volume/gap effects:

MC (McPTRAN.RZ)



Graphite to water conversion 1: interaction cross sections (ICRU-49 and ICRU-63)



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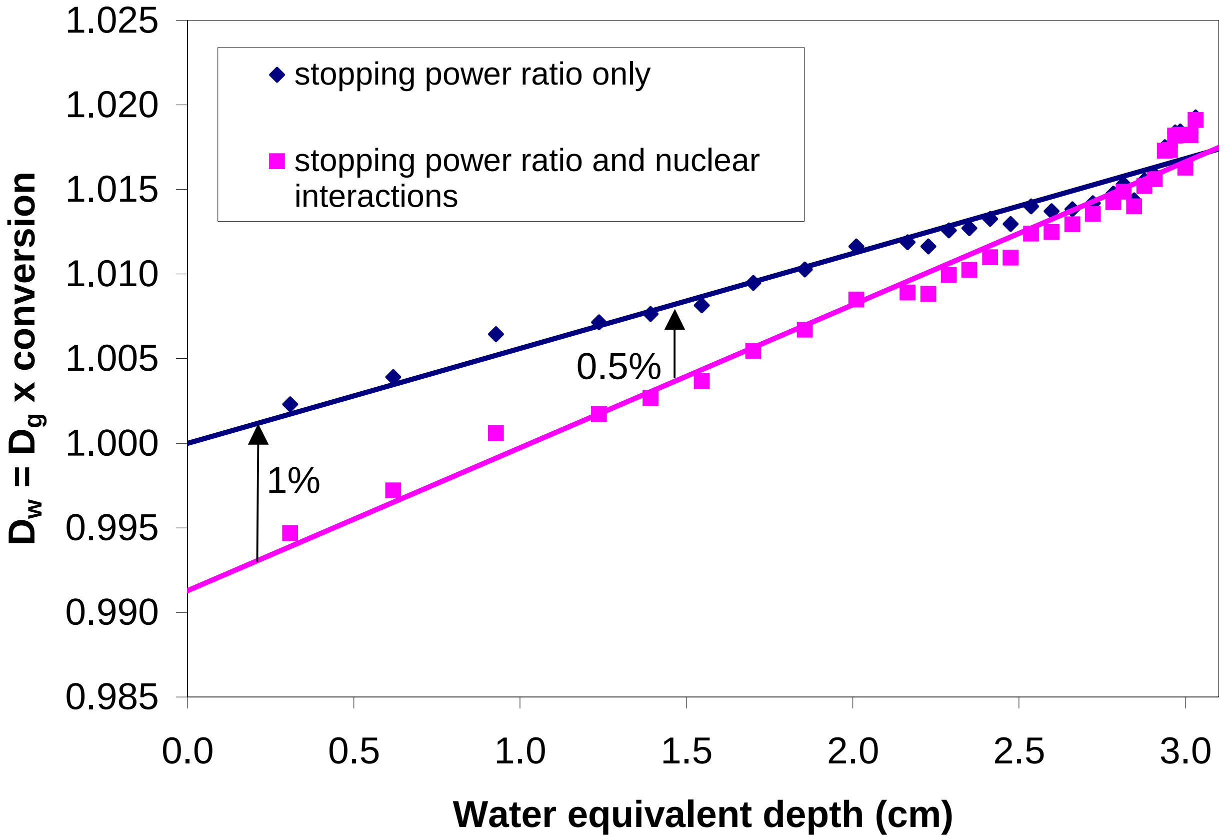
Graphite to water conversion 2: dose conversion (ICRU-49 and ICRU-63)



$$D_w(z_w) = D_g(z_g).s_{w,g}$$

$$D_w(z_w) = D_{g,C}(z_g).s_{w,g} + D_{g,N}(z_g).(\sigma_n/A)_{w,g}$$

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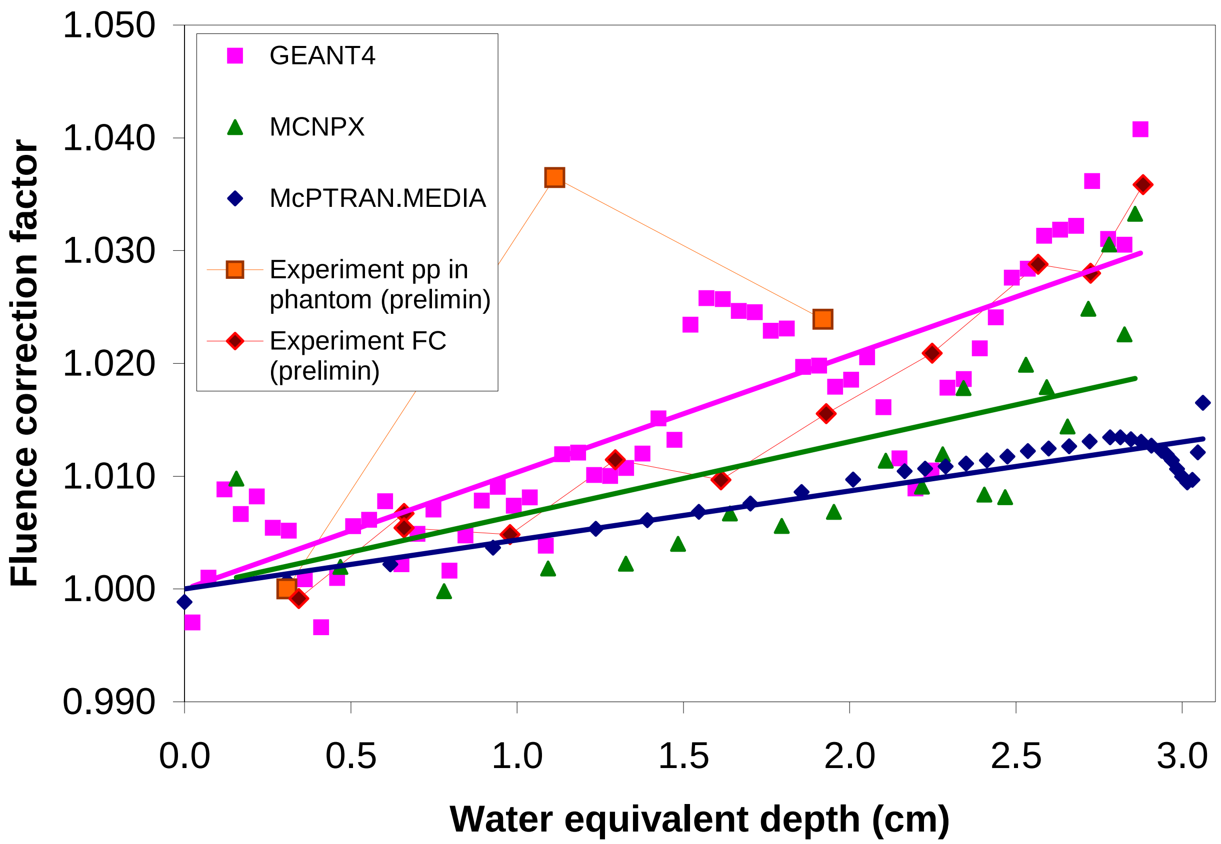
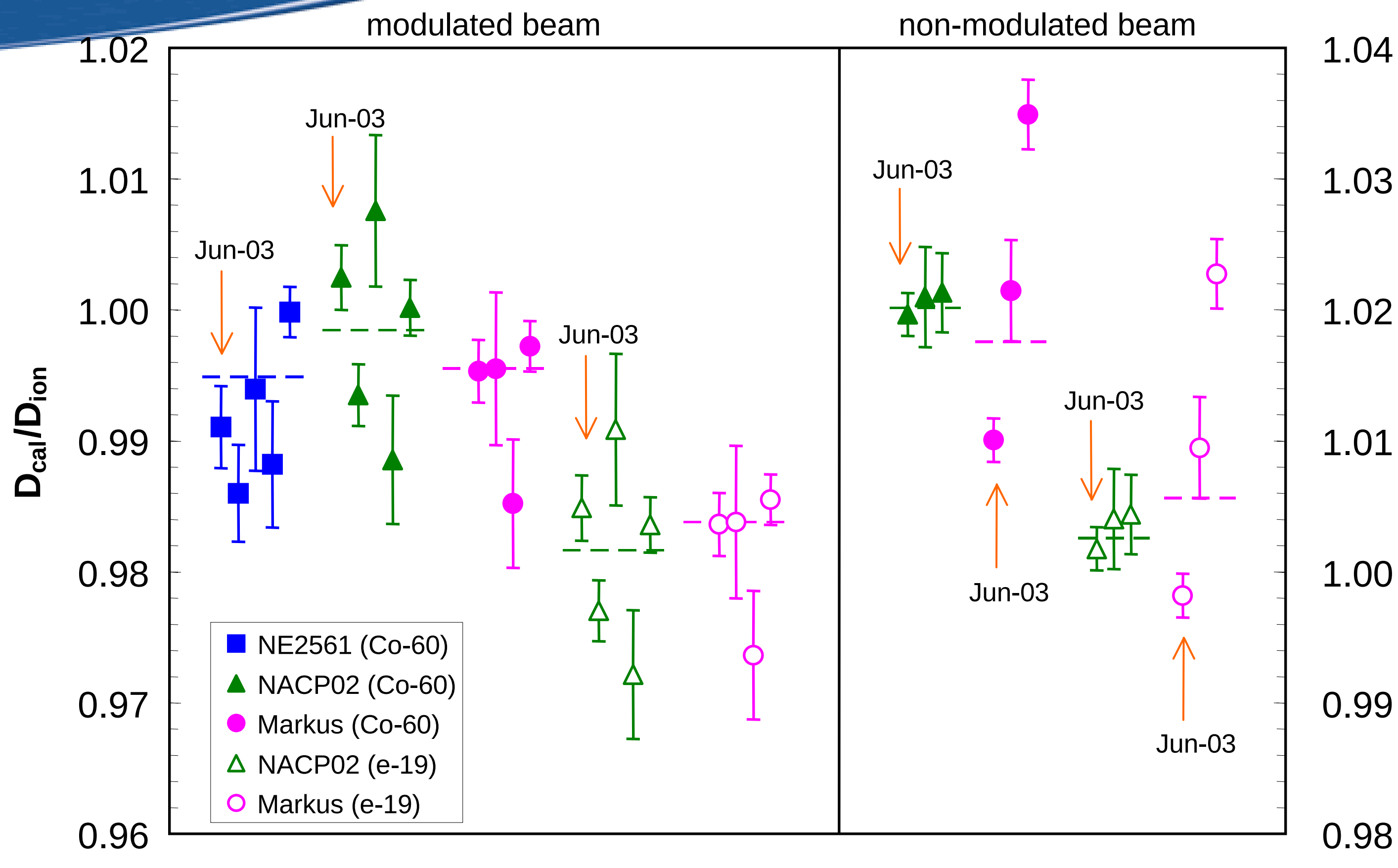
Graphite to water conversion 3: fluence correction



Graphite calorimetry results CCO



	$D_{w,SPGC}/D_{w,IC}$	
Calibration beam quality	modulated	non-modulated
^{60}Co	0.996	1.019
ϱ_{e19}	0.983	1.004

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Uncertainty

Source of uncertainty	Based on ^{60}Co	Based on Q_{e19}	type
	for SPGC		
thermistor calibration	0.10		B
specific heat	0.08		B
$s_{w,g}$	1.00		B
k_{gap}	0.05		A
k_{volume}	0.05		A
extrapolation	0.06		B
	for NACP-02		
reproducibility	0.29	0.27	A
positioning	0.30	0.30	B
p_{ion}	0.10	0.10	B
p_{pT}	0.05	0.05	B
k_{SDD}	0.06	0.06	B
k_{pdd}	0.00	0.00	B
$k_{fluence}$	0.05	0.05	B
$k_{profile}$	0.21	0.21	B
$N_{D,w}$	0.75	0.75	B
k_Q	2.10	1.40	B
$u(D_{w,SPGC}/D_{w,IC})$	2.5	1.9	
$u(k_Q)$	1.4	1.3	

New standard level graphite calorimeter for light-ion beams (cfr Mark Bailey / this workshop)

- Either calibrate ionization chambers or measure k_Q data
- Large enough for scatter build-up
- Light enough to be portable
- Robustness, vacuum operation, core size, perturbation, alignment and beam monitoring considerations

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Derivation of $(w_{air})_p$ from calorimeter measurements

$$k_Q = \frac{N_{D,w,p}}{N_{D,w,c}} = \frac{D_{w,cal,p} / M_p}{N_{D,w,c}} \approx \frac{(w_{air})_p \cdot (s_{w,air})_p \cdot p_p}{(W_{air})_c \cdot (s_{w,air})_c \cdot p_c}$$

$$(w_{air})_p = \frac{D_{w,cal,p} \cdot (W_{air})_c \cdot (s_{w,air})_c \cdot p_c}{M_p \cdot N_{D,w,c} \cdot (s_{w,air})_p \cdot p_p}$$

	$(w_{air})_p$ in $J\,C^{-1}$	
Calibration beam quality	modulated	non-modulated
^{60}Co	34.1	34.9
Q_{e19}	33.6	34.4

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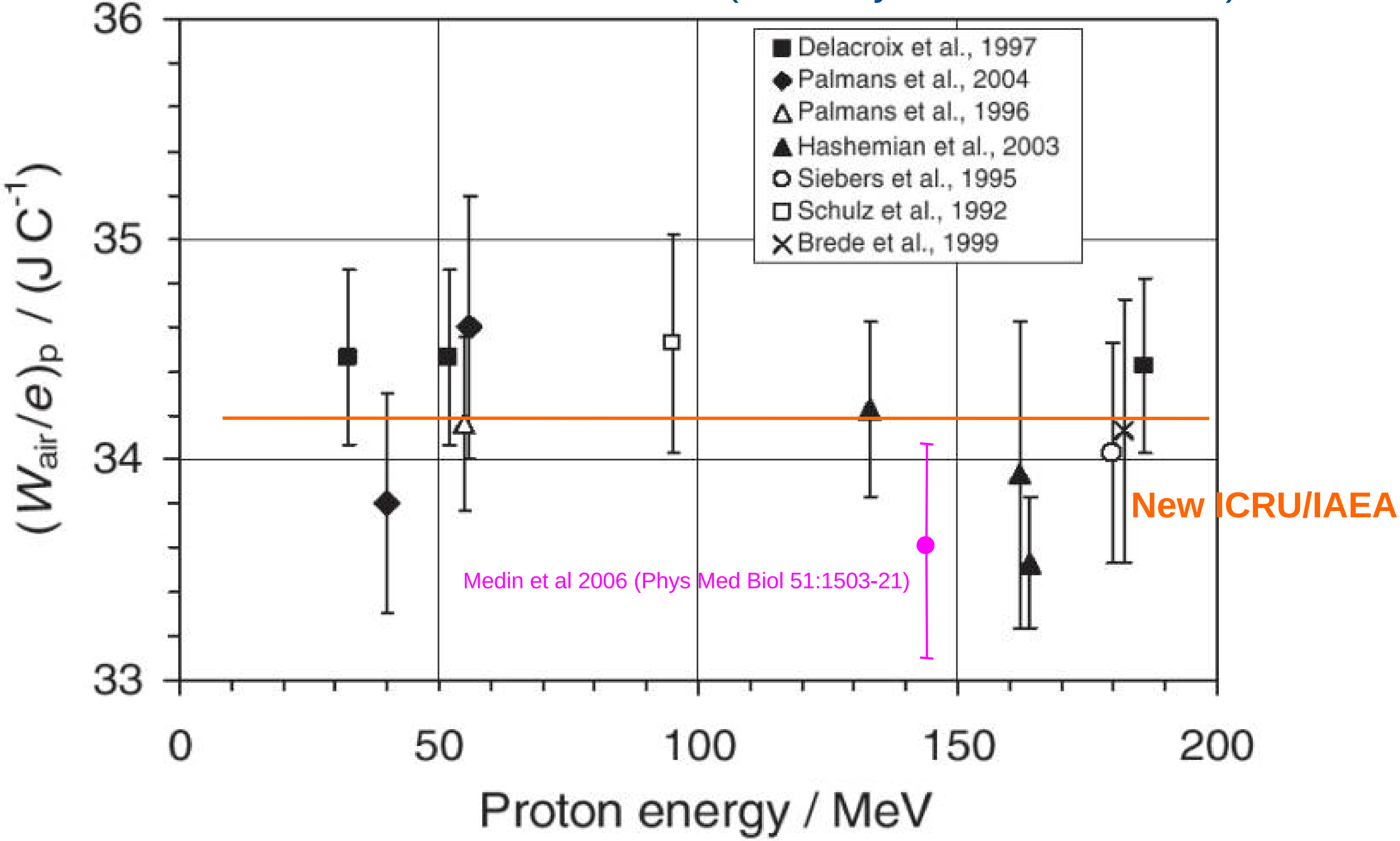
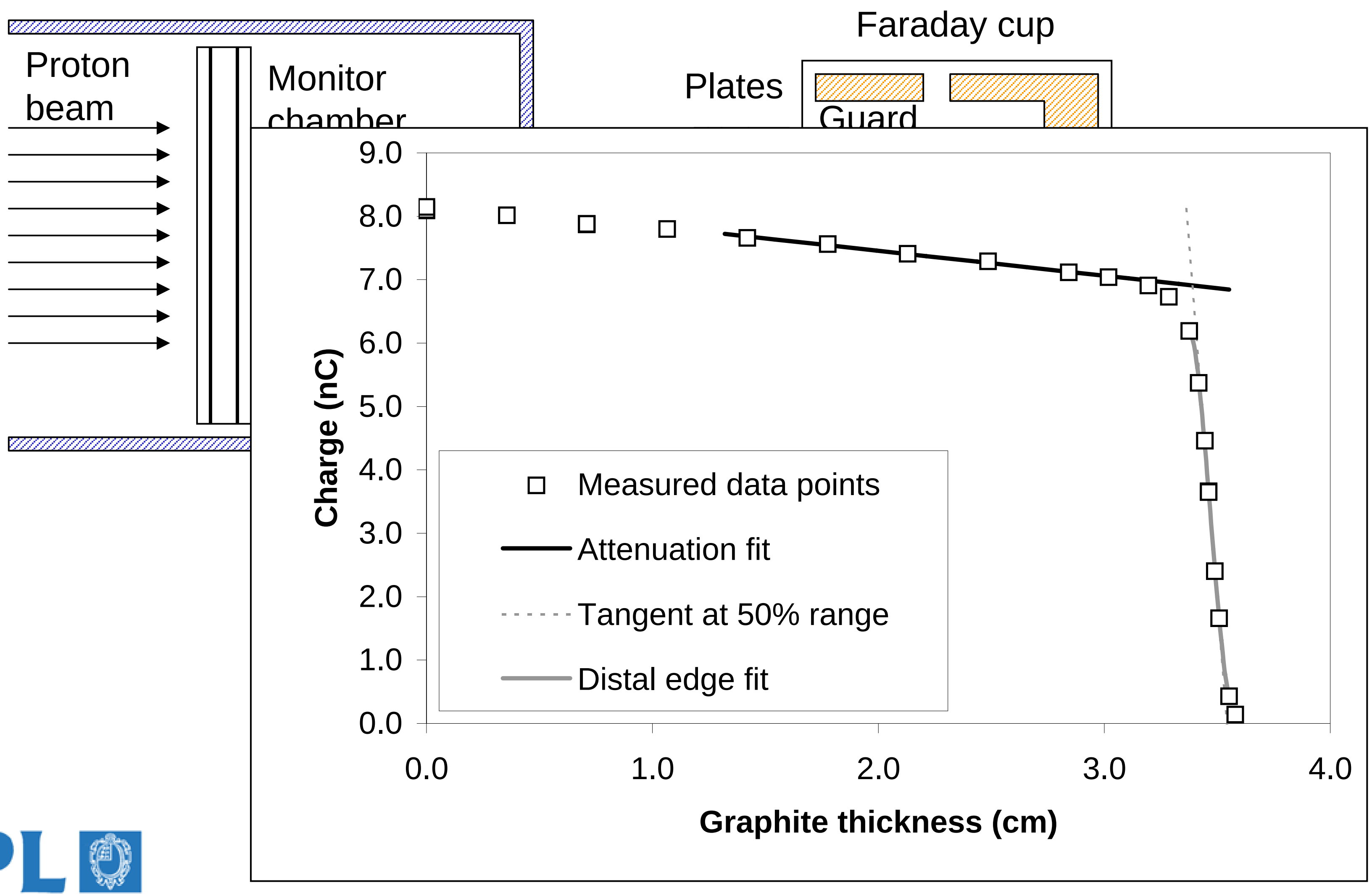
Importance: new recommendation on proton dosimetry by ICRU/IAEA

New ICRU/IAEA – Jones 2006 (Rad Phys Chem 75:541-50)



Faraday cup measurements for range and attenuation measurements

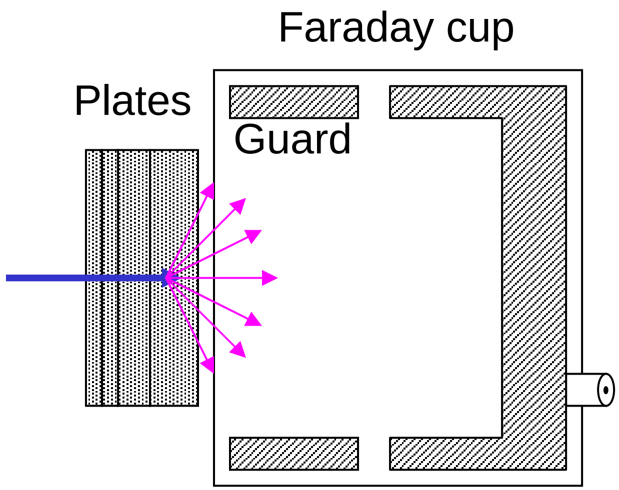


Range results

Material	Range (g cm^{-2}) measured	Range (g cm^{-2}) ICRU 49	Difference in g cm^{-2}	in mm
Graphite	3.467	3.428	0.04	0.2
Polystyrene	3.097	3.125	-0.03	-0.3
PMMA	3.143	3.150	-0.01	-0.1
Aluminium	3.932	4.016	-0.08	-0.3
A150	3.039	3.037	0.00	0.0
Lead	6.535	6.844	-0.31	-0.3
Water	3.049	3.009	0.04	0.4

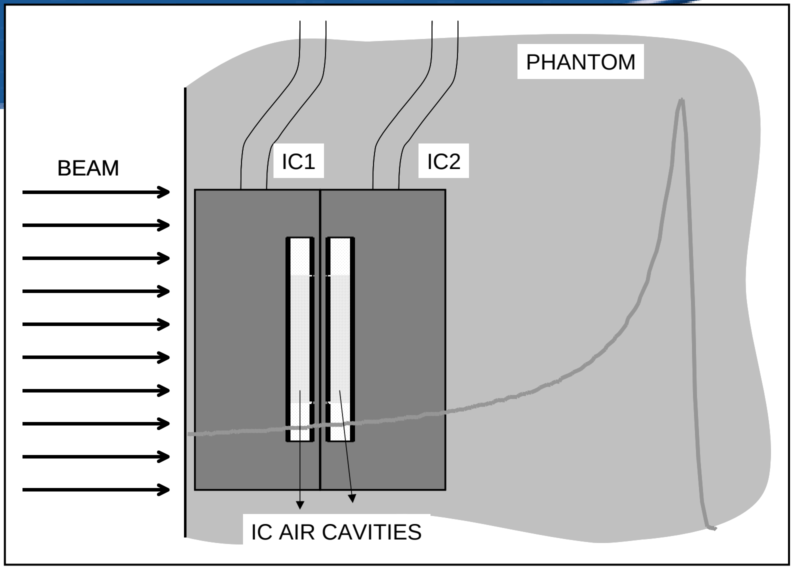
Nuclear attenuation results

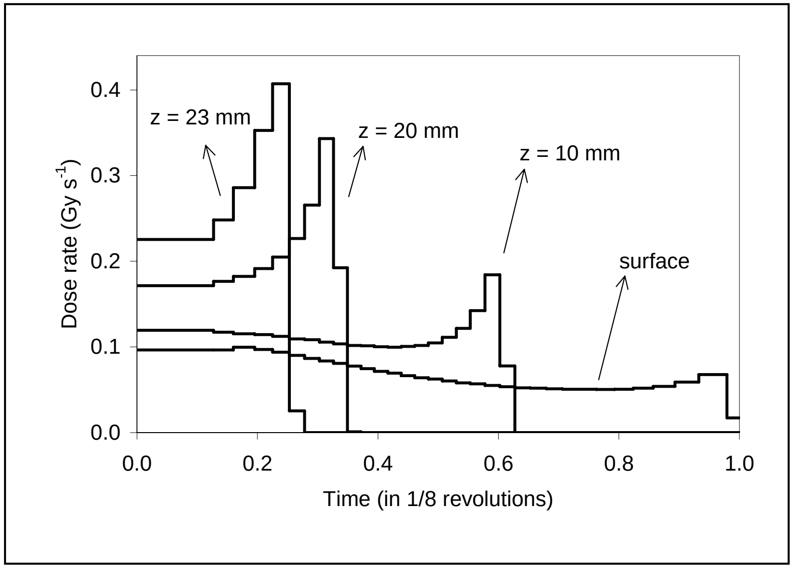
- Factor 2 to 3 higher than expected from ICRU 63 tables: not as yet understood.
- Hypothesis: wide angle secondary protons:

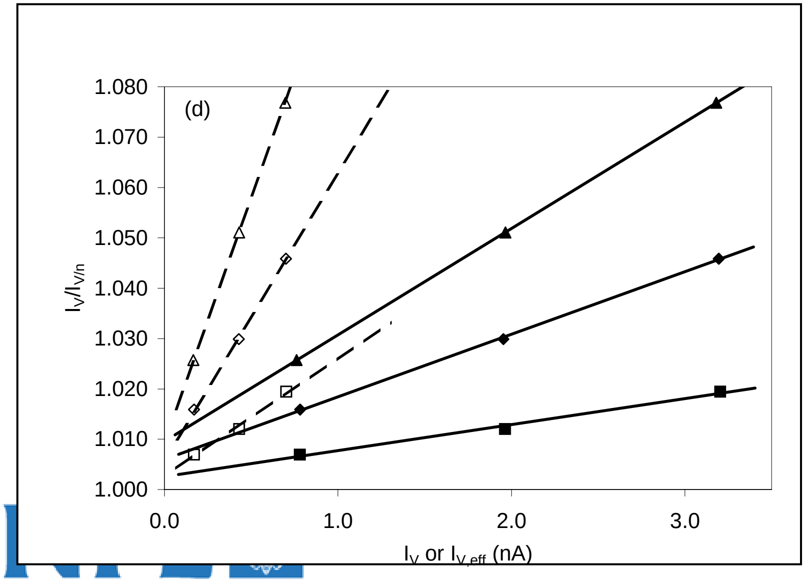


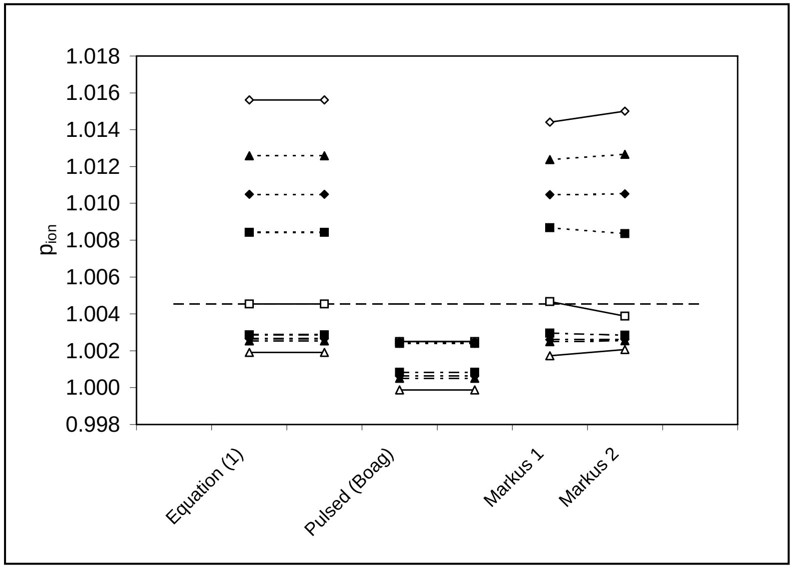
Correction factors for ionization chambers: recombination

(Palmans et al 2006, Phys Med Biol 51:903-17)

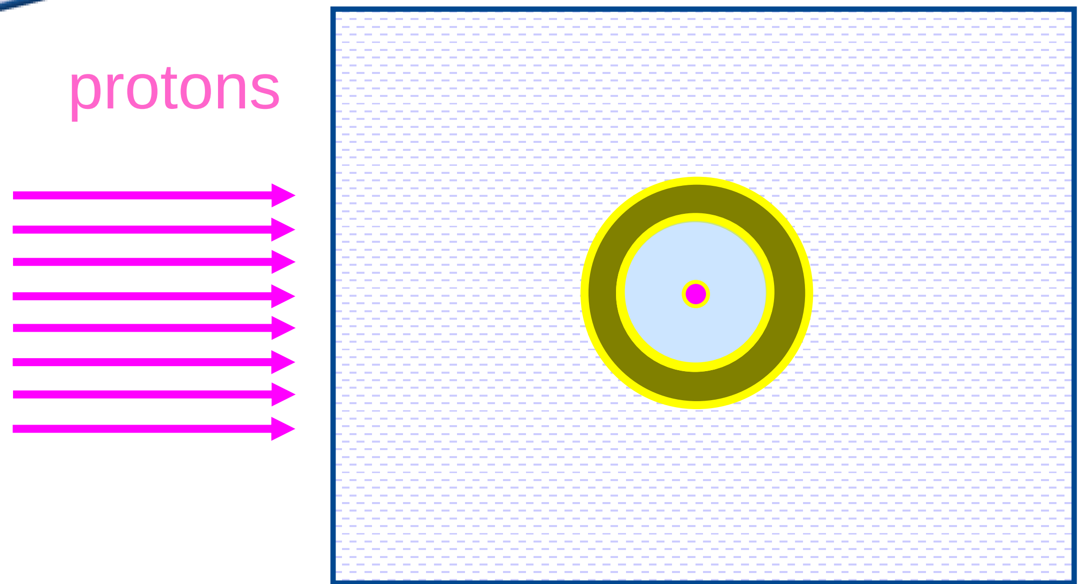








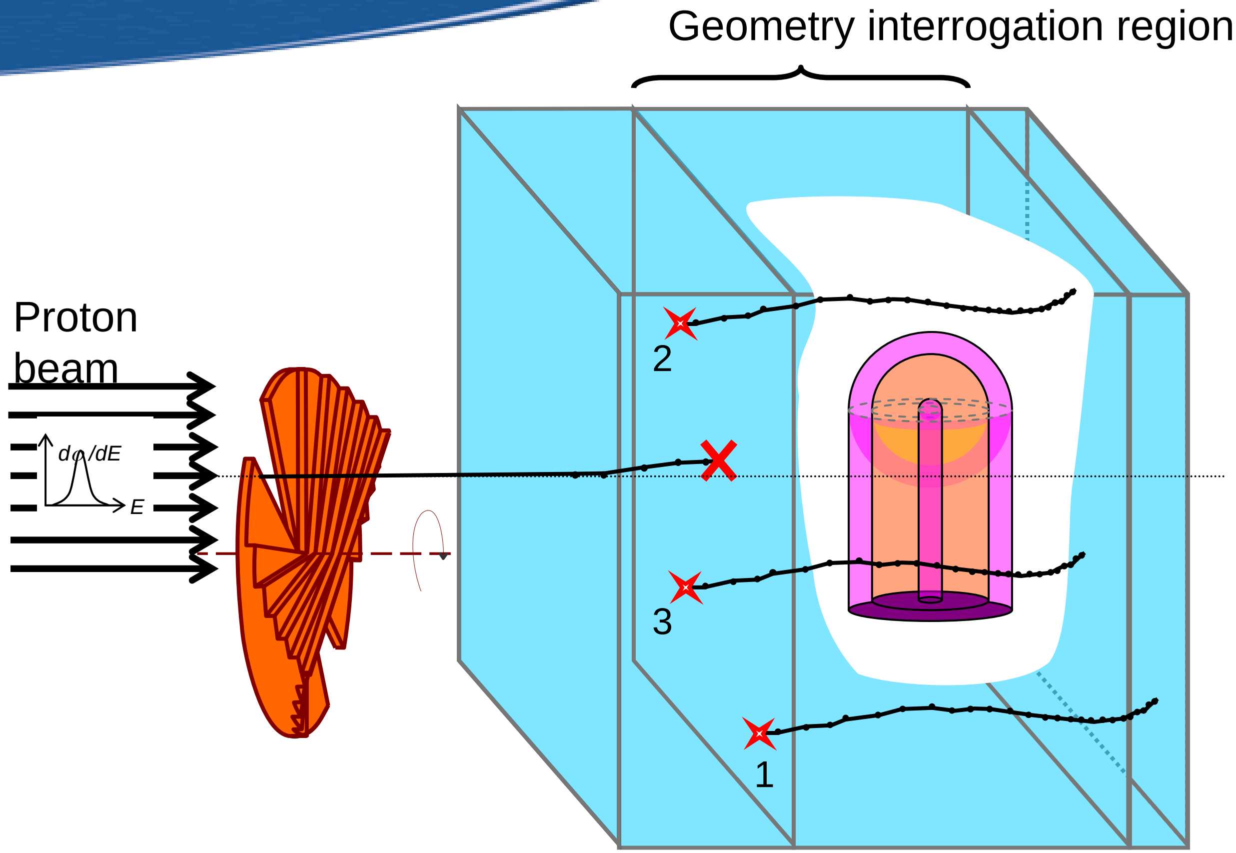
Perturbation correction factors for ionization chambers



$$D_{water} = D_{air} \cdot \left(\frac{S^{SA}}{\rho}\right)_{air}^{water} \cdot p_{cav} \cdot p_{wall} \cdot p_{cel} \cdot p_{dis}$$

- For high-energy x-rays: typical corrections of level 1% applied since 1970’s
- For protons: not applied in any recommendation

p_{dis}: Monte Carlo - McPTRAN.CAVITY
(Palmans 2006, Phys Med Biol 51:3483-501)



- D in cavities

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- Histories resumed
  - Chamber complete
  - New depth

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- Variance reduction
  - Lateral range rejection
  - History splitting

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- PDD_{IC} compared with PDD in homogeneous water

Secondary electrons:

EGSnrc + variance reduction techniques (Verhaegen&Palmans 2001 *Med. Phys.* 28:2088)
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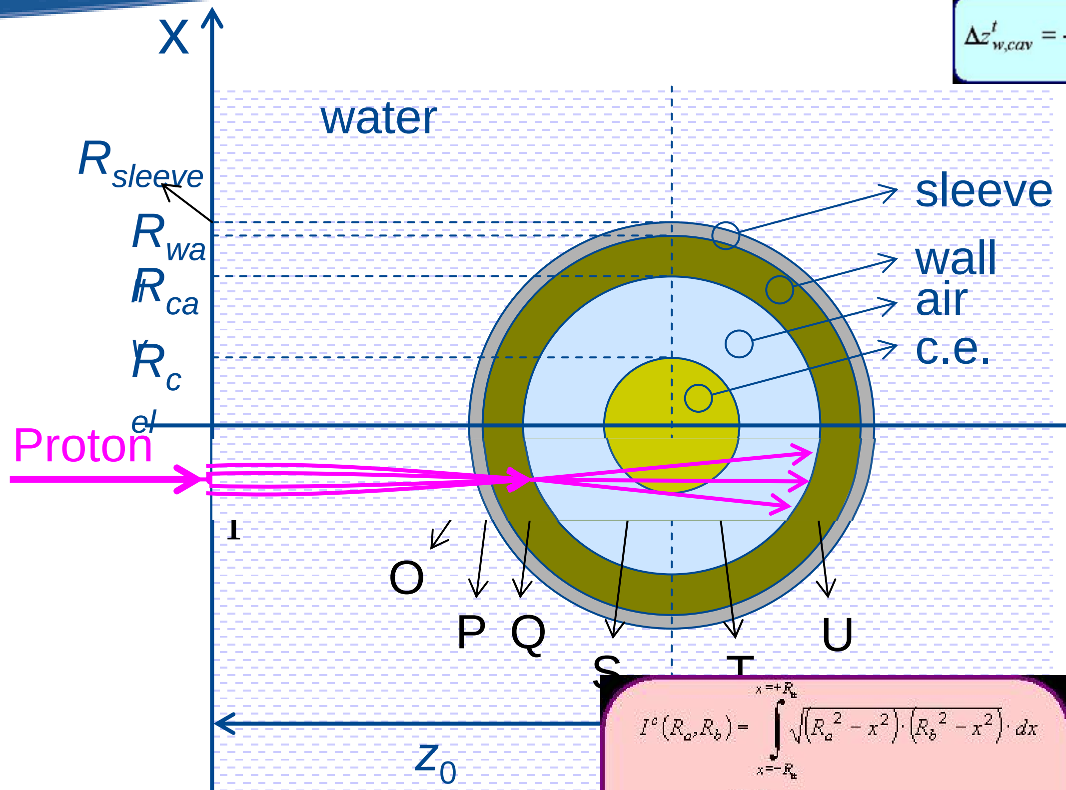
p_{dis}: analytical model
Integrating the depth dose curve
(Palmans 2006, Phys Med Biol 51:3483-501)



$$\Delta z^t_{w,cav} = -\frac{K^t(R_{cav})}{J^t(R_{cav})}$$

$$\Delta z^t_{w,wall} = (F_{wall} - 1)\cdot\frac{I^t(R_{cav},R_{wall}) - K^t(R_{cav})}{J^t(R_{cav})}$$

$$\Delta z^t_{w,cel} = \left[(F_{wall}-1)\cdot\frac{I^t(R_{cav},R_{wall})}{J^t(R_{cav})} - F_{wall}\cdot\frac{K^t(R_{cav})}{J^t(R_{cav})}\right]\cdot\frac{\gamma^t_{cel}}{1-\gamma^t_{cel}} - \left[(F_{wall}-1)\cdot\frac{I^t(R_{cel},R_{wal})}{J^t(R_{cav})} - F_{wall}\cdot\frac{I^t(R_{cel},R_{cav})}{J^t(R_{cav})}\right]\cdot\frac{1}{1-\gamma^t_{cel}} + F_{cel}\cdot\frac{I^t(R_{cel},R_{cav}) - K^t(R_{cel})}{J^t(R_{cav})}\cdot\frac{1}{1-\gamma^t_{cel}}$$

$$\Delta z^t_{w,sleeve} = (F_{sleeve}-1)\cdot\frac{I^t(R_{cav},R_{sleeve}) - I^t(R_{cav},R_{wall})}{J^t(R_{cav})}\cdot\frac{1}{1-\gamma^t_{cel}} - (F_{sleeve}-1)\cdot\frac{I^t(R_{cel},R_{sleeve}) - I^t(R_{cel},R_{wall})}{J^t(R_{cav})}\cdot\frac{1}{1-\gamma^t_{cel}}$$

$$I^c(R_a,R_b) = \int_{x=-R_a}^{x=+R_a}\sqrt{(R_a^2-x^2)\cdot(R_b^2-x^2)}\cdot dx$$

$$J^c(R_a) = \int_{x=-R_a}^{x=+R_a}\sqrt{(R_a^2-x^2)}\cdot dx = \frac{\pi}{2}\cdot R_a^2$$

$$K^c(R_a) = \int_{x=-R_a}^{x=+R_a}(R_a^2-x^2)\cdot dx = \frac{4}{3}\cdot R_a^3$$

$$I^s(R_a,R_b) = \int_{r=0}^{r=R_a}\sqrt{(R_a^2-r^2)\cdot(R_b^2-r^2)}\cdot r\cdot dr = \frac{1}{8}\cdot R_a\cdot R_b\cdot(R_a^2+R_b^2) + \frac{1}{16}\cdot(R_a^2-R_b^2)^2\cdot\ln\left(\frac{R_b-R_a}{R_b+R_a}\right)$$

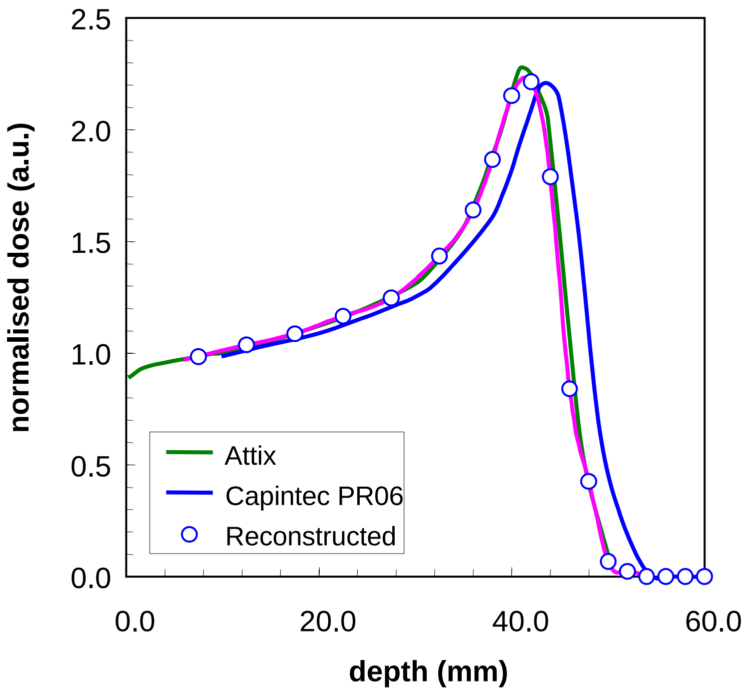
$$J^s(R_a) = \int_{r=0}^{r=R_a}\sqrt{(R_a^2-r^2)}\cdot r\cdot dr = \frac{1}{3}\cdot R_a^3$$

$$K^s(R_a) = \int_{r=0}^{r=R_a}(R_a^2-r^2)\cdot r\cdot dr = \frac{1}{4}\cdot R_a^4$$

p_{dis}: comparison with experiment PDD's
(Palmans 2006, Phys Med Biol 51:3483-501)

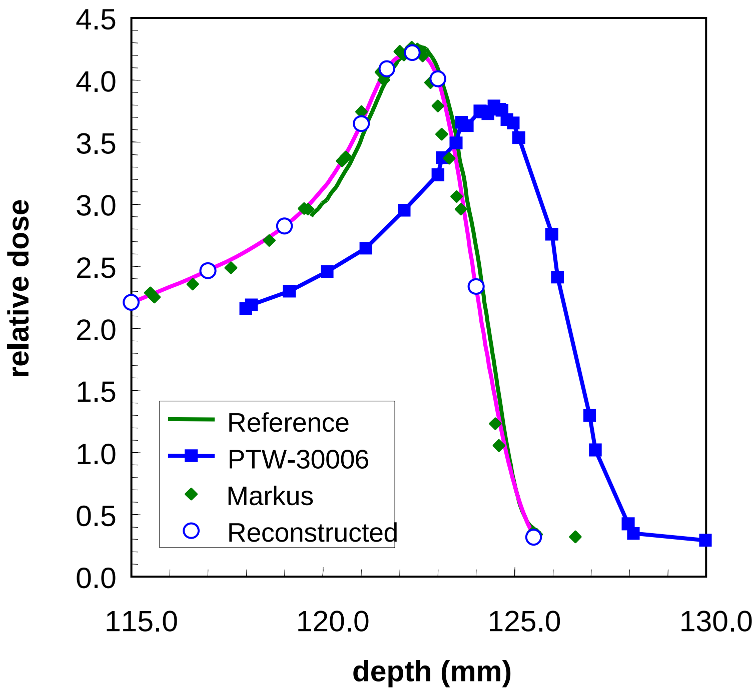
Mobit et al. 2000 *Med. Phys.* 27:2780-2787

78 MeV protons



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

3 GeV ^{12}C



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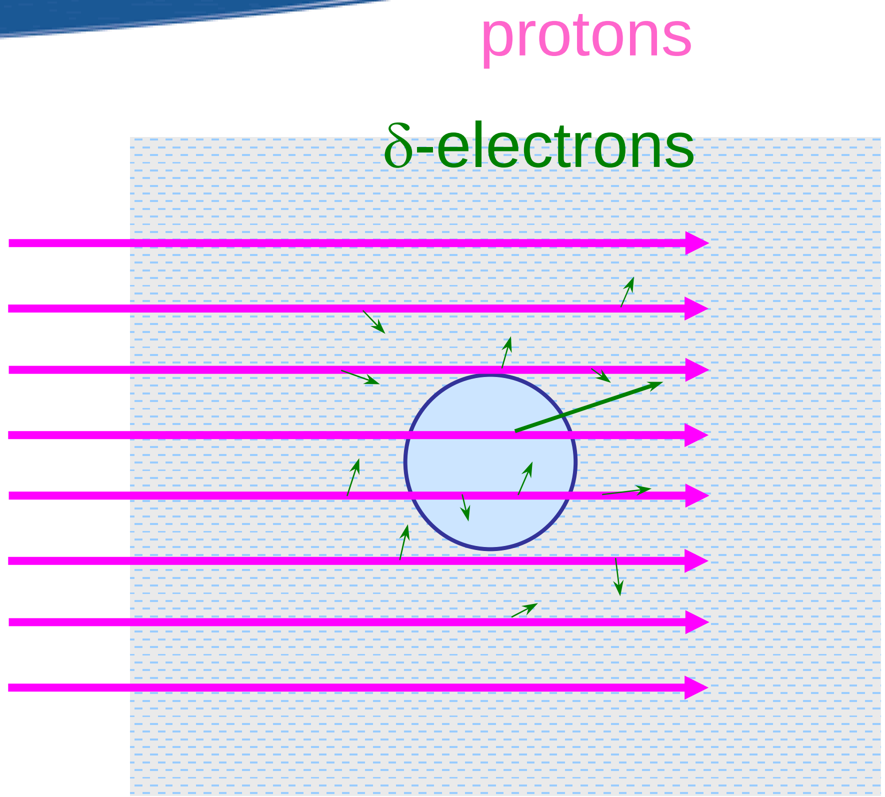
$p_{cav,e}$: SA cavity theory

due to secondary electrons



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

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

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

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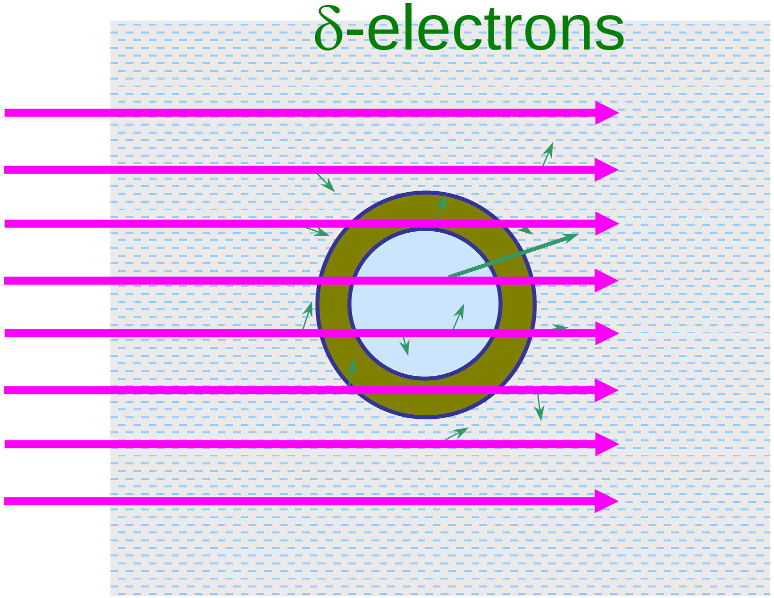
$p_{wall,e}$: SA cavity theory

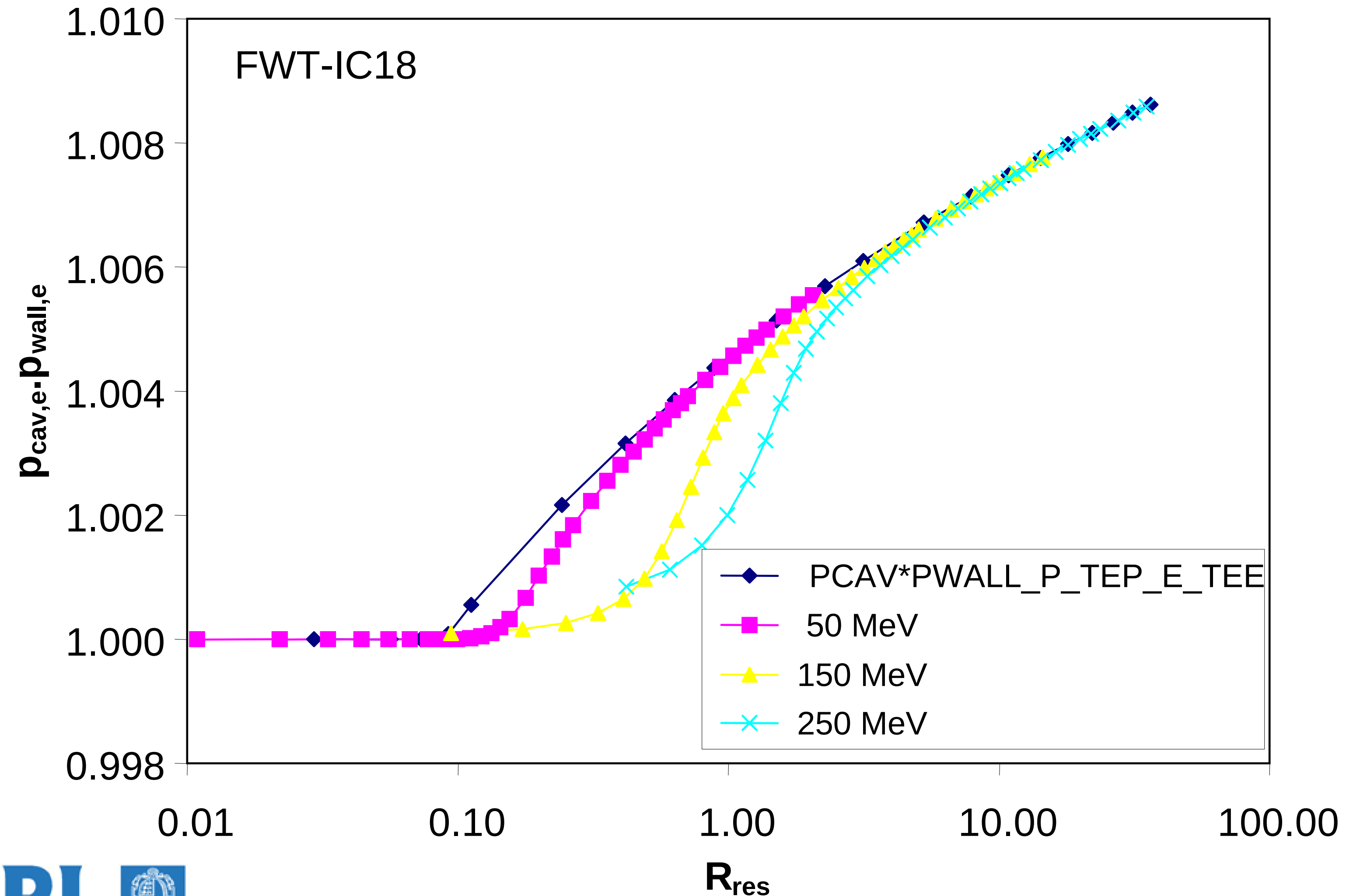


$$D_{med} = D_{air} \cdot \left(\frac{S^{SA}}{\rho}\right)_{air}^{wall} \cdot \left(\frac{S}{\rho}\right)_{wall}^{med}$$

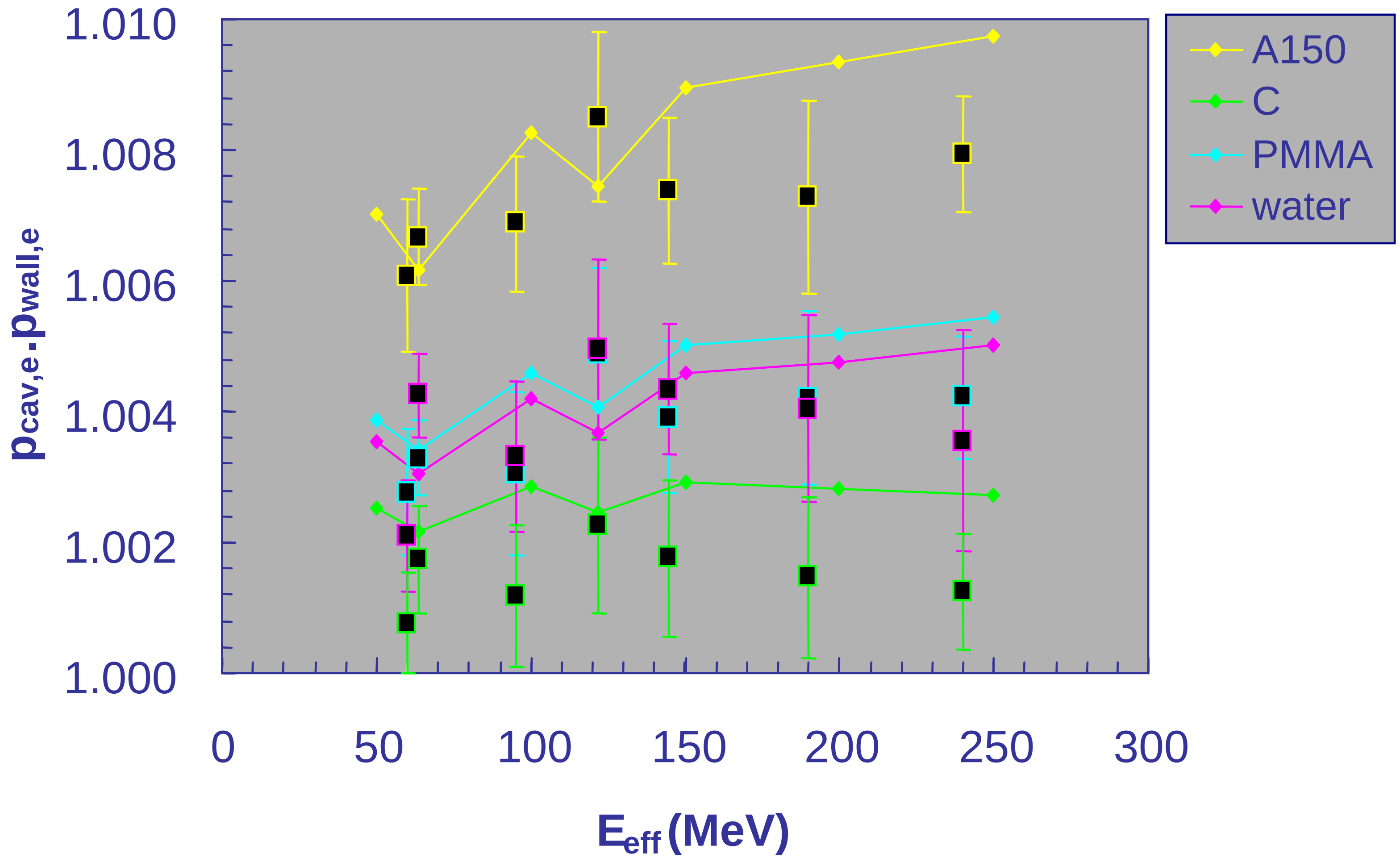
$$= D_{air} \cdot \left(\frac{S^{SA}}{\rho}\right)_{air}^{med} \cdot p_{wall,e}$$

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

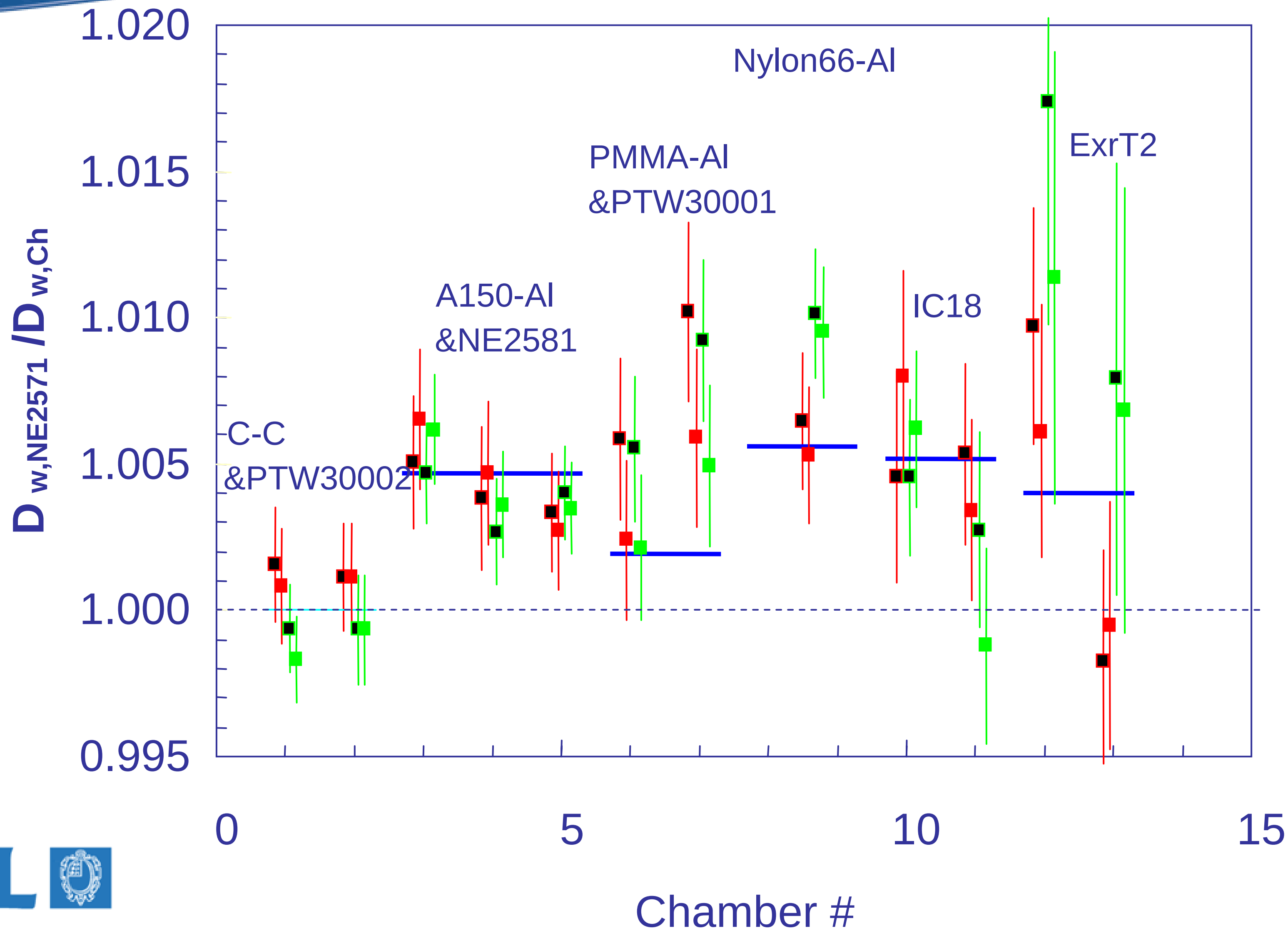
$p_{cav,e}$ & $p_{wall,e}$: SA cavity theory for FWT-IC18 type chamber



$p_{cav,e}$ & $p_{wall,e}$: Monte Carlo versus SA cavity theory (spher r = 0.25cm, Δ = 13.2 keV)



$p_{cav,e}$ & $p_{wall,e}$: comparison with experiment



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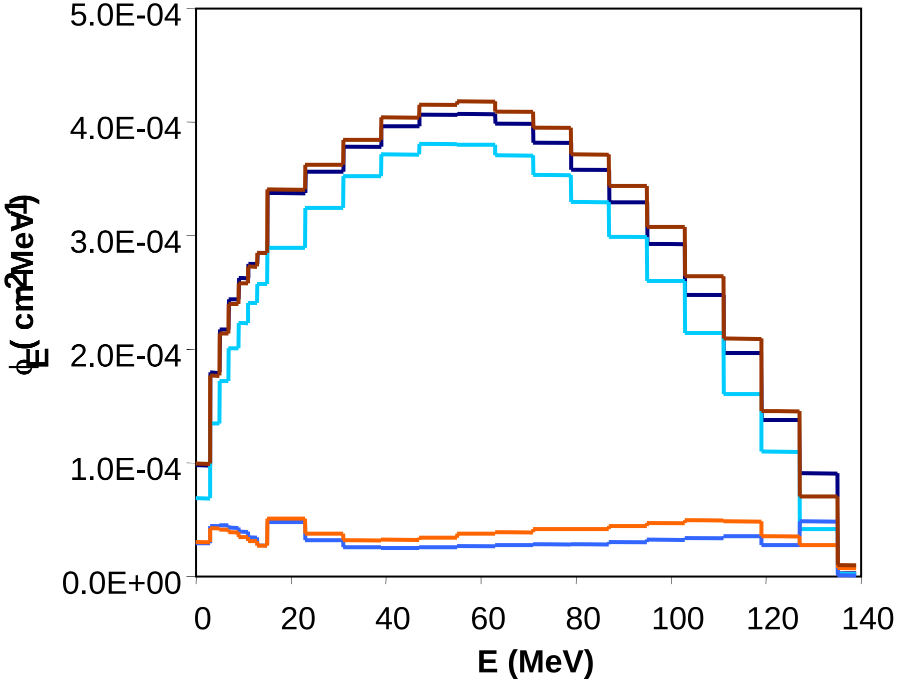
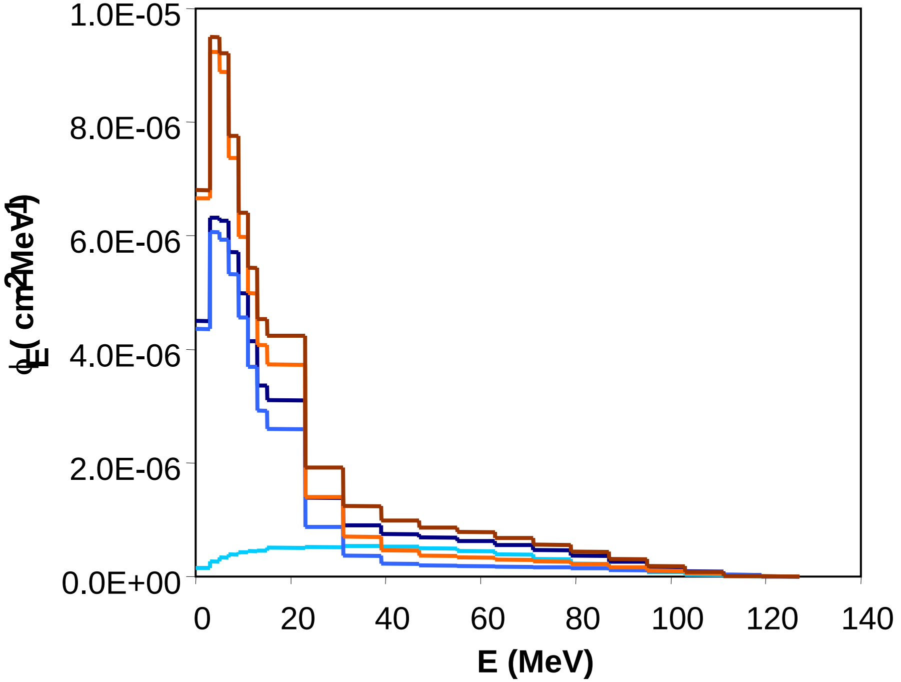
$p_{wall,n}$: (simplistic) analytical model for slowing down spectra secondary p & α (NE2571, 150 MeVp)

due to secondaries from nonelastic nuclear interactions

p:



α:

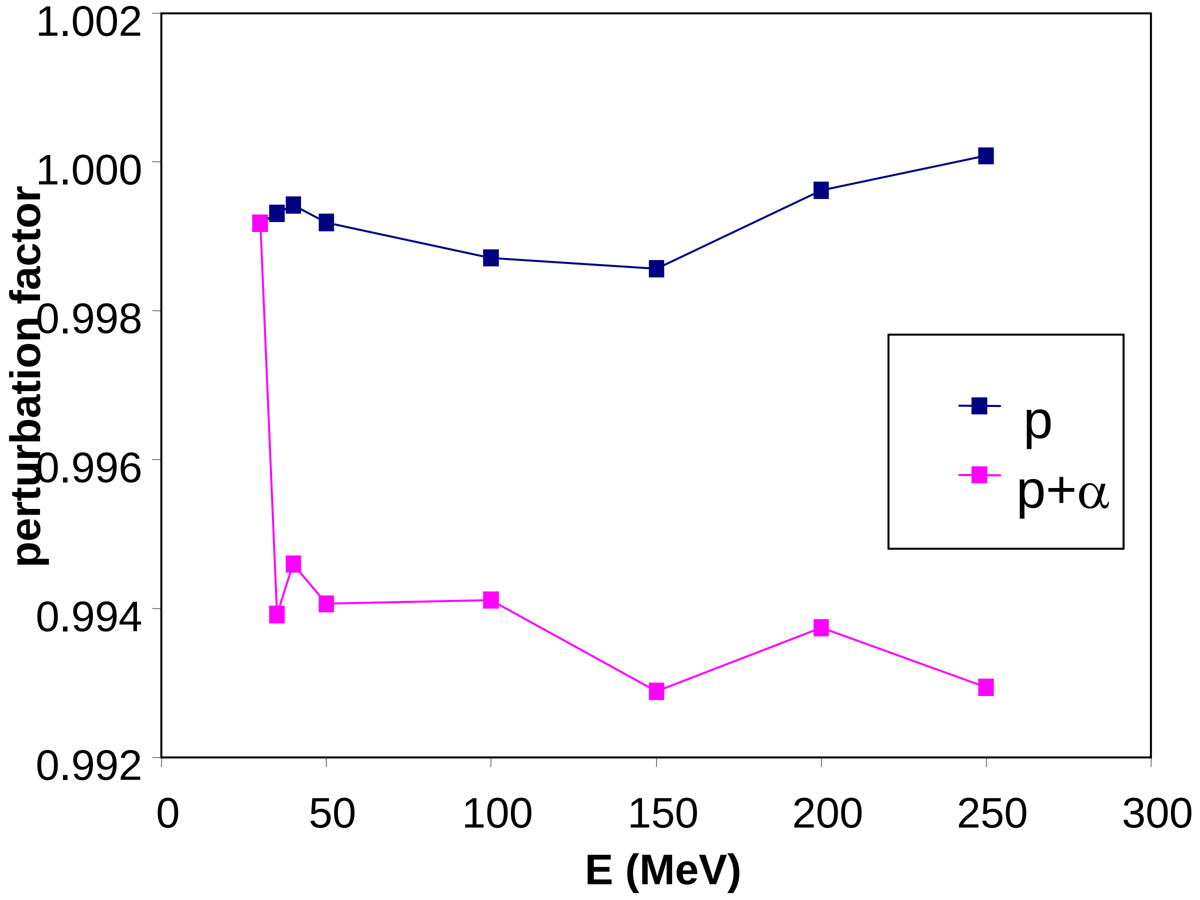


water bulk

“water” wall

graphite wall

$p_{wall,n}$: secondary p & α perturbation (NE2571)



- BUT:
- ICRU 63 data (u_C ~ 30-40%)
- Crude model
- → MC study needed

Summary

- Graphite calorimetry
  - Many operation characteristics, perturbation factors and heat transfer phenomena are similar as for photons
  - Primary standard level calorimeter is being built
  - Conversion to dose to water is a serious issue
- Interaction/basic data:
  - Substantial contribution to $(w_{air})_p$ value
  - Range and attenuation measurements
- Ionization chambers
  - Corrections for recombination, gradients and secondary electrons
  - Further work: non-elastic nuclear interactions

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- Simon Duane, Thomas Russell, David Shipley, Mark Bailey, Alan DuSautoy, Andrzej Kacperek (CCO), Frank Verhaegen, Jan Seuntjens and…

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