Monte Carlo Applications in Measurement Dosimetry

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CANADA

Clinical Dosimetry for Radiotherapy, 2009 AAPM Summer School

Question

- Are the k_Q factors in the AAPM TG-51 calculated purely by Monte Carlo techniques?

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Educational Objectives

- Understand measurement dosimetry fundamentals
- Understand the role of Monte Carlo transport in measurement dosimetry
- To appreciate the possibilities MC can give us in terms of making measurement dosimetry more accurate

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Clinical Measurement Dosimetry

- Measurement of dose using detectors:
  - Ionization chambers
  - Diodes
  - TLD's
  - Radiochromic Film
  - MOSFETS

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Classification of dosimeters

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Measurement dosimetry

$$D_{\mathrm{med}}(Q) = f(Q)k_{bq}(Q)k_{dr}(\dot{D})k_l M_{\mathrm{det}}(Q, D, \dot{D}, \theta, \phi)$$

- $f(Q)$: Energy dependence
- $k_{bq}(Q)$: Intrinsic energy dependence, LET effects…
- $k_{dr}(\dot{D})$: Dose rate
- k_l: Linearity
- M_{det}: Detector reading

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A few known cases…

	$f(Q)$	$k_{bq}(Q)$	$k_{dr}(\dot{D})$	k_l	M_{det}
Ionization chamber	$\left(\frac{L}{\rho}\right)^{w}_{air} P_Q$	$\left(\frac{W}{e}\right)_{\text{air}} \frac{1}{m_{\text{air}}}$	1	1	Q_{corr}
Fricke dosimeter	$(D)^{w}_{F}$	$\frac{1}{\epsilon(Fe^{3+})G}$	1	1*	$\frac{\Delta OD}{\rho l}$
Water calorimeter	1	$c_w \frac{1}{1-h}$	1	k_c	ΔT_w

*: away from region of supra-linearity

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The meaning…

"Calibrating" the detector means determining:

$$f(Q)k_{bq}(Q)k_{dr}(\dot{D})k_l$$

by explicitly measuring:

$$\frac{D_{\mathrm{med}}(Q)}{M_{\mathrm{det}}(Q, D, \dot{D}, \theta, \phi)} \text{ or } \frac{K_{\mathrm{air}}(Q)}{M_{\mathrm{det}}(Q, D, \dot{D}, \theta, \phi)}$$

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$f(Q)$ is the "energy dependence" of the detector

For absorbed dose:

$$f(Q) = \left(\frac{\overline{L}}{\rho}\right)_{\text{air}}^{\text{med}} P_{\text{repl}} P_{\text{wall}} P_{\text{stem}} P_{\text{cel}}$$

For air kerma:

$$f(Q) = \frac{1}{1 - g_{\text{air}}} \left(\frac{\overline{L}}{\rho}\right)_{\text{air}}^{\text{wall}} \left(\frac{\overline{\mu_{\text{en}}}}{\rho}\right)_{\text{wall}}^{\text{air}} K_{\text{wall}} K$$

How does TG51 fit into this?

$$k_{\mathrm{Q}} = \left(f(Q)\right)^{\mathrm{Q}}_{\mathrm{Co}}$$

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Role of Monte Carlo calculations in measurement dosimetry…

…determining f_Q

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The correction factors...

$$D_{\text{air}} = \frac{D_{\text{air}}}{D^{w}_{\text{air}}} \cdot \frac{D^{w}_{\text{air}}}{D^{w,c}_{\text{air}}} \cdot \frac{D^{w,c}_{\text{air}}}{D^{w,c,s}_{\text{air}}} \cdot D^{w,c,s}_{\text{air}}$$

$$= P_{\text{wall}} \quad P_{\text{cel}} \quad P_{\text{stem}} \cdot D^{w,c,s}_{\text{air}}$$

$$D_{\text{w}}(z) = D_{\text{air}} \cdot \left(\frac{\overline{L}}{\rho}\right)^{\text{w}}_{\text{air}} P_{\text{repl}}$$

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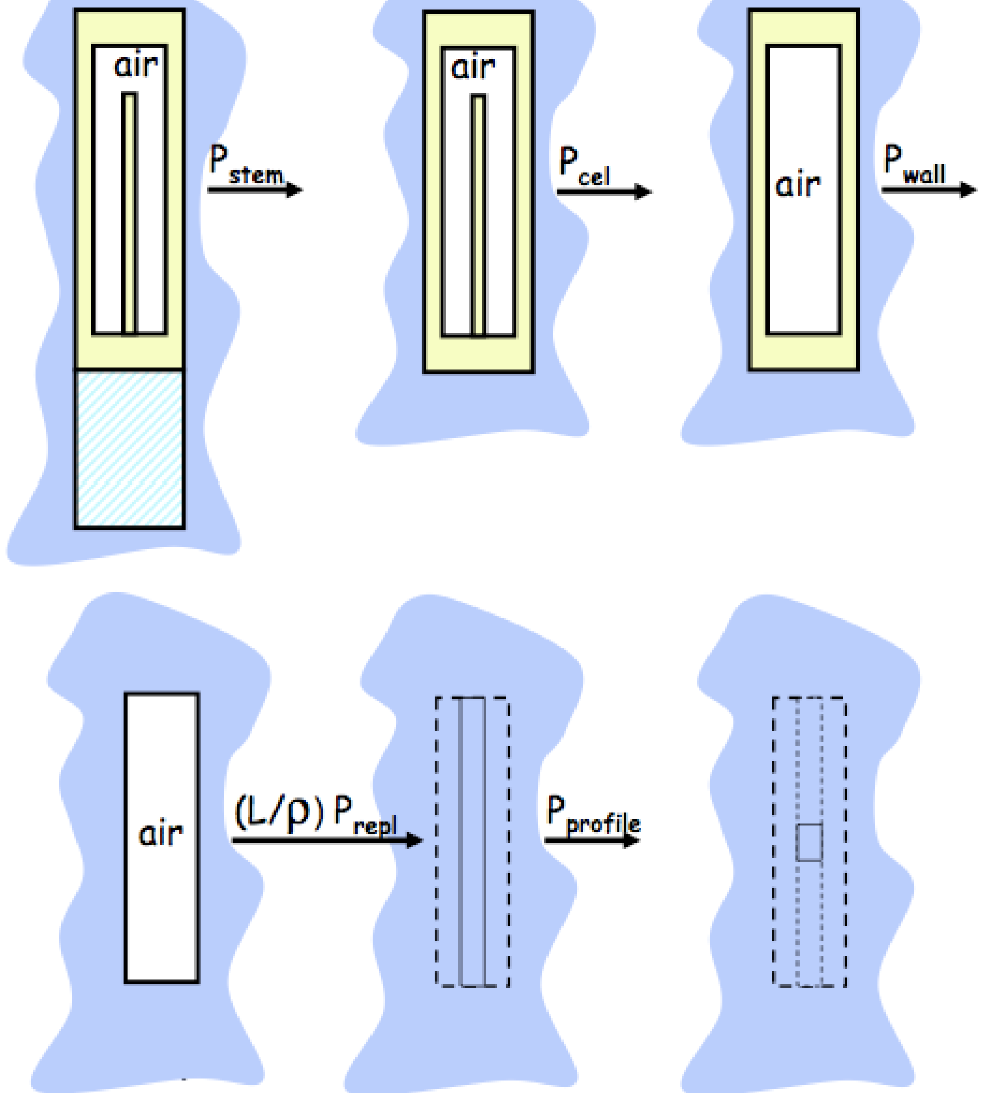
In-phantom ion chamber correction factors



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What is a MC simulation?

"The Monte Carlo technique for the simulation of the transport of electrons and photons through bulk media consists of using knowledge of the probability distributions governing the individual interactions of electrons and photons in materials to simulate the random trajectories of individual particles. One keeps track of physical quantities of interest for a large number of histories to provide the required information about the average quantities"

TG105 → Rogers and Bielajew

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What is a Monte Carlo simulation?

Particles move in discrete steps from one interaction site to the next

Step length selection from probability distributions

Interaction type selection from probability distributions

(Cross sections)

Random Number Generator

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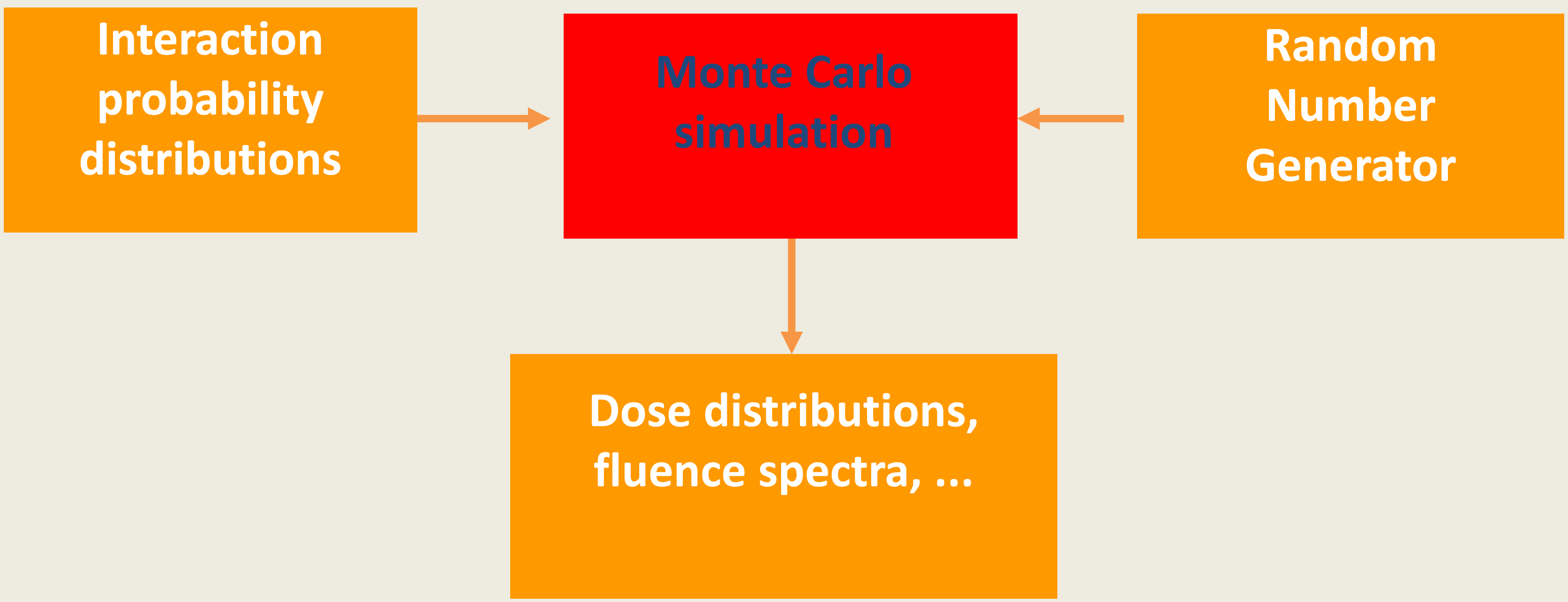
Putting a Monte Carlo simulation together:



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Simple photon simulation

- say: $\Sigma_{total} = \Sigma_{compton} + \Sigma_{pair}$ cm^{-1}

- select 2 random numbers R1, R2
  - uniform between 0 and 1
  - whole careers devoted to doing this
  - cycle length now $10^{>40}$

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Photon transport (cont)

How far does photon go before interacting?

$$X = -\ln(R1) \quad / \Sigma_{total} \quad \text{cm}$$

is exponentially distributed $[0,\infty)$

with a mean of $1/\Sigma_{total}$

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Photon transport (cont)

After going x, what interaction occurs?

$$\text{if } R2 < \frac{\Sigma_{compton}}{\Sigma_{total}}$$

then a compton scatter occurs

otherwise

a pair production event occurs

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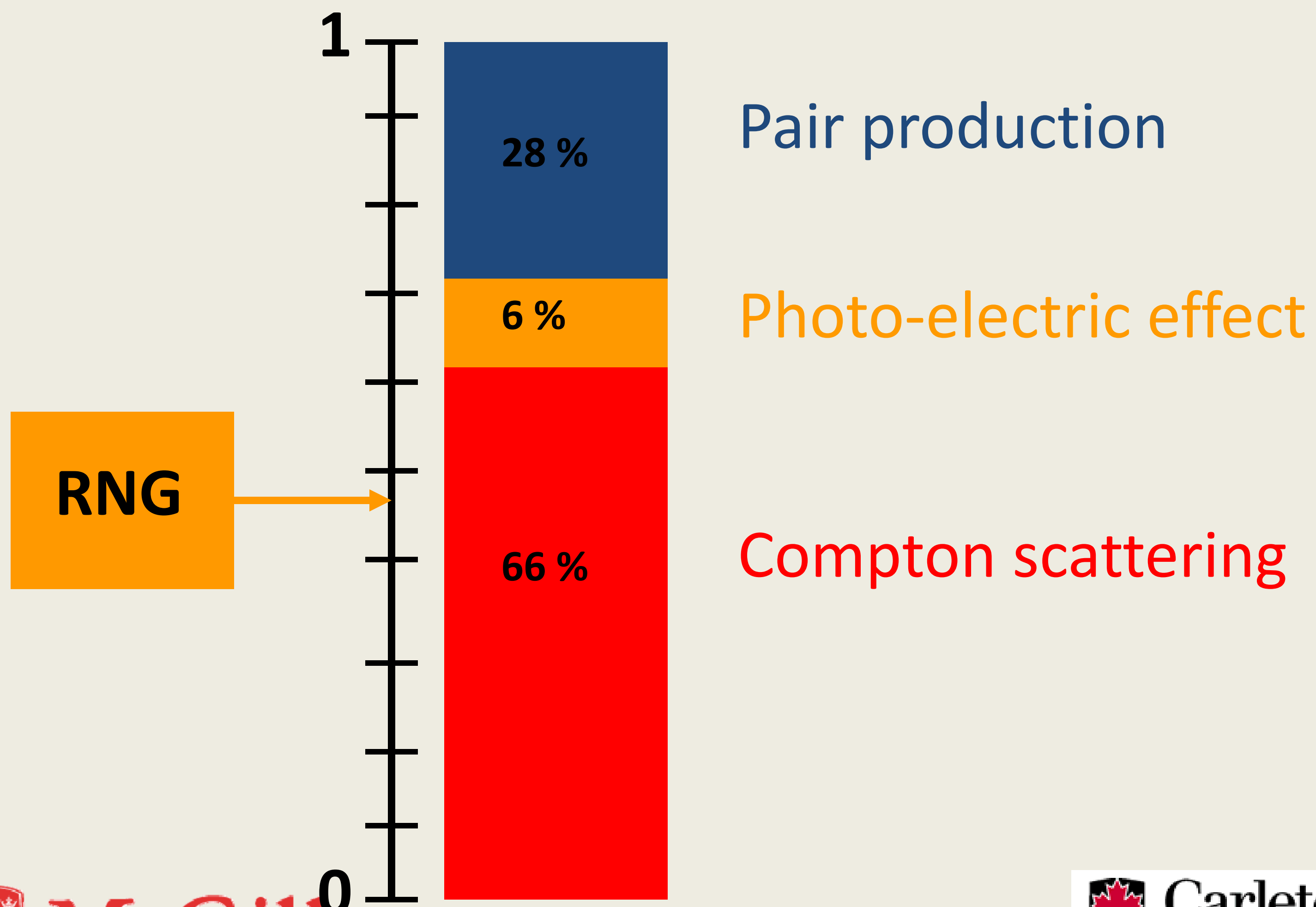
Sampling an interaction type:

e.g. 3 MeV photon in Pb



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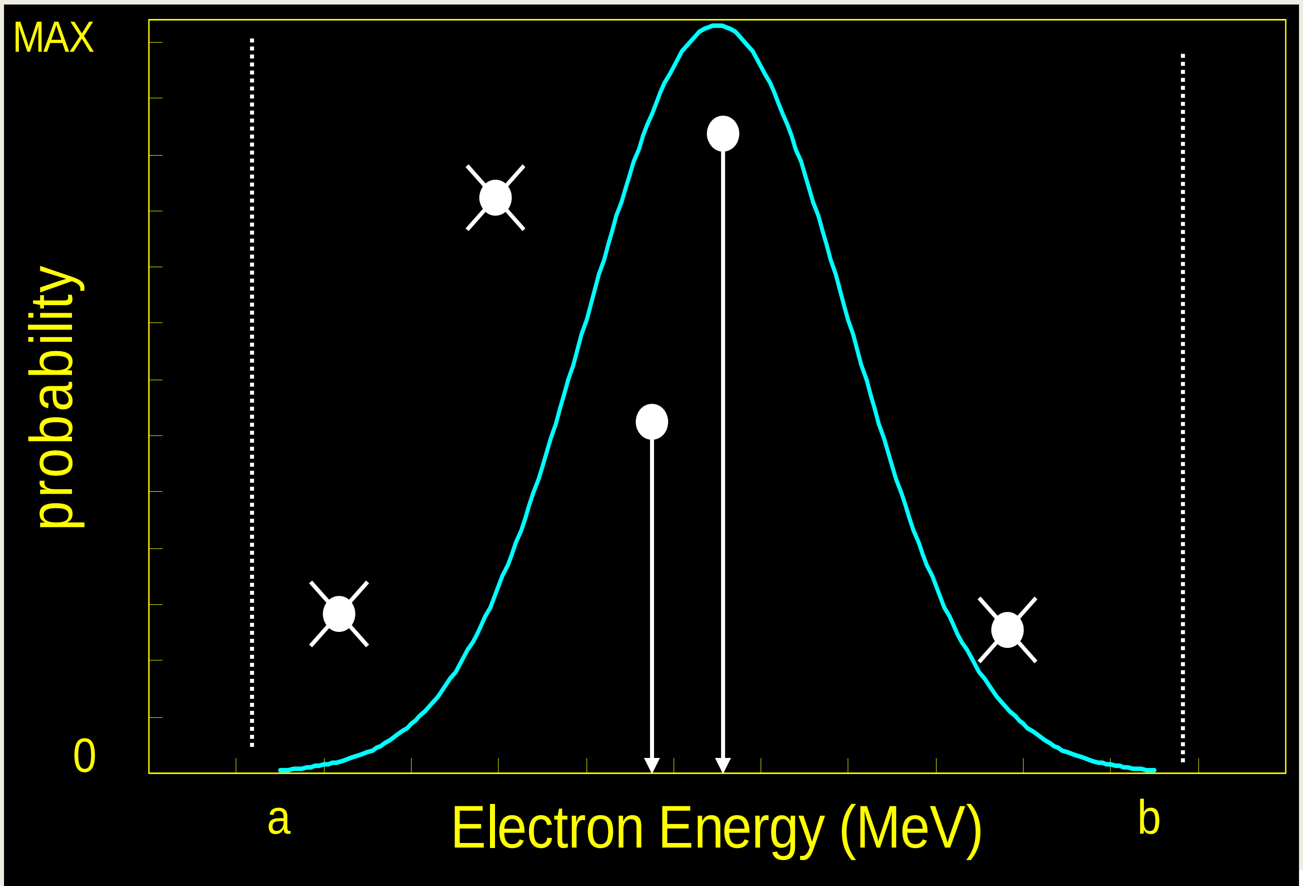
Random sampling from probability distributions: *Rejection method*



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How is simulation used?

- score whatever data wanted
  - average distance to interaction
  - how many of each type
  - energy deposited by each type
  - etc
- more useful in complex cases

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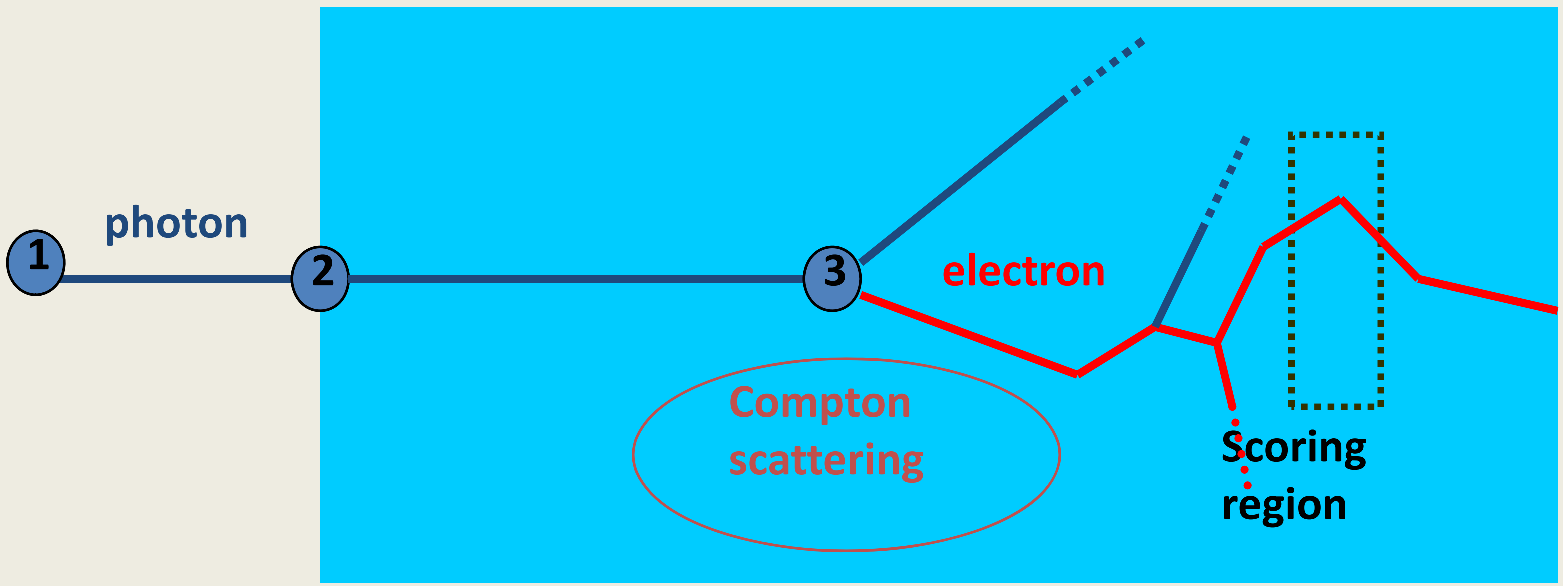
A simple MC simulation



1 : sample particle energy, direction, starting position, ...

2 : sample distance to interaction

3 : sample type of interaction

4 : sample direction, energy, ... of new particles

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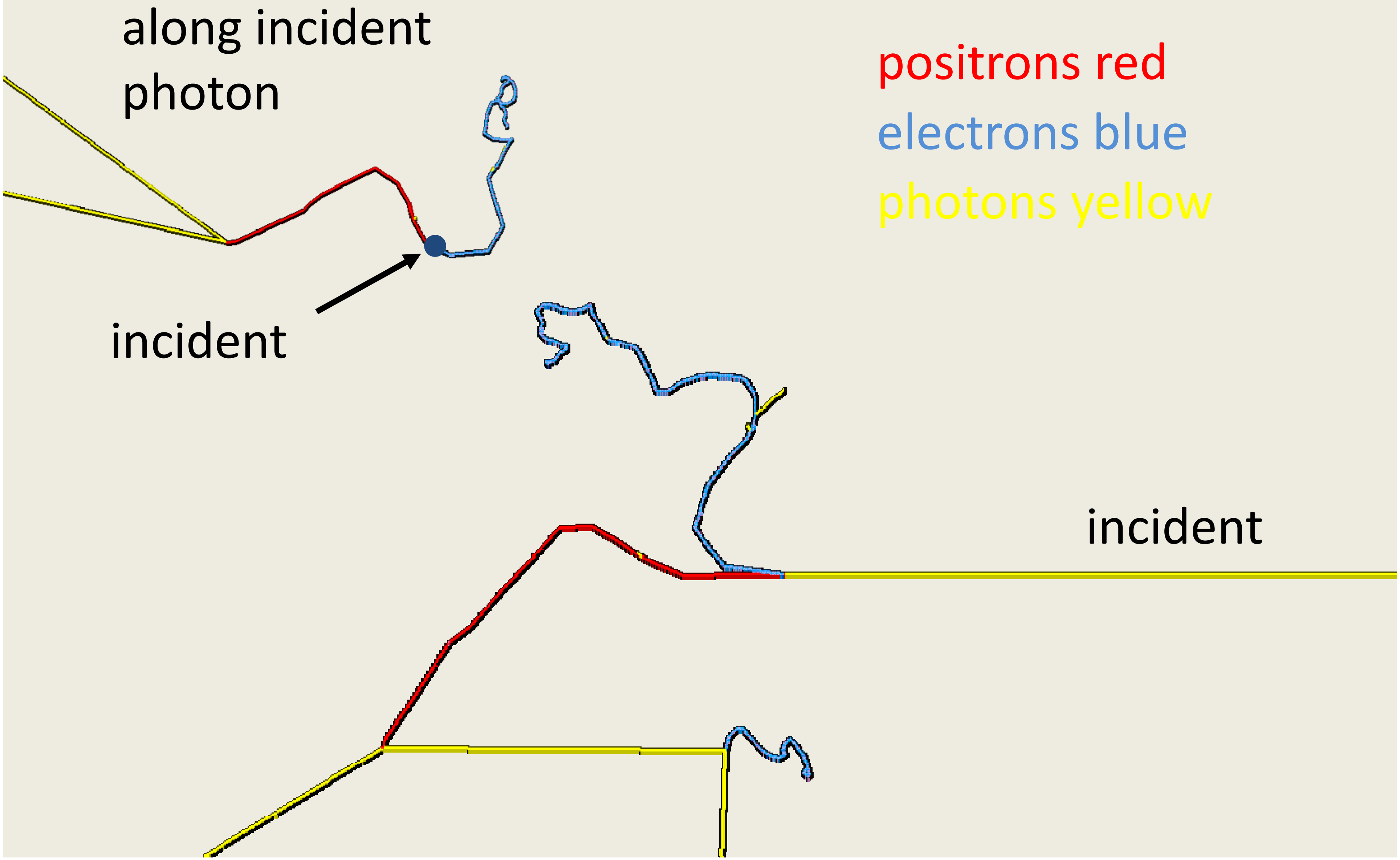
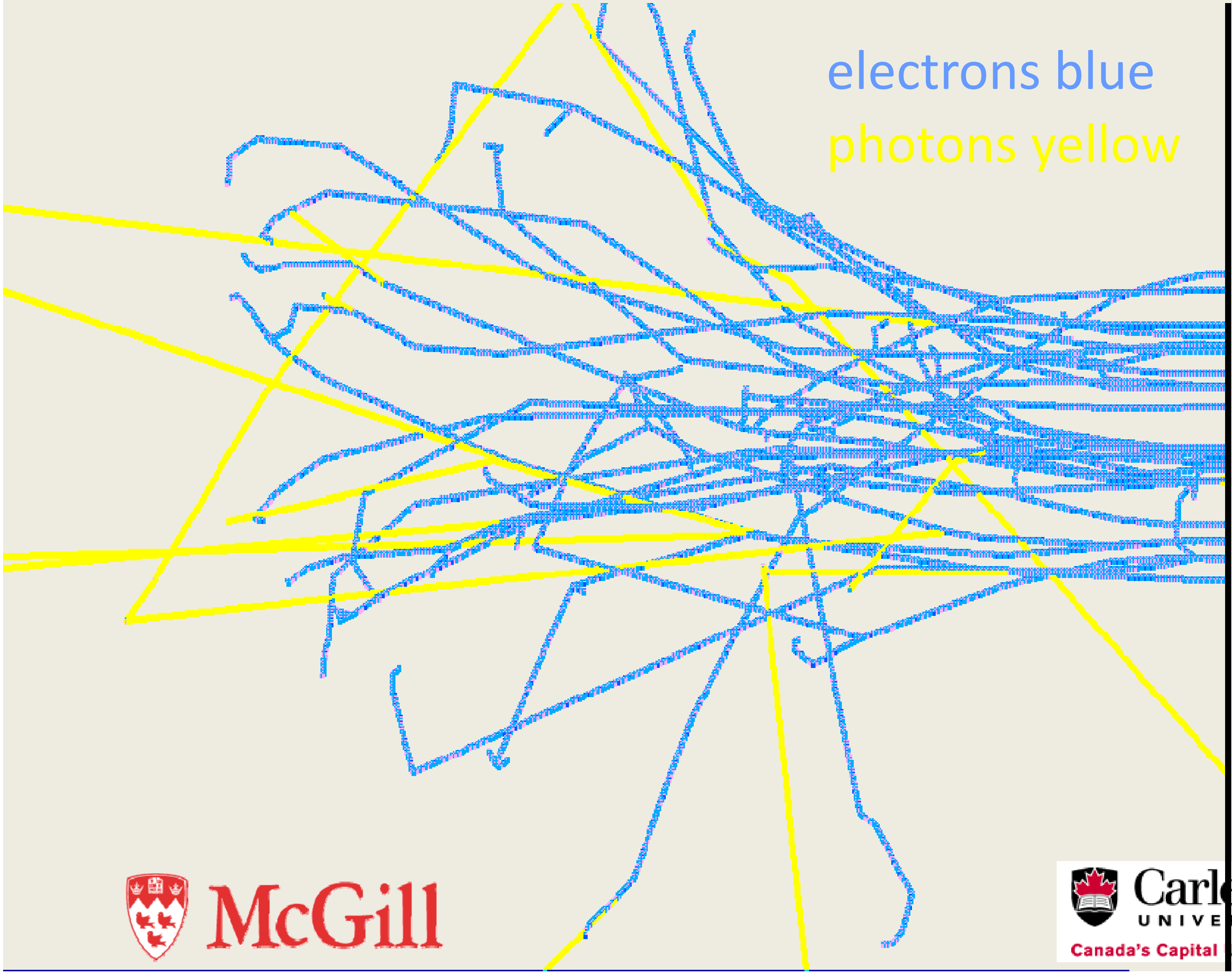
10 MeV photon on lead



10 MeV electrons on water from right



Condensed history technique fore- transport

- as electrons slow down, they have many interactions
- Berger's grouping into condensed history steps made Monte Carlo transport of electrons feasible.
  - individual scattering events grouped via multiple-scattering theories
  - low-energy-loss events grouped into restricted stopping powers
- increases efficiency by decreasing time,T, (a lot)
- modern transport mechanics algorithms are very sophisticated in order to maximize step size while maintaining accuracy (to gain speed).

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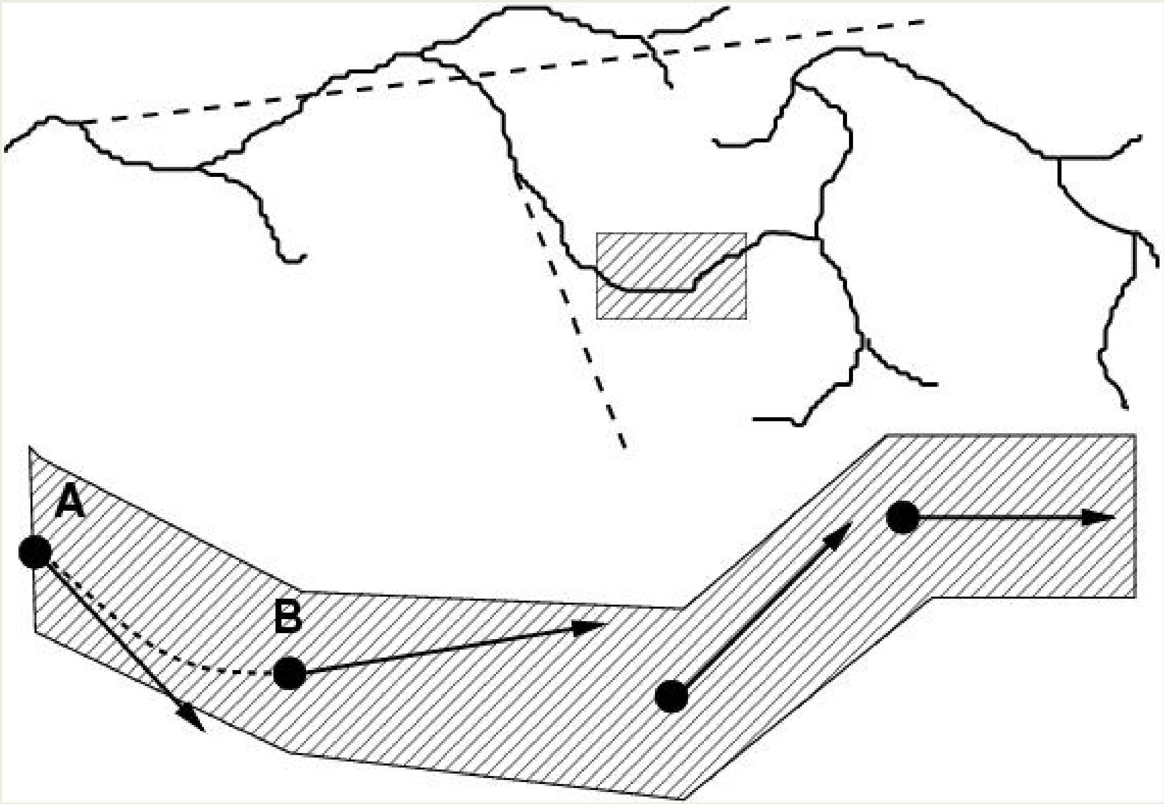
e- transport is much more complex

hard collisions
create secondaries
eg δ-rays / brem



soft collisions
-grouped
-multiple scatter
-restricted energy loss

condensed history technique: group many individual interactions into steps

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Energy deposition near boundary

422 *A F Bielajew et al*

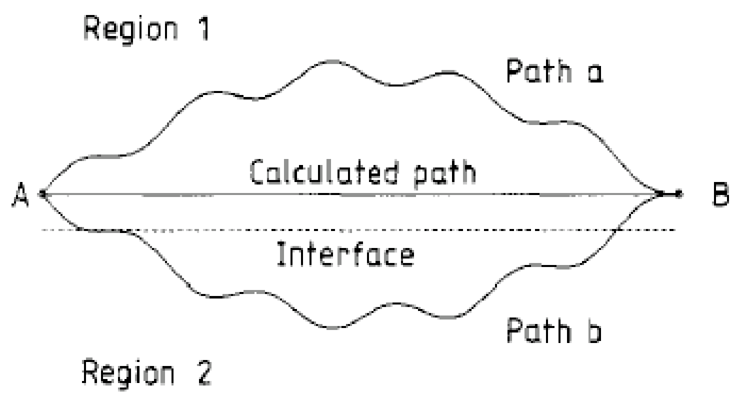

Figure 1. The calculated path and two possible 'physical' paths near an interface. The dose is correctly calculated for path a but is incorrect for path b. If region 2 is a vacuum, for example, path b is not physically possible. These interface artefacts can be avoided by reducing the size of the straight line path in the simulation.

Bielajew, Rogers, Nahum (Phys Med Biol. 1985, Vol. 30, No. ***5, 419-427***)

The step size is parameter-controlled

- We want long steps to speed up the simulations
- But … we want short steps to make the calculation accurate
- →Step control:
  - – Distance to next catastrophic interaction
  - – Fractional energy loss / step
  - – Absolute step length maximum
  - – Proximity of boundary

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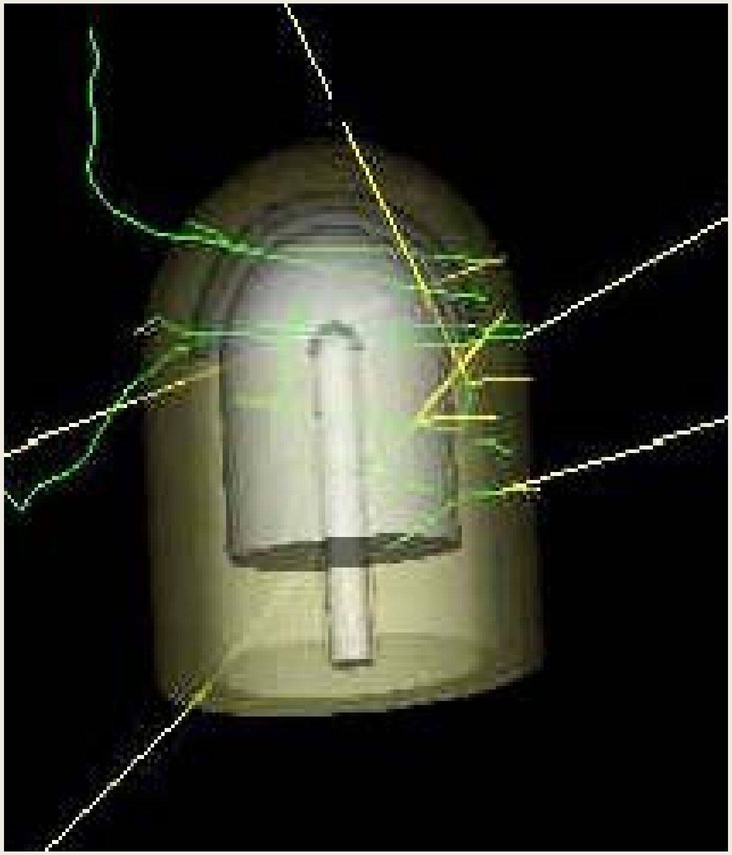
Back to dosimetry…



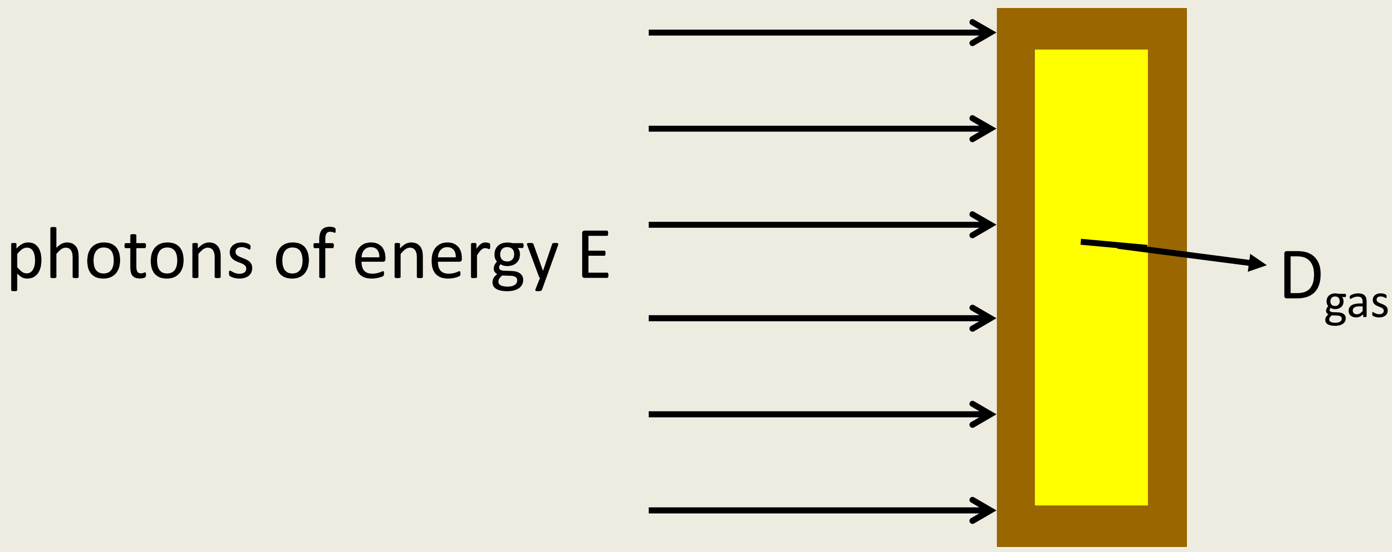
Farmer type ionization chamber

photons and

secondary electrons

David Shipley, NPL

Ionization chamber formalism for photon beams



$$D_{gas} = K_{air}(1-\bar{g})\left(\frac{\bar{L}}{\rho}\right)_{wall}^{gas}\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{air}^{wall} A_{wall} A_{fl}$$

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Ionization chamber formalism for photon beams

with: $\bar{g}$ average energy lost in bremsstrahlungin air

$\left(\frac{\bar{L}}{\rho}\right)_{wall}^{gas}$ restricted stopping power ratio cavity gas-to-cavity wall

$\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{air}^{wall}$ mass-energy absorption coefficient ratio wall-to-air

A_{wall} wall correction (attenuation & scattering)

A_{fl} fluence perturbation correction factor

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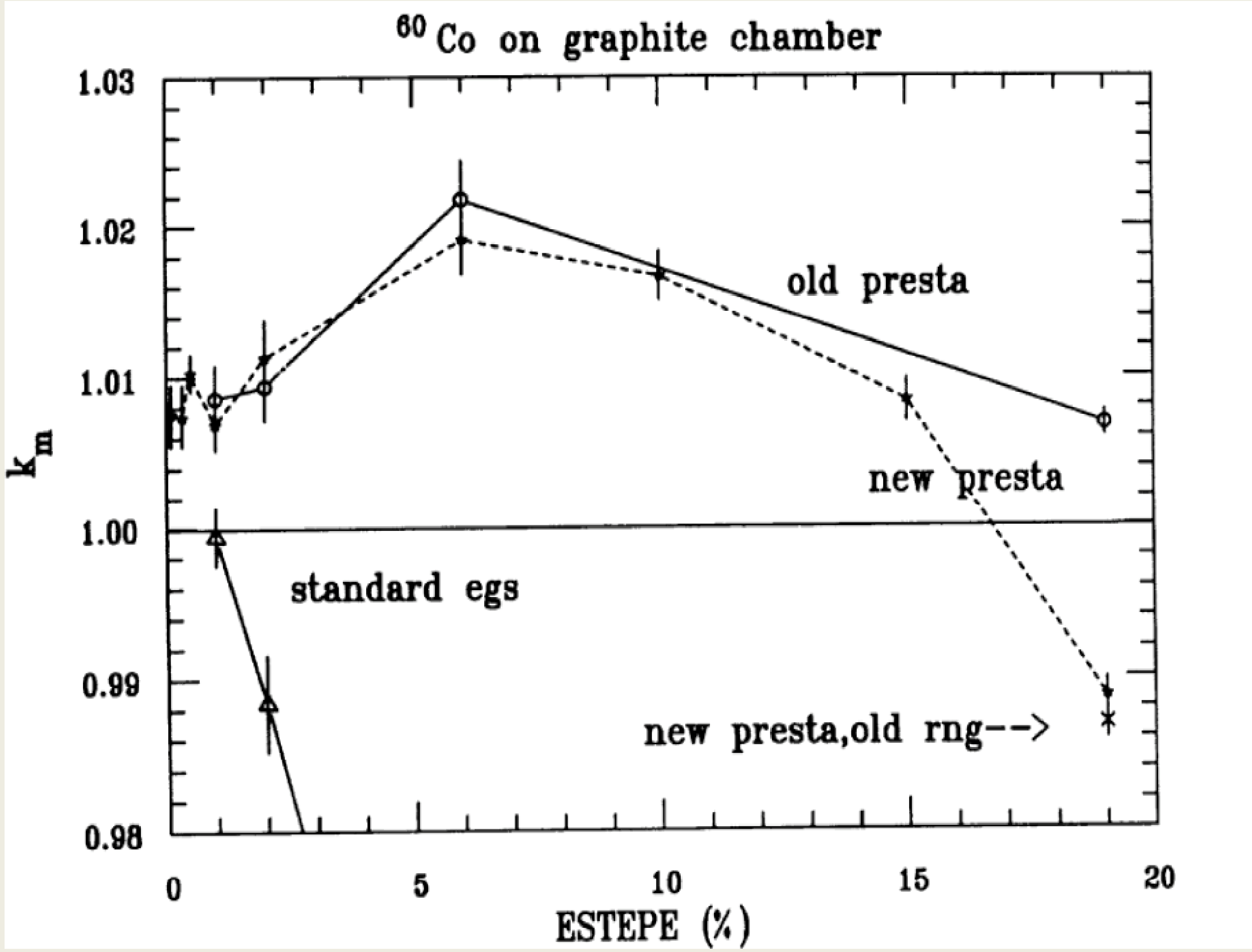

Rogers, Med Phys 20, 319 (1993)

Improvements in the EGS4 system in the lead up to the EGSnrc system (I. Kawrakow)

- new any angle multiple elastic scattering theory based on screened Rutherford c.s.
- improved electron-step algorithm
- correct treatment of discrete interactions
- improved evaluation of energy loss
- exact boundary crossing

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Ionization chamber simulation at ^{60}Co: EGS4/PRESTA artifacts

Artifact	Aluminium 20%	Carbon 20%	Aluminium 1%	Carbon 1%
electron step	-9.0%	-5.0%	-1.4%	-0.7%
BCA	+3.4%	+2.6%	+1.5%	+0.9%
energy loss	+0.3%	+0.5%	+0.0%	+0.0%
discrete interactions	+0.7%	+0.7%	+0.7%	+0.7%
Totals	-4.6%	-1.2%	+0.8%	+0.9%

Kawrakow, Med. Phys. 27 499 (2000)

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Conditions for accurate MC calculations of dosimeters in radiation therapy

1. MC code must be consistent, *i.e.*, results must be in agreement with fundamental dosimetry theorems
2. MC code must use accurate cross sections, realistic geometry description and beam description
3. Precision of results

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Fano theorem

"Under conditions of equilibrium in an infinite medium, the particle fluence will not be altered by density variations from point to point"

U. Fano, 1954

Fanocavity implementation in MC

$$D_{gas} = K_{air}(1-\bar{g})\left(\frac{\bar{L}}{\rho}\right)_{wall}^{gas}\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{air}^{wall} A_{wall} A_{fl}$$

- gas and wall material are set the same, except for density:

$$\left(\frac{\bar{L}}{\rho}\right)_{wall}^{gas} = 1 \quad and \quad A_{fl} = 1$$

- remove the effect of photon attenuation: unweighting of fluence
  - regeneration technique: A_{wall}=1
  - normalization on A_{wall}

Fano cavity implementation in MC (cont'd)

- since: $$K_{coll,wall} = K_{air}(1-\bar{g})\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{air}^{wall}$$
- Accuracy test:

$$D_{gas,unw}(Fano) = K_{coll,wall}$$

Test on accuracy of electron MC system

Straightforward photon Monte Carlo

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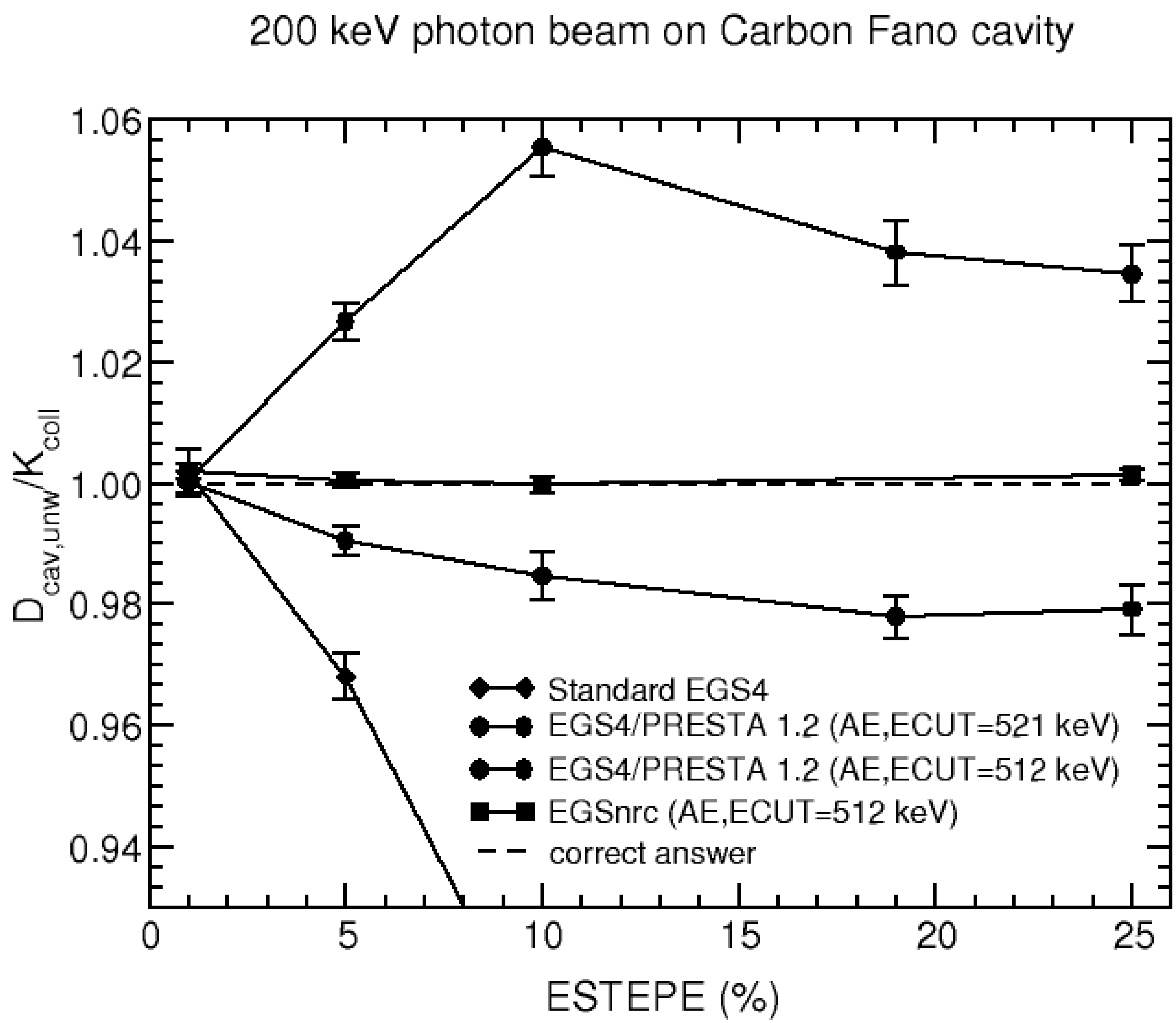

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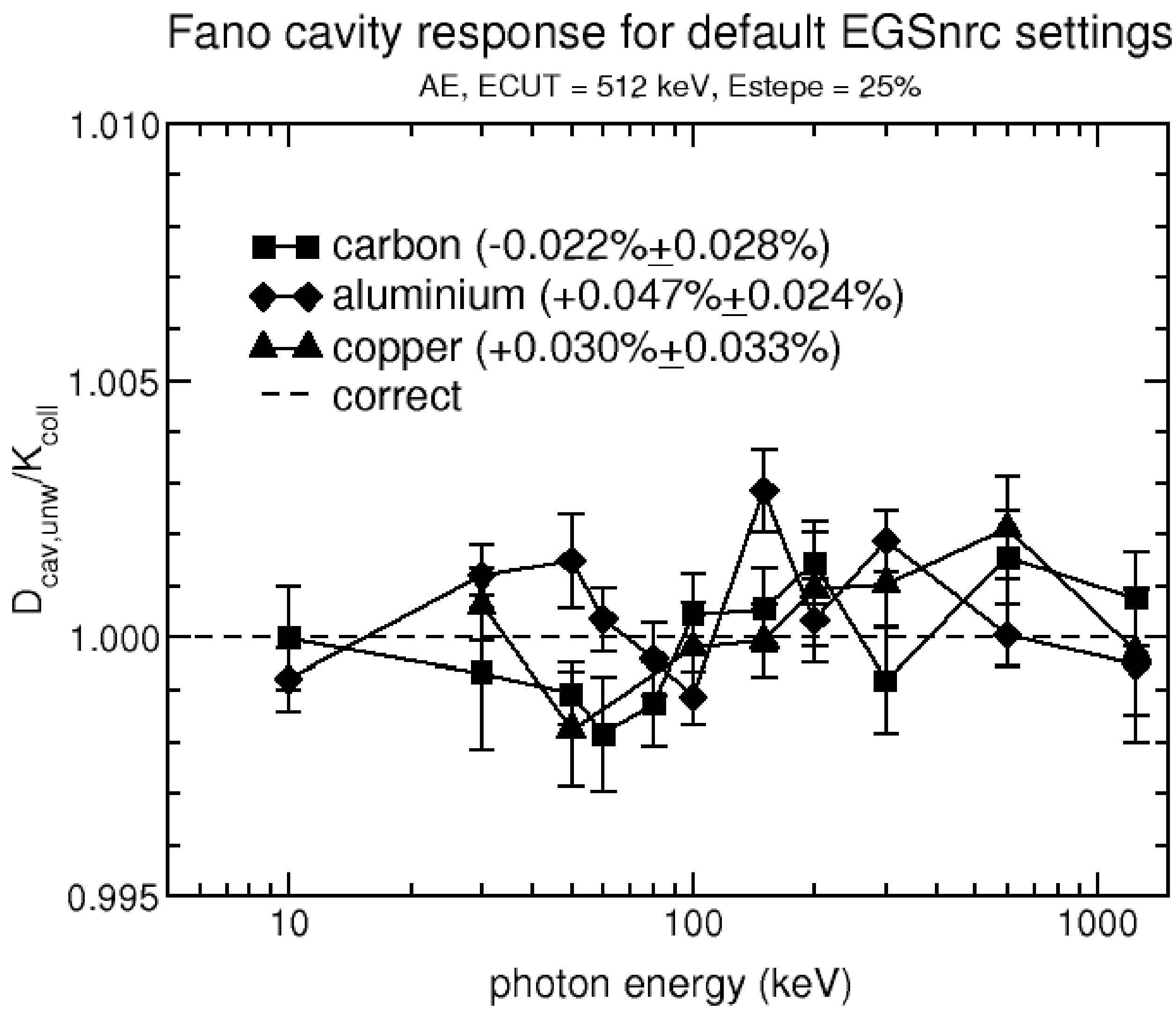

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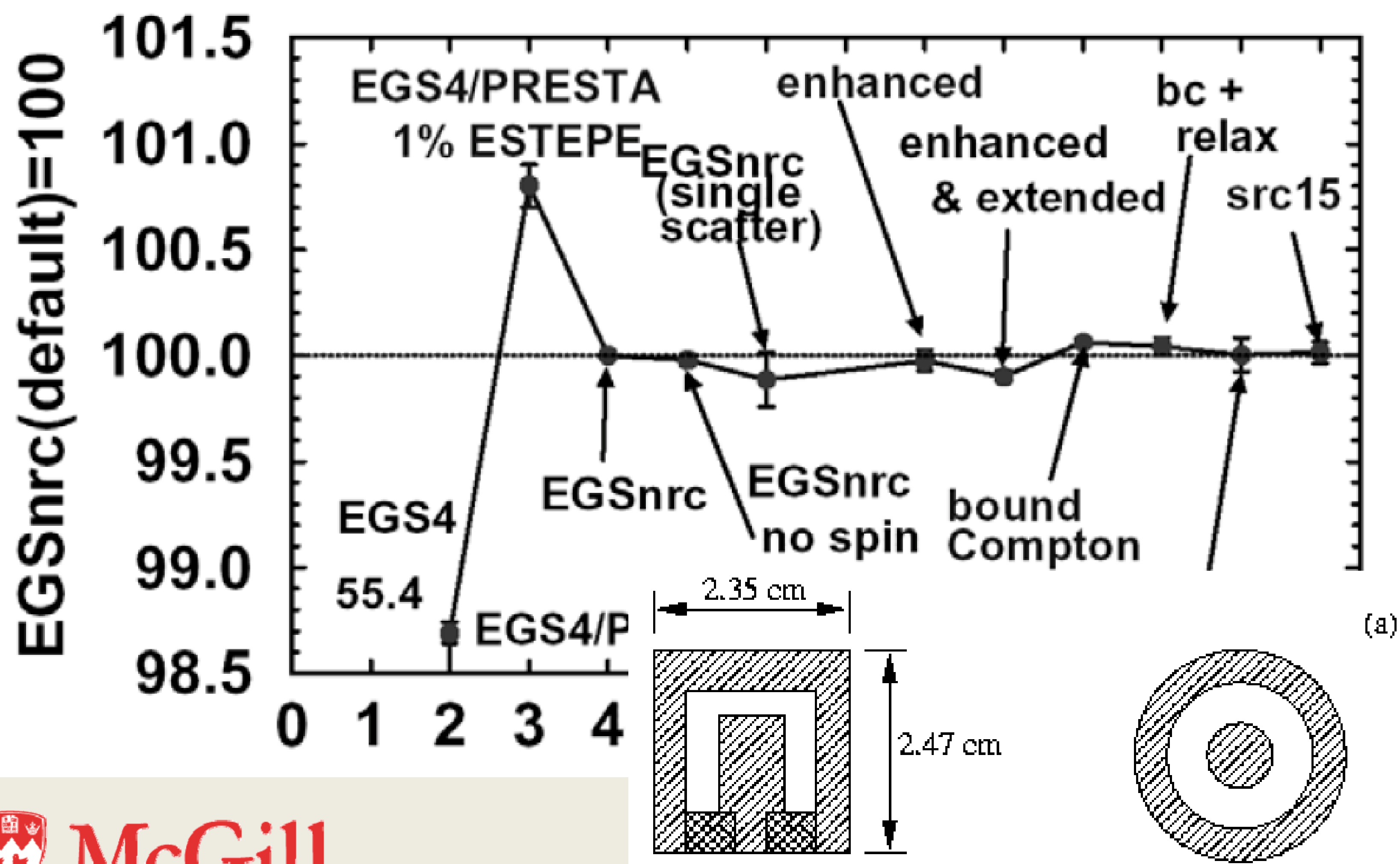
Effect of different cross-section options on dose calculated in 3C chamber



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Cross section effects more important at low energies…

C552 plastic: ICRU 37 composition by weight:
H: 2.4%, C: 50.2%, O: 0.5%, F: 46.5%, Si: 0.4%

mass spectrometrical analysis

Element	ppm	Element	ppm
B	17.4	Ti	3.0
Na	25.0	Vn	3.5
Mg	9.8	Mn	3.4
Al	20.0	Fe	70.0
P	250.0	Rb	8.8
S	12.0	Cr	<50

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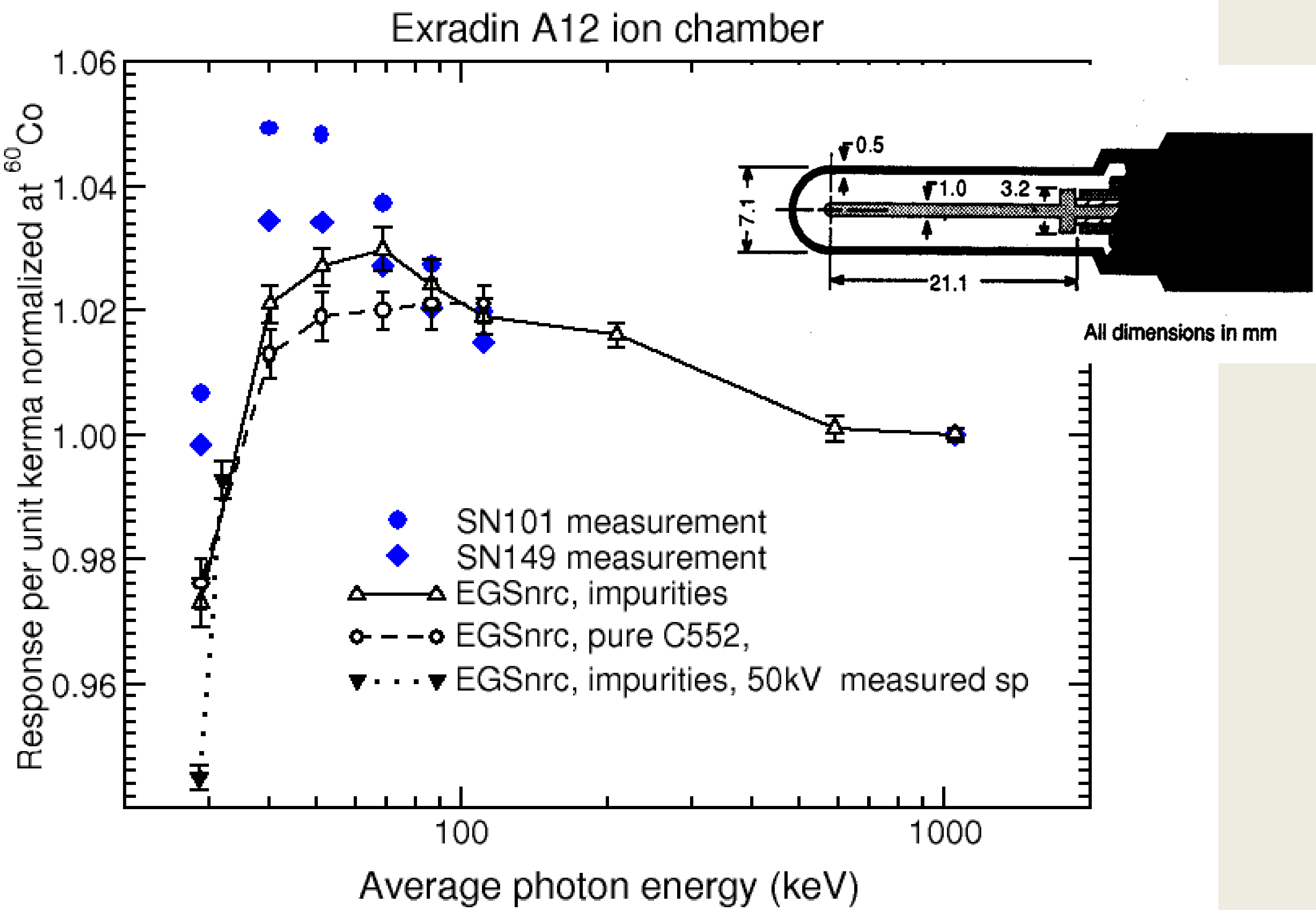

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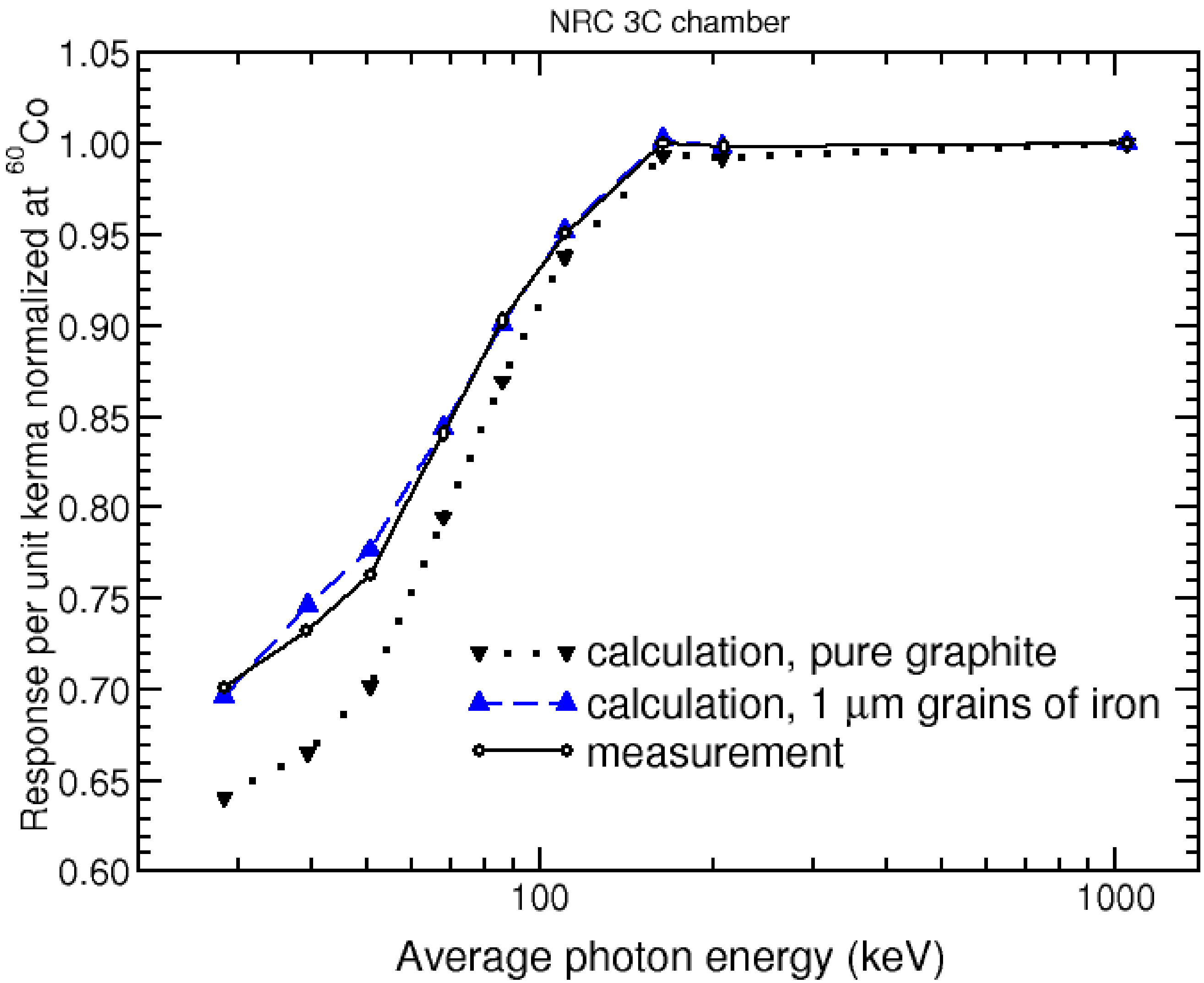

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Question

- What is more challenging?
  - Doing a MC treatment planning dose calculation
  - Doing a MC dosimeter response calculation
  - Staying awake during this presentation

MC method is a statistical method

- Type A uncertainties…
- Need many many many histories
- Need variance reduction techniques
  - The events that lead to the effects of interest are rare

$$\epsilon = \frac{1}{\sigma^2 T}$$

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Variance reduction techniques (VRTs)

- A VRT is a method which increases the efficiency for some quantity of interest by decreasing s^2 for a given N while not biasing the result.
  - they often increase time per history
  - VRTs may simultaneously make s^2 for some other quantity increase
    - egpathlength shrinking will improve the efficiency for dose near the surface but decrease the efficiency for dose at depth

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Variance reduction techniques

- for a review, see Sheikh-Bagheri et al's 2006 AAPM summer school chapter

  http://www.physics.carleton.ca/~drogers/pubs/papers/SB06.pdf

- examples
  - splitting (brem splitting: UBS, DBS; in-phantom)
  - Russian roulette
  - interaction forcing
  - track repetition
  - STOPS (simultaneous transport of particle sets)
  - cross section enhancement

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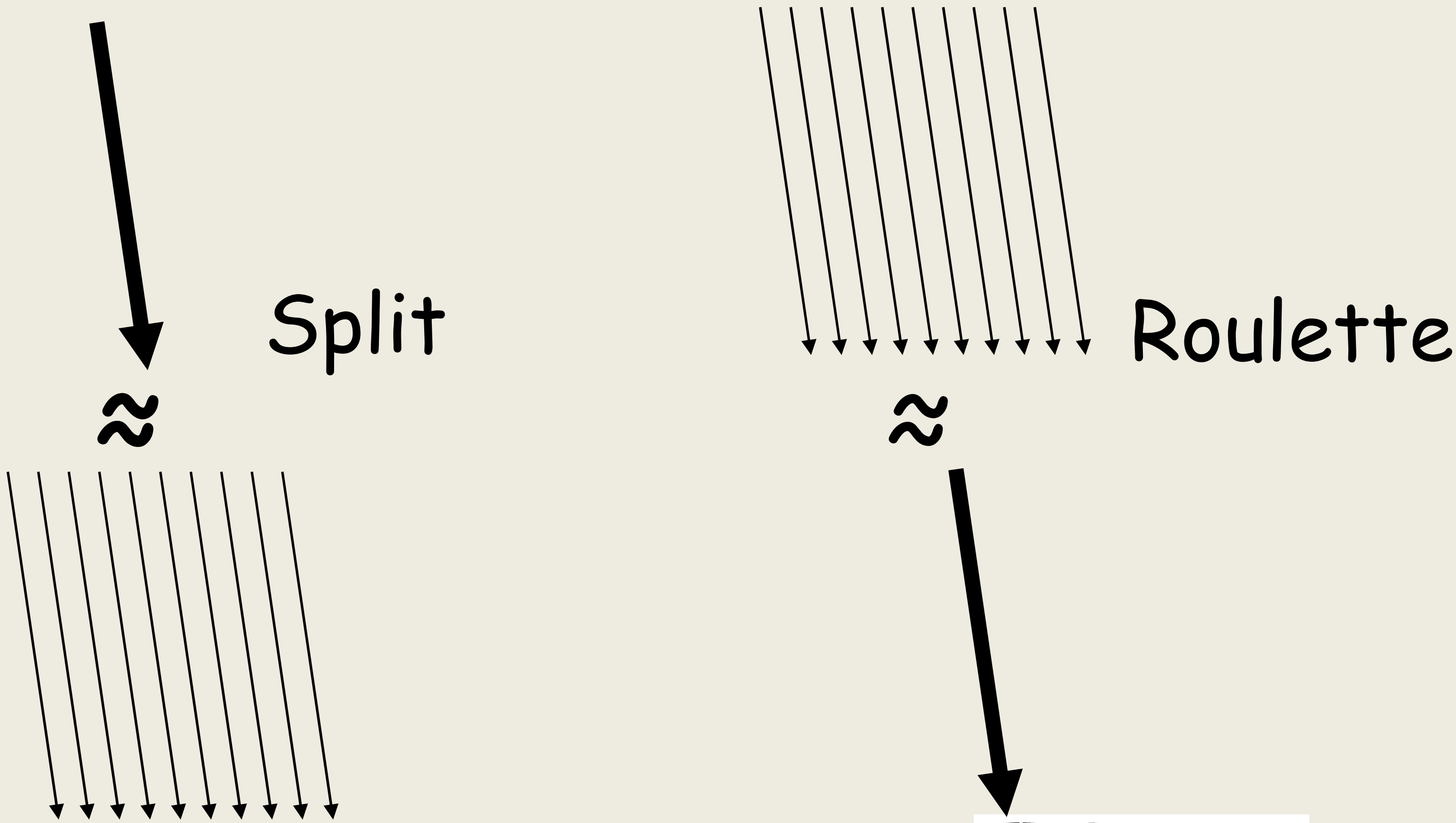
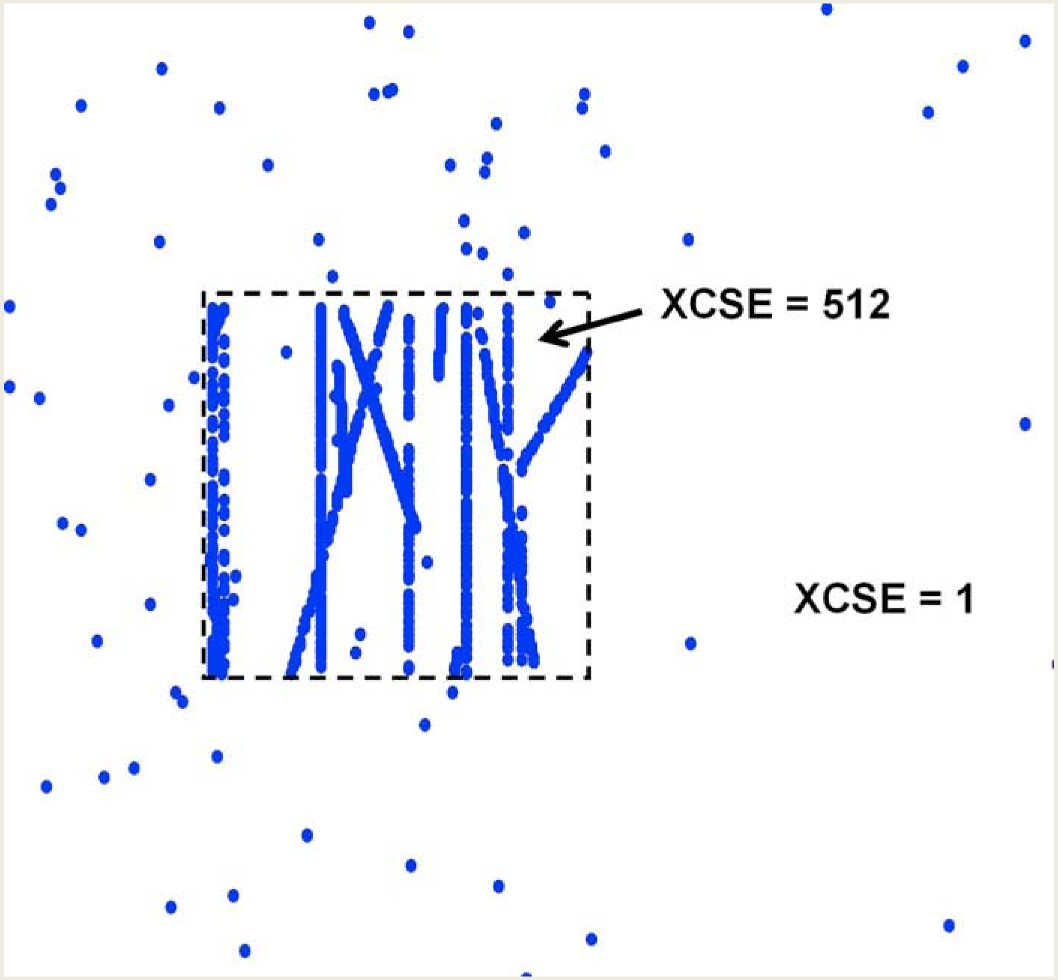
Splitting, Roulette &particle weight

$1\ w_i = 10\ w_f$ $\quad$ $10\ w_i = 1\ w_f$



from Sheikh-Bagheri's 2006 summer school lecture

Photon cross section enhancement



Enhance cross section in region of interest. Weigh subsequent particles accordingly.

Wulff, Zink, Kawrakow Med Phys 35, 1328 (2008)

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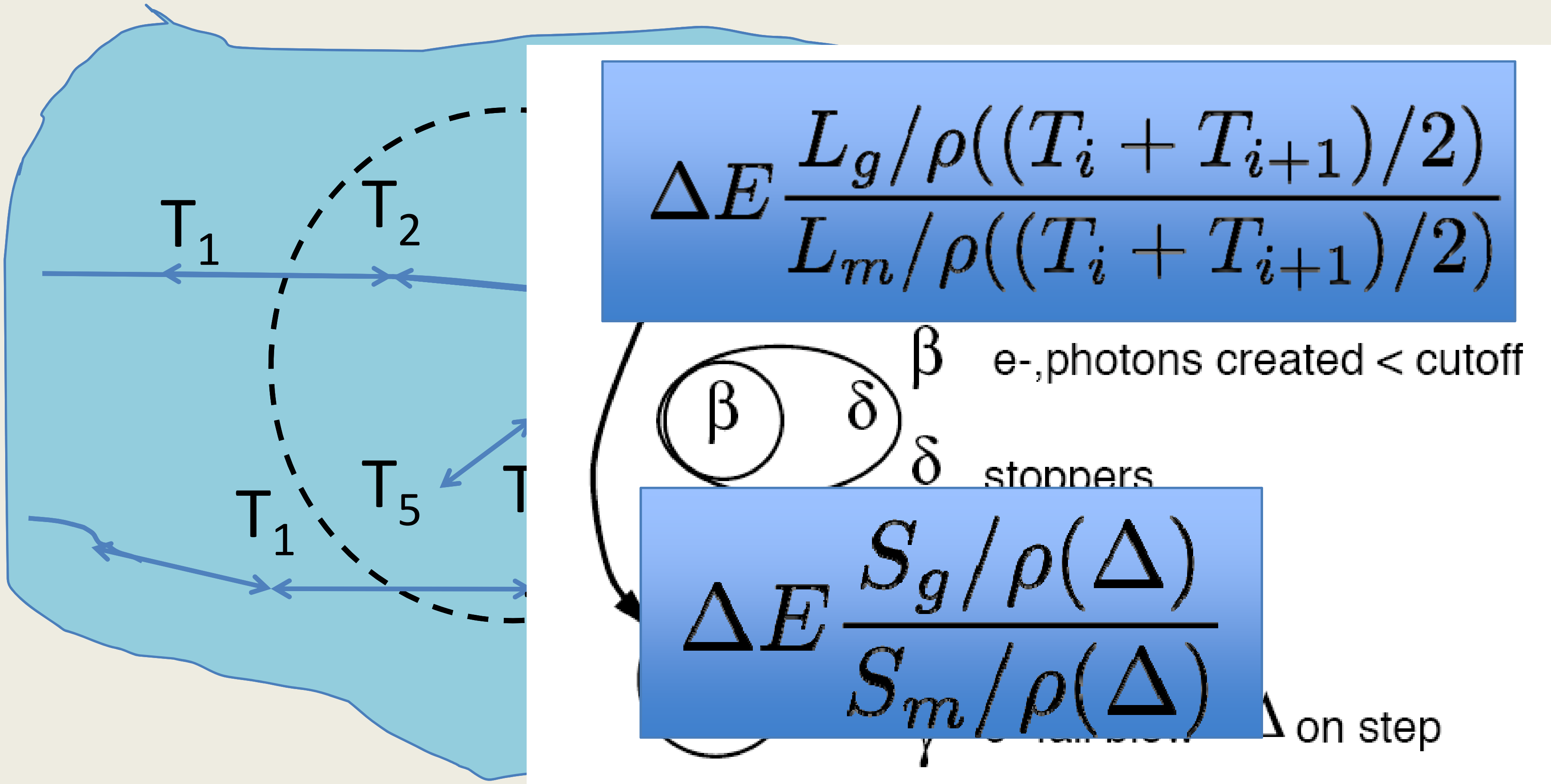
Stopping power ratios (SPRs)

SPRs are central in measurement dosimetry

SPRs are theoretical quantities, not always an accurate representation of *f*(Q)

$$\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{m}}_{\mathrm{g}} = \frac{\int_{\Delta}^{E_{\mathrm{max}}} (\Phi_T)_m (L_\Delta/\rho)_m dT + TE_m}{\int_{\Delta}^{E_{\mathrm{max}}} (\Phi_T)_m (L_\Delta/\rho)_g dT + TE_g}$$

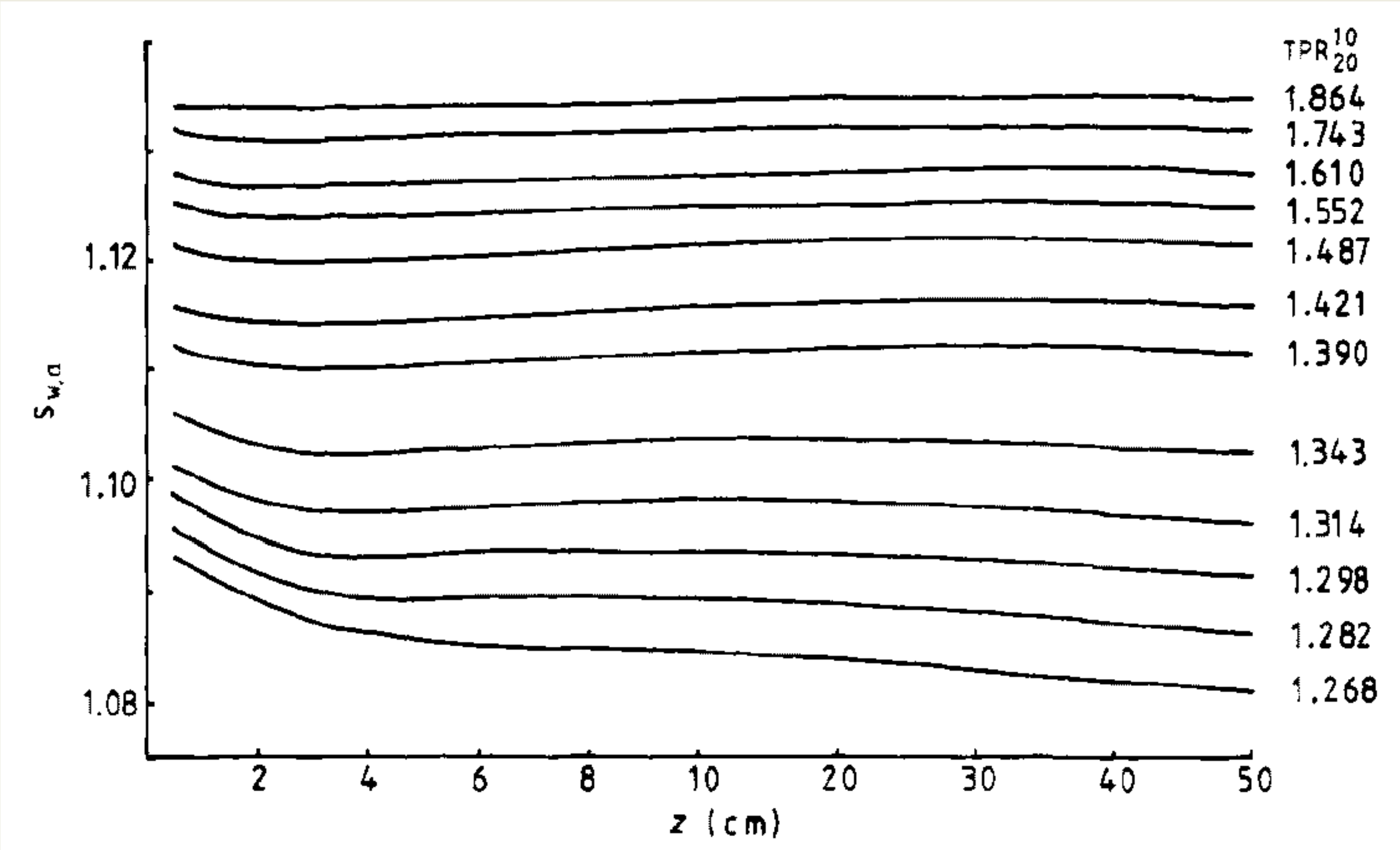
Stopping power ratios (cont'd)



$$\Delta E \frac{L_g/\rho((T_i + T_{i+1})/2)}{L_m/\rho((T_i + T_{i+1})/2)}$$

$$\Delta E \frac{S_g/\rho(\Delta)}{S_m/\rho(\Delta)}$$

$s_{w,air}(z)$ for plane parallel bremsstrahlung beams - no e - contamination, central axis



^{60}Co

10 MV

20 MV

30 MV

Andreo and Brahme, Phys. Med. Biol. , 31, 839 (1986)

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One of the very many impacts…

- David Burns – by choosing:

d_{ref}= 0.6R_{50}-0.1 [cm]

makes the SPR at the reference point a very simple function of R_{50} only…

$$\left(\frac{\overline{L}}{\rho}\right)_{\text{air}}^{\text{w}}(d_{\text{ref}}) = 1.2534 - 0.149(R_{50})^{0.214}$$

This is the basis of electron dosimetry in TG-51 and TRS-398

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Small fields

Sanchez-Doblado et al
Phys. Med. Biol. **48** 2081-2099 (2003)

Table 1. Spencer-Attix ($\Delta = 10$ keV) stopping-power ratios water/air, $s_{w,air}$, and PMMA/air, $s_{PMMA,air}$, at 5 cm depth in water for various 6 MV radiosurgery and MLC beams, including irregular homogeneous and IMRT fields. The $s_{w,air}$ value for the spectrum of transmitted leakage in the MLC is also given. The type A (statistical) standard uncertainty of the calculated values is lower than 0.1% except in the case of the MLC transmission (0.8%).

6 MV beams	Beam quality ($TPR_{20,10}$)	$s_{w,air}$ Andreo (1994)[a]	$s_{w,air}$ This work	$s_{w,air}$ Ratio this work/ Andreo	$s_{PMMA,air}$ Andreo (1994)[a]	$s_{PMMA,air}$ This work	$s_{PMMA,air}$ Ratio this work/ Andreo	Configuration
Elekta SL-18 radiosurgery								
10 × 10 cm^2	0.690	1.1187	1.1188	1.000	1.0853	1.0856	1.000	figure 1(a)
1.0 cm diameter			1.1155	0.997		1.0819	0.997	figure 1(b)
0.3 cm diameter			1.1153	0.997		1.0817	0.997	figure 1(c)
Siemens Primus MLC								
10 × 10 cm^2	0.677	1.1213	1.1221	1.001	1.0880	1.0892	1.001	figure 1(d)
2 × 2 cm^2 irregular on-axis			1.1203	0.999		1.0870	0.999	figure 1(e)
2 × 2 cm^2 irregular 8 cm off-axis			1.1250	1.003		1.0922	1.004	figure 1(f)
MLC transmission			1.1300	1.008				figure 1(i)
IMRT beam (10 × 10 cm^2 approx)			1.1201	0.999				figure 12

[a] These are the values in the IAEA TRS-398 code of practice (Andreo *et al* 2000).

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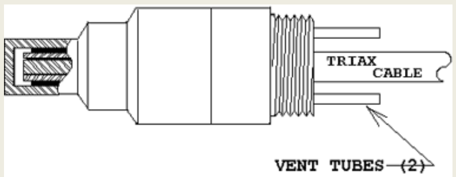
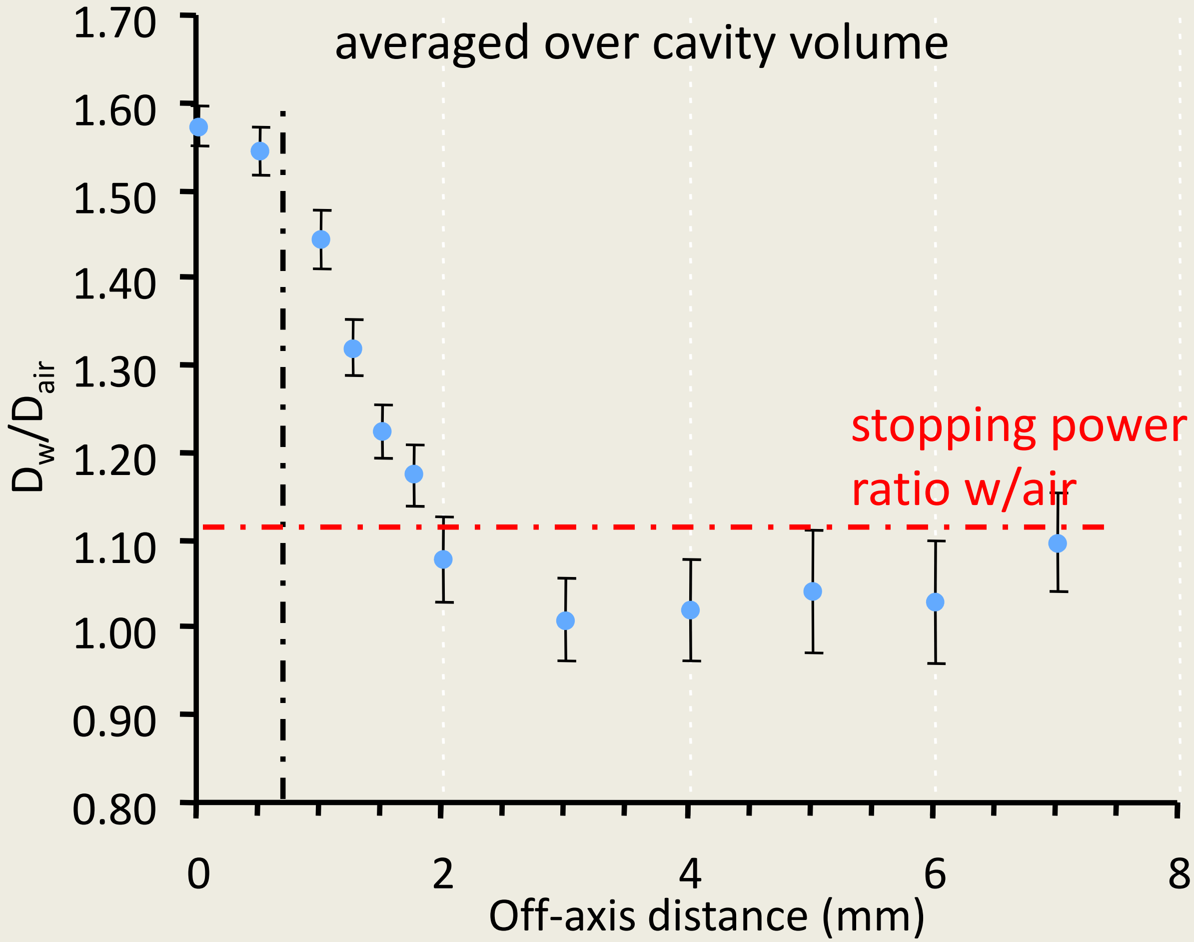
Narrow1.5 mm field

Ratio of dose to water to dose to air



Collecting electrode diameter: 1.5 mm
Separation: 1 mm

Paskalev, Seuntjens, Podgorsak (2002) AAPM Proc. Series 13, Med. Phys. Publishing, Madison, Wi, 298 – 318.



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Choice of Δ

- Δ is not well-defined: “the lowest energy of electrons, which can just cross the cavity”
- Shown that use of mean chord length 4V/S improves accuracy

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Wall correction factors for air kerma based dosimetry

- Wall corrections for air kerma based dosimetry have been calculated since the late 70's (Nath and Schulz 1978)
- These calculations were the basis of TG-21 and TRS-277 protocol dosimetry wall correction factors
- The results are not sensitive to the electron transport accuracy

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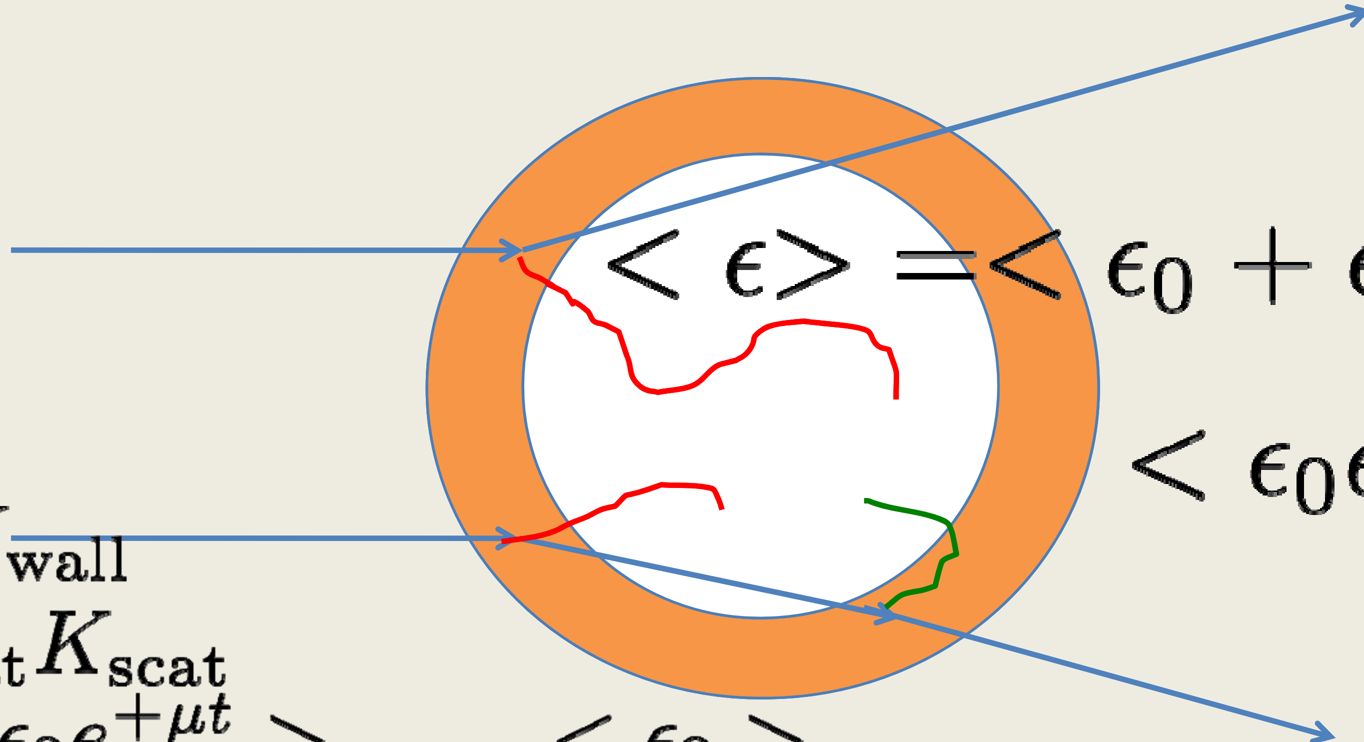
Wall correction factors



$$< \epsilon > = < \epsilon_0 + \epsilon_{scat} >$$

$$< \epsilon_0 e^{\mu t} >$$

$$K_{wall} = K_{at} K_{scat} = \frac{< \epsilon_0 e^{+\mu t} >}{< \epsilon_0 >} \cdot \frac{< \epsilon_0 >}{< \epsilon_0 + \epsilon_{scat} >} = \frac{< \epsilon_0 e^{+\mu t} >}{< \epsilon_0 + \epsilon_{scat} >}$$

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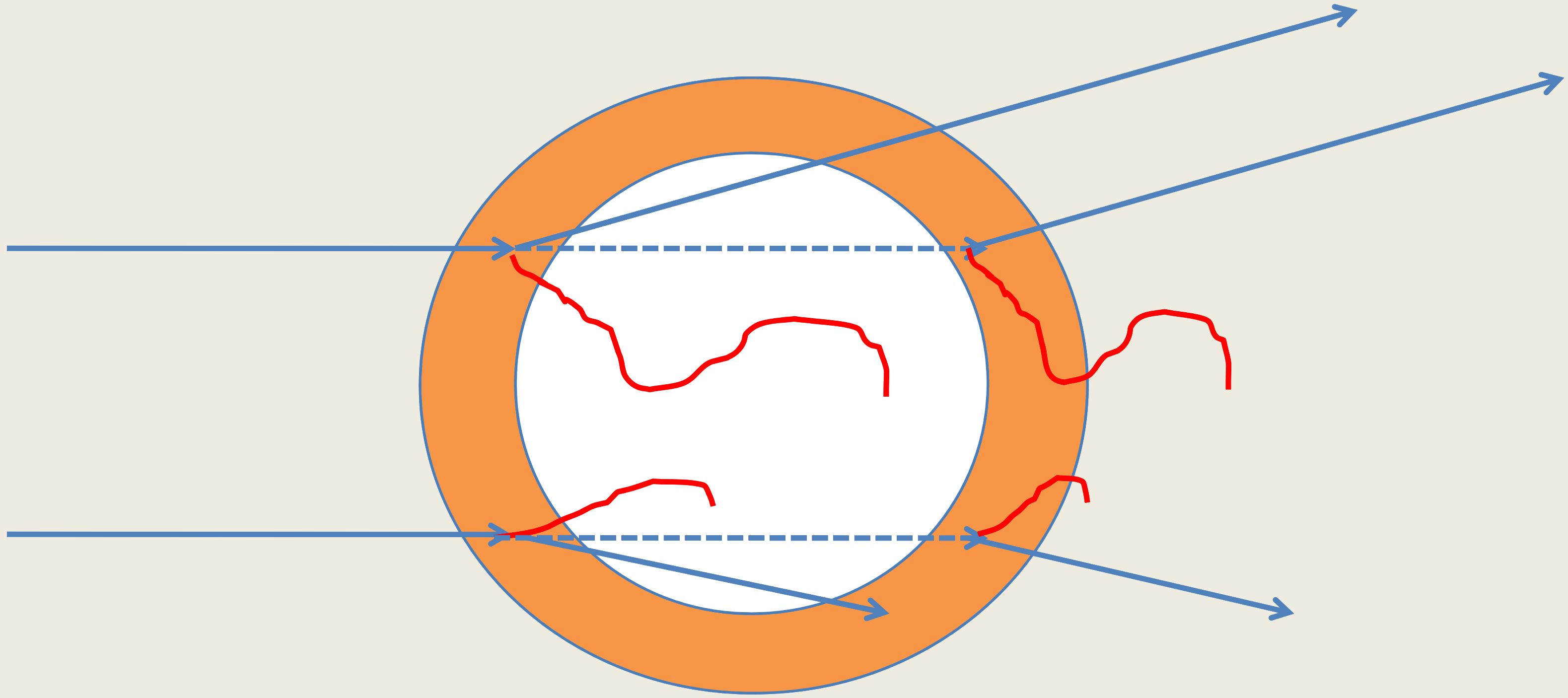
Wall correction factors (alternatively)



$$K_{\mathrm{wall}} = D_{\mathrm{gas,unw}} / D_{\mathrm{gas}}$$

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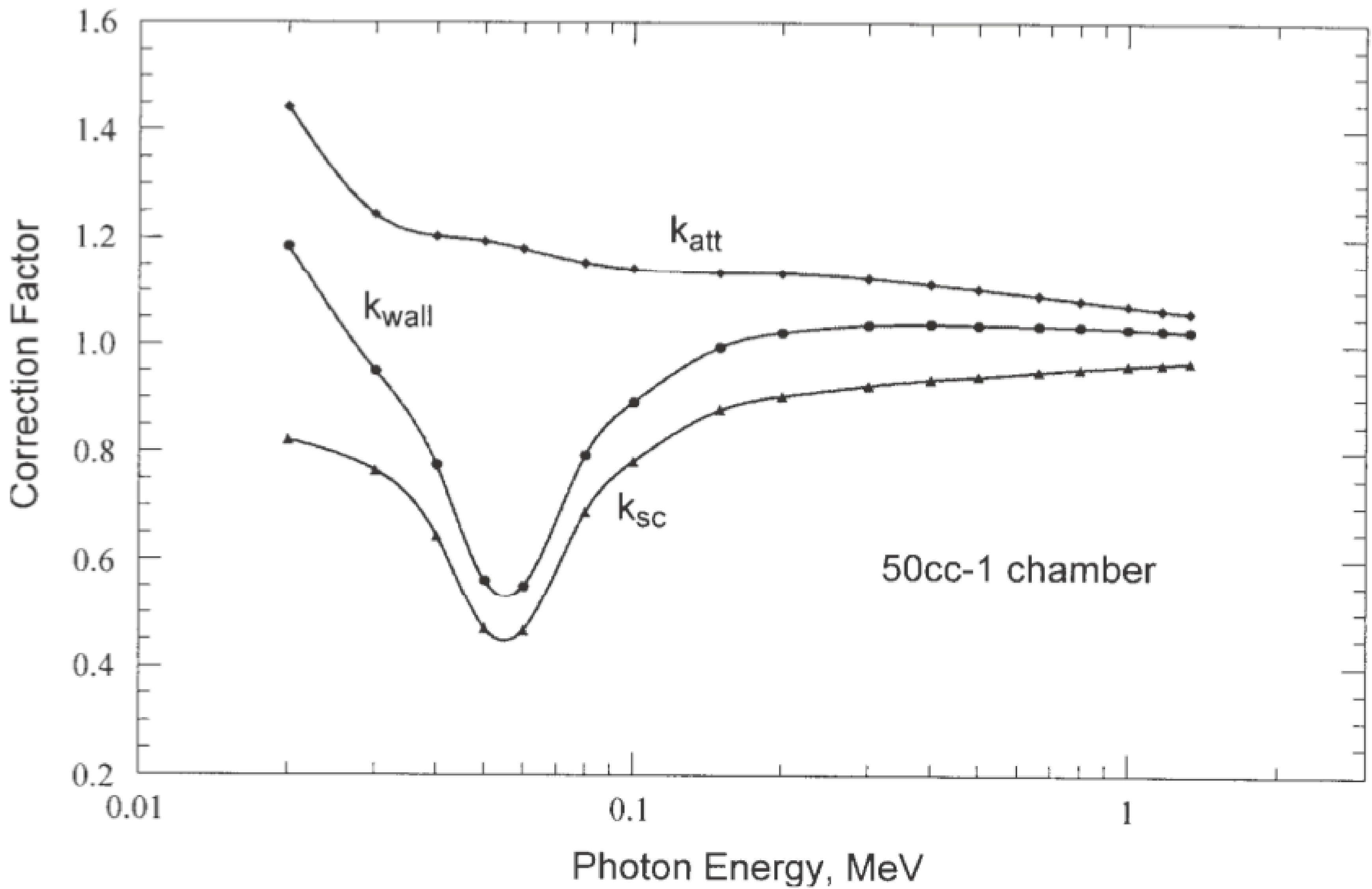

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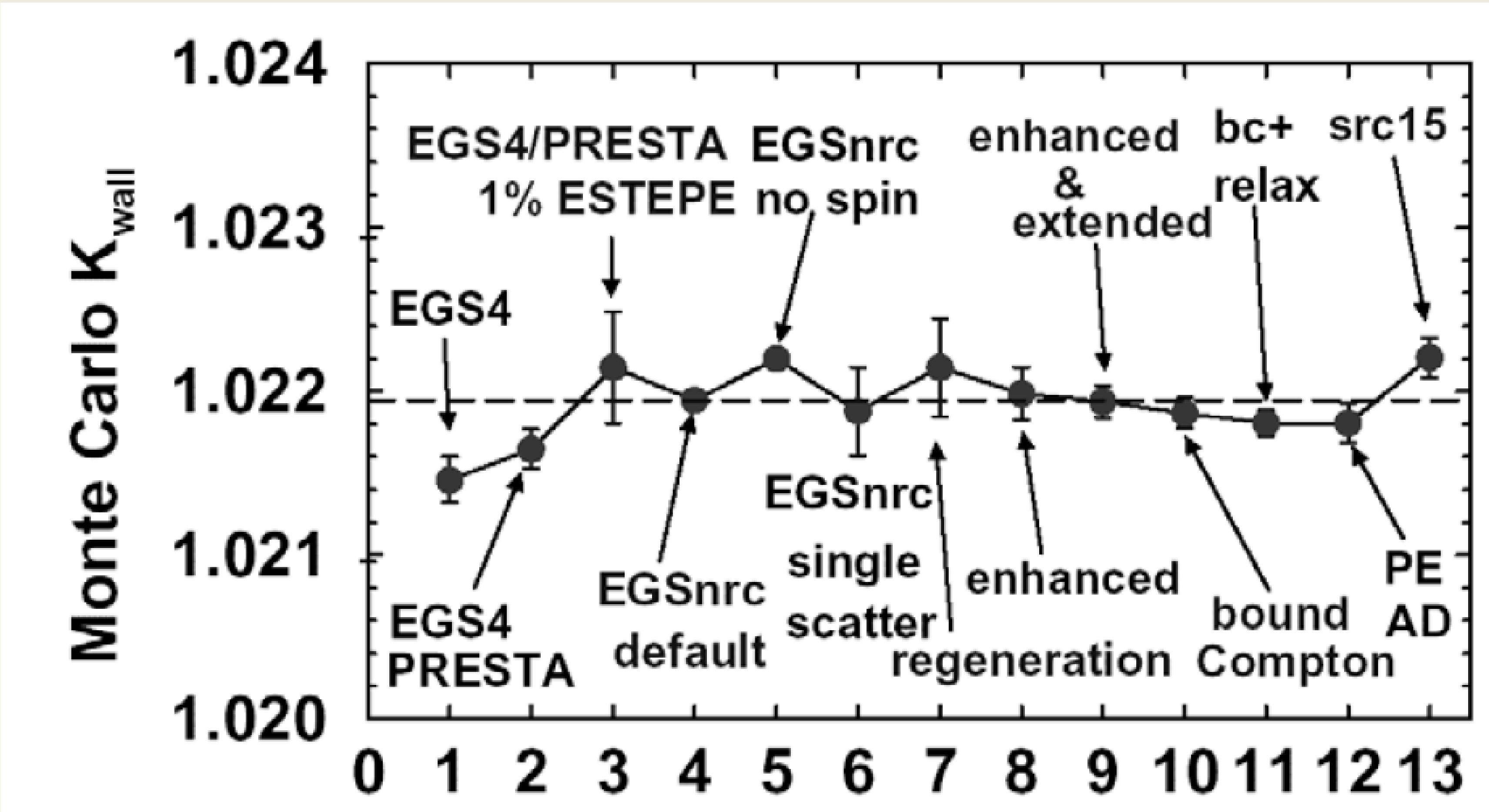
Effect of errors in transport on calculations of K_{wall} of 3C chamber



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Correlated sampling

- To calculate ratios of doses or differences of doses between geometries that are very similar
- The statistical uncertainty on the ratio or difference of quantities is lower than on the absolute quantities
- Applied by Ma and Nahum in the early 90's in a variety of cases related to ionization chamber and other dosimeter correction factors

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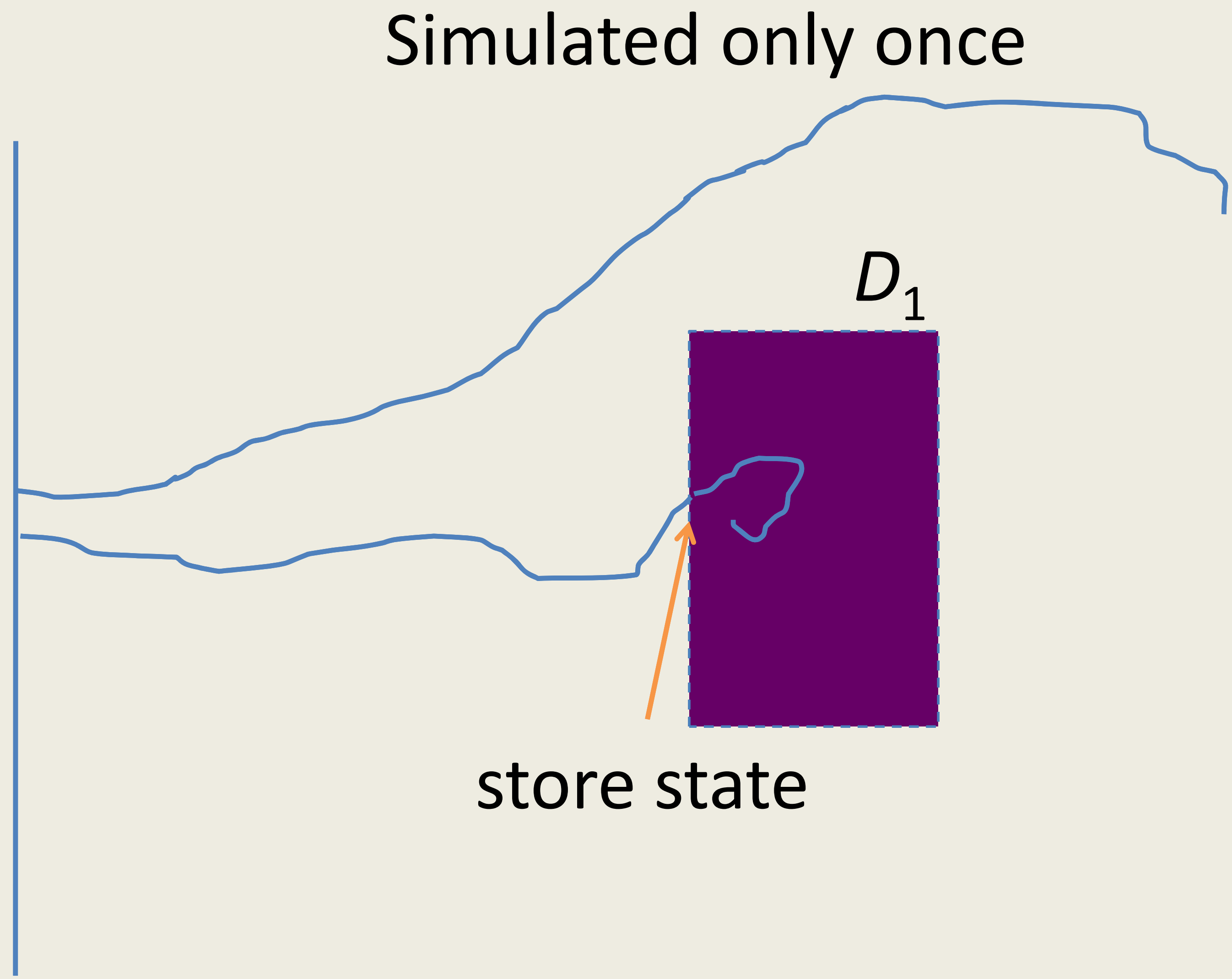

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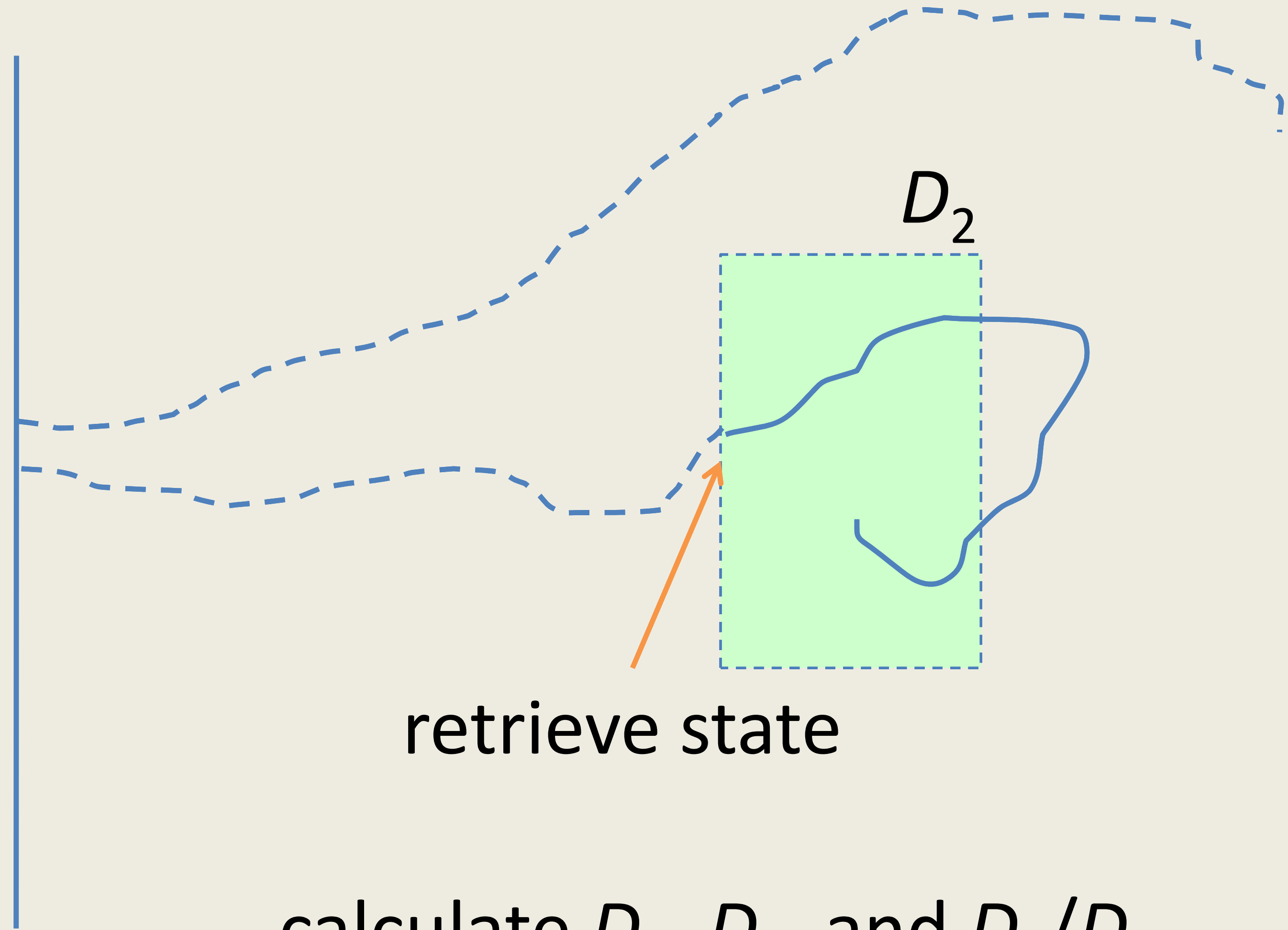
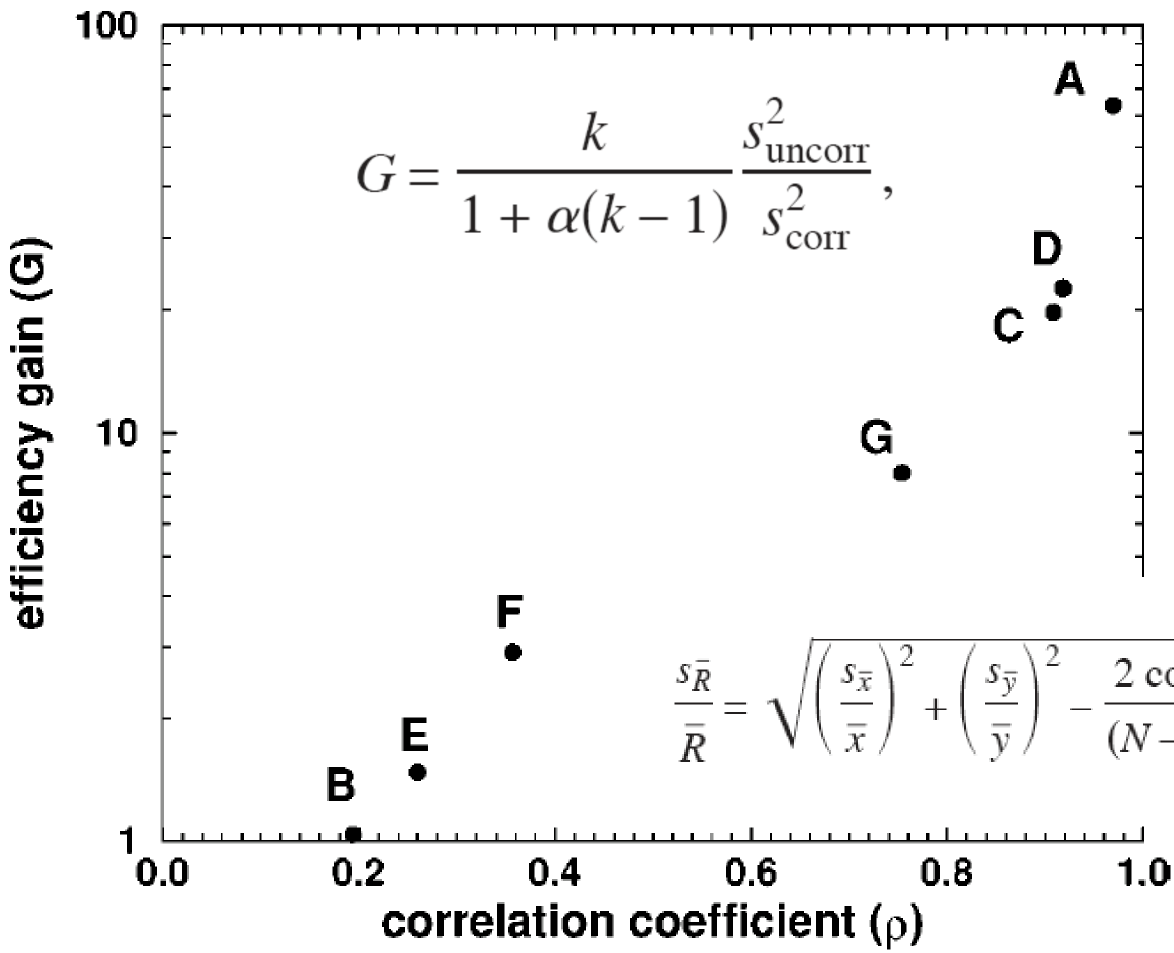


calculate D_1, D_2, and D_1/D_2

Correlated sampling efficiency gain



$$G = \frac{k}{1+\alpha(k-1)} \frac{s^2_{\mathrm{uncorr}}}{s^2_{\mathrm{corr}}},$$

$$\frac{s_{\bar{R}}}{\bar{R}} = \sqrt{\left(\frac{s_{\bar{x}}}{\bar{x}}\right)^2 + \left(\frac{s_{\bar{y}}}{\bar{y}}\right)^2 - \frac{2\,\mathrm{cov}(x,y)}{(N-1)(\overline{xy})}},$$

Buckley et al, 2004
Med Phys 31, 3425

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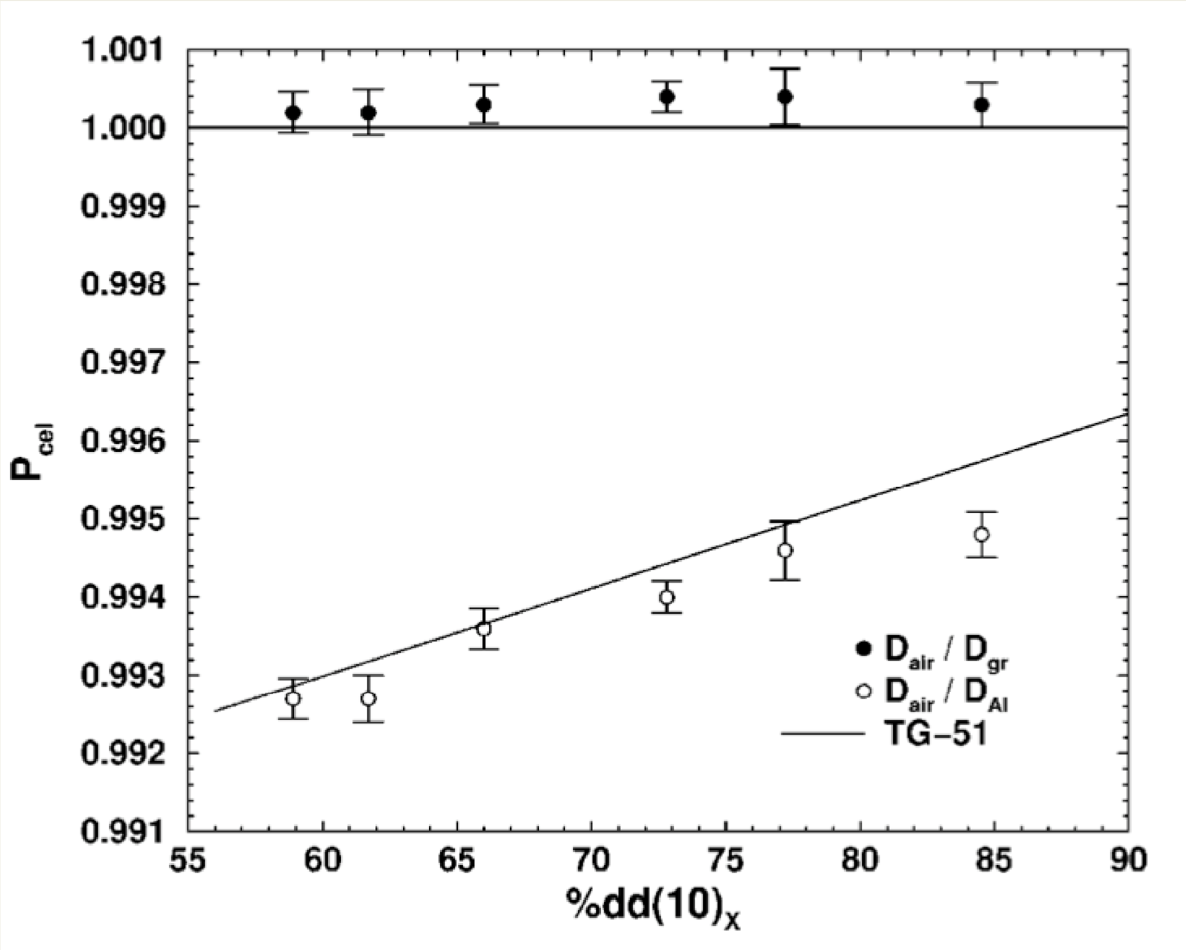
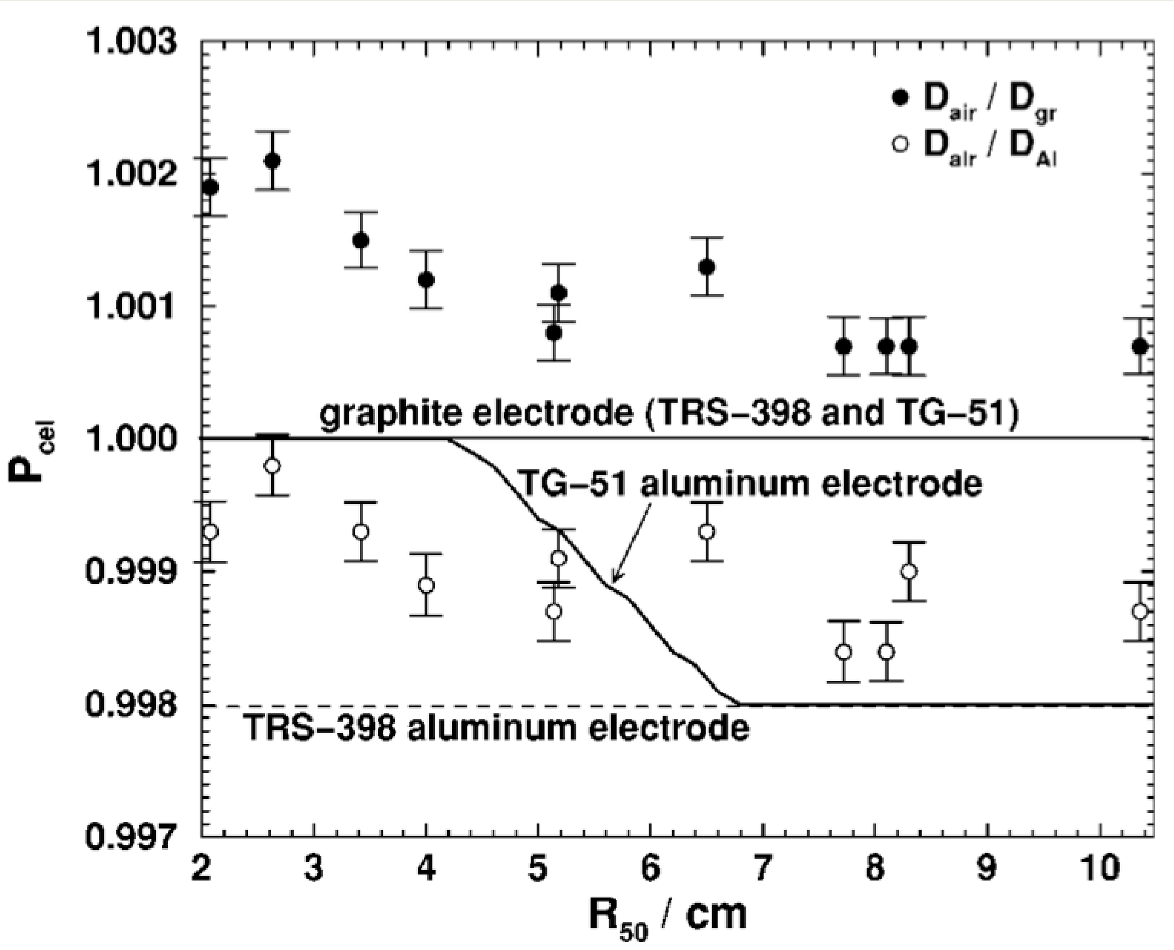
Clinical reference dosimetry – central electrode corrections – photon beams



Buckley et al, 2004
Med Phys 31, 3425

At Co:
D_{gr}/D_{Al}=0.9927±0.0001

Clinical reference dosimetry – central electrode corrections – electron beams



Buckley et al, 2004
Med Phys 31, 3425

Protocols assume no correction for graphite wall

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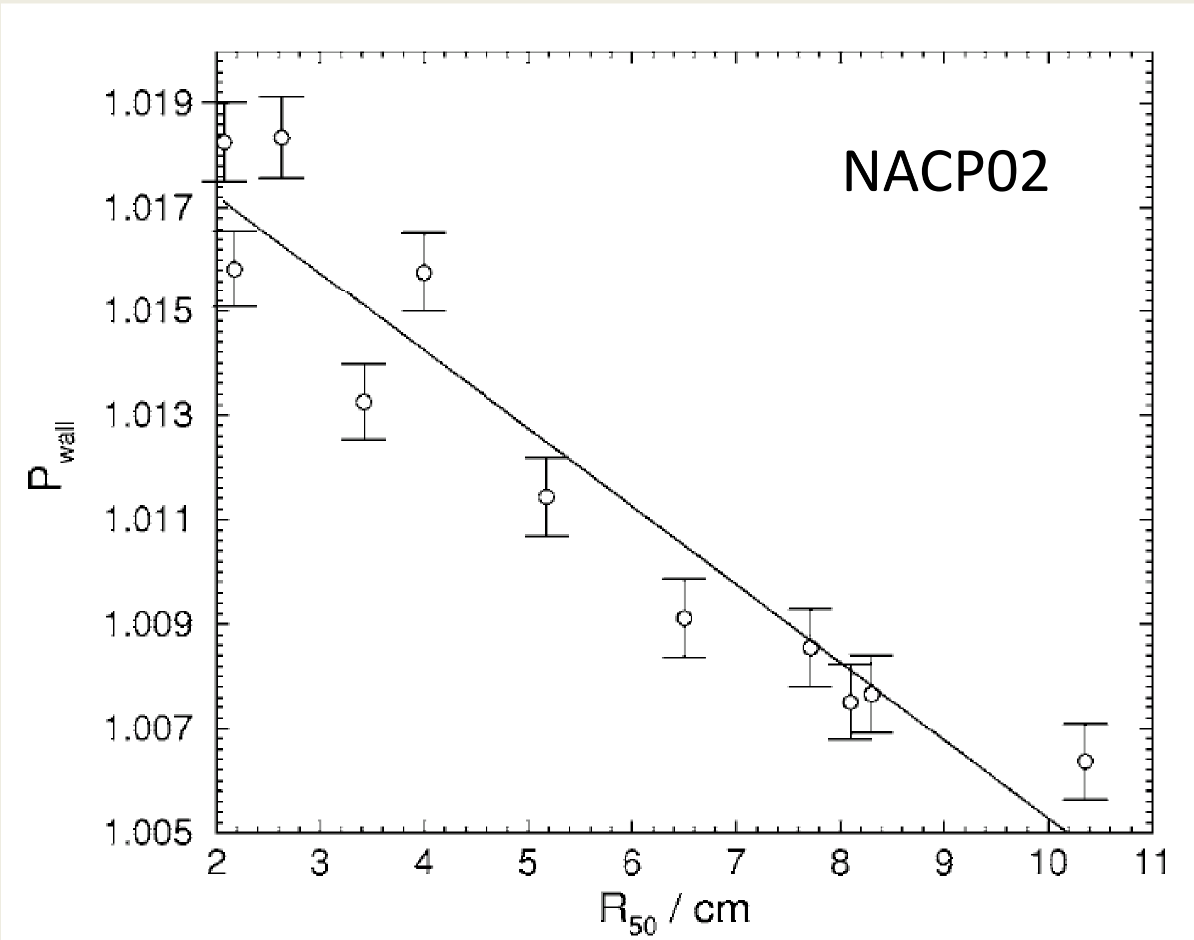
Clinical reference dosimetry – wall correction factors – electron beams



TG-51 &TRS-398 assume P_{wall} = 1

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Clinical reference dosimetry – wall correction factors

$$P_{\text{wall}} = \frac{\alpha\left(\frac{\bar{L}}{\rho}\right)_{\text{air}}^{\text{wall}}\left(\frac{\overline{\mu_{\text{en}}}}{\rho}\right)_{\text{wall}}^{\text{med}} + (1-\alpha)\left(\frac{\bar{L}}{\rho}\right)_{\text{air}}^{\text{med}}}{\left(\frac{\bar{L}}{\rho}\right)_{\text{air}}^{\text{med}}},$$

The Almond - Svensson 2-component model

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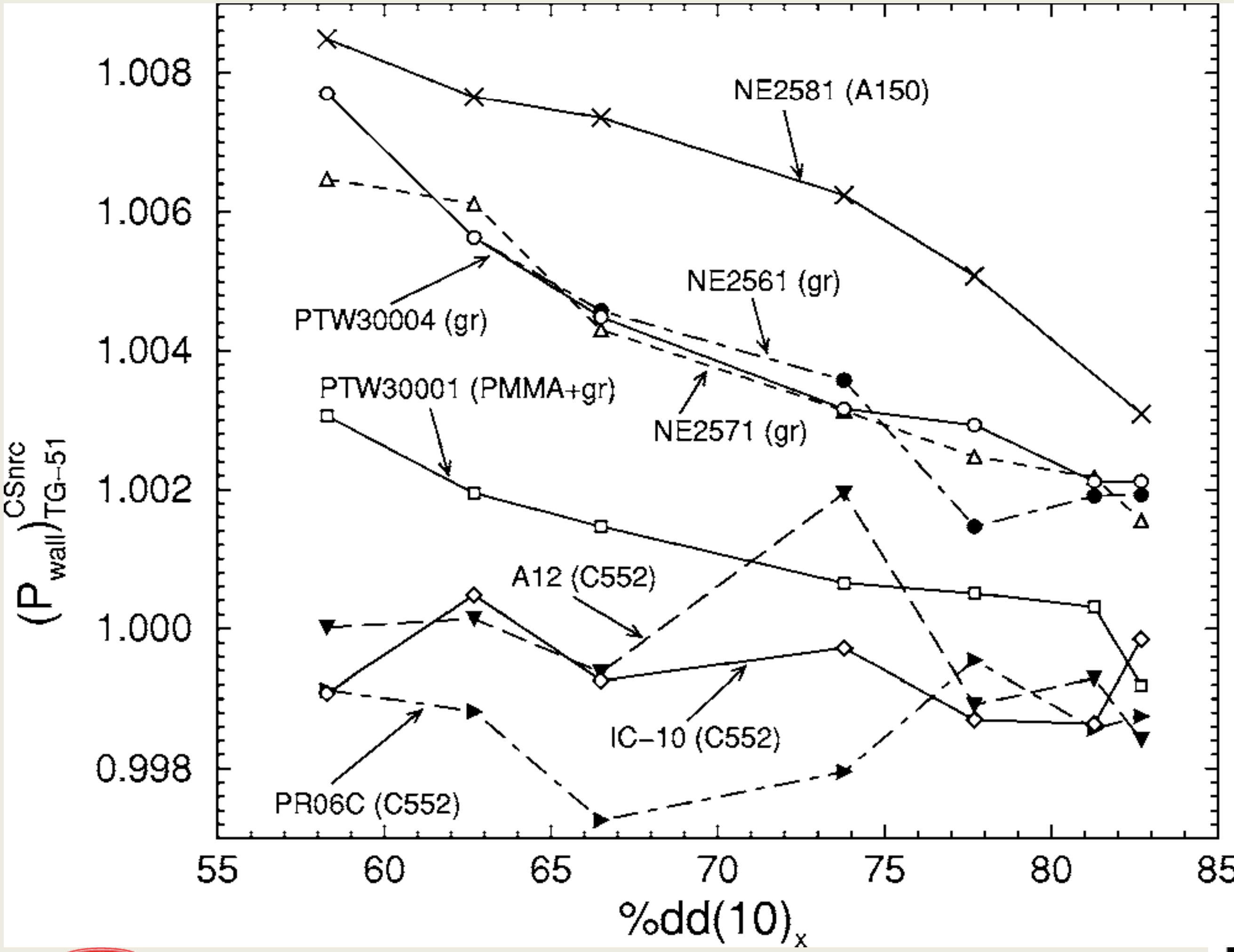
Clinical reference dosimetry – wall correction factors



TG-51 and TRS-398
base their data on the Almond - Svensson 2-component model

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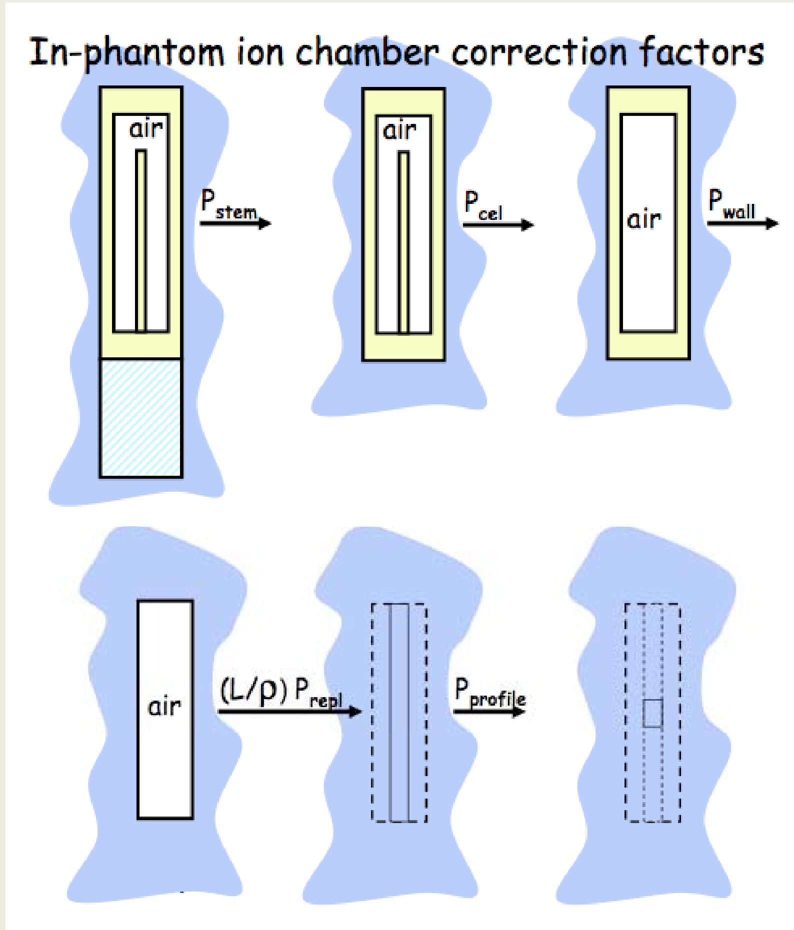
P_{repl} correction factor - recall



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P_{repl} in dosimetry protocols

Electron beams

- "well-guarded" plane-parallel chambers: $P_{repl} = 1$
- cylindrical chambers: measured P_{repl} at d_{max} ($= P_{fl}$)

Photon beams

- plane-parallel chambers: $P_{repl} = 1$
- cylindrical chambers: measured $P_{repl} = P_{gr}$

TRS-398: the uncertainty in value of P_{repl} in photon beams "is one of the major contributions to the final uncertainty in k_Q"

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P_{repl} – four methods (L. Wang)

Method		
SPR	$P_{\text{repl}} = \dfrac{D_{\text{water}}}{D_{\text{air}}} \Big/ \left(\dfrac{\bar{L}_\Delta}{\rho}\right)^{\text{water}}_{\text{air}}$	Calc of different quantities required
HDA	$P_{\text{repl}} = \dfrac{D_{\text{HDA}}}{D_{\text{air}}}$	Layer thickness of HDA slab
LDW	$P_{\text{repl}} = \dfrac{D_{\text{water}}}{D_{\text{LDW}}}$	Fluence perturbation
FLU	$P_{\text{repl}} = \dfrac{\Phi_{\text{Total,water}}}{\Phi_{\text{Total,air}}}$	Fluence in cavity proportional to fluence in medium

Note: Calculation not done using correlated sampling; the correlations are weak

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P_{repl} for NACP02 chamber in electron beams and ^{60}Co beam

Calculation is done at d_{ref} for electron beams & at depth 5 cm for ^{60}Co beam

	SPR	FLU	HDA	LDW
6 MeV	0.9956 (0.06%)	0.9977 (0.10%)	0.9976 (0.08%)	0.9959 (0.06%)
18 MeV	1.0001 (0.06%)	1.0007 (0.06%)	1.0011 (0.07%)	1.0005 (0.05%)
^{60}Co	1.0059 (0.10%)	1.0063 (0.10%)	1.0062 (0.10%)	1.0065 (0.10%)

In all dosimetry protocols: P_{repl}= 1

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P_{repl} for Farmer chamber in ^{60}Co beam

Cavity diameter: 6 mm
Cavity length: 2 cm
Depth in water: 5 cm

SPR	FLU	HDA	LDW
0.9963 (0.08%)	0.9952 (0.08%)	0.9969 (0.09%)	0.9974 (0.07%)

P_{repl} value in dosimetry protocols:

AAPM 0.992

IAEA 0.988

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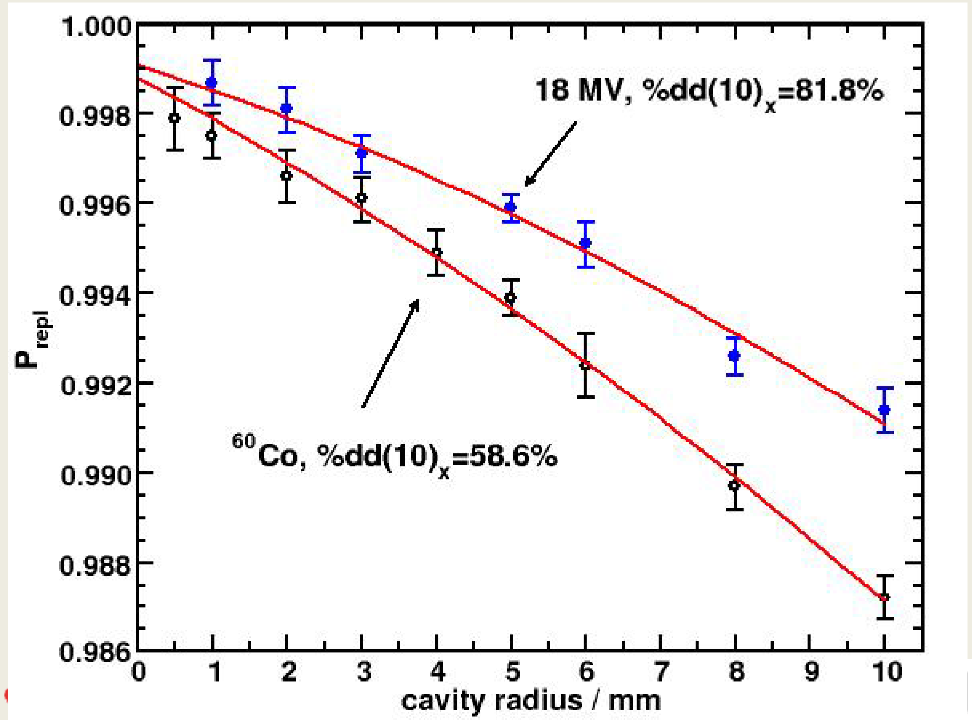
P_{repl} in high energy photon beams

$$P_{repl} = 0.9974 - 0.00183\, r + 3.36\times10^{-5}\, \%dd(10)_x - 2.7\times10^{-5}\, r^2 - 1.6\times10^{-7}\, (\%dd(10)_x)^2 + 1.58\times10^{-5}\, r\, \%dd(10)_x,$$

$$P_{repl} = 1.0021 - 0.00188\, r - 0.0108\, TPR^{20}_{10} - 2.5\times10^{-5}\, r^2 + 0.009\, (TPR^{20}_{10})^2 + 0.00169\, r\, TPR^{20}_{10},$$



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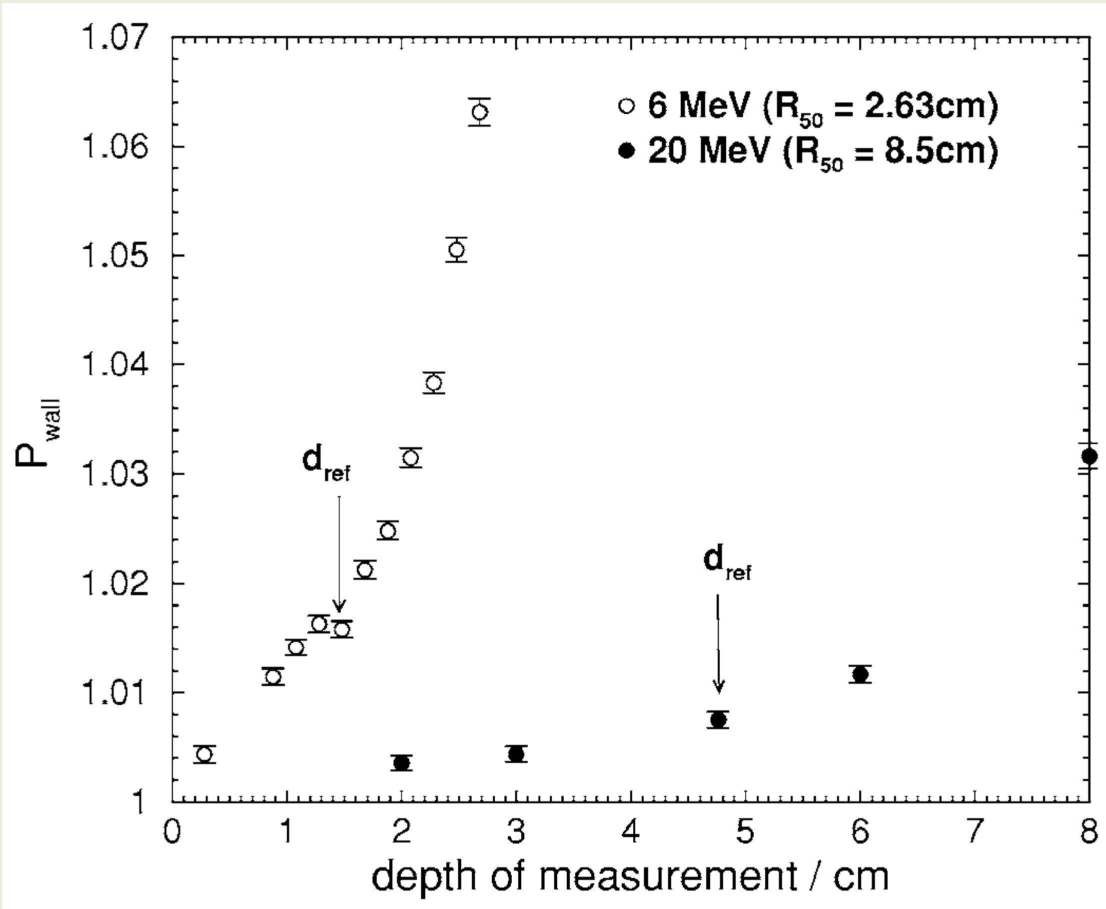
Relative dosimetry: the need for correction factors at multiple depths



NACP chamber in 6 MeV and 20 MeV electrons

Buckley and Rogers, Med. Phys. 33 455 - 464 (2006)

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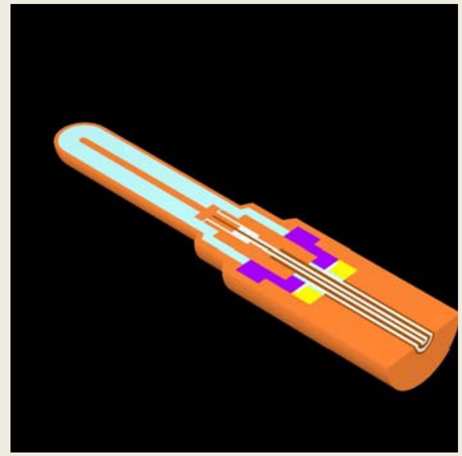
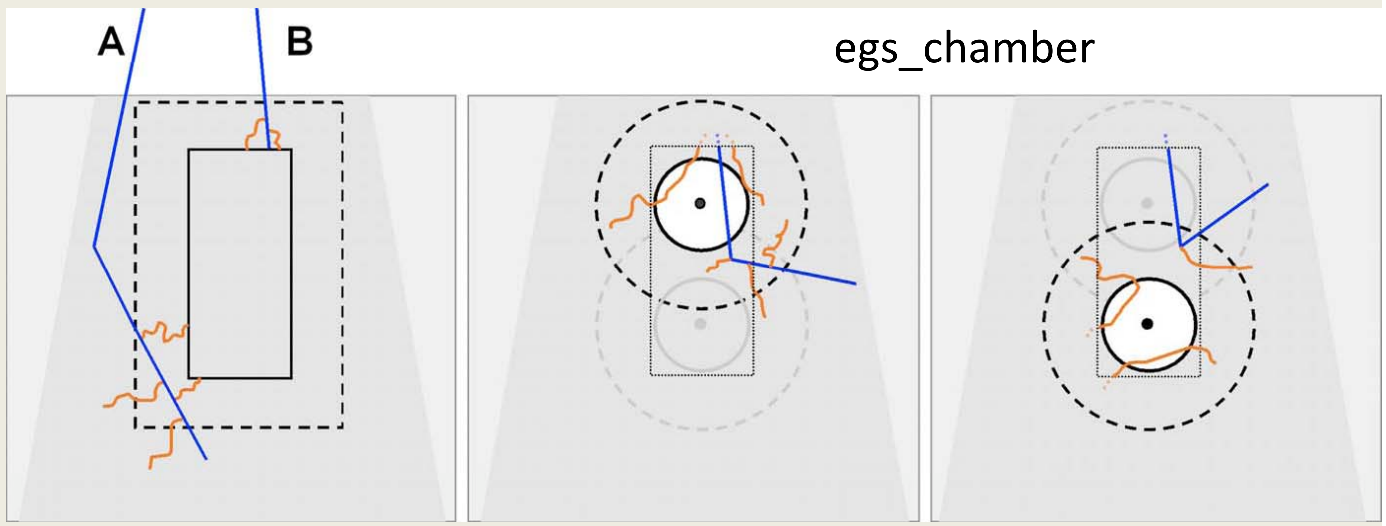
Further improvements…

Excruciatingly detailed geometry modeling



egs++ libraries

Dose calculations at multiple depths, done efficiently



Wulff, Zink, Kawrakow Med Phys 35, 1328 (2008)

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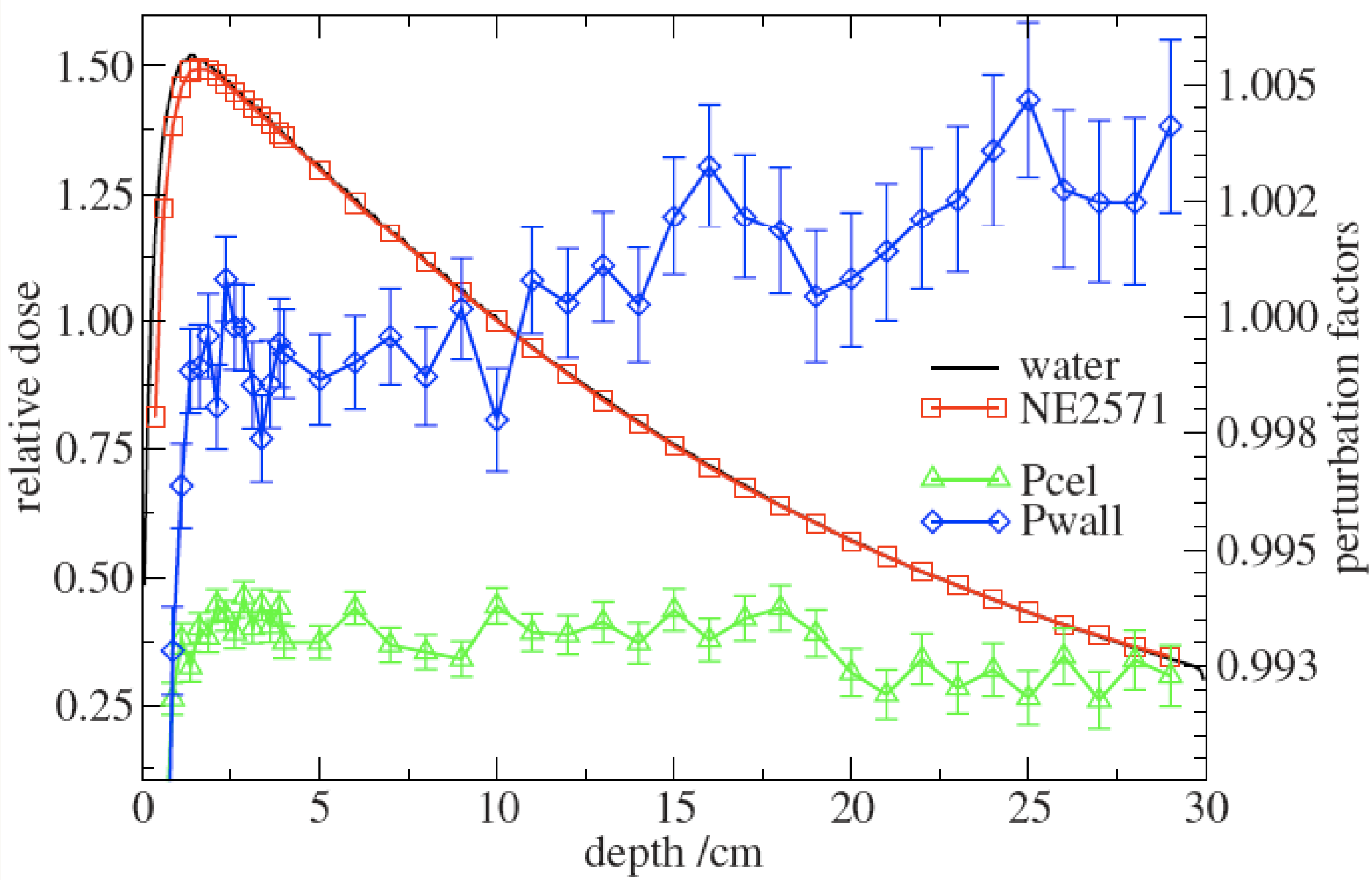

Wulff, Zink, Kawrakow Med Phys 35, 1328 (2008)

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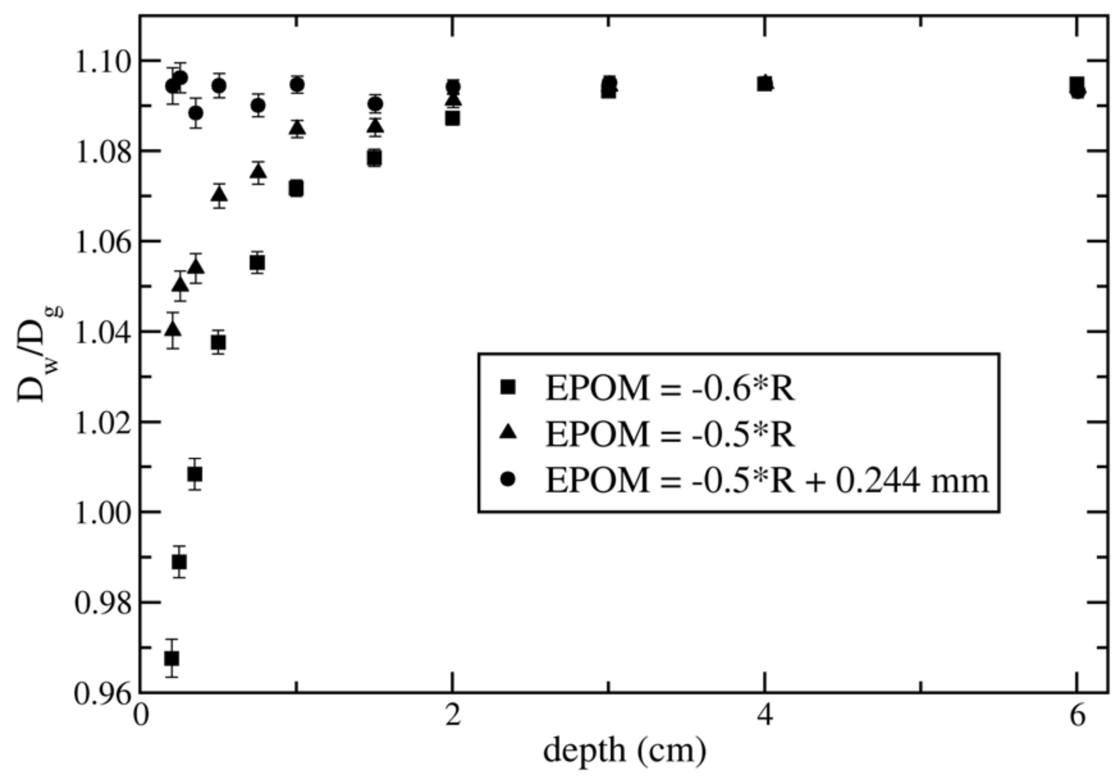
What to do with all this information?

Reconciling measurements and calculations in the build-up region by adjusting EPOM

->simple if it works; but is chamber dependent!



Kawrakow (2006)Med. Phys. ***33****, 1829*

Table 5-1. Shift in Effective Point of Measurement Relative to the NE2571 Chamber

All data were shifted by the default 0.6*r* upstream. The table indicates the additional shifts to apply to the chambers in order to achieve agreement with the NE2571 data. Positive shifts indicate moving the chamber downstream, towards the center of the chamber. The "air gap" represents the radial distance between the inside of the outer electrode and the outside of the inner electrode.

	Shift (mm)	Wall Thickness (g/cm^{-1})	Air Gap* (mm)	Electrode Diameter (mm)
NE2571	0	0.064	2.64	1
NE2581	0.18	0.040	1.64	3
PTW30001	0.20	0.045	2.55	1
PTW30013	0.10	0.056	2.55	1
Exradin A12	–0.06	0.088	2.55	1
Capintec PR-06G	0.23	0.050	2.70	1
NE2561/NE2611	0.33	0.090	2.70	2
PTW233642	–0.02	0.078	2.25	1
Exradin A16	–0.02	0.088	1.05	1

[Reproduced from McEwen et al. (2008) with permission from American Association of Physicists in Medicine.]

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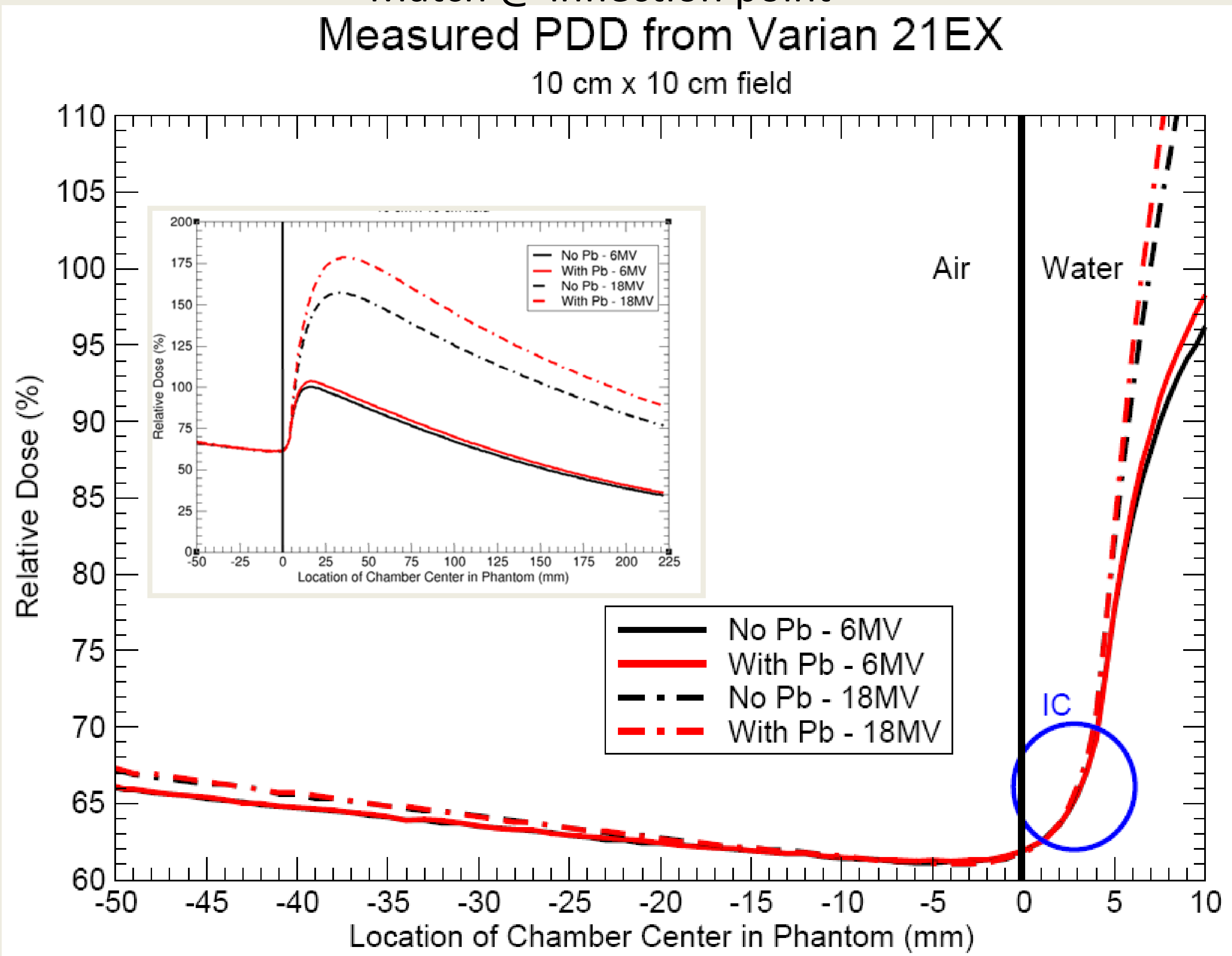
Inflection point variability

Match @ inflection point



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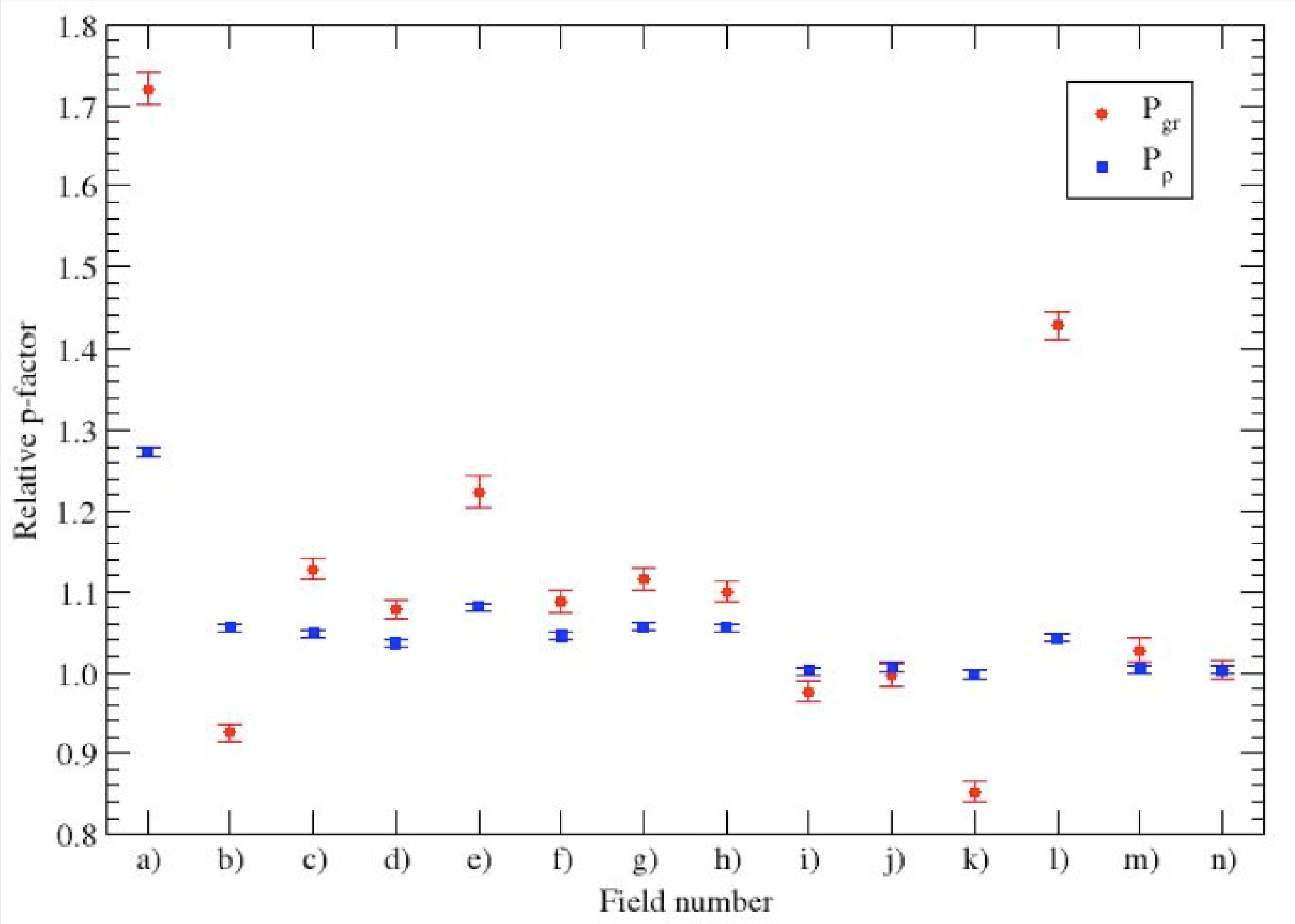
Correction factors in nonstandard beams



14 IMRT fields

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Conclusions

- Have reviewed:
  - MC techniques as applied to measurement dosimetry
  - Attempted to give some background & examples
- Monte Carlo can play an important role in measurement dosimetry
- Techniques have drastically developed
- There is a need to design methods to make practical use of the high quality data coming out especially for relative dosimetry and dosimetry of nonstandard beams

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Thank You

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