Monte Carlo simulation of electron-photon transport: from particle physics to cancer radiotherapy

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Overview

- a 10-fold increase in the efficiency of the BEAM code (with Iwan Kawrakow and Blake Walters)
- brachydose- an efficient code for Monte Carlo dose calculations in brachytherapy (with Gultekin Yegin)
  - inter-seed effects in ^{125}I prostate treatments
- a correlated sampling code to increase efficiency of dosimeter calns with EGSnrc (with Lesley Buckley and Iwan Kawrakow)
  - OSL and electrode correction examples

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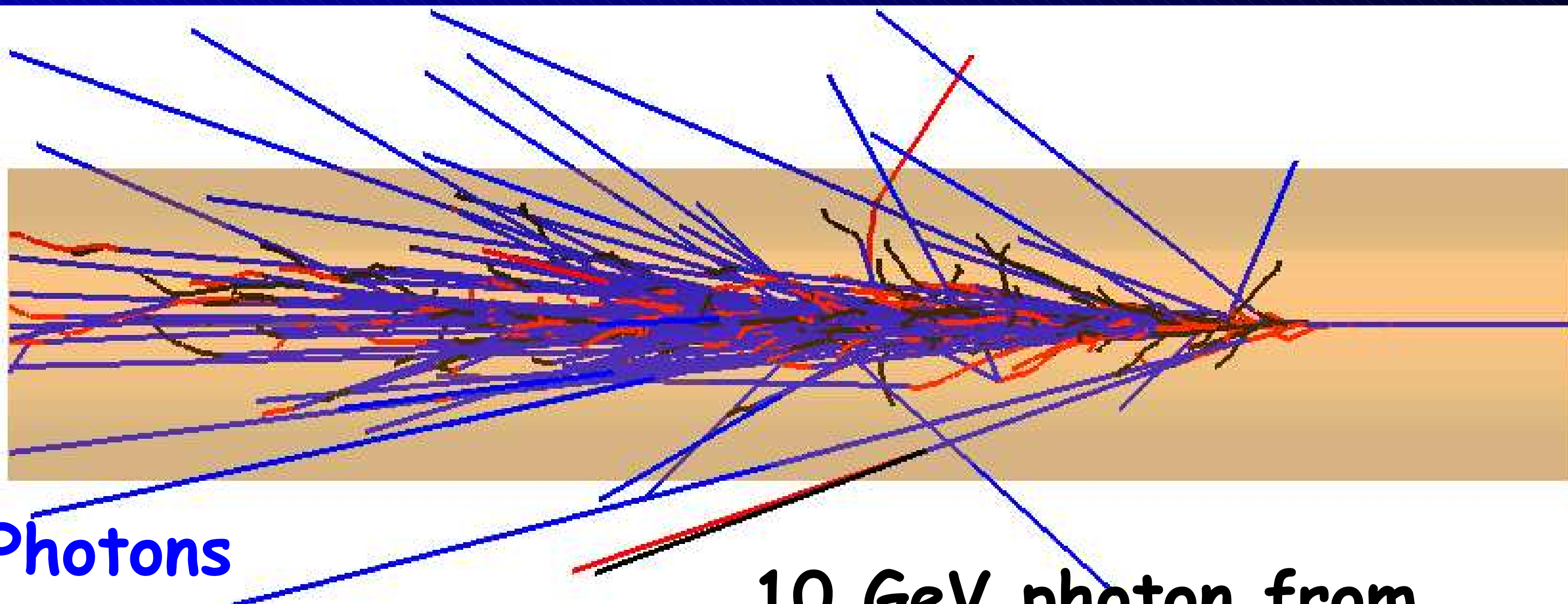
Monte Carlo transport

- simulate paths of many particles
  - use random numbers
  - known probability distributions
    - from physics of interactions
- keep track of physical quantities
  - learn average properties
  - stochastic distributions of events

EGS: Electron Gamma Shower



Photons

Electrons

positrons

10 GeV photon from right on 10 cm lead cylinder

EGS3 Ford and Nelson, SLAC 1978

EGS4 Nelson et al, SLAC, NRC 1985

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BEAM code

- general purpose code to simulate radiotherapy beams
  - accelerators -electrons & photons
  - ^{60}Co units
  - x-ray units

- Part of the OMEGA project with Rock Mackie's group in Madison
  - many grad students, RAs and TOs involved

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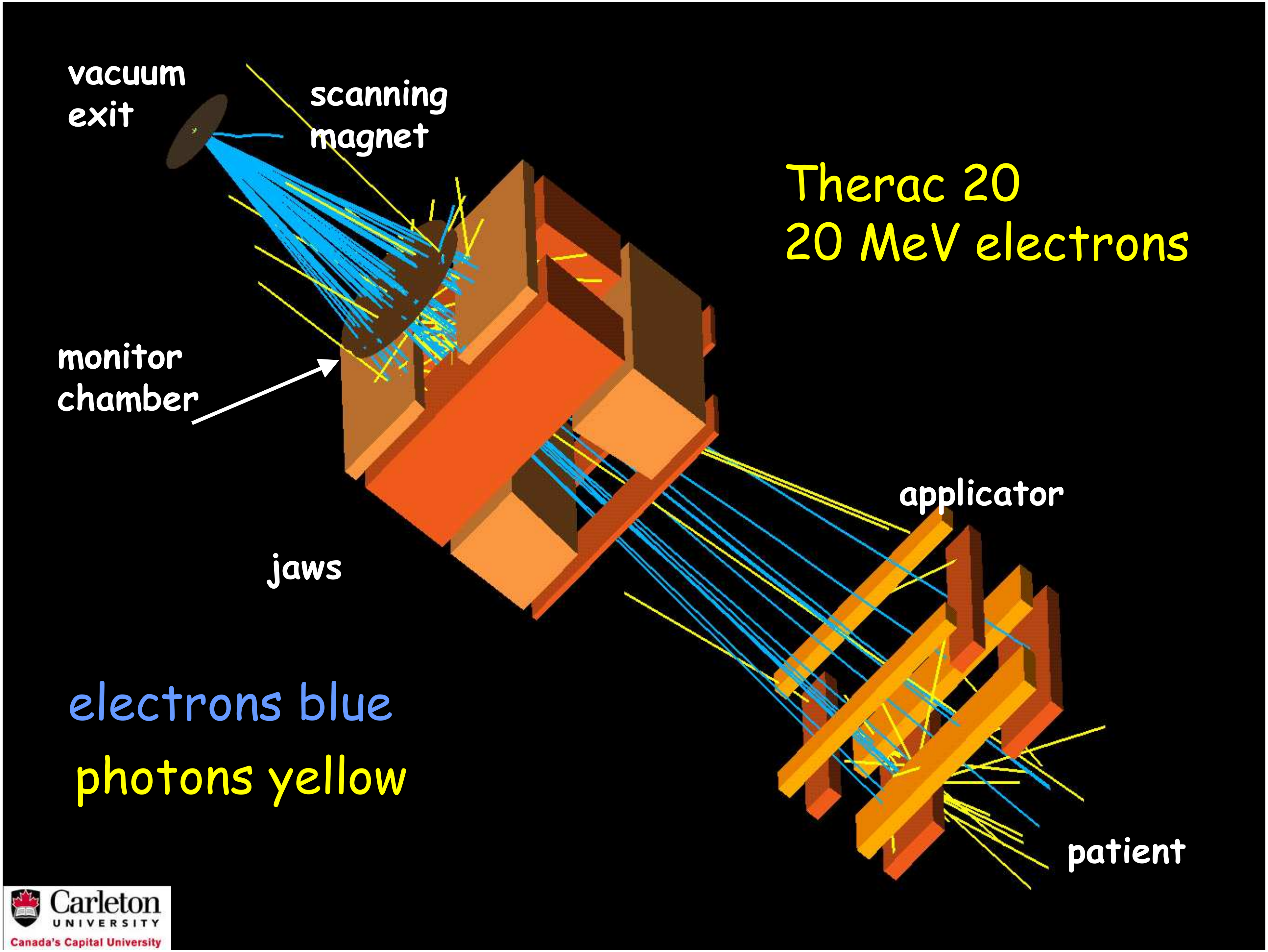
BEAM developers

Dave Rogers
Charlie Ma
Jiansu Wei
Geoff Zhang
Michel Proulx
Iwan Kawrakow

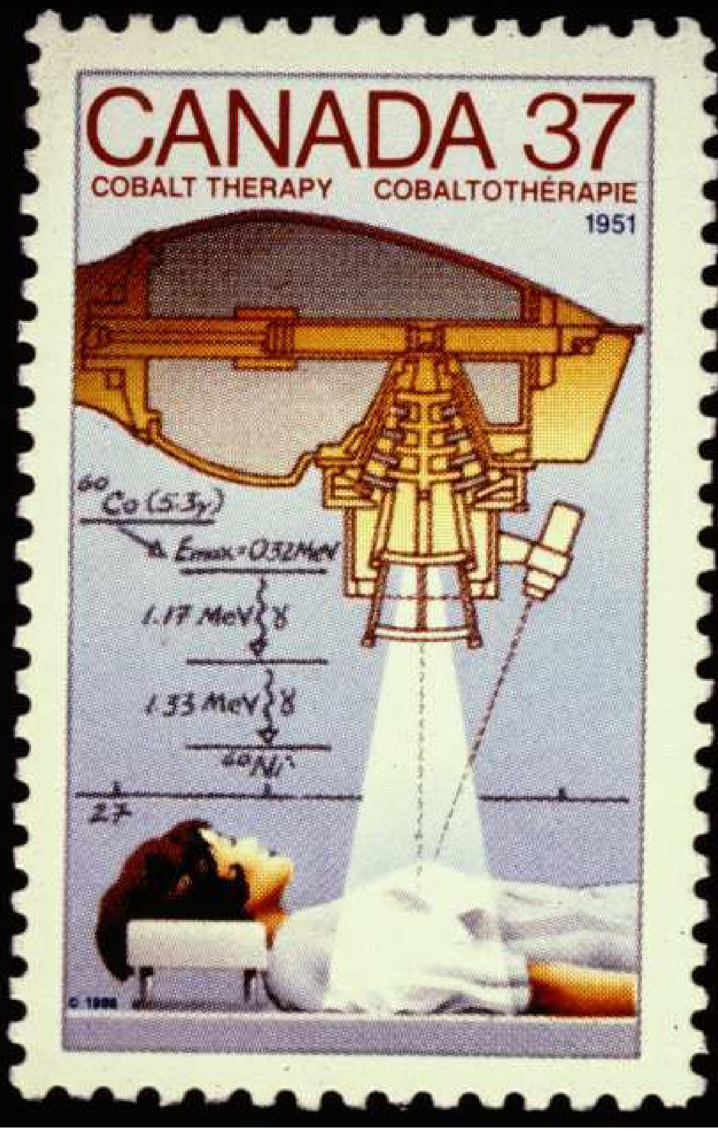
Blake Walters
Bruce Faddegon
George Ding
Joanne Treurniet
Daryoush Sheikh-Bagheri

EGS4: Ralph Nelson and Alex Bielajew

EGSnrc: Iwan Kawrakow


vacuum
exit
scanning
magnet
Therac 20
20 MeV electrons
monitor
chamber
applicator
jaws
electrons blue
photons yellow
patient

^{60}Co therapy unit



Issued
June 17,
1988

Thanks to
Jerry Battista

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What is efficiency?

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

T: computing time

σ^2: variance on quantity of interest

- sum of uncertainty^2
  - -fluence in $1 \times 1 cm^2$ regions in beam
  - -dose on central axis or profile

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Problems to overcome

-in photon accelerators, majority of time is spent following electrons

-most photons are absorbed in the primary collimator

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Uniform Brem Splitting (UBS)

-when an electron undergoes a radiative event, create nsplit photons with weight 1/nsplit

-overcomes most time being for electrons

-particles have same weight

EGSnrc has an efficient algorithm

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Russian Roulette

Still creating a large number of electrons in collimators, jaws etc

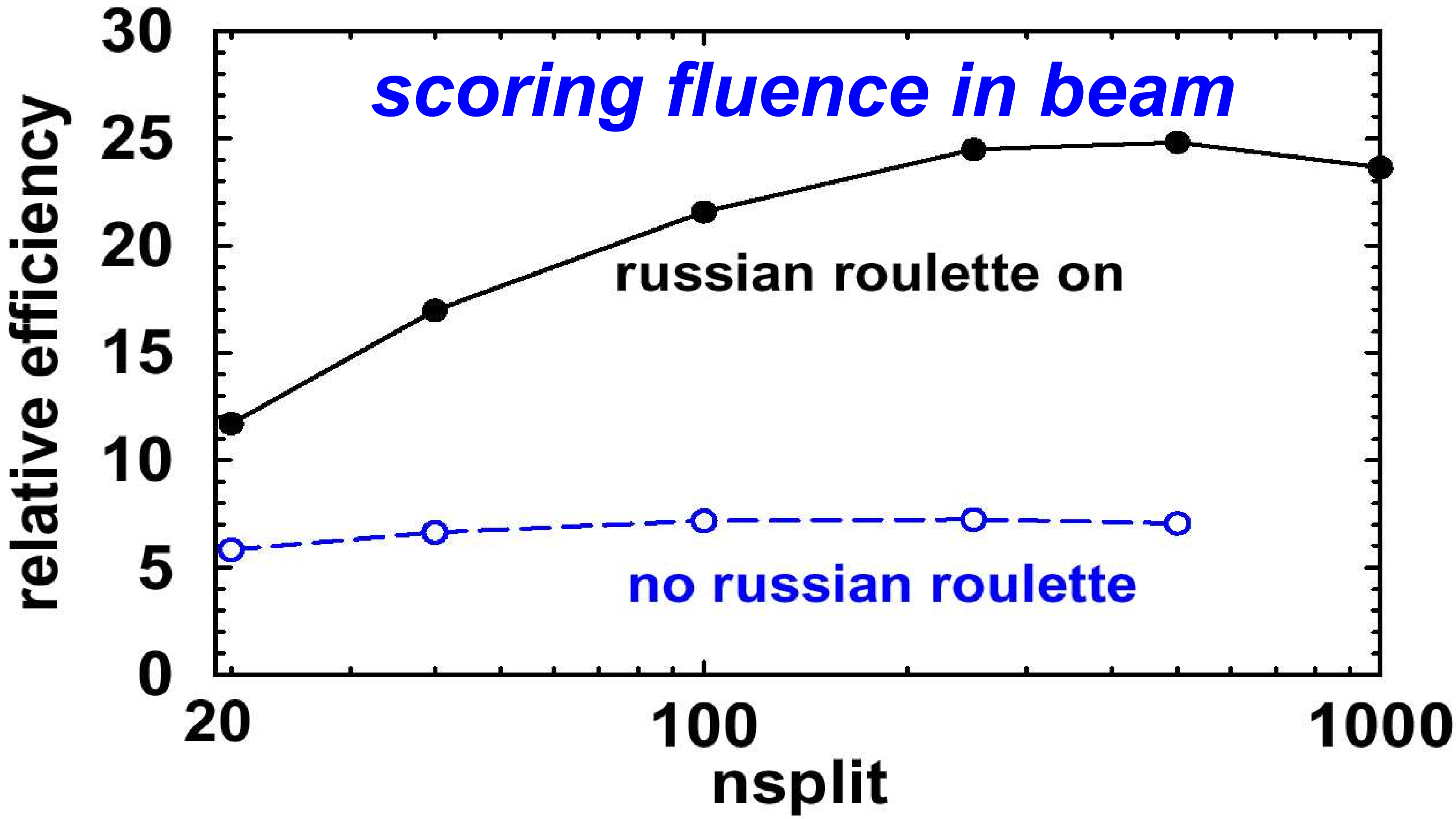
-play Russian Roulette on secondary electrons (weight of e- is 1)

-split nsplit times in further radiative events

=> photons weight still 1/nsplit

=> not many electrons in phase space

Uniform Brem Splitting



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Selective Brem Splitting (SBS)

Daryoush Sheikh-Bagheri

-split photons more often if likely to be in the beam (calculated probability)

-`fat' photons a problem

=> minimum split about 10% of max

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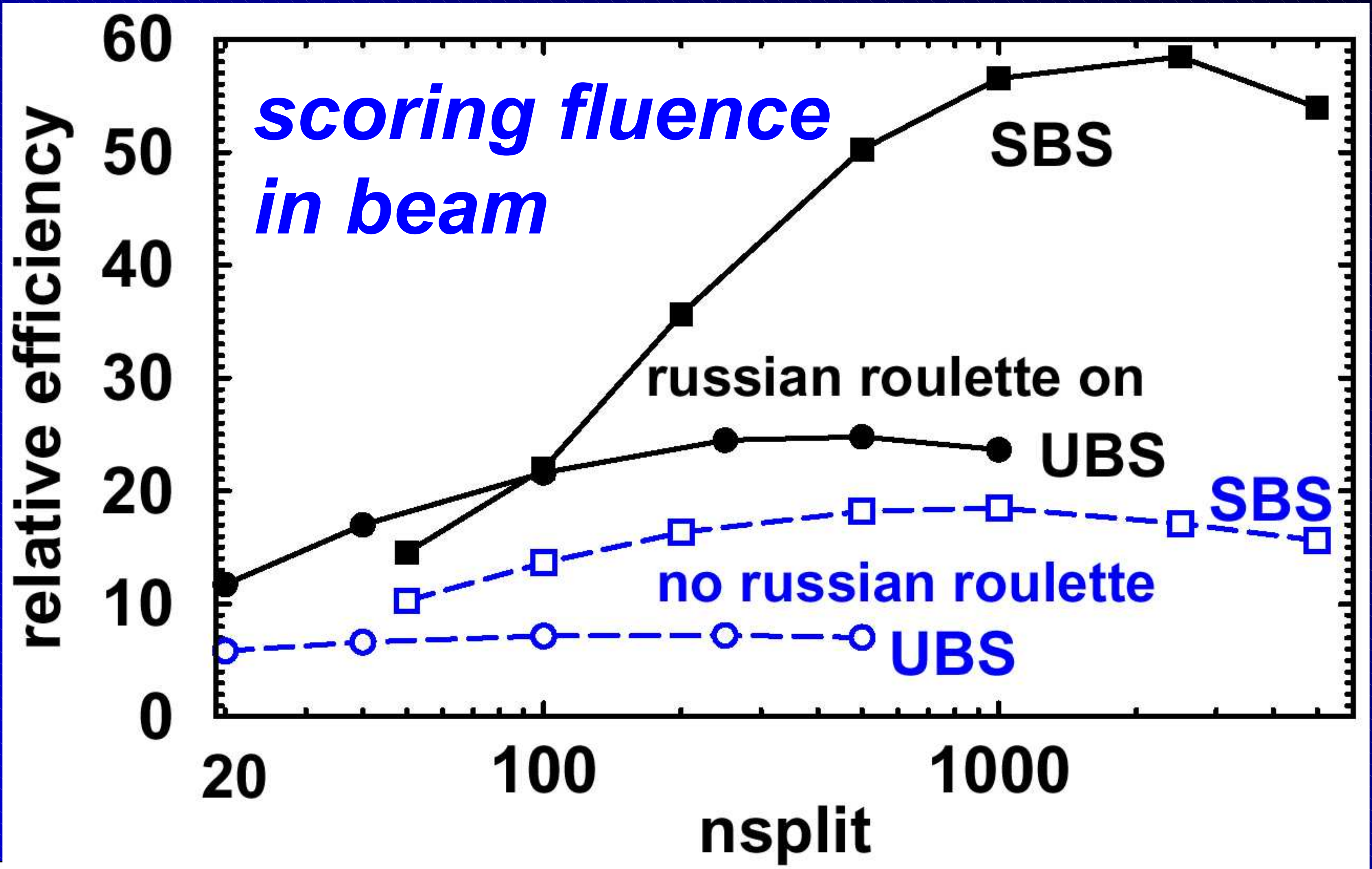
Selective Brem Splitting (SBS)



SBS problems

-large variation in weights
`fatter' photons still affect efficiency

-wasting lots of time on electrons which
cannot get to the phase-space file

-with Russian roulette on, the electron
efficiency is poor

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Directional Brem Splitting (DBS)

-goal: all particles in field when reach phase space have same weight

Procedure

i) brem from all fat electrons split nsplit times

ii) if photon aimed at field of interest, keep it, otherwise Russian roulette it: if it survives, weight is 1 (i.e. fat)

iii) if using only leading term of Koch-Motz angular dist'n for brem: **`do_smart_brems`** and similar tricks for other interactions

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DBS (cont)

photons

- reaching field have weight 1/nsplit
- outside field are fat

electrons in the field

-usually fat

-a few have weight 1/nsplit from interactions in the air

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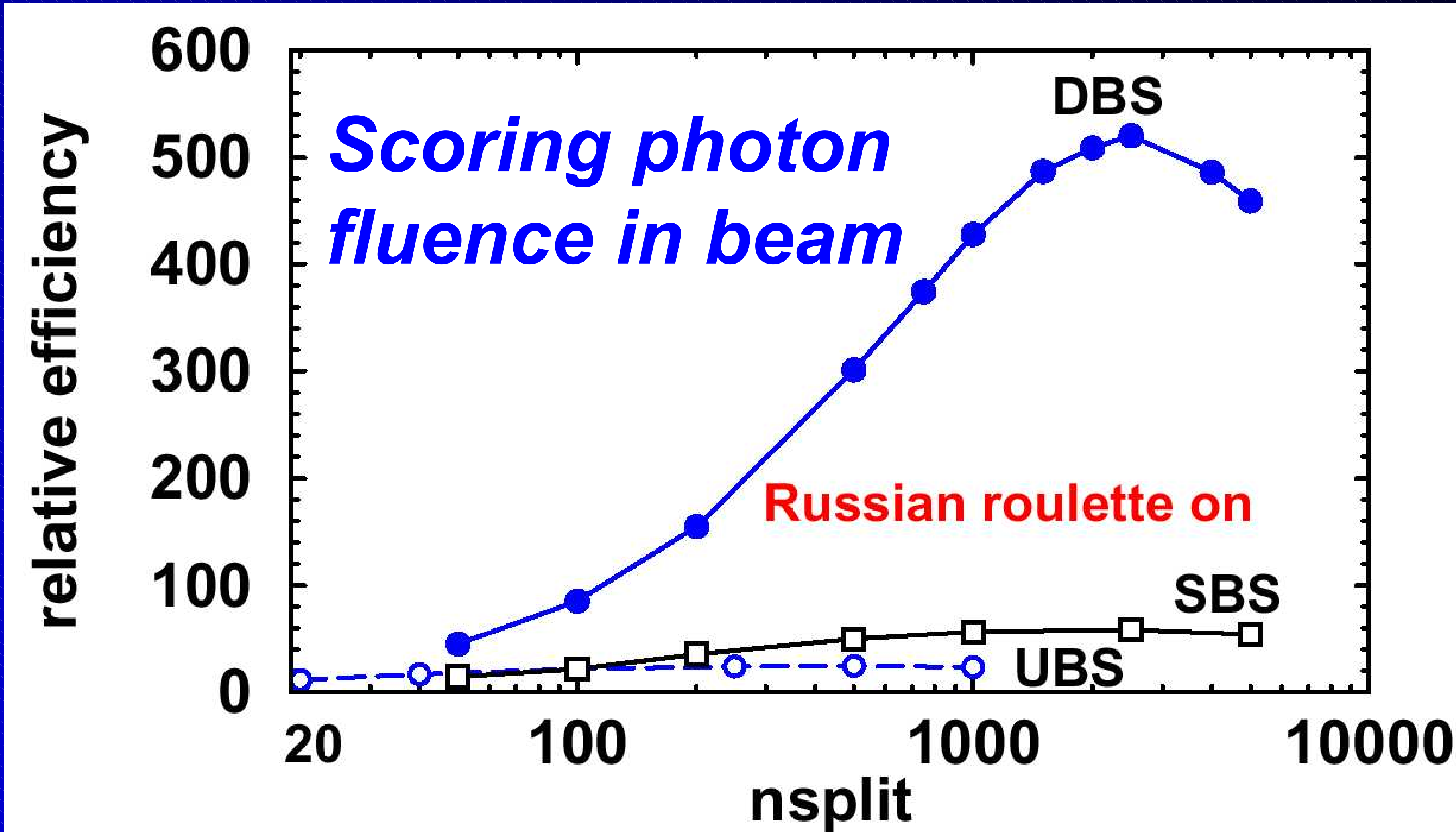
Directional Brem Splitting



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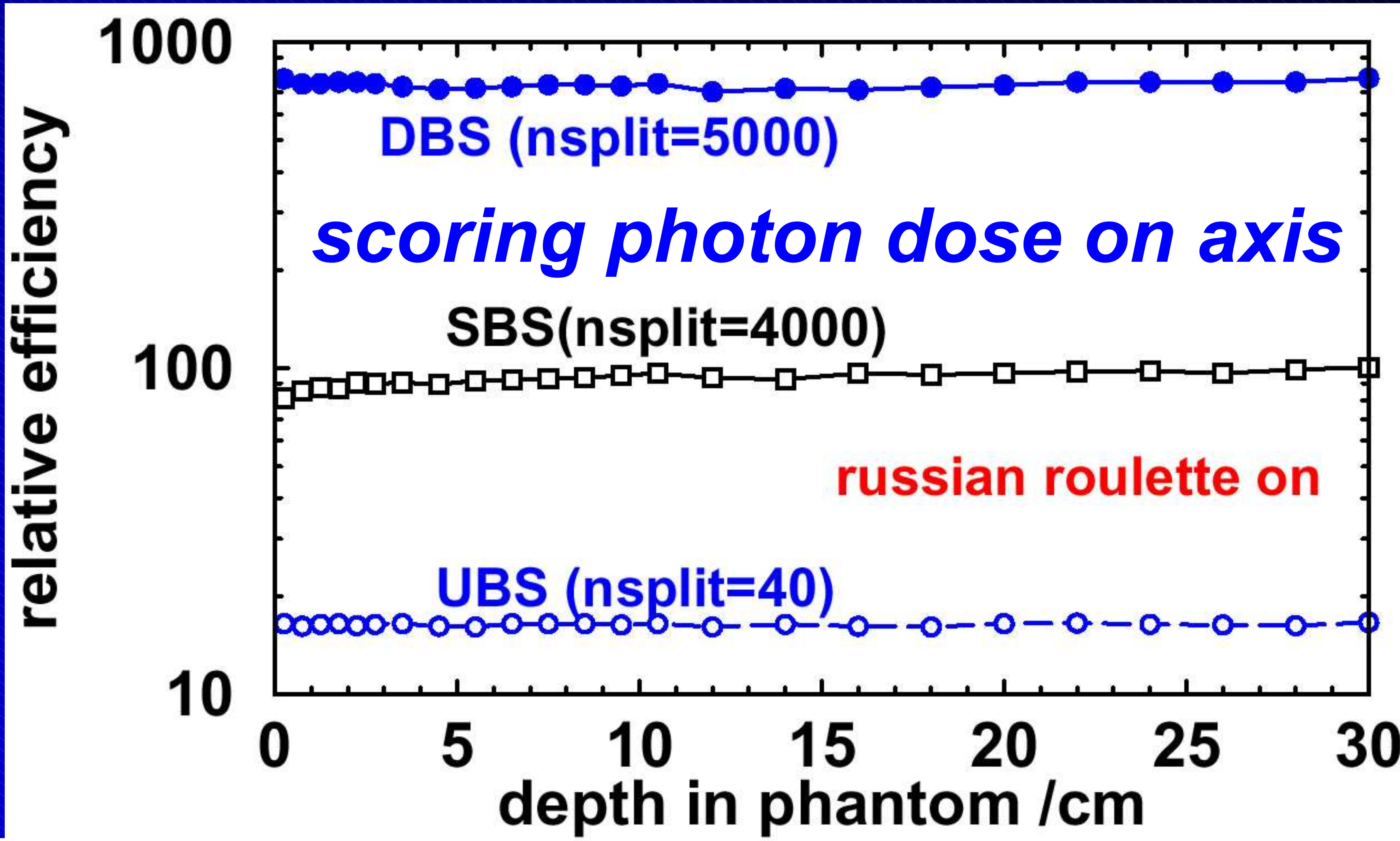
Directional Brem Splitting



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Electron problem

-efficiency gain for electrons is only 2

Basis of the solution

-electrons are, almost entirely, from flattening filter and below

-major gains are from treatment of electrons in primary collimator

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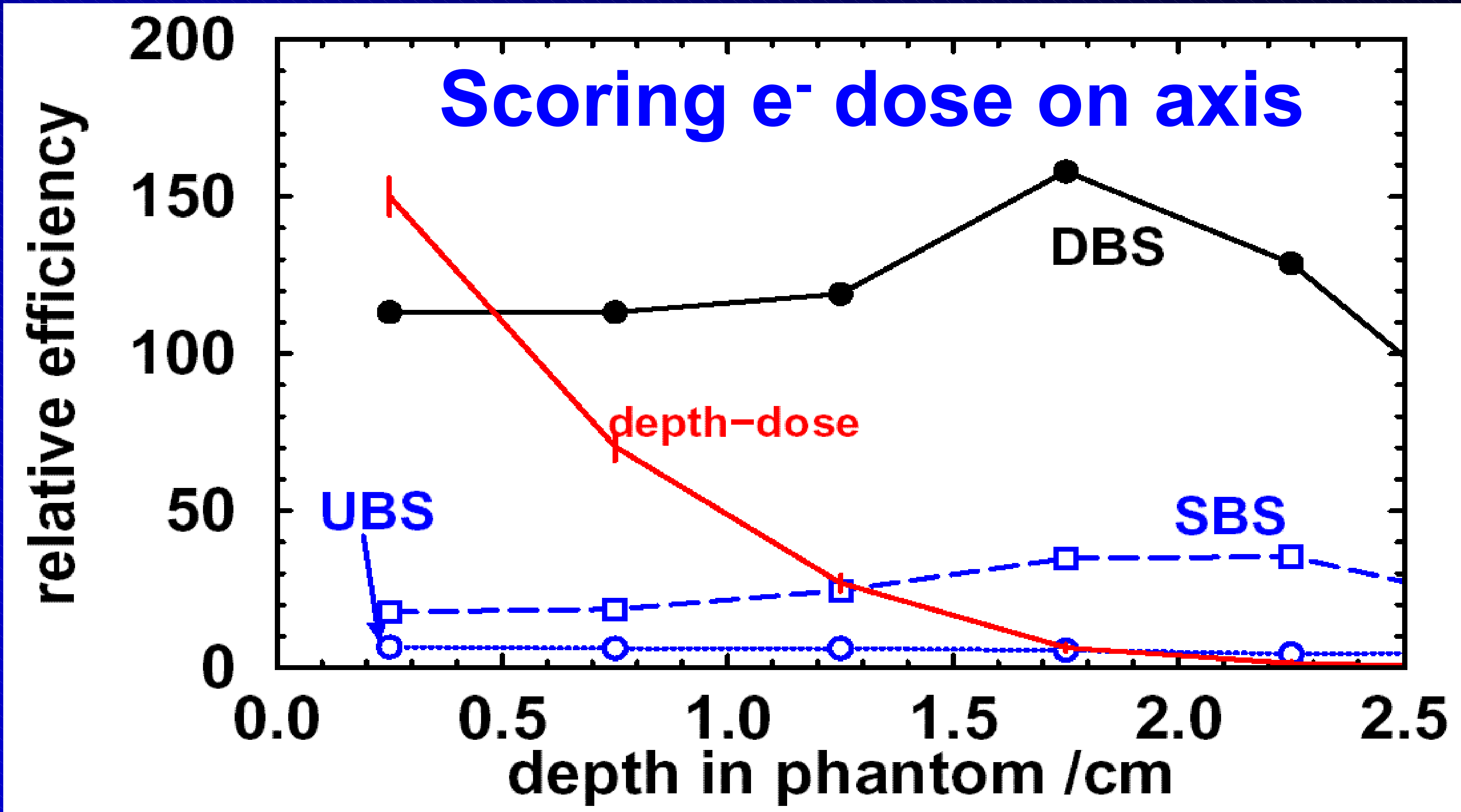
Electron solution

introduce 2 planes

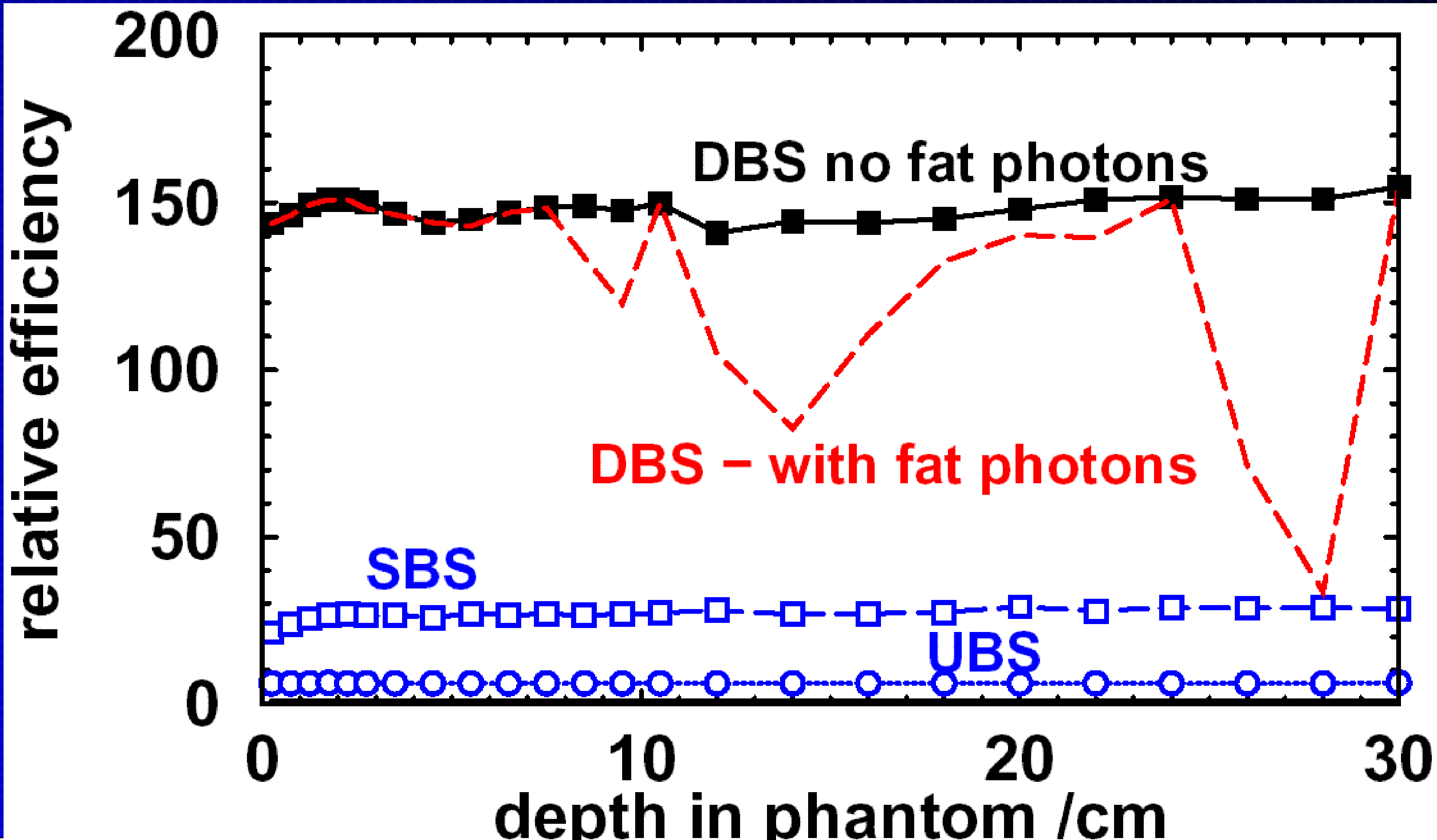
-splitting plane: split weight 1 charged particles nsplit times (may distribute symmetrically)

-Russian roulette plane: below this turn off Russian roulette and split all fat photon interactions nsplit times

Efficiency increase for e⁻



Efficiency: total dose



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Summary re DBS

DBS, directional brem splitting, improves BEAMnrc's efficiency by a factor of 800 (10 vs SBS) for photon beams (ignore small dose from photons outside field).

For total dose calculations the efficiency improves by factor of 150 (5 vs SBS)

SBS is optimized for greater nsplit than previously realized (5000)

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Monte Carlo for brachytherapy dose

- Gultekin Yegin of Turkey has developed the multi-geometry technique for EGSnrc (NIMB)
- we applied it to multiple seeds in a phantom
- using tracklength scoring improves efficiency by a factor 20
- complete calculation, 125 seeds in 1 mm^3 voxels takes 12 min for 2% stats on a 2.4MHz P-IV
- code called brachydose
- What is the effect of inter-seed shielding?

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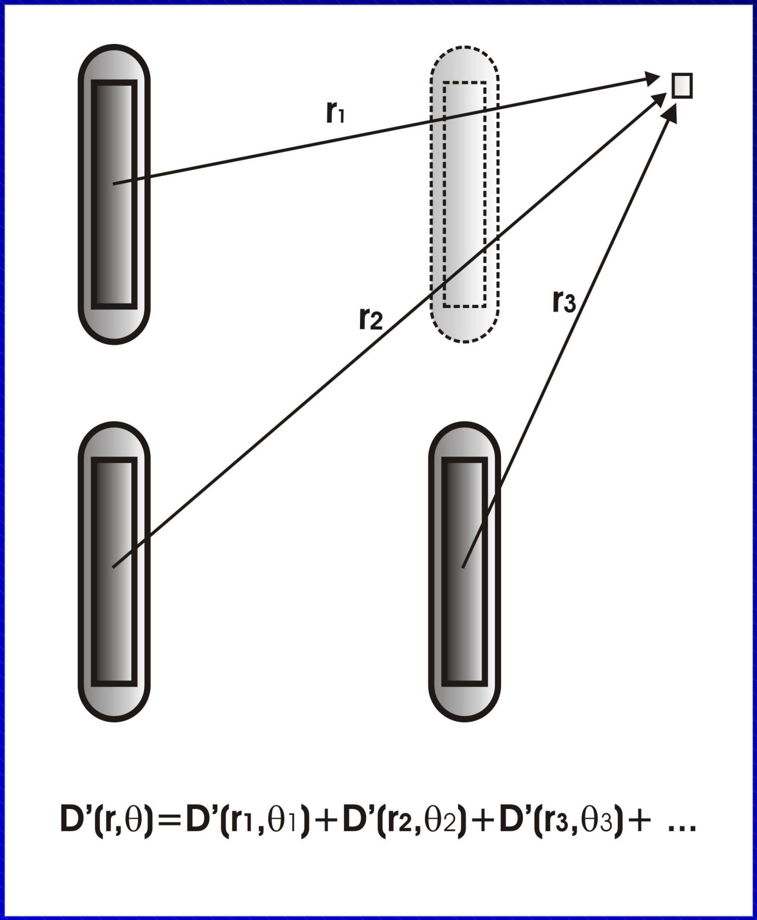
Inter-seed effects in brachytherapy



Standard planning systems ignore self-shielding

Only a few papers have investigated inter-seed effects.

In those papers, a small number of seeds are used in fixed configurations

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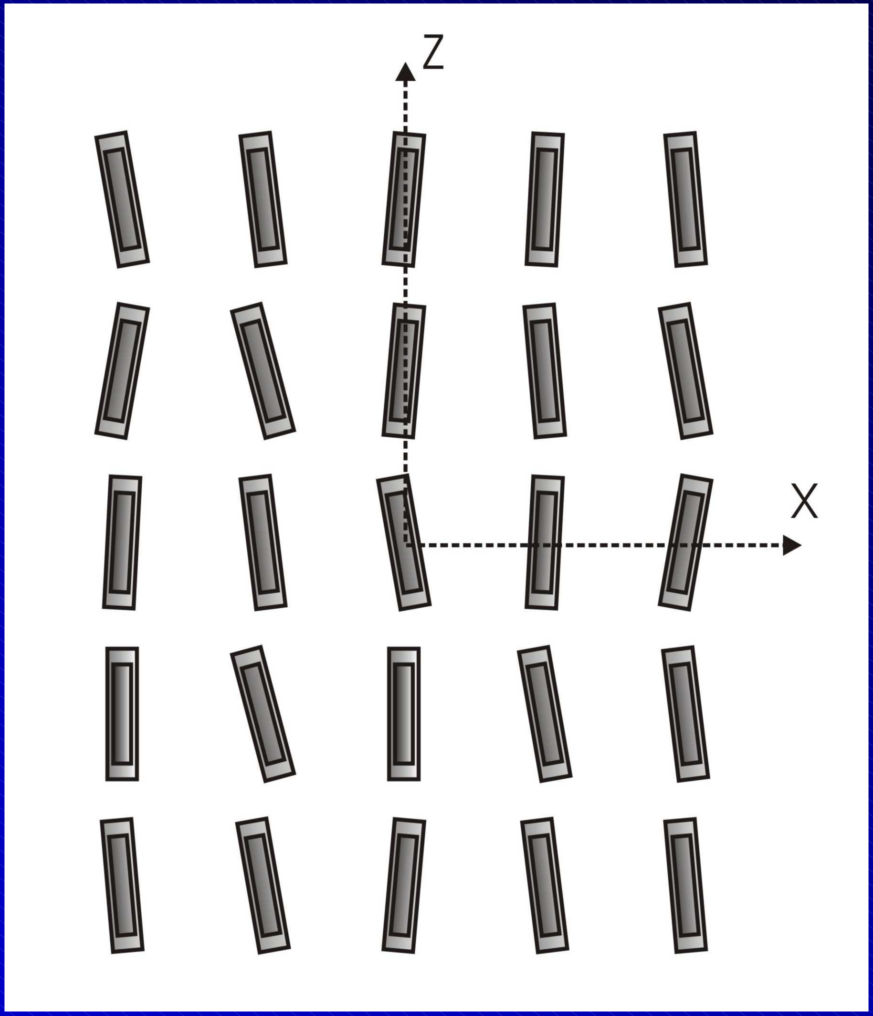
G Yegin/AAPM04

Rotations of seeds



5 layers deep

125 seeds

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G Yegin/AAPM04

Dose perturbation factor

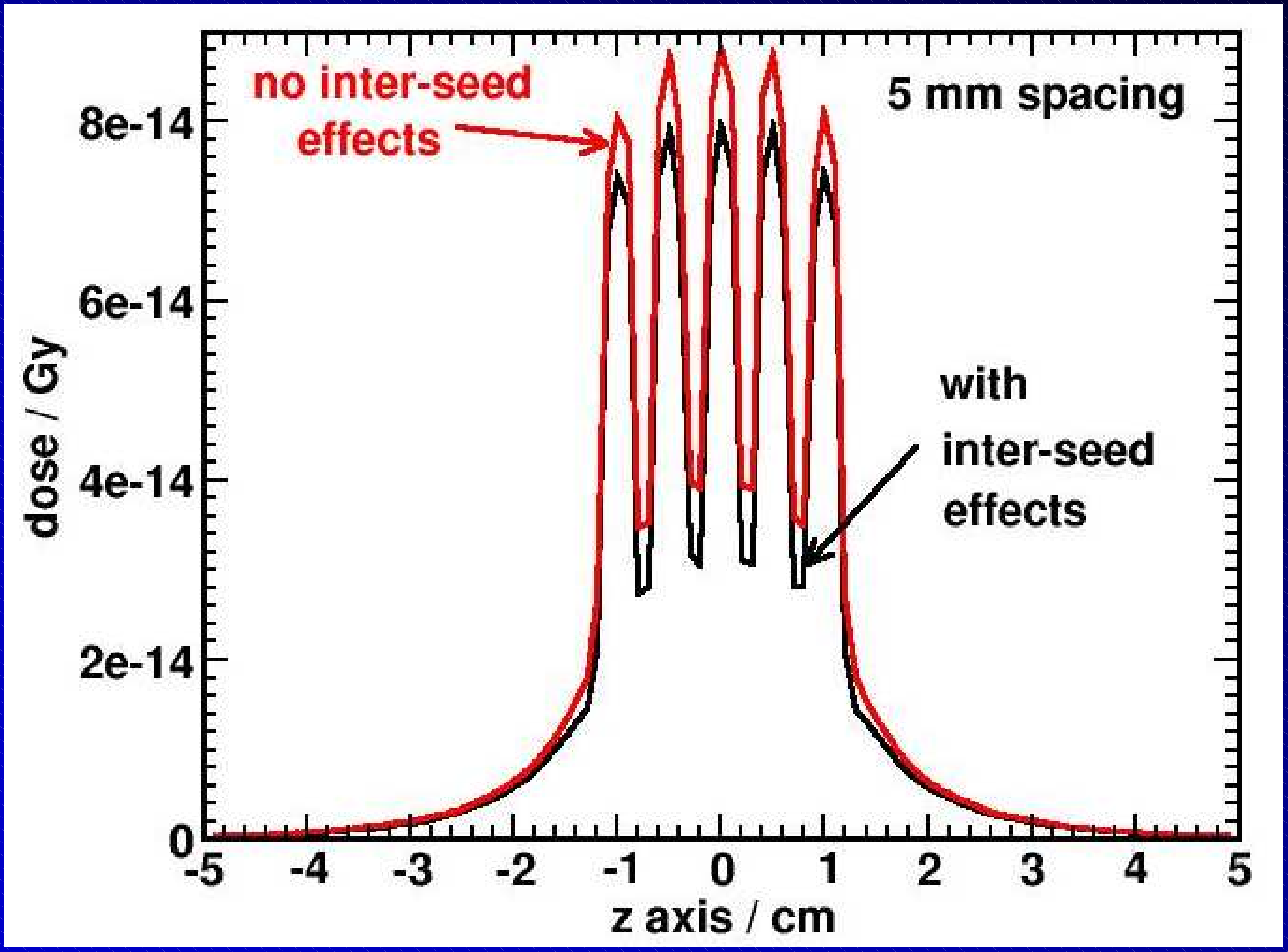
$$P = 100 \times [D(r,\theta) - D'(r,\theta)] / D(r,\theta)$$

P : Dose perturbation factor

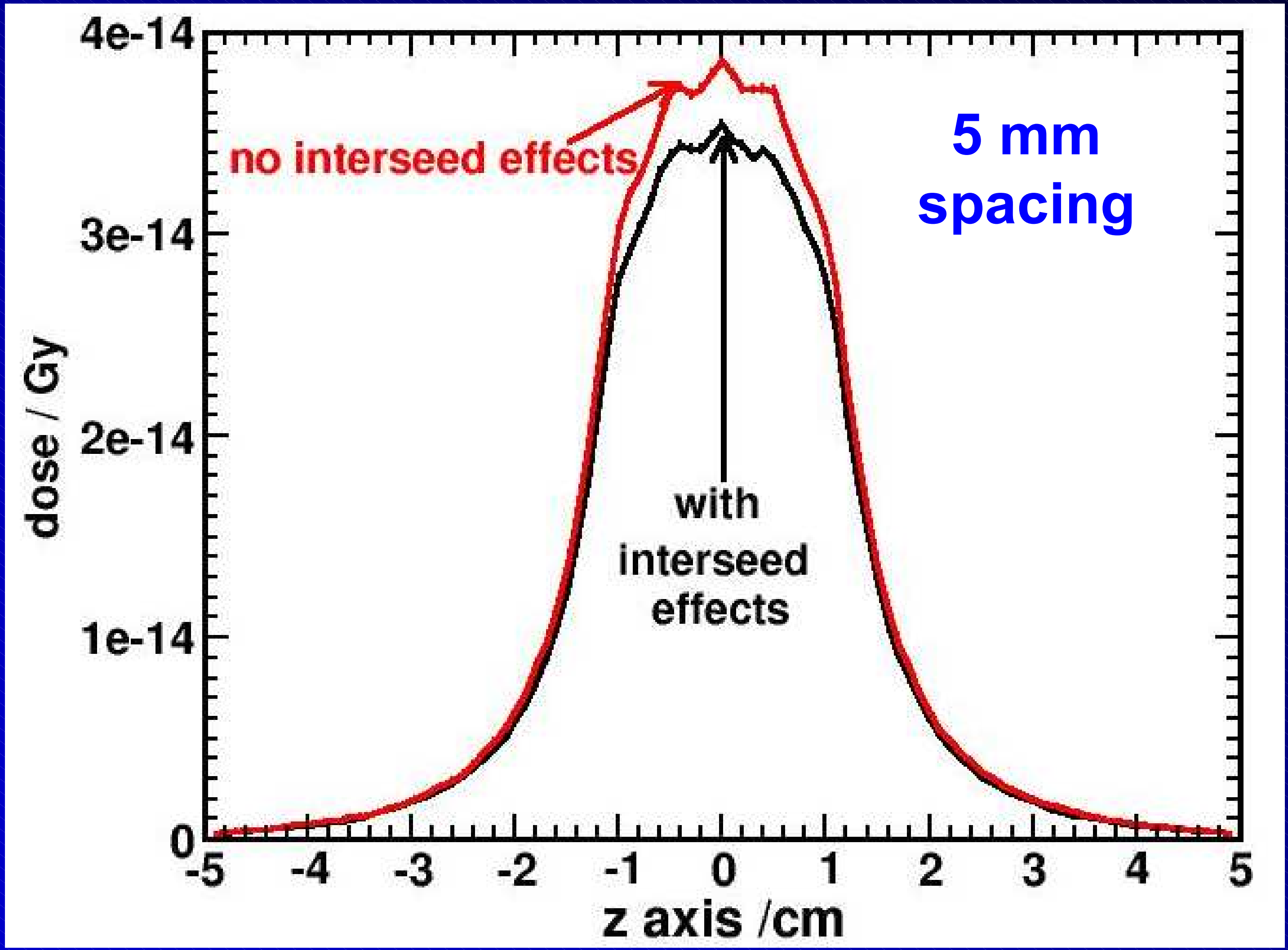
D: calculation with all inter-seed effects included

D': calculation with all seeds (except that emitting the photon) treated as water

central axis dose for 5mm spacing



Dose on a line close to central axis



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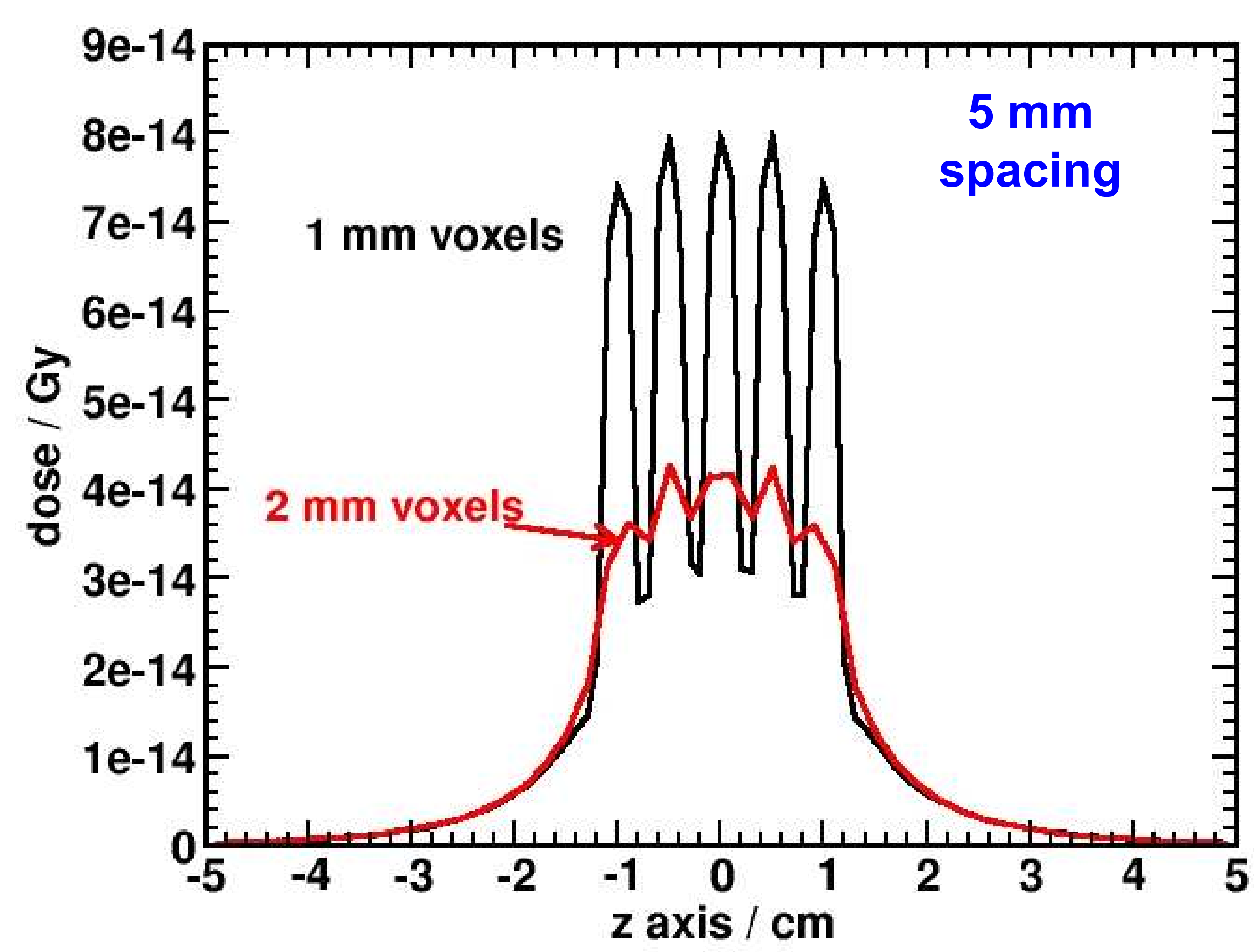
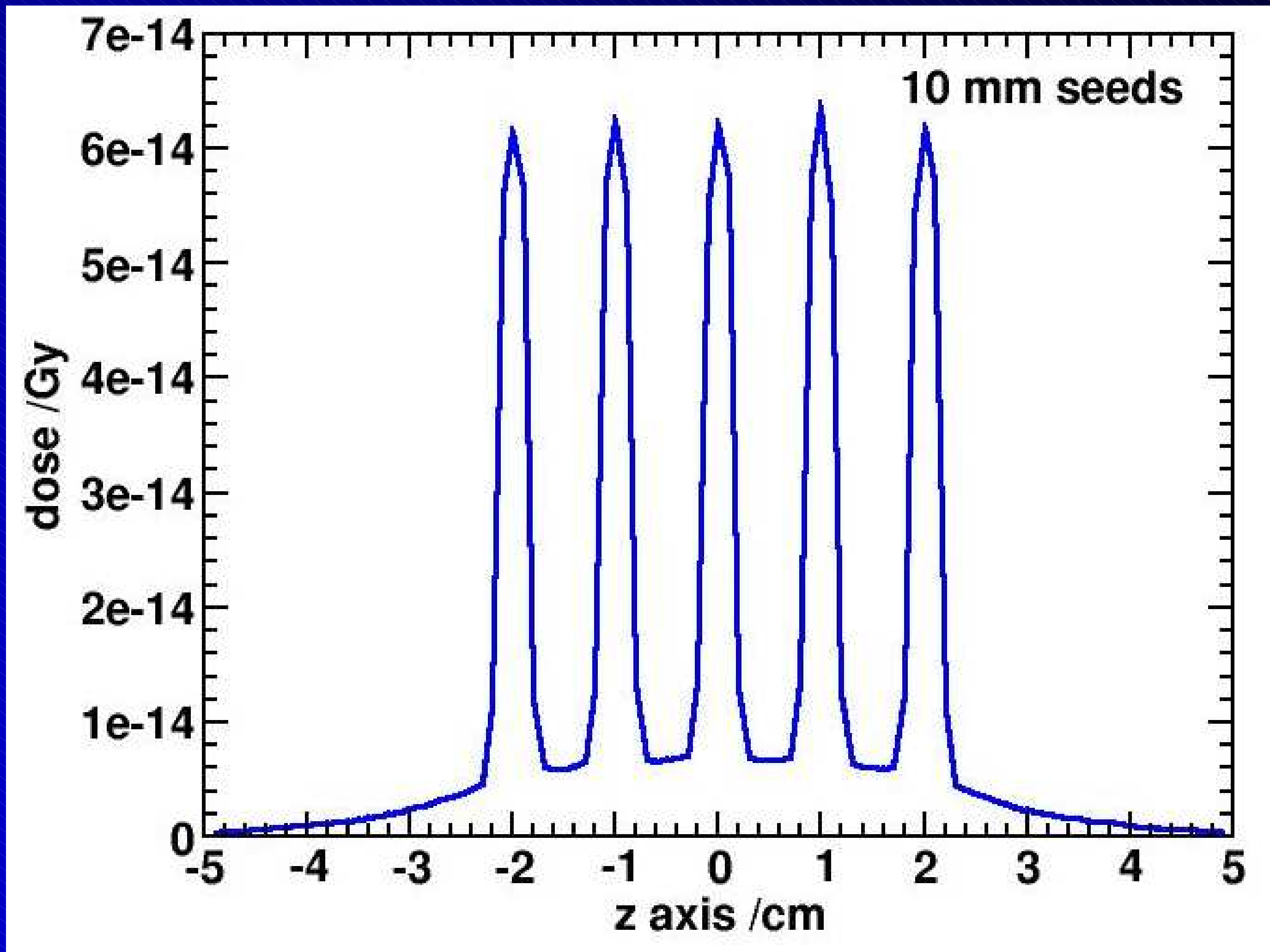
Influence of voxel size



10 mm spacing => 9 to 1 ratio



Summary re brachydose

- calculated dose perturbation factors are
  - 3% to 8% for 1 cm spacing of seeds
  - 4% to 30% for 0.5 cm spacing
- Using 1x1x1 mm voxel size, calculation of a dose distribution with 2% statistical uncertainty takes about 12 minutes on a pentium-4 2.4GHz cpu
  - expect a factor of 2 faster
- we hope to develop a generally available, clinically useful, code

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Kawrakow's EGSnrc

Accurate condensed history Monte Carlo simulation of electron transport. I. EGSnrc, the new EGS4 version

I. Kawrakow
National Research Council, Ottawa, ON K1A 0R6, Canada

(Received 10 March 1999; accepted for publication 8 December 1999)

485 Med. Phys. 27 (3), March 2000

Accurate condensed history Monte Carlo simulation of electron transport. II. Application to ion chamber response simulations

I. Kawrakow
National Research Council, Ottawa, ON K1A 0R6, Canada

(Received 10 March 1999; accepted for publication 8 December 1999)

499 Med. Phys. 27 (3), March 2000

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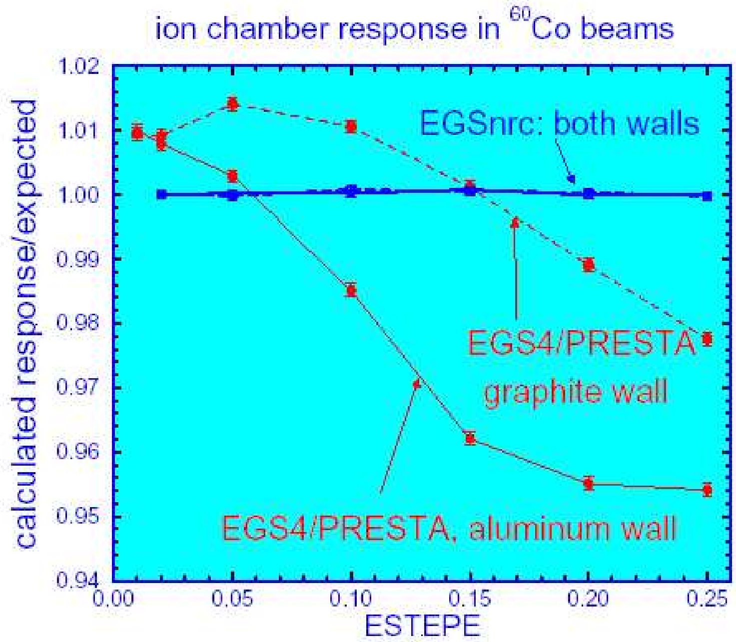
The EGSnrc Code System:

Monte Carlo Simulation of Electron and Photon Transport

I. Kawrakow and D.W.O. Rogers
Ionizing Radiation Standards
National Research Council of Canada
Ottawa, K1A OR6
iwan@irs.phy.nrc.ca
dave@irs.phy.nrc.ca

May 8, 2001

NRCC Report PIRS-701

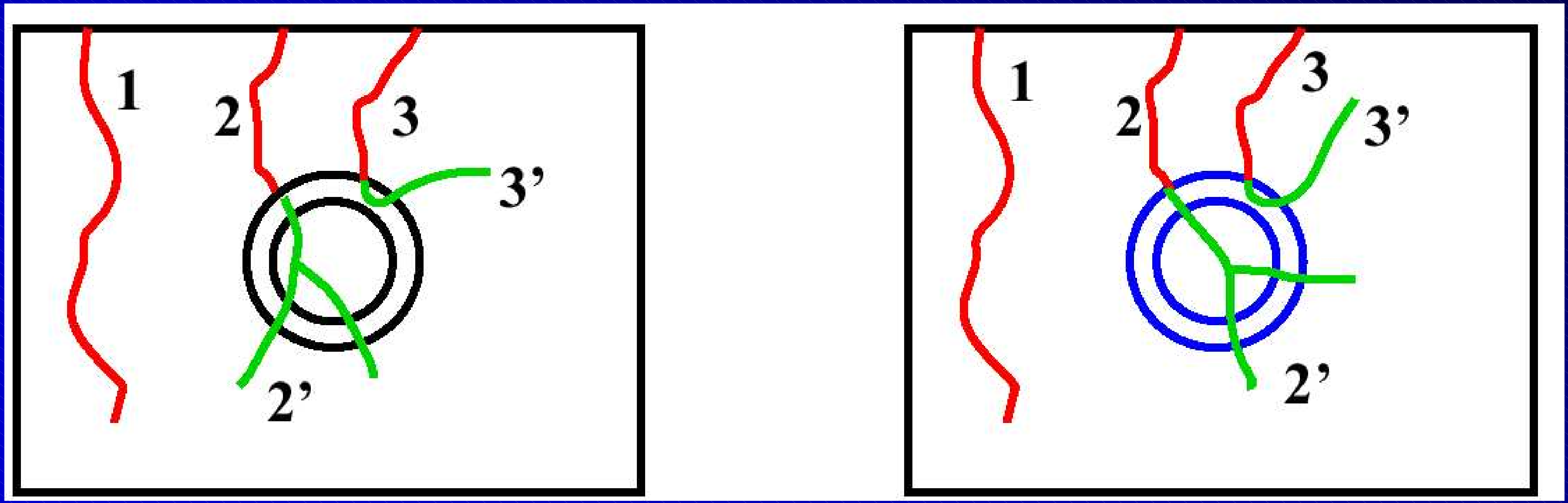


Available on-line via:
http://www.irs.inms.nrc.ca/inms/irs/EGSnrc/EGSnrc.html

What is correlated sampling?

Of use when there are two or more similar geometries in which one wants the ratio of doses
eg: electrodes, TLDs, wall effects, dosimeters in phantom, etc, etc

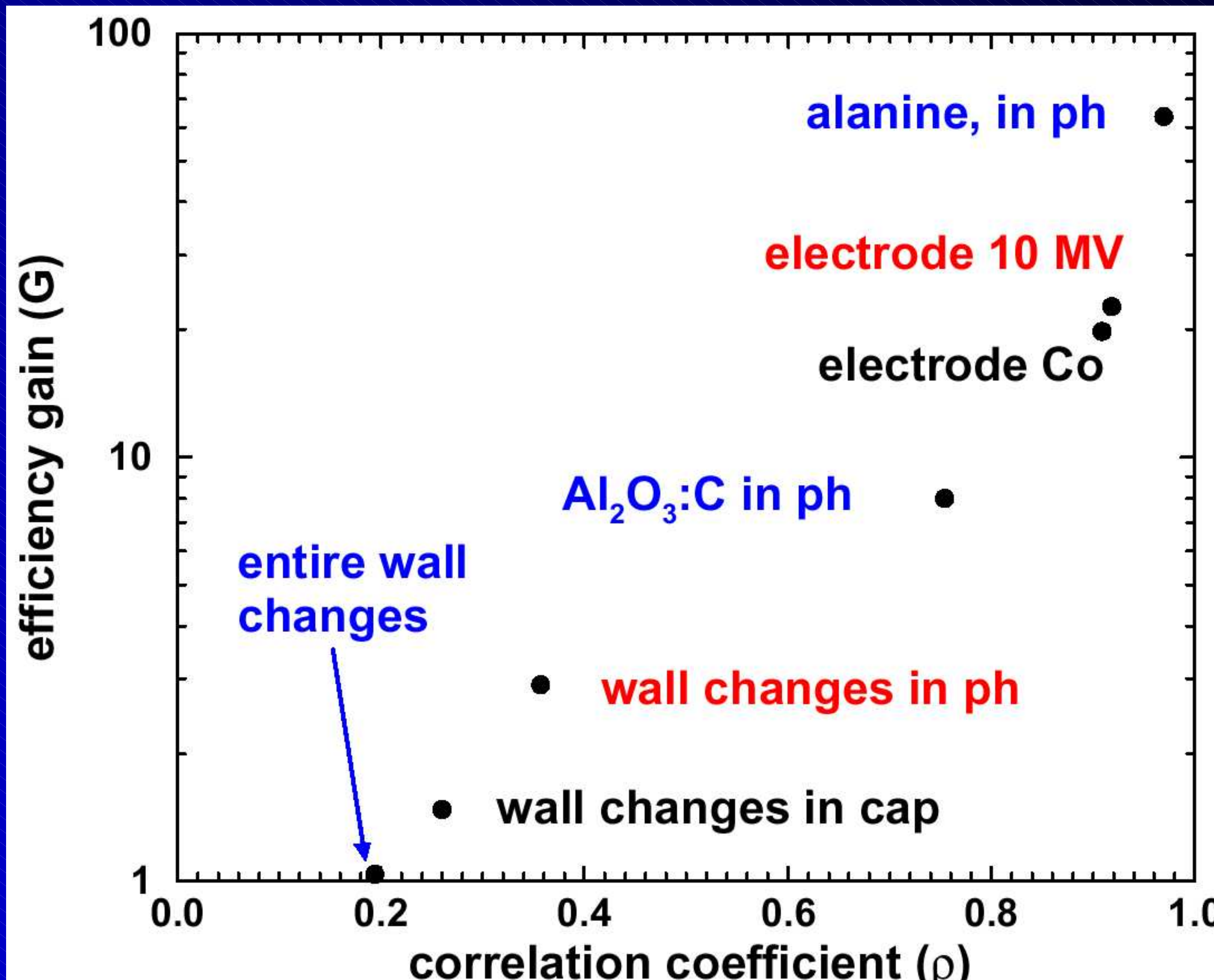
Originally developed by Ma and Nahum for EGS4



geometry 1

geometry 2

efficiency gain vs correlation



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Buckley et al, submitted to Med Phys

P_{cel}: Al electrode correction

–for electrode of wall material could be considered part of P_{fl}

Ma and Nahum(93) showed aluminum electrodes have an effect

-larger in photon beams

-but biggest effect is in electron beams because it cancels in photons

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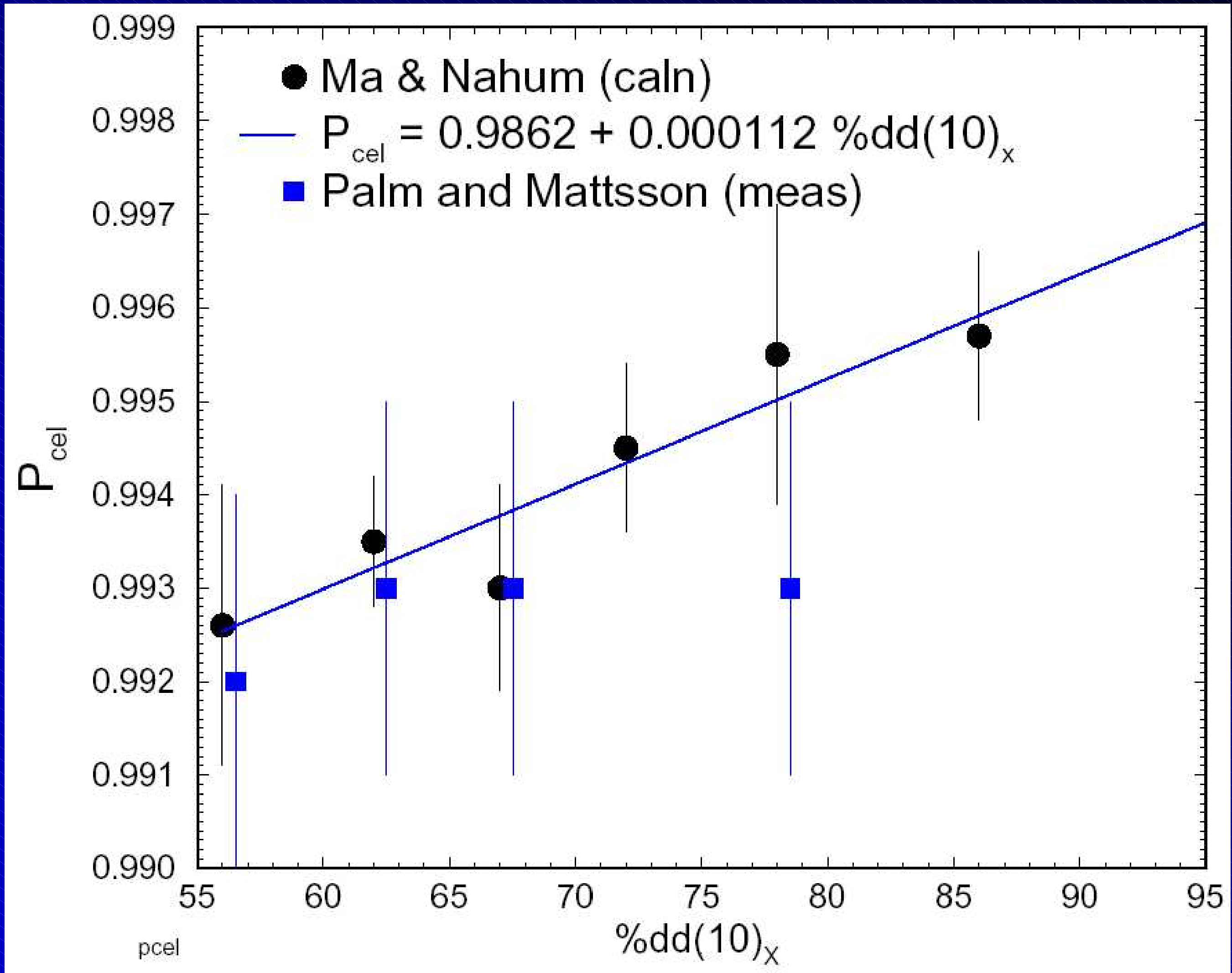
Ma & Nahum PMB 38 (1993) 267

P_{cel}: Al electrode correction

-expts confirm calns

but not as precise



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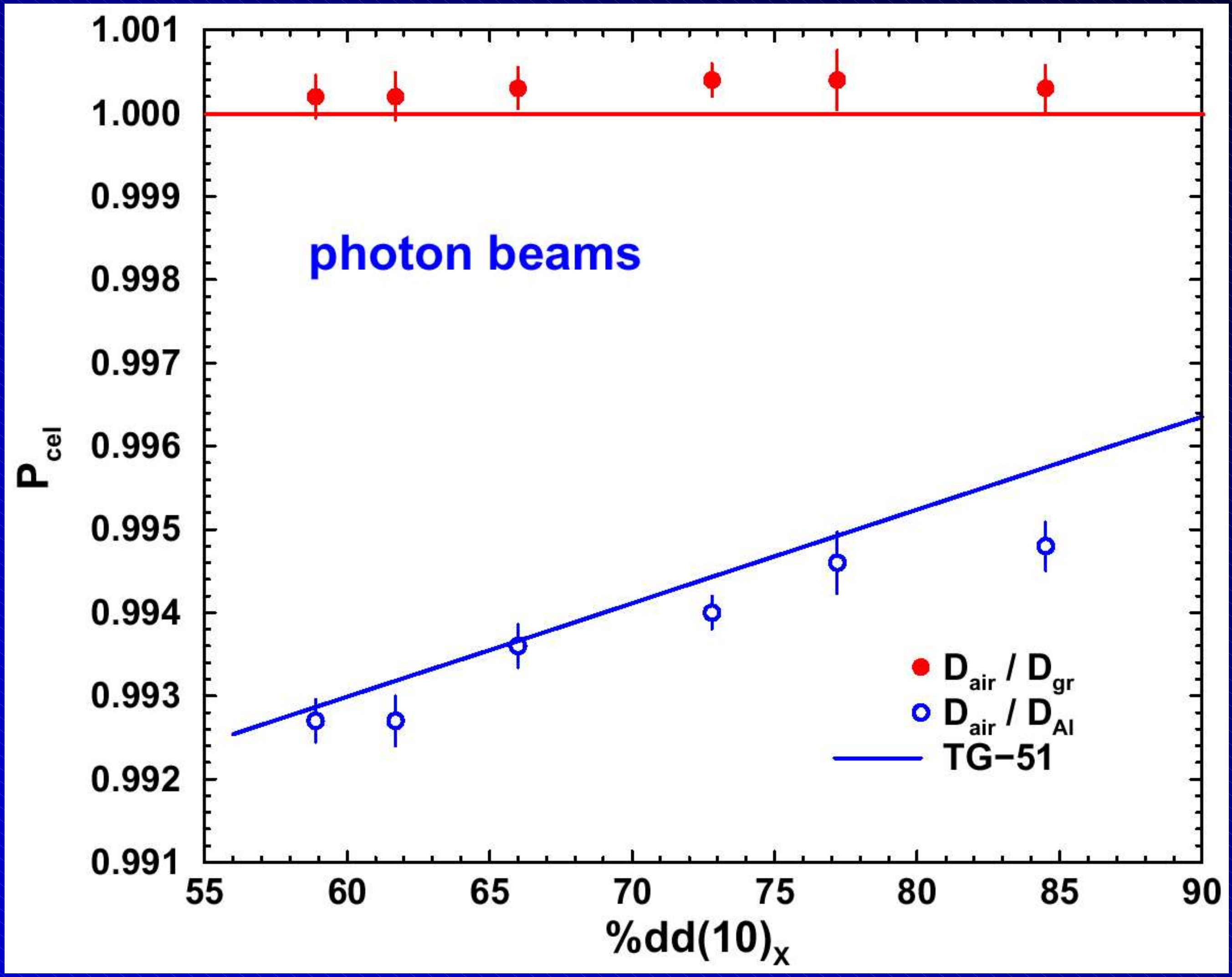
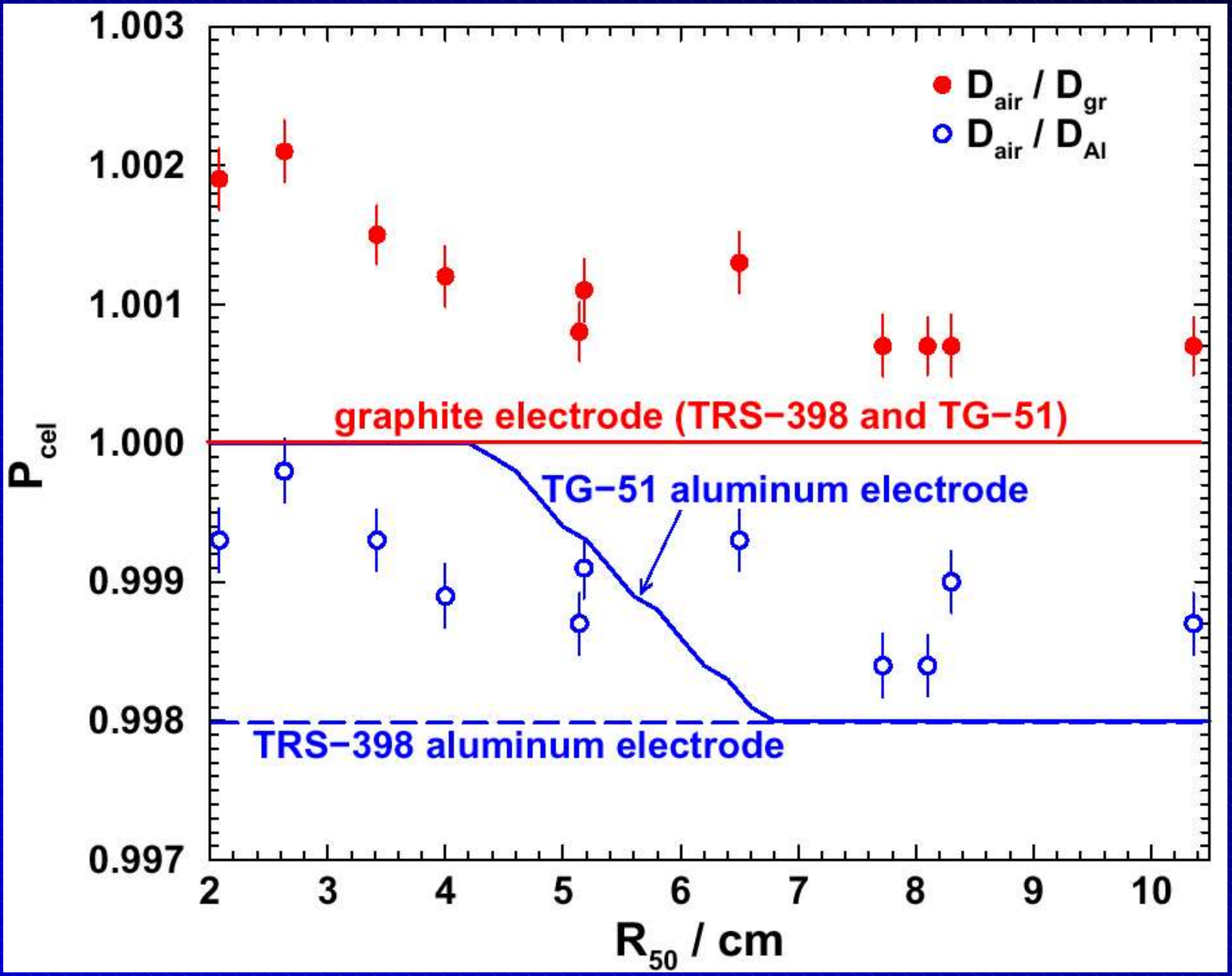
Palm & Mattsson PMB 44 (1999) 1299

New P_{cel} values for photon beams



Buckley et al, submitted to Med Phys

New P_{cel} values for electron beams



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Buckley et al, submitted to Med Phys

Al_2O_3:C in radiation dosimetry

- uses optically stimulated luminescence (OSL)
- OSL uses a light source to stimulate luminescence
- signals from the dosimeter are relayed via a 1 mm core diameter fiber optic cable

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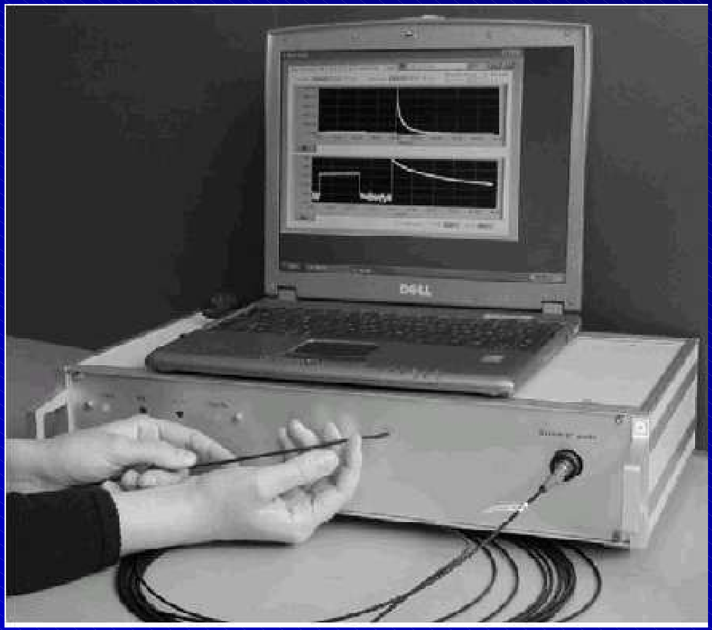
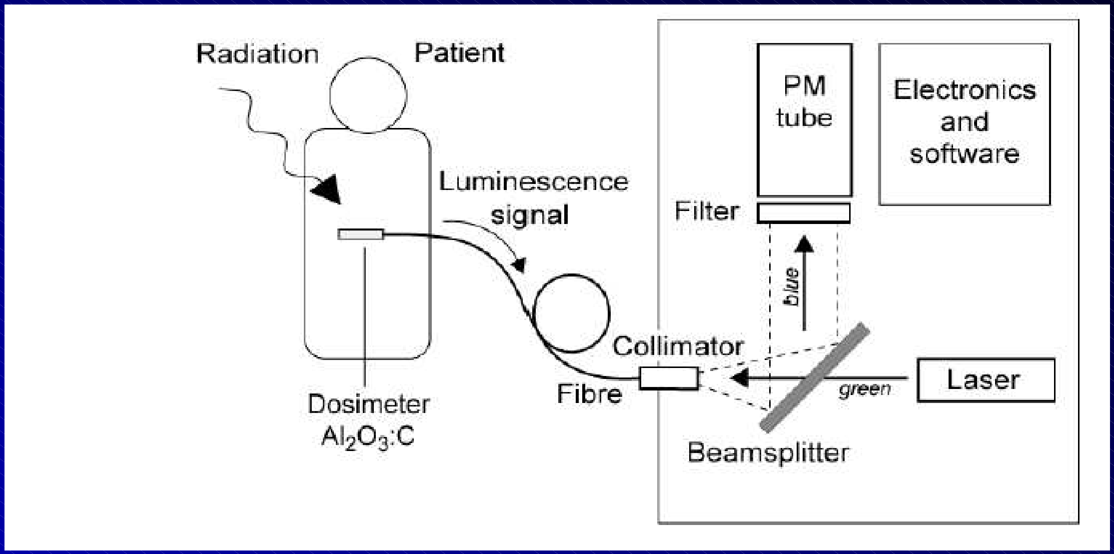
Al_2O_{3}:C in radiation dosimetry





- small size detector (1 mm^3 or 2 mm^3)
- sensitive over a wide range of dose & dose rates
- can measure both dose and dose rate in real time

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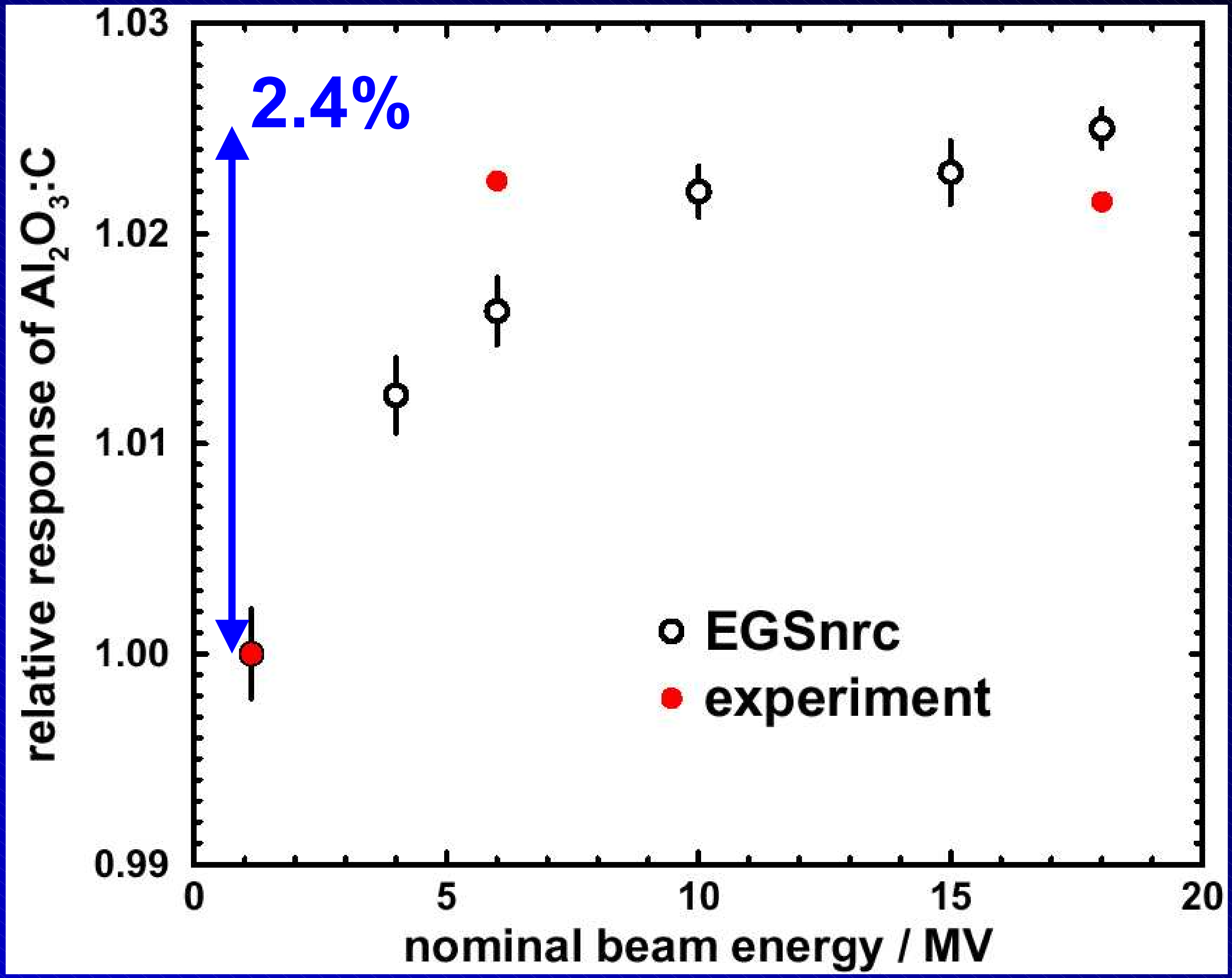
from Aznar et al: PMB 49(2004)1655

OSL calculations vs measurement

Results normalized at ^{60}Co

Preliminary experimental uncertainty estimate is on the order of 1.5%



Expt: Aznar et al: extension of PMB 49(2004)1655

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SNOMAN -MC for SNO

- the Monte Carlo simulation of the SNO detector (SNOMAN) uses EGS4 to simulate the slowing of electrons
  - this is critical in determining the light output
- recently a discrepancy with the calibration data has been removed by adding in a patch to include Mott scattering in the simulation
- comparisons with EGSnrc demonstrate that the SNOMAN patch gets the right answer

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Conclusions

- Monte Carlo is useful
- making dosimetry more accurate
- improving radiotherapy
- golden age ahead as machines and codes faster and more flexible
- the future will see modelling to the biological level, not just physical dose

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Thanks to

- many, many colleagues who have helped develop the BEAM/EGS codes discussed: Kawrakow, Walters, Nelson, Ding, Faddegon, Ma, Zhang, Mackie, Bielajew, Sheikh-Bagheri, Proulx + many users reporting bugs (sometimes patches!)
- Gultekin Yegin for slides and collaborating on brachydose
- Lesley Buckley for her data on correlated sampling
- Jerry Battista for good slide of the stamp

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