

Review of TG105: Issues associated with clinical implementation of Monte Carlo-based photon and electron external beam treatment planning

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AAPM Annual Meeting Minneapolis

7:30-8:25 Mon 07/07/23

Disclosure

I used to work for, and still receive some royalty income from the National Research Council of Canada which has licensing agreements re Monte Carlo software with:

Elekta Philips/ADAC NAS/NOMOS
Nucletron Varian

The following companies have provided support for my group at Carleton University:

Nucletron Canada TomoTherapy Inc
Philips/ADAC MDS Nordion Varian

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Charge of TG-105

Develop an **overview report** on the Monte Carlo method and its application to radiotherapy treatment planning.

Aims are:

- **educational**: provide an understanding of the MC method and how it is used in radiotherapy
- **discuss issues** associated with clinical implementation and experimental verification
- **provide perspectives** and **possible methods** on how to deal with the issues

Not meant to be prescriptive or to provide specific guidance on clinical commissioning.

Status of TG-105

- approved by appropriate AAPM committees and councils
- **submitted** to Medical Physics **April 2006**
 - substantial useful input from the referees & AE
 - difference of opinion with AE on goals of the TG
 - revision 2 sent in recently
 - acceptance expected (hoped for?) soon

What is the Monte Carlo method?

"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**" *

In principle, **very straightforward application of radiation physics**. Much easier to understand than convolution / superposition or EQTAR.

Virtually no approximations of consequence.

*TG105 quotes Rogers&Bielajew, 1990, in Dosimetry of Ionizing Radiation V3 <http://www.physics.carleton.ca/~drogers/pubs/papers/RB90.pdf>

10 MeV photon on lead

along incident
photon

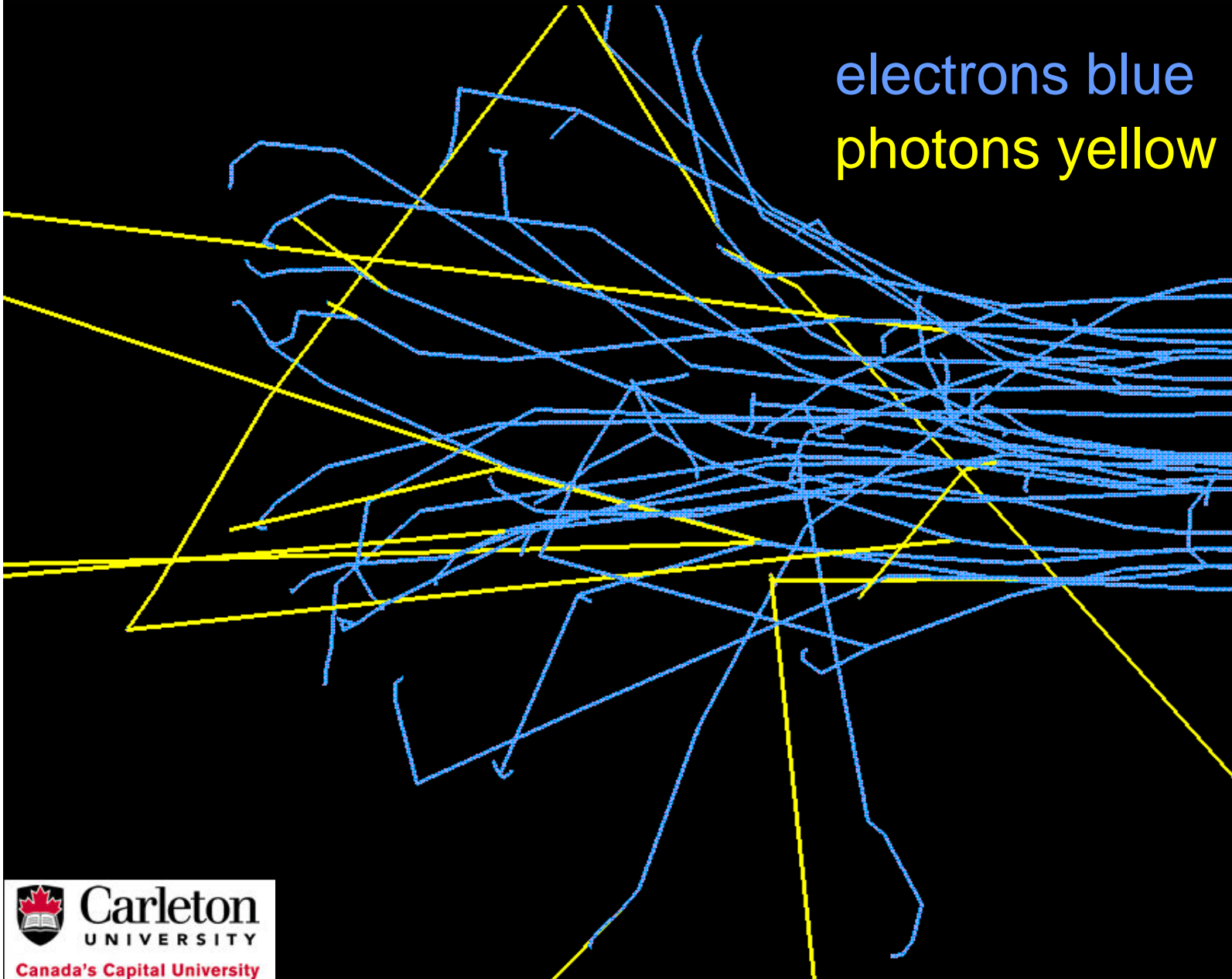
positrons red
electrons blue
photons yellow

incident

incident

10 MeV electrons on water from right

electrons blue
photons yellow



Simple photon simulation

- say: $\Sigma_{\text{total}} = \Sigma_{\text{compton}} + \Sigma_{\text{pair}} \text{ cm}^{-1}$
- select 2 random numbers **R1, R2**
 - uniform between 0 and 1
 - whole careers devoted to doing this
 - cycle length now 10^{40}

Photon transport (cont)

How far does photon go before interacting?

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

is exponentially distributed $[0, \infty)$

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

Photon transport (cont)

After going x , what interaction occurs?

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

then a compton scatter occurs

otherwise

a pair production event occurs

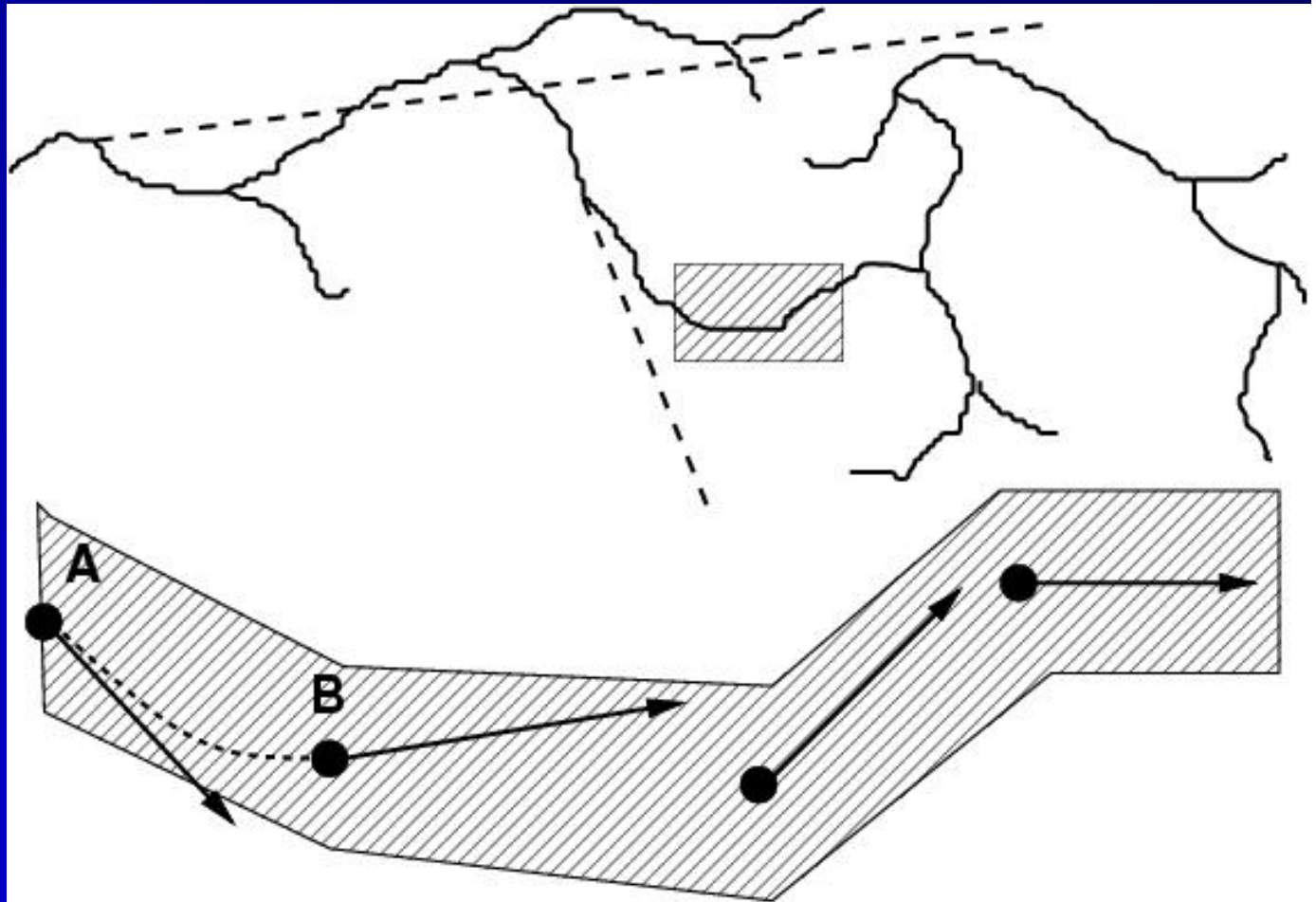
How is simulation used?

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

e- transport is much more complex

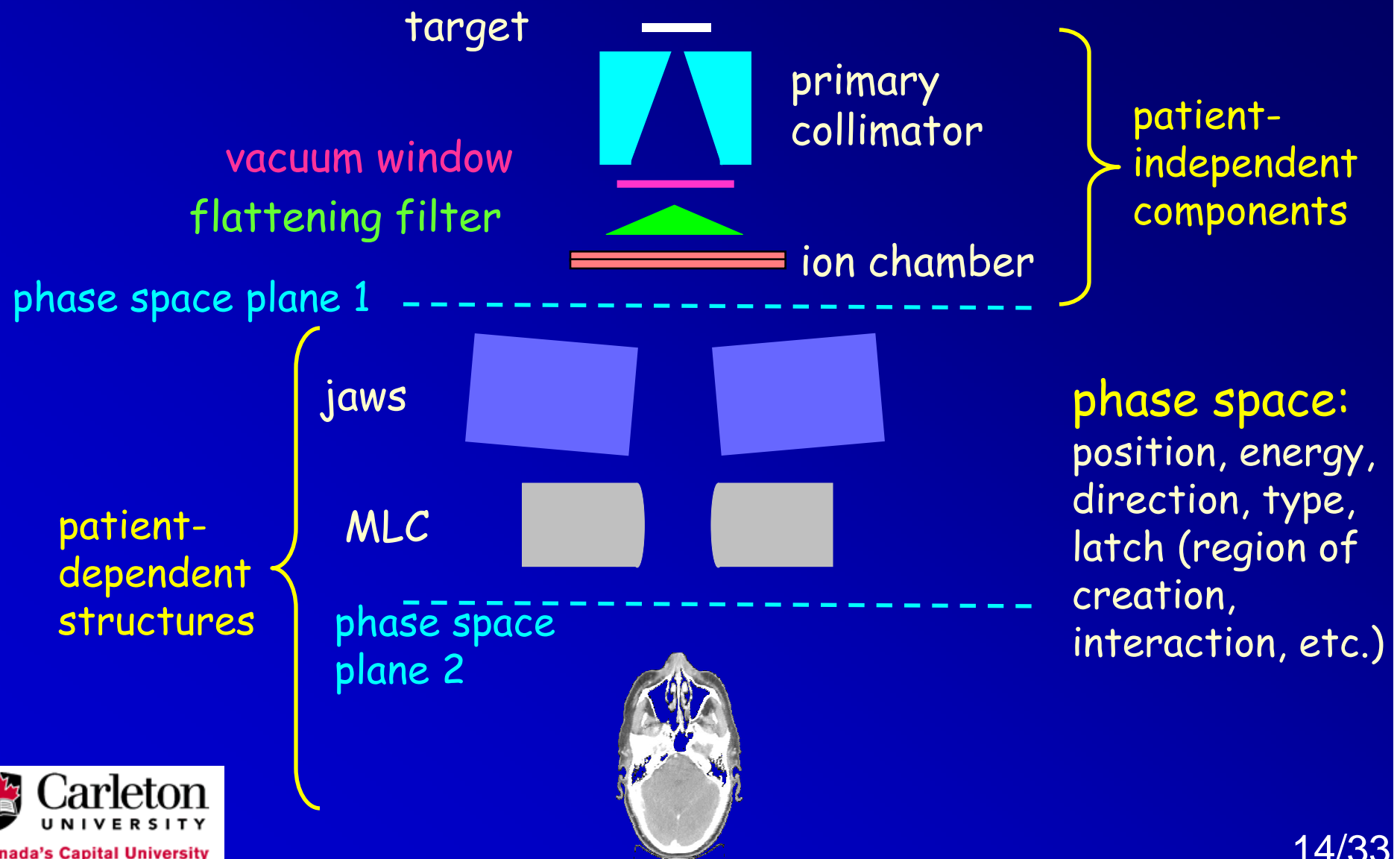
hard collisions
create
secondaries
eg δ -rays / brem

soft collisions
-grouped
-multiple scatter
-restricted
energy loss



condensed history technique: group many individual interactions into steps

Overview of the entire process



How do we get calculational efficiency?

- the **efficiency** of a calculation is given by

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

- s^2 is an estimate of the variance (σ^2) on a quantity of interest
- T is the **CPU time** for the calculation

$$s^2 \propto \frac{1}{N} \quad T \propto N \Rightarrow \epsilon \text{ is independent of } N$$

- improve the efficiency **by decreasing s^2 or T**

Condensed history technique

- as electrons slow, 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**
- this **increases efficiency by decreasing T (by a lot)**
- modern transport mechanics algorithms are very sophisticated in order to **maximize step size** while maintaining accuracy (to gain speed).

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
 - eg pathlength shrinking will improve the efficiency for dose near the surface but decrease the efficiency for dose at depth

Variance reduction techniques

- for a recent 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)
 - enhanced cross sections (brem: BCSE)

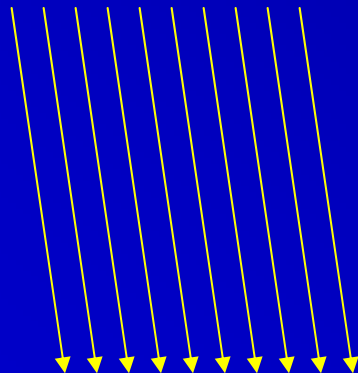
Splitting, Roulette & particle weight

$$1 w_i = 10 w_f$$

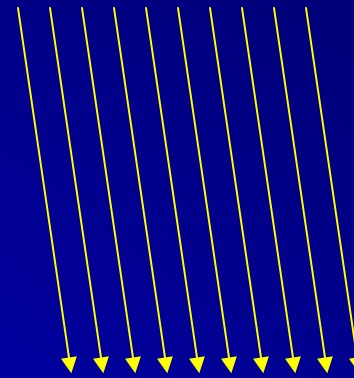


Split!

≈



$$10 w_i = 1 w_f$$



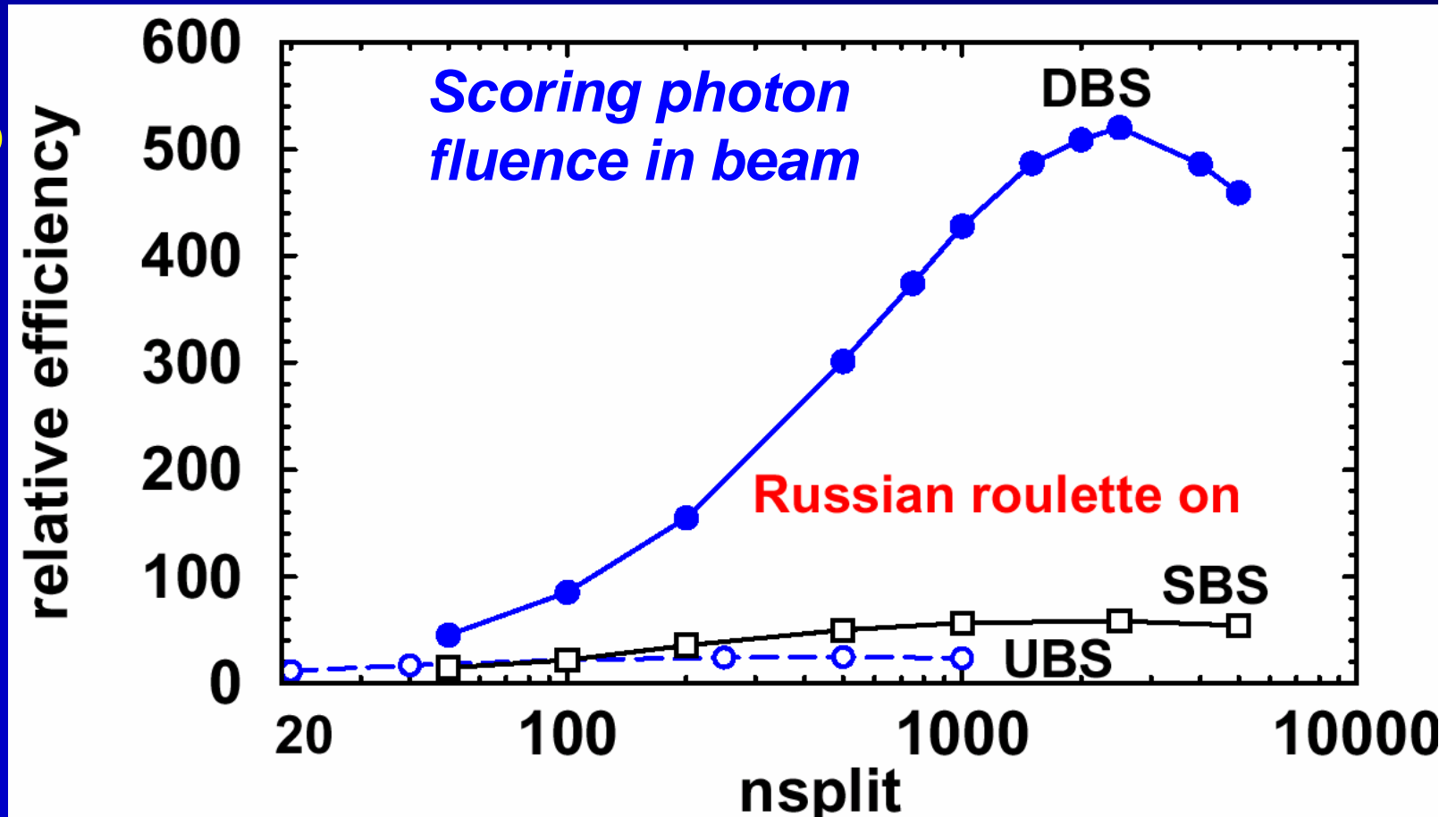
Roulette!

≈

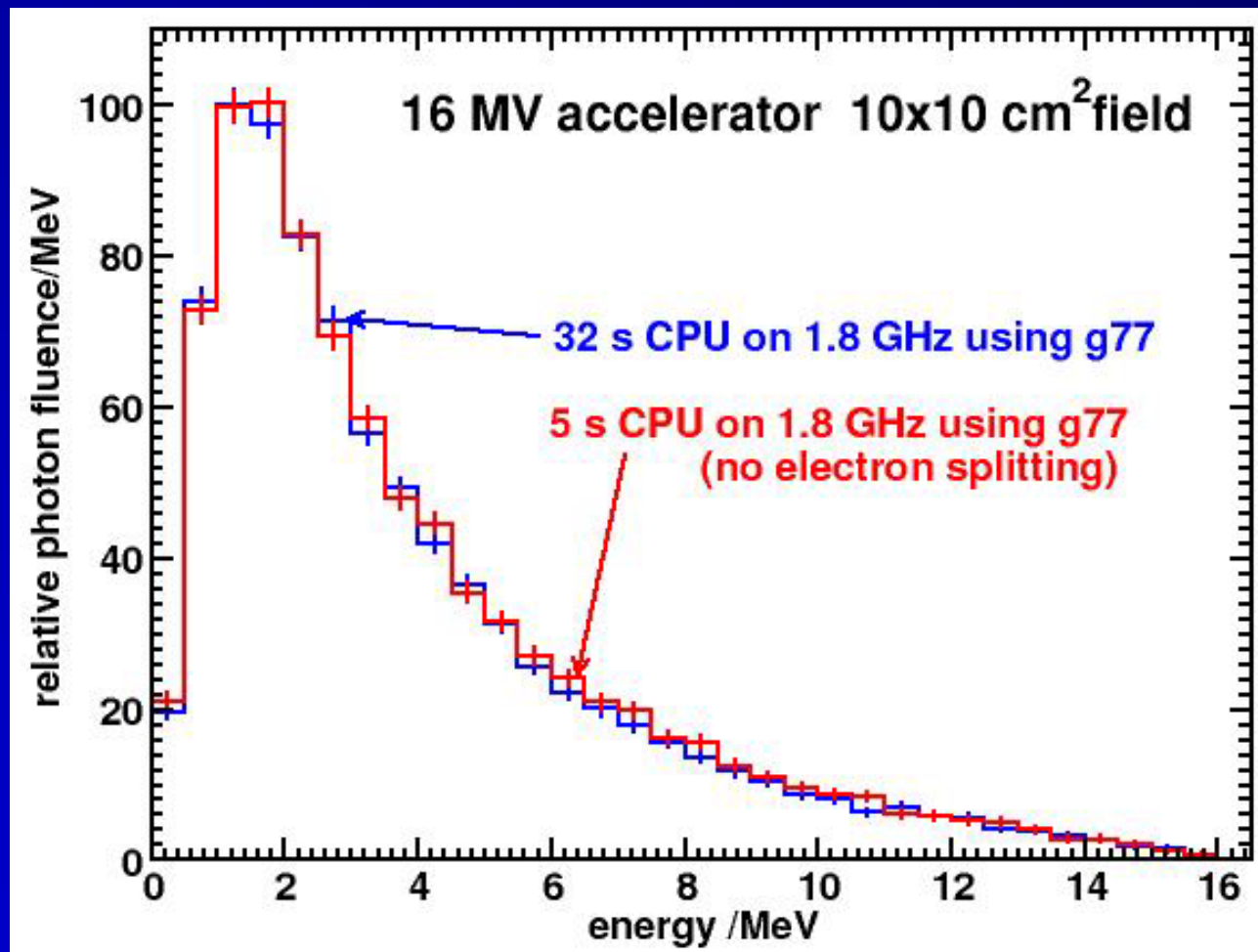


Directional Brem Splitting

trick is to
only split
when it
pays off



Tx head simulation using BEAMnrc with Directional Bremsstrahlung Splitting



Other efficiency-improving techniques

- one can improve the efficiency by decreasing T
 - usually implies an approximation being made
 - must demonstrate the approximation does not lead to significant errors
- Examples
 - range rejection: terminate an e- history if it cannot reach any boundary
 - an approximation since no brem possible
 - higher cutoff energies: terminate tracks sooner
 - an approximation since energy deposited locally
 - both are usually OK (within reason)

Monte Carlo in radiotherapy

- Monte Carlo calculations are the basis of much of clinical dosimetry for years.
 - AAPM's dosimetry protocols
 - TG-51 (and earlier TG-21) external beam dosimetry
 - TG-43 brachytherapy dosimetry
 - TG-61 x-ray dosimetry

Monte Carlo transport: major general purpose codes

- Berger 1963/ **ETRAN**/ CYLTRAN/ ITS/ MCNP
- EGS3 1978/ **EGS4**/ PRESTA/ **EGSnrc**
- **MCPT** (photon only – brachytherapy)
- **PENELOPE** 1995
- GEANT3/GEANT4
- **BEAMnrc** for modelling accelerators

Commercial codes available/under development

- **PEREGRINE** (North American Scientific/NOMOS)
 - developed by Livermore National Lab
 - **photon beams only**
 - modified EGS4 electron transport
 - beam modelling based on source models and BEAM code simulations of accelerators
 - **multiple processors** for speed

Commercial codes available/under development (cont)

- VMC/XVMC/VMC++
 - developed by Kawrakow and Fippel
 - new code, multiple variance reduction techniques
 - various approaches to accelerator beam models
 - VMC++ commercially available for electrons (Nucletron)
 - VMC++ or XVMC for photon beams is in pipeline with
 - Varian
 - BrainLab
 - CMS
 - Elekta
 - Nucletron

Commercial codes available/under development (cont)

- MMC - Macro Monte Carlo
 - developed by Neuenschwander et al
 - uses pre-calculated distributions and runs a MC simulation based on the "kugels".
 - commercialized by Varian

Summary of ICCR timing/accuracy benchmarks

Timing: 6 MV 10x10 cm², 5 mm³ voxels, 2% uncertainty > $D_{\max}/2$

Accuracy: 18 MV, 1.5x1.5 cm², 5x5x2 mm³ voxels

Monte Carlo code	Time estimate (minutes)	% mean difference relative to ESG4/PRESTA/DOSXYZ
ESG4/PRESTA/DOSXYZ	43	0, benchmark calculation
VMC++	0.9	± 1
XVMC	6.6	± 1
MCDOSE (modified ESG4/PRESTA)	1.6	± 1
MCV (modified ESG4/PRESTA)	22	± 1
DPM (modified DPM)	7.3**	$\pm 1^*$
MCNPX	60***	max. diff. of 8% at Al/lung interface** (on average $\pm 1\%$ agreement)
PEREGRINE	43****	$\pm 1^{***}$
GEANT 4 (4.6.1)	193*****	± 1 for homogeneous water and water/air interfaces****

Summary of ICCR timing/accuracy benchmarks(footnotes from Table 1 slide)

* Results not originally part of the ICCR benchmark study, from Ref. No. 76.

** Results not originally part of the ICCR benchmark study, reported independently by author IJC for the modified version of DPM developed for clinical planning calculations.

*** Timing results not originally part of the ICCR benchmark study, reported independently by author JJD. Calculations were performed using the *F8 (energy deposition) tally. Dose was calculated by dividing the energy deposited by the mass of the scoring voxel.

**** Timing and accuracy results not originally part of the ICCR benchmark study, reported independently by author DS-B.

***** Timing and accuracy results not originally part of the ICCR benchmark study. Estimated independently by author JS based on Poon and Verhaegen⁹⁴ and ICCR type speed-test dose calculations (by E. Poon and F. Verhaegen, private communication). Timing results are for the standard physics model; the low-energy and the *PENELOPE* model lead to a factor of 2 more CPU time. The accuracy result reported is derived from the interface perturbation studies in Poon and Verhaegen⁹⁴, applies to 1.25 MeV monoenergetic photon beams and represents the difference with EGSnrc using PRESTA-II electron step algorithm and “exact” boundary crossing. For a water/Pb interface and 1.25 MeV photons, the maximum difference with EGSnrc increases to 6%⁹⁴.

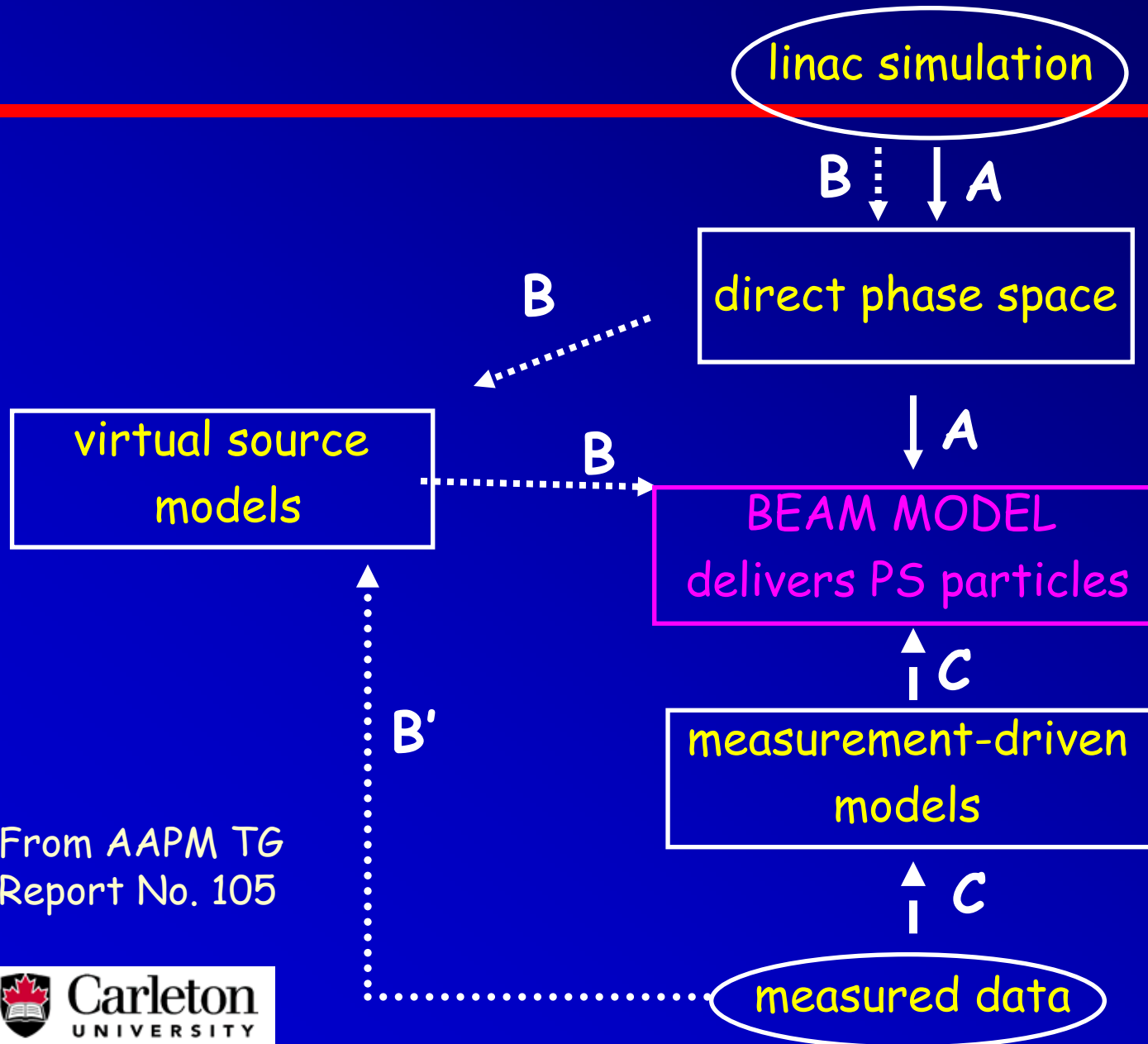
Beam models

- a **beam model**, in this context, is any algorithm that delivers the **location, direction and energy** of particles to the patient dose-calculating algorithm.
- one type of beam model is a **direct MC simulation** of the accelerator head, but we refer to it as a **beam simulation** for clarity
- beam simulations can be done accurately if all the parameters are known - **but they often are not**

A summary of the findings of Sheikh-Bagheri and Rogers reproduced from Verhaegen and Seuntjens

Linac Characteristic	Effect on off-axis factors	Effect on depth dose
Primary electron energy	Linear decrease with primary electron energy: $-0.105/\text{MeV}$ for a 6 MV Siemens beam. 0.2 MeV change has an observable effect	0.2 MeV change effects an observable effect
Gaussian width of electron energy distribution	No effect of Gaussian widening (0-20%) observed for a 6 MV beam. Asymmetrical energy distribution has small effect	Weak dependence on Gaussian energy spread at large depths. Asymmetrical energy dist'n affects dose in build-up region: up to 1.5% for 18 MV Siemens beam
Radial intensity distribution of electron beam	Quadratic decrease with radial spread: 6% for 0.15 cm FWHM increase for an 18 MV Varian beam	No effect
Divergence of the electron beam	Slight effect when changing beam divergence from 0-1° for 18 MV photon beam	No effect changing beam divergence from 0-5° for 18 MV photon beam
Upstream opening of primary collimator	Sensitive to a 0.01 cm change in lateral opening	No effect
Material / density of flattening filter	Large effect: 1 g cm ⁻³ change of tungsten density causes 6% change in off-axis ratio for 15 MV	Not reported

possible ways to specify a beam model -new



From AAPM TG
Report No. 105

Thank you

Now over to Indrin Chetty for the second part