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

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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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Report of the AAPM Task Group No. 105: Issues associated with clinical implementation of Monte Carlo-based photon and electron external beam treatment planning

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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.

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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.

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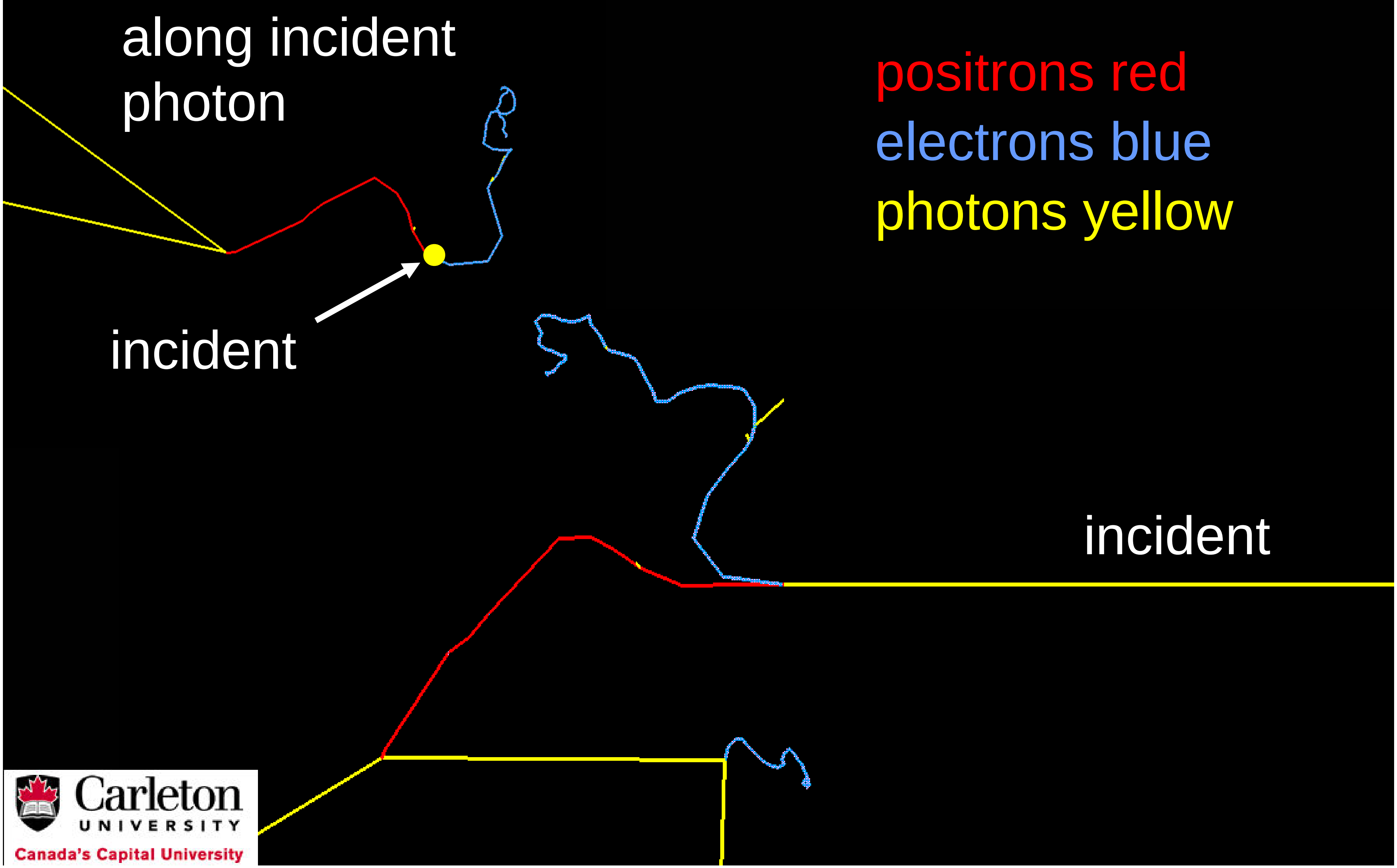
*TG105 quotes Rogers&Bielajew, 1990, in Dosimetry of Ionizing Radiation V3 http://www.physics.carleton.ca/~drogers/pubs/papers/RB90.pdf

10 MeV photon on lead



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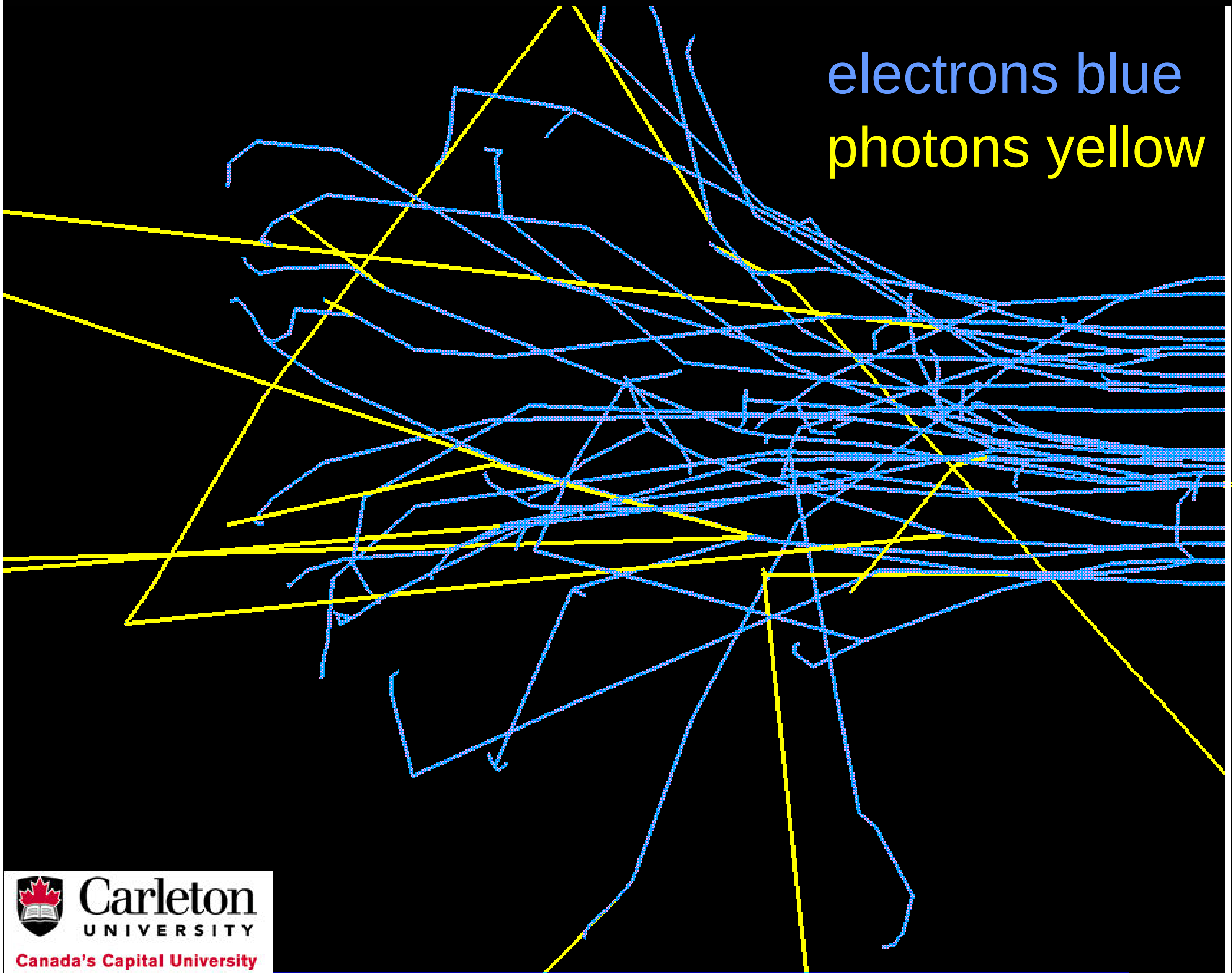
10 MeV electrons on water from right



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Simple photon simulation

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

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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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

Condensed history technique for e- transport

- 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
- 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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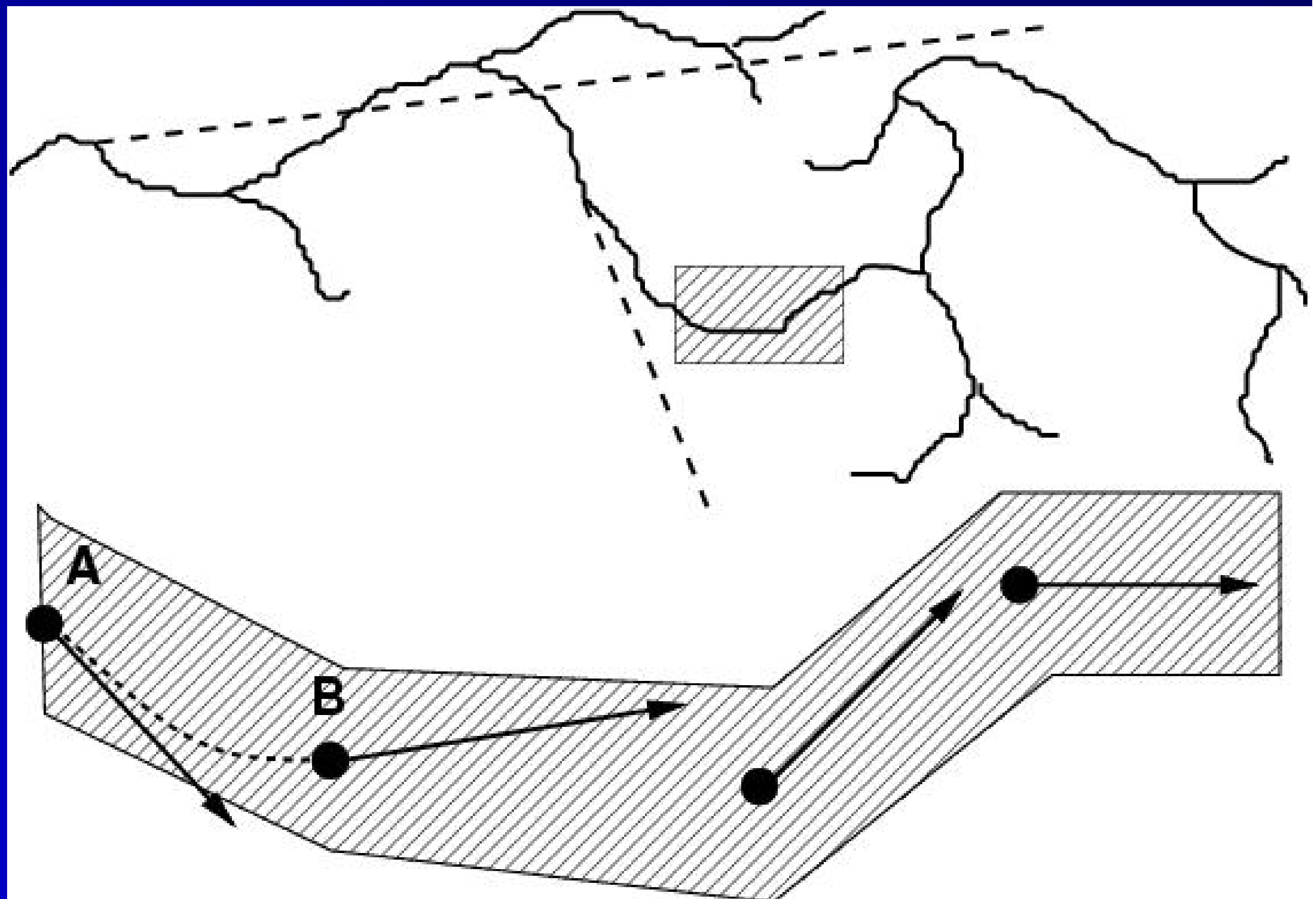
e- transport is much more complex

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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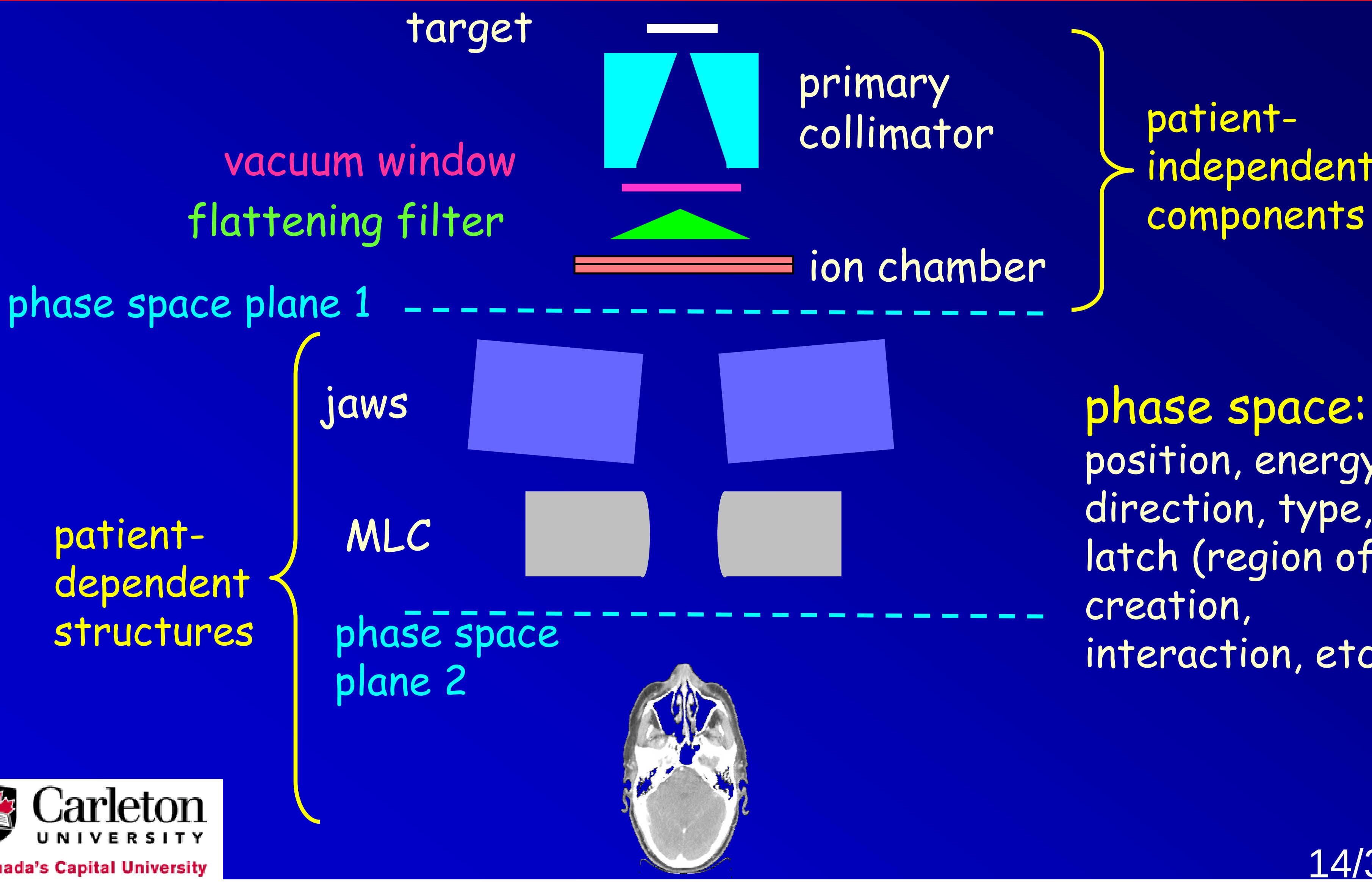
Overview of the entire process



phase space:
position, energy, direction, type, latch (region of creation, interaction, etc.)

How do we get calculational efficiency?

- the efficiency of a calculation is given by $\epsilon = \dfrac{1}{s^2 T}$
  - s^2 is an estimate of the variance (σ^2) on a quantity of interest (Indrin to discuss s^2)
  - 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

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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
    - eg pathlength 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 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)

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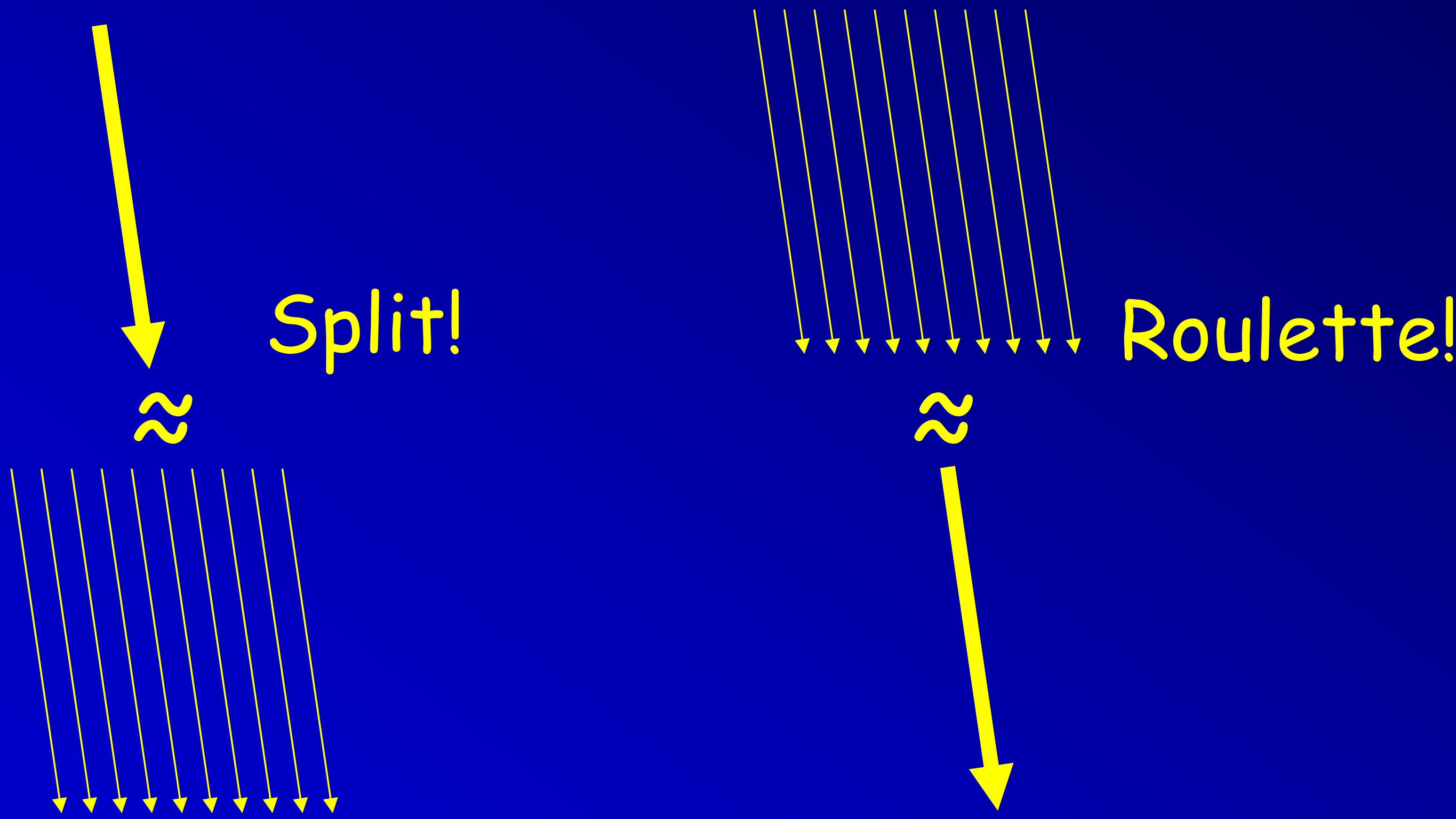
Splitting, Roulette & particle weight

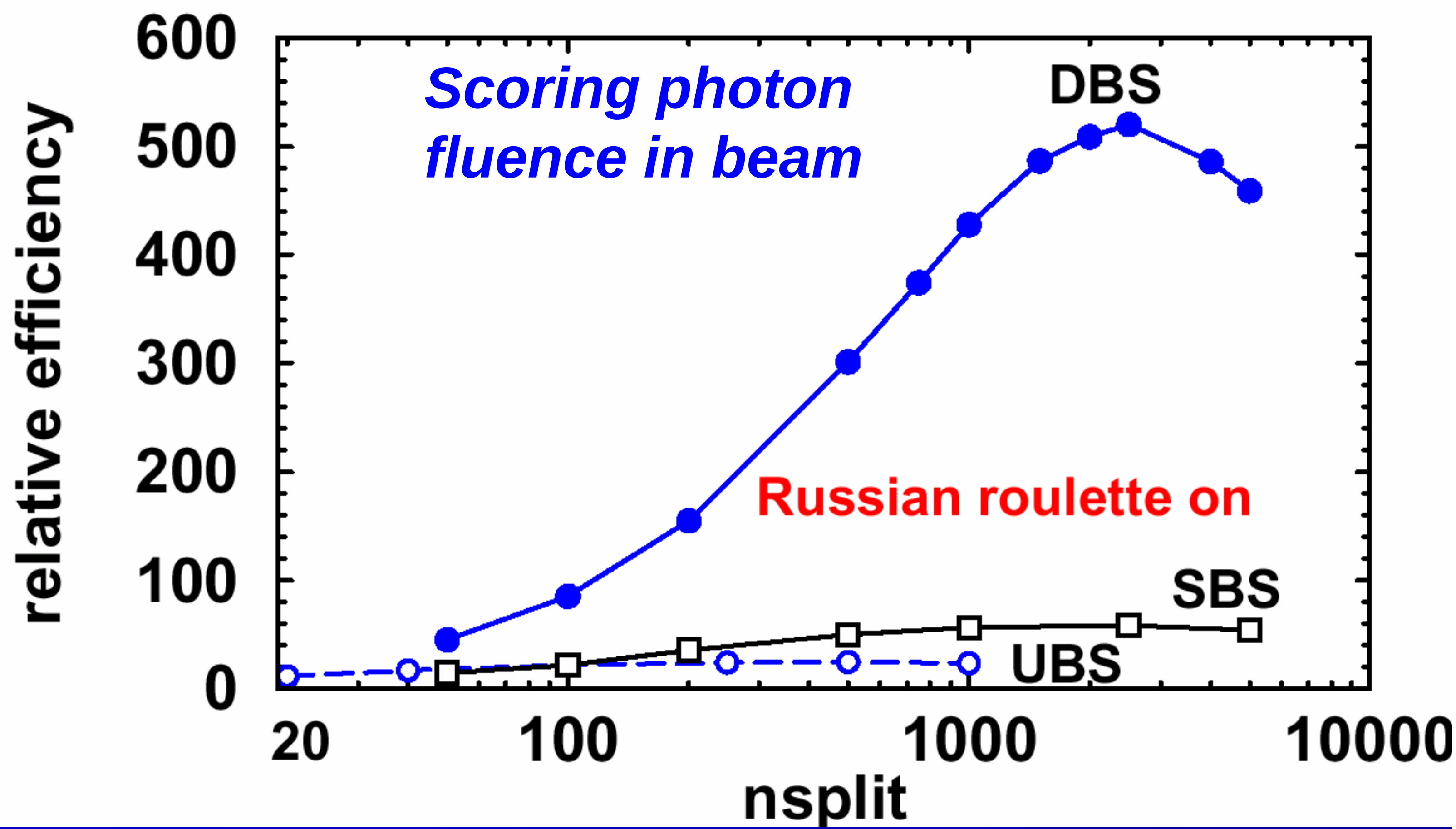
$1\ w_i = 10\ w_f$ $\qquad$ $10\ w_i = 1\ w_f$



from Sheikh-Bagheri's 2006 summer school lecture

Directional Brem Splitting

trick is to only split when it pays off



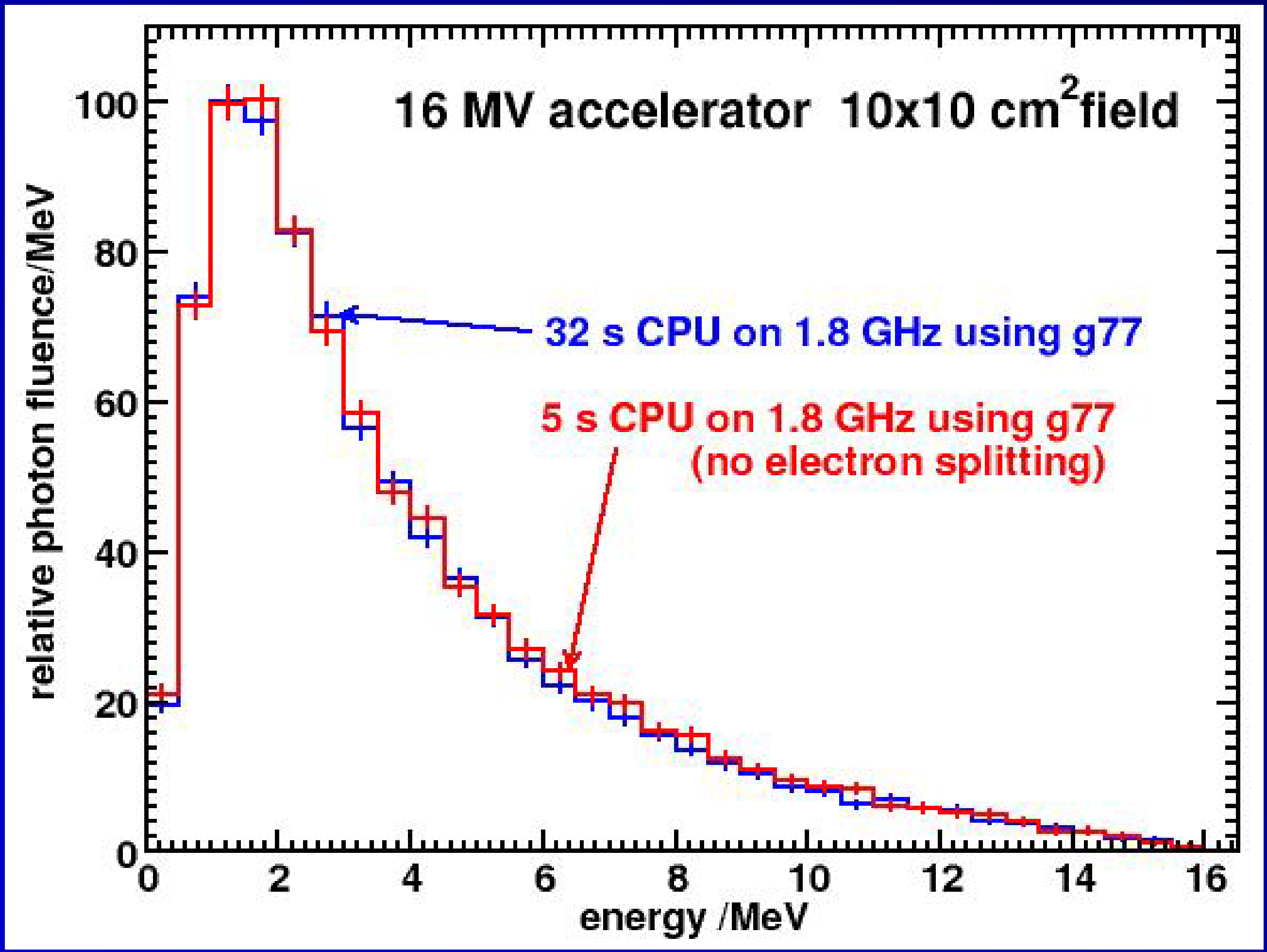
Kawrakow et al Med Phys 31 (2004) 2883

Tx head simulation using BEAMnrc with Directional Bremsstrahlung Splitting

Todays commodity PCs are 5 times faster

& BCSE => 2.6 times faster

Ali Med Phys 34(2007)2143



from Sheikh-Bagheri et al. Efficiency Improvement Techniques and Statistical Considerations AAPM Summer School 2006

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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)

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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

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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

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Commercial codes available/under development (cont)

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

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Summary of ICCR timing/accuracy benchmarks

Timing: 6 MV 10x10 cm^2, 5 mm^3 voxels, 2% uncertainty > $D_{max}/2$

Accuracy: 18 MV, 1.5x1.5 cm^2, 5x5x2 mm^3 voxels(H_2O,Al,lung slabs)

Monte Carlo code	Time estimate (min) P IV 3GHz	% mean difference relative to ESG4/PRESTA/DOSXYZ
ESG4/PRESTA/DOSXYZ	43	0, benchmark calculation
VMC++	0.9	±1
XVMC	1.1[a]	±1
MCDOSE (modified ESG4/PRESTA)	1.6	±1
MCV (modified ESG4/PRESTA)	22	±1
DPM (modified DPM)	7.3[b]	±1
MCNPX	60[c]	Maximum difference of 8% at Al/lung interface (on average ±1% agreement)
PEREGRINE	43[d]	±1
GEANT4 (4.6.1)	193[e]	±1 for homogeneous water and water/air interfaces

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[abcde] footnotes are longer than table in TG105!

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

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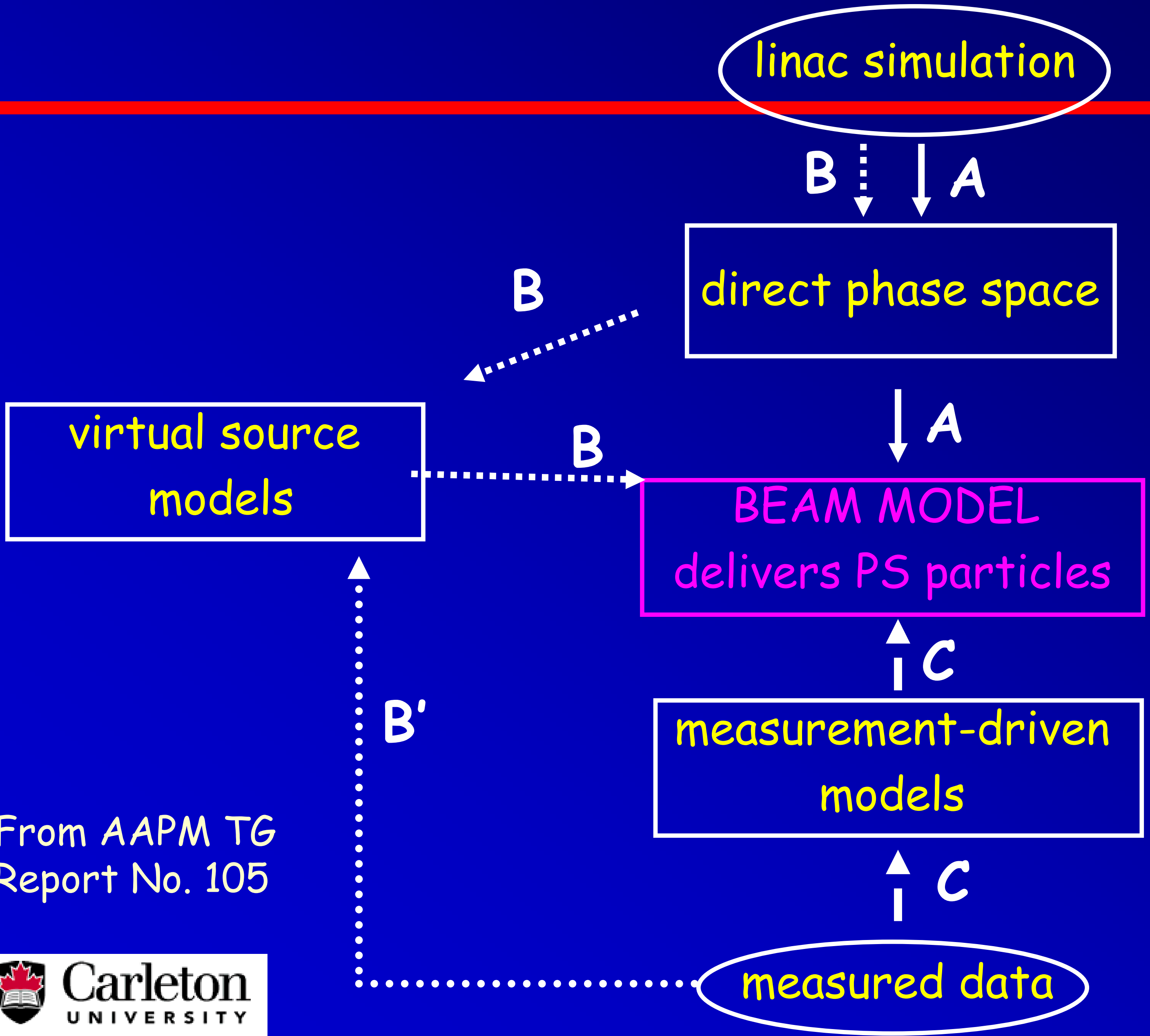
possible ways to specify a beam model -new



From AAPM TG Report No. 105

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Thank you

Now over to Indrin Chetty for the second part

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