Creative Simulation:

A Flexible Hands-on Approach to Building a Deeper Understanding of Critical Concepts in Radiation Physics

Shahid A. Naqvi, Ph.D.

Saint Agnes Cancer Institute

Baltimore, MD

SAINT AGNES

CONFLICT OF INTEREST

None

Evolution of Teaching method

Teaching method evolved over time with the experience of teaching and one to one interaction with

- Radiation oncology residents
- Dosimetry school students
- Postdocs from secondary fields
- Starting medical physicists

at University of Maryland, Baltimore from 2001-2010

Students attitudes to learning Radiation Physics

- The teaching experience was also a learning experience.

- Some observations include:
  - Students showed a desire to understand the physics, and not just pass exams or be proficient in clinical calculations.

  - trouble connecting the concepts in clinical physics with the underlying basic physics.

  - would quickly get bored if we only focus on clinical problem solving without a clear mental picture of what is happening.

Basic physics   clinical physics
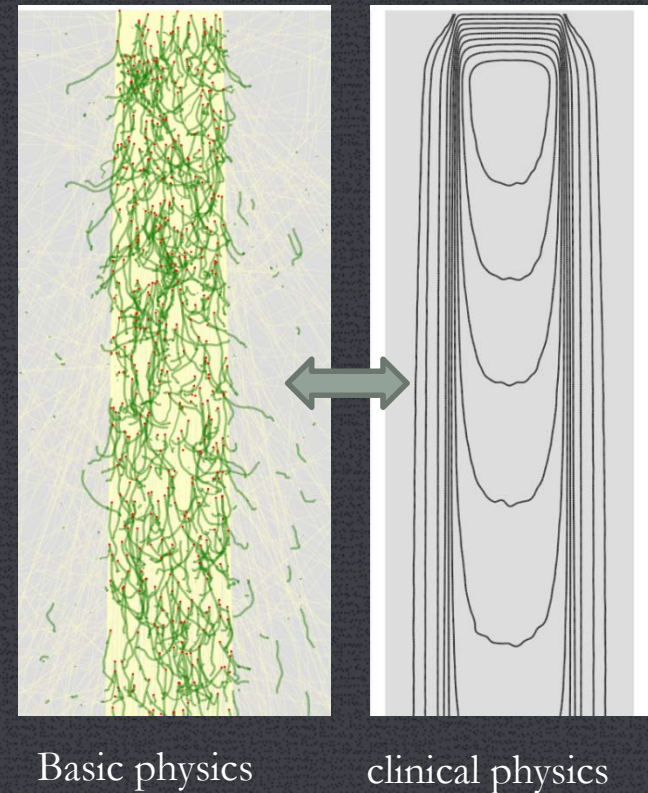
Some common misconceptions…

- "Electronic equilibrium is needed to measure dose."
- "Terma represents primary dose and kernels represent scatter dose"
- "Physical Penumbra is caused by scatter."
- Buildup in photon beams is due to
  - "the fact that photons interact after some distance" or,
  - "the fact that electrons deposit energy after some distance," or,
  - "the fact that the highest energy electrons are released at the surface."
  - "Scatter"

Practically all the misunderstandings are caused by
- not appreciating the role of secondary electrons in dose deposition
- indiscriminate use of the word "Scatter!"

Monte Carlo as a teaching tool…

- To facilitate explicit visualization of radiation physics, and
- To enable students to make explicit connections with clinical physics.
- A Monte Carlo code ("Athena") is developed with medical physics education in mind.

Relating attenuation & photon interactions

- Photons can interact at random depth with the probabilty of surviving a journey of length x through the forest of atoms given by $e^{-\mu x}$

- Each interaction removes a primary photon, which reduces the photon intensity downstream (attenuation) : $\dfrac{\varphi}{\varphi_0} = e^{-\mu x}$

- The diagram allows the students to "see" that interactions & beam attenuation are flip sides of the same coin.

x
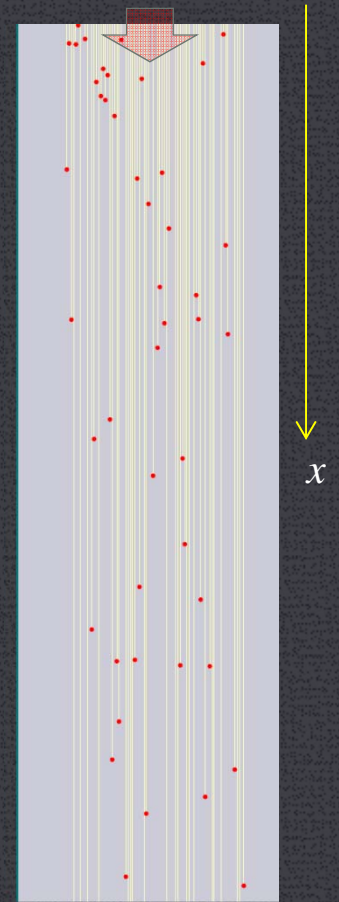
Emphasizing the electrons!

- All dose is due to ionization and excitation produced by secondary electrons released by photons (indirectly ionizing).

- Electrons can travel a few cm from their release site.

- Follow electrons to understand dose!

Primary interaction points and secondary electrons
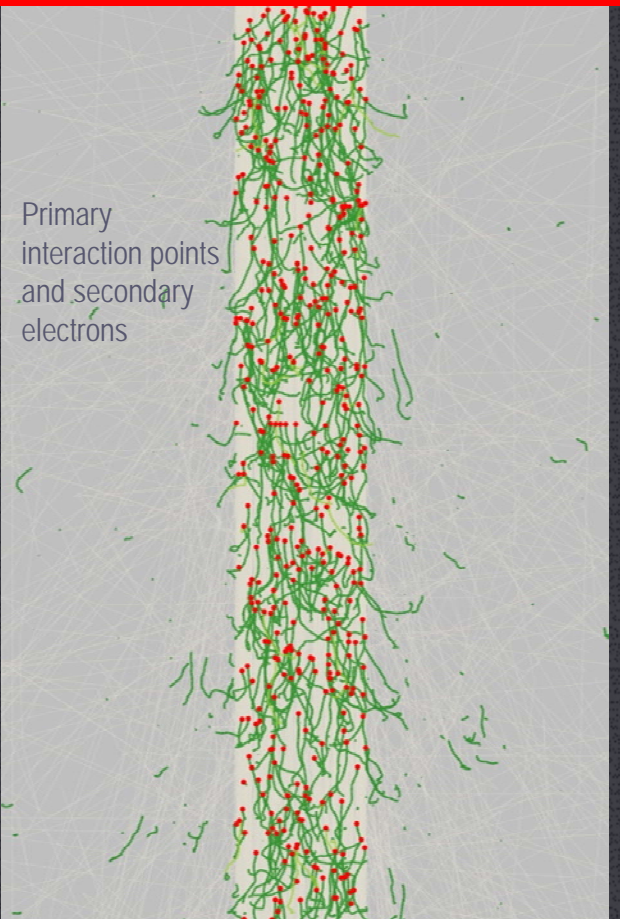
Interaction density, fluence & Primary Kerma, K_p

- Interaction density follows the fluence
- fewer photons available downstream produce fewer interactions.

- "Primary kerma" in box A counts energy imparted to electrons in primary photon interactions in A:
  - regardless of where the electrons go.
  - does not depend on electron transport.

- Exponential fall off in primary:
  - fluence,
  - kerma,
  - interaction density.

Primary Interaction points

K_p

A

A
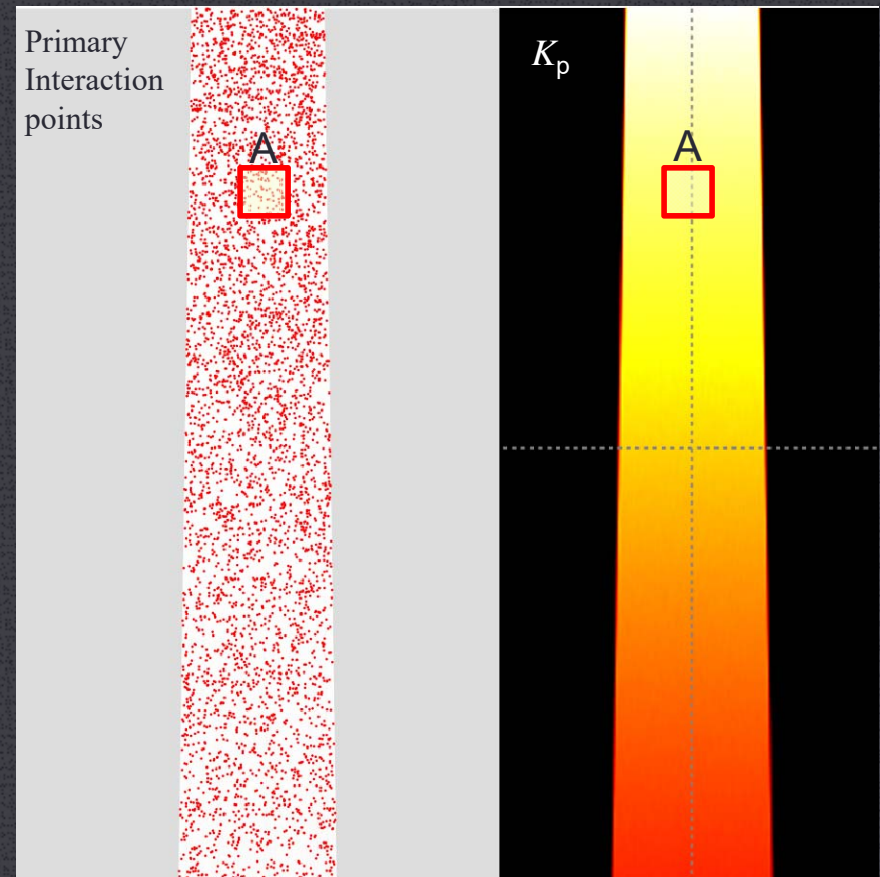
Primary dose, D_{p}

- Dose in "box A" counts energy deposited by electrons in A regardless of where they originate.

- Primary dose deposited electrons released in first photon interactions.

- (D_{p} does not count interactions of scatter photons).

(Label the order of the interaction in the MC code and display only 1st order interactions).
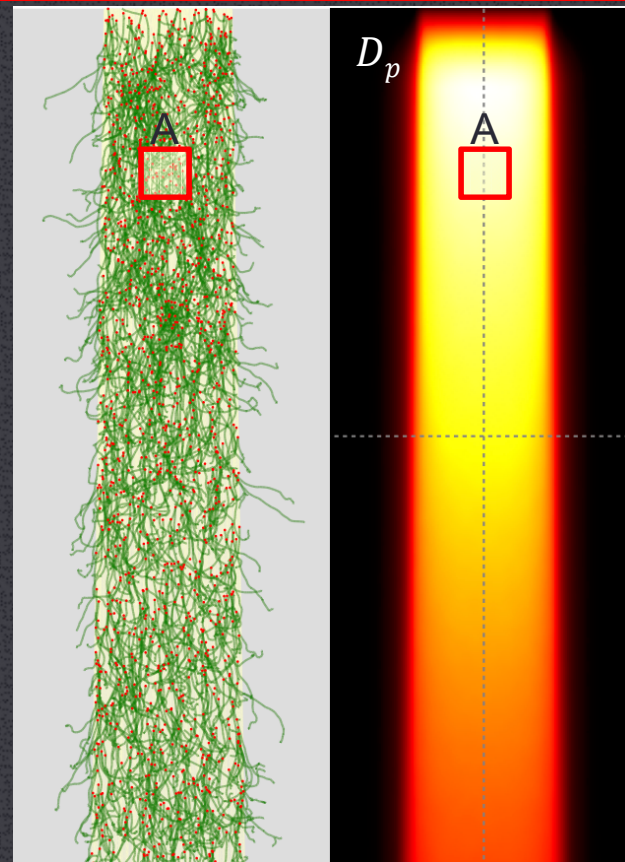
Scatter dose

- "Scatter" dose is due to electrons released in second or higher order photon interactions. The scatter photons originate from:
  - compton scatter,
  - Bremstrahlung of e-, e+,
  - annihilation of e+.

- e⁻ tracks are detached from the primary interaction sites.

- Scatter photons can carry energy far away from beam edge.

- But are not the reason for the physical penumbra
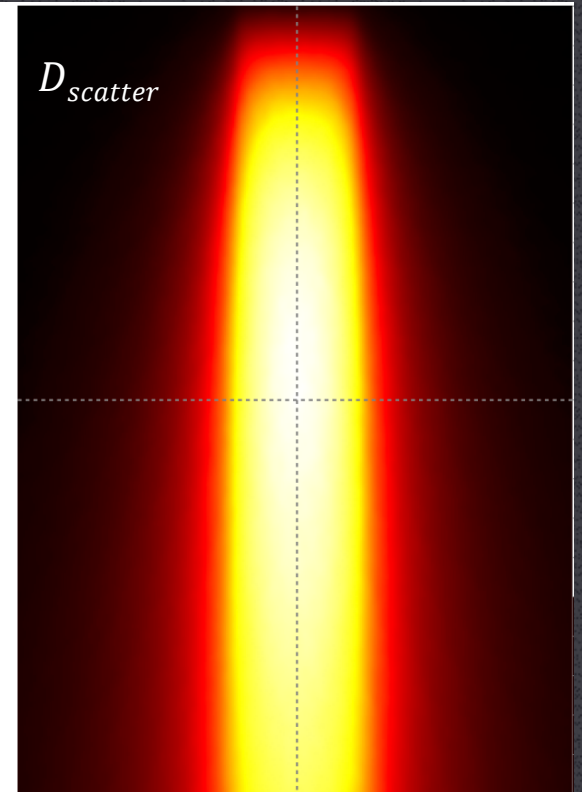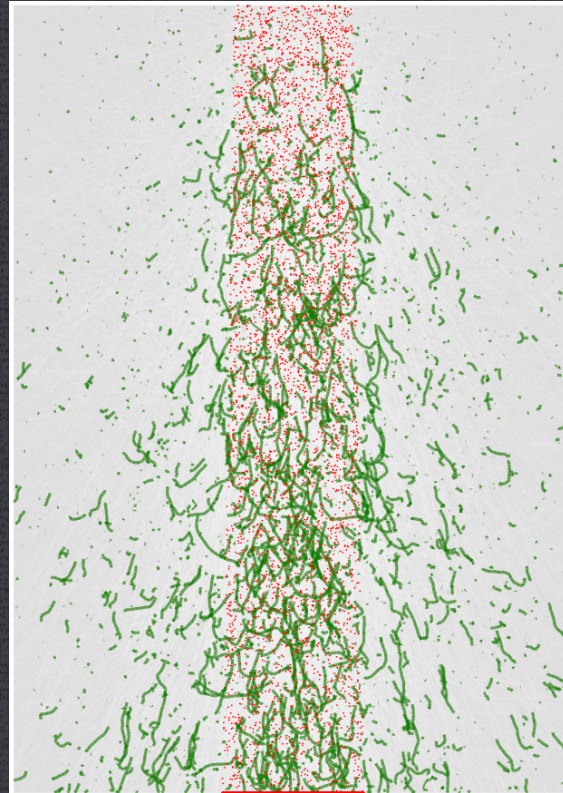
$D_{scatter}$

# Profile comparisons: $K_\mathrm{p}, D_\mathrm{p}, D_\mathrm{s}$

- Primary kerma is sharp for a perfect point source.

- Primary dose has physical penumbra due to lateral spread of electrons.

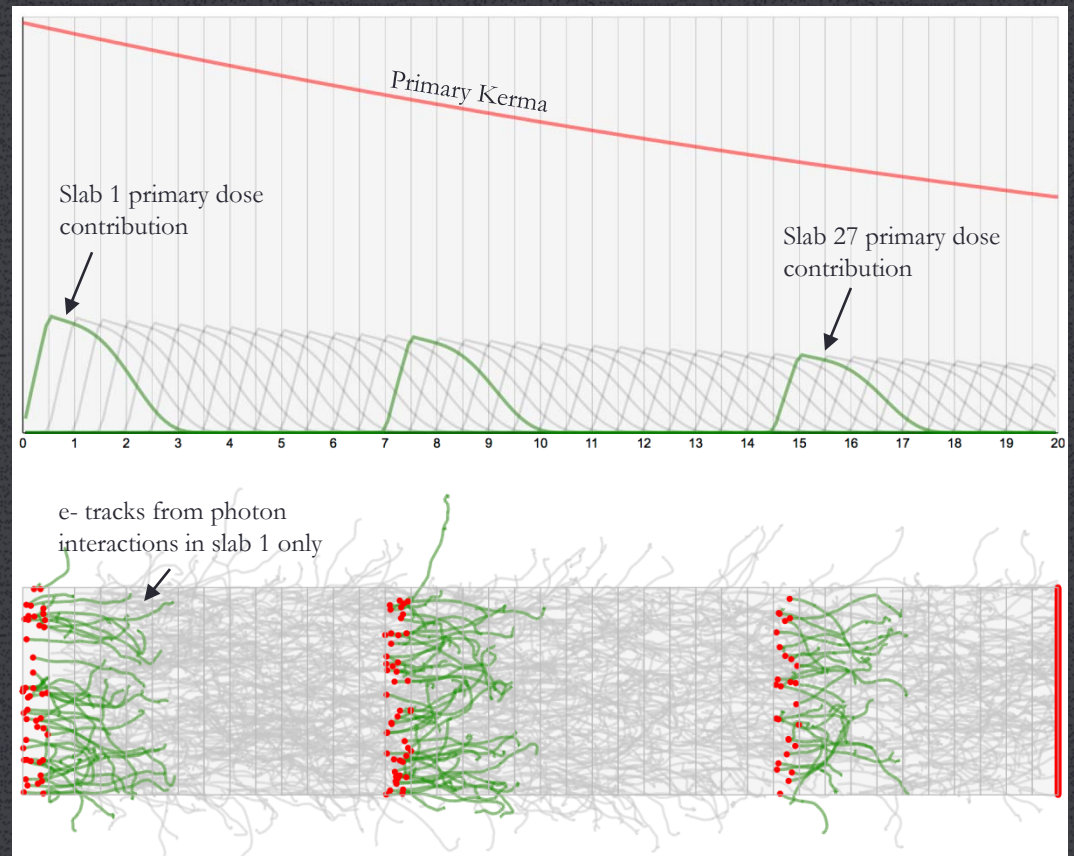- Scatter dose is diffuse as scatter photons can interact outside the beam edge.

K_primary
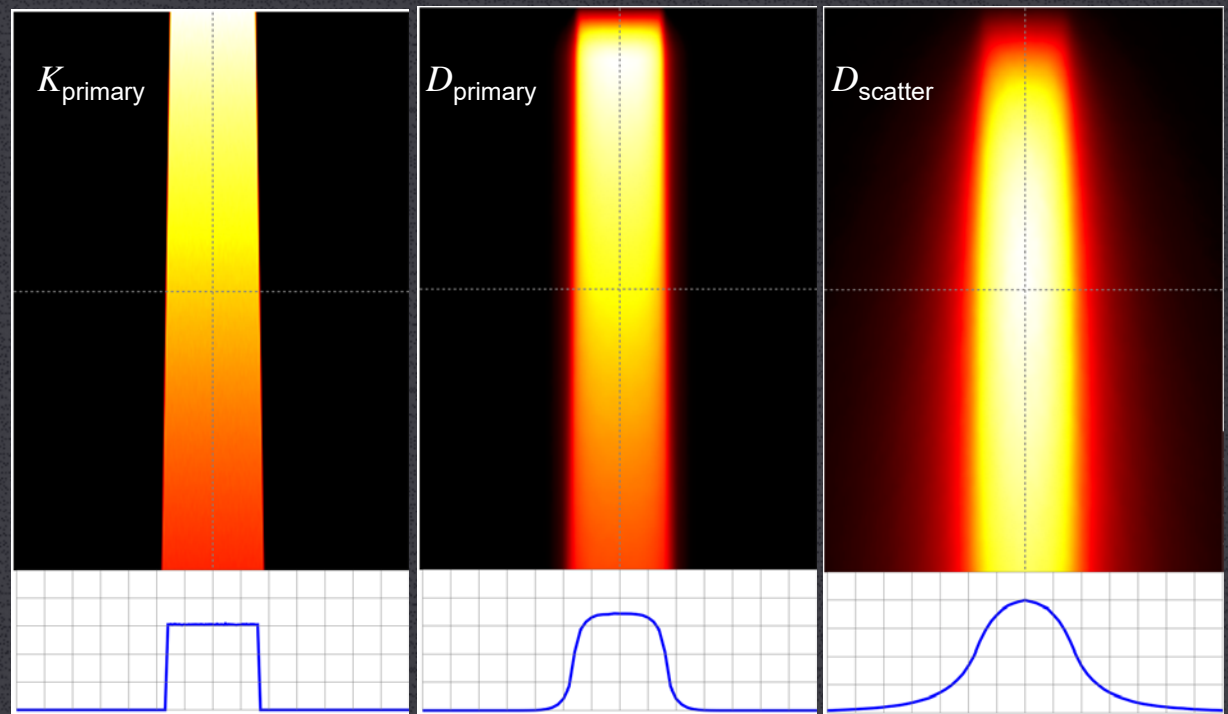
D_primary

D_scatter

(profiles are normalized individually)

Physical penumbra vs. scatter tails

- Physical penumbra is present in the primary dose profile.

- Tails of the profile are made of scatter dose.
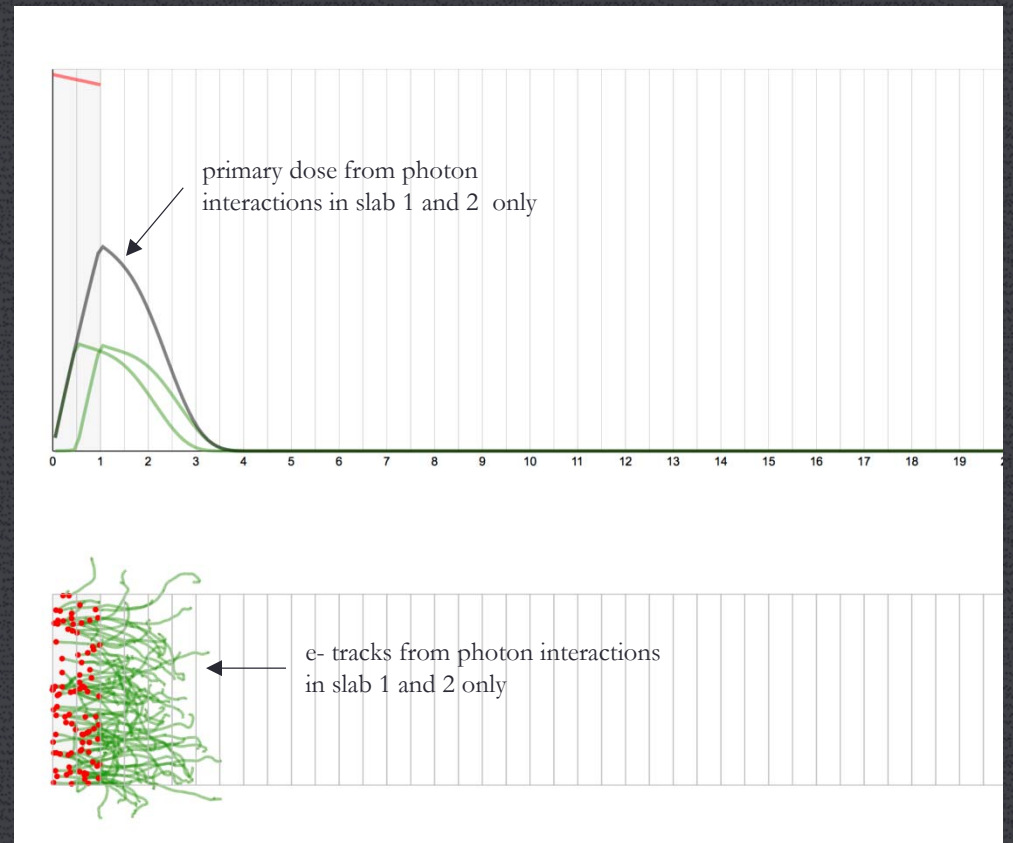
- Scatter does not affect physical penumbra much
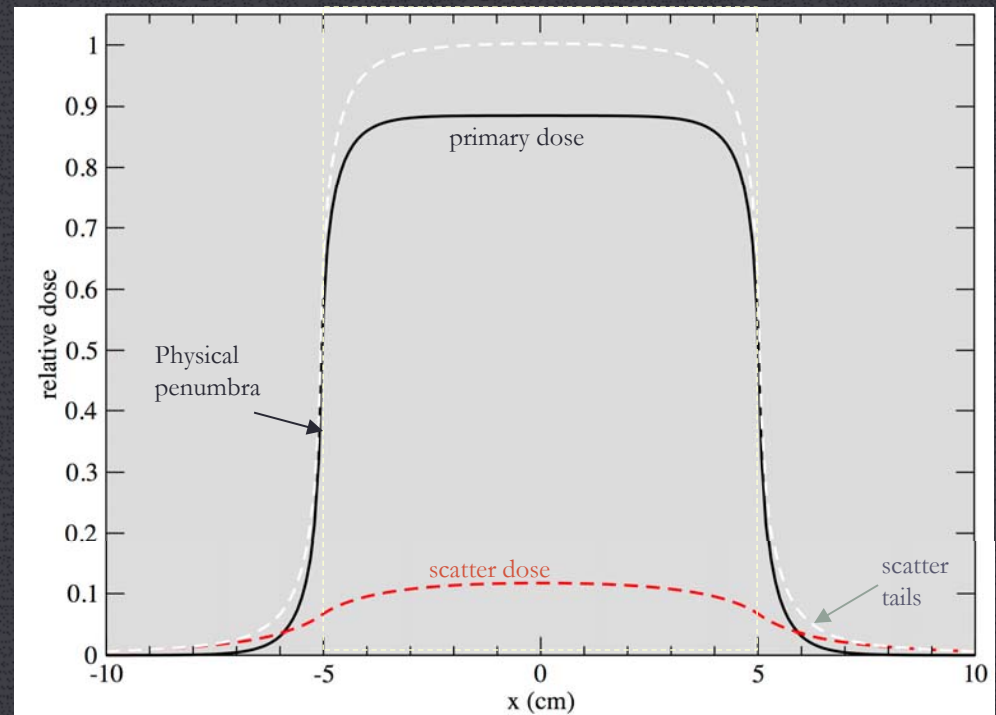
Understanding photon buildup (regional analysis)

- Divide phantom into imaginary slabs.

- Find contribution of each slab.

- Note the shape of the dose distribution does not change

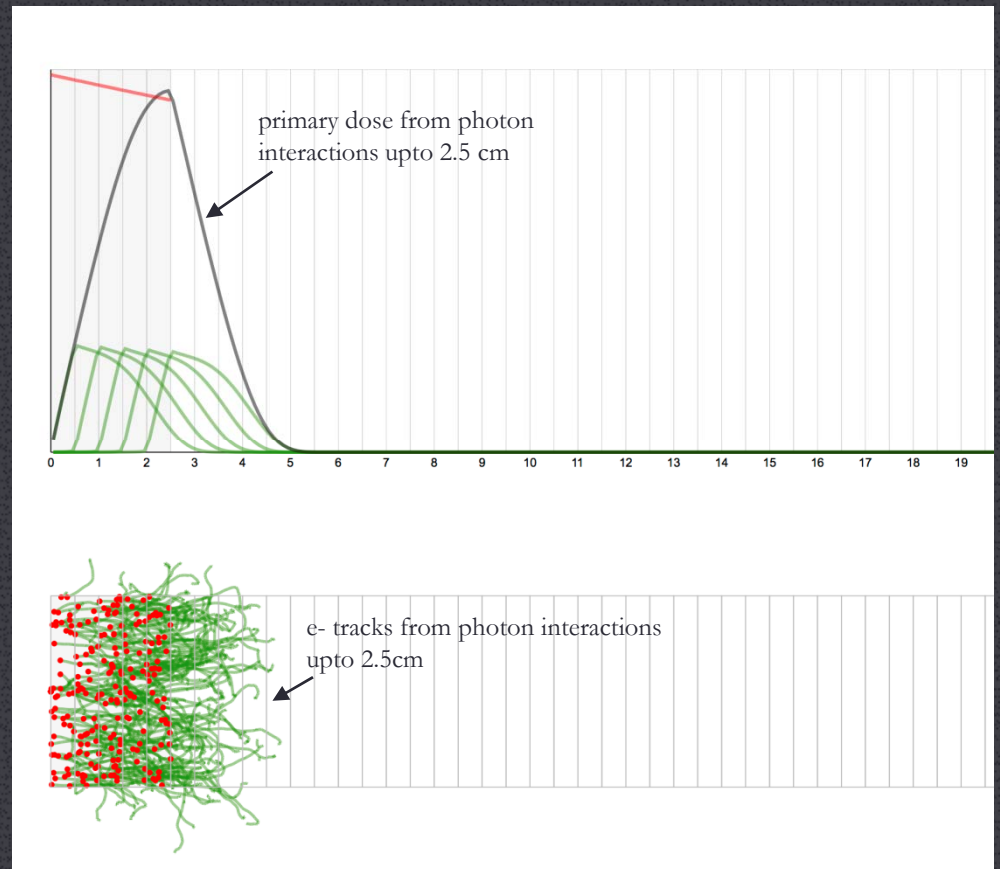- Height changes due to exponential attenuation of fluence (and kerma)

Primary Kerma

Slab 1 primary dose contribution

Slab 27 primary dose contribution

e- tracks from photon interactions in slab 1 only

Understanding Buildup: Two slabs…

- 2nd slab receives upstream contribution from 1st slab.

- Keep adding slabs until we are beyond the range of the 1st slab electrons

primary dose from photon interactions in slab 1 and 2 only

e- tracks from photon interactions in slab 1 and 2 only

Understanding Buildup: Five slabs…

- 5th slab receives little contribution from 1ˢᵗ slab.

- "Saturation" is reached.

- Electrons "lost" out of slab5 are essentially replaced by electrons from points upstream, (electronic equilibrium) and

- Kerma and Dose are nearly equal.

primary dose from photon interactions upto 2.5 cm

e- tracks from photon interactions upto 2.5cm

Understanding buildup…

In Summary:

- Dose at each point depends on electrons released in slabs upstream.

- Surface slab has no upstream contribution, hence lowest dose.

- Maximum track overlap is reached around d_{max}, which is one forward e-range away from the surface (~3cm)

- Upstream contribution beyond d_{max} stays constant except for decreasing strength due to attenuation.

Primary Kerma

Total primary dose

Slab dose component

PDD: primary and scatter components

- Buildup is mainly in primary dose

- Scatter has little influence on buildup.

18MV beam

Total dose

Primary dose

Scatter dose
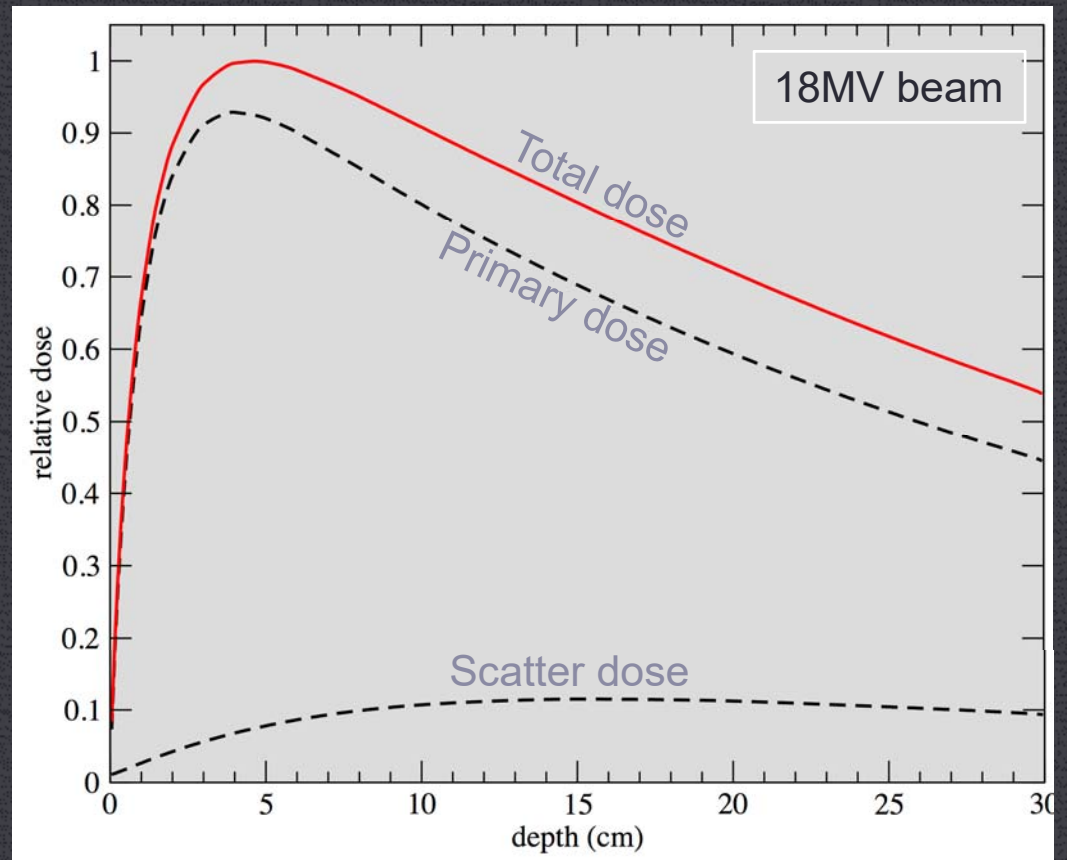
Lateral buildup and lateral equilibrium

Primary dose **water**

Primary dose **lung**
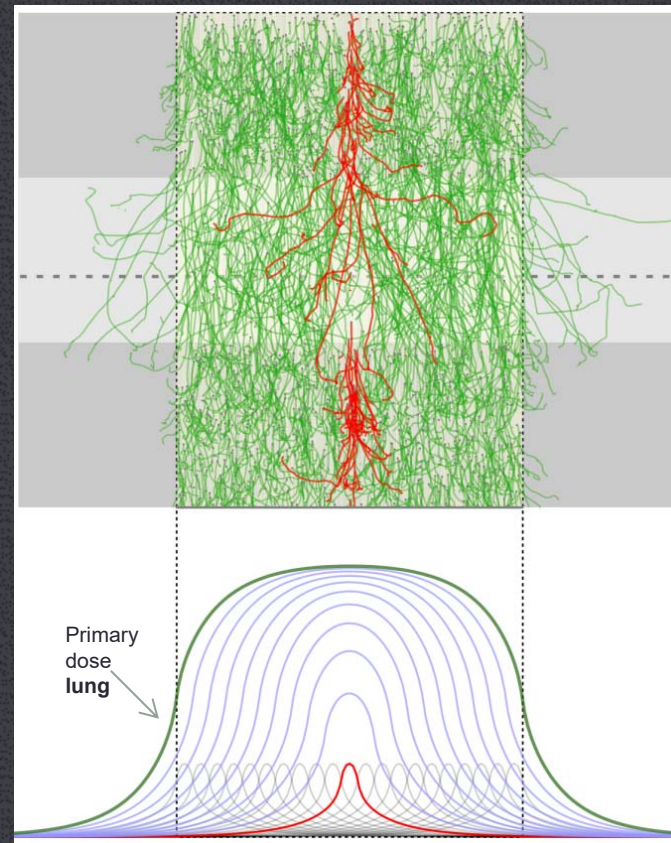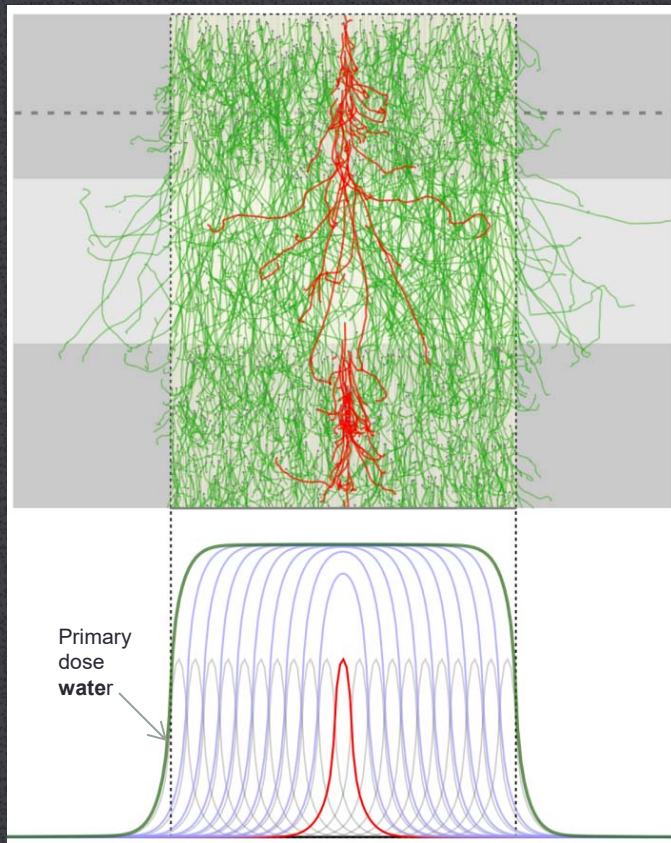
Studying interface effects

- Students find it hard to understand why there are build-up and build-down effects.

- Overlaying the isodose lines on the electron tracks show how the increased e- spread in the low density region results in lateral disequilbrium.
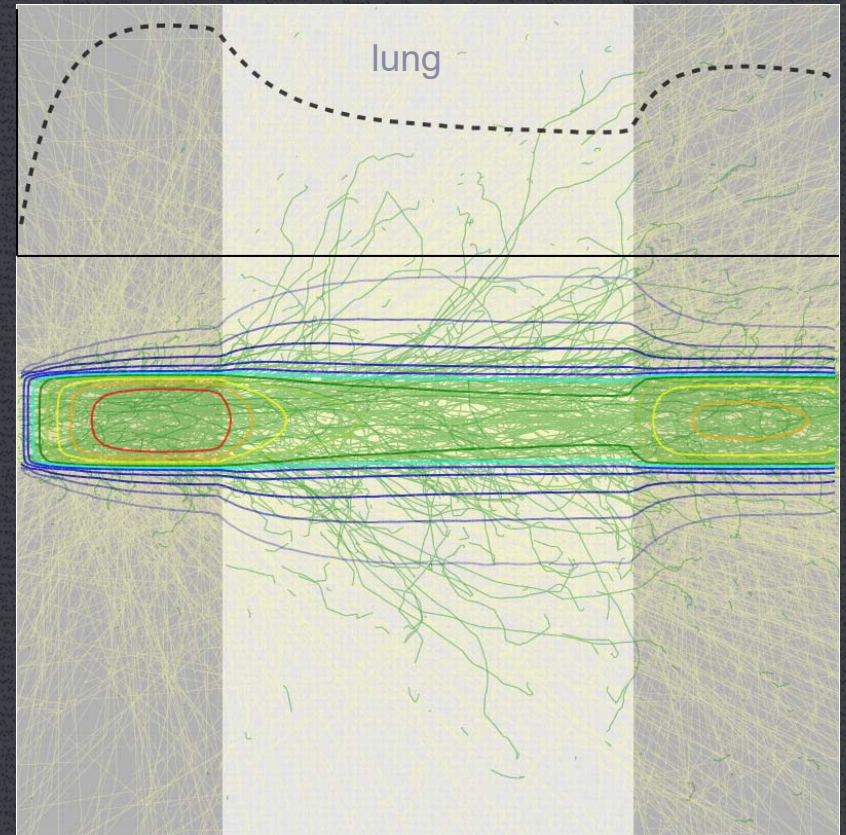
Interface effects: (regional analysis)

- Buildup due to interactions in lung never reach the level of water since
  - Electrons lost outward are not compensated by electrons moving inward.
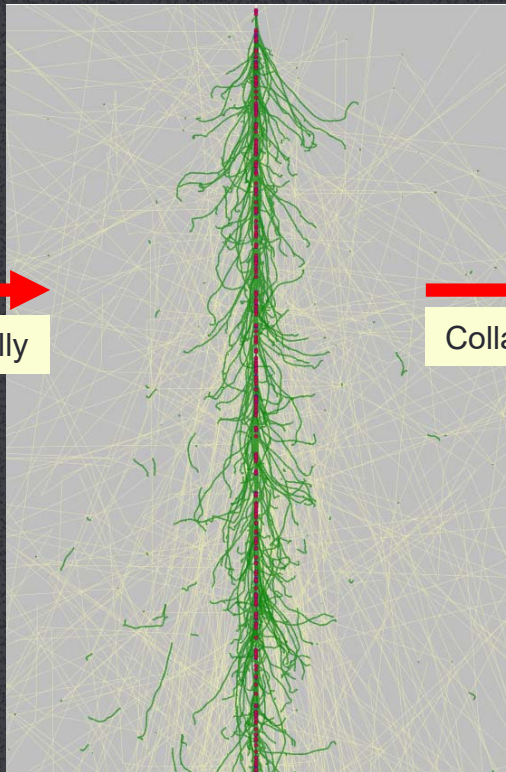 - lateral buildup is incomplete (disequilbrium)
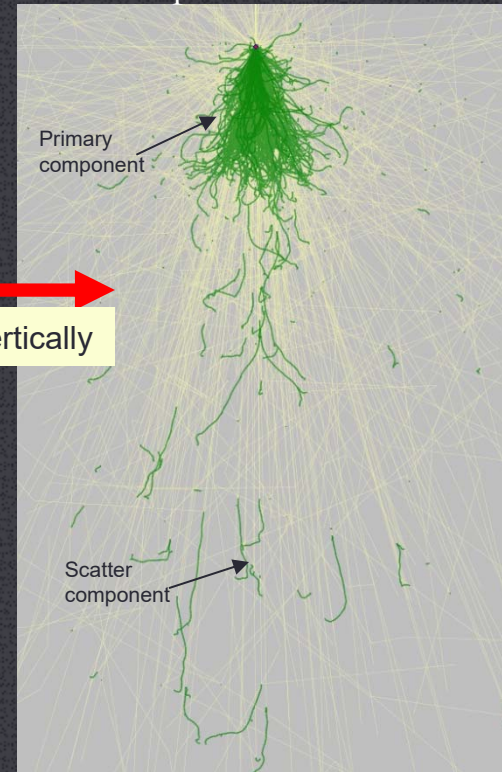

total dose
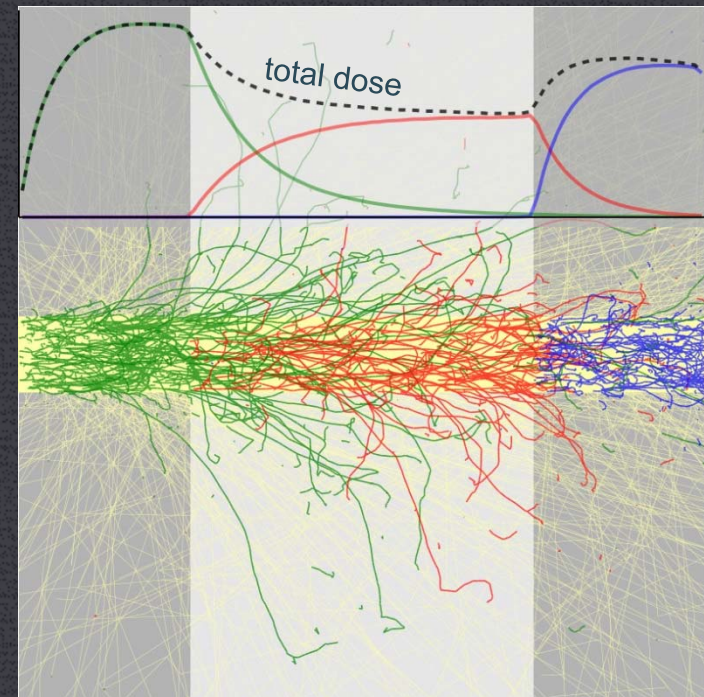
Visualizing a kernel

real photon beam

pencil beam kernel
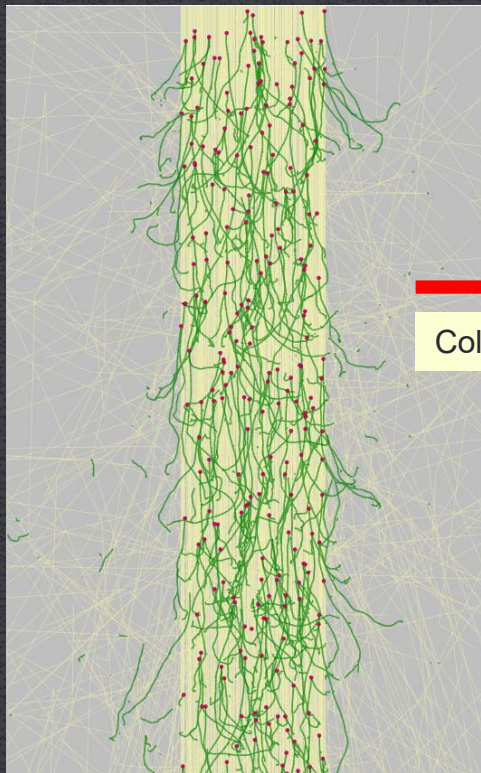
point kernel

Collapse laterally

Collapse vertically

Primary component

Scatter component

How do kernels look in convolution/superposition

- Allow interactions at only few discrete points:
  - Illustrates kernel shapes in water and low density medium
  - Illustrates reduced weights downstream due to attenuation.
  - Illustrates density scaling of tracks and corresponding kernel stretching
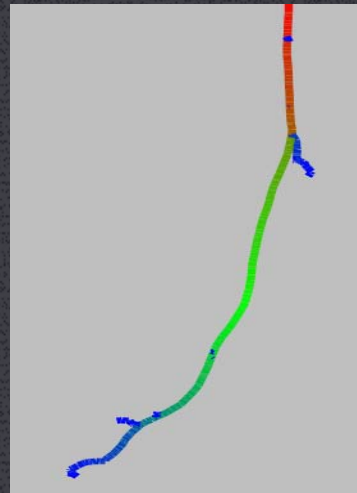 - Provides insights into convolution superposition method with addition of weighted kernels.
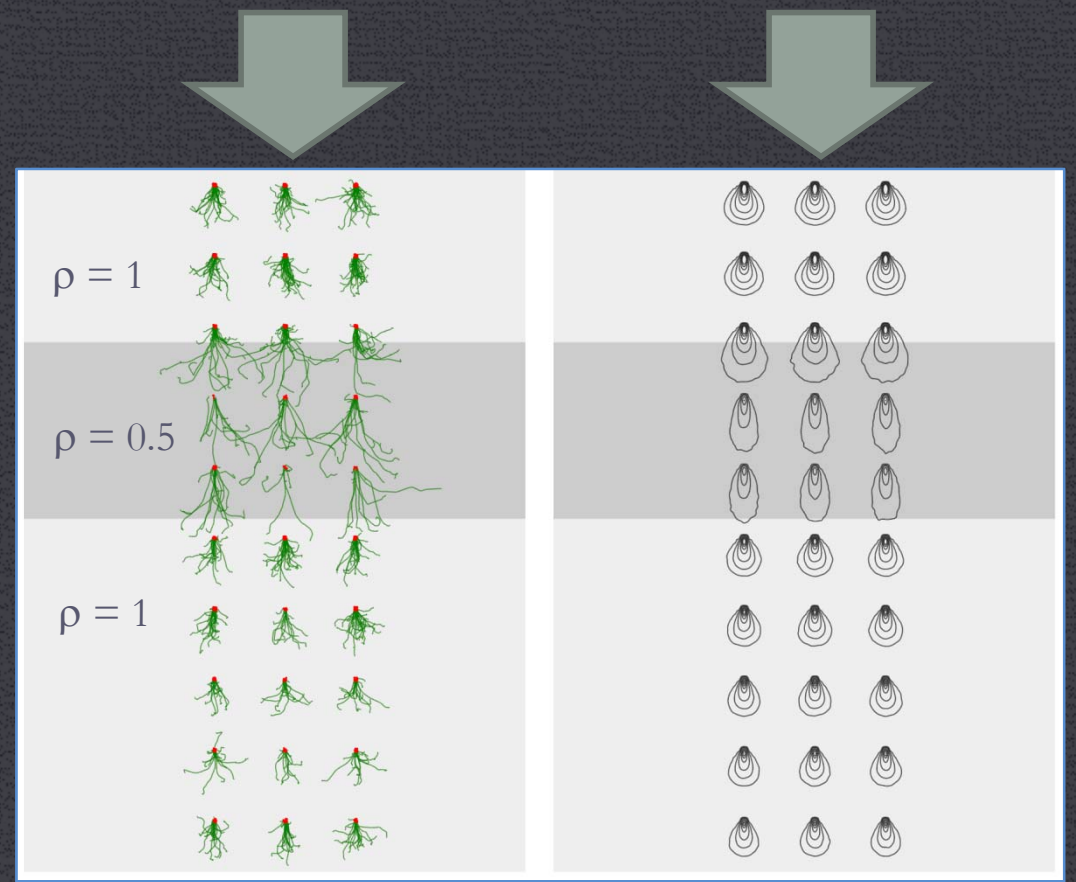
Color coding electron tracks

20MeV *e*- incident
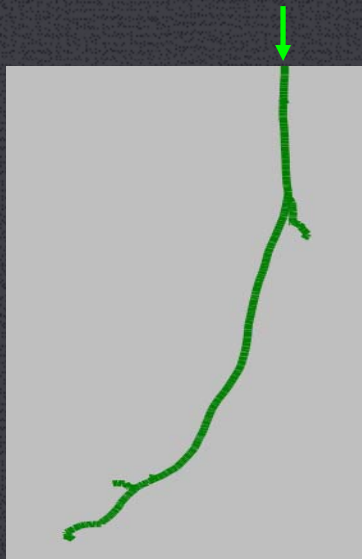
No coding

Energy
(red=20MeV)

Energy loss rate
(color coding)

Energy coding application: electron and photon beams

- Illustrates how electron energy spectrum changes with depth in electron beams.

- But photon beam electron spectrum remains essentially fixed.

- Explains need of water-air stopping power ratio in PDD measurement for e-beams with ion-chambers

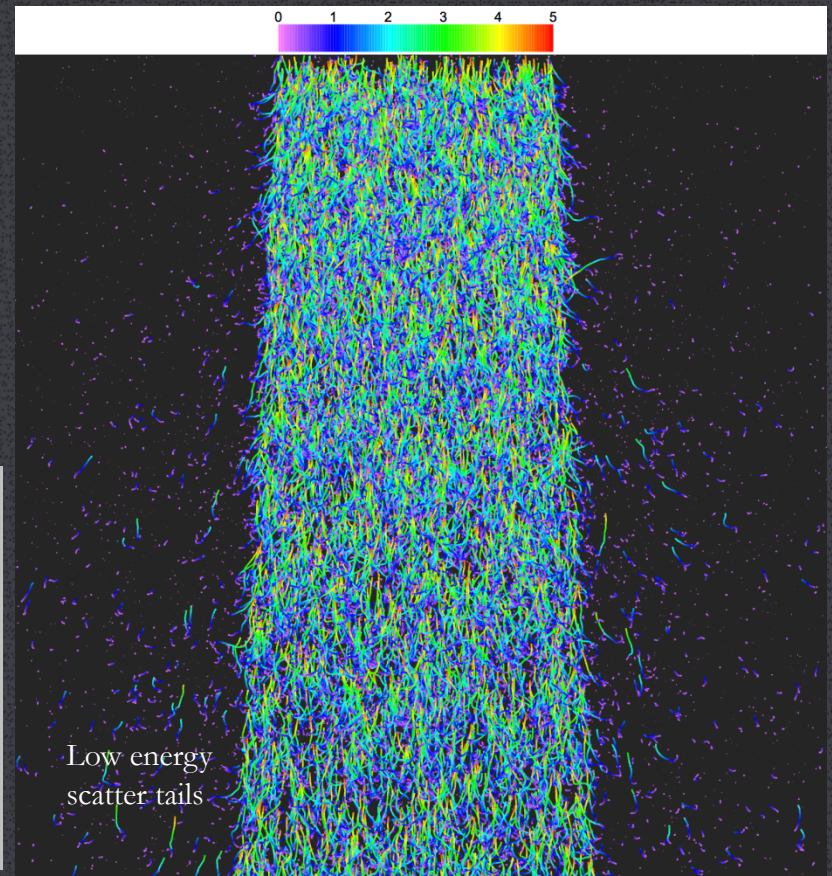- No correction generally needed for photons
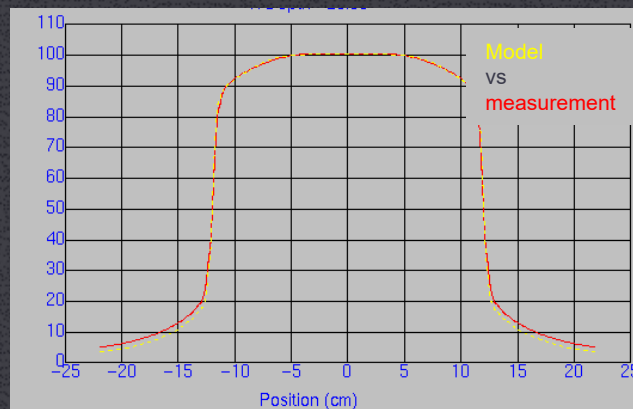
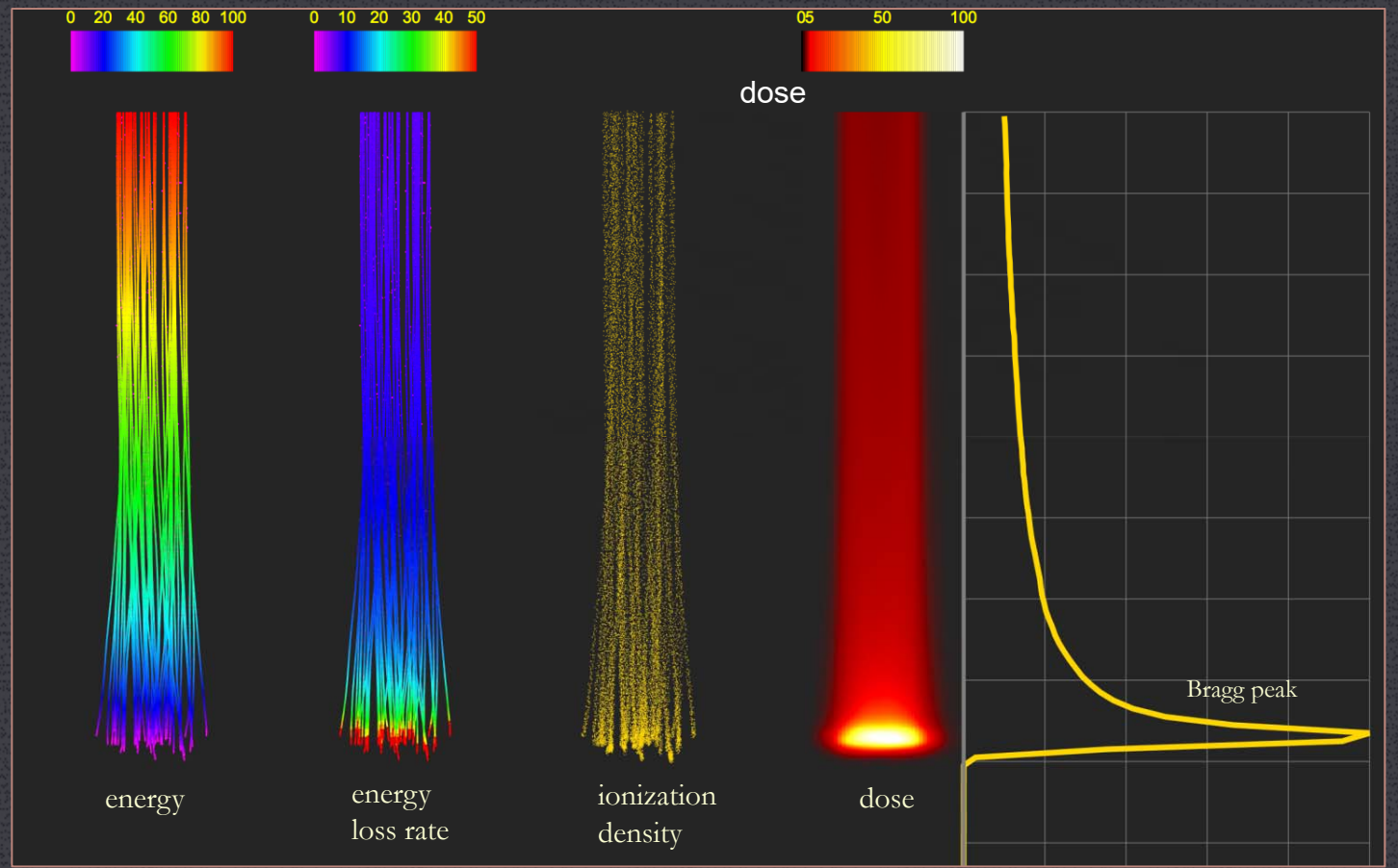10 MeV e- incident
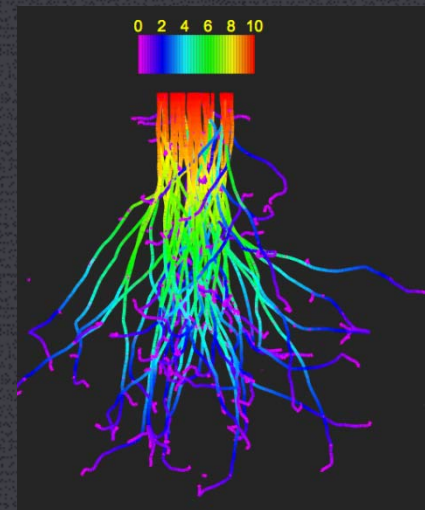
5 MeV photons incident
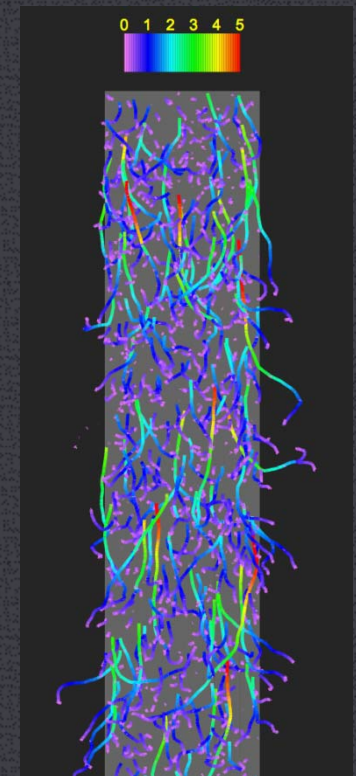
Spectral corrections for detector in tail?

- Corrections needed in the tail at large depths where e- energy is much lower?

- Shall we "force" the model to match measurements everywhere?

Model vs measurement

Low energy scatter tails

Color coding application: Protons & Bragg peak

Electron Beams: Where is the "Bragg peak" ?

- End of track ionization density is higher as stopping power rises with decreasing energy.

- But increase rate of energy loss happens when there is not much energy left to deposit.

- Also all individual "bragg peaks" get smeared out due to excessive lateral scattering, which this results in no bragg peak!

energy

energy loss rate
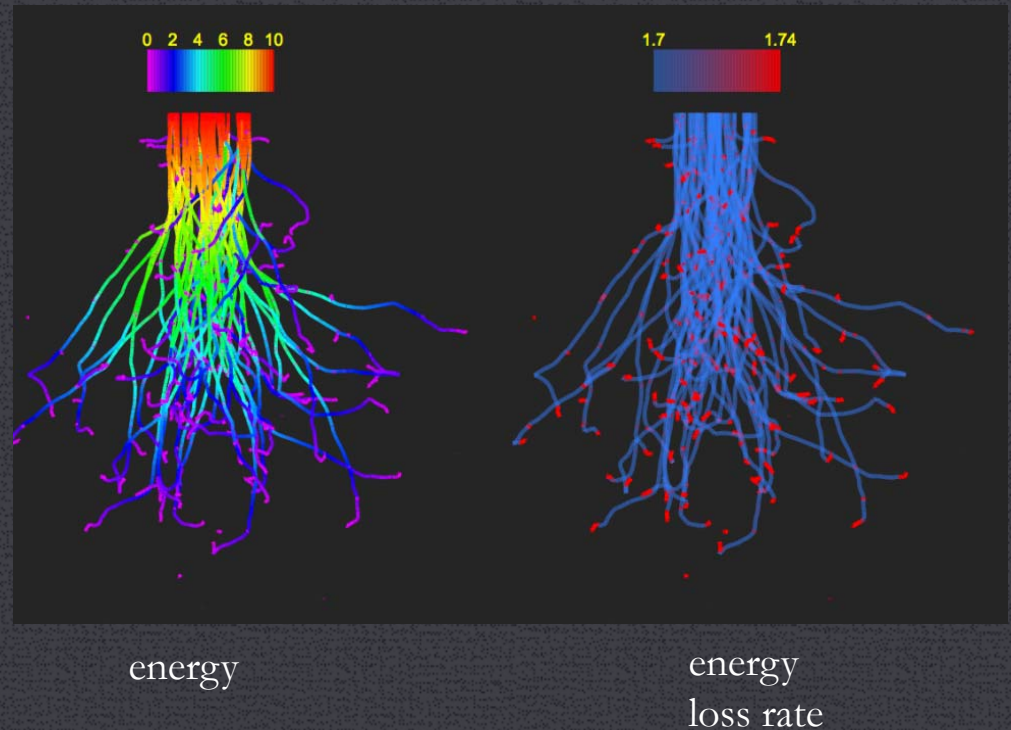
Conclusion

- In this work, it is shown
  - Monte Carlo simulations can be used as an effective educational tool

  - help to elucidate the physics by breaking the physical processes into layers of complexity.

  - Help in making explicit connections with clinical concepts.

  - Helps develops physical insight so that new situations can be evaluated with sound judgement.

  - Could excite a sense of "discovery" where a desire for understanding for its own sake overcomes extrinsic motivation factors such as passing exams!

  - Could make learning more fun, and leave a longer lasting understanding of crucial concepts in radiation physics.