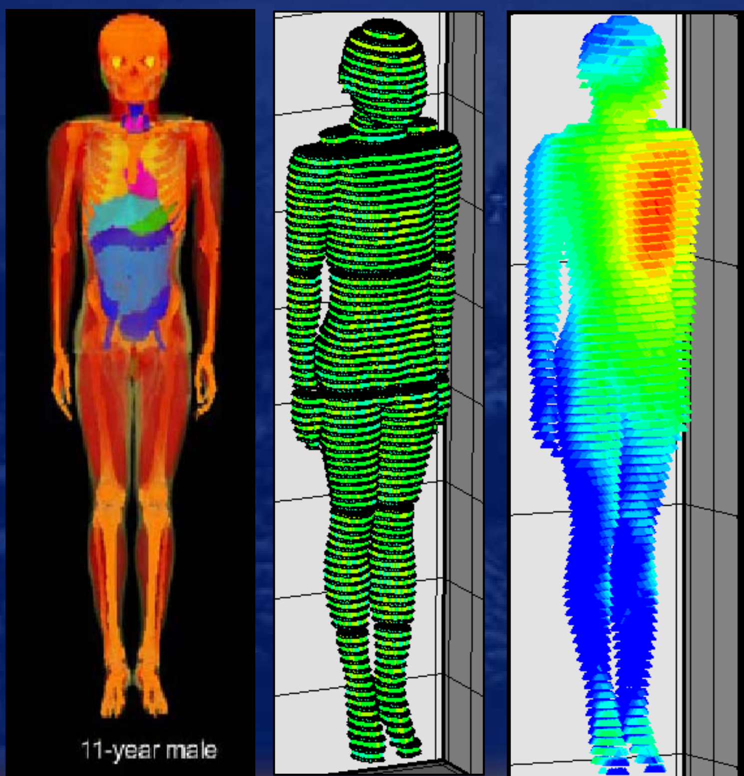
Electron Dose Kernels (EDK) for Secondary Particle Transport in Deterministic Simulations



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Proposed work

To develop a new state-of-the-art, three dimensional, deterministically coupled, dose calculation tool

- Based on the discrete-ordinates transport methods
- Specifically tailored to Radiation Therapy (RT) applications
- Employ parallel computing to achieve rapid solutions

Overview

- Photon Treatment Simulations
- PENTRAN-MP Code System
- Charged Particle Equilibrium Limits
- Monte Carlo Based Electron Dose Kernel (EDK)
- Summary

- Over 1 million patients per year are diagnosed with cancer in the US.
  - Half of them receive radiation therapy (ACS 2006)

- Patient-specific radiation treatment planning (RTP) is needed to
  - Determine the radiation field that provides sufficient dose to the desired treatment volume
  - Minimize exposure to healthy tissues
- Radiotherapy procedures depend solely on the accuracy of the radiotherapy treatment planning system
  - A small change in the dose delivered (± 5%) can result in a dramatic change in local response of the tissue (± 20%) (Shukovsky et al.)

Photon Treatment Planning Algorithms

Empirical Model

- All input data are based on the measurements in water
- Output factors
- Percent depth dose can be converted to TMR or TAR
  - TMR: Tissue Maximum Ratio
  - TAR: Tissue Air Ratio
- Open and wedge beam profiles as functions of field size and depth
- Limitations of the model includes:
  - Tissue in-homogeneities
  - Dose in the buildup region
  - Dose in penumbra region

Theoretical Model

- Photon Pencil beam kernel
- Monte Carlo Simulation (T. R. Mackie et al. 1995)

PENTRAN-MP Code System

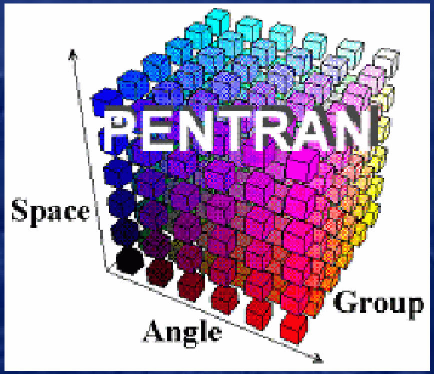
Pre-processing

GHOST-3D and DXS (**3-D General Collapsing Code** determines an effective phantom material distribution, **DXS** yields sources distributions)

PENMSH-XP (prepares mesh, source, and material distributions)

CEPXS (prepares multi-groups Cross-section libraries)

Transport Calculation



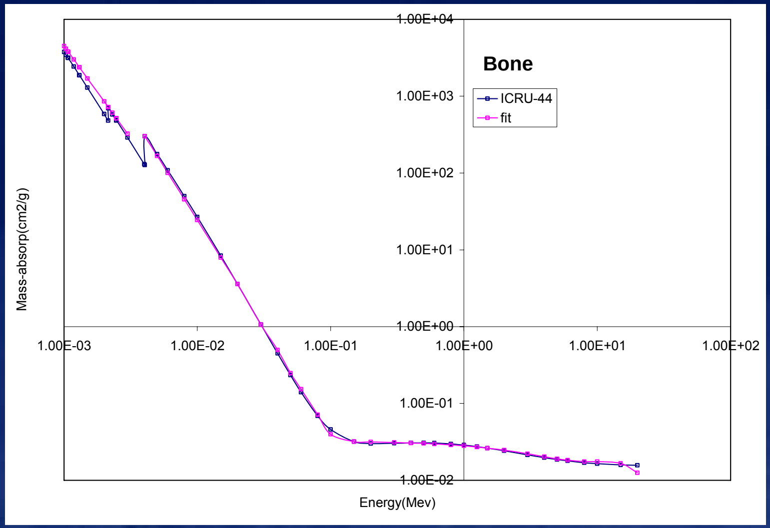
(Parallel Environment Neutral-particle TRANsport)

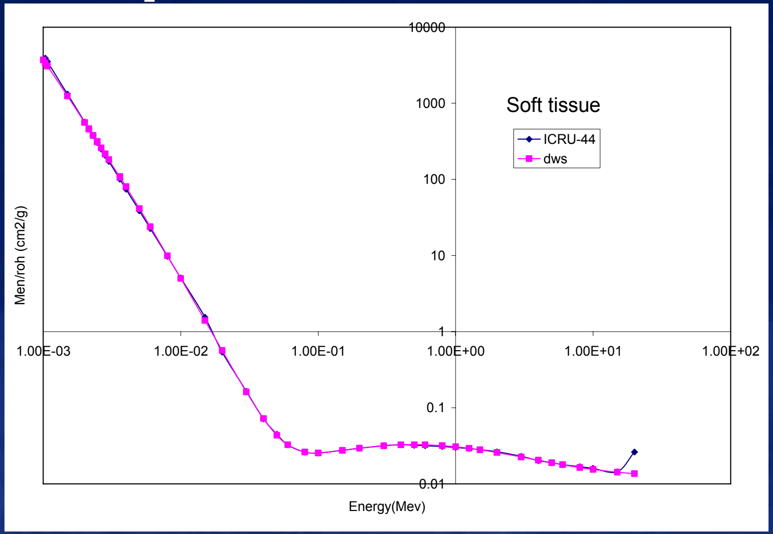
Post-processing

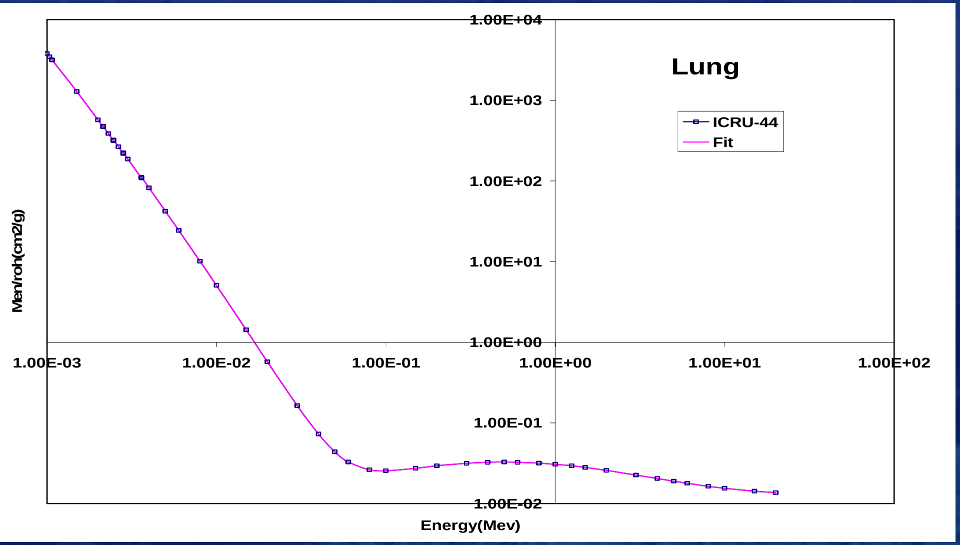
3D-Dose (calculate total 3D-dose distributions for all energy Group based on mass absorption coefficients)

EDK (calculate total 3D-dose distributions for all Energy Groups based on Electron Dose Kernels generated by Monte Carlo Calculations)

Fitting Mass Energy-Absorption Coefficients

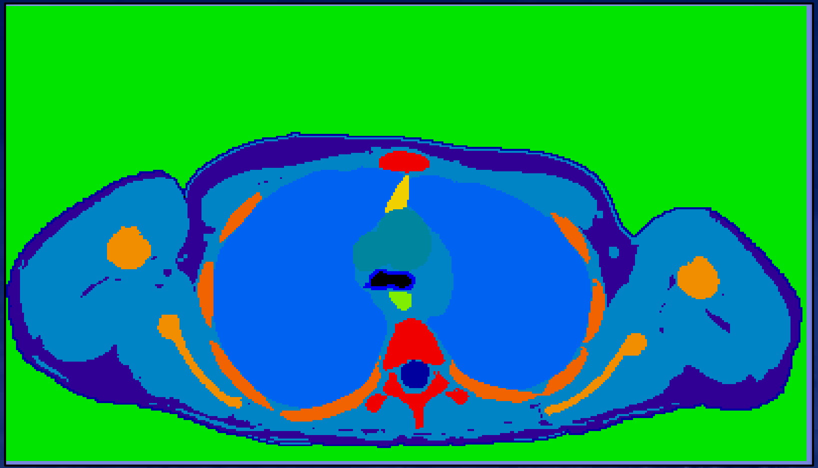




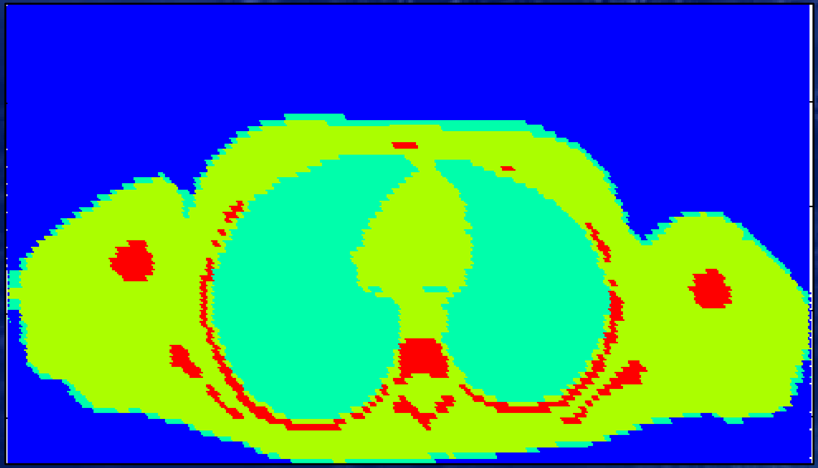


Mass energy-absorption coefficient as a function of photon energy, for cortical bone, lung tissue and soft tissue.

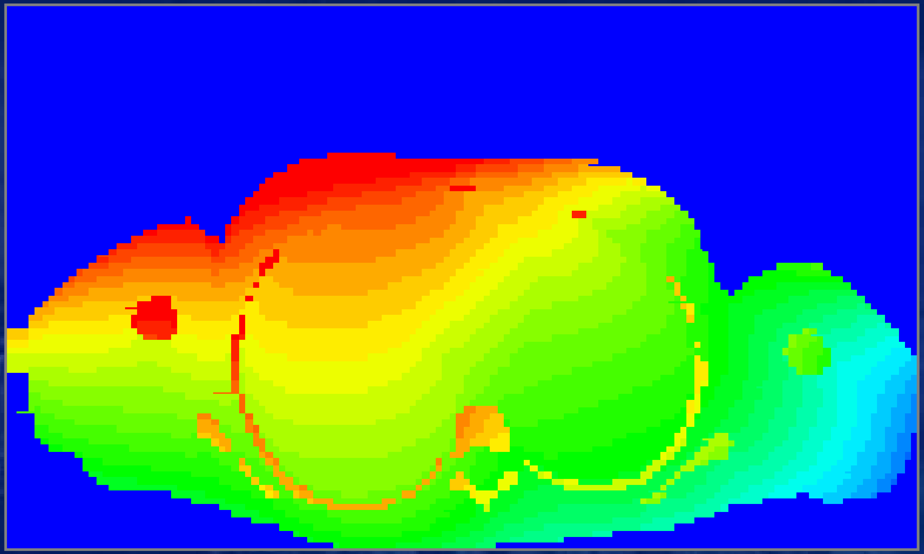
SELECTED IMAGE SLICES OF THE UF SERIES B PHANTOMS COMPARED TO PENTRAN-MP MODEL ANDTHE CORRESPONDING DOSE USING 3D-DOSE



CT Image slice 27M voxel phantom

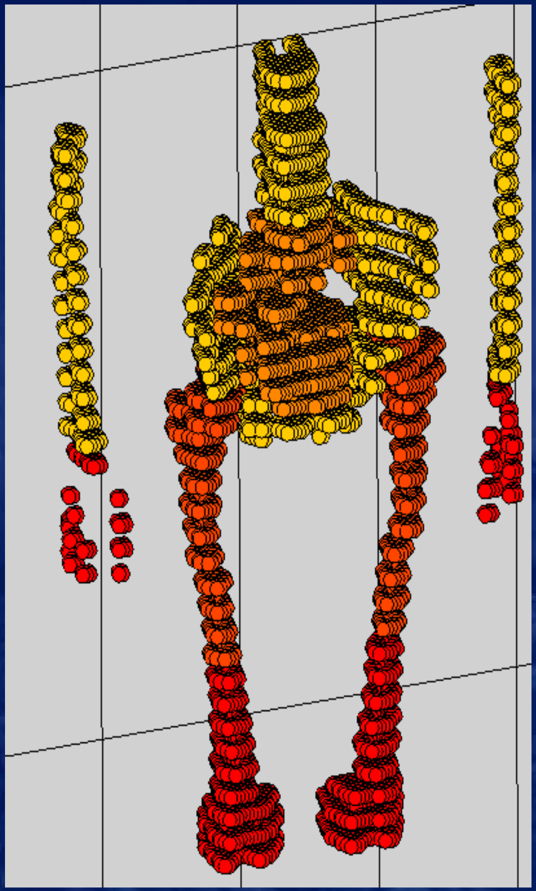


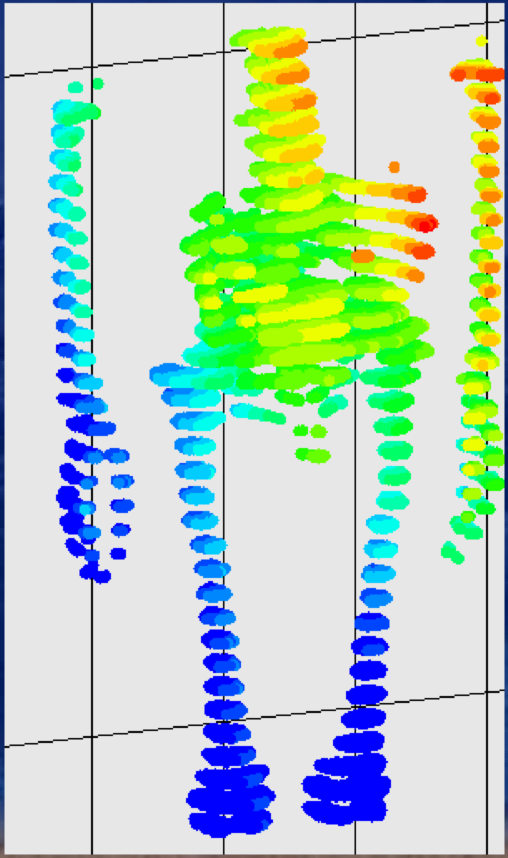
4materials 900K voxel phantom

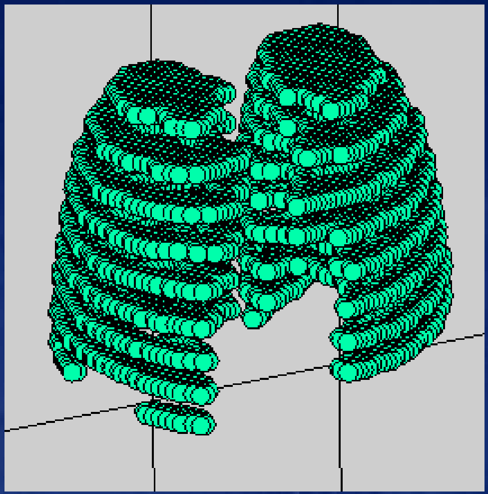


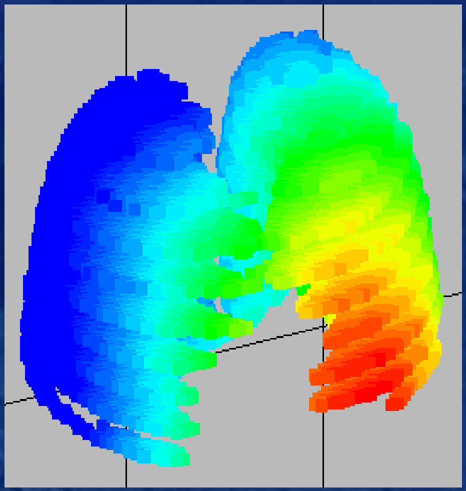
Corresponding dose distribution from Cardiac x-ray source

Individual Organ dose is readily obtainable via post processing…

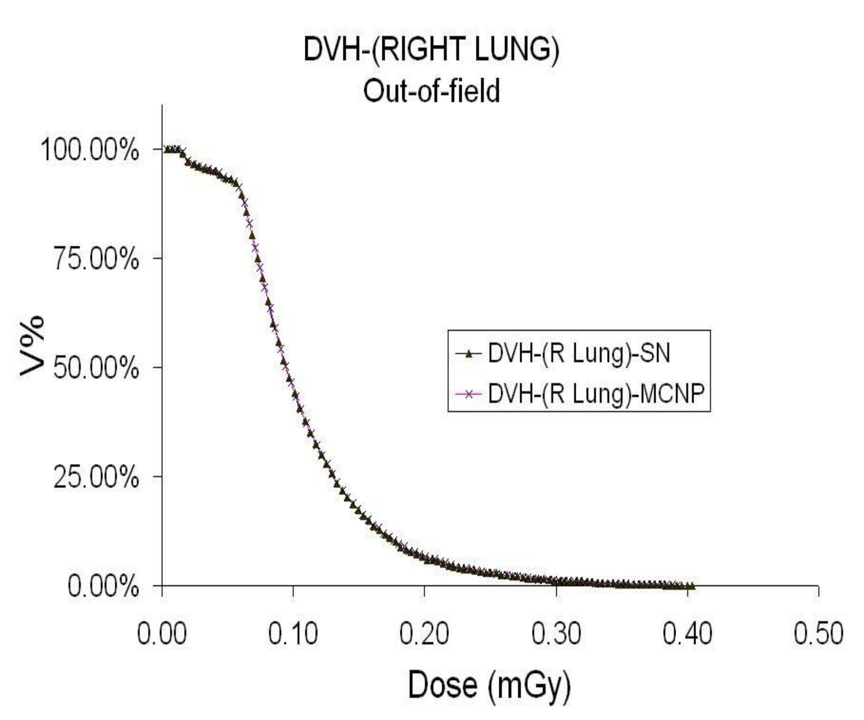


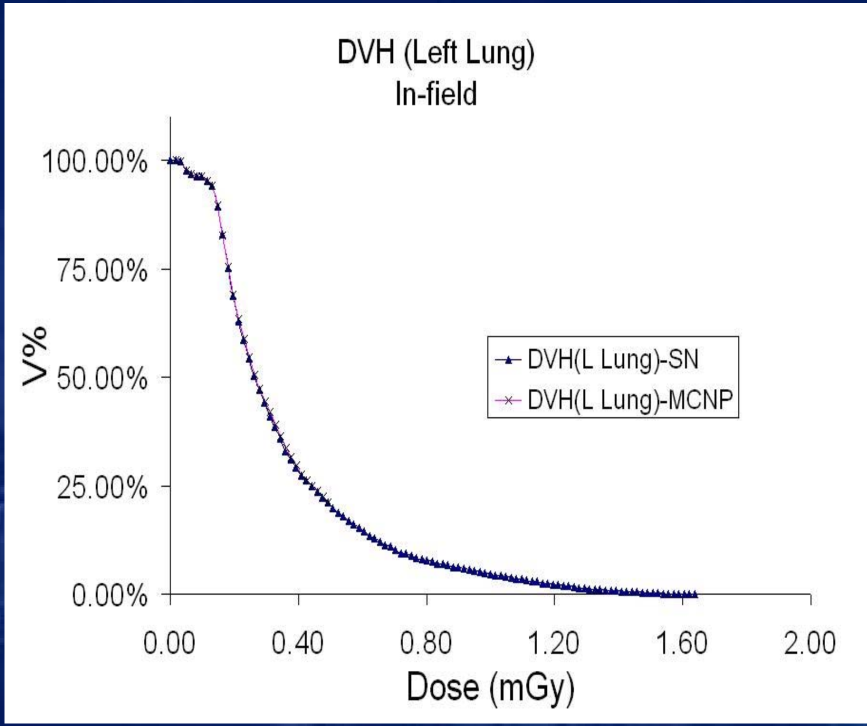






Dose Volume Histograms (DVH)





Left lung (organ in the radiation field). Liver (organ is partially in the radiation field) Right lung (organ is out side the radiation field where MC didn't converge).

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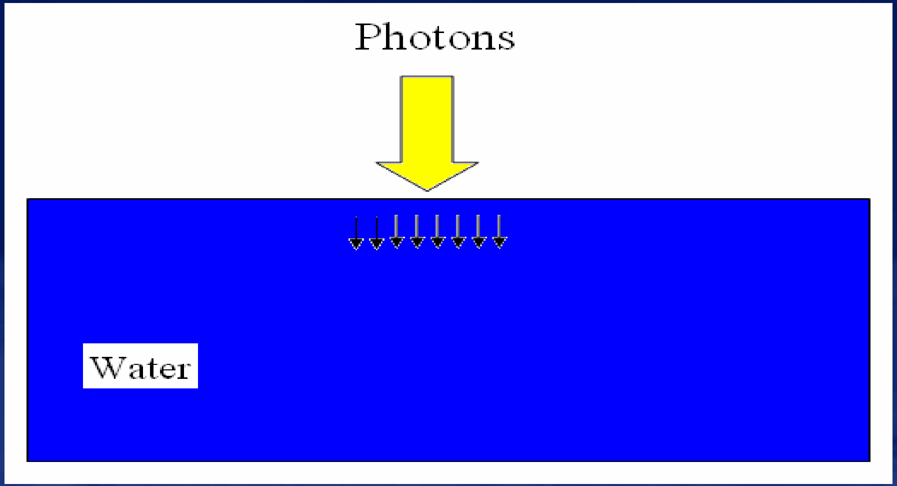
Charged Particle Equilibrium (CPE)

For low energy photons, Charged Particle Equilibrium (CPE) usually exists within the patient treatment volume, in which case the photon absorbed dose is equal to the collisional kerma.

according to Attix:

- As the energy of the ionizing radiation increases, the penetration power of the secondary charged particles increases more rapidly than the penetration power of the primary radiation…
- this leads to CPE failure.

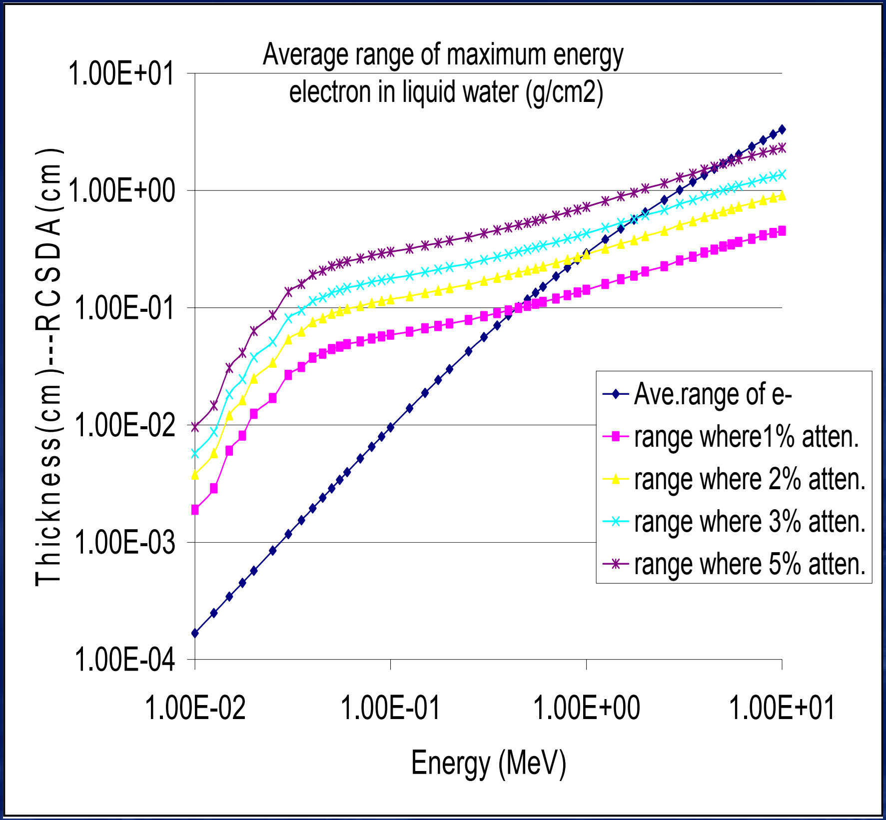
Limits of Charged Particle Equilibrium

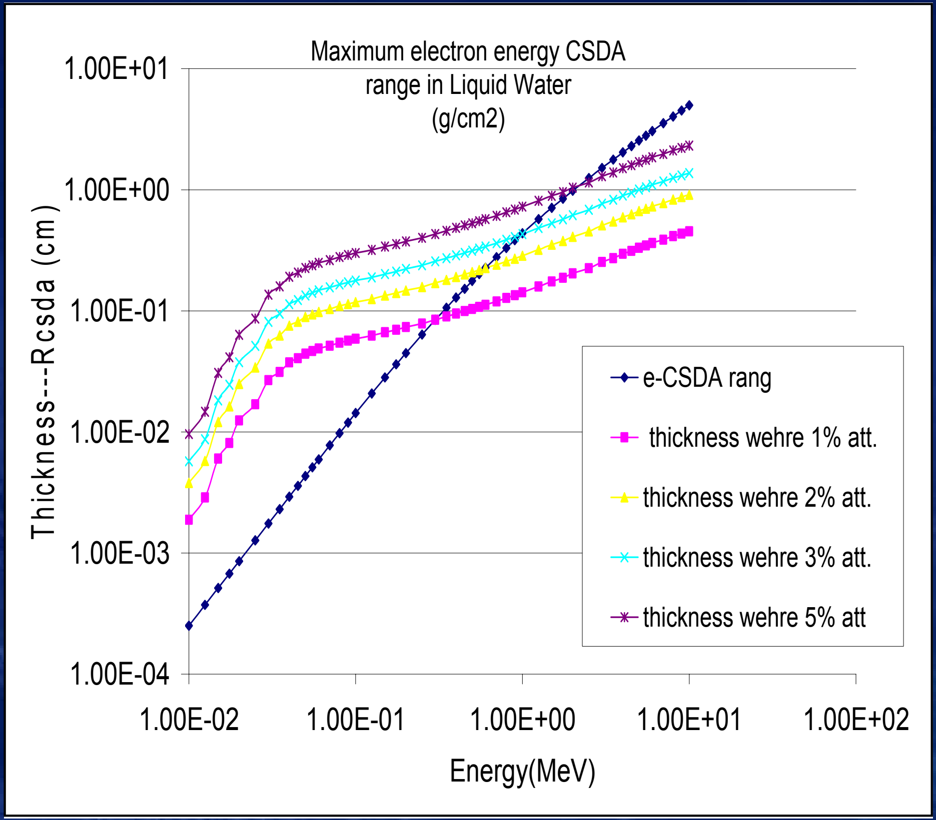


Photon Energy (MeV)	Voxel Thickness (cm) at which CPE is conserved by				Average electron range (cm)	R_{CSDA} (cm)
	1%(r/r_0)	2%(r/r_0)	3%(r/r_0)	5%(r/r_0)		
0.3	0.085	0.17	0.256	0.431	0.056	0.085
0.6	0.112	0.225	0.34	0.572	0.15	0.225
1.0	0.142	0.286	0.43	0.726	0.286	0.43
2.0	0.203	0.41	0.617	1.04	0.617	1.04

Approximate thickness of water needed to achieve various attenuation compared to maximum energy electron ranges generated by the same beam.

Limits of Charged Particle Equilibrium





Comparison between thickness required to attenuate different percentages of primary photons and range for maximum energy secondary electrons produced by the same beam.

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Engineering

Limits of Charged Particle Equilibrium

- With proper model discretization of the angle-energy-spatial transport phase space and
- At low photon energies that yield primary and secondary electron interactions…
  - Small electron transport paths and deposited dose locally
  - 3-D SN methods can directly yield very accurate dose distributions
- At higher photon energies, this is not the case
  - Interactions yielding energetic electrons must account for the mechanism of electron transport through the problem phase space
  - Deliver a dose after electron transport distances

Electron Dose Kernels (EDK)

- To properly treat the physics deterministically, yet be
  - Reasonably fast
  - Accurate whole body computation times
  - using high energy photons, energy dependent electron transport dose "kernels"
  - Can be pre-computed using Monte-Carlo to extremely low variances in various tissue media.
- These Electron Dose Kernels (EDKs) can then be implemented to enable:
  - Direct attribution of the final equivalent dose initiated by photon "beamlets"
  - placed in various tissue types and
  - energies relative to a specific direction of photon travel.
- This will permit complete attribution of the dose ultimately due to electron straggling,
  - EDK can be fashioned as an "equivalent electron dose look-up table" for each photon "beamlet" in a discrete ordinates transport code that stores angular radiation transport information.
- Since the angular data is available and is explicitly stored in scalable parallel data arrays in the PENTRAN SN code
  - This "electron kernel" treatment should effectively attribute dose from even high energy photons provided the direction.

Monte-Carlo Based EDK

When CPE Breaks

- At high energies were CPE doesn't exist for satisfaction, the program will accumulates the energy deposited in each voxel for each photon energy group and polar angle using the EDK method descried in the previous section.

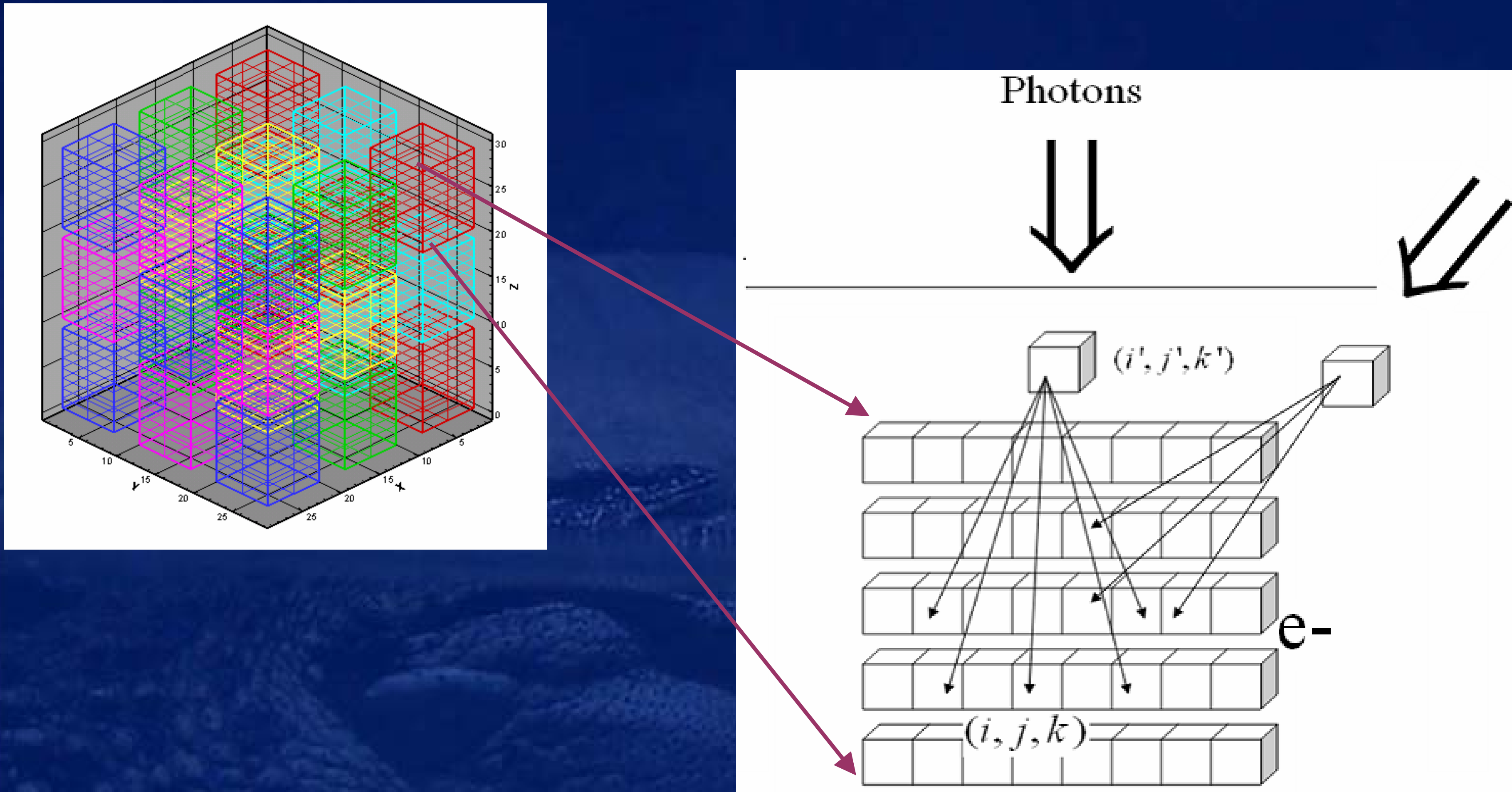
Detailed Physics Treatment

- For EDK calculations, we used detailed physics treatment implementing *F8(p, emode) tally
- As an alternative to F4 tally method or F6 tally
- This is to insure accurate absorbed dose estimation and not collisional kerma for each energy group.

Cutoff of Low Energy Photons

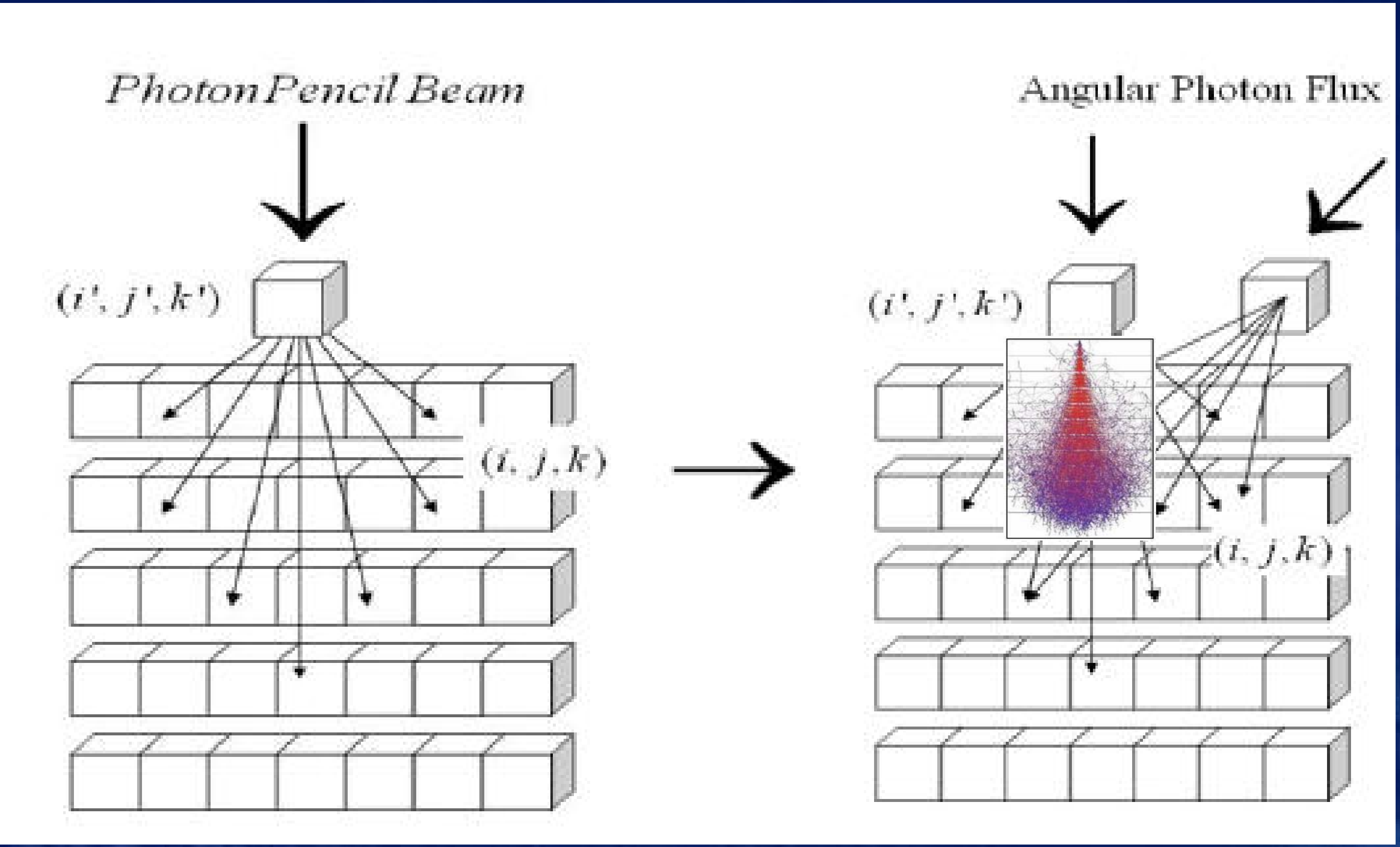
- It is important to notice that for each Energy group calculation, the Monte Carlo model used was set to cutoff photons with energy lower than the lower limit of the energy group.
- This is important to prevent counting the dose multiple times.

Monte-Carlo Based EDK



A beamlet of mono-energetic photons is forced to interact at the center of a water phantom. Kernels are computed and then applied around the direction of the deterministically computed beams for each energy group.

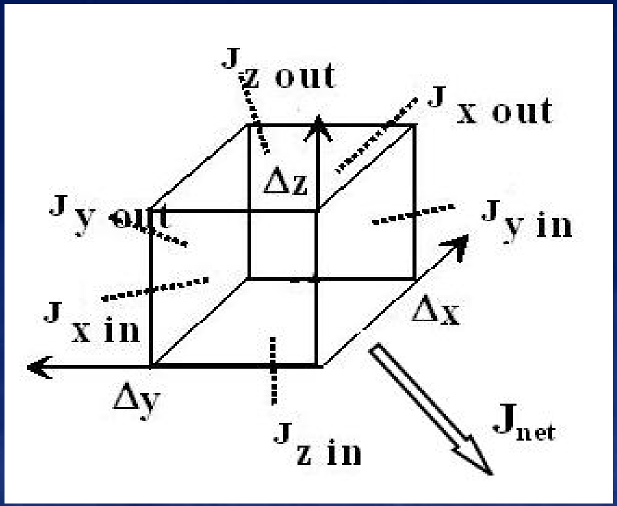
Electron Dose Kernels (EDK) for Secondary Particle Transport



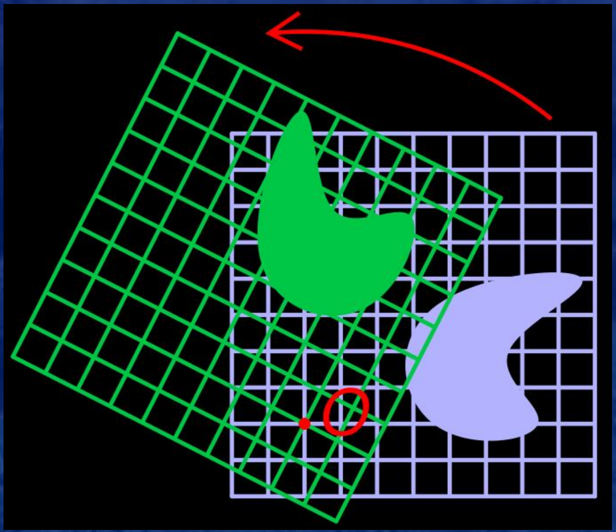
Using Monte Carlo radiation transport, a pencil beam of mono-energetic photons is forced to interact at the center of a water phantom. Kernels are computed and radii (r_g) and cosines ($\cos\theta_g$) are scored.

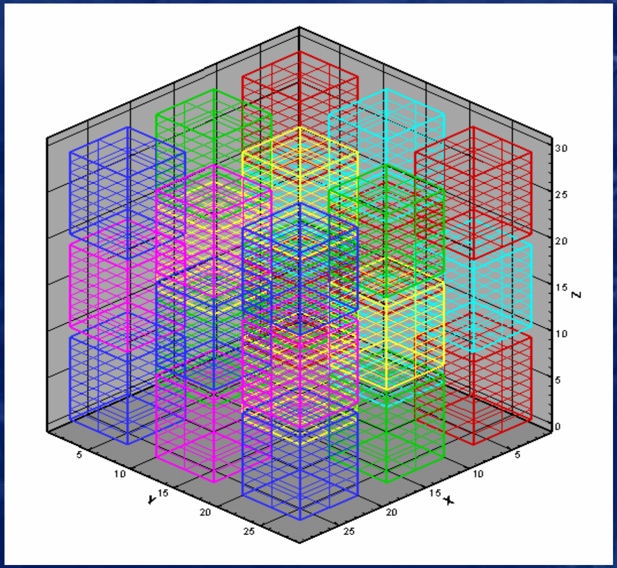
EDK Strategy

Transport Calculations



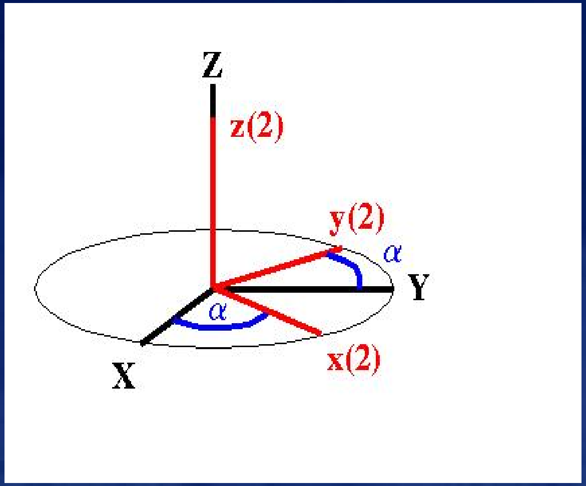
Calculating EDK for produced by each Voxel

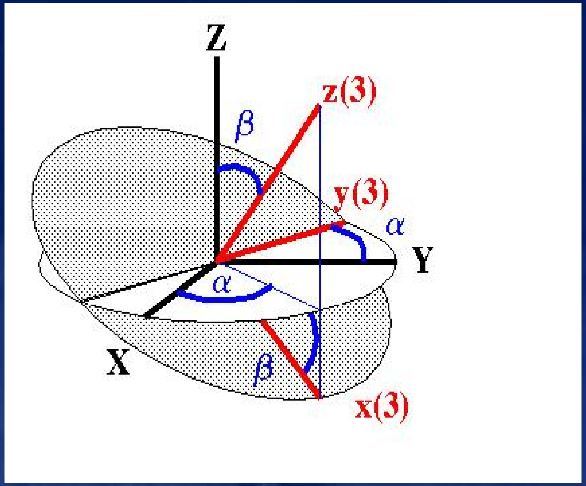


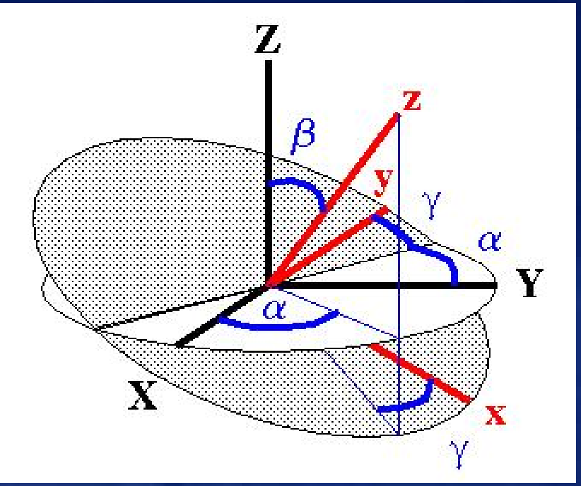


Projecting calcualted EDK back on the Original Phantom

Euler Angles







$$R_z(\alpha) = \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

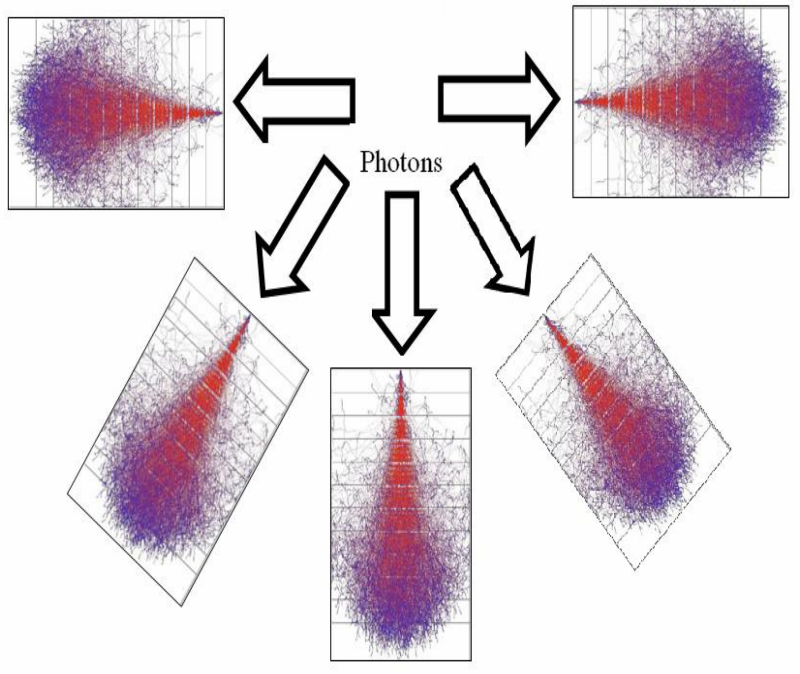
$$R_y(\beta) = \begin{pmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{pmatrix}$$

$$R_z(\gamma) = \begin{pmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

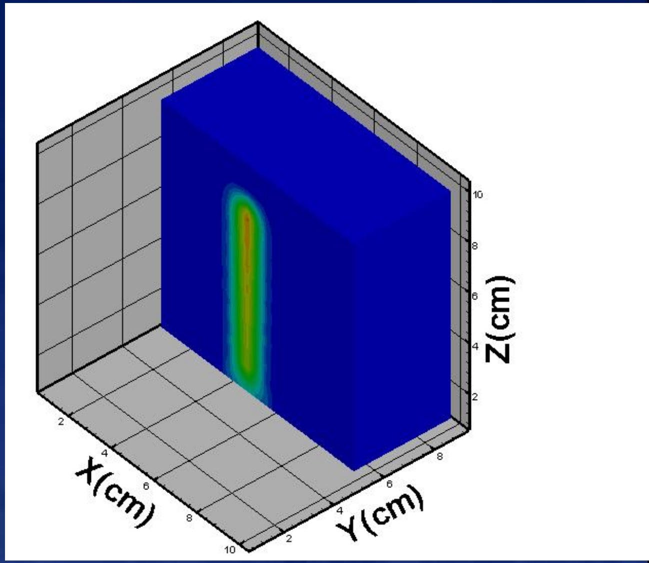
$$[A'] = [R][A]$$

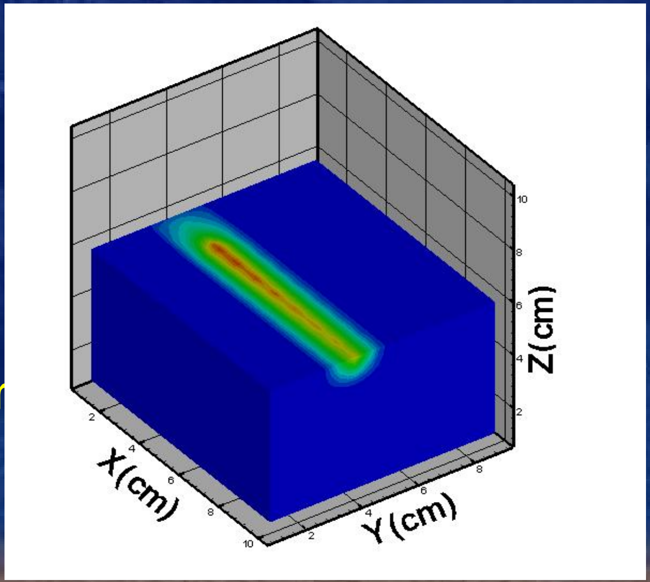
$$[R] = [R_z(\alpha)][R_y(\beta)][R_z(\gamma)]$$

Resulting Electron Dose Kernels for Different Angels



EDK values calculated by MCNP5 for 7.5-8.0 Mev





EDK values shifted using Euler Angels by 90 around the Y axis

It is important to notice that for each Energy group calculation, the Monte Carlo model used was set to cutoff photons with energy lower than the lower limit of the energy group. This important to prevent counting the dose multiple times

Monte-Carlo Based Dose Kernels

fractional electron dose kernels $EDF_g(i, j, k)$ for pre-determined photon energy groups in terms of the energy deposited in voxel (i', j', k') as a result of the incident primary photon beamlet in a given energy group *g* propagated from a voxel (*i, j, k*)

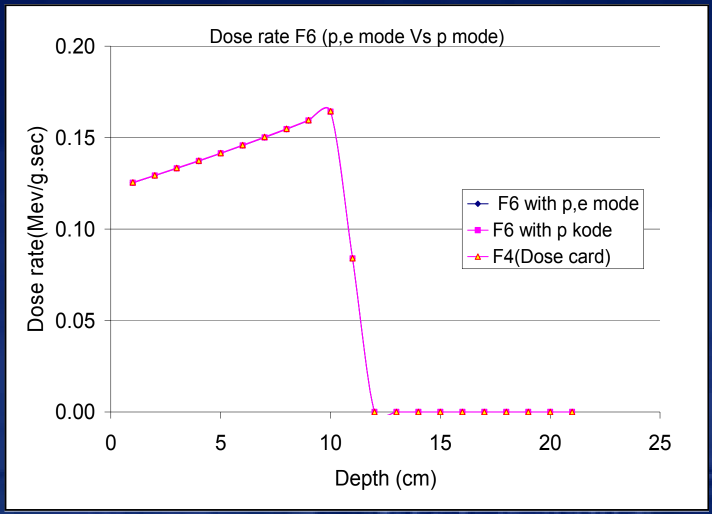
$$EDF_g(i, j, k) = EDK_g(i, j, k) / \phi_g(i', j', k')$$

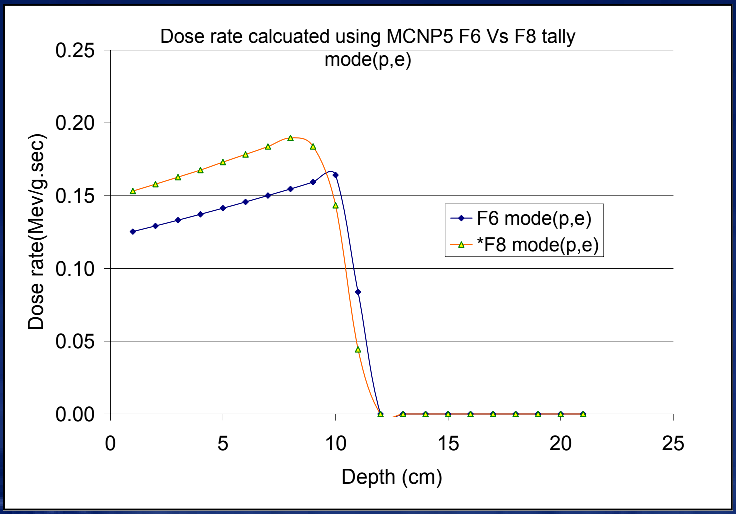
$$D(i, j, k) = \sum_g \sum_s [EDF_g\ (i, j, k)\ ]_s \phi(i, j, k)_g\ / M(i, j, k)$$

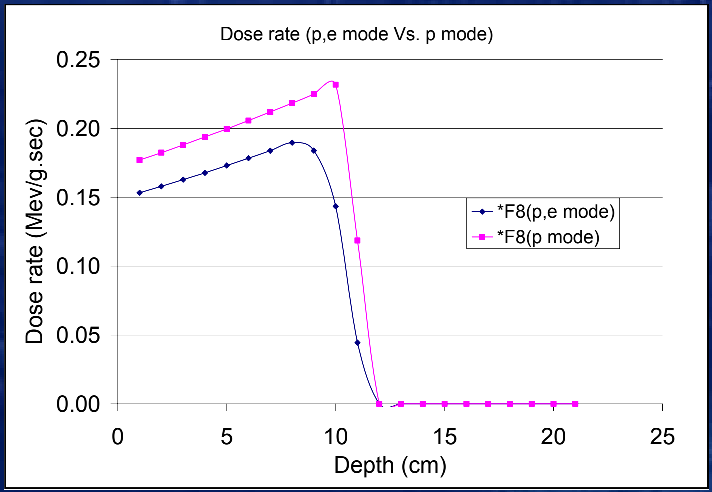
$EDK_g(i, j, k)$ is the amount of energy deposited in voxel (*i, j, k*) in energy bin (s) per flux per source particle,

M (*i, j, k*) is the voxel mass

EDK Estimation Based on MCNP5







- MCNP5 Monte Carlo code, there are three different methods by which one can tally to yield doses to be used for integrated organ dose calculations
- This is achieved by using either F4, F6, or *F8

Dose calculations using MCNP5 (Mode P E) Vs. (Mode P)

- If electron transport is turned on (Mode P E), then all photon collisions except coherent scatter can create electrons that are banked for later transport.

- If electron transport is turned off (no e on the Mode card), then a thick-target bremsstrahlung model (TTB) is used. This model generates electrons, but assumes that they are locally "slowed to rest".

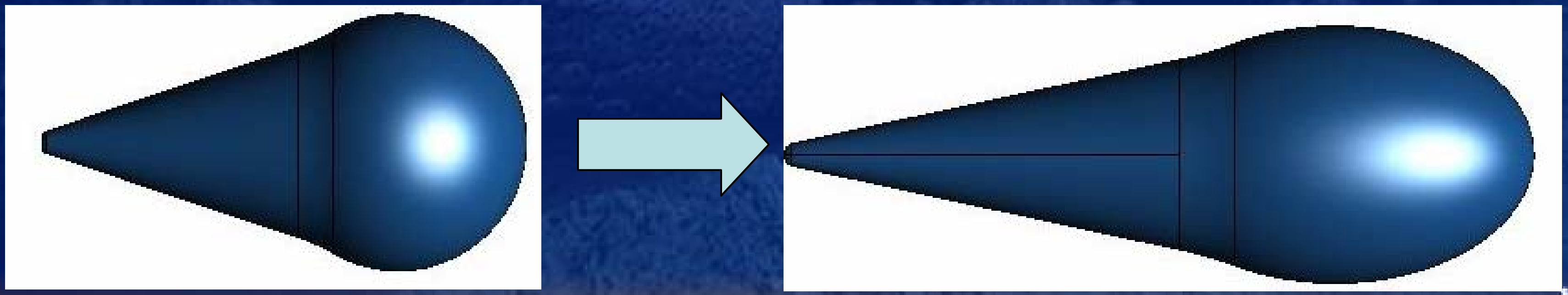
in the TTB production model contains many approximations compared to models used in actual electron transport. In particular, the bremsstrahlung photons inherit the direction of the parent electron

also the expensive electron transport step is omitted !!!.

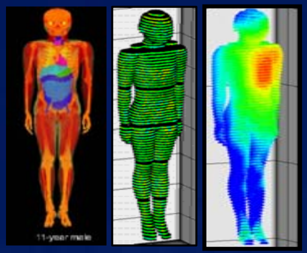
Heterogeneities (under investigation)

We will be investigating some techniques such as kernel stretching:

- The kernel will stretch out into low density areas and will be compacted in high density areas.
- The kernel stretching corresponds photons and electrons which stream out into low density regions



Conclusions



- By following the EDK approach, the whole body dose as a result of any incident photon beam (pencil, fan, areal, etc) can be readily determined based on a coupling of photon transport and application of the EDK methodology.
- This procedure can be readily accomplished by
  - Applying the PENTRAN discrete ordinates code, since it is a parallel code design and stores, via partitioned parallel storage, all angular problem data and fine mesh net current vector.
  - Since PENTRAN is based on a Cartesian geometry, CT voxel data can readily be mapped into the problem geometry to define the tissue and organ geometry structure.
- As a result, this will render the first application of integrated electron transport kernels to properly account for the total dose in photon radiotherapy scenarios.