Radiation Treatment Planning Using Discrete Ordinates Codes

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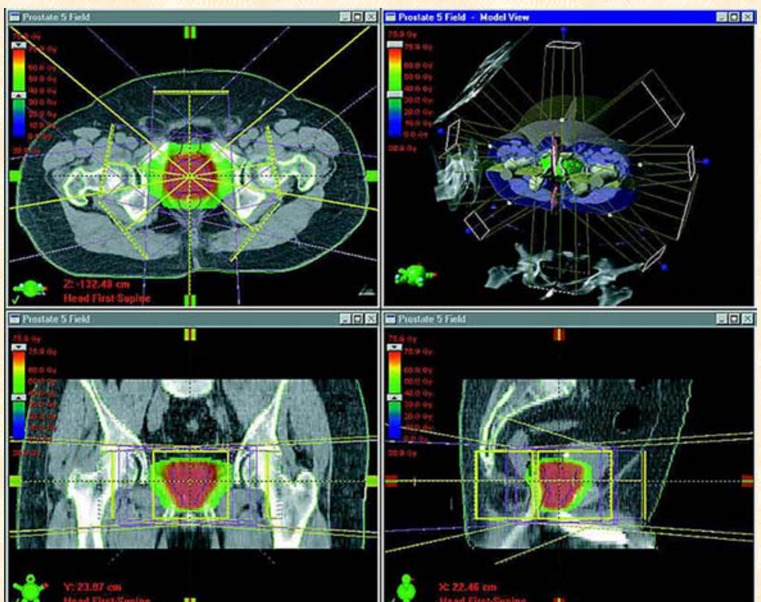
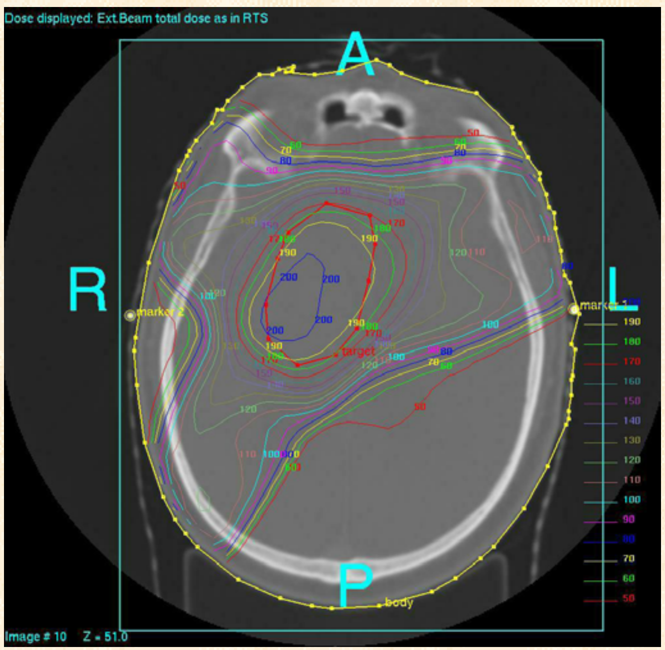
Outline

- Motivation
- Investigation
- Results
- Conclusions
- Future Work
- Acknowledgements

Motivation

- Cancer can be treated with external gamma beams which generate the electrons that cause the dose to the patient.
- As treatment methods become more precise it is essential to quickly model electron transport.





Motivation(2)

- Monte Carlo methods can model electrons accurately, but often require long run times to obtain the required statistics.
- Discrete Ordinates methods run quickly but have not been developed for electron transport*.
- Speed and accuracy are important for treatment optimization.
- Research: Can TORT handle charged particle transport without modification if cross sections are defined in a manner that accounts for the electrons?

*ATILLA has been successfully applied to 3D radiotherapy problems.

Boltzmann-Fokker-Planck

- The BFP equation is a Boltzmann equation that has been modified to treat charged particles.

$$
-\frac{\partial}{\partial E}\left[\beta(\vec{r},E)\psi\right]-T(\vec{r},E)\left\{\frac{\partial}{\partial\mu}\left[(1-\mu^2)\frac{\partial\psi}{\partial\mu}\right]+\frac{1}{1-\mu^2}\frac{\partial^2\psi}{\partial\varphi^2}\right\}+(\vec{\Omega}\vec{\nabla})\psi+
$$

$$
\sigma_t(\vec{r},E)\psi(\vec{r},\mu,\varphi,E)=\int_0^\infty dE'\int_0^{2\pi}d\varphi'\int_{-1}^{+1}d\mu'\sigma_s(\vec{r},E'\to E,\mu_s)\psi(\vec{r},\mu',\varphi',E')
$$

$$
+F(\vec{r},\mu,\varphi,E)
$$

- The first two terms are the Fokker-Planck operators:
  - The first term accounts for CSD.
  - The second term accounts for CS.

Boltzmann-Fokker-Planck(2)

- Details of these two terms:

$$\beta(E) = \int_0^E 2\pi \int_{-1}^{+1} \sigma_{\text{sing}}(E \rightarrow E', \mu_s)(E - E')\, d\mu_s\, dE'$$

➢ **Restricted stopping power**

$$\sigma_{\text{sing}}(E \rightarrow E', \mu_s)$$

➢ **Singular part of cross section**

$$\alpha(E) = \int_0^E 2\pi \int_{-1}^{+1} \sigma_{\text{sing}}(E \rightarrow E', \mu_s)(1 - \mu_s)\, d\mu_s\, dE'$$

➢ **Restricted momentum transfer**

$$T(E) = \frac{\alpha(E)}{2}$$

- The remaining terms make up the Boltzmann equation, including an inhomogeneous source.

Codes Used

- CEPXS-BFP: generated cross sections
- ARVES: processed cross sections
- GIP: formatted cross sections
- GRTUNCL3D: generated uncollided plus a first-collided source for TORT calculations
- ANISN, DORT, TORT: transport with discrete ordinates
- EGSnrc: transport with Monte Carlo, used for reference case

Code Use of BFP

- CEPXS-BFP chosen because it creates electron cross sections that account for CSD and CS.
  – CSD operator treated directly
  – CS operator treated indirectly
- ARVES processes cross sections – uses a step method to convert direct treatment of CSD term to indirect.
- Total and scattering cross sections are modified in the indirect treatments.
- DOORS designed to solve standard multi-group neutral-particle transport equation.

Problems Solved

- Sources
  - Photons: first 40 energy groups from Vitamin B6
  - Electrons: 40 group linear structure
  - Photons generate electrons
- Homogeneous water cube
  - Solved with TORT only.
  - Solved with photons only, photons generating electrons, and with electrons only.
- Lung Phantom
  - Solved with ANISN, DORT, and TORT.
  - Solved with photons generating electrons.

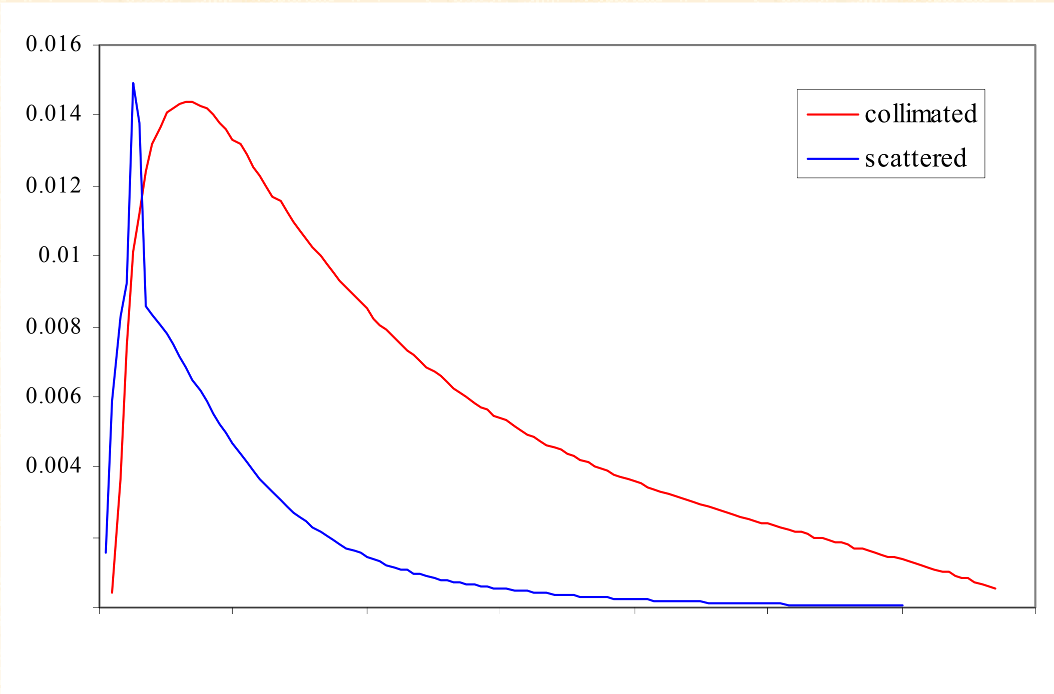
Water Box

- Water in a 2.5 cm x 2.5 cm x 2.5 cm cube with a 0.25 cm mesh.
- Density of water = 1 g/cm^3.
- Scattering order of P_9 and quadrature order of S_{16} were used.
- An isotropic point source was located at 1.25 cm, 1.25 cm, -0.625 cm.
- The point source was chosen for ease of use with GRTUNCL3D.
- Source normalized to one.

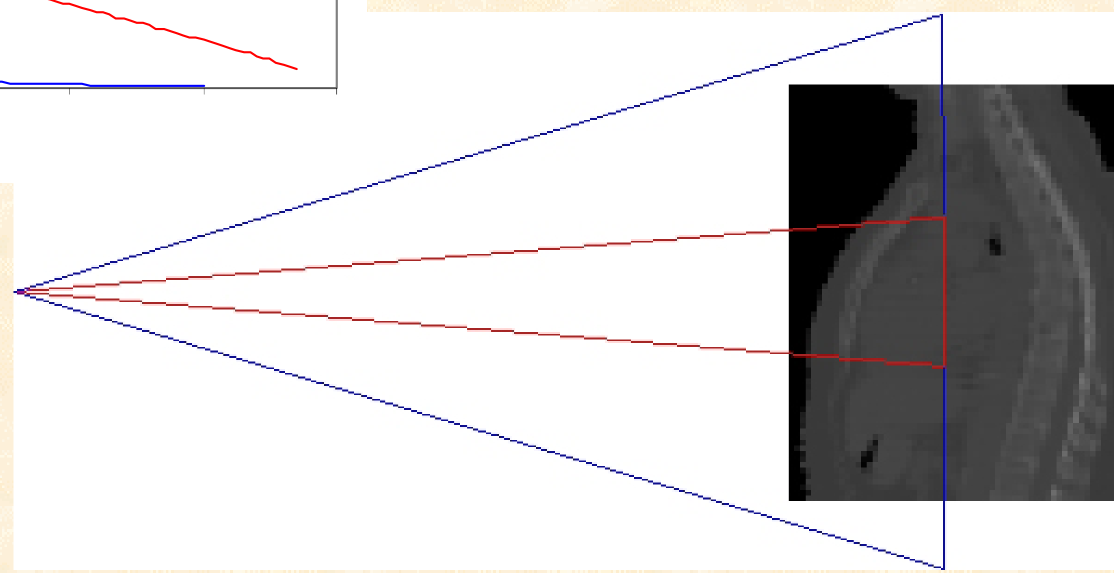
Phantom Lung

- One row of voxels from model based on reformatted CT data from the Department of Radiation Oncology at UNC Chapel Hill.
- Row passes through high and low density tissue.
- Voxels 1-7 are outside of phantom, set to 0.001 g/cm^3 in DOORS analysis.
- Source distributed over a 1 cm thick voxel at leading edge of model.
- Energy distribution represents collimated beam.

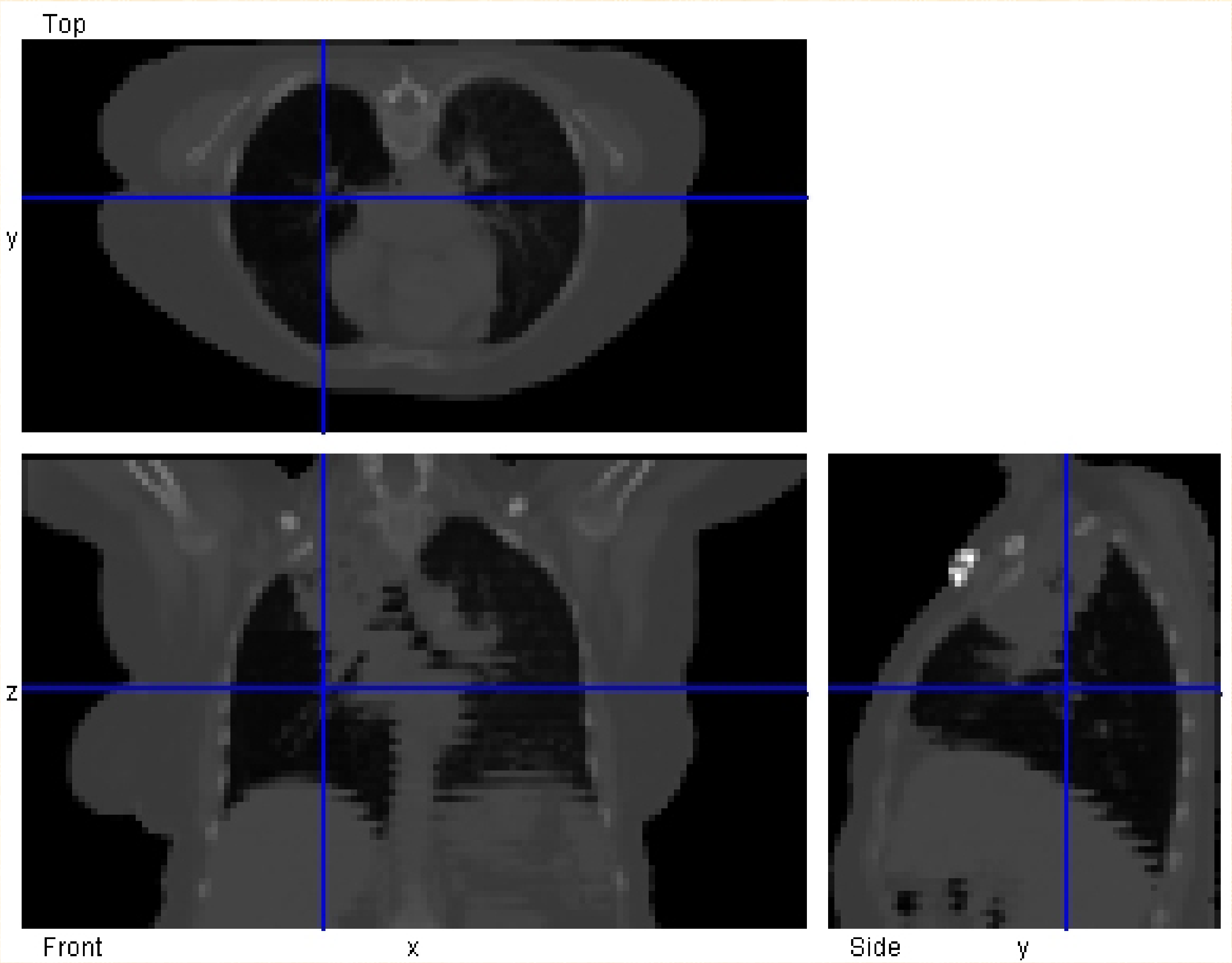
Energy Distribution of Source



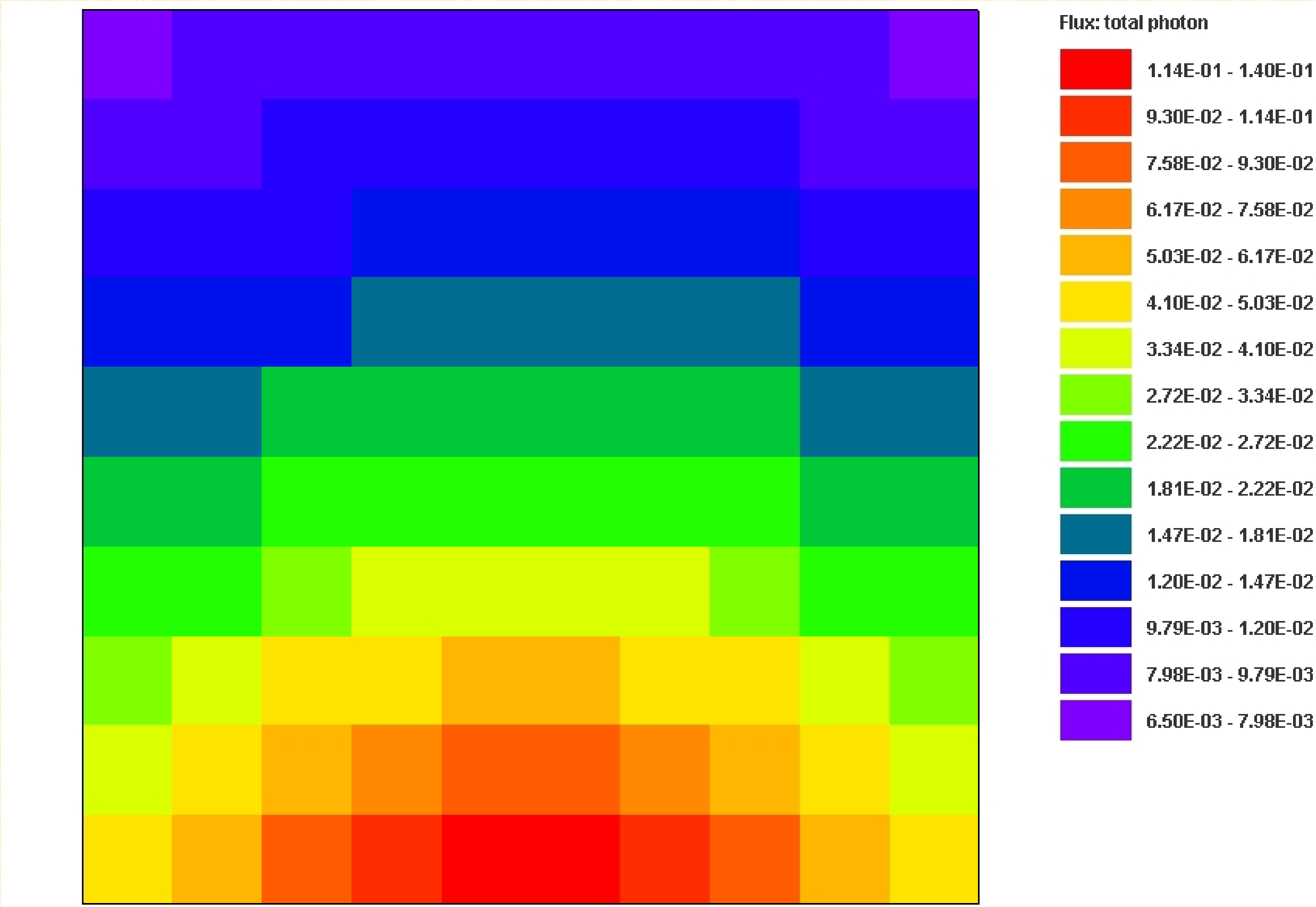
Source energy taken from approximation of CT scan (UNC Chapel Hill)



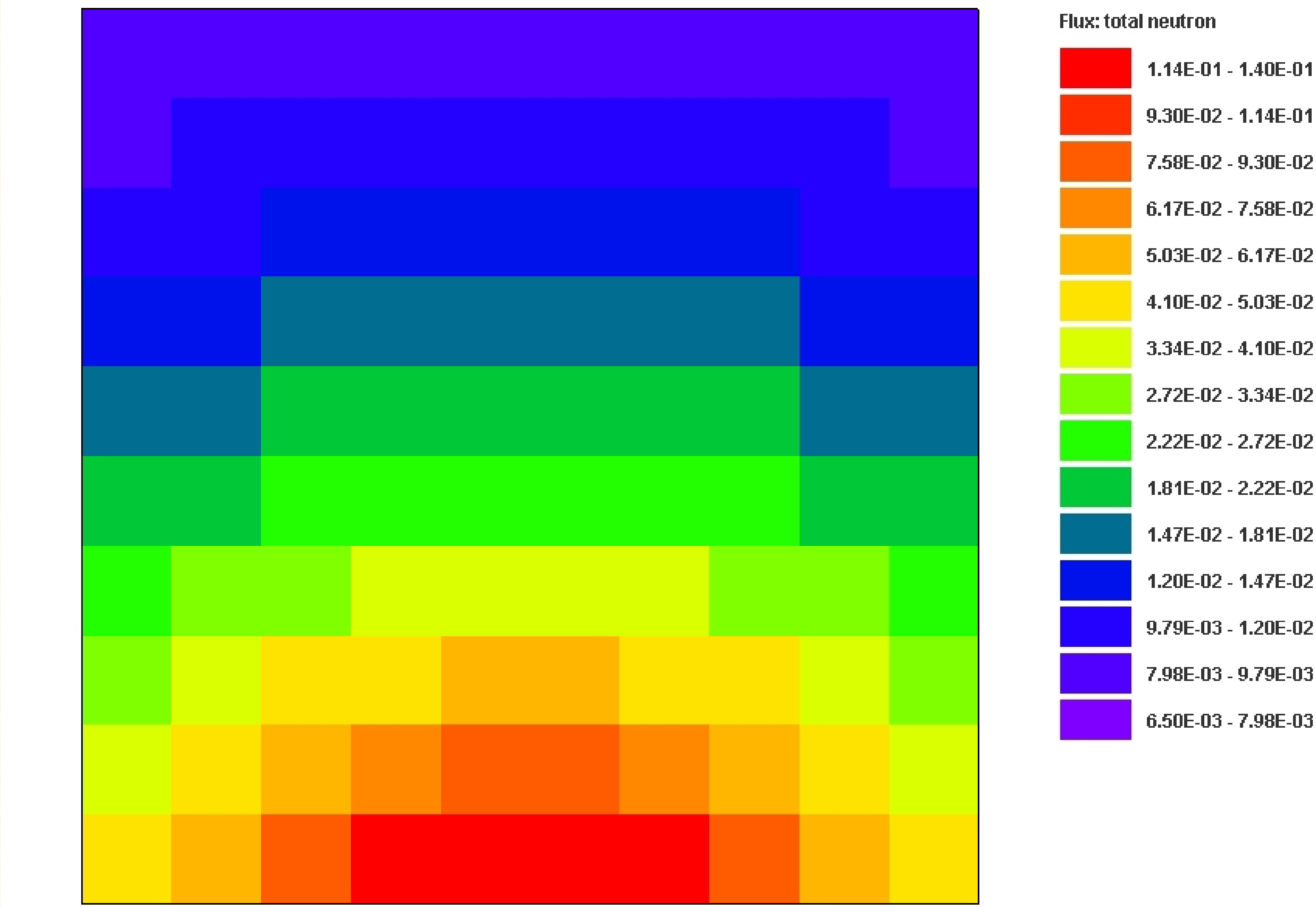
Position of Voxels on CT Image



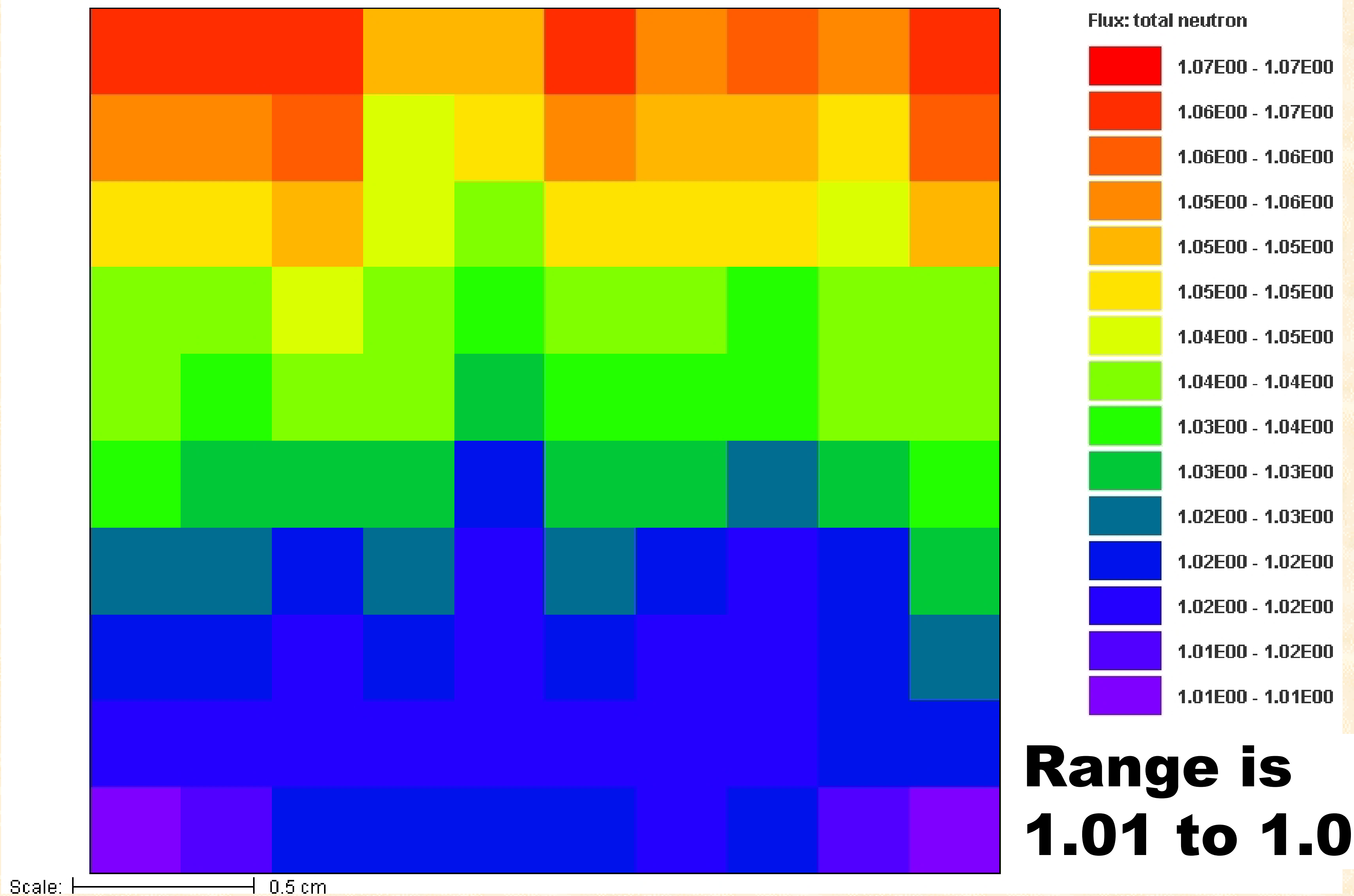
EGSnrc Photon Flux in Water Box



TORT Photon Flux in Water Box

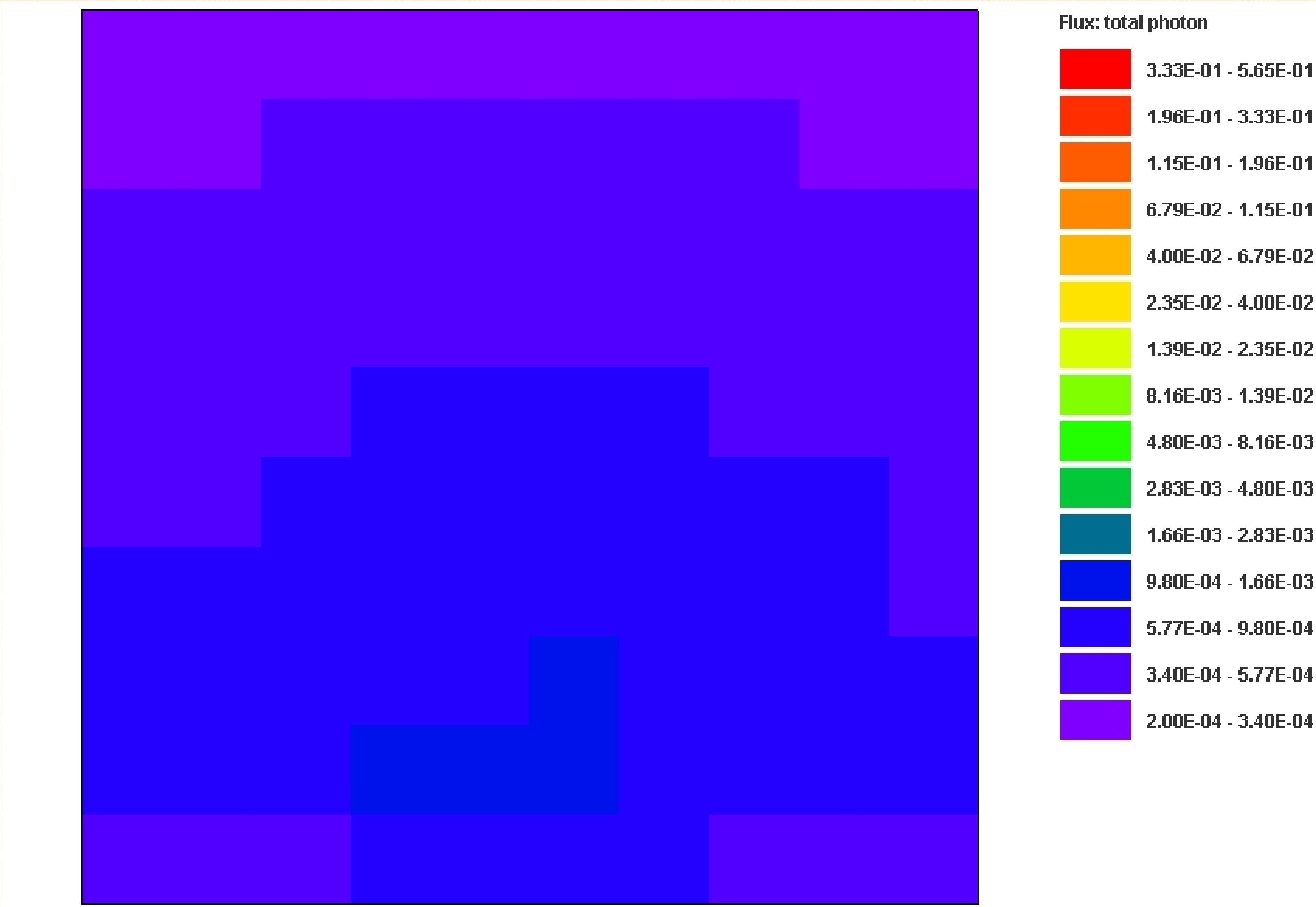


Ratio of EGSnrc to TORT Photon Flux

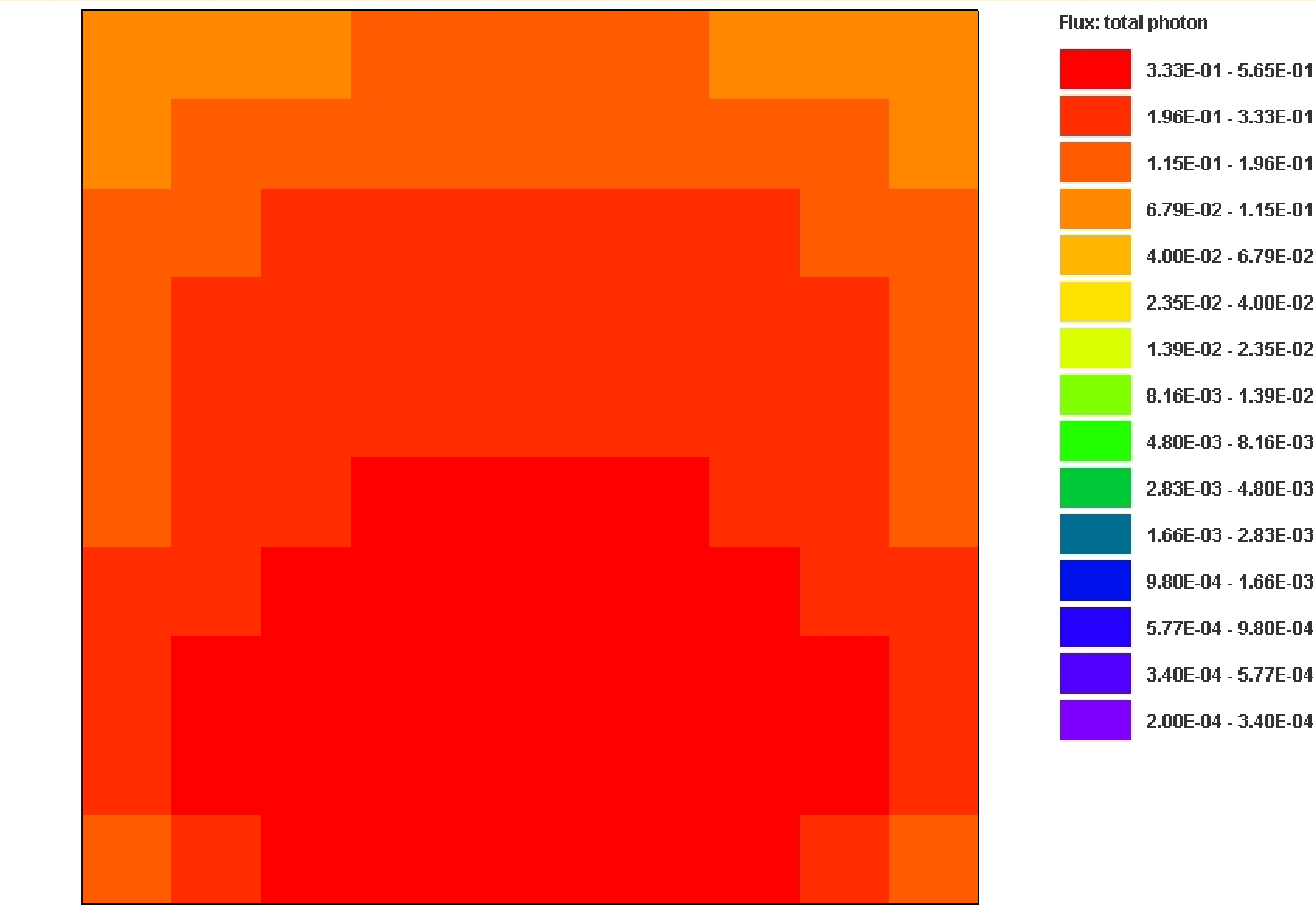


Range is 1.01 to 1.07

EGSnrc Electron Flux in Water Box



TORT Electron Flux in Water Box

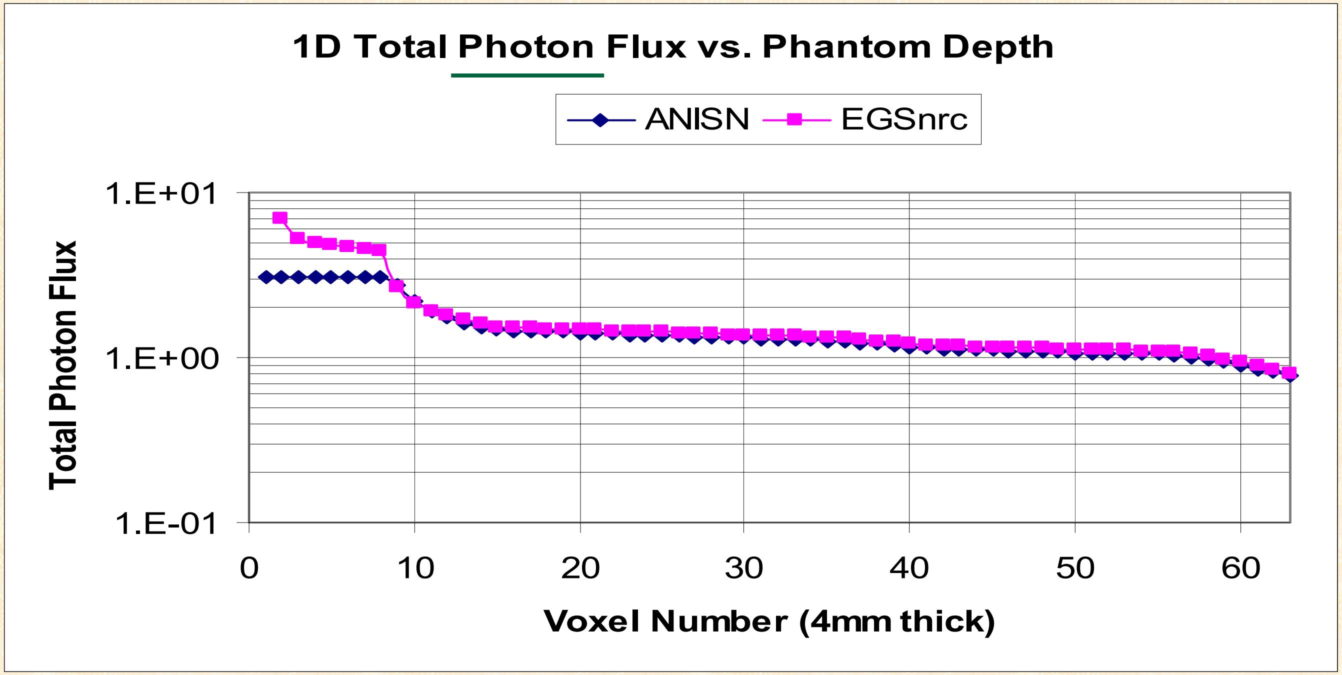


TORT Electron Flux in Water Box

- TORT photon flux was within about 5% of EGSnrc photon flux in all cases.
- TORT had disproportionately high electron flux in group 40.
- A source of only electrons was varied by group.
- Groups 1 through 5: flux only in 1 through 5 and in 40.
- Beyond group 5: flux in every group beyond the source group.
- This anomaly may be due to oscillations in the TORT electron solution.

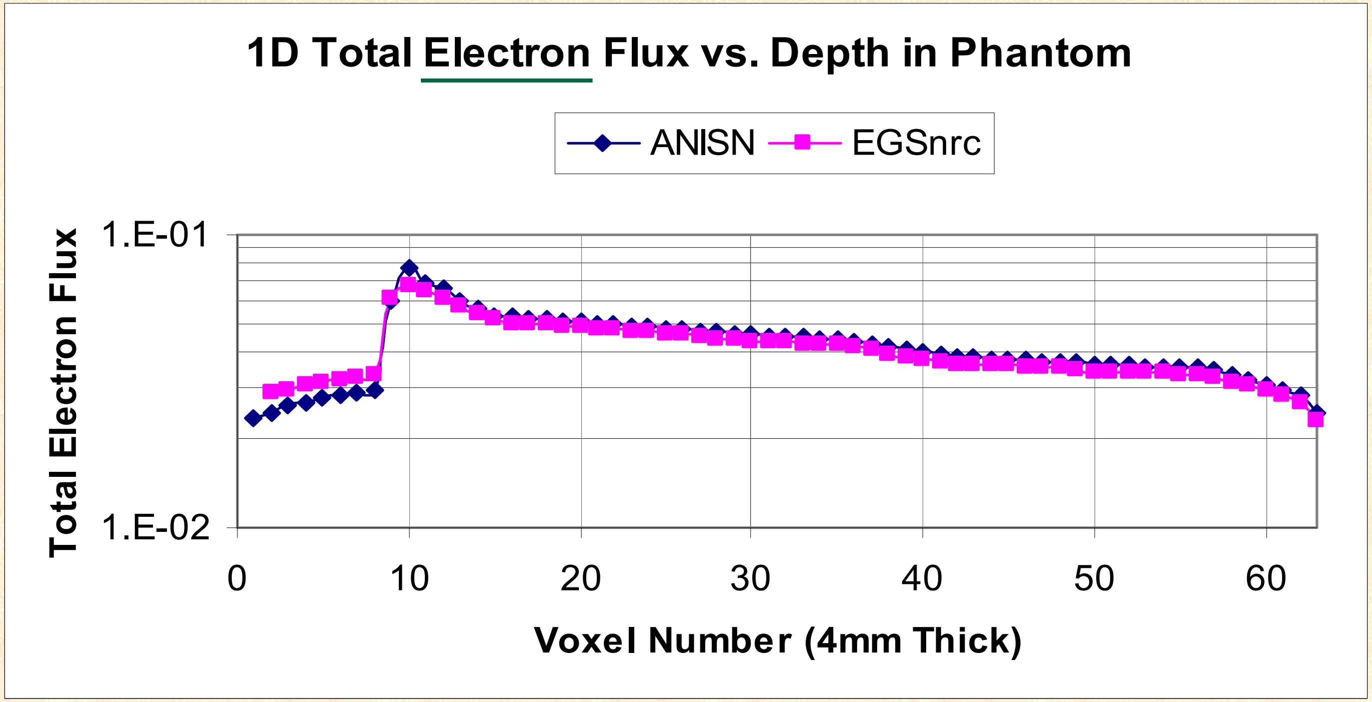
ANISN Flux in Lung Phantom(1)

- ANISN agreed well with the EGSnrc results after voxel number 10 for photons and electrons.
- The Differences were 4.4% with S_{16} and 4mm mesh size and 4.2% with S_{64} and 1mm mesh size.

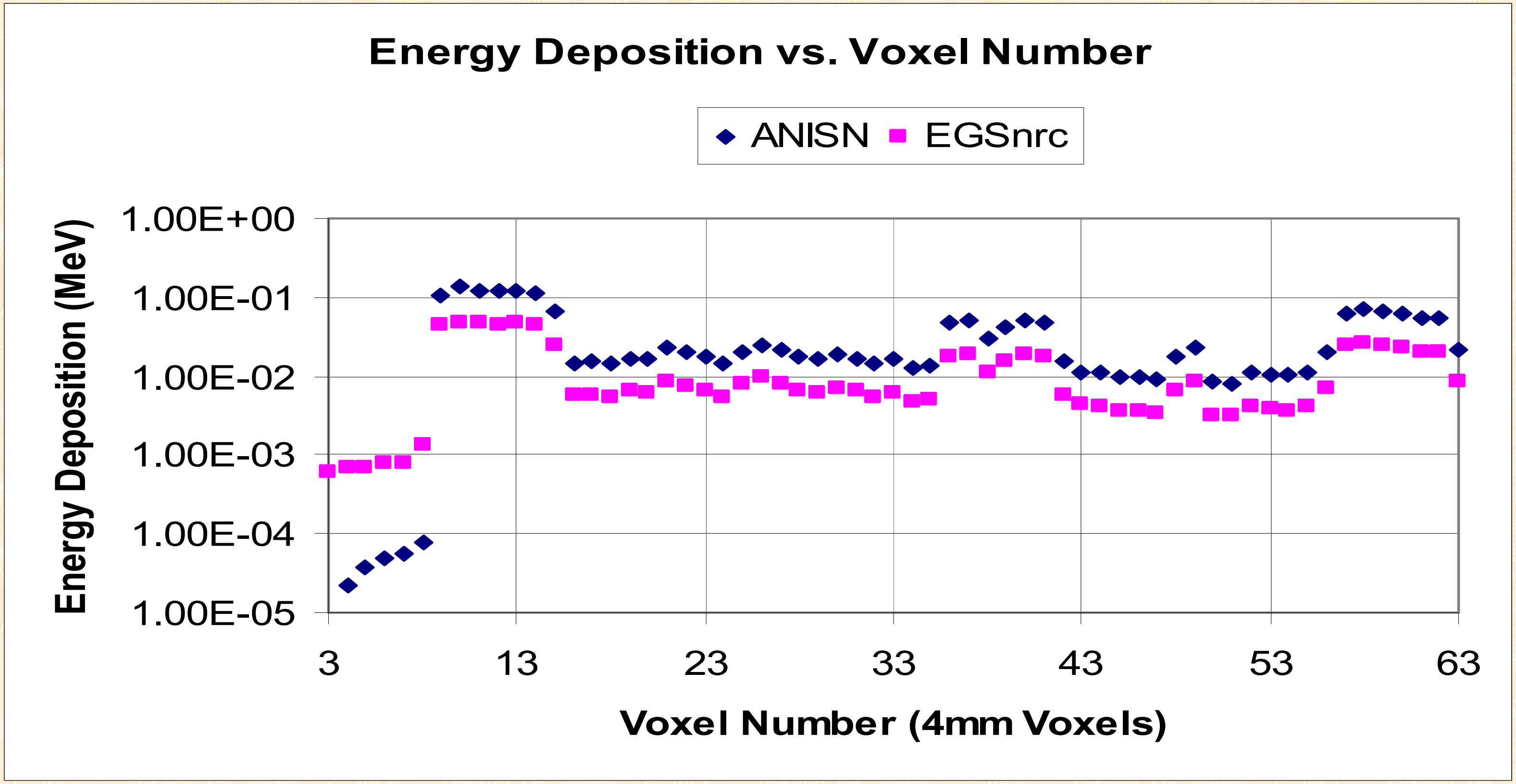


ANISN Flux in Lung Phantom(2)

- The agreement of the electron fluxes from both EGSnrc and ANISN is highly encouraging.
- ANISN results were in between EGSnrc and MCNP, which differed by 5%.



ANISN Energy Deposition in Lung Phantom



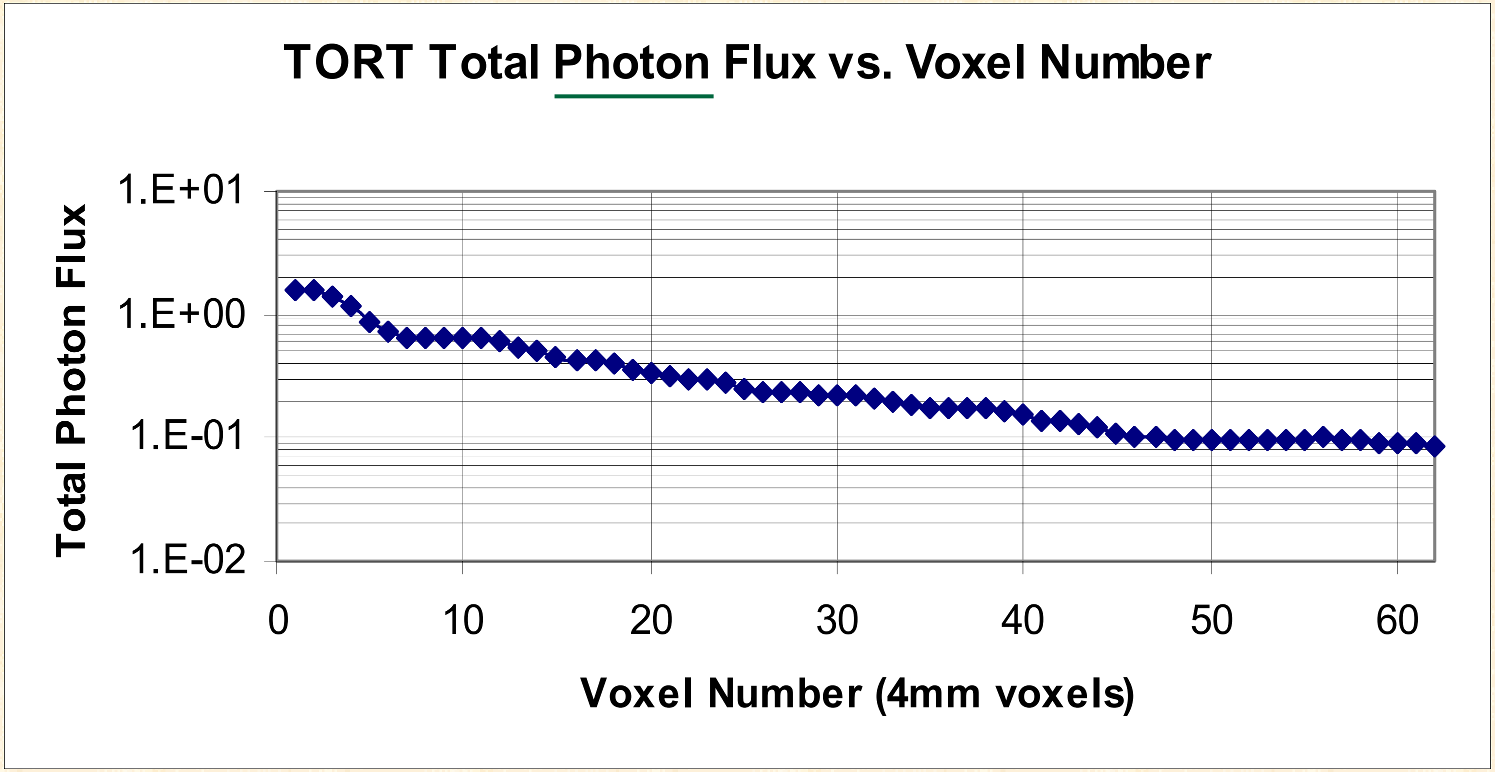
- High by a factor of 3.8, but the general trend is correct.
- Treatment of the kerma factors needs further investigation.

DORT Flux in Lung Phantom

- For photon flux in most voxels had errors of less than 5%; the largest error was within 10%.
- DORT generally overestimated the electron flux by about 10%.
- Some error may have come from approximating a 1-D solution with a 2-D code, but was still not as good as ANISN case .
- The energy deposition exhibited the same behavior as in ANISN.
- This confirms the need to further investigate the kerma factors.

TORT Flux in Lung Phantom

- TORT photon flux did not agree with EGSnrc.
- This is likely due to the implications of modeling a 1-D problem in 3-D.



Conclusions(1)

- The TORT results, coupled with the DORT results, suggest that the electron cross sections
  1) Are too large for the transport methods to give accurate answers in multi-D; or
  2) Are erroneous due to processing with CEPXS-BFP; or
  3) Large anisotropy might have made the Pn scattering approximation too inaccurate.

Conclusions(2)

- There is promise in continuing to investigate the use of discrete ordinates for RTP.
- ANISN accurately produced photon and electron fluxes, but overestimated the energy deposition.
- DORT had promising electron flux results, but had the same energy deposition trend as ANISN.
- TORT exhibited strange group behavior of the electron flux.
- The DOORS package proved to be able to handle some aspects of the charged particle transport, but also showed limitations.

Future Work

- Investigate why the energy deposition results from ANISN and DORT were off by a factor of almost 4 (i.e. kerma factors).
- Determine the source of electron flux error in multi-D.
- Future work could involve using the DOORS package and CEPXS-BFP as a foundation to develop a new code that incorporates the BFP formula for treating charged particles.

Acknowledgement and References

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