Optimization of the Selection Filter for Scattering-Based Proton Imaging

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INTRODUCTION

PROTON INTERACTIONS INSIDE MATTER

When protons are used for imaging purposes, they undergo various physical interactions which in turn yields to unique image formation characteristics, hence a more comprehensive diagnosis. That is, they interact with matter in two ways: with atomic electron by electromagnetic interaction and with the atomic nucleus via nuclear interaction, shown in figure 1.

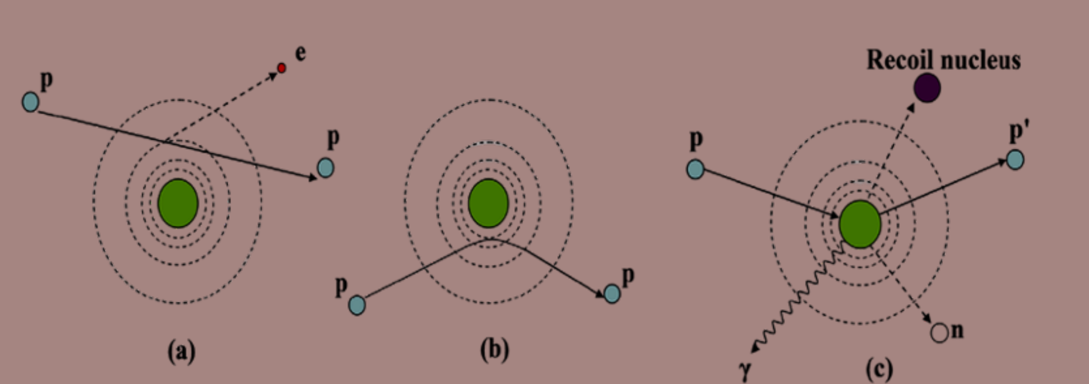

Figure 1. Schematic illustration of proton interaction mechanisms: (a) energy loss via inelastic Coulombic interactions, (b) deflection of proton trajectory by repulsive Coulomb elastic scattering with nucleus, (c) removal of primary proton and creation of secondary particles via non-elastic nuclear interaction (p: proton, e: electron, n: neutron, γ: gamma rays) [1].

Primarily, protons lose energy in Coulombic interactions with the outer shell electrons of the target atoms. Since they are relatively massive than electrons, they only lose a small fraction of their energy in a single interaction and are deflected by small angles in each interaction, characterized by multiple Coulomb scattering (MCS) illustrated below.

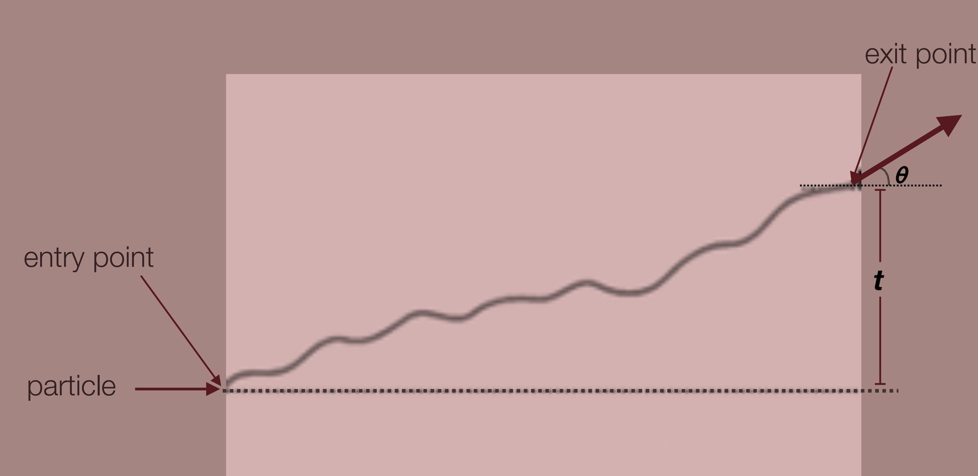

*Figure 2: Multiple Coulomb scattering of charged particles inside matter of thickness u. The scattering at the exit point is depicted by the lateral displacement **t** and an angular displacement **θ** [2].*

Aside from utilizing proton energy-loss and attenuation, we can further exploit proton interaction by considering the variance of the small – angle MCS [3].

METHODOLOGY

Data Simulation (GATE v.8.0)

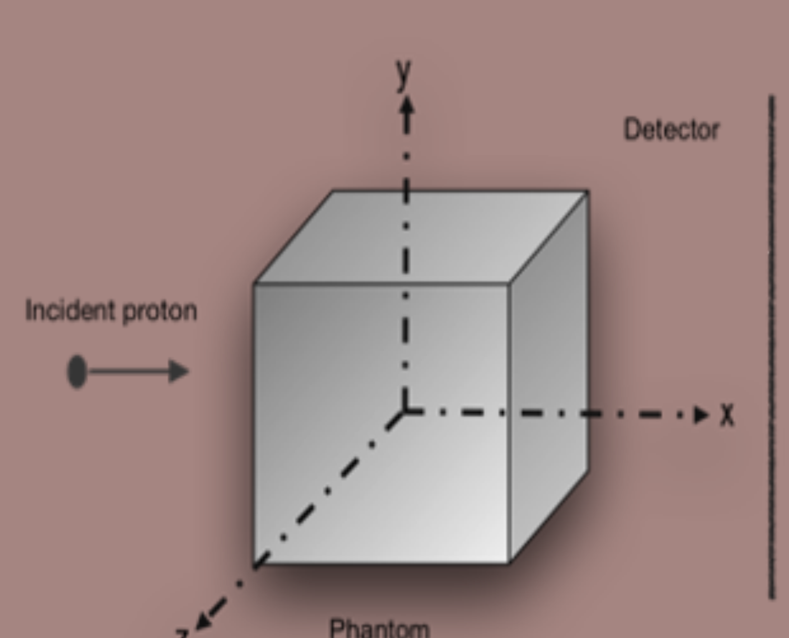

Figure 3: *Geometry of the Simulation*

The phantoms considered in the study are homogeneous water and alternating slab of water-bone-water with dimension 20 cm x 20 cm x 20 cm. The incident source is a pencil beam of monoenergetic and unidirectional protons of energy 200 MeV (homogeneous) and 300 MeV (hetereogeneous) positioned 10 cm before the phantom. A nuclear actor is then attached to the phantom to record the nuclear events of the detector located 10 cm away from the phantom.

Data Processing (ROOT v.6.19/01)

Employment of Selection Filter

Statistical Approximation: Sigma Cut

$$n\sigma_{cut} = \mu + n\sigma \quad \text{(upper limit)}$$

$$n\sigma_{cut} = \mu - n\sigma \quad \text{(lower limit)}$$

RESULTS AND DISCUSSION

HOMOGENEOUS WATER PHANTOM - 200 MeV

For homogeneous water phantom with 200 MeV incident proton energy, the angular variance of all protons recorded at the exit detector is measured to be 1.70x10^{-3} rad^2 while as for the reconstruction model, that is the angular variance of the distribution of primaries without nuclear interactions, this is accounted as 1.147x10^{-3} rad^2. In the figures below, x-axis indicates the sigma cut on exit angular distribution, y – axis as the sigma cut applied on exit energy distribution, and the z – axis which indicates the absolute percentage difference.

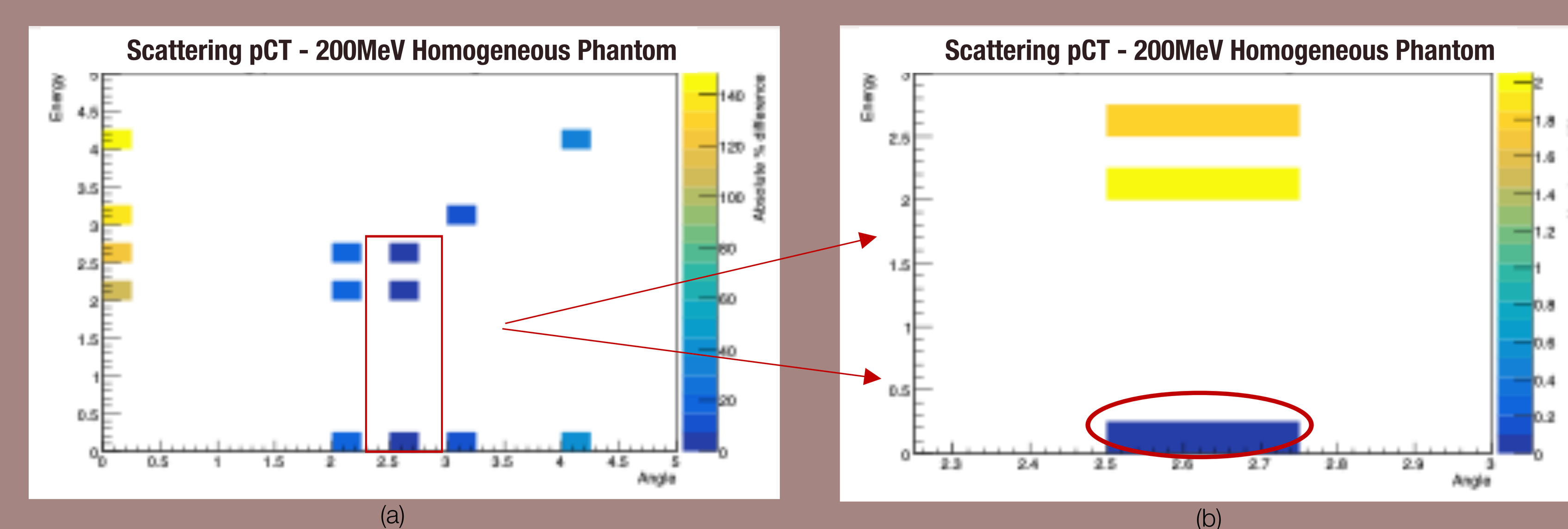

Figure 4. *3D plot of the calculated percentage difference of the angular variance after the application of selection filter for 200 MeV incident energy on 200 mm homogeneous water box. (b) zoomed in view of (a). *Note: The color variation (blue to yellow) indicates the absolute percentage difference with blue as the lowest and yellow as the highest percentage difference. Data point(s) enclosed with red circles are the optimal cuts for a given simulation setup.*

This yields to 15.19% error on the collected data. After applying 2.5σ_{cut} on exit angular distribution, the percentage error is reduced to 0.0265% for 200 MeV (see figure 4 (b)).

HETEROGENEOUS PHANTOM - 300 MeV

For the slab phantom, as shown in figure 5 (a), six (6) data points have the same darker blue shade. Zooming on these data points yields us fig. 5 (b), in which we have now two data points with the same green shade. Looking closely into these two points as presented in fig. 5 (c), we found that 2.5σ_{cut} on angular distribution provides the lowest percentage difference, improving further the accuracy of data selection by ~43%.

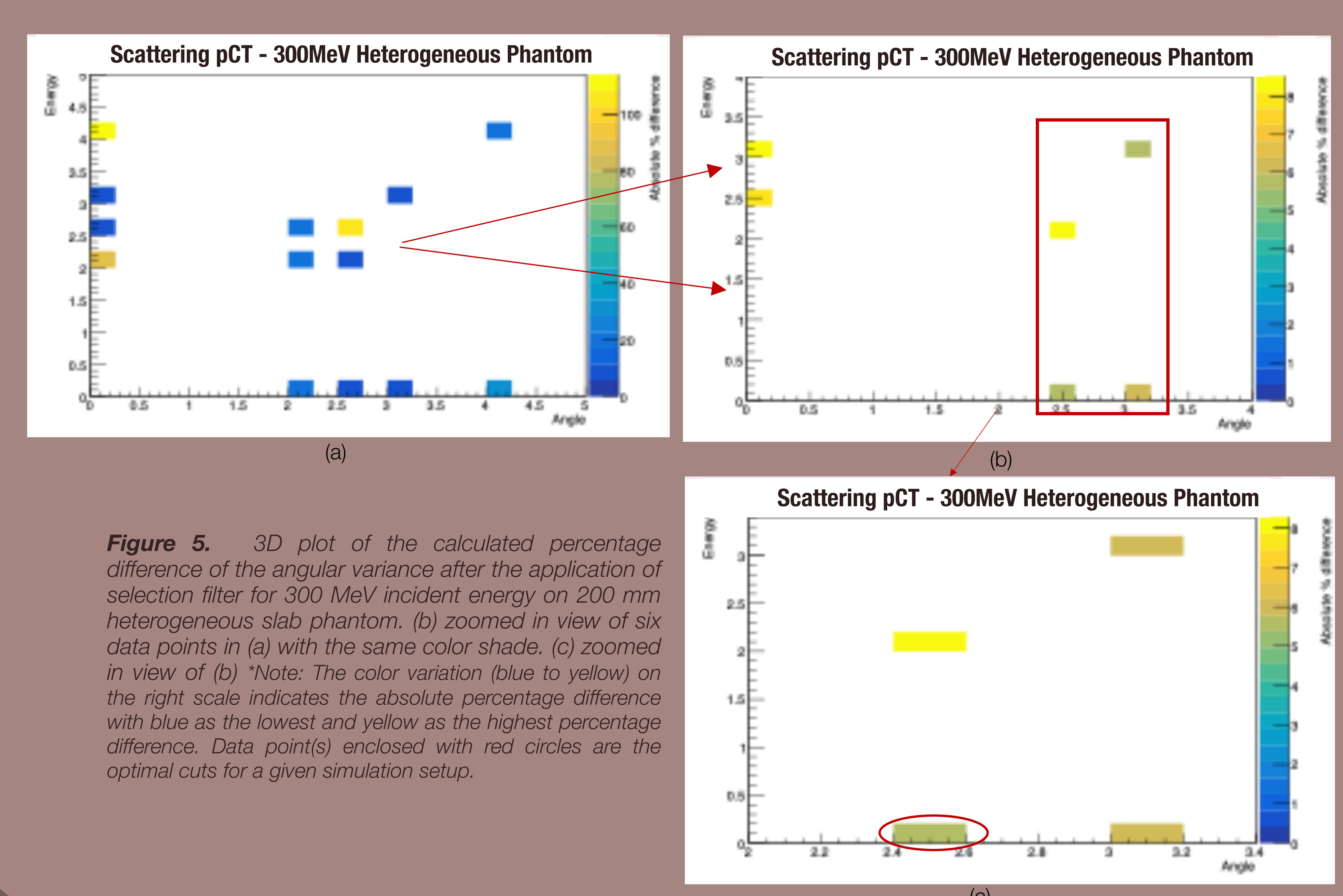

Figure 5. *3D plot of the calculated percentage difference of the angular variance after the application of selection filter for 300 MeV incident energy on 200 mm heterogeneous slab phantom. (b) zoomed in view of six data points in (a) with the same color shade. (c) zoomed in view of (b) *Note: The color variation (blue to yellow) on the right scale indicates the absolute percentage difference with blue as the lowest and yellow as the highest percentage difference. Data point(s) enclosed with red circles are the optimal cuts for a given simulation setup.*

CONCLUSION

In scattering pCT, the filter should be sensitive on the angular variance of the distributions since only those small-angle scattering protons are to be considered. Application of 2.5σ_{cut} on angular distribution closely mimics the reference angular variance for homogeneous water phantom with 200 MeV incident energy and for inhomogeneous slab phantom.

In clinical nature, proton therapy is rendered to human body consisting of inhomogeneous tissues of varying density and irregularity, it is recommended to extend the study on using target phantoms of considerably large distribution of tissue densities and compositions and verify the performance of the obtained optimal cut.

REFERENCES

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