

# Reduced Calibration Curve for Proton Computed Tomography

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**Abstract.** The pCT deals with relatively thick targets like the human head or trunk. Thus, the fidelity of pCT as a tool for proton therapy planning depends on the accuracy of physical formulas used for proton interaction with thick absorbers. Although the actual overall accuracy of the proton stopping power in the Bethe-Bloch domain is about 1%, the analytical calculations and the Monte Carlo simulations with codes like TRIM/SRIM, MCNPX and GEANT4 do not agreed with each other. A tentative to validate the codes against experimental data for thick absorbers bring some difficulties: only a few data is available and the existing data sets have been acquired at different initial proton energies, and for different absorber materials. In this work we compare the results of our Monte Carlo simulations with existing experimental data in terms of reduced calibration curve, i.e. the range – energy dependence normalized on the range scale by the full projected CSDA range for given initial proton energy in a given material, taken from the NIST PSTAR database, and on the final proton energy scale – by the given initial energy of protons. This approach is almost energy and material independent. The results of our analysis are important for pCT development because the contradictions observed at arbitrary low initial proton energies could be easily scaled now to typical pCT energies.

**Keywords:** Proton beams, Energy measurement, Calibration curve, Monte Carlo methods.

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## INTRODUCTION

The interaction of heavy charged particles with thick absorbers has well established analytical description [1]. In addition, the Monte Carlo simulation for this process has a long and successful history [2]. Nevertheless, we have meet the situations while our simulations with such popular codes like TRIM/SRIM [2], MCNPX [3] and GEANT4 [4] do not agreed with each other [5]. It should be stressed that naturally we do not expect an absolute coincidence of the proton spectra generated by such different codes. However, the differences in mean final energy of about 10 MeV for protons with initial energy 250MeV after 34 cm water absorber pied our attention [6].

A tentative to validate the codes against experimental data for thick absorbers bring us some difficulties: only a few data is available and the existing data sets have been acquired at different initial proton energies, and for different absorber materials. In particular, we succeed to compare TRIM, MCNPX and GEANT4 simulations with the experimental spectra for a number of Al absorbers with various thicknesses for 19.68 MeV [7] and 49.1 MeV [8] protons passing through, for two Au targets and 49.1 MeV protons [9], and for polyethylene absorber and 25 MeV protons [10].

In this work we will try to generalize these results to cover the initial proton energy range from approximately 25 MeV up to 250 MeV having in mind the applications for proton computed tomography (pCT) [11]. We hope, however, that our analysis will light up some unobvious nuances in the  $\Delta E$ -E method exploration as well.

It should be stressed that our analysis is strictly limited to the so-called "Bathe-Bloch region" [1,2], i.e. the formation of the so-called "Bragg peak" is out of our interest. Two criteria were employed to cut the Bragg peak from the analysis: first, the final proton energy after absorber should be above 2 MeV, and second, the so-called "Detour factor" predicted by the NIST PSTAR [12] should not be less than 1.00 within 1% tolerance.

Although the GEANT4 has been validated against the NIST PSTAR stopping powers (SP) for protons [13], and the TRIM use SRIM reference SP table [2], the simulated spectra have significant contradictions with experiment for thick absorbers. It means that in this case the about 1% accuracy of SPs (for the discussed proton energies) in [2,12] is not enough.

## REDUCED CALIBRATION CURVE

### WET Calibration Problem in pCT

The calibration curve in pCT is the average residual energy as a function of the proton pass in water for fixed initial energy, which permits to determinate the Water Equivalent Thickness (WET) of any absorber by the measurement of mean outgoing proton energy [14,15]. This curve could be easily build basing on NIST PSTAR and SRIM reference tables for the projected ranges, or calculated within the Continuous Slowing Down Approximation (CSDA) [1,2]. However, the problem is that the absolute values will be different depending on the way of curve constructing.

For example, one can easily checkup that the 250 MeV protons will be totally stopped by only 375 mm of water according to the SRIM, while the NIST PSTAR projected range value is 379 mm. Correspondently, while estimate the final energy of these protons after 30 cm of water, the difference will be about 2.5 MeV, or 2.5% as the energy is very closed to 100 MeV (See **FIGURE 1**). It is interesting to note also that the Monte Carlo simulations with GEANT4 and TRIM/SRIM are agreed with NIST PSTAR and SRIM based calibration curves correspondently (See **FIGURE 1**). It should be noted that for all figures in this work the statistical error bars are smaller than the point dimensions.

This 2.5% disagreement of these two calibration curves takes place while the differences in total, and (which is practically the same) electronic SP given by reference tables is less than 1.2% in the proton energy range 100÷250 MeV. This

reflects the fact that the measuring of "integrated" energy loss in a thick absorber provides more sensitive test than the measurements of "differential" energy loss in a very thin target.

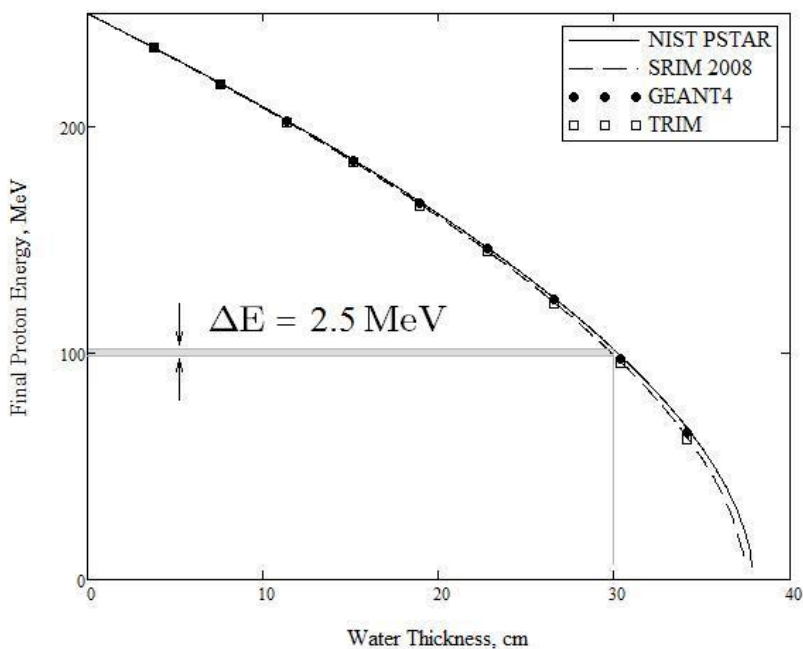


FIGURE 1. The WET calibration curve for 250 MeV protons.

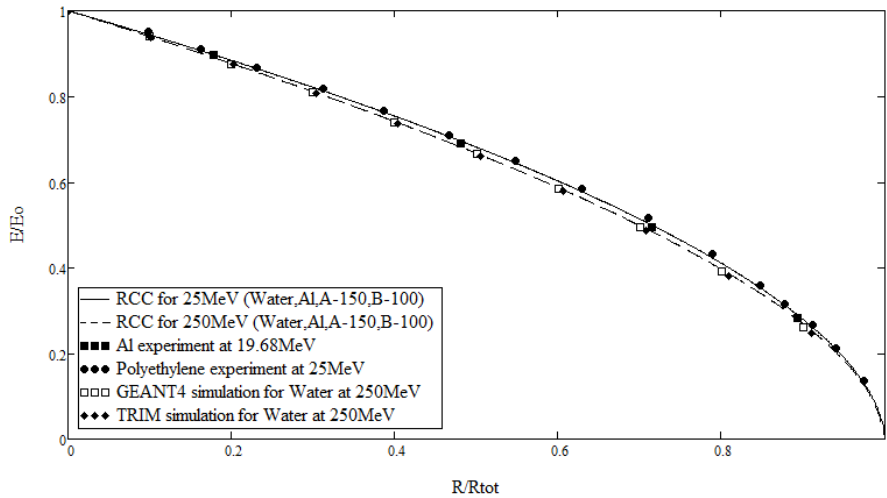
## Reduced Calibration Curve

In experimental practice a solid target is obviously preferable. In literature, there are several experimental data sets obtained on solid targets [16,17]. However, these data sets were obtained for different materials at different initial proton energies. The method we propose to include these data in analysis is to use the reduced calibration curve.

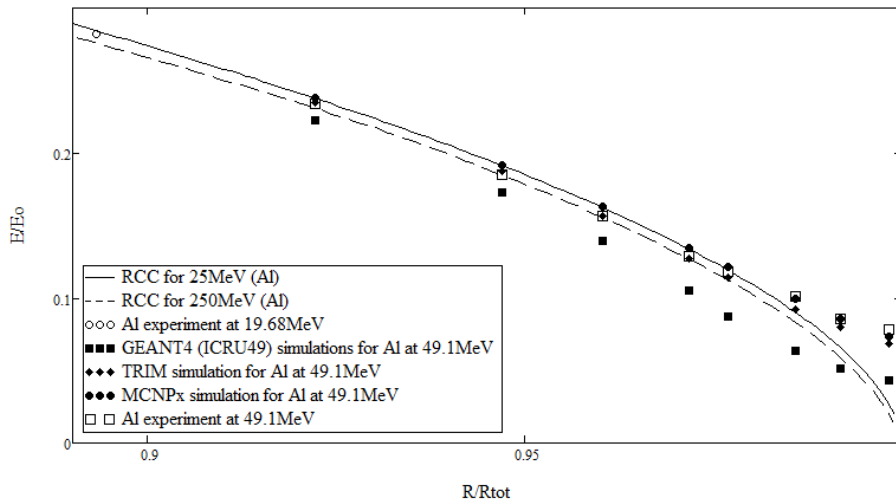
It is easy to show that if one will measure absorber thickness in the full CSDA range units, i.e. as  $R/R_{tot}(E_0)$  ratio, and the outgoing proton energy in the initial energy units, i.e. as  $E/E_0$  ratio, the resulted range – energy dependence (calibration curve) will be almost energy and material independent (See FIGURE 2). It is not absolutely true for any energy and material, but at least for the initial proton energies from approximately 25 MeV to 250 MeV and chemical elements and mixtures with  $Z/A \sim 1/2$  it happens within a few percent accuracy.

For instance, there was no any possibility to show separately the calibration curves for H<sub>2</sub>O, Al, A-150 and B-100 plastics for 25 MeV and 250 MeV protons on FIGURE 2 just because the relative differences are less than 0.5%. There are no visible differences between the NIST PSTAR and SRIM based curves as well, if only the thickness scale is normalized for  $R_{tot}$  from the corresponding table.

It is interesting to note that GEANT4 and TRIM/SRIM simulated results for water absorber and 250 MeV protons became agreed with each other and the corresponding calibration curve (Compare **FIGURE 1** and **FIGURE 2**). The experimental data for Al absorber obtained with 19.68 MeV protons in [16] and for polyethylene at 25MeV [17] are in a very good agreement with reduced calibration curve on **FIGURE 2** as well.



**FIGURE 2.** The reduced calibration curve for 25÷250 MeV protons.



**FIGURE 3.** The reduced calibration curve for 25÷250 MeV protons – only the part of thickest absorbers.

## MONTE CARLO SIMULATIONS AGAINST EXPERIMENT

Let us now compare our Monte Carlo simulations with existing experimental data for thick Al absorber [16] in the terms of reduced calibration curve (See **FIGURE 3**). This method of comparison has obvious advantage – the data obtained at 19.68 MeV and 49.1 MeV can now be treated as a unique sequence (the open circles and open boxes at the figure). As the **FIGURE 3** just represents the bottom-right part of the **FIGURE 2** in an amplified form, but with additional data has not been easy to visualize within the scale of **FIGURE 2**, it becomes obvious that the 49.1 MeV data for Al are roughly perfectly falling on the general trend.

It can be seen that our TRIM/SRIM2008 and MCNPX simulations reproduce the experimental data for 49.1 MeV protons. At the same time, the GEANT4 simulation in the standard execution mode does not imitate well the experimental values. Moreover, it is far from the general trend in this case.

## CONCLUSIONS

The reduced calibration curve was proposed as a tool for simultaneous analysis of the experimental data or/and the computer simulations obtained for any initial proton energy from the range 25÷250 MeV and any absorber material with  $Z/A \sim 1/2$ . The reduced calibration curves were erected from NIST PSTAR and SRIM reference data tables for H<sub>2</sub>O, Al, A-150 and B-100 absorbers.

The curves were compared with TRIM/SRIM and GEANT4 simulations for water and 250 MeV protons. It was shown that in the reduced form, the noticeable disagreements between NIST PSTAR and SRIM data, and, consequently, between GEANT4 and TRIM/SRIM simulations are generally disappearing.

The method was tested involving the experimental data for polyethylene obtained with 25 MeV protons, and Al absorbers measured with 19.68 MeV and 49.1 MeV protons. The last ones were compared with TRIM/SRIM, MCNPX and GEANT4 simulations.

It was shown that our GEANT4 simulations have a tendency to fall down from the general trend with the increasing of the absorber thickness at least for this case. It gives us an additional strong argument to discard absolute error in the energy scale of experiment [16] as a possible reason of disagreement with GEANT4 simulations.

However, the comparison with only a few sets of experimental data was not enough to make a definitive choice for the most adequate way to use GEANT4 for pCT simulations. Thus, we are planning to continue this work involving other experimental data and computer simulations into analysis within the reduced calibration approach.

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