2024 International Nuclear Atlantic Conference – INAC 2024
Escola de Guerra Naval, Rio de Janeiro, RJ, May 6 - 10, 2024

ISBN: 978-65-594-1256-3

Study of the Behavior of 3 MeV Proton Beams on PMMA: Monte Carlo Simulations and Experimental Data

J. Pereira[1], F. Matias[1], P. Antunes[1], J. Shorto[1], P. Siqueira[1], T. Silva[2], C. Rodrigues[2], L. Otubo[1], G. Ferreira[1] and H. Yoriyaz[1]

[1] *juliojose-jj@usp.br, Instituto de Pesquisas Energéticas e Nucleares, IPEN-CNEN/SP, Av. Prof. Lineu Prestes, 2242 – Cidade Universitária – CEP 05508-000, São Paulo – SP – Brasil*

[2] *tfsilva@if.usp.br, Instituto de Física da Universidade de São Paulo, IFUSP, Rua do Matão, trav. R187 – Cidade Universitária – CEP 05508-090, São Paulo – SP – Brasil*

1. Introduction

The proton interacts with matter in various ways, including energy loss through inelastic Coulomb interactions, deviation of its trajectory due to Coulomb repulsive scattering by the nucleus, removal of the primary proton, and creation of secondary particles through non-elastic nuclear interactions [1]. These mechanisms were fundamental to the development of proton therapy, a cancer treatment approach proposed in 1946 by Robert Wilson [2]. This technique utilizes the finite range and Bragg peak of proton beams to treat deep targets within healthy tissue [3].

The main advantage of proton therapy lies in its ability to control the depth at which most of the energy is released. This phenomenon is observed due to the nearly constant energy deposition of protons initially, followed by a sharp increase as the beam penetrates matter, reaching a peak near and then abruptly decreasing until reaching the particle's final range [4].

Measurements of Dmax, which indicate the depth where the maximum radiation dose is reached [5], are equivalent to the beam's energy depth and play a crucial role in analyzing the characteristics of a proton beam. The range of this beam is directly linked to the initial energy and the medium it traverses [4], highlighting the importance of Dmax measurements in characterizing and understanding beam behavior.

In light of this, Monte Carlo simulations were conducted using the TOPAS (Tool for Particle Simulation) code [6] and MCNP (Monte Carlo N-Particle) [7], in addition to irradiation experiments conducted at the Laboratory of Materials Analysis by Ion Beam at the University of São Paulo (LAMFI – USP) and analyses at the Microscopy and Microanalysis Laboratory of IPEN. The aim of these activities was to determine the value of Dmax and compare the results obtained through simulations with experimental data.

2. Methodology

Figure 1 depicts the geometry employed in the simulations, which comprises an "infinite" vacuum cylinder surrounding a cylindrical simulator object made of PMMA, with a radius of 1.5 cm and a length of 133 µm, subdivided into 700 layers of 0.19 µm each. The radiation source consists of a monoenergetic beam of protons with a circular shape, having a radius of 0.1 mm and an energy of 3 MeV. The aforementioned proton beam is positioned at a distance of 5.0 cm from the simulator object along the central axis.

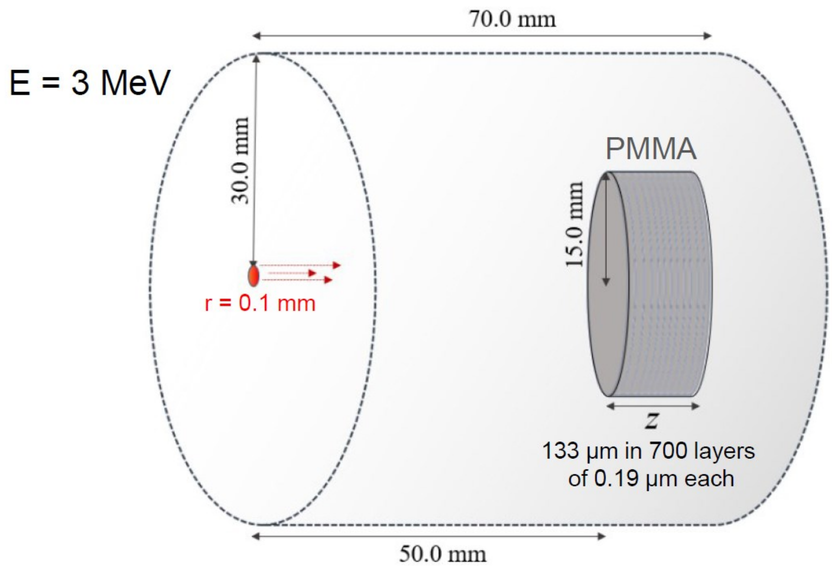

Figure 1: Representation of the geometry used in the simulations.

In TOPAS, the estimator named "EnergyDeposit" was used, which, when divided by the mass of each layer, provides the absorbed dose in MeV/g.particle from the source. In the case of MCNP, the same measure was obtained through the F4 estimator, which computes the fluence in 1/cm².particle from the source, which is then converted to Dose in MeV/g.particle by multiplying by the stopping power, using the DE (Dose Energy) and DF (Dose Function) cards.
After calculating the Absorbed Dose, the data were analyzed in Excel for each combination of energy and material. During this process, the depth layers z were organized along with their corresponding doses, and then normalized. The goal was to precisely identify the point at which the maximum dose occurred, along with the depth corresponding to this maximum dose. This procedure provided the determination of the value of Dmax.
Beyond simulations, irradiations of PMMA were carried out using 3 MeV beams at the LAMFI-USP facilities. This laboratory features a Pelletron-tandem electrostatic accelerator, model 5SDH.
Sample analyses were performed using a high-resolution scanning electron microscope (JSM-6701F, Jeol) located at the Microscopy and Microanalysis Laboratory within the Materials Science and Technology Center (CECTM) at IPEN.

3. Results and Discussion

The figure 2 displays the dose graph in MeV/g•source particle for simulations involving TOPAS and MCNP, providing visualization of the differences between the curves generated by the respective codes.

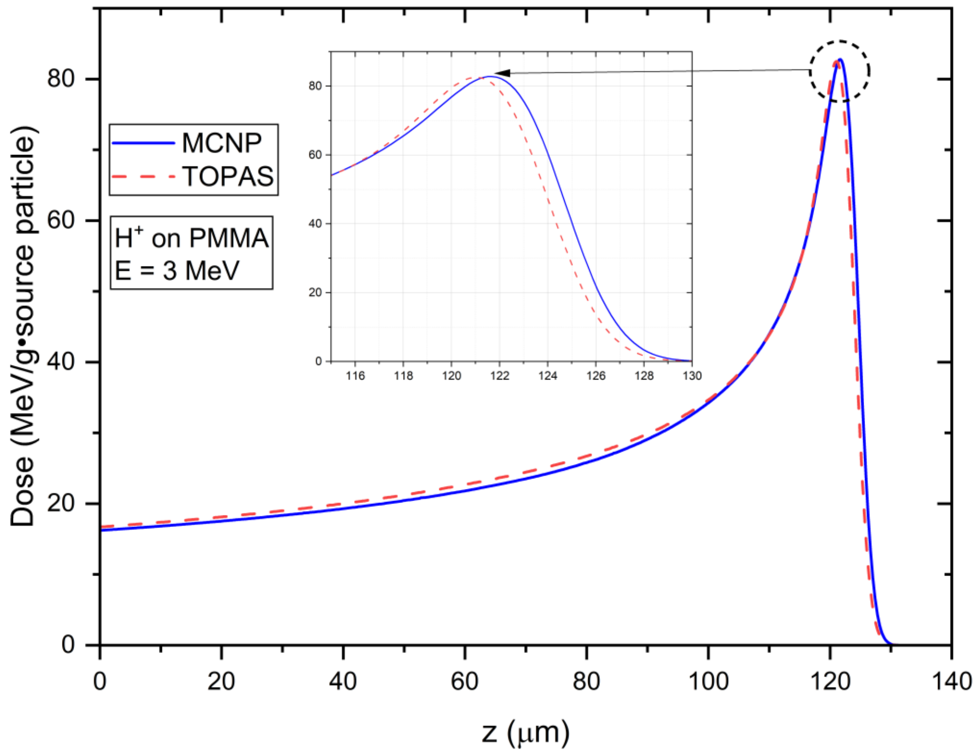

Figure 2: Dose graph in MeV/g•source particle for simulations involving TOPAS and MCNP.

The Dmax value for TOPAS was 121.13 µm, whereas for MCNP it was 121.70 µm. Both demonstrated a relative error smaller than 0.05% in the result. When considering TOPAS as the reference, a absolute difference of -0.57 µm and a relative difference of 0.47% between the codes were observed.
In figure 3, the depth results for two different samples of PMMA when exposed to a 3 MeV energy beam are presented, with values recorded at 105.07 µm and 106.25 µm, respectively.

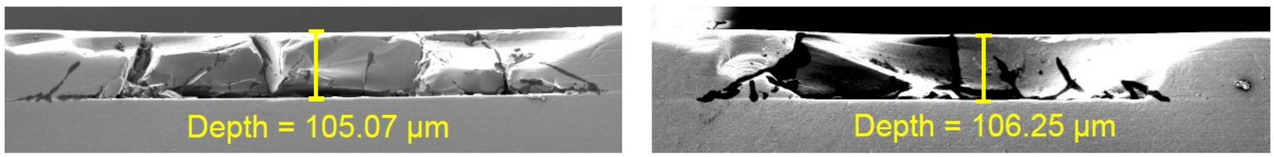

Figure 3: Depth values for two PMMA samples exposed to a 3 MeV energy beam.

4. Conclusions

Although the maximum discrepancy between experimental results and Monte Carlo simulations is less than 17 µm, additional studies will be required to delve deeper into investigating PMMA's response to beam energy in the material and understanding the analysis of samples using a high-resolution scanning electron microscope.
The acquisition of conclusive experimental results will enable direct validation of simulated results and provide a solid foundation for interpreting and applying these simulations in various contexts.

Acknowledgements

To CAPES for granting the scholarship under process 88887.704665/2022-00 and to IPEN for funding project 2020.06.IPEN.32.

References

[1] W. Newhauser, “The physics of proton therapy”, *Physics in Medicine and Biology*, vol. 60, pp. 155-209 (2015).

[2] H. Paganetti, *Proton Therapy Physics*, CRC Press, Boca Raton USA (2020).

[3] R. Wilson, “Radiological Use of Fast Protons”, *Radiology*, v. 47, n. 5, pp. 487-491 (1946).

[4] H. Yoriyaz, “Fundamentos de Transporte e Cálculo de Dose em Tratamentos com Feixes de Prótons”, *Revista Brasileira de Física Médica*, v.13, n.1, pp. 141-149 (2009).

[5] “Module 1: An Introduction to Proton Therapy”, https://www.oncolink.org/healthcare professionals/oncolink-university/proton-therapy-professional-education/oncolink-proton-education-modules/module-1-an-introduction-to-proton-therapy (2024).

[6] B. Faddegon, “The TOPAS tool for particle simulation, a Monte Carlo simulation tool for physics, biology and clinical research”, *Physica Medica*, v. 72, pp. 114-121 (2020).

[7] C. Werner, *MCNP Users Manual*, Los Alamos National Security, Los Alamos USA (2017).