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On the accuracy of Monte Carlo based beam dynamics models for the degrader in proton therapy facilities

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ABSTRACT

In a cyclotron-based proton therapy facility, the energy changes are performed by means of a degrader of variable thickness. The interaction of the proton beam with the degrader creates energy tails and increases the beam emittance. An accurate model of the degraded beam properties is important not only to better understand the performance of a facility already in operation, but also to support the development of new proton therapy concepts. The precision of the degraded beam properties, in terms of energy spectrum and transverse phase space, is influenced by approximations in the model of the particle–matter interaction. In this work the model of a graphite degrader has been developed with four Monte Carlo codes: three conventional Monte Carlo codes (FLUKA, GEANT4 and MCNPX) and the multi-purpose particle tracking code OPAL equipped with a simplified Monte Carlo routine. From the comparison between the different codes, we can deduce how the accuracy of the degrader model influences the precision of the beam dynamics model of a possible transport line downstream of the degrader.

1. Introduction

In particle therapy facilities, the depth–dose distribution to the tumor requires the delivery of different beam energies. In a cyclotron-based facility the different energies are obtained slowing the proton beam down in a degrader of variable thickness [1]. However, a consequence of the degradation process is the increase of the beam emittance and energy spread.

In the last years, several studies have been performed to improve and optimize the efficiency of the energy degrading process. Besides graphite, the use of alternative materials, such as beryllium [2] or boron carbide [3], was investigated to minimize emittance growth by energy degradation. In the same way, different degrader geometries were proposed to minimize the beam losses and limit the beam phase space [4,5].

These studies are normally performed using fully integrated Monte Carlo (MC) codes (e.g. FLUKA [6], GEANT4 [7], MCNPX [8]). The energy loss, elastic and inelastic scattering and secondary particle production due to the proton interaction with the degrader can be modeled precisely. In other studies, some approximations are used, for example assuming different approaches for the multiple Coulomb scattering [9], small angle scattering [10] or thin degrader with negligible variation of the particle momentum [11]. In these cases, the model accuracy of the particle–matter interaction is of course reduced in comparison with the results from general MC codes.

For a cyclotron-based proton therapy facility, an accurate particle–matter interaction model for the degrader allows a better understanding of important beam parameters such as the reference energy, transverse emittance and beam current at the degrader exit. The undesired side-effects of the degradation process are compensated, at the cost of beam intensity, by the use of a pair of collimators that reduce the beam phase space to match the acceptance of the transport line. The energy spread is controlled by means of an energy selection system (ESS), i.e. an horizontal slit in the dispersive area between two bending magnets downstream of the degrader. The accuracy of the degrader model determines the precision of the predicted proton beam properties along the transport line downstream of the degrader as well as the losses at the collimators and at the ESS [12].

Here we investigate how the accuracy of the degrader model is influenced by the use of different particle–matter interaction algorithms and approximations. In particular, we compare the results of a graphite degrader simulated with three fully integrated conventional MC codes (FLUKA, GEANT4 and MCNPX) and with a multi-particle accelerator tracker, called OPAL, equipped with a simplified MC model for particle–matter interaction [13]. In order to obtain precise and reliable predictions of the beam properties, the use a tracking code with the ability to

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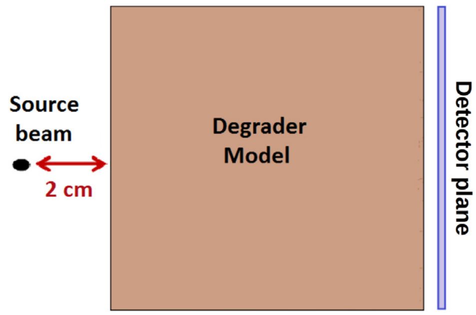

Fig. 1. Sketch of the model setup for the degrader simulation.

perform MC simulations of particle–matter interaction is of advantage. The multi-purpose particle tracking code OPAL has this capability and its potential in such an application has been already proven in [14].

The comparison between the four MC codes is performed on the main beam parameters (e.g. degraded energy spectrum, growth of the phase space volume, contribution of the inelastic scattering to the total spectrum) which are normally used as starting conditions to develop the beam dynamics model of the transport line downstream of the degrader. Our goal is to deduce how different particle–matter interaction models influence the beam parameters after the degrader and hence the accuracy of the beam dynamics model of the subsequent transport line.

In Section 2, the model setup used in this work is described. The main features of the four MC codes are summarized in Section 3. The methods developed for the analysis and results of the comparison are presented in Section 5. In Section 6 the influence that the degraded beam parameters from the four MC codes have on the model of the transport line downstream of the degrader is discussed.

2. The model setup

The model described in this work is based on the graphite degrader installed in the PROSCAN facility at the Paul Scherrer Institut (PSI) in Switzerland [15]. In this facility, a 250 MeV proton beam is extracted from the superconducting cyclotron COMET and focused by a quadrupole triplet onto the degrader, which consists of two pairs of three movable graphite wedges (see Section 2.2 for more details).

Here the model setup is quite simple: an ideal proton beam source (see Section 2.1) interacts with the graphite degrader placed 2 cm downstream. The model setup does not include any focusing element. This avoids additional complications arising from the use of the magnetic elements in the four MC codes. The degraded beam phase space is recorded at the detector plane placed 1 mm after the degrader, as shown in Fig. 1. Keeping the distance fixed between the source beam and the degrader, five different degrader settings, which correspond to five different final energies, are analyzed.

In the following subsections, the main components of the model setup are explained in detail.

2.1. Proton beam source

In this work, an ideal proton beam with the parameters of Table 1 is used. The choice of an ideal beam with zero transverse divergence and hence zero transverse emittance is motivated by the evaluation of the emittance growth only due to the particle–matter interaction.

The initial sample is filled with 10^7 particles: this assures good statistics for the MC simulations in a reasonable computational time.

Table 1
Parameters of the ideal input beam.

Parameter	Value
Number of particles	10^7
Initial kinetic energy	249.49 MeV
Transv. distribution type	Gauss
Transv. spatial distribution (FWHM)	2.35 μm
Transv. angular distribution (FWHM)	0 mrad
Energy spread	0 MeV
Longitudinal bunch length	0 cm

(a) Real layout: wedges [16]. (b) Model geometry: slabs.

Fig. 2. PROSCAN degrader: wedge and slab geometry. The colors of the slabs underline that the outer slabs (in orange) have half of the thickness of the inner slabs (in green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Degrader

As mentioned before, the PROSCAN degrader consists of two pairs of three movable wedges of graphite with a density of 1.88 g/cm^3 (Fig. 2(a)). Moving the wedges increases or reduces the thickness of graphite that the beam encounters. In less than 50 ms any proton beam energy in the range of 230–70 MeV is delivered with an accuracy of ± 0.1 mm water-equivalent [16].

In the model setup, a simplified geometry of the degrader is implemented with rectangular slabs in place of the wedges (Fig. 2(b)).

Five different degrader settings that correspond to five final energies between 230 and 70 MeV are simulated. For each setting, the wedge position is converted into the equivalent slab thickness. The length of the drift space between the slabs is also consequently adjusted. As in the real degrader layout (Fig. 2(a)), the first and last slab have half of the thickness of the inner slabs. The degrader parameters for the five settings are given in Table 2.

The transverse extension of the slabs (perpendicular to the beam direction) is set to ± 40 cm. In this way all scattered particles remain inside the degrader.

2.3. Detector plane

The properties of the beam emerging from the degrader are recorded 1 mm after the last slab (see Fig. 1). At this position, the transverse phase space and the energy of each particle are collected and used for the analysis. The transverse extension of the detector plane is also set to ± 40 cm, as for the degrader slabs. This ensures that the scattered particles emerging from the degrader are included in the analysis.

3. The four Monte Carlo codes

In the following sections, the four MC codes are briefly described, with particular focus on the features used in the development of the models.

3.1. FLUKA

FLUKA is a fully integrated MC simulation code used in a wide range of applications (e.g. high energy physics, shielding, cosmic ray studies,