Physica Medica xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Physica Medica

journal homepage: http://www.physicamedica.com

Original paper

On the lateral dose profile of ^{4}He beams in water

A. Embriaco [a,b,*], V.E. Bellinzona [a], A. Fontana [b], A. Rotondi [a,b]

[a] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[b] Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, Pavia, Italy

ARTICLE INFO

Article history:
Received 20 March 2017
Received in Revised form 4 July 2017
Accepted 6 July 2017
Available online xxxx

Keywords:
Ion therapy
^{4}He beams
Lateral dose profile

ABSTRACT

Purpose: We investigate the possibility to improve the accuracy of the lateral dose profile for ^{4}He beams with a novel approach, by extending an already validated model for proton beams to heavier ions.
Methods: The full Molière theory for the Coulomb multiple scattering is applied to the case of ^{4}He beams, with a complete separation of the electromagnetic and of the nuclear contributions in the calculation of the total dose. The latter is described with only three free parameters.
Results: The accuracy of the results compared with Monte Carlo predictions already validated with experimental data is comparable with other studies at low energy, but improves by a factor 2 at high energy. In addition the found solution is more stable with respect to (multi-) Gaussian and other parameterizations. This result makes this method of interest for applications to Treatment Planning Systems (TPS) in ion beam therapy.
Conclusions: We propose a model, named MONETα (MOdel of ioN dosE for Therapy for α), for the calculation of the lateral dose of ^{4}He beams in water that allows fast and accurate dose calculations by requiring a small data base of parameters as input.

1. Introduction

The use of ^{4}He ion beams in hadrontherapy is currently evaluated in many centers in Europe, like HIT, CNAO and MedAustron, as testified by the recent literature [1,2]. These beams were used mainly for pediatric tumors in the early years of particle therapy in the US, but were dismissed in favor of proton and ^{12}C beams that gained a primary role in the last 20 years. The advantages of using ^{4}He are the lower lateral beam spread with respect to protons and the lower projectile fragmentation with respect to ^{12}C ions. In addition, the availability of new data in recent years [3]4 and a deeper theoretical knowledge of nuclear fragmentation make possible to improve their effectiveness and their application.

In this context the accurate lateral dose profile of ^{4}He beams in ion therapy has become a crucial issue since the (multi-) Gaussian parameterizations currently used for protons and ^{12}C ions [5–7], despite the good results in clinical practice, are not based on physical assumptions. The lateral profile, even for low doses, requires a correct calculation particularly for fields with many pencil beams and more accurate beam profile models are needed.

A recent attempt to improve the parameterization can be found in [8] where the Gauss-Rutherford parameterization, introduced by us in a previous paper [9] for protons beams, is applied to ^{4}He beams.

At present most TPS software rely on Gaussian approximations (à la Fermi-Eyges [10]) and the best accuracy is achieved with a Monte Carlo TPS (MC-TPS) [11]. But this technique at the moment is not available clinically due to the long calculation times: therefore, accurate pencil beam parameterizations are very important.

In this paper we propose a new model based on the complete Molière theory for multiple scattering and on a simple parameterization for nuclear interactions with only three free parameters. The model, originally developed for protons [12,13] with name MONET (MOdel of ioN dosE for Therapy), is here extended to ^{4}He beams with name MONETα (MOdel of ioN dosE for Therapy for α). MONETα is based on the distinction between the electromagnetic (e.m.) interaction, which is known exactly, and the nuclear interaction which is parametrized in a phenomenological way: this is the original contribution of this work not present in the parameterizations of references [1,8]. In this way MONETα is able to achieve accuracies comparable to those of the Gauss-Rutherford model at low energies (below 150 MeV/u) and also to improve the results at higher energies in the region of clinical interest. All results are compared with the FLUKA code[14,15] which is currently used in many hadrontherapy centers and has been recently validated for ^{4}He beams [3,4]: for this reason, given the good

* Corresponding author at: Dipartimento di Fisica, Università di Pavia, Pavia, Italy.
E-mail address: alessia.embriaco@pv.infn.it (A. Embriaco).

http://dx.doi.org/10.1016/j.ejmp.2017.07.007
1120-1797/

results shown in these publications, no reference to experimental data is made in this work.

2. Methods and materials

In this context the accurate lateral dose profile of ^4He beams in ion therapy has become a crucial issue since the (multi-) Gaussian parameterizations currently used for protons and ^{12}C ions [5–7], despite the good results in clinical practice, are not based on physical assumptions. The lateral profile, even for low doses, requires a correct calculation particularly for fields with many pencil beams and more accurate beam profile models are needed.

A recent attempt to improve the parameterization can be found in [8] where the Gauss-Rutherford parameterization, introduced by us in a previous paper [9] for protons beams, is applied to ^4He beams.

2.1. Parameterizations

The main parameterizations are:

- Double Gaussian (DG)

$$f(y) = N\left\{(1-W)\frac{1}{\sqrt{2\pi}\sigma_1}\exp\left[-\frac{y^2}{2\sigma_1^2}\right] + W\frac{1}{\sqrt{2\pi}\sigma_2}\exp\left[-\frac{y^2}{2\sigma_2^2}\right]\right\}$$

- Triple Gaussian (TG)

$$f(y) = N\left\{(1-W_1-W_2)\frac{1}{\sqrt{2\pi}\sigma_1}\exp\left[-\frac{y^2}{2\sigma_1^2}\right] + W_1\frac{1}{\sqrt{2\pi}\sigma_2}\right.$$
$$\left.\times\exp\left[-\frac{y^2}{2\sigma_2^2}\right] + W_2\frac{1}{\sqrt{2\pi}\sigma_3}\exp\left[-\frac{y^2}{2\sigma_3^2}\right]\right\}$$

- Gauss-Rutherford (GR)

$$f(y) = N\left\{(1-W)\frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{y^2}{2\sigma^2}\right] + W\frac{2b^{3/2}}{\pi}\frac{1}{(y^2+b)^2}\right\}$$

The use of a double Gaussian function to describe the tails of the dose distribution was proposed by R. Fruhwirth and M. Regler [5] and was applied already in clinical environment [6]. The triple Gaussian was used successfully for ^{12}C ion therapy [7], while the Gauss-Rutherford was an attempt to distinguish the effects of multiple scattering at small angles and of single nuclear scattering at large angles. Further details can be found in [9].

2.2. Model (MONETα)

The model based on the Molière theory has been described in [12] and in this study we briefly review its key features, focusing on the necessary modifications for its use with ^4He beams. In essence our procedure allows the calculation of the electromagnetic effects without any free parameter, so that the nuclear part remains better defined and can be easily parametrized: this strategy produces a more stable solution compared with others [16,17] and in case of protons is in excellent agreement with MC codes[12]. This approach still holds in the case of ^4He beams: being based on the general theory of the multiple Coulomb scattering for a charged particle, only small changes are required for the electromagnetic contribution, and a new best fit of the tails, where nuclear interactions are more important with respect to the case of protons, is required to determine the model parameters. A database of these parameters at different energies and depths will be created to allow the reconstruction of lateral profiles.

2.2.1. Electromagnetic interaction

The Molière theory is based on the two parameters χ_c^2 and χ_α^2 (see equations (A.2) and (A.3) of [12]). These parameters represent the root mean square of the distribution and the effect of the electron screening of the Coulomb potential, respectively, and allow to calculate the distribution for the lateral displacement in the final form:

$$f_M(y) = \frac{1}{\pi\chi_c\delta}\int_0^\infty \cos\left(\frac{y\eta}{\chi_c\delta}\right)\exp\left[-\frac{\eta^2}{4}\left(b - \ln\frac{\eta^2}{4}\right)\right]d\eta, \quad (1)$$

where $b = \ln(\chi_c^2/\chi_\alpha^2) - 0.154432$[18] is connected to the number of collisions suffered by the primary particle in the material and δ represents the scale factor that allows the passage from the angular to the spatial distribution observed after the passage of a thickness x (see [12] for more details).

To extend the formalism from protons to ^4He beams, two modifications are required for the charge and the mass of the projectile and for the formula for the CSDA range. For the latter we have found a good agreement with a fit to the data from the NIST tables [19] using an Ulmer-Schaffner [20] like parameterization:

$$R(\mathrm{cm}) = \frac{1}{\rho}\frac{A_M}{Z_M}\sum_{n=1}^{N}\alpha_n E_I^{p_n}E_k^n, \quad (2)$$

with the same notation and values of [12]. The coefficients α_i and p_i from the fit are reported in Table 1 and the ^4He range is plotted in Fig. 1.

2.2.2. Nuclear interaction

To take into account the effect of the nuclear interaction, we add to the e.m. distribution the Cauchy-Lorentz function $t(y)$:

$$t(y) = \frac{1 - A\exp\left[-\frac{y^2}{2b^2\sigma^2}\right]}{\pi b\left(\frac{y^2}{b^2}+1\right)} \quad (3)$$

as in the case of proton beams, where the free parameters, the amplitude A and the Half Width at Half Maximum (HWHM) b (the variance σ^2 is fixed to 1), are obtained by a fit to FLUKA simulations. The behaviour of the two free parameters as function of normalized depths (i.e. current depth z divided by CSDA range R) is analyzed in the following for three energies with Chebyshev polynomials. The total lateral distribution is given by:

$$f(y) = W_p f_M(y) + (1-W_p)\frac{t(y)}{\int t(u)du} \quad (4)$$

where $f_M(y)$ is Molière distribution, W_p is the weight of the e.m. interactions of the primary (p) particles and $(1-W_p)$ is the weight of the nuclear contribution.

3. Results

To verify the accuracy of the model for the lateral dose profile of ^4He beams in water, we have analyzed three different energies (100, 150 and 200 MeV/u) at different depths (7, 10 and 15 cm respectively) and we have compared the model results both with

Table 1
Parameters used for the range calculations of Eq. (2).

Order	α_i	p_i
1	0.013695	0.937675
2	0.507739	0.934832
3	−0.0243788	0.912081
4	0.0790533	0.891479