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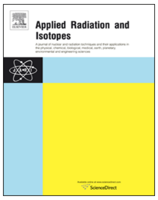

Beam shaping assembly optimization for ^{7}Li(p,n)^{7}Be accelerator based BNCT

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HIGHLIGHTS

- A Beam Shaping Assembly for accelerator based BNCT has been designed.
- A conical port for easy patient positioning and the cooling system are included.
- Several configurations can deliver tumor doses greater than 55 RBEGy.
- Good tumor doses can be obtained in less than 60 min of irradiation time.

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ABSTRACT

Within the framework of accelerator-based BNCT, a project to develop a folded Tandem-ElectroStatic-Quadrupole accelerator is under way at the Atomic Energy Commission of Argentina. The proposed accelerator is conceived to deliver a proton beam of 30 mA at about 2.5 MeV. In this work we explore a Beam Shaping Assembly (BSA) design based on the ^{7}Li(p,n)^{7}Be neutron production reaction to obtain neutron beams to treat deep seated tumors.

1. Introduction

In the framework of Accelerator-Based Boron Neutron Capture Therapy (AB-BNCT) a ~2.5 MeV, 30 mA proton beam accelerator is being developed in our group (Kreiner et al., 2011 and references therein). The final objective is to install a BNCT facility at the Roffo Cancer Institute in Buenos Aires. The project includes the development and construction of the accelerator and all its anxiliary systems, the beam shaping assembly (BSA) and the patient irradiation room. This article is devoted to the BSA.

One of the possible reactions to produce neutrons is the ^{7}Li(p,n)^{7}Be. Although this reaction has important difficulties regarding the target construction, its relative high neutron yield and the fact that it is an endothermic reaction makes protons on lithium the optimal choice from a neutronic point of view. The near threshold option – i.e. proton energies of about 1.9 MeV – has the advantage of not requiring a BSA due to the fact that the neutrons have energies not far from those required for the treatment; but it has the disadvantage of a low yield. Some authors have worked with good results in this regime (Tanaka et al., 2004). On the other hand, working at energies near the resonance (~2.5 MeV) the neutron spectra are a bit harder and need to be moderated but the higher yields compensate the losses in the beam shaping process. In this manuscript the last option has been explored as a neutron source for BNCT.

In previous work (Minsky et al., 2011) we have designed a BSA based on the ^{7}Li(p,n) reaction which could provide high doses to tumor without exceeding healthy tissues tolerance doses. In that design the port was sited on a plane of a prism shaped BSA; in the new design shown in this manuscript a cone shaped port has been used to help in the patient positioning and avoiding unnecessary doses to regions away from the target. The new design also takes into account the cooling system of the target. This article is devoted to the optimization of the BSA.

2. Materials and methods

2.1. Reaction yield calculation

The generation of the neutrons is based on the reaction of protons on a metallic lithium target. A code developed for the previous design with a lithium fluoride target was extended to calculate the yields for metallic lithium which offers a factor of 3 greater neutron yield than lithium fluoride. The double differential neutron yield per solid angle and energy has been calculated following Lee and Zhou (1999), but more recent cross section data

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has been used and since higher proton energies have been studied the ^{7}Li(p,n)^{7}Be* channel which is open at proton energies above 2.37 MeV has also been included. For further details on the cross section data refer to Minsky et al. (2011). A matrix consisting in the double differential neutron yield every 1 degree and 1 keV is generated with this code.

MCNP cards for this source are generated by a Perl script. Instead of using the usual source definition by defining histograms of the energy and angle distributions, the distributions are constructed by linear interpolations between some defined points in the distribution. The number of points and their values are defined in order that the error in any distribution does not exceed 1%. The definition of the angular distribution has been made every 10 degrees.

2.2. Beam shaping assembly

A Beam Shaping Assembly with cylindrical symmetry has been designed (Fig. 1). The BSA consists in a moderating volume of a stack of layers of aluminum, Teflon® and natural lithium carbonate. A cooling system that has been developed and tested in our group (not shown) has been considered since the important amount of water has important implications on the neutron transport and moderation. The moderator is surrounded by a neutron lead reflector that also serves as shielding. An external layer of polylithium (7% in weight natural lithium) further shields from thermal neutrons. The 12 cm diameter port has a 95% ^{6}Li enriched lithium carbonate layer to avoid undesirable thermal neutrons in the beam. The proton beam current was adopted to be 30 mA as the specification of the accelerator being developed at CNEA (Kreiner et al., 2011).

The proton energy (E_p), the target to front distance (TFD), the target to back distance (TBD) and the moderator radius (MR) has been varied in discrete steps (Table 1). Each set of these parameters constitutes a different setup configuration that has been simulated by means of MCNP5 (Brown et al., 2002) Monte Carlo simulations. A total of 2376 configurations have been analyzed.

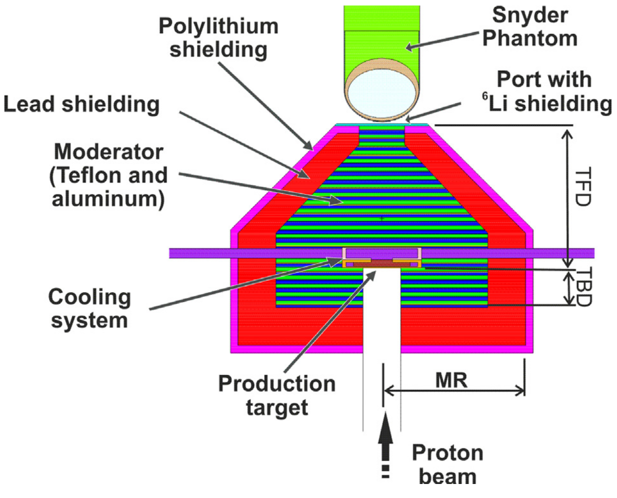

Fig. 1. Beam shaping assembly design.

Table 1
Parameters that have been varied and their values.

Parameter	Analyzed values
Proton Energy	2.2, 2.3, 2.4 ... 3 MeV
Target to front distance (TFD)	22, 26, 30 ... 54 cm
Target to back distance (TBD)	2, 6 and 10 cm
Moderator radius (MR)	10, 12, 14, 16, 18, 20, 24, 28 cm

2.3. Dosimetry

A Snyder head phantom (Goorley, 2002) was sagitally positioned in the setup and depth dose profiles have been computed. ICRU 46 (1992)

Table 2
Weight factors assumed for dose calculations.

Tissue	γ RBE	Neutron RBE	^{10}B CBE	^{10}B concentration [ppm]
Healthy brain	1	3.2	1.3	15
Skin	1	3.2	2.5	22.5
Tumor	1	3.2	3.8	52.5

Table 3
Prescriptions for the treatment session.

Maximum healthy brain punctual dose	11 RBEGy
Maximum skin dose	16.7 RBEGy
Maximum healthy brain mean dose	7 RBEGy
Maximum irradiation time	60 min

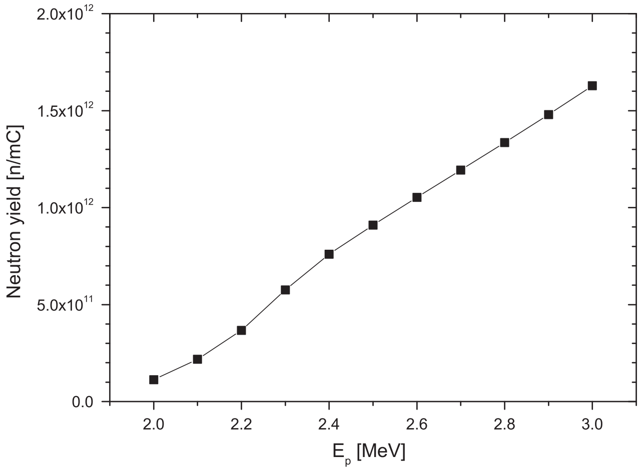

Fig. 2. Neutron yield for ^{7}Li(p,n) vs. proton energy.

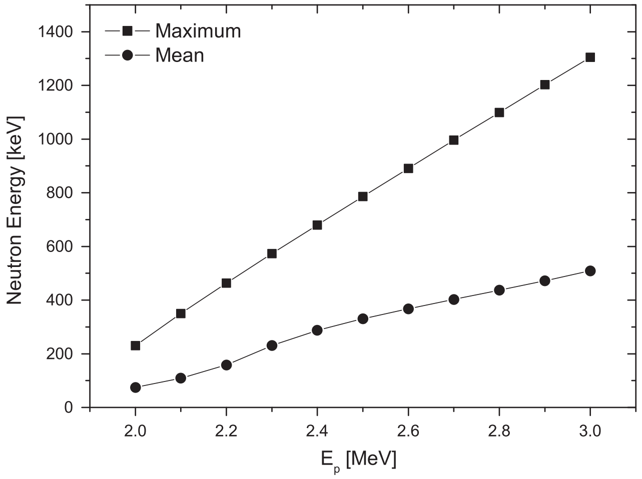

Fig. 3. Maximum and mean energy of the resulting neutrons for ^{7}Li(p,n) vs. proton energy.

tissue compositions have been considered. Assumed relative biological effectiveness factors (RBEs), compound biological effectiveness factors (CBEs) and boron concentrations are shown in Table 2.

A single field has been considered for the irradiation and the criterion for the optimization was to maximize the tumor dose along the central depth profile. The irradiation time for each configuration was set as long as possible without exceeding the prescriptions shown in Table 3. Longer irradiation times have also been explored.

The Treatable Depth has been defined as the maximum depth for which the Tumor Control Probability (TCP) for a 1 cm^3 tumor is greater than 98%, i.e. 38 RBEGy.

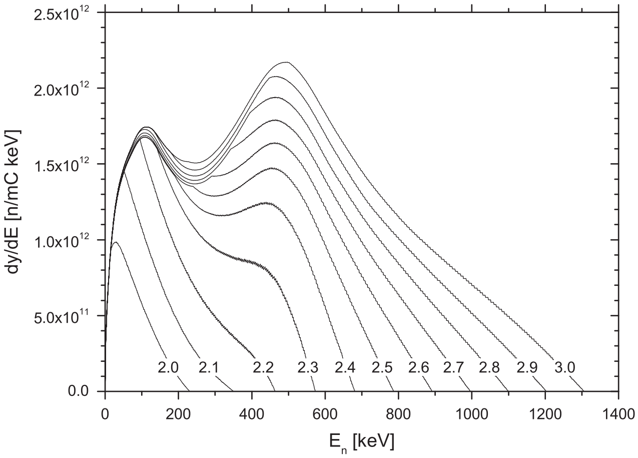

Fig. 4. Neutron spectra for different bombarding proton energies. Labels indicate proton energy in MeV.

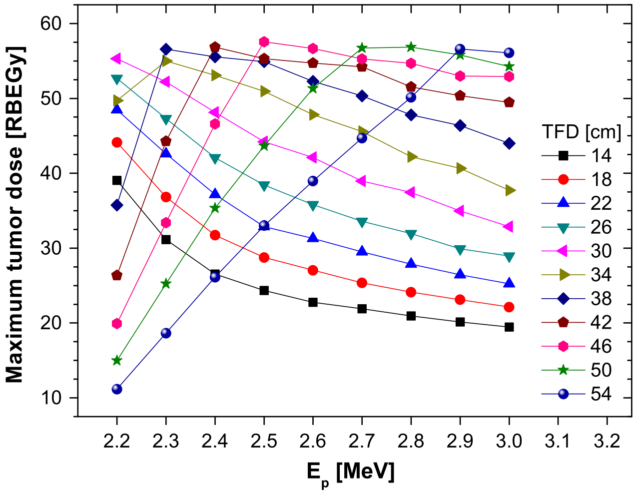

Fig. 5. Maximum tumor dose vs. proton energy for different TFD's.

3. Results

3.1. Neutron source

Neutron yields for ^{7}Li(p,n)^{7}Be for proton energies between 2 and 3 MeV have been calculated with the developed software. Fig. 2 shows the total yield versus the bombarding proton energy. The advantage of the increasing yield with proton energy has the drawback of the spectra becoming harder. Fig. 3 shows the mean and maximum energy of the resulting neutrons as functions of the proton beam energy and Fig. 4 shows the resulting variation in the neutron spectra.

3.2. BSA optimization

In the optimization process four parameters have been varied (E_p, MR, TFD and TBD), The proton energy and the target to front distance are the most relevant and their influence in the maximum tumor dose is shown in Fig. 5. For each bombarding energy there is an optimal TFD which increases with E_p.

The moderator radius and the target to back distance have low influence on the optimization result. Fig. 6 shows the Maximum Tumor Dose (MTD) vs. TFD parametrized with the Moderator Radius for the particular case of 2.3 MeV bombarding energy. In the same figure the treatment time is also shown. The MTD increases with TFD until the treatment time limit is reached. Although the moderator radius has almost no influence on the doses to the patient, larger is better in terms of radioprotection since radiation dose in contact with the lateral part of the BSA is reduced with the MR (data not shown). No figure is shown for the target to back distance since its influence is lower than the involved errors.

Fig. 7 shows the optimized parameter TFD and the obtained tumor dose for different proton energies and maximum treatment times. As the maximum treatment time is relaxed, greater TFD can be used and lead to better moderation. Above 120 min of irradiation time there is no gain in tumor doses.

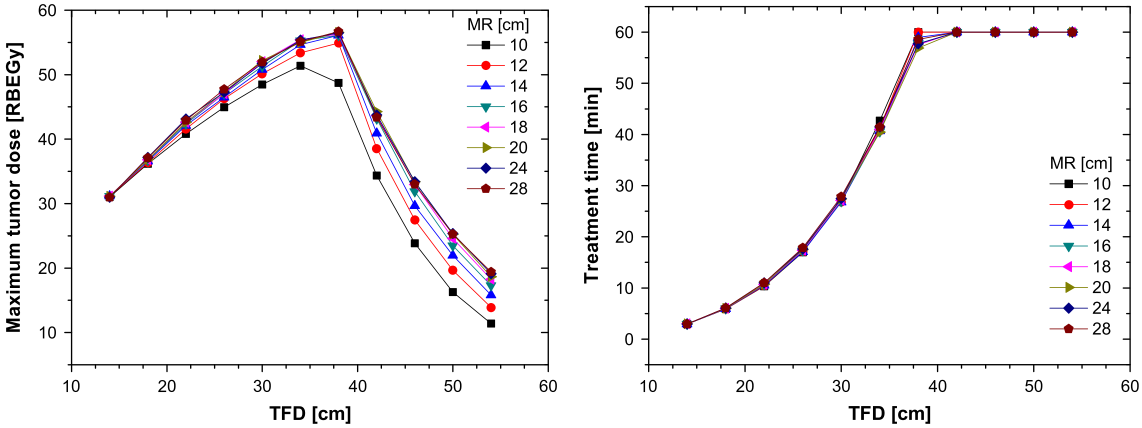

Fig. 6. Optimization of the target to front distance for the particular case of 2.3 MeV protons.

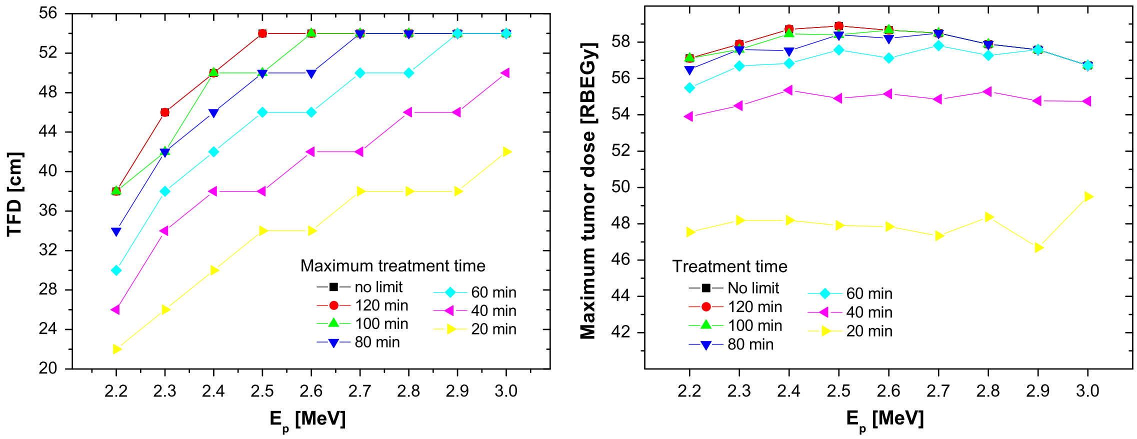

Fig. 7. Optimization of TFD vs. proton energy for different maximum irradiation times. Optimal TFD (left) and the obtained maximum dose to tumor (right).

Table 4
Optimized parameters for the particular case of 2.3 MeV protons.

E_p	2.3 MeV
MR	28 cm
TFD	38 cm
TBD	10 cm
Maximum tumor dose	56.7 RBEGy
Treatment time	58.6 min
Mean brain dose	4.10 RBEGy
Maximum healthy brain punctual dose	11 RBEGy
Maximum skin dose	12.4 RBEGy
Treatable depth	5.38 cm

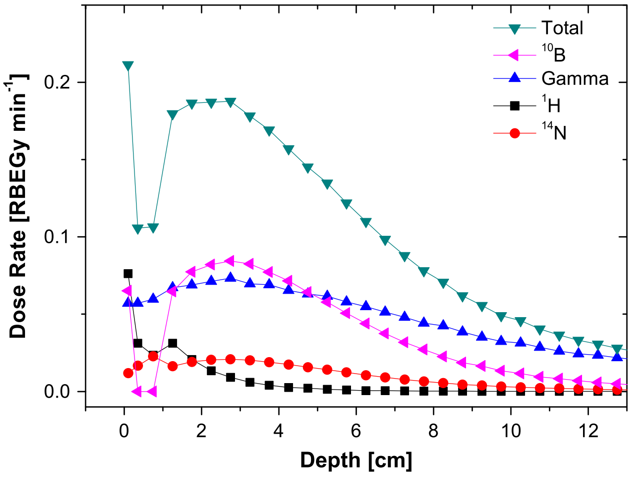

Fig. 8. Depth profiles of dose rate components for the 2.3 MeV optimized setup.

3.3. Optimized BSA for 2.3 MeV proton energy

As an example, results for the particular case of 2.3 MeV protons are shown. Table 4 shows the optimized parameters for this case and the treatment capabilities.

Fig. 8 shows the depth profile of the dose components rate for healthy tissue. In the brain the boron component due to non-specific boron deposition in healthy tissue dominates. The next dose component contribution is the gamma dose which is mainly due to gammas produced inside the phantom. These two components are the limiting factors in healthy brain while at the skin the two dominant dose components are gamma and hydrogen recoil due to fast neutrons. Fig. 9 shows the total healthy tissue and total tumor dose for the treatment; tumor dose is only calculated for brain since this BSA was developed for deep seated tumors.

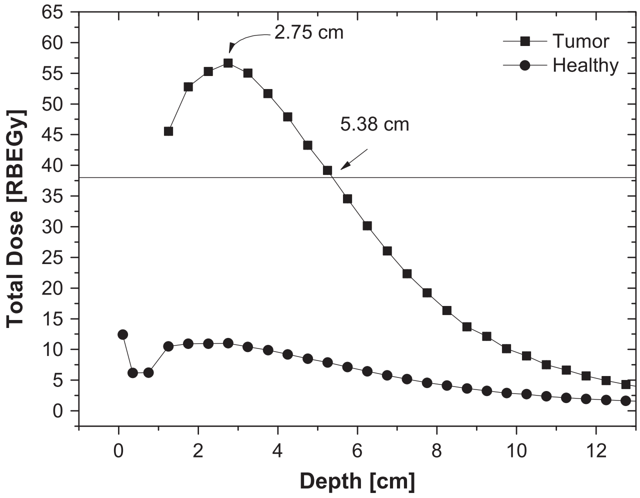

Fig. 9. Total healthy tissue and tumor dose profiles for the 2.3 MeV optimized setup. The treatable depth and the position of the maximum dose to tumor are indicated.

4. Conclusions

A beam shaping assembly for accelerator based BNCT has been designed and optimized especially for the specifications of a TANDEM electrostatic quadrupole accelerator being developed in our group. This BSA is based on the ^{7}Li(p,n)^{7}Be reaction as a neutron source working at proton energies near 2.5 MeV. The proposed setup can deliver more than 55 RBEGy to a tumor in one hour for different proton beam energies. The distance from the target up to the port is the main parameter that defines the doses for each proton energy. In case of irradiations of only 20 min, the optimization parameters – i.e. the dimensions of the setup – can be chosen in a way that the tumor receives about 47 RBEGy.

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