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A project to develop a Tandem-ElectroStatic-Quadrupole (TESQ) accelerator for Accelerator-Based Boron Neutron Capture Therapy (AB-BNCT) is described. A folded tandem, with 1.25 MV terminal voltage, combined with an ElectroStatic Quadrupole (ESQ) chain is being proposed. The project goal is a machine capable of delivering 30 mA of 2.5 MeV protons to be used in conjunction with a neutron production target based on the ^{7}Li(*p,n*)^{7}Be reaction slightly beyond its resonance at 2.25 MeV. This machine is conceptually shown to be capable of accelerating a 30 mA proton beam to 2.5 MeV. These are the specifications needed to produce sufficiently intense and clean epithermal neutron beams, based on the ^{7}Li(p,n)^{7}Be reaction, to perform BNCT treatment for deep-seated tumors in less than an hour. This electrostatic machine is the technologically simplest and cheapest solution for optimized AB-BNCT.

Keywords: Accelerator-based BNCT, Tandem-ESQ, ^{7}Li(p,n) reaction.

1. Introduction

We report here on a project, recently started in Argentina in collaboration with LBNL [1,2], to develop a Tandem-ElectroStatic-Quadrupole (TESQ) accelerator for BNCT. The project goal is a machine capable of delivering 30 mA of approximately 2.3 MeV protons to be used in conjunction with a neutron production target made of Li metal (or a refractory Li compound) and based on the ^{7}Li(*p,n*)^{7}Be reaction slightly beyond its resonance at 2.25 MeV. The technologically simplest and cheapest solution points to an electrostatic machine. Existing electrostatic accelerators, produce only a few mA of proton beam current limited by the column design (An important precursor has been the compact Tandem developed at LABA, MIT [3,4]). High current density, as implied by a size limited 30 mA proton beam, needs strong focusing in the transverse plane. In this regard ESQ´s [1] have a much stronger focusing capability than the aperture lenses used in conventional Tandem accelerators. A TESQ column can be designed using a lower longitudinal electric field gradient than a Pierce column in multi-MeV beam energy applications. Strong transverse fields due to the ESQ´s will also suppress secondary electrons sideways through the electrodes hence preventing induced X-rays and minimizing the risk for electrical breakdown. In the present work a compact combination of an ESQ column with a Tandem in a folded geometry is discussed. This option would allow the ion source to be operated at ground potential and would require the generation of only 1.25 MV to reach the desired 2.5 MeV proton energy. Such a machine requires an H^- ion source and the transport of a high intensity beam through a gas stripper.

2. Materials and Methods

Measurements and simulations to define the performance parameters of an accelerator for AB-BNCT have been performed by several groups [5-7]. Within this frame, the ^{7}Li(p,n) reaction, relatively close to its energy threshold, is the most promising due to its high neutron yield without a too hard neutron energy spectrum. This reaction was explored using a thick LiF target at the electrostatic tandem accelerator TANDAR (TANDem ARgentino) at CNEA's facilities in Buenos Aires. Two different experiments, both involving a water-filled head phantom, were performed as a testing ground for simulations [7]. These experimental results were subsequently compared with Monte Carlo simulations and used to validate the calculational tool in our laboratory. Extensive Monte Carlo simulations were performed to obtain an optimized neutron production and beam shaping assembly design and included a study of the optimal beam energy subject to healthy tissue dose and treatment time constraints. The conclusion relevant to this work was that a proton beam of 20 mA at 2.3-2.5 MeV on pure Li is sufficiently intense. However, taking into account that Li-metal melts at 180 ℃ and in spite of the fact that the heat dissipation problem can be solved [4,8], we have decided to also explore refractory Li compounds of much higher melting point to minimize complications. The penalty in terms of yield for doing so is not too high for some compounds (like Li_3N). Hence our design goal has been taken at 30 mA (considering also a safety margin, the possibility of smaller irradiation times and/or smaller beam energies, etc).

In order to make a decision as to the most appropriate accelerator for BNCT, different options have been evaluated, comprising d-d and d-t neutron generators, RFQ's and electrostatic machines of various types. The technologically simplest and cheapest solution points to an electrostatic machine. Most existing DC electrostatic accelerators can produce only a few mA of beam current, limited by the column design. For sufficiently high space-charge densities, as implied by a size limited multi-mA beam, particles carrying the same charge will repel each other, causing the ion beam to self-expand. Hence high beam current density needs strong transverse focusing. In conventional machines, thick apertures accomplish the beam focusing. In such arrangements the equipotential lines are periodically compressed and expanded, creating a series of alternating converging and diverging lenses, which provide net focusing. However, for such a cylindrical geometry, the radial focusing force is functionally coupled to the longitudinal acceleration force. Thus, the threshold of electrical breakdown along the beam axis limits beam focusing. In the paraxial approximation one has $E_r(r,z) = -(r/2)\partial E_z(0,z)/\partial z$ [9], which means that sufficiently strong transverse focusing means large longitudinal field gradient. A TESQ column can be more easily designed without exceeding the axial acceleration gradient limit [1]. In fact an ESQ chain can provide much stronger transverse fields than the aperture lens by effectively decoupling the two functions: longitudinal acceleration in the gaps between the quadrupoles and transverse focusing within each quadrupole. The strong transverse field in an ESQ not only focuses the beam but also suppresses secondary electrons, and associated induced X-rays, preventing them from cascading downstream and minimizing the risk of electrical breakdowns. The alternating compression and decompression of the beam in successive quadrupoles in both x and y-axes of the ESQ chain produces a net beam focusing effect.

3. Results and Discussion

Fig. 1 shows a general layout of the facility based on a folded Tandem and two electrostatic quadrupole chains within the acceleration tubes. In the present work a compact combination of an ESQ column with a Tandem in a folded geometry is discussed. This option allows the ion source to be operated at ground potential and requires the production of only 1.15 MV to reach the desired 2.3 MeV proton energy.

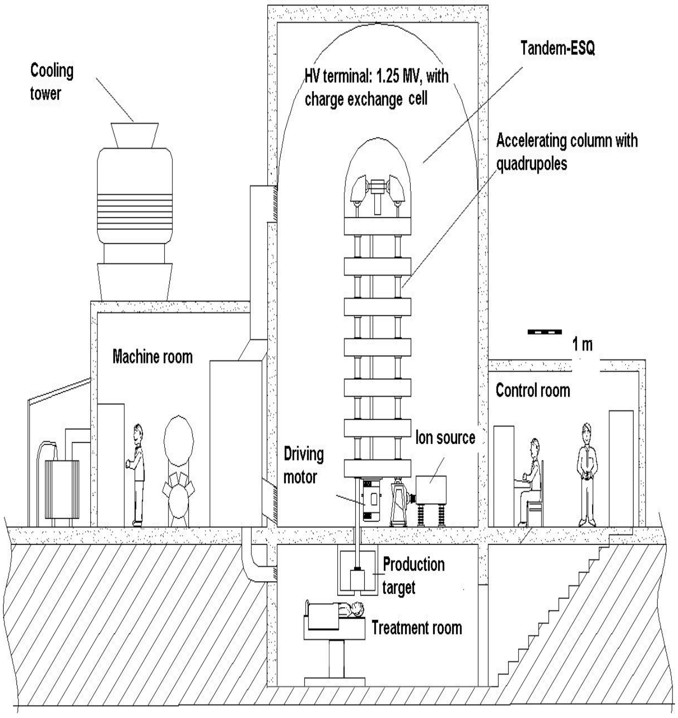

Fig.1. General layout of installation showing the folded Tandem-ESQ (1.25 MV high voltage terminal in air with gas stripper cell), the control room, the neutron production target and the treatment room.

On the other hand such a machine requires an H^- ion source and the transport of a high intensity beam through a gas stripper. Intense H^- sources have been developed at LBNL and JAERI [10,11] and some progress has also been recently made at the Tandar Laboratory in Buenos Aires [12]. An appropriate source design is based on permanent magnet arrays to create multicusp magnetic fields to effectively increase the ionization efficiency in the source. The transport of an intense proton beam through an N_2 gas stripper has been studied in detail by Bayanov et al. [13] at BINP and IPPE, who also proposed a vacuum insulated Tandem accelerator for BNCT, and does not seem to present insurmountable difficulties. In our design we envisage a closed N_2 recirculation based on a turbomolecular pump located at the high voltage terminal.

Fig. 2 partially shows the ascending and descending quadrupole chains within the accelerator tubes, the 100 kV high-voltage units (switching type power supplies) operating in air and the low frequency generators driven by insulated

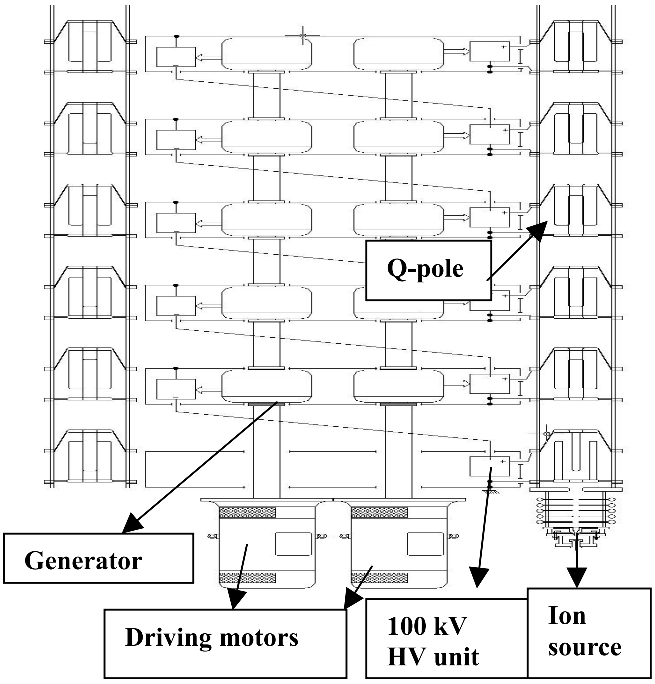

Fig.2. View of part of Tandem-ESQ. Ion source and upgoing and downgoing quadrupole chains (right and left hand sides respectively) within the accelerator tube (in vacuum). The 100 kV power supply units. Low frequency generators driven by insulated shafts attached to motors.

shafts attached to motors, which in turn feed the 100 kV power supplies. The whole machine could alternatively be placed into an SF6-filled tank to reduce its size.

Fig. 3 shows the beam envelopes for the vertical and horizontal planes containing the propagation axis (Z). These beam envelopes for a 30 mA proton beam have been calculated including (1) a finite normalized invariant emittance [9] of $\pi\varepsilon_n = \beta\gamma\pi\varepsilon = \beta\gamma \iint dx dx' = 0.253$ π.mm.mrad on both YZ and XZ planes and (2) space charge effects (ε_n corresponds to 4 times the true rms emittance to reproduce the emittance value of a K-V distribution; β and γ are the usual relativistic magnitudes for the accelerated particle). Six quadrupoles have been used: all 50 cm long and with a bore hole radius of 3 cm. The voltages between the opposite polarity Y and X poles are: 11, -6.5, 13.3, -15.1, 19.9 and -27.8 kV respectively. The beam is accelerated to 1.25 MeV in the upgoing quadrupole chain (and to 2.5 MeV in the downgoing chain, after charge exchange in the gas stripper and bending in the high voltage terminal). These calculations show that it is possible to guide a 30 mA beam confined to a radius smaller than about 10 mm through the accelerator.

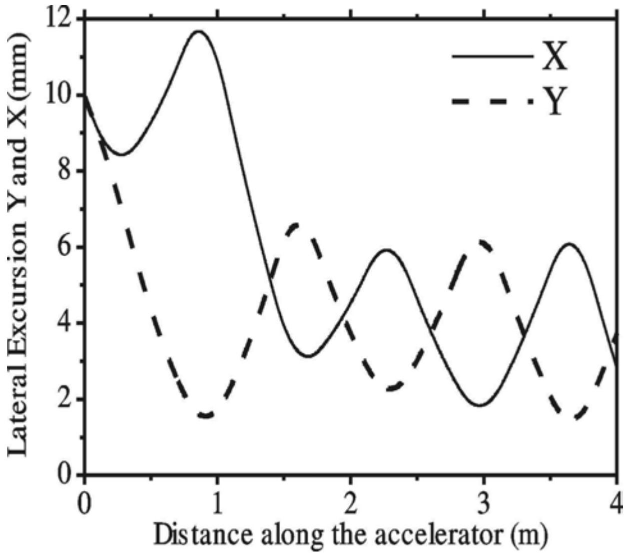

Fig.3. Calculation of beam envelopes of a 30 mA proton beam including finite emittance (normalized invariant emittance of 0.794 mm.mrad on both YZ and XZ planes at the entrance to the upgoing quadrupole chain) and space charge. YZ and XZ beam envelopes. Acceleration up to 1.25 MeV.

4. Conclusions

High proton-current (20-30 mA) machines are necessary for hospital based AB-BNCT. This high current requires strong transverse focusing and hence the proposal to use an ESQ. A folded Tandem requires a terminal voltage of only 1.25 MV and less space. It allows ion source operation outside of the machine at ground potential. Electrostatic technology is most appropriate for its low cost and simplicity.

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