# Development of a Tandem-ElectroStatic-Quadrupole accelerator facility for Boron Neutron Capture Therapy (BNCT)

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**Abstract.** There is a generalized perception that the availability of suitable particle accelerators installed in hospitals, as neutron sources, may be crucial for the advancement of Boron Neutron Capture Therapy (BNCT). An ongoing project to develop a Tandem-ElectroStatic-Quadrupole (TESQ) accelerator facility for Accelerator-Based (AB)-BNCT is described here. The project goal is a machine capable of delivering 30 mA of 2.4-2.5 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. A folded tandem, with 1.20-1.25 MV terminal voltage, combined with an ESQ chain is being designed and constructed. 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 one of the technologically simplest and cheapest solutions for optimized AB-BNCT. At present there is no BNCT facility in the world with the characteristics presented in this work. For the accelerator, results on its design, construction and beam transport calculations are discussed. Taking into account the peculiarities of the expected irradiation field, the project also considers a specific study of the treatment room. This study aims at the design of the treatment room emphasizing aspects related to patient, personnel and public radiation protection; dose monitoring; patient positioning and room construction. The design considers both thermal (for the treatment of shallow tumors) and epithermal (for deep-seated tumors) neutron beams entering the room through a port connected to the accelerator via a moderation and neutron beam shaping assembly. Preliminary results of dose calculations for the treatment room design, using the MCNP program, are presented.

***KEYWORDS: Accelerator-Based BNCT (AB-BNCT), $^7$Li(p,n) reaction, Tandem ElectroStatic Quadrupole (TESQ) accelerator, Electrostatic design, Accelerator tubes, Beam transport, Treatment room design.***

## 1. Introduction

Within the frame of Accelerator-Based BNCT (AB-BNCT), a project to build a Tandem-ElectroStatic-Quadrupole (TESQ) accelerator facility is under development in Argentina [1] based on the $^7$Li(*p,n*)$^7$Be reaction, slightly beyond its resonance, at 2.3 MeV. The machine being designed and constructed is a folded TESQ with a terminal at 1.2 MV intended to work in air, to avoid the need for a pressure vessel and for an insulating gas installation. The project aims at developing a machine

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capable of delivering a proton beam of about 2.4 MeV and 30 mA to irradiate a Li metal (or a refractory Li compound) target in order to produce the therapeutic neutron beam after appropriate beam shaping. In this work, we report on the present status of the project. The general physical layout, its associated electrostatic fields, and the acceleration tube are simulated using a 3D finite element procedure. The design and construction of the ESQ modules is discussed and their electrostatic fields are calculated. Beam transport calculations through the accelerator are briefly mentioned [1-3]. Likewise, work related to strippers and neutron production targets is briefly described. Progress on the beam shaping assembly [4] and the design of a patient treatment room is discussed [5].

## 2. Materials and Methods

### 2.1 General layout

A first qualitative version of the TESQ accelerator general layout has already been discussed in previous publications [1] and is shown in fig. 1. The accelerating column consists of a series of stacked cylindrical boxes which are separated by 200 kV in voltage and 40 cm air gaps (a total of 7 to reach 1.2 MV, the first one being at ground potential). This column houses the up- and down-going acceleration tubes with the quadrupoles inside. A partial view of the current design of this structure is shown in fig. 2. The cylindrical boxes house generators, driven by vertical insulating rotating shafts, connected to electric motors (two motors of about 70 kW each) placed at ground potential, which provide the necessary power to feed the high-voltage supplies (100 kV and 60 mA units also housed within the boxes but not shown) which will energize the whole installation.

**Fig.1.** General layout of installation showing the folded Tandem-ESQ (TESQ) with the 1.2-1.25 MV high voltage terminal in air with stripper cell, the control room, the neutron production target, the treatment room, the machine room and cooling tower.

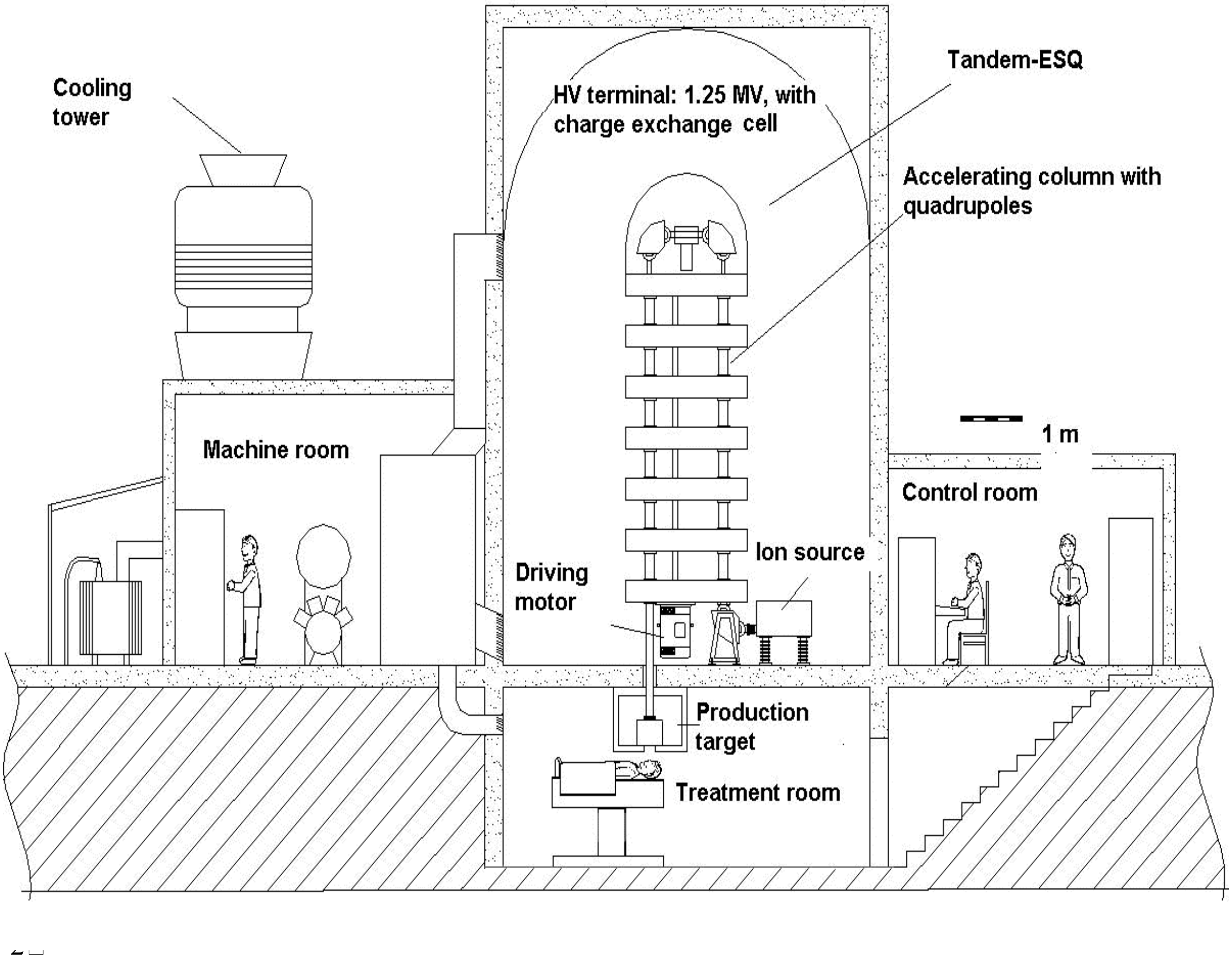
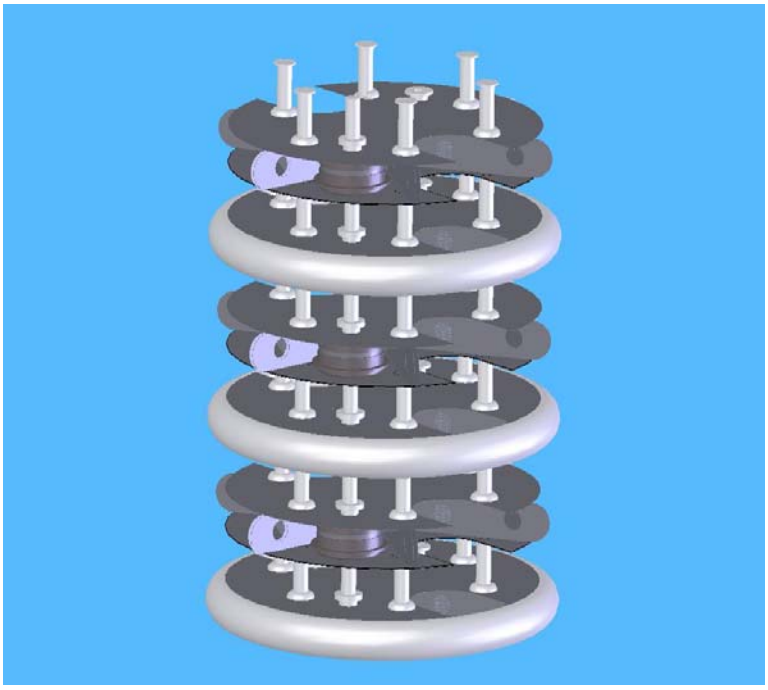


**Figure 2:** Partial view of the high-voltage column showing 6 boxes (3 open with generators and 3 closed, surrounded by semitoroidal shields). The successive boxes are separated by 6 insulating posts.



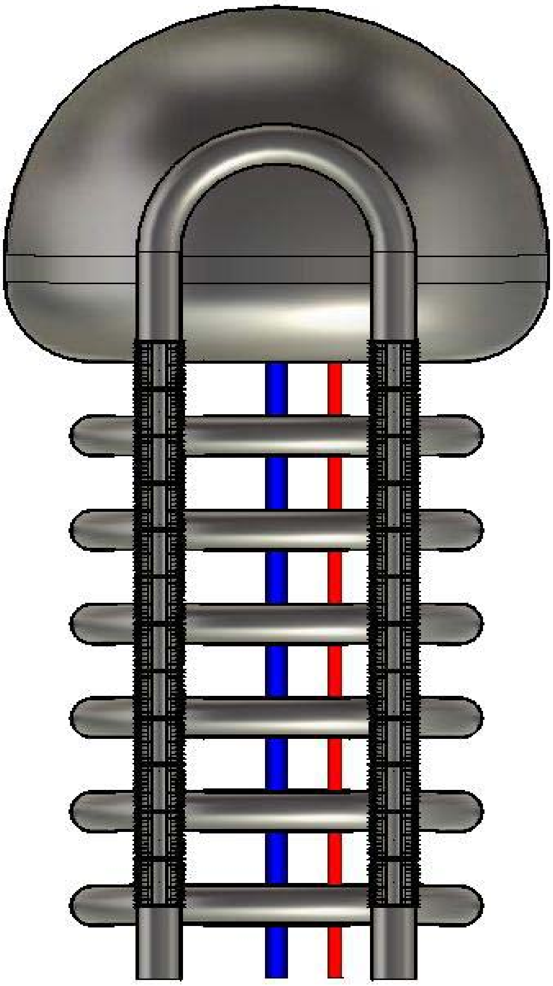
These boxes are traversed vertically by the up- and down-going acceleration tubes (only holes for them are shown in fig.2), which are made of slices of borosilicate glass and stainless steel electrodes. The electrostatic fields have been calculated by means of 3D finite element and other numerical codes and a detailed design has been made paying special attention to the avoidance of sharp edges and points to limit the fields to safe values. The criteria have been to limit the fields on metal surfaces in air to values not exceeding 12 kV/cm, to 5 kV/cm at the interfaces between insulators and air (the room which will house the machine will have controlled temperature and humidity, about 20 $^0$C and 35% respectively) and to 45 kV/cm on metal surfaces in vacuum. We shall address further the geometric layout of the column and the accelerator tube composed of focusing quadrupoles and accelerating gaps.

## 3. Results

### 3.1 General layout

Fig. 3 shows the general geometric layout of the high-voltage column. It is being built as a right cylinder of 2.5 m diameter crowned at its upper ending by a partly hemispherical (radius r is 1.85 m), cylindrical and semi-toroidal (r=0.60 m) dome at 1.2 MV (the 180$^0$ bending magnet within the dome is not shown). The maximum field can be kept below 12 kV/cm. The column consists of a series of stacked cylindrical boxes (30 cm in height to accommodate the generators and the high-voltage power supplies), surrounded by semi-toroidal surfaces, which are separated by 200 kV in voltage and 40 cm air gaps (a total of 6 to reach the 1.2 MV dome plus one at ground potential, not shown).

**Figure 3:** Vertical cut of the column and dome through its mid-plane, showing the two tubes with connection within the dome, one post and one rotating shaft (right). The height is about 7 m.



The distance to the wall (a cylindrical grounded Faraday cage, not shown) is also optimized in order to keep the electrostatic field at its minimum value. In our case the required distance from the box column is 3.5m. The height from ground to roof turns out to be about 10 m.

Figs. 4 and 5 show details of two and one focusing and accelerating tube sections respectively. Each tube section is 35 cm long and consists of slices of borosilicate glass (outer diameter of 30 cm and thickness along the tube axis of 3.15 cm) bonded to stainless steel electrodes and end-flanges. The electrodes are protruding to the inside, with a curved geometry, in order to block the direct view of the beam by the insulating glass walls. To the outside they are terminated in rings to limit the maximum field at the sharp edges. In addition, the tubes house a series of quadrupole focusing elements. These are made of semi-cylindrical rounded-edge stainless steel pieces which are held in place by both conducting and insulating supports. The total voltage across the two tube sections, located between the mid-planes of two consecutive boxes, is designed to be 200 kV. The voltage between poles for each quadrupole is typically between 20 to 40 kV, and the voltage between poles of consecutive quadrupoles (accelerating gaps) is of the order of 70 keV for most of the tube. This last voltage is responsible for acceleration along the machine.

Fig.6 shows the equipotential lines in a transverse mid-plane cut inside a tube section, where the quadrupole character is apparent. Here the function is only to transversely focus the beam.

**Figure 4:** Vertical cut of two consecutive tube sections through their mid-plane, showing three (partial) quadrupole electrodes, the protruding shielding electrodes, the grading rings outside and the transparent insulating glass slices.

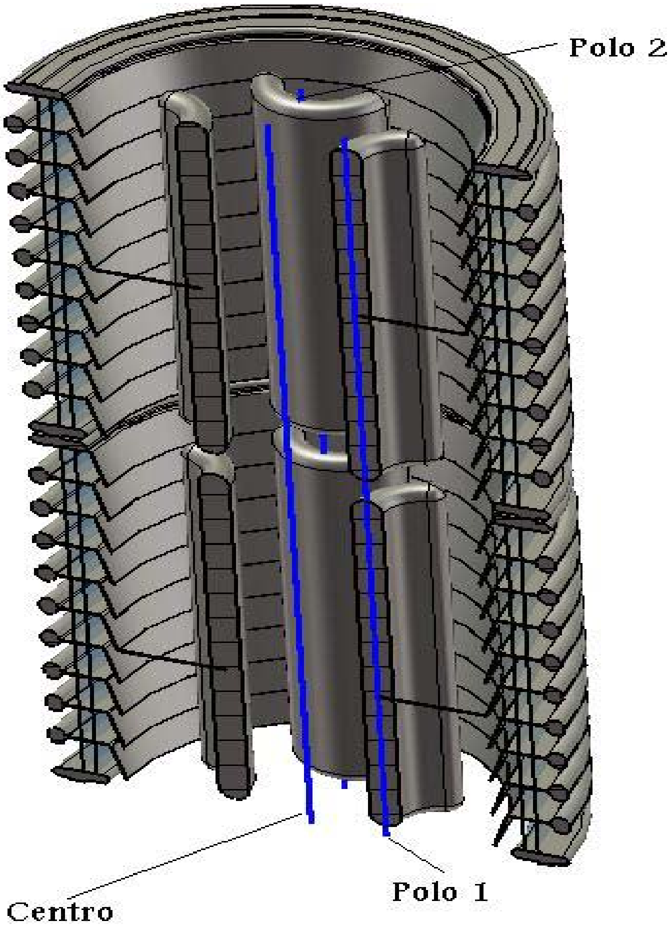
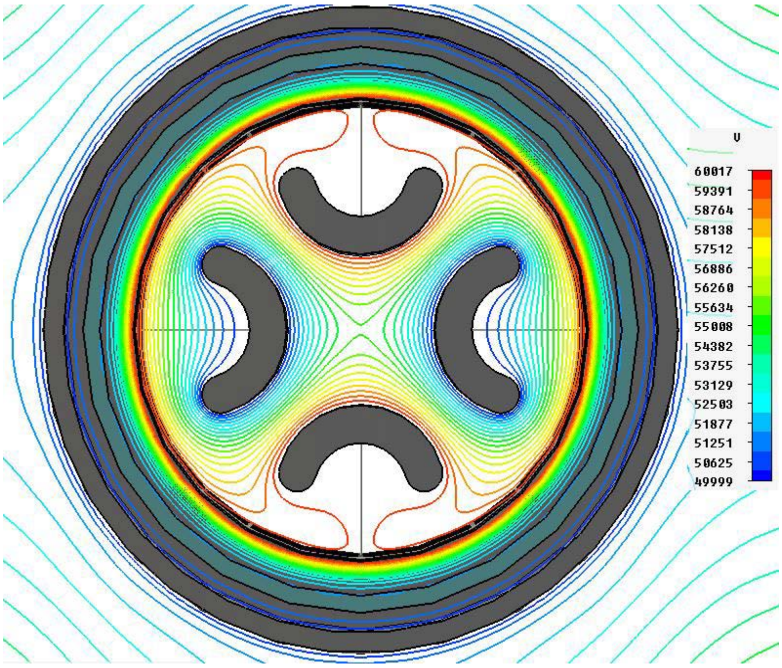


**Figure 5:** View of an entire tube section showing all four quadrupole electrodes.

**Figure 6:** Equipotential lines in the transverse mid-plane of a quadrupole.



### 3.2 Beam transport

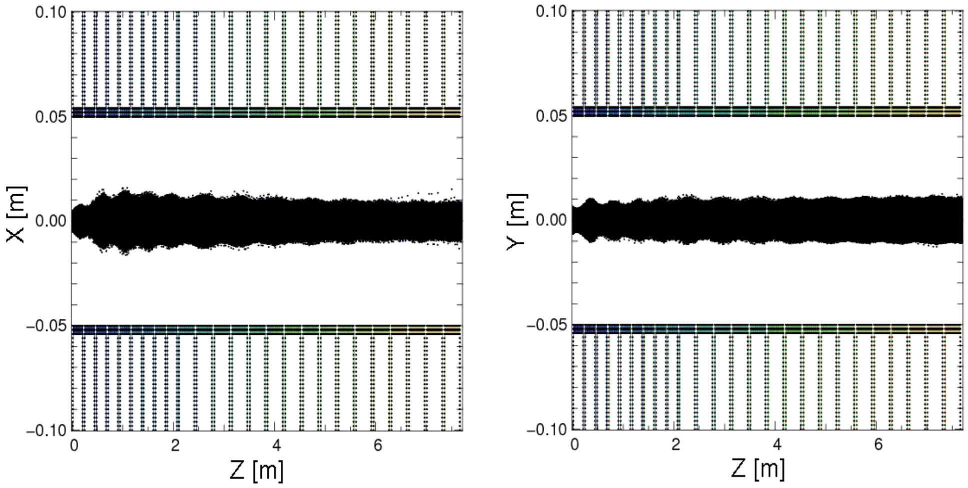
The simulation of the transport and acceleration of the 30 mA proton and deuteron beams through the tube is accomplished by means of self-consistent 3D Vlasov-Poisson calculations [3, 6], which are implemented through the self-consistent 3D code WARP [7]. In a first step, we utilized the Kapchinskii-Vladmirsky (KV) envelope equations [6, 8] to study the force balance between focusing achieved by quadrupole doublets and defocusing caused by space charge and finite emittance. The envelope equation approach for our TESQ accelerator has already been described in previous publications [1-3]. We propose here a modular geometry and a gradual adjustment of the focusing (quadrupole) voltages, while maintaining fairly constant the acceleration field and the beam radius, averaged over a quadrupole doublet. As mentioned, we use the code WARP [7] to simulate the transport of the beam with a realistic geometry and without constraining the form of the distribution function. This is performed in a self-consistent way, meaning that the beam propagation is done by taking into account both applied and self-generated fields, the latter being dependent on the evolution of the beam itself. This is accomplished by the following procedure: First the Laplace equation is solved and particles are propagated throughout the structure, without considering any space charge forces. The positions at each time step are stored and a density function is created. Then the Poisson equation is solved considering the electrodes and this density function, electrical fields are calculated and particles are propagated once again. A new density function is then created, and the process is repeated until convergence is reached.

The strategy to make a first estimate of the voltages along the column consists in balancing the main repulsive effect, due to space-charge, with the focusing action of the quadrupoles: this leads to a scaling law proportional to $E^{1/4}$ for the quadrupole voltages, for a given quadrupole length, being E the kinetic energy of the particles at a given position along the accelerator. The voltage differences between all electrodes along the accelerating tube, including the quadrupole electrodes, can only be adjusted to multiples of 10 kV, due to the design of the high voltage supplies. To preserve a modular design we have restricted ourselves to just two different quadrupole sizes. 9 quadrupoles of 20.3 cm length and the rest of 31 cm length. The shorter quadrupoles are useful to reduce the phase advance per cell at lower energies, minimizing envelope oscillations and providing a more stable transport [8]. In the end, only two values of focusing voltages where used, one for the short quadrupoles section and one for the large quadrupoles section, due to the high voltage supplies restriction. The pole tip (or bore hole) radius of the quadrupoles is 5 cm, roughly 5 times larger than the actual beam radius, which implies a safe operation.

In the actual simulation a 200 keV semi-gaussian beam was injected, accelerated and transported through the system. This kind of beam corresponds to a uniform distribution in position (within a given range) and gaussian in velocities. The chosen normalized emittance value (for both x and y) is 0.253 π.mm.mrad. The extraction and pre-acceleration to 200 keV will be carried out using a cylindrical geometry, with the exception of the matching section just before the quadrupoles. The purpose of this section is to shape the beam in a way that it is suitable for transport through the quadrupole structure.

In fig. 7 we can see that the beam radius remains approximately constant throughout the entire structure, without essentially incrementing its normalized effective emittance.

**Figure 7:** XZ and YZ projections for a 30 mA proton beam (Z is the propagation axis). In the lower and upper part of the figure we see the successive quadrupoles along the machine. Their pole tip radius is 5 cm.



### 3.3 Targets and strippers

As an intermediate step, with the machine operating as single-ended, we shall first produce a 1.2 MeV deuteron beam to hit a thin Be target to produce neutrons through the $^{9}$Be(d,n) reaction [9]. This reaction, in the bombarding energy range 1.2 to 1.1 MeV is a very interesting source of low-energy neutrons, due to the strong population of excited states at 5 MeV in the residual nucleus $^{10}$B [10]. In relation to this possibility we are studying thin Be targets and likewise stripper materials (for the TESQ final design). To test their durability and study different alternatives we have used the heavy ion microbeam of our TANDAR tandem accelerator, which provides beams of comparable fluence rate to those expected for the TESQ facility (i.e., about 10 mA/cm$^2$). Our preliminary results indicate that Be foils about 1 μm thick would last at least for a few hours when subjected to a 30 mA, 1-2 MeV proton beam. In fact, the best present-day carbon strippers withstand about 40 mAh [11], a number which starts to turn a solid stripper into a realistic option for the operation of a BNCT TESQ. As far as targets are concerned we are studying different alternatives from solid Li metal, refractory compounds like $Li_2O$ and liquid Li. The liquid Li option is very attractive provided the temperature is not higher than about 250 $^{0}$C (in order to keep the vapor pressure sufficiently low) and a very efficient $LN_2$ trap is installed next to the neutron production target [12].

### 3.4 Beam shaping assembly

Also an optimized beam shaping assembly (BSA) has been designed [4]. In this section, the performance of an accelerator-based neutron source design is compared with that of a modern fluoride-filtered reactor-based epithermal beam having near-optimal quality for treatment of deep seated tumors in relation to its applicability for BNCT. The accelerator is our Tandem-ElectroStatic-Quadrupole (TESQ), described in previous sections. The reactor is the Massachusetts Institute of Technology reactor upgraded with a Fission Converter Beam (MIT-FCB) and improved with an 8mm thick $^6$Li Filter [14]. The comparison has been done by means of data reported on the MIT-FCB + $^6$Li Filter performance and MCNP simulations on our TESQ design considering the doses delivered in a human phantom by both devices. The results show a deeper advantage depth (AD) for the TESQ which turns out to be a promising alternative to a reactor-based BNCT treatment. Our calculations show that the TESQ facility may reach a 98% Tumor Control Probability at 6.4 cm inside the brain in a 27 minutes treatment keeping the maximum healthy tissue RBE dose at 11.6 RBEGy (considering 12.5 RBEGy as the maximum allowed healthy tissue dose) utilizing 34 cm of moderator and a 30 mA proton beam for an optimized patient position in front of the emerging neutron beam. It is also shown that the optimized BSA in conjunction with a 30 mA beam from our TESQ accelerator would have a larger advantage depth that the MIT fission converter facility (11.5 vs. 9.9 cm) [4].

### 3.5 Treatment room

This section presents two MCNP simulation studies [5] dealing with the radiation shielding for a treatment room of an AB-BNCT facility. In the first one, the dose was calculated at various positions within the room walls using neutrons generated by the $^7$Li($p,n$)$^7$Be reaction at 2.5 MeV in order to determine the required protection for staff and personnel outside of the treatment room. The results show good agreement with data presented in the literature [13] for 1% $^{10}$B loaded walls. Furthermore, we have evaluated the dose outside of the room walls for other $^{10}$B concentrations and for $^6$Li as a neutron absorber which does not produce gamma contamination. From our calculations, walls of about 1 m thickness keep the dose rates below 25 μSv/hr (see fig. 8).

In the second study, the neutron and gamma fluences around a phantom patient head were calculated with and without inner wall shielding. In this case the inner walls of the treatment room were covered with other shielding materials such as polyethylene loaded with 5% $^6$LiF (see fig. 9). Significant decreases in the thermal neutron and gamma doses were obtained for the shielded case which appears as a useful method to diminish the unwelcome dose on the patient (see fig. 10).

**Figure 8:** Equivalent Neutron and Gamma doses for different wall thicknesses. A 100 cm wall provides adequate protection.

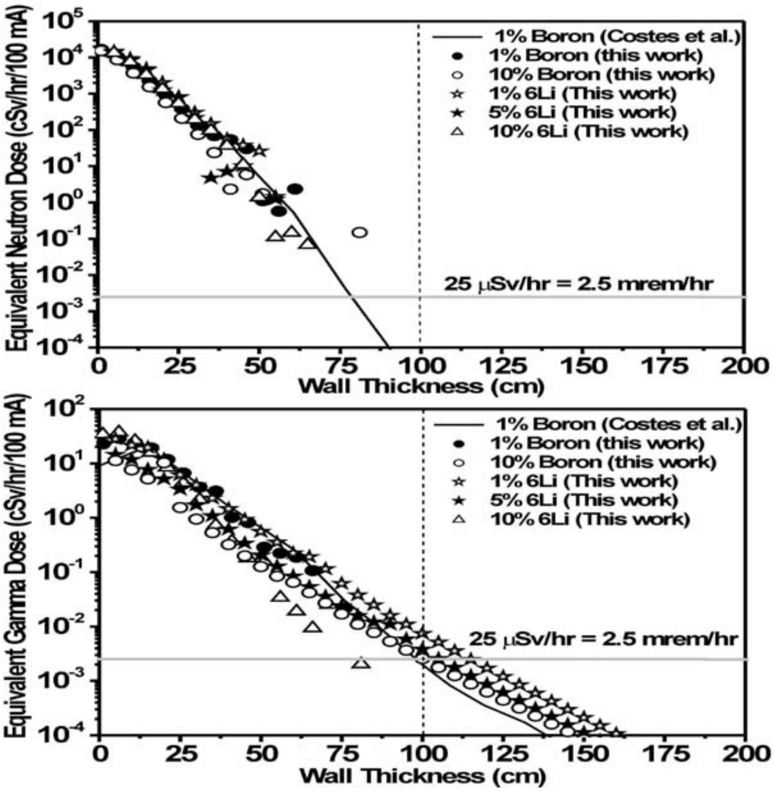


**Figure 9:** Top view of the treatment room for MCNP simulations. The ceiling and the floor are also covered with slabs of polyethylene +5% $^6$LiF.

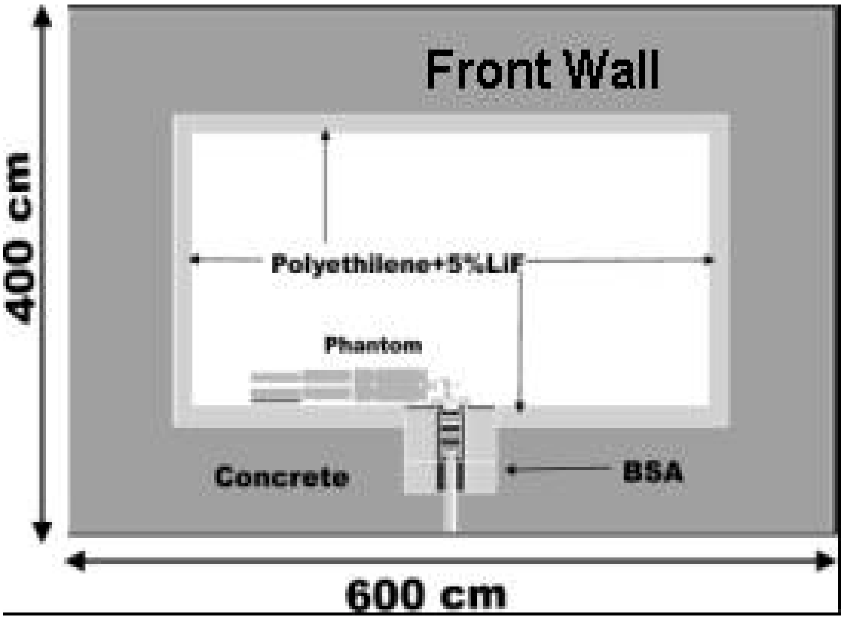
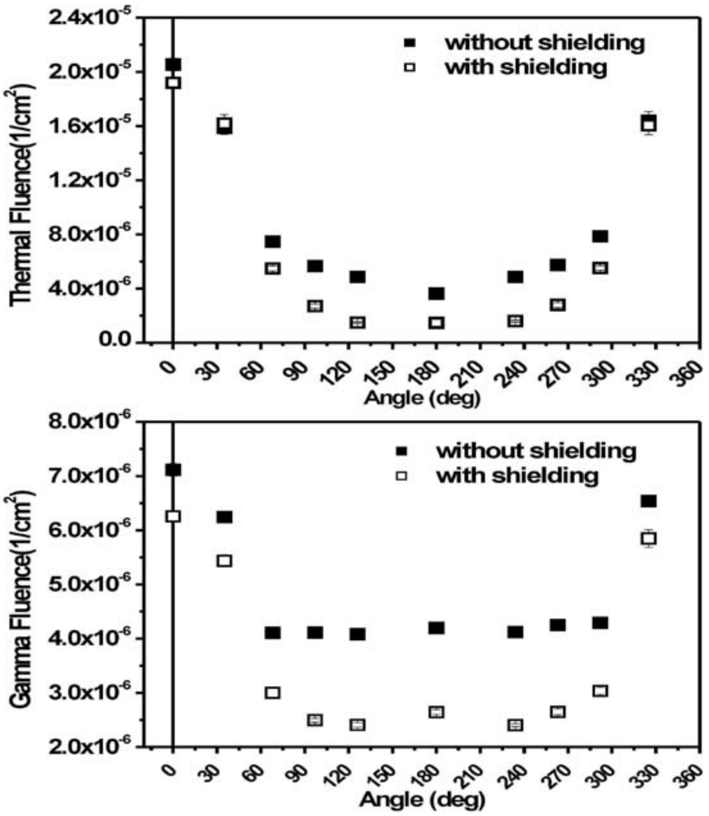


**Figure 10:** Thermal neutron and gamma fluence around the head phantom with and without shielded walls (No significant differences were observed for epithermal and fast neutron fluences for the shielded and unshielded cases).



## 4. Discussion and conclusions

A Tandem-ElectroStatic Quadrupole accelerator facility for AB-BNCT is being designed and constructed at CNEA, Argentina. The general layout of the facility, the accelerator column and tube, and several other subsystems like strippers, neutron production targets, beam shaping assembly, treatment room, power and high voltage generation and ion sources are being defined and built.

Since an accelerator can be sited in a hospital environment, is easier and safer to operate and of lower cost than a reactor, our present results provide a strong justification for the ongoing efforts to develop such a machine as a means to achieve further progress in the field of BNCT.

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