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Accelerator-based BNCT

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HIGHLIGHTS

- The activity in accelerator development for accelerator-based BNCT (AB-BNCT) both worldwide and in Argentina is described.
- Projects in Russia, UK, Italy, Japan, Israel, and Argentina to develop AB-BNCT around different types of accelerators are briefly presented.
- The present status and recent progress of the Argentine project will be reviewed.
- Topics cover intense ion sources, accelerator tubes, transport of intense beams and beam diagnostics, among others.

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ABSTRACT

The activity in accelerator development for accelerator-based BNCT (AB-BNCT) both worldwide and in Argentina is described. Projects in Russia, UK, Italy, Japan, Israel, and Argentina to develop AB-BNCT around different types of accelerators are briefly presented. In particular, the present status and recent progress of the Argentine project will be reviewed. The topics will cover: intense ion sources, accelerator tubes, transport of intense beams, beam diagnostics, the $^{9}Be(d,n)$ reaction as a possible neutron source, Beam Shaping Assemblies (BSA), a treatment room, and treatment planning in realistic cases.

1. Introduction

Accelerator-based BNCT (AB-BNCT) is being established worldwide as the future modality to start the era of in-hospital facilities. There are projects in Russia, UK, Italy, Japan, Israel, and Argentina to develop AB-BNCT around different types of accelerators which will be briefly reviewed. In particular, the present status and recent progress of the Argentine project will be presented. The topics will touch on intense ion sources, accelerator tubes, transport of intense beams, beam diagnostics, control systems, the $^{9}Be(d,n)$ reaction as a possible neutron source, Beam Shaping Assemblies (BSA), a treatment room, treatment planning in realistic cases, etc. Complete 100 kV tube units have been built and successfully tested. Extensive selfconsistent space charge beam transport simulations have been performed and some validated with experimental results. The beam diagnostics has been made through the observation with CCD cameras of induced fluorescence in the residual gas. A 200 kV ESQ accelerator prototype has been constructed to test most of the components. The control system based on Labview and optical fiber technology has been developed. In addition to the traditional $^{7}Li(p,n)^{7}Be$ reaction, $^{9}Be(d,n)^{10}B$ using a thin Be target has been thoroughly studied as a candidate for a possible neutron source for deep seated tumors, showing a satisfactory performance. BSA's and production targets have been optimized through simulations and partially constructed. A treatment room complying with current regulations has been designed. Finally, realistic treatment planning cases for both $^{7}Li(p,n)$ and $^{9}Be(d,n)$-based, AB-BNCT have been studied showing promising results.

2. Overview of accelerator development for AB-BNCT worldwide

Presently there are about 8 initiatives to develop AB-BNCT. Table 1 gives the present status and performance of the different accelerators for AB-BNCT facilities worldwide. Some of the

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accelerators are already developed and some are under construction. We include only proton or deuteron machines. There is a first group of accelerators which are already operational, they are mainly low energy machines working stably on relatively low currents and using the ^{7}Li(p,n) reaction although some of them may be upgradable. The exception is the KURRI project which uses a 30 MeV proton cyclotron and Be as a neutron producing target, having to deal with a very hard neutron spectrum. The last four rows describe facilities under development conceived to operate at higher current levels.

Our group is working towards the development of a Tandem-ElectroStatic-Quadrupole (TESQ) accelerator facility to be installed at the Roffo Cancer Institute in Buenos Aires (Kreiner et al., 2011). The project final 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) reaction. In a first stage, the accelerator will be able to produce proton and deuteron beams of about 1.4 MeV. At this stage, no neutrons can be produced through the ^{7}Li(p,n)^{7}Be reaction (the threshold energy is 1.88 MeV) and the ^{9}Be(d,n) reaction appears as a very attractive alternative (Capoulat et al., 2011). A smaller machine of 200 kV is also being developed.

3. Materials and methods

3.1. The different accelerators under development

The 200 keV deuteron accelerator is a single-ended electrostatic machine. This accelerator is intended as a test bench for all components like electrostatic and mechanical structures, vacuum chambers, tubes, high voltage power supplies, cooled targets, etc., but also has a meaning in itself. This machine, using the Ti-D(d, n)^{3}He or Ti-T(d,n)^{4}He reactions, can be used as an intense neutron source (producing 1.1×10^{11} and 10^{13} neutrons/s and per 100 mA, respectively). These significant fluxes, particularly those associated with 14 MeV neutrons from the T(d,n) reaction, can be used for different nuclear applications. Fig. 1 shows the different types of accelerators being developed: (a) The single ended 200 kV electrostatic machine for testing. (b) A 700 kV TESQ accelerator for neutron production through the ^{9}Be(d,n) reaction. (c) A 1.4 MV TESQ for the ^{7}Li(p,n) reaction or in a single ended version also for the ^{9}Be(d,n) reaction operating with a positive source in the terminal. The primary power for the TESQ accelerator is generated by an electric motor installed at ground potential which drives a chain of insulating and rotating shafts which in turn drive alternators located at the different high-voltage levels. These alternators feed floated high-voltage power supplies connected in series which finally generate the total voltage of the dome and of the different levels. Within the dome there is in both cases a bending magnet and a charge exchange cell (gas stripper). These Tandems are designed to work in combination with negative ion sources installed at ground level. In this way the 700 kV Tandem may produce 1.4 MeV proton or deuteron beams and the 1.4 MV Tandem will be able to produce 2.8 MeV proton or deuteron beams. We may also envisage a single-ended version of these accelerators working with positive ion sources installed at the respective terminals. For instance the 1.4 MV-terminal machine may produce 1.4 MeV deuteron beams.

This last option may be used as a neutron producing machine in combination with the ^{9}Be(d,n) reaction leading to an approximate neutron production of 0.9×10^{13} neutrons/s for a 30 mA beam. This is in fact a very attractive option for accelerator-based BNCT (Capoulat et al., 2011). On the other hand the 1.4 MV Tandem can be used with the ^{7}Li(p,n) reaction leading to a total yield of 3×10^{13} neutrons/s for a 30 mA beam. This intensity is enough to carry out a single session high-quality BNCT treatment.

4. Results and discussion

4.1. The 200 kV single ended machine

Fig. 2 shows the assembled and high-voltage tested 200 kV accelerator developed in-house.

It has a positive ion source at ground potential, a pre acceleration stage, two glass and metal tubes with electrostatic quadrupoles inside to guide the intense beam, and a high voltage dome at 200 kV. Fig. 3 shows a closer view of the accelerating column consisting mainly of the two glass–metal tubes also developed in-house. Each tube is a 100 kV unit.

4.2. The electrostatic quadrupole

Fig. 4 shows a quadrupole doublet. This quadrupole (and others in a chain) are installed inside the high voltage tubes. They are needed to provide the strong transverse fields necessary to transport the high intensity beam and counteract the repulsive space-charge forces.

4.3. The ion source development

The ion source being developed is a volume plasma discharge and filament driven proton source. Fig. 5 shows the last version of the source already tested. Intense proton beams have been produced and transported to a suppressed Faraday cup. A complete new test stand has been built and commissioned for intense proton and deuteron beam production and characterization.

Fig. 6 shows an image, taken with a CCD camera, of the intense proton beam taken through a vacuum window, visible due to the fluorescence induced in the residual hydrogen gas.

Table 1
Current status and performance of the different accelerators intended for AB-BNCT facilities worldwide.

Institute-location	Machine (status)	Target and reaction	Beam energy (MeV)	Beam Current (mA)	Reference
Budker Institute Russia	Vacuum insulated Tandem (ready)	Solid ^{7}Li(p,n)	2.0	2	Aleynik et al (2011)
IPPE-Obninsk Russia	Cascade generator KG-2.5 (ready)	Solid ^{7}Li(p,n)	2.3	3	Kononov et al. (2004)
Birmingham Univ. UK	Dynamitron (ready)	Solid ^{7}Li(p,n)	2.8	1	Culbertson et al. (2004)
KURRI Japan	Cyclotron (ready)	^{9}Be(p,n)	30	1	Tanaka et al. (2011)
Soreq Israel	RFQ-DTL (ready)	Liquid ^{7}Li(p,n)	4	1	Halfon et al. (2011)
Legnaro INFN Italy	RFQ (under construction)	^{9}Be(p,n)	4–5	30	Ceballos et al. (2011)
Tsukuba Japan	RFQ-DTL (under construction)	^{9}Be(p,n)	8	10	Kumada et al. (2011)
CNEA	Single ended	^{9}Be(d,n)	1.4	30	Kreiner et al. (2011)
Argentina	Tandem Electrostatic Quadrupole (under construction)	Solid ^{7}Li(p,n)	2.5	30	

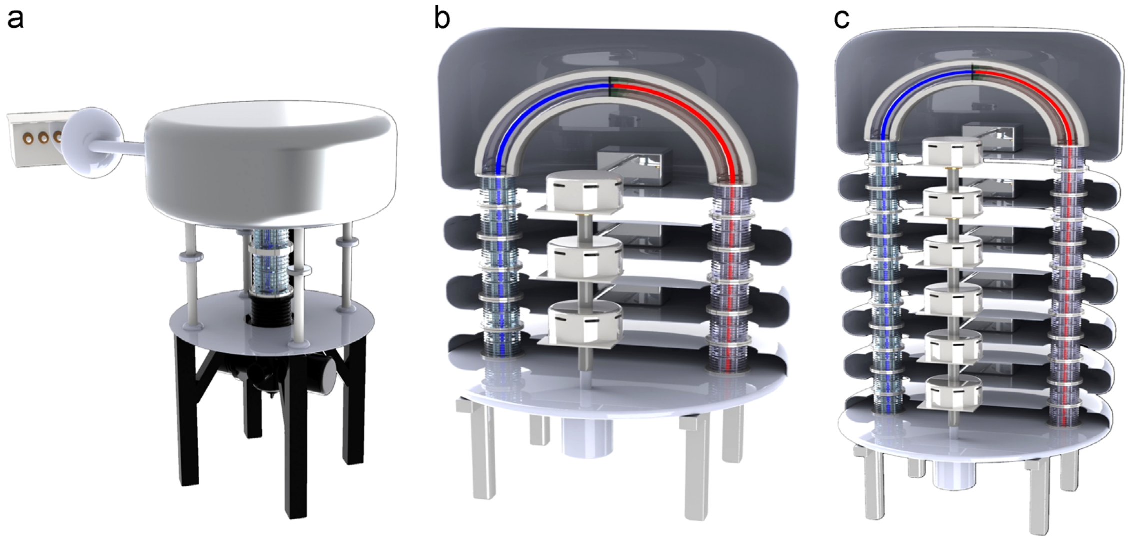


Fig. 1. Different types of accelerators being developed: (a) Single ended 200 kV electrostatic machine. (b) 700 kV TESQ. (c) 1.4 MV TESQ for the $^{7}Li(p,n)$ reaction or in a single ended version also for the $^{9}Be(d,n)$ reaction operating with a positive source in the terminal.

Fig. 2. Assembled and high-voltage tested 200 kV accelerator.

Fig. 3. Accelerating column composed mainly of two high-voltage and vacuum tested tubes.

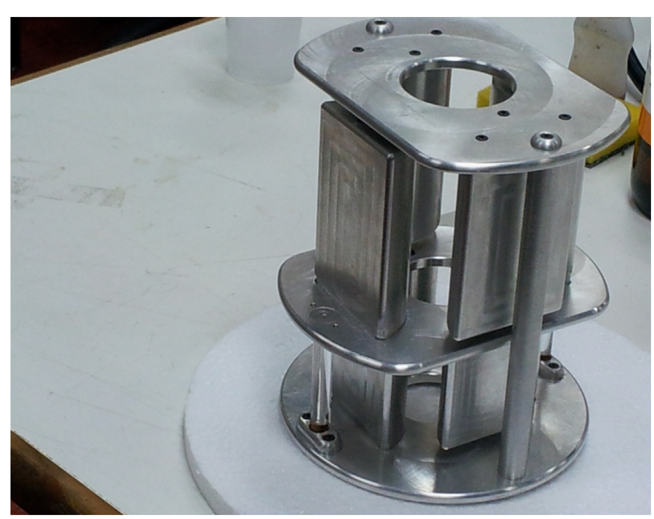


Fig. 4. Electrostatic quadrupole doublet, assembled with a mechanical precision of 0.01 mm.

4.4. Other issues

Significant progress has also been achieved in other matters: Extensive self-consistent space charge beam transport simulations have been performed and validated with experimental results on the beam profile. The measurement of the profile has allowed the determination of the main beam parameter, namely the emittance, which is the crucial parameter which enables us to predict the propagation on the beam through the accelerator (Kreiner et al., 2007). Fig. 7 shows the comparison between measured points of the beam profile (blue points) and the theoretical adjustment (red curve).

The control systems based on Labview and optical fiber technology have been developed.

In addition to the traditional $^{7}Li(p,n)^{7}Be$ reaction, $^{9}Be(d,n)^{10}B$ using a thin Be target has been thoroughly studied as a candidate for a possible neutron source for deep seated tumors, showing a satisfactory performance (Capoulat et al., 2011). Compared to the traditional $^7Li(p,n)^7Be$, the $^9Be(d,n)^{10}B$ reaction also implies important advantages concerning the implementation of a stable neutron production target. First, metallic Be has suitable thermal and mechanical properties. This fact allows us to avoid most of the difficulties related to cooling requirements of a lithium-based target. On the other hand, there is no residual radioactivity in the $^9Be(d,n)$ case, while the ^7Be, 53 day radioactivity produced by the $^7Li(p,n)$ reaction is a non-negligible complication to deal with. And last but not least a significantly lower-energy machine can be used. Our Monte Carlo simulations have shown that viable brain tumor treatments are feasible by means of low-energy deuteron beams (approximately 1.4 MeV) and simple AlF_3-based beam shaping assemblies.

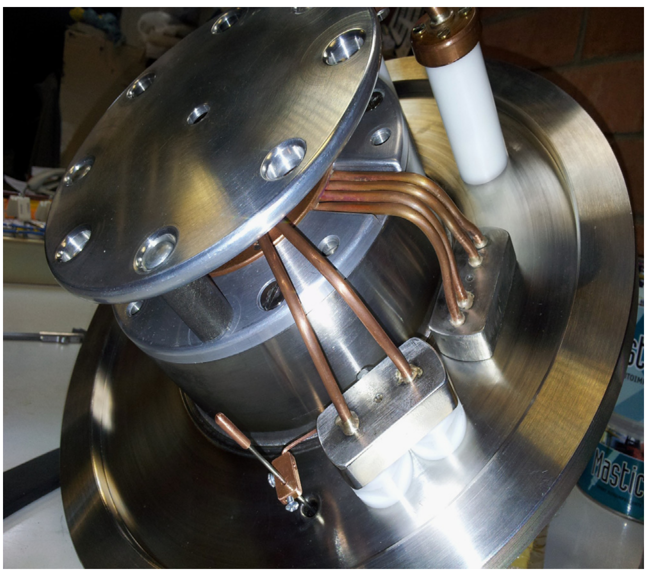


Fig. 5. View of assembled high power proton ion source.

BSA's and production targets have been optimized through simulations and partially constructed (Burlon et al., 2005; Minsky et al., 2011). A treatment room complying with current regulations has been designed (Burlon et al., 2011).

Finally, realistic treatment planning cases for both $^7Li(p,n)$ and $^9Be(d,n)$-based, AB-BNCT have been studied showing satisfactory results (Herrera et al., 2011). We have assessed the performance of an accelerator design (2.4 MeV Tandem for $^7Li(p,n)$) for treating different tumor targets with AB-BNCT. The obtained results showed that the proposed accelerator is suitable for treating different pathologies presenting both superficial and deep-seated tumors. Following different clinical protocols in BNCT for GBM (Glioblastoma Multiforme), Head and Neck and cutaneous nodular melanoma, and optimizing the treatment strategy for each analyzed case, the proposed design shows a tumor and normal tissue dosimetry and irradiation times as good as those for reactor-based BNCT.

5. Conclusions

The world wide situation concerning AB-BNCT has been briefly reviewed. In particular the status of the Argentine project is described.

A 200 kV single ended electrostatic accelerator has been mounted and vacuum and high-voltage tested.

The accelerator tubes and the quadrupoles have been developed. Beam transmission tests will start soon. A new high power ion source has been developed and tested. A complete new test stand comprising the source, an extraction and pre acceleration section and a small tube with a quadrupole doublet has been mounted and successfully operated with voltages of up to 40 keV, for intense proton and deuteron beam production and characterization. Complete 100 kV tube units have been built and successfully tested.

Extensive self-consistent space charge beam transport simulations have been performed and validated with experimental results on the beam profile. The beam diagnostics has been made through the observation with CCD cameras of induced fluorescence in the

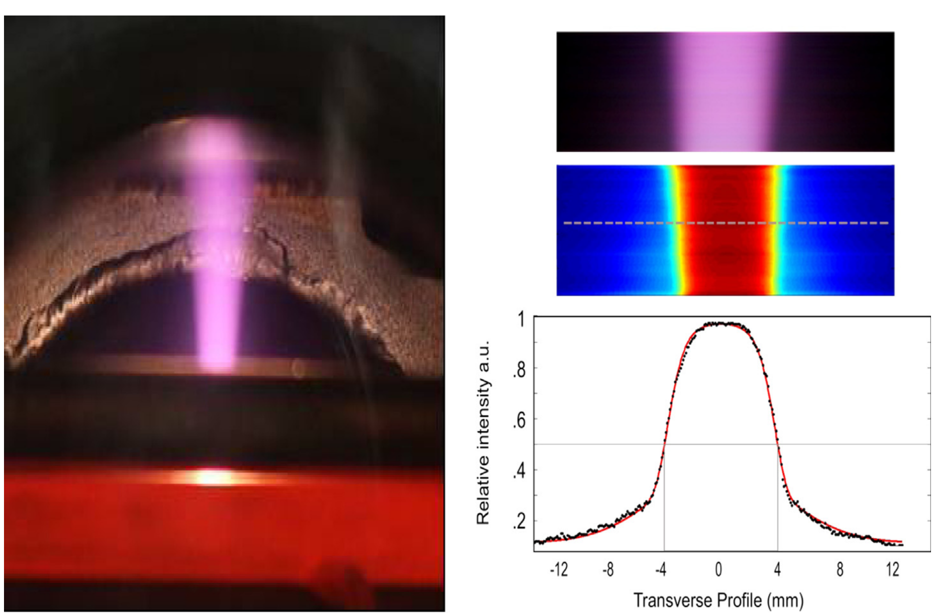
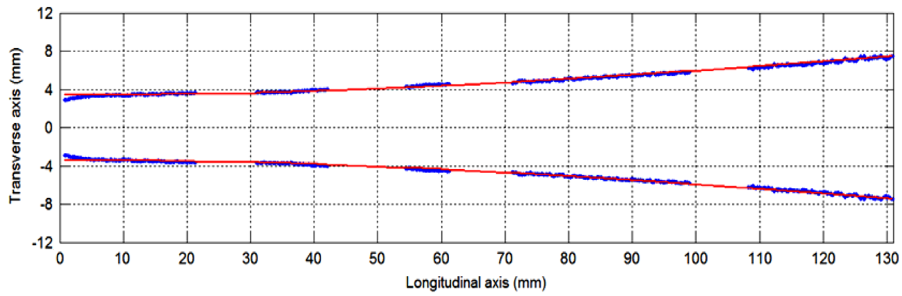


Fig. 6. View of proton beam near the ion source via the fluorescence induced in the residual gas of the column (left hand side). This image has been used to characterize the beam profile (right hand side) along the propagation axis. A small portion of the beam is shown in the upper part. Below that (middle part) a color-scale analysis of that portion showing the dashed transverse line along which the profile is adjusted. Finally in the lower portion of the right hand figure one sees the intensity distribution of the beam. The vertical scale is linear and proportional to the beam intensity (arbitrary units). The horizontal scale shows the width of the beam in mm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



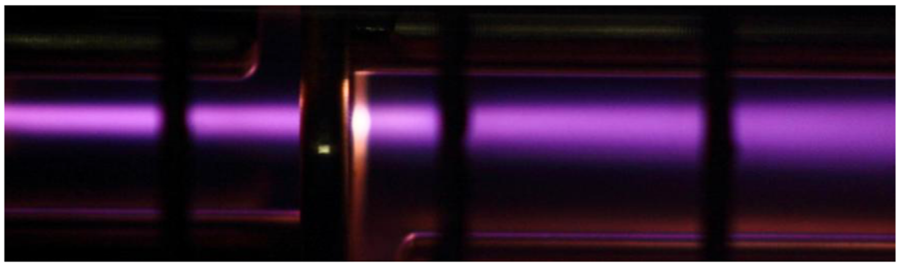


Fig. 7. Comparison between measured points of the beam profile (blue points) and the theoretical adjustment (red curve), in the upper part of the figure. Lower part: view of the same portion of the proton beam via the fluorescence induced in the residual gas propagating inside the quadrupole channel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

residual gas. The control system based on Labview and optical fiber technology is ready. In addition to the traditional ^{7}Li(p,n)^{7}Be reaction, ^{9}Be(d,n)^{10}B using a thin Be target has been thoroughly studied as a candidate for a possible neutron source for deep seated tumors, showing a satisfactory performance. BSA's and production targets have been optimized through simulations and partially constructed. A treatment room complying with current regulations has been designed. Finally, realistic treatment planning cases for both ^{7}Li(p,n) and ^{9}Be(d,n)-based, AB-BNCT have been studied showing promising results.

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