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EPITHERMAL NEUTRON BEAM GENERATOR DESIGN FOR BNCT

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Abstract. *BNCT is a radiotherapy modality based on the neutron capture and fission reactions that occur when boron-10 is irradiated by thermal neutrons. This reaction generates alpha and lithium that produce high density of ionizations in close to the reaction site. The concept provides high absorbed doses into the cancerous cells preserving the adjacent healthy tissues. Nowadays, the available neutron sources for BCNT are large research reactor facilities, which represent a highly complex and expensive technology involving large dimension and radiological concerns due to radiation protection. The present paper describes accelerator-based epithermal neutron source in order to overcome limitations of reactor technology in BNCT. The main goal is to design the mechanical structure and simulate the electromagnetic behavior of the device. The methodology consist in apply the AutoCAD Mechanical package in the design and CST package for electromagnetic evaluations. As conclusion, the device provides a neutron flux capable of sustaining boron fission reaction in suitable levels for generating effective and selective therapeutic doses at the brain.*

Keywords: *bnct, neutron generator, cst modeling, mcnp simulation, deuteron accelerator.*

1. INTRODUCTION

An ideal therapy for cancer would be one whereby all tumor cells were selectively destroyed without damaging normal tissues. Most of the cancer cells should be destroyed, either by the treatment itself or with the help from the body's immune system, otherwise the danger exists that the tumor may reestablish itself. Although today's standard treatments - surgery, radiation therapy and chemotherapy - have successfully cured many kinds of cancers, there are still many treatment failures. The promise of a new experimental cancer therapy with some indication of its potential efficacy has led many scientists from around the world to work on an approach called boron neutron capture therapy (Brownell *et al.*, 1978; Barth *et al.*, 1990).

Boron Neutron Capture Therapy (BNCT) is a binary radiation therapy modality that brings together two components that when kept separate have only minor effects on cells. The first component is a stable non-toxic isotope of boron (boron-10) that can be concentrated in tumor cells by attaching it to tumor seeking compounds. The second is a beam of low-energy neutrons. Boron-10 in or adjacent to the tumor cells disintegrates after capturing a neutron and the high energy heavy charged particles produced destroy only the cells in close proximity to it, primarily cancer cells, leaving adjacent normal cells largely unaffected (MIT, 2012).

There are three basics modalities of neutron beam production: nuclear reactors, radioisotope sources and particle accelerators. Nuclear reactors can provide high level of neutron flux; nevertheless reactors are complex, expensive and possesses large dimensions. Besides, reactors has been demonstrated being potentially unsafe technology. Sealed radioisotope source emits radiation whose strengths decays with time. Hence, these sources are associated to continuum radiation protection requirements. Another method of neutron generation is represented by particle accelerators. In this case, the generator can be assembled in compact dimension due to the appreciable isotope hydrogen fusion cross section at relative low-energy acceleration. Fig. 1 presents the cross-section of d-d and d-t fusion. This device provides advantages over the others two available neutron sources since it is mobile and able to turn off (Araujo and Campos, 2012).

The essence of a small size neutron generator comprises the design of a modern and compact accelerator, a gas-control reservoir, a plasma and ion source to generate and gather the ions in a beam shape, and a metal target loaded of deuterium (^{2}H) or tritium (^{3}H) hydrides. The plasma source produces the ions generally through magnet and electrode configurations or radio frequency antenna. Subsequently, the deuterium or tritium ions, deuterons (d) or tritons (t), are accelerated by an electrode system toward a hydride target loaded with deuterium, tritium, or a mixture of both; in which the neutron generation reactions occur. Those reactions are described by (Tester *et al.*, 2005). Neutrons are emitted with energy of 2.45 MeV from d-d and 14.1 MeV from d-t reactions (Mills, 1971). Although the d-t reaction is more prolific in terms of neutron generation, tritium is a radioisotope while deuterium is stable. For minimizing the radiological concerns, the generator project will employ the d-d reactions. In this case, the design must to achieve high collision rates on the target to allow suitable neutron yield for BNCT.

Nowdays, the neutrons beam for BNCT is supplied by reactor technology. Although the concept of neutron generation by accelerators for BNCT has been presented (Yoon *et al.*, 1999), there are no accelerator-based devices being applied in this therapeutic modality. This paper addresses the system to generate epithermal neutrons for BCNT applications by means of a d-d neutron generator presenting the CAD 3D designs and electromagnetic simulations.

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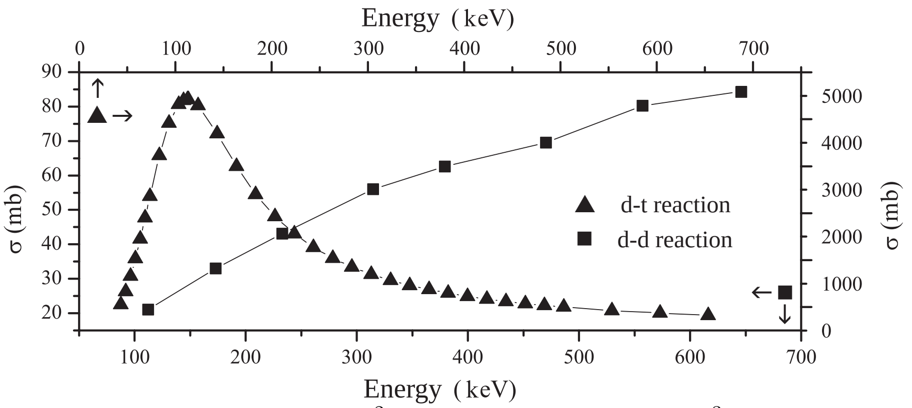

Figure 1: Cross sections of neutron production for ^{2}H (Leonard *et al.*, 2006) and ^{3}H (Stewart and Hale, 1975) target bombarded by deuterons.

2. CONSIDERATIONS ON THE GENERATOR DESIGN

The neutrons emitted in d-d fusion reactions have energies of 2.45 MeV. However, the cross section for neutron capture by boron-10 is greatest for neutrons of energy around 1 eV. Neutrons with energies less than one electron volt are commonly referred to as thermal neutrons since they have energies similar to what particles have as a result of ordinary room-temperature thermal energy. It is necessary to slow down the neutrons for efficient operation of the device, this process is called moderation. When a neutron collides elastically with another nucleus at rest in the medium, it transfers some of its energy to it. The maximum transfer of energy occurs when the target nucleus is comparable in mass to the projectile. Water and carbon (graphite) are commonly used moderators. Water is a good moderator, but the hydrogens in the light water molecule have a fairly high cross section for neutron capture, removing neutrons from the fission process. In the design presented here, heavy water was chosen to minimize this loss and provide refrigeration for the target. The volume of moderation [5] is depicted in Fig. 4b .

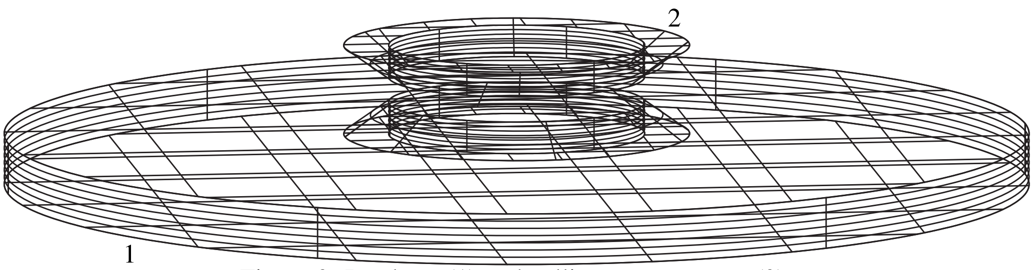

Figure 2: Insulator (1) and collimator structures (2).

Neutrons produced from the fusion reaction are emitted isotropically from the target - shown in Fig. 3 [4]. To maximize the neutron flux in the effective beam direction, a neutron reflecting material must incorporated in the generator. The neutron reflector is external of the insulator structure [1], which is presented in Fig. 2. For collimating the beam, the volume [2], Fig. 2, was designed.

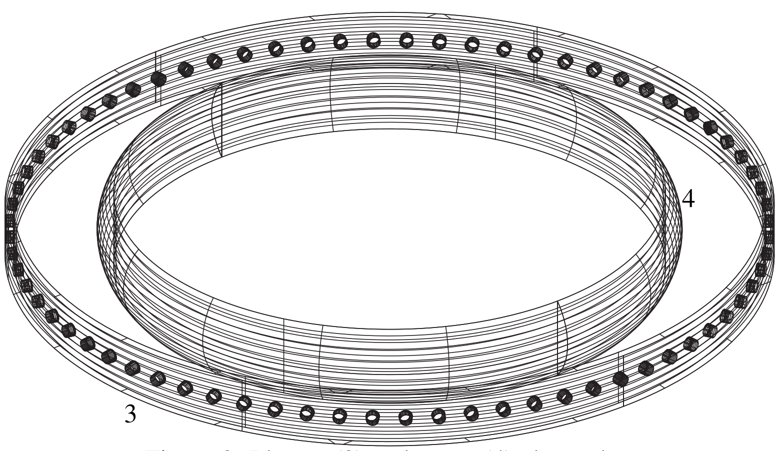

Figure 3: Plasma (3) and target (4) electrodes.

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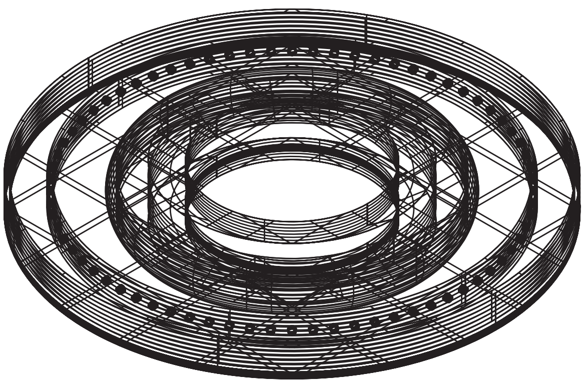

(a) Generator CAD.

(b) Basics elements of the generator: insulator (1), collimator (2), plasma electrode (3), target (4), epithermal moderation volume (5), and plasma reservoir (6).

Figure 4: Generator design.

Device aperture has internal radius of 20 cm, the moderation cylindrical volume [5] has 6 cm in radial length, and the distance between the plasma [3] and the target electrodes is 7 cm. Plasma electrode is composed of 72 frusto-conical geometry apertures with 0.5 cm external radius and 0.7 cm of external radius. This parameters were obtained by an exhaustive setup investigation in electromagnetic simulations, following geometric changes for optimizing the beam current. Deuteron source was defined in the plasma region [6] in Fig. 4b.
Section 3 describes the method employed by the electromagnetic simulation code and the results. Neutron yield of the generator is estimated in section 4.

3. ELECTROMAGNETIC EVALUATION

The package CST - Computer Simulation Technology (CST, 2013) is employed in the electromagnetic design and simulation. This tool computes the particles path through a pre-calculated electromagnetic field. Electric and magnetic fields are evaluated on a computation grid, in which the code interpolates the fields to the particle position following a linear interpolation scheme. Particle trajectory equations are based on updates of time (Equation (1)) and position (Equation (2)), as follows:

$$m^{n+1}\vec{v}^{n+1} = m^n\vec{v}^n + q\Delta t(\vec{E}^{n+\frac{1}{2}} + \vec{v}^{n+\frac{1}{2}} \times \vec{B}^{n+\frac{1}{2}}) \tag{1}$$

$$\vec{r}^{n+\frac{3}{2}} = \vec{r}^{n+\frac{1}{2}} + \vec{v}^{n+1}\Delta t \tag{2}$$

where $\vec{B}$ is the magnetic field, q is the particle charge, $\vec{r}$ is the particle position, and Δt interval of time.

A potential of 30 kV and -150 kV were apllied in the plasma and the target electrode, respectively. Electromagnetic behavior was evaluated and the results is appraised in the next subsections.

3.1 Equipotential surfaces

The behavior of the electric field can be depicted by equipotential surfaces. In order to illustrate it, the potential distribution diagnosis inside the housing of the accelerator is depicted, in transaxial plane, by the Fig. 5a, and in a longitudinal plane by the Fig. 5b. Electric field presents strictly parallel behavior near the plasma electrode, then assumes a converging profile towards the target due to the electrode toroidal geometry. It is observed that particle beams is generally composed of the same type of charge, defining a natural dispersion profile. If the electric field lines diverge as it approaches to the target, it is necessary to design a third electrode in order to converge or minimize the beam divergence.

3.2 Beam path

Trajectory of the beams is shown in Fig. 6a and Fig. 6b. Deuteron current of the generator reaches 6.102 A in the target with energy of 186 keV. The energy value defines a cross-section of about 35 mb. This results are applied in the next section to estimate the yield of the device.

4. Yield estimation

The neutron yield (γ) of the generator, considering a deuteron beam composed of monoatomic and molecular species impinging on a titanium target loaded with deuterium, could be appraised considering the Equation (3) (Verbeke *et al.*,

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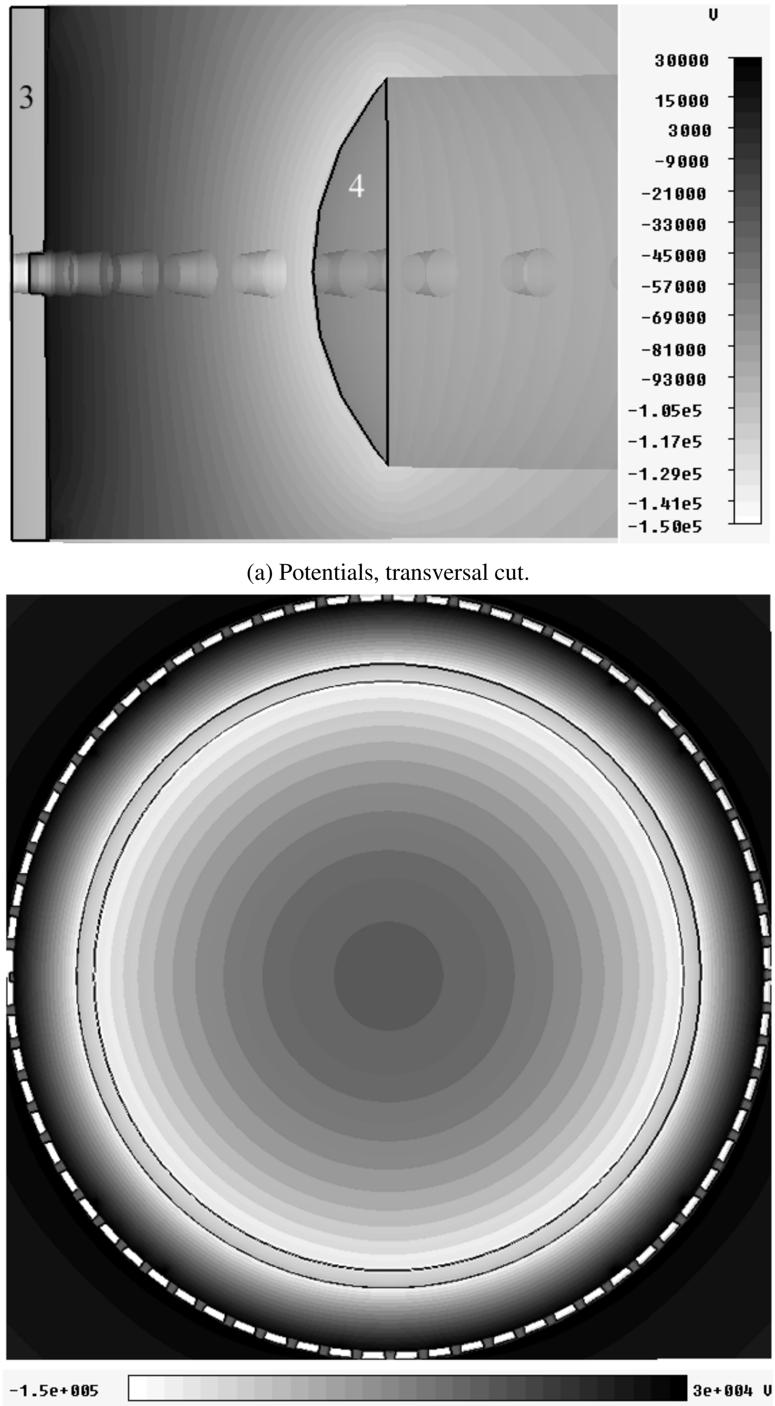

(a) Potentials, transversal cut.

(b) Potentials, longitudinal cut.

Figure 5: Equipotential surfaces.

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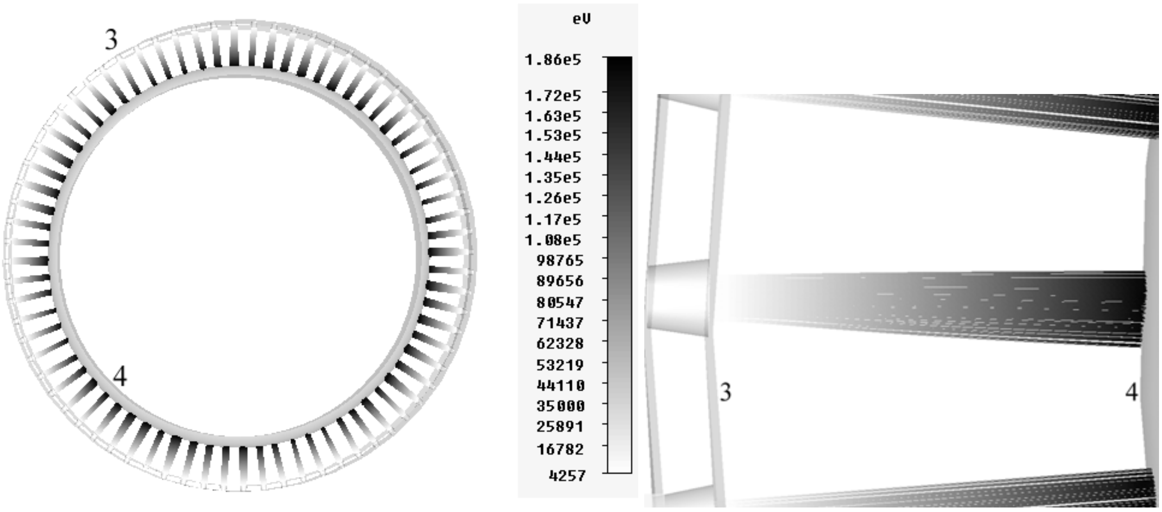

(a) General behavior of all beams. (b) Zoom at the beams.

Figure 6: Deuteron beams path.

2000).

$$\gamma = \frac{\eta_d \, i}{e} \sum_{k=1}^{2} k f_k \int_0^E \frac{\sigma_{dd}}{dE/dx} dE, \tag{3}$$

where η_d is the number of deuterons per cm^3 in the target, i is the beam current, $\sigma_{dd}(E)$ is the neutron production cross section of the fusion reaction d-d in function of deuteron beam energy. Ion species are weighted by their fraction f_k and their number of nuclei k per ion. $\frac{dE}{dx}(E)$ is the molecular stopping power of the target loaded with deuterium. We apply the Bragg's law of additivity (Heaton *et al.*, 1989) to determine the stopping power in the target, as shown in the Equation (4).

$$\frac{dE}{dx} = \frac{dE}{dx}_M + \eta_d \frac{dE}{dx}_d, \tag{4}$$

where the index M and d represents the metal and deuterium on the target. The stopping power values was obtained by means of SRIM code (Ziegler, 2012). Equation (3) was solved by numerical integration, discretizing the energy in intervals of 30 keV and considering the deuterium density in the target ρ_d equals to 3.76 g cm^{-3} (Benveniste and Zenger, 1954). Literature does not provide enough cross-section data of d-d fusion in energies less than 100 keV in order to be possible to reduce significantly the adopted value. The interval reduction will require an interpolation of the experimental data. However, we can expect a soft variation of the d-d cross-section at low energy (more critical and unknown data). Therefore, an interpolation cannot bring abrupt alteration on the integral and therefore on the neutron yield. η_d is given by $\rho_d N_A / A_{Ti-d}$, where N_A is the Avogadro number and A_{Ti-d} the hydride atomic mass. The result provides a neutron yield in order to 10^{14} n s^{-1}.

5. CONCLUSION

This paper presented a device that employs d-d fusion and incorporates a system of neutron collimation and moderation in order to produce epithermal neutrons for BNCT. The present design was obtained by means of geometric changes and simulations in order to optimize the flow of deuterons toward the target. The configuration established well-defined beams that allows a current of 6 A of deuterons at the target with energy of about 180 keV. The results provides an estimative of 10^{14} n s^{-1}. Although this yield is distributed in 1% of the effective irradiation area and only 10% of neutrons are available in this area are employed in the reaction with boron, it provides a flow of approximately 10^{10} n s^{-1} cm^{-2}. In the near future, the shielding and moderation system will be evaluated by nuclear codes.

6. ACKNOWLEDGEMENTS

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