A SINGLE-BEAM DEUTERON COMPACT ACCELERATOR FOR NEUTRON GENERATION

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ABSTRACT

Portable neutron generators are devices composed by small size accelerators that produce neutrons through fusion between hydrogen isotopes. These reactions are characterized by appreciable cross section at energies at the tens of keV, which enables device portability. The project baselines follow the same physical and engineering principles of any other particle accelerators. The generator consists of a gas reservoir, apparatus for ion production, few electrodes to accelerate and focus the ion beam, and a metal hydride target where fusion reactions occur. Neutron generator applications include geophysical measurements, industrial process control, environmental, research, nation’s security and mechanical structure analysis. This article presents a design of a compact accelerator for d-d neutron generators, describing the physical theory applied to the deuteron extraction system, and simulating the ion beam transport in the accelerator.

Key Words: deuteron accelerator, portable neutron generator, ion extraction system simulation, deuteron beam transport simulation, d-d neutron generator simulation.

1. INTRODUCTION

Neutron beams have been used in many applications on health, industry to science. For instance, in the health area, neutrons are used in radiotherapy, imaging or even palliative surgery for reducing the pain [1, 2]. Fast neutrons have been used as primary radiation on hypoxic tumours, such as Cf-252 brachytherapy [3], while epithermal neutron beams have been focused on the treatment of glioblastoma multiforme [4] on BNCT. In archeology and geology, fast neutrons beams are applied to irradiate samples for geochronological dating [5]. In aerospace industry, neutron radiography is a nondestructive evaluation method in the analysis of corrosion, of impact damage and of foreign objects and manufacturing defects [6]. In analytical chemistry, neutron activation analysis have been employed to determine the concentration of heavy and intermediary chemical elements using prompt gamma spectrometry [7]. In airports and at borders, non-invasive inspection techniques related to fast neutron beam are also applied to hinder the smuggling of drugs, explosives, nuclear materials and other merchandise [8, 9]. In research focused on basic sciences, physicists, chemists, material scientists and biologists use neutron diffraction, always looking for solution to a variety of challenges of science [10]. Neutron beams can be provided by nuclear reactors, radioisotopes or generators based on particle accelerators. The last method has played considerable interest in recent decades and is the
focus of the present work.
The most common type of nuclear fusion reaction is between two hydrogen isotopes: deuterium and tritium. Reaction based on hydrogen isotopes is easier to perform and also is a plenty neutron sources. The reaction $^2\text{H}(d, n)^3\text{He}$ or d-d was historically the first source of monoenergetic fast neutrons [11]. Another reaction is $^3\text{H}(d, n)^4\text{He}$ or d-t. Neutrons in excess on tritium increase the size of the nucleus and so, the probability of fusion. The main advantage of employment of d-d fusion to neutron generator occurs essentially due to the fact that deuterium is stable. Thus, its manipulation does not produce logistical complications generated by radiological protection dealings. Figure 1 shows the differential cross section in function of deuteron energy for target bombarding with deuterons.

Compact neutron generators are devices that contain linear accelerators and produce neutrons by means of d-d or d-t reaction, which takes place in those devices via acceleration of deuteron or triton, or the mixture of both, towards a hybrid target of metal; composed of deuterium, tritium or a mixture of two; where occur the nuclear reaction that provides neutrons. Here the main goal is to address physical and geometrical parameter in order to dictate a design for the linear deuteron accelerator as a portable neutron generator, which utilizes a 200 kV voltage generator. Also, structure modeling, electromagnetic simulations, and deuteron ion transport will be focus on this paper.

![Figure 1: Cross section of neutron production for $^2\text{H}$ [12] and $^3\text{H}$ [13].](image)
2. ION EXTRACTION AND ACCELERATOR SYSTEM

2.1 Basic principle on ion extraction system

The ion sources provide the charged particles, deuterons, to be accelerated toward the target. It consists, basically, of two parts. One is the plasma generator that provides ions, which serves as a ion reservoir. Another is the extraction system which receives ions from the reservoir, forming the beam. This system determines the beam properties such as ion current and quality. Thus, the extraction system performs the task of adapting the generator to the plasma beam transport system.

2.2 Physical Modelling

An expression will be determined to optimize the flow of extracted ions. To this end, departing from the Poisson equation, potential voltage addressed as:

\[ \nabla^2 V = -\frac{\rho}{\epsilon}, \tag{1} \]

in which \( V \) is the voltage between the plasma and the ground electrode, \( \rho \) is the charge density, and \( \epsilon \) is the electric permittivity. In module, and for one-dimensional system, it can be expressed as follow:

\[ \frac{d^2 V}{dx^2} = \frac{\rho}{\epsilon}. \tag{2} \]

Equation 3 relates the current density \( J \) with the charge density and ion velocity \( v \).

\[ J = \rho v. \tag{3} \]

It will be supposed that the initial velocity of the deuteron is zero, outside of the plasma chamber. Later, experimental data will be introduced to optimize the phenomenological model. The distance between the plasma and ground electrode is \( d \). Equation 4 associates the ion velocity with the voltage.

\[ \frac{m_d v^2}{2} = q_d V \Rightarrow v = \sqrt{\frac{2q_d V}{m_d}}, \tag{4} \]

in which \( m_d \) and \( q_d \) are the deuteron mass and charge, respectively. The equations 3 and 4 provides:

\[ \rho = J \sqrt{\frac{m_d}{2q_d V}}. \tag{5} \]

The equations 2 and 5 allow writing to the following expression:

\[ \frac{d^2 V}{dx^2} = \frac{J}{\epsilon} \sqrt{\frac{m_d}{2q_d V}}. \tag{6} \]

We obtain the ion current by means of equation 6 solution, considering the case of a circular aperture of radius \( r \), and an experimental data provided by Coupland [14]. It is presented as follow:

\[ I = \frac{4\pi \epsilon}{9} \frac{0.279}{1 + 3S^2} \sqrt{\frac{2q_d V^2}{m_d}}, \tag{7} \]
in which $S$ is the aspect ratio defined by $r/d$. Kilpatrick [15] obtained the maximus voltage between electrodes. This result is rewritten as:

$$V_K \approx 1.7 \times 10^6 d^\frac{3}{2}.$$  \hspace{1cm} (8)

The experimental data, from equation 8, drives us to equation 9, which describes the ion current associated to the maximus voltage in function of the aspect ratio, as follow.

$$I_K = \frac{4\pi \epsilon}{9} \frac{0.279r}{S + 3S^3} \sqrt{\frac{2q_d}{m_d}} (1.7 \times 10^6)^\frac{3}{2}. \hspace{1cm} (9)$$

The maximum current is obtained with the condition defined by $r = 7$ mm in the plasma electrode (PE), as presented in equation 11.

$$\frac{I_K}{dS} = 0 \Rightarrow S = 0.58. \hspace{1cm} (10)$$

The aspect ratio, given by equation 11, will be applied in the extraction system design.

2.3 Extraction and accelerator system design

The extraction system will be composed of an accel-decel electrode configuration [16]. The apperture is circular with radius of 7 mm containing an aperture in plasma electrode defining an Pierce angle [17]. For collimating the deuteron beam is designed a focusing electrode (FE) after the ground electrode (GND). The aperture in the scanning electrode (SE) and GND were defined with a radius of 12 mm, and the aperture radius in the FE is 23.4. SE was designed at 2 mm from the ground electrode, and FE was positioned at 9 cm from the PE. The target is at 24 cm from the plasma electrode. All electrodes have a thickness of 4 mm and radius of 10.8 cm. Figure 2 shows the proposed accelerator design.

Figure 2: Accelerator housing outlined in red and electrodes, from left to right, are arranged as PE, SE, GND, FE, and the target.

3. SIMULATION AND RESULTS

3.1 Fundamentals and simulation parameters

We apply the solver Particle Tracking of the CST - Computer Simulation Technology to simulate the accelerator. This tool computes the particles path through a pre-calculated electromagnetic
field. Electric and magnetic fields are computed on a computation grid. The code interpolates the fields applied to the particle position based on a linear interpolation scheme. Trajectory equations of the particles are based on updates in time and in position. The discrete equations applied to update the time are described by equation 11, and the position update by equation 12.

\[
m_d^{n+1}v^{n+1} = m_d^n v^n + q_d \Delta t(E^{n+\frac{1}{2}} + \frac{v^{n+\frac{1}{2}}}{2} \times B^{n+\frac{1}{2}})
\]

\[
x^{n+\frac{3}{2}} = x^{n+\frac{1}{2}} + \Delta t v^{n+1}
\]

\(E\) represents the electric field and \(B\) represents the magnetic field. The source of deuterons was defined as a cylindrical volume placed at 1.5 mm in the left side (Figure 2) of the plasma electrode aperture. The applied potentials are presented in Table I.

### Table I: Electrodes Potentials

<table>
<thead>
<tr>
<th>PE</th>
<th>SE</th>
<th>GND</th>
<th>FE</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 kV</td>
<td>-700 V</td>
<td>0</td>
<td>-50 kV</td>
<td>-150 kV</td>
</tr>
</tbody>
</table>

3.2 Results

Simulated trajectory of the deuteron beam is shown in Figure 3. Collisions were not diagnosed with the elements of the accelerator. The behavior of the electric field can be pointed out by

![Figure 3: (A) Profile of the beam path; and, (B) degrees of energy.](image-url)
Figure 4: (A) Equipotential lines, (B) contour, and (C) color degrees.

equipotential lines. In order to illustrate this behavior, the potential distribution diagnosis inside the housing of the accelerator is presented in the Figure 4. It is observed that the electric field is slightly divergent in the extraction system and after it becomes almost parallel to the focusing electrode. Subsequently, the field assumes a convergent profile becoming parallel as it approaches to the target.

4. CONCLUSIONS

The designs project of the accelerator was based in a semi-empirical model, which helps to define geometric dimensions and the electrode potentials. Following the design, deuteron beam transport has been simulated using the software CST Particle Studio. The deuteron beam energy reached values suitable for d-d fusion, taking into account the portability of voltage generators capable of producing about 200 kV. In this case, results present a very interesting ion beam profile, whose volume filled by the deuteron beam shows no collision with the electrodes and whose energy reaches about 170 keV at target. The present design motivates a future experimental development of the compact generator. The parameters presented here provide initial data for assembling the small size neutron generator based on a single-beam accelerator. Future work will also address d-d or d-t reaction rate and neutron source yield.

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REFERENCES


