Nuclear Instruments and Methods in Physics Research B 350 (2015) 88–93

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Development of high flux thermal neutron generator for neutron activation analysis

Jaakko H. Vainionpaa [a,*], Allan X. Chen [a], Melvin A. Piestrup [a], Charles K. Gary [a], Glenn Jones [b], Richard H. Pantell [c]

[a] Adelphi Technology, 2003 E Bayshore Rd, Redwood City, CA 94063, United States
[b] G&J Jones Enterprice, 7486 Brighton Ct, Dublin, CA 94568, United States
[c] Department of Electrical Engineering, Stanford University, Stanford, CA, United States

ARTICLE INFO

Article history:
Received 19 December 2014
Accepted 30 December 2014
Available online 29 January 2015

Keywords:
Neutron generator
Neutron source
Ion optics
Neutron moderator
ECR

ABSTRACT

The new model DD110MB neutron generator from Adelphi Technology produces thermal (<0.5 eV) neutron flux that is normally achieved in a nuclear reactor or larger accelerator based systems. Thermal neutron fluxes of 3–5 · 10^7 n/cm^2/s are measured. This flux is achieved using four ion beams arranged concentrically around a target chamber containing a compact moderator with a central sample cylinder. Fast neutron yield of ~2 · 10^{10} n/s is created at the titanium surface of the target chamber. The thickness and material of the moderator is selected to maximize the thermal neutron flux at the center. The 2.5 MeV neutrons are quickly thermalized to energies below 0.5 eV and concentrated at the sample cylinder. The maximum flux of thermal neutrons at the target is achieved when approximately half of the neutrons at the sample area are thermalized. In this paper we present simulation results used to characterize performance of the neutron generator. The neutron flux can be used for neutron activation analysis (NAA) prompt gamma neutron activation analysis (PGNAA) for determining the concentrations of elements in many materials. Another envisioned use of the generator is production of radioactive isotopes. DD110MB is small enough for modest-sized laboratories and universities. Compared to nuclear reactors the DD110MB produces comparable thermal flux but provides reduced administrative and safety requirements and it can be run in pulsed mode, which is beneficial in many neutron activation techniques.

1. Introduction

The deuteron–deuteron fusion reaction (D–D) has been a utilized extensively in recent years in various Adelphi Technology neutron generators [17,19,4] to produce neutrons without using radioactive material. Without the need for tritium, the design and maintenance of D–D generators are much more simple and flexible, ultimately driving down the cost of very high flux neutron generators. The DD110MB manufactured by Adelphi Technology creates high intensity thermal neutron flux to irradiate samples for neutron-activation analysis (NAA).

$$ {}_1^2\mathrm{H} + {}_1^2\mathrm{H} \rightarrow {}_2^2\mathrm{He} + {}_0^1 n + 3.27\ \mathrm{MeV} \qquad (1) $$

The neutron generator consists of four radial deuteron ion sources surrounding a central target cavity. Deuteron ions are generated by electron cyclotron resonance (ECR) [2,6,12] which are then accelerated to 120 keV and bombard a titanium target. Fast neutrons (2.45 MeV) are produced via the D–D reaction (Eq. (1)) at the rectangular cavity walls and then thermalized immediately by an integrated polyethylene moderator on the back of the target. To further enhance the thermal neutron flux at the sample area, the target cavity is surrounded by a neutron reflector. The moderator is designed such that the thermal flux peaks at the center of the target cavity where the radiated sample is located. A sample rabbit transfer system was implemented to minimize the time between irradiation and counting.

The DD110MB (Fig. 1) pushes the boundary of achievable neutron fluxes from compact D–D neutron generators. Thermal neutron flux on the order of 0.5–1·10^8 n/cm^2/s with less than 12 kW of beam power have not been available on compact D–D fusion based neutron generator systems. DD110MB provides compact and simple solution with minimal regulatory burden for NAA applications that previous required reactor-based or traditional accelerator-based systems.

* Corresponding author. Tel.: +1 650 474 4750; fax: +1 650 4755.
E-mail address: hannes@adelphitech.com (J.H. Vainionpaa).

http://dx.doi.org/10.1016/j.nimb.2014.12.077
0168-583X/

2. Generator design

The DD110MB is considered a low energy beam transport (LEBT) system because of the low energy ion acceleration needed to achieve neutron production, the following considerations are critical in order to design a neutron generator that has stable operation and high neutron production efficiency [2,11,14,8,9,18]:

- Ion beam envelope steers clear of contact with the puller electrode.
- Electric field gradients remain below design limit of 5 MV/m on the extraction gap [11].
- Power density and the temperature at the target remains within acceptable limits, which depends on the target design.

2.1. Beam optics and puller electrode

Transport of the ion beam is critical to the design of the neutron generator. As the ion beam passes through the neutral background, low energy electrons are generated through ion stripping. These back-streaming electrons accelerate backwards towards the ion source with energies up the accelerating voltage, potentially causing damage to the ion source flange. Lowering the background pressure will reduce the back-streaming electrons due to increase in ion-neutral collision mean free path. Electrons are also generated through secondary emission as the ion beam hits solid material, such as the titanium target. Typically, two to three electrons are emitted per incident ion. Because the emitted electron current can be up to three times the ion current, these electrons must be stopped by electronic and magnetic suppression to prevent damage to the electrodes or excessive arcing.

To prevent secondary emission electrons from accelerating back towards the ion source, we use a diode design with electron suppressor. This requires design of a puller electrode that also acts as the electron repeller or suppressor. The remaining back streaming electrons current that cannot be handled by the suppression voltage is steered to safe electron beam dump using magnetic fields. Without magnetic suppression or with very weak magnetic suppression, we observed the formation of an electron beam that was directed virtually straight back to the ion source and melting it. Extensive beam optics design was done using the IBSIMU library [10] to model the ion beam behavior in the HV accelerator. The software library is used to define the electrode geometries on the accelerator section. Fig. 2 shows the ion beam transport through the acceleration region. With an extraction voltage of 120 kV (top), the beam envelops steers well clear of the suppressor electrode and hits the target as designed. Secondary electrons that are emitted from the target will be repelled back to the target by the negative suppressor electrode. However, if the extraction voltage is dropped down to 80 kV (bottom) or below, the of the beam begins to strike the puller electrode, causing electrode heating and possibly increase in back streaming electron current from the puller electrode.

When the acceleration voltage is reduced, the beam optics changes mainly due to the changing of the plasma meniscus shape. This causes the beam envelope increase at the entrance of the puller electrode. At some critical extraction voltage the beam envelope will begin to bombard the electrode and generate secondary electrons that are emitted from the puller electrode. Because the puller electrode is the highest potential electrode in the acceleration system [2,7], these electrons are free to fly back to the ion source without any suppressive force. The resultant effect is a large increase in the apparent extraction current, which consist of both the ion current and secondary electron current. This limits the range of operable acceleration voltage on the generator due to the large back streaming electron current increase [15].

2.2. Target design

To achieve effective neutron production, the titanium target needs to remain cool in order to retain the deuteron ions that are the target nuclei for the D–D fusion. A thin titanium sheet is explosively bonded to copper for reduced thermal resistance at the interface. Micro-channel grooves are machined in the copper structure to increase the surface area for convective heat transfer (Fig. 3). The power density on target was obtained using IBSIMU, which shows uniform heat flux across the target. Using a comprehensive thermal and fluid flow analysis, the temperature on the titanium surface was verified to stay below 100 °C and the water flow stays in the single phase regime even at the copper-to-water interface.

2.3. Monte-Carlo modeling

In order to accurately characterize the DD110MB, major components of the neutron generator were modeled in MCNP [1] to calculate the theoretical neutron flux ($n/cm^2/s$) at the sample ports. Fig. 4 (left) shows a section view of the neutron generator and the various components in vacuum. Because the DD110MB is a pumped system, we used Ultra High Molecular Weight (UHMW) polyethylene as the high voltage insulator and neutron moderator. This feature allows the DD110MB to have an integrated moderator design, making the generator very compact and cost effective.

The reflector is also another integral component of the DD110MB. Due to the conservation of momentum, high Z-materials are known to elastically scatter neutrons while barely lowering

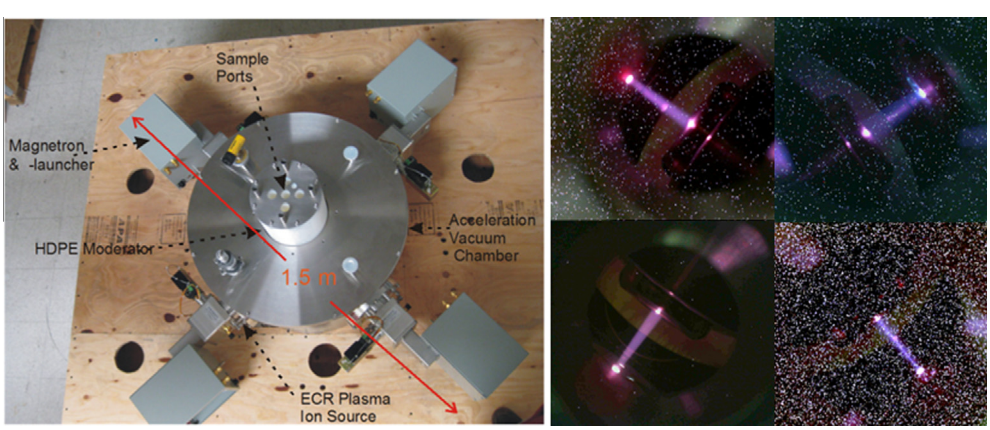

Fig. 1. (Left) Photo of the DD110MB showing major components of the generator. (Right) Camera view of the four beams operating.