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PROPOSAL FOR A COMPACT NEUTRON GENERATOR BASED ON A NEGATIVE DEUTERIUM ION BEAM

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Abstract

Interest in high intensity generators of neutrons for basic and applied science has been growing, and thus the demand for an economical neutron generator has been growing. A major driver for the development of high intensity neutron generators are studies of neutron disturbance in integrated circuits, for which a compact generator that can be easily accommodated in an ordinary size lab would be highly desirable. We have investigated possible designs for neutron generators based on the D-D fusion reaction, which produce direction dependent mono-energetic neutrons with carry-off energy larger than 2.45 MeV. Specifically, we find a negative deuterium ion beam most attractive for this application, and plan to construct such a system with a negative deuterium ion beam of 200 keV energy and 100 mA current as a prototype of this concept.

INTRODUCTION

The National Institute for Quantum Science and Technology (QST, Chiba) hosted a long-standing program of neutron irradiation of biological specimens under pathogen-free background conditions, the Neutron exposure Accelerator System for Biological Effect Experiment (NASBEE). Neutrons were produced by 4 MeV positive hydrogen and deuterium ion beams striking on a beryllium target through the ^{9}Be(p,n) and ^{9}Be(d,n) reactions [1]. Unfortunately, due to the large size of the neutron generating system, and its high operational cost, its operation had to be terminated.

Similarly, there is an unmet need of widely available neutrons for radiation effect studies on integrated circuits. Such studies are imperative, particularly for electronics in space and high-altitude flight, as cosmic rays collide with nuclei in the atmosphere, producing approximately ten neutrons per cm^2 per hour. These cosmic rays create secondary neutrons of 1 MeV or higher [2]. These neutrons undergo scattering in integrated circuits and cause soft errors in them, also known as single-event upsets. Soft errors are a phenomenon by which one or more bits within the data on the semiconductor device have their values reversed. A soft error does not damage the semiconductor device itself. Given the large and growing number of high-altitude aircrafts and satellites being deployed, there is a great need for chip testing and certification capacity, particularly with fast neutrons, but below 3 MeV. This need also points to the necessity of new types of neutron generators [3].

In Japan, accelerator driven neutron generators based on the ^{9}Be(p,n) reaction are commonly used; these involve the acceleration of protons to ~10 MeV directed onto a beryllium target. There are currently many neutron generators of this kind are available [4]. However, the requirement of an ion source and an accelerator makes this design very large and very expensive. Furthermore, the target area becomes highly activated due to the high neutron flux emitted at all angles, not just those neutrons impinging on the sample of interest. The maintenance expenses likewise are not small.

The two examples above, from the biomedical and semiconductor sectors, are indicative of the general demand for commercial neutron applications, and which are increasing over all energy ranges. Thus we would like to develop a compact neutron generator with its power supply system, that could be affordably acquired, and occupy an ordinary size laboratory room of a university or a private company.

D-D REACTION BASED NEUTRON GENERATORS

Neutron generators based on the D-D fusion reaction, and isotopically producing neutrons of carry off energies larger 2.45 MeV (zero deuterium ion incident kinetic energy) have a long and successful history. The mono-energetic energy-angle distribution changes only as a function of incident deuterium ion energy. One design of a deuterium ion source-driven neutron generator, based on a self-loading target [5], has been developed and utilized for a broad range of basic and applied science interests (geochronology, medical isotope studies, nuclear data for reactor design, etc.) at the Nuclear Engineering Department of University of California Berkeley.

The near mono-energetic neutrons with an energy of approximately 2.8 MeV at zero degrees with respect to the deuterium ion beam direction was obtained. The basic concept for this particular device, the High Flux Neutron Generator (HFNG) owes to K.-N. Leung, with elaborations and upgrades being carried out largely by students and postdocs [6,7].

In the HFNG, positive deuterium ions are accelerated up to 125 keV after extraction from the high atomic ratio RF-driven plasma ion source. The symmetric planar water-cooled (cathode) target is positioned in between two opposing plasma ion sources, 10 cm away on each side

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(although typically only one is used). The target has a thin slot machined edgewise in it, allowing a cassette of small samples to be inserted within 8 mm of where the beam strikes the target, i.e. the production point of the neutrons [6,7]. As the target is at negative high voltage, secondary emission electrons from the target will accelerate back to the ion source, impeding the beam irradiation and damaging the ion source, unless these secondary electrons are suppressed. In the case of the HFNG, suppression of secondary electrons is accomplished by a specially designed shroud around the target, held at a more negative voltage, e.g. if the target is at –100 kV, the shroud would generally be at –102.5 kV; this solution worked very well. To produce a large number of neutrons and produce a flat profile at the sample cassette, multi-aperture electrodes are used. An electrode with only a single aperture is used, when one wants to measure a cross section as a function of energy over the available range 2.2-2.8 MeV. This can be done accurately and all at once, with a sample holder that positions different samples at several angles with respect to the plasma beam axis, taking advantage of the energy-angle correlation of the emitted neutrons.

The target is made of a thin layer either welded or explosion-bonded onto the water-cooled copper plate. Titanium is a very favourable target both due to its good thermal properties, but most importantly due to its very high (and reversible) affinity for hydrogen, which allows the surface of the target to be fully loaded within half an hour, at which time the HFNG reaches maximum neutron output. Under continuous bombardment of deuterium ions, the titanium eventually erodes, requiring a fresh target to be swapped in; this feature of the source is only a minor inconvenience and not a fundamental problem, solved by having two or three targets whereby one is undergoing a replacement of its titanium layer while the irradiation continues with a fresh target. A maximum of 10^{10} n/sec was obtained continuously under best conditions, resulting in a flux on the surface of small samples in the slot well of $10^{(8\text{-}9)}$ n/cm^2-sec.

NEUTRON GENERATOR USING A NEGATIVE DEUTRIUM ION BEAM

In principle, secondary emission electrons do not arise when negative ions impinge on a positive biased target. If negative ions are employed, one does not need a shroud with finite aperture to control the secondary emission electrons and therefore one can achieve an even larger ion extraction area with a multi-aperture cathode. In this case, the neutron output is simply limited to the negative deuterium ion beam current. Another positive feature is that there is no molecular negative deuterium ion. A single aperture (~1-mm-diameter) negative deuterium ion source is already in use at the Sandia National Laboratory neutron generator [8]. However, a negative deuterium ion source with multi-aperture electrodes has not yet been utilized for neutron generators even though it is being used in neutral beam injection systems (NBIs) for a future fusion reactor.

A large area negative deuterium ion source with filament cathodes has been developed at QST, Naka as NBIs for JT 60, a large plasma confinement tokamak for nuclear fusion experiments. Twenty-five years ago a 10-A negative deuterium ion beam had been accelerated up to 410 keV and 2.3×10^{12} n/sec neutrons were detected near the water-cooled cylindrical copper beam dump [9]. At that time those neutrons had been considered to be an obstacle to the development of a NBI. This is a demonstration that 10^{12} n/sec can be produced with a 10 A 400 keV negative deuterium ion beam striking on a copper target.

A RF deuterium multi-cusp ion source (without filaments) was developed at Lawrence Berkeley National Laboratory (LBNL), in which RF antenna is placed outside the ion source chamber [10]. Its maintenance under the influence of radiation is very simple since the antenna is located outside the vacuum. A long service interval for the ion source is also possible. If we replace the filaments with the RF antenna in the QST negative ion source, we can construct a new neutron generator of which the generator maintenance is much easier. This new neutron generator combines the RF negative deuterium multi-cusp ion source and the copper target, and will be very compact.

PROPOSAL OF 100 mA 200 keV NEGATIVE ION BEAM SYSTEM

We would like to construct a negative deuterium ion beam system of 100 mA 200 keV as a possible compact neutron generator, using a water-cooled copper target. The heat conductivity of copper is very high and the copper target is effectively cooled and maintain neutron production for a long time without a target replacement. The deuterium ion source is situated at ground potential while the copper target is at a high positive potential. A vacuum system with gas handling apparatus and a special water circulation system to supply the target with cooling water will be employed. A 13.56 MHz RF power generator will be used to operate the multi-cusp deuterium ion source. A dc high voltage supply is needed to accelerate negative deuterium ions up to 200 keV. See Figure 1.

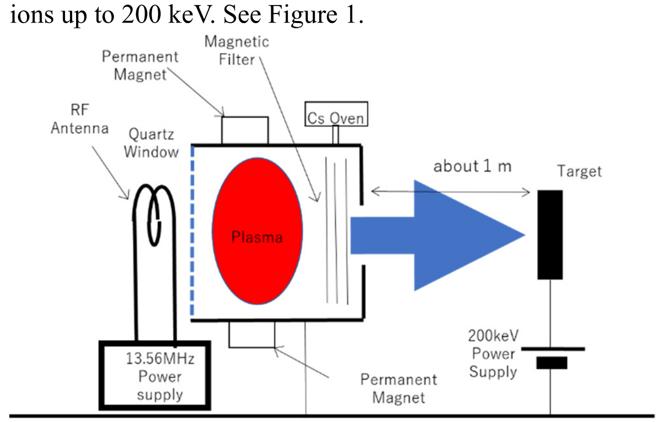

Figure 1: A conceptual image of the compact negative deuterium ion neutron generator.

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CONCLUSION

We plan to construct a prototype compact neutron generator which consists of a negative deuterium ion beam system with a copper target; this will position us to demonstrate an effective D-D fusion mono-energetic neutron generator, in which neutron energies depend on the direction.

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