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Near term, low cost, 14 MeV fusion neutron irradiation facility for testing the viability of fusion structural materials

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ABSTRACT

For over 50 years, engineers have been looking for an irradiation facility that can provide a fusion reactor appropriate neutron spectrum over a significant volume to test fusion reactor materials that is relatively inexpensive and can be built in a minimum of time. The 14 MeV neutron irradiation facility described here can nearly exactly duplicate the neutron spectrum typical of a DT fusion reactor first wall at damage rates of ≈4 displacements per atom and 40 appm He generated over a 2 l volume per full power year of operation. The projected cost of this multi-beam facility is estimated at ≈$20 million and it can be built in <4 years. A single-beam prototype, funded by the U.S. Department of Energy, is already being built to produce medical isotopes. The neutrons are produced by a 300 keV deuterium beam accelerated into 4 kPa (30 Torr) tritium target. The total tritium inventory is <2 g and <0.1 g of T_2 is consumed per year. The core technology proposed has already been fully demonstrated, and no new plasma physics or materials innovations will be required for the test facility to become operational.

1. Introduction

For over 50 years scientists and engineers have been concerned about the effects of 14 MeV neutrons on the components of DT fusion reactors. Each 14 MeV neutron will produce many more displacements per atom (dpa) than a fission neutron even more importantly, the number of transmutations/neutron (especially the production of gaseous atoms like H and He) will be orders of magnitude larger in DT fusion reactors than produced in a fission system per unit of thermal energy released [1,2].

It has been widely recognized that unless the safe operation of the structural components in a 14 MeV neutron environment can be experimentally demonstrated, it will be difficult to construct commercial DT fusion reactors.

The obvious solution is to build a 14 MeV neutron irradiation facility. Ideally, the facility must:

- provide the proper neutron energy spectrum at a sufficient neutron flux to produce the damage in a reasonable time frame,
- provide a sufficiently large test volume with minimal spatial variation,
- produce the total magnitude of damage in a time frame so as to have data available before the design of a commercial DT fusion reactor is completed,
- be constructed with a reasonably low capital cost,
- have an early deployment schedule,
- operate with a low recurring cost.

The solution presented in this paper is to use existing technology that has been funded, among others, by the U.S. Departments of Energy to generate intense DT neutron fluxes for medical isotope production in the United States [3].

2. Basic concept

Phoenix Nuclear Labs (PNL) has built and delivered a number of high output neutron generators with measured yields of up to 3×10^{11} n/s (DD). One of the systems that contain a gaseous tritium target is shown in Fig. 1. This beam target arrangement is used as the basis for the 14 MeV neutron source in the irradiation facility in this paper [4–7].

The 14 MeV neutron generator utilizes a custom 300 kV accelerator and a microwave ion source. The resulting D^+ ion beam is focused and directed into a gaseous 4 kPa (30 Torr) deuterium or tritium target. A pressure differential of approximately 10^6 is achieved between the gas target and the accelerator region that allows

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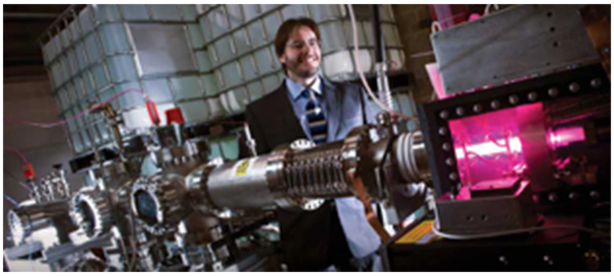

Fig. 1. An early version of a 14 MeV neutron generator delivered by Phoenix Nuclear Labs to SHINE Medical Technologies for the production of Mo-99 isotopes.

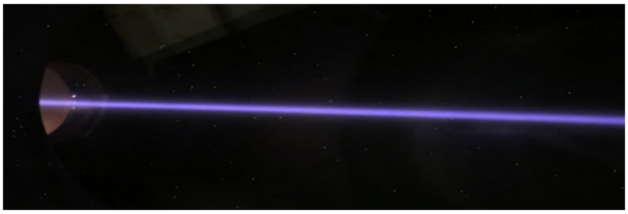

Fig. 2. Beam of 300 keV deuterium ions injected into a deuterium gaseous target [4–7].

Fig. 3. Photo of SHINE neutron generator prototype.

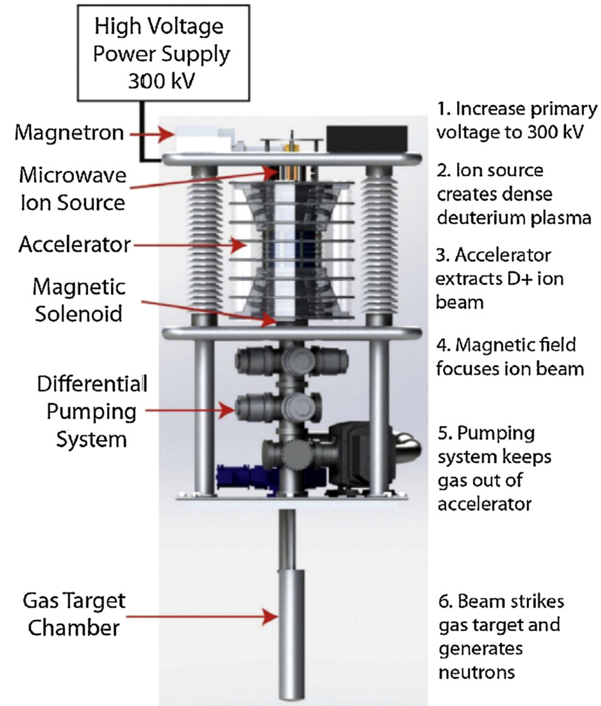

Fig. 4. Schematic of SHINE neutron generator prototype.

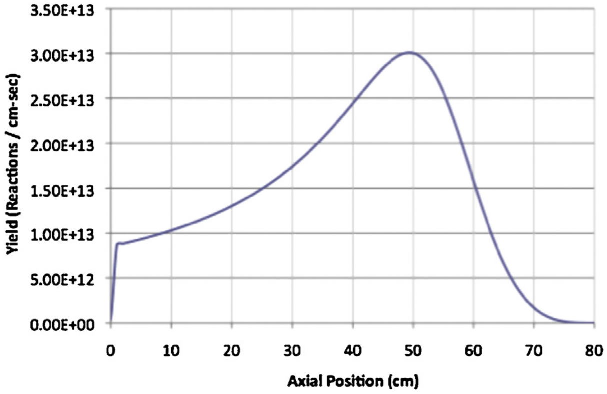

Fig. 5. Calculated neutron production rate for D$^+$ stopping in 4 kPa (30 Torr) tritium target gas [4–7].

sufficient target density to stop the beam while keeping accelerator pressure low. The total tritium inventory in device, including the processing equipment, is <2 g and the burnup rate of tritium is <0.1 g/FPY. Ref. [8] discusses the tritium system. The D$^+$ beam slows down over ~70 cm and the resulting line source of neutrons is <1 cm in diameter. Fig. 2 shows a D beam slowing down in a D$_2$ background target.

SHINE Medical Technologies will be operating a number of these accelerators in their isotope production facility. A photograph and schematic of the SHINE prototype neutron generator built by PNL is shown in Figs. 3 and 4. SHINE will require that the accelerators operate with a tritium gas target, with projected 14 MeV DT neutron source strength of at least 5×10^{13} n/s. As the D$^+$ beam enters the gas target at an energy well above the peak energy of the DT fusion cross section, the incremental neutron yield actually increases as the beam energy decreases, with the peak yield near the center of the gas target. This effect is shown in Fig. 5.

The DT neutrons are used to drive an aqueous subcritical assembly that contains uranium enriched to 19.5% ^{235}U in a uranyl sulphate solution. For every fusion neutron, ~50 fission neutrons are produced. The ~110 W of DT fusion power drives the subcritical fission assembly to ~75 kW during operation. The fission process produces ^{99}Mo ($t_{1/2}$ = 67 h) with a cumulative fission yield of 6.3%. ^{99}Mo decays to ^{99m}Tc, which is used in nearly 50,000 medical procedures per day in the U.S. alone.

The fusion neutron materials test facility described in this paper builds upon the existing PNL neutron generator technology by utilizing a large number (12–16) of DT neutron line sources around a materials test capsule. This configuration allows for significantly higher neutron flux in the test capsule than is achievable with a single line source. In addition, PNL is working toward higher deuteron current operation, which would allow each beamline to produce

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