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A NOVEL NEUTRALIZED-BEAM INTENSE NEUTRON SOURCE FOR FUSION TECHNOLOGY DEVELOPMENT*

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Abstract

We describe a neutralized-beam intense neutron source (NBINS) as a relevant application of fusion technology for the type of high current ion sources and neutral beamlines now being developed for heating and fueling of magnetic fusion energy confinement systems. This near term application would support parallel development of highly reliable steady-state higher-voltage neutral D^0 and T^0 beams and provide a relatively inexpensive source of fusion neutrons for materials testing at up to reactor-like wall conditions. Beam-target examples described include a 50-A mixed D-T total (ions plus neutrals) space-charge-neutralized beam at 120 keV incident on a liquid Li drive-in target, or a 50-A $T^0 + T^+$ space-charge-neutralized beam incident on either a LiD or gas D_2 target with calculated 14-MeV neutron yields of 2×10^{15}/s, 7×10^{15}/s, or 1.6×10^{16}/s, respectively. The severe local heat loading on the target surface is expected to limit the allowed beam focus and minimum target size to ≥ 25 cm^2.

1. Introduction

The use of a high energy ion beam incident upon a suitable target for intense neutron production is not, by itself, new. Examples of fusion (or fusion energy range) neutron sources of this type are the Rotating Target Neutron Source (RTNS II) facility operating at the Lawrence Livermore National Laboratory (LLNL), described by Logan et al.,[1] and the larger Fusion Materials Irradiation Test Facility (FMIT) now under construction at the Hanford Engineering Development Laboratory (HEDL), described by Trego et al.[2] Previous major studies for beam-target neutron sources also include the Intense Neutron Source (INS) at Los Alamos Scientific Laboratory, described by Armstrong et al.,[3] and the Neutron Generator with Rotating Self-Charging Target (NEGROS) at KfK Jülich described by Cloth et al.[4] A study similar to NBINS is now also underway at KfK, Karlsruhe, under the name "Neutronenquelle mit Rotierendem Feststofftarget" (NERO).[5] Table 1 summarizes the neutron source characteristics of various facilities.

The novel features for NBINS include: (1) the proposed use of one (or more) of the high energy, relatively high current neutral beamlines being independently developed for the magnetic fusion energy (MFE) program; and (2) focusing the total (ion plus neutral) beam on a relatively large target area (25 to 100 cm^2). This larger target area will allow testing of larger samples, operational testing of blanket segments, or simply 14-MeV fusion neutron calibration of the more intense FMIT stripping neutron source (a wider energy neutron spectrum but similar 14-MeV mean energy).

We describe the 14-MeV fusion neutron yield, calculated with the BDUMP code by Perkins et al.,[6] for several beam-target combinations as examples of the NBINS capability. Present MFE beamlines are capable of focused power

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Table 1. Summary of neutron source characteristics for various facilities.

Facility	Beam detail	Target detail	Yield (neutron/s)	Area (solid angle)
RTNS II [1]	0.1A D^+ at 380 keV	T_2 loaded Ti	$\sim 2 \times 10^{13}$	~ 1 cm^2 (4π)
FMIT [2]	0.1A D^+ at 35 MeV	Li stripping	$\sim 3 \times 10^{16}$	~ 3 cm^2 (beam)
INS [3]	1.1A T^+ at 300 keV	D_2 gas jet	$\sim 10^{15}$	~ 1 cm^3 (4π)
NECROS [4]	1.5A D^+/T^+ at 200 keV	Ti drive-in	$\sim 6 \times 10^{13}$	$\sim \pi$ cm^2 (4π)
NERO [5]	40A D/T at 200 keV	Sc drive-in	$\sim 4 \times 10^{15}$	~ 200 cm^2 (4π)

loadings in the MW/cm^2 range, as reported by Cooper.[7] However, we consider total beam loadings of $\leq$ few hundred kW/cm^2 (with $\lesssim 5$-μm implantation depth) as the maximum power loading allowed (and needed) to yield the 10^{13} to 2×10^{14} 14-MeV neutrons/s-cm^2 (approximately isotropic over 4π steradians) of reasonable interest for producing reactor-wall-like neutron fluxes. This is because 4.4×10^{13} 14-MeV neutron/s-cm^2 - directed flux corresponds to a reactor first wall neutron loading of ~ 1 MW/m^2.

The cost for this application would largely be for new target development and associated cooling and gas pumping equipment. The ancillary equipment needed for any extended D-T beamline and test facility operation is assumed to be already included in the MFE reactor development and technology budget.

2. General Arrangement of NBINS

2.1. Ion Source and Neutral Beamline Considerations

The increased neutron yield at a higher beam energy favors operation with the highest-voltage ion source available. The specific examples given in Section 3 include a 160-kV beam as representative of the maximum energy positive-ion-source-based neutral beamlines now under development. Higher energy negative-ion-source-based beamlines would therefore have an advantage, when available, for this application, although there is no particular gain here for the higher negative ion conversion efficiency to neutrals. The higher fusion neutron yield with energy also strongly favors using an ion source with a high atomic ion output fraction, since any half and one-third energy components contribute mostly to target heating.

The beam density, divergence, and focal properties of present pulsed sources (and expected in future steady state sources) are satisfactory for the NBINS application. Calculations indicate that operation will likely be limited by beam-target heat loading to $\leq$ a few hundred kW/cm^2 several meters from the source (as required for beamline and target gas vacuum pumping or perhaps the use of several beamline modules).

Beamline (or target) operation with T or D-T would require special remote-handling facilities and the use of a special D-T gas processing loop. Our choice of a T beam is based on minimizing the T_2 inventory in the much larger recirculating volume of target material, although the velocity-dependent fusion cross section would favor the use of a D beam incident upon a T-loaded target. Space-charge-limited ion source currents for different species or mixed beams would scale such that

$$\sum_i j_i \,(\mathrm{mA/cm^2})\, [M_i\,(\mathrm{amu})]^{1/2} \approx 1.72\, V_0\, (\mathrm{kV})^{3/2}/d(\mathrm{cm})^2\ \mathrm{mA/cm^2} \quad ,$$

where V_x is the extraction voltage and d is the effective extraction spacing, and where the index i is summed over the species involved for a mixed beam.

Beamline operation for this application requires sufficient background gas (10^{-4} to 10^{-5} Torr) for good space-charge neutralization for beam transport, but not as much gas as is needed for optimization of the maximum charge-exchange output of the full energy neutral fraction. The net beam current density focused on the target must be carefully controlled and interlocked because of the extreme surface heat load on the target and because of a likely target wall failure with a loss of target cooling.

2.2. General Target Considerations

The high specific power loading per cm^3 required for a given fusion neutron yield is reduced by going to higher voltages (up to $\sim$500 kV) or by using target materials of lower Z or with a higher fraction of D atoms (for a T beam). However, target surface damage or decomposition appears highly likely, so some renewable or liquid surface appears essential.

The target, particularly the first $\sim$10 μm near the surface, must either contain the D or T atoms for fusion reactions with an energetic T or D beam, or support self-loading of D-T with a mixed incident D-T beam.

A relatively narrow beam height (in the direction of target rotation or target material flow) and wider beam spread for the desired total area are favored as a means of minimizing target heating. Depending on the target material and design, the target desorption or decomposition will likely form the major gas load to be pumped.

3. Specific Examples of Targets and Fusion Neutron Yields

3.1. Target Design

Because of the very high beam power densities on the target surfaces (up to $\sim$5[illegible] kW/cm^2), thermal and mechanical engineering of the target system present some very formidable design problems, which in turn will require innovative design solutions. Accordingly, the following are some preliminary comments on several possible beam-target combinations:

- Liquid Li Drive-In Target with a D-T Beam. This target depends on both the use of high-thermal-conductivity flowing Li for cooling and the buildup (and retention) of sufficient D-T target atoms for subsequent energetic, mixed D-T atoms to generate the D-D and D-T neutrons through D(d,n), T(d,n), and D(t,n) fusion reactions. A flowing liquid Li target like the FMIT [2] appears capable of handling the beam power loading. However such a circulating fluid system would likely be turbulent and would not build up the target D-T concentration in the Li to the equilibrium density. Therefore, a new, perhaps, rotary Li target design would probably be needed. At the very least, tests would have to be performed to evaluate the effective drive-in D-T target density buildup before considering this approach further. In the case of a rotating solid drive-in target such as NEGROS, [4] the D-T buildup is more predictable, but the higher target atomic number (Z) and the limitation on temperature rise before desorption could possibly degrade large area target performance.

- Liquid LiD Target with a T Beam. This target appears attractive because it solves the target atom problem by providing a high density ($\sim$5.9 x $10^{22}/cm^3$) of D bonded to an element with a low atomic number and, therfore, a low competing atomic stopping power. As in the case of the Li target, the LiD would likely be in a liquid form for circulation as a high speed curtain for the target surface and would be pumped through a suitable heat exchanger for cooling. LiD has a melting point of 686°C, a liquid density of $\sim$0.76 gm/cm^3, and does not appear appreciably corrosive with common stainless steels, although it is quite reactive with air or water at $\sim$700°C. However, the use of LiD at $\sim$700°C would introduce at least three serious problems. First, the target and its associated structure must also operate at $\sim$700°C; thus, special structural materials with high temperature strength and low T_2 permeation rates (e.g., TZM) would be required. Second, LiD exhibits relatively poor thermo-physical properties relative to Li (e.g., low thermal conductivity and diffusivity). Therefore, the thermal-hydraulic aspects of the design would be more demanding than the FMIT Li target. Third, liquid LiD at this temperature is accompanied by a significant overpressures of D_2 gas. Typical vapor pressures would be several tens of torr, thus increasing demands on the vacuum system. One variation under study is to replace the flowing liquid LiD curtain with a high speed jet curtain of finely divided LiD powder at a much lower initial ($\sim$100°C) temperature, and use the heat capacity, heat of fusion (melting), and heat of dissociation to hopefully reduced the gas pumping problem.

- D_2 Gas Target with a T Beam. The use of a high pressure D_2 gas jet similar to the INS [3] design remains still another attractive possibility although it would have to be scaled to a much larger area and reacting volume. In this target design, a high pressure D_2 gas jet target is formed by compressive flow through a supersonic plug nozzle. The incident neutralized T beam would then interact with the convergent jet flow of the target D_2 gas, and the deposited heat would be carried out by the exhaust gas to a downstream large heat exchanger. This target design has some advantages over the LiD target, including a higher specific neutron yield (see below) and a simpler heat removal scheme. It does, however, have the disadvantage of a distributed source volume, a relatively bulky target and associated gas ducting, and some uncertainty in beam heating limits within the supersonic jet.

3.2. Target Neutronics

As a result of a previous study on neutron generation from high power neutral beam dumps, a BDUMP code was formulated and reported by Badger et al. in the TASKA study.[8] This code computes absolute neutron yields and angular distributions resulting from the implantation and subsequent interaction of D, T, or mixed D-T beams with solid or liquid surfaces. The BDUMP code includes a numerical solution of the equilibrium gas density from beam deposition and diffusion as a function of temperature and depth, and follows the energy-dependent fusion-reaction cross section along the range of the incident energetic ion, subject to the stopping power of the target material and accumulated D-T gas. Full details of the code can be found in the report by Perkins.[6]

- Yield from a Liquid Li Drive-In Target. Figure 1 shows the total neutron yield from the Li target computed by BDUMP and plotted as a function of the temperature of the liquid Li surface. We used typical beam conditions of 50 A of 50% D and 50% T at a beam energy of 120 keV. We assumed Li thickness of 1 cm and a temperature gradient of 10°C (across the surface). Note that the yield is a strong function of the surface temperature because of the dependence of the steady-state D-T volume distribution on the temperature-dependent diffusion coefficient. Further calculations for a Li drive-in target with a 400°C surface temperature indicate a neutron yield of αI^2 up to a beam current density of $j \sim 4$ A/cm^2, at which point the yield starts to saturate and the yield becomes αI.

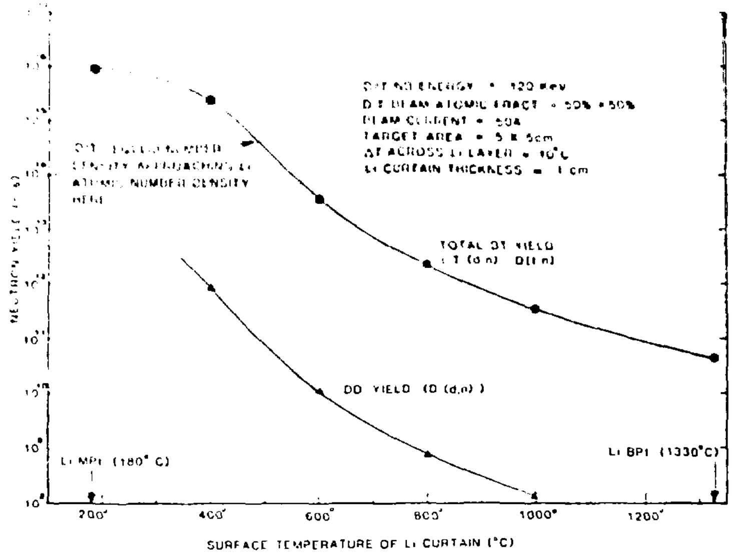

Fig. 1. Neutron yields as a function of the surface temperature of a Li curtain target.

- <u>Yield from a LiD or D_2 Gas Target</u>. The neutronics calculations for these targets are somewhat simpler than those for the Li drive-in target because we only need to consider the deceleration of a T beam in a constant target composition and D number density. Figure 2 shows the neutron yield/A of a T beam on either a liquid LiD or D_2 gas jet target as a function of beam energy. The temperature of the LiD target surface is taken as 720°C. Two interesting features are evident in Fig. 2. First, at lower beam energies there is a rapid rise in neutron yield with the beam energy reflecting the energy variation of the D-T fusion cross section, which has a peak at ~110 keV and rapidly falls off at lower energies. This gives a strong incentive for going to the highest beam energy consistent with the MFE neutral beam technology development. Second, the neutron yield for the pure D_2 reference case is more than twice the yield obtained with LiD for the same beam energy. This shows the strong competing effect of the atomic stopping power of Li (proportional to Z) in LiD on the deceleration of the incident tritons. In either case, fusion heat contribution to the target is negligible because the probability of fusion for 160 keV T on D_2 is only $\sim 6 \times 10^{-5}$ and the resultant 14-MeV neutron would carry most of the 17.6-MeV fusion reaction energy away from the target volume. Both of these targets have desirable neutronics, but both are also subject to major questions of gas evolution and pumping from either dissociation of the ~700°C LiD target or from a small percentage of scattered gas from a high pressure supersonic D_2 gas jet.

4. <u>Conclusion</u>

The presently planned focused neutral beamlines of the MFE program are quite capable of producing the fusion neutron fluxes of interest for materials testing under ion source operating conditions that would support advanced beamline development for fueling and heating large fusion confinement systems. However, the associated target heat load is so severe that it limits the target design, target size, and the steady-state available neutron flux. A brief summary of the characteristics of the various NBIS target options is shown in Table 2.

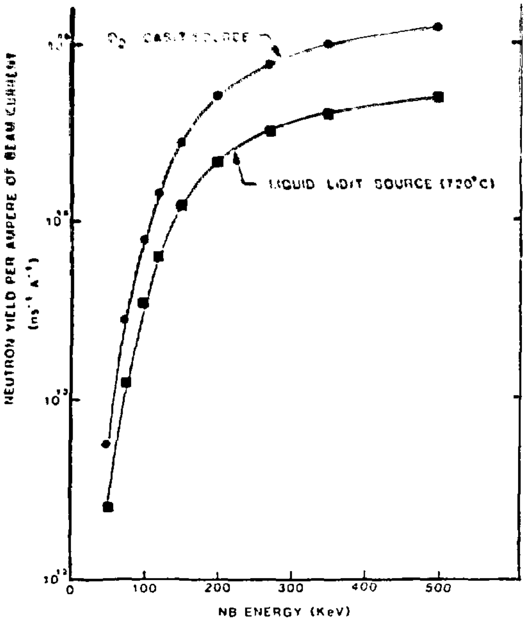

Fig. 2. Comparison of D(t,n) yields for liquid LiD and D_2 gas targets vs incident T beam energy.

Table 2. Summary of NBINS characteristics for various target options.

Beam detail	Target	Yield (neutron/s)	Area (cm^2)	Limiting problem
50 A D-T 120 keV	Li drive-in	$\sim 2 \times 10^{15}$	25 cm^2	D-T loading
50 A T 160 keV	LiD curtain	$\sim 7 \times 10^{15}$	$\sim$100 cm^2	Dissociated gas flow
50 A T 160 keV	D_2 gas jet	$\sim 1.6 \times 10^{16}$	$\sim$25 cm^2	Gas scattering

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