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TITLE: **HIGH-PERFORMANCE DEUTERIUM-LITHIUM NEUTRON SOURCE FOR FUSION MATERIALS AND TECHNOLOGY TESTING**

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High-Performance Deuterium-Lithium Neutron Source for Fusion Materials and Technology Testing *

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Abstract

Advances in high-current linear-accelerator technology since the design of the Fusion Materials Irradiation Test (FMIT) Facility[1] have increased the attractiveness of a deuterium-lithium (D-Li) neutron source for fusion materials and technology testing. This paper discusses a new approach to such a source aimed at meeting the near-term requirements of a high-flux high-energy International Fusion Materials Irradiation Facility (IFMIF). The concept employs multiple accelerator modules[2] providing deuteron beams to two liquid-lithium jet targets oriented at right angles.[3] This beam/target geometry provides much larger test volumes than can be attained with a single beam and target and produces significant regions of low neutron-flux gradient. A preliminary beam-dynamics design has been obtained for a 250-mA reference accelerator module. Neutron-flux levels and irradiation volumes were calculated for a neutron source incorporating two such modules, and interaction of the beam with the lithium jet was studied using a thermal-hydraulic computer simulation. Cost estimates are provided for a range of beam currents and a possible facility staging sequence is suggested.

Introduction

According to a recent international assessment,[4] the present understanding of materials behavior in a fusion reactor radiation environment is insufficient to guarantee the required performance and endurance of future reactor components. The perceived need for a high-flux materials-testing neutron source resulted in the current International Energy Agency (IEA) initiative to examine the source requirements and to evaluate the technologies available for meeting them in the near term.[5]

This paper presents an accelerator-driven source concept that is derived from FMIT, but takes advantage of improvements in the technology of high-current ion accelerators[6,7] to offer a more attractive and cost effective facility for fusion materials testing. As in FMIT, 35 MeV deuterons are used to generate a fusion like neutron spectrum from the thick target yield of the Li(d,n) nuclear stripping reaction. This spectrum, which peaks near a neutron energy of 14 MeV, produces atomic displacements (dpa) and transmutation products (e.g., Helium) in irradiated materials with ratios that bracket the complete range of fusion reactor environments. Because the deuteron energy is adjustable, the dpa/He ratio could, in principle, be tuned to study possible spectrum dependent effects.

A modular accelerator and target configuration is envisaged, as shown in Fig. 1, which provides for test cell flux and volume flexibility, flux gradient tailoring, staged expansion of capability, and improved facility availability. Although many accelerator design variations are possible, this paper focuses on a two module source, with each unit delivering a 250 mA cw beam. Each accelerator module would consist of two D+ dc injectors, two radio frequency quadrupoles (RFQ), a beam funnel, and a single drift tube linac (DTL). The reference neutron source contains two lithium jet targets oriented at 90°, with each target receiving one beam. As implied in the figure, total current could be expanded to 1000 mA by adding two more accelerator modules or reduced to 250 mA by eliminating one RFQ from each module.

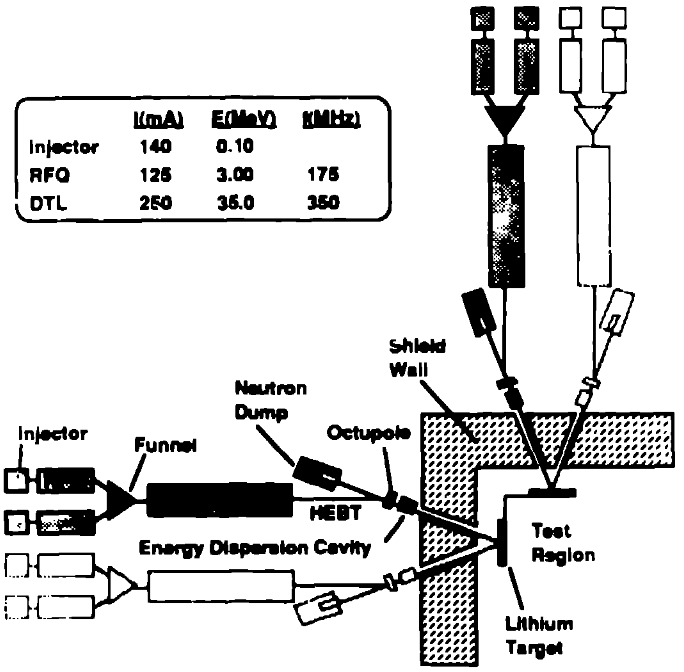

Fig 1. **Reference Neutron Source:** Two 250-mA accelerator modules and two lithium targets. Lightly drawn modules indicate upgrade potential.

FMIT Technology Base

The FMIT facility was to provide a 100 mA deuteron beam to a lithium jet target, generating a 0.5 litre test volume exposed to a minimum uncollided neutron flux of 10^{14} n/cm² s (equivalent to fusion reactor wall loading power of 2.3 MW/m²), and a 10 cm³ volume at 10^{15} n/cm² s (23 MW/m²). Flux gradients in the test zone were high. The accelerator consisted of a 100 keV D+ cw injector followed by a 2 MeV RFQ and a 35 MeV DTL, both operating at 80 MHz. The DTL accelerating gradient was 1 MV/m, and the total RF power required was 5.4 MW. The deuteron beam was to be conveyed to the lithium jet by a high energy beam transport (HEBT) system that included an energy modulating rf cavity for broadening the beam energy spread to 0.5 MeV (rms). Lithium flow rate in the jet was 17.3 m/s, and peak beam power deposition density in the jet reached 1.8 MW/cm³.

Before the project termination in 1984, FMIT firmly established technical feasibility for the D-Li source concept. The program included neutronics calculations to determine test cell flux levels and volumes, thermal hydraulic calculations to model the beam target interaction, development and operation of a prototype lithium jet and circulation system, construction and cw operation of a prototype injector and RFQ, and a complete engineering design for the facility.

New Accelerator Concept

Since the completion of the FMIT design there have been significant advances in high current ion linac technology that will [illegible]

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construction of an improved D-Li neutron source, with higher performance at lower effective cost. These advances include: a comprehensive emittance-growth theory; better beam-dynamics simulation codes; development of the beam-funneling concept for current multiplication; the use of high accelerating-structure frequencies, permanent-magnet quadrupoles (PMQ), and ramped accelerating gradients to control beam-emittance growth and halo growth; and the use of high-order optics in beam transport systems to manipulate beam profiles.

The 250-mA accelerator module proposed as the building block of our reference source concept is sketched in Fig. 1, which also tabulates frequencies, currents, and energies selected for each component. Preliminary beam dynamics simulations have been carried out for this module and are discussed below.

Injector, RFQ, and Funnel

Because of beam loss inherent in the RFQ bunching process, about 140 mA of D^+ must be injected to obtain 125 mA at the output. This requirement could be met by a duopigatron ion source similar to one operating at Chalk River Nuclear Laboratory.[8] The selected RFQ frequency (175 MHz) is more than twice that of FMIT, allowing a large reduction in transverse structure dimensions. High-power (0.5 to 1.0 MW cw) tetrodes are commercially available to provide the accelerating energy.

Beam behavior in the RFQ was simulated with the code PARMTEQ, using a 1000-superparticle input distribution uniformly filling a four-dimensional transverse phase-space hyperellipsoid. The longitudinal distribution was that of a continuous beam with zero energy spread. Figure 2 shows the radial distribution, phase width, and energy spread of these particles as the beam traverses the RFQ. Table I lists important RFQ parameters not displayed in Fig. 2; the transverse (T) and longitudinal (L) beam emittances shown are normalized rms values.

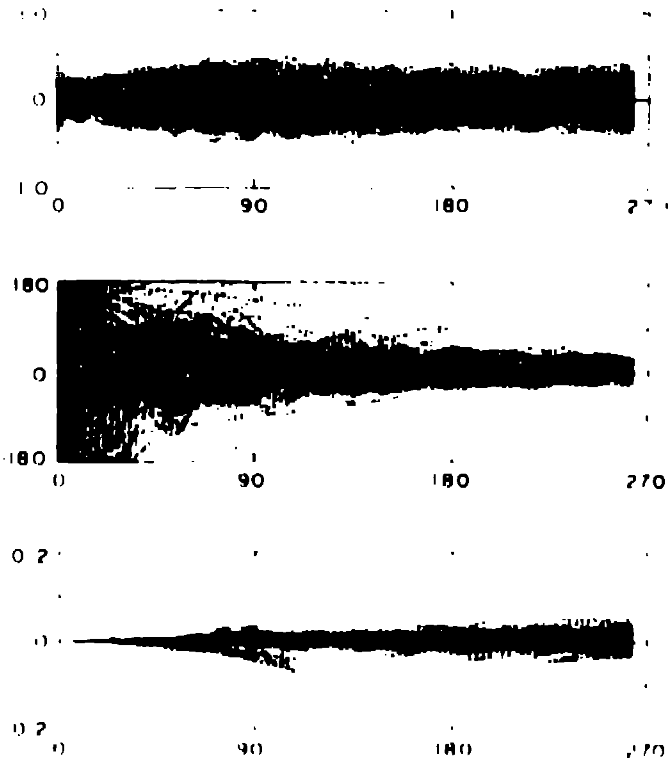

Fig. 2. Beam parameters in RFQ vs PARMTEQ cell number
TOP Horizontal displacement (cm)
MIDDLE Phase deviation from synchronous (degrees)
BOTTOM Energy deviation from synchronous (MeV)

The output beams from the two RFQs are combined longitudinally at twice the RFQ frequency in a funnel of the type soon to be tested at Los Alamos. At the funnel entrance, the beams are 16.4 cm apart and are converging at a relative angle of 20°. Each beam is transported separately through four PMQs and a 175-MHz buncher to the beam combining elements, which consist of a large-aperture defocusing PMQ and a 175-MHz rf-deflection cavity. The bunches from each RFQ are separated by 180° in phase, and are kicked onto a common longitudinal axis by the rf deflector. An additional four PMQs and two 350-MHz bunchers provide a six-dimensional phase-space match from the funnel into the DTL.

Table I. RFQ Parameters

Mean aperture	1.2 cm	RF power (copper)	0.3 MW
Tank diameter	36 cm	RF power (beam)	0.4 MW
Structure length	5.4 m	RF power (total)	0.7 MW
Surface field (peak)	25 MV/m	Output emittance (T)	0.27π mm-mr
Transmission	89.3%	Output emittance (L)	0.46π mm-mr

Drift-Tube Linac

The DTL consists of two 350-MHz tanks operating as 1βλ structures. The focusing pattern of the drift-tube quadrupoles is FOFO DODO, and their field gradient is ramped from 120 to 100 T/m with increasing beam energy. The accelerating field in the first tank is ramped from 3 to 4 MV/m, while in the second the field is held constant at 4 MV/m. Radio-frequency power would be supplied by 1-MW cw, 350-MHz klystrons now available from several manufacturers. The frequency is more than four times that of FMIT, and the accelerating gradient is three to four times higher, resulting in a much more compact accelerator. Improved control of beam halos (and beam loss) is expected with the higher frequency structure.

The simulation code PARMILA was run with 1000 superparticles to examine the DTL beam dynamics at 250 mA. The input phase space distribution is that of a uniformly filled six-dimensional hyperellipsoid whose rms dimensions match those obtained from the RFQ output. No particles from this distribution were lost from interception by the drift tubes. Figure 3 shows the beam's radial dimension as it traverses the DTL, along with its phase width and energy spread. Table II lists important DTL parameters not mentioned above.

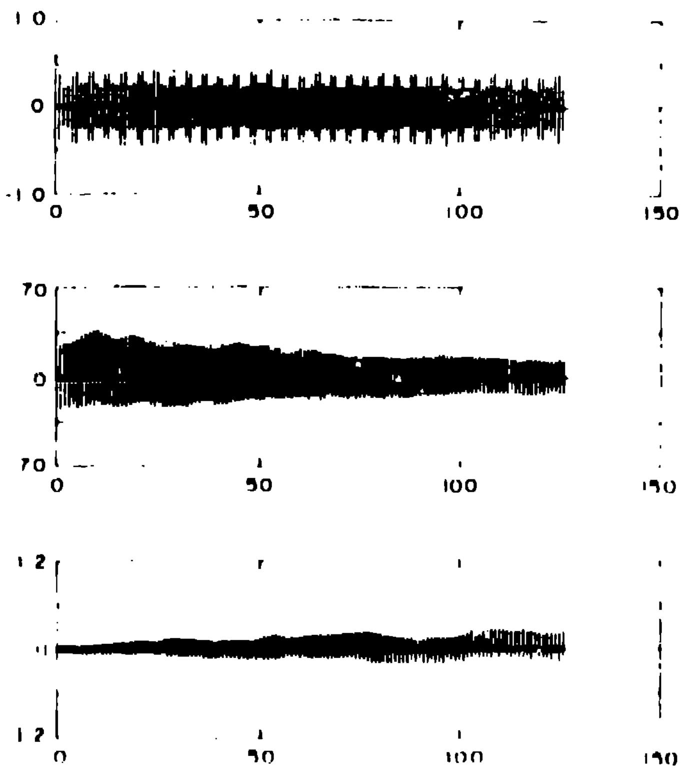

Fig. 3. Beam parameters in DTL vs PARMILA cell number
TOP Horizontal displacement (cm)
MIDDLE Phase deviation from synchronous (degrees)
BOTTOM Energy deviation from synchronous (MeV)

Table II. DTL Parameters

Tank diameter	50 cm	Output emittance (T)	0.30π mm-mr
No. of drift tubes	128	Output emittance (L)	0.51π mm-mr
Drift-tube aperture	2.0 cm	RF power (copper)	3.3 MW
Total length	13 m	RF power (beam)	8.0 MW
Beam loading	71%	RF power (total)	11.3 MW

High-Energy Beam Transport

The HEBT will consist of a periodic focusing system with at least one bend, so that back-angle neutrons from the target strike a shielded dump rather than the accelerator. A spur line and a high-power beam stop will be needed to permit accelerator tuning before beam is switched to the target. Special elements will be inserted into the HEBT to increase the beam's energy spread to 1.0 MeV (rms) and to flatten and widen the transverse distribution. These manipulations are required to maintain sufficiently low peak power deposition density in the lithium jet.

Both internal and external forces can be used to obtain the required beam energy spread. If the periodic-focusing system at the end of the DTL is continued into the HEBT, longitudinal space-charge forces will increase the rms energy spread of a 250-mA beam from 70 to 500 keV within five meters. A 2 MV, 350-MHz energy dispersion cavity placed near the end of the HEBT can provide an additional 500 keV energy spread. Preliminary calculations show the feasibility of using non-linear optics (octupoles)[9] in the HEBT to obtain a wide, flat, horizontal-plane beam density profile at the lithium target rather than the Gaussian distribution assumed for FMIT. In addition to lowering the power deposition in the target, this feature provides a more uniform neutron flux distribution in the test volume.

Target Heating

The steady-state interaction of a 250-mA deuteron beam with the lithium jet was modeled by a Los Alamos adaptation of the two-dimensional Patankar-Spalding thermal hydraulic code[10] using the same flow conditions as in FMIT (17.3 m/s flow velocity, 220°C inlet temperature, 1.9 cm inlet jet thickness). Energy deposition vs depth profiles for 35-MeV deuterons were calculated using the code TRIM-89,[11] assuming a Gaussian beam energy distribution with a 1.0-MeV rms value. The beam spatial profile at the target was specified as a 4-cm wide rectangular distribution with 1-cm rms Gaussian edges in the direction normal to the lithium flow and a 1-cm rms Gaussian distribution in the flow direction. Figure 4 compares the specific energy deposition profile calculated for a monoenergetic 35-MeV beam with that for a beam with a 1.0-MeV rms energy spread, showing that a factor of 2 reduction in dE/dx can be obtained at the Bragg peak.

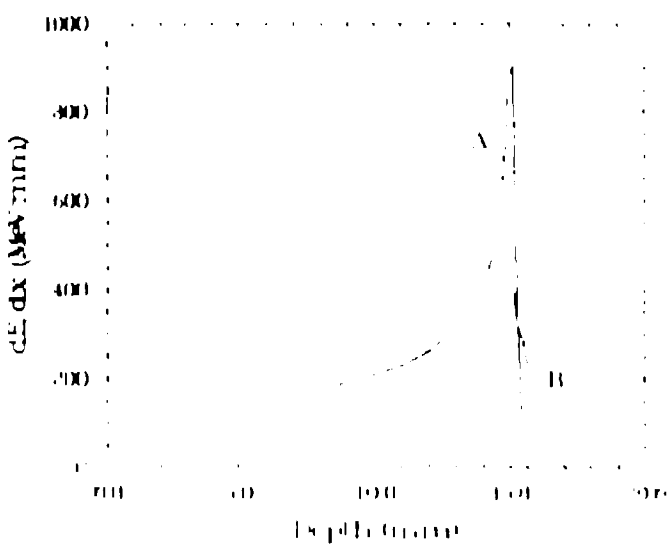

Fig. 4. Energy loss in lithium target for 35-MeV deuterons.
A. Monoenergetic beam.
B. Beam with 1.0-MeV rms energy spread.

Figure 5 compares the maximum lithium temperature in the jet with the saturation temperature (boiling point) as a function of distance from the target back wall. The selected temperature profile passes through the maximum temperature point in the lithium, about 3 cm below the beam centerline; at this location the jet thickness is 2.1 cm. For the chosen beam parameters, the lithium temperature remains safely below the local boiling point, even with 2.5 times the FMIT deuteron current, except in a very thin layer at the jet surface. The lithium evaporation rate from this surface layer is found to be negligible.

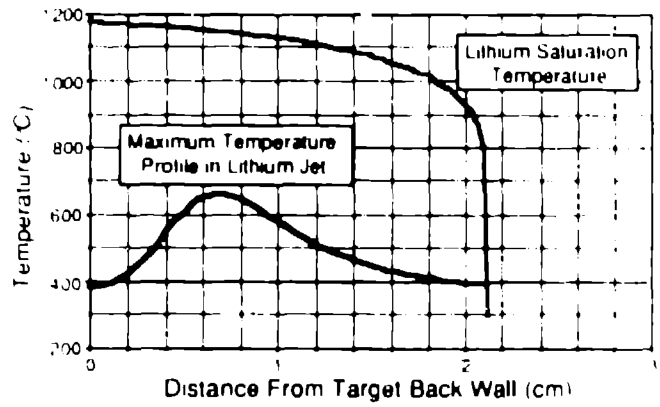

Fig. 5. Jet temperature and lithium boiling temperature vs distance from target back wall. Temperature profile is taken through hottest point in target.

Neutronics

Uncollided neutron flux contours were calculated for several beam-target configurations. A representative contour plot, presented in terms of equivalent neutron wall-loading power, is shown in Fig. 6 for the reference case of two 250-mA beams incident on two targets oriented at 90° and centered 10 cm from their common vertex. These plots were produced from point-wise flux data generated by the computer code used for the original FMIT neutronics calculations.[12] This code is based on a complete set of differential cross sections for several deuteron energies and several neutron energies and angles. The cross sections are generated from semi-empirical fits of experimental measurements to Li(d,n) stripping theory as well as other contributing nuclear reactions. The resulting three-dimensional point-source neutron flux maps were then combined to give contour plots for selected beam/target geometries.

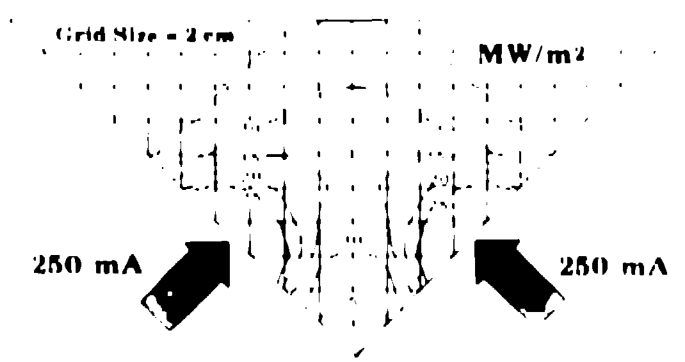

Fig. 6. Neutron wall loading power contour plot for two 250-mA beams and two lithium targets at relative orientation of 90° and spaced 10 cm from vertex.

In addition to the reference case, contour plots were [illegible] other lithium target orientations and spacings. These [illegible] test region neutron flux gradients could be tailored to [illegible] experimental requirements by varying these parameters [illegible] orientation and spacing over a limited range.

Using the 3-D flux maps, it was possible to estimate the available test volume exposed to a specific average neutron flux (in the simplifying limit of no perturbation introduced by test samples or the lithium jet). This volume is plotted in Fig. 7 as a function of total beam current for different (average) wall loadings. The beam/target geometry is as given in Fig. 5. Test volumes estimated for FMIT are shown for comparison.

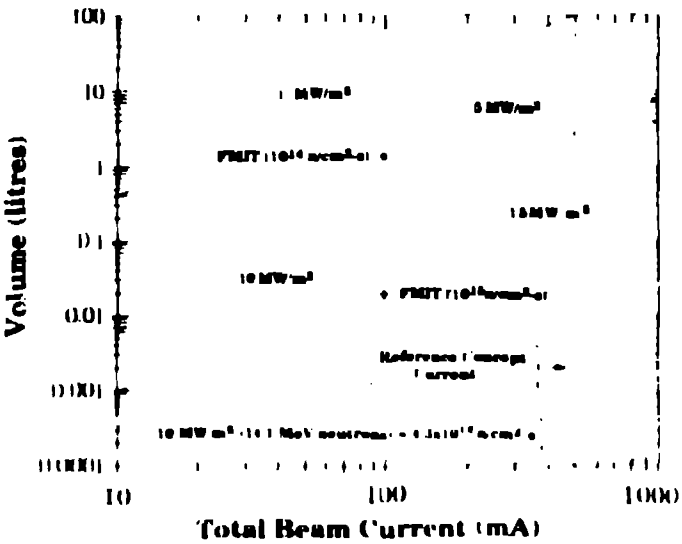

Fig. 7. Test volume vs total beam current at several neutron-wall loading levels for contour map of Fig. 6. FMIT test volumes are shown for comparison.

Conclusions

We described a D-Li neutron source that would have five times the deuteron current of FMIT. In the reference beam/target geometry, the test volume at a specific average uncollided neutron flux scales approximately as $(I_d)^{1.8}$, where I_d is the total deuteron current. The test volume available in the reference IFMIF concept would therefore be 18 times greater than in FMIT (for the same average uncollided neutron flux). Beam-dynamics simulations show that a compact, high-frequency RFQ/DTL accelerator design is feasible at 250 mA, and that it should perform with small emittance growth and negligible beam loss. Target heating simulations show that the energy deposition problem is tractable at 250 mA with suitable manipulation of the beam energy spread and spatial profile in the HEBT.

In a multimodule facility, each accelerator unit would be housed in a separately shielded vault so that maintenance could be carried out on any unit without shutting down the entire neutron output. This feature would increase overall facility availability for users.

One can imagine a facility staging scenario that starts with a single linac module with an output current as low as 25 mA (1 RFQ), but which is designed with the correct choice of frequency, gradient, etc. to operate at up to 250 mA. The facility could be upgraded in steps by adding RF power, then a second RFQ, and then a second accelerator module to reach 500 mA. The final upgrade to 1000 mA would involve the addition of two more accelerators as suggested in Fig. 1.

A preliminary construction and operation cost analysis has been carried out for the range of total beam currents and is summarized in Table III (costs are in 1988 $US). The accelerator estimates are based on recent component costs; target and test facility costs are extrapolated from FMIT. Electric power costs assume 90% beam-on time,

Table III. Facility Cost Estimate Summary

Total current	125 mA	250 mA	500 mA	1000 mA
Construction	107 M	150 M	232 M	384 M
Electric power	5.3 M/yr	8.7 M/yr	17.4 M/yr	34.8 M/yr
Total operating	13.9 M/yr	19.8 M/yr	32.7 M/yr	54.5 M/yr

conventional ac/RF power-conversion efficiency (0.46), and a line source as economical as that for FMIT ($0.035/kW·h). A plot of the construction cost estimates as a function of total deuteron current reveals that these costs scale approximately as $(I_d)^{0.62}$.

Acknowledgments

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