ENERGY VARIABLE DEUTERON LINAC FOR MATERIALS RESEARCH NEUTRON SOURCE*

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Abstract

Basic research in new materials and materials technology is a key national resource, and several countries are making plans for advanced capabilities, including intense neutron sources. Advances in high-intensity linear accelerator technology can provide efficient drivers for such sources. Aspects such as energy variability, uniformity of target dose distribution, target bombardment from multiple directions, time-scheduled dose patterns, and other features can be provided, opening new opportunities in the experimental program. These considerations are discussed in the context of a 20-40 mA continuous-current, 35-MeV compact deuteron linac facility, as a subset of designs with much larger (250 mA) current capability. The possibility for a current-upgradeable facility is briefly described.

Introduction

Advanced neutron sources are needed for basic and applied materials research.[1] The neutron spectrum produced from the D-Li reaction has been judged useful for many materials research problems, especially for fusion reactor materials. Earlier programs, including the Los Alamos Meson Physics Facility (LAMPF) and the Fusion Materials Irradiation Test (FMIT) facility prototype, demonstrated key features of the required high-intensity accelerator and target technology. FMIT was to be an internationally funded D-Li neutron source based on a 100-mA, 35-MeV cw D^+ linear accelerator, with a materials test volume characterized as 60 dpa/year in 10 cm^3 (1.0×10^{15} $n/cm^2{\cdot}s$) and 6 dpa/year in 400 cm^3 (1.0×10^{14} $n/cm^2{\cdot}sec$). Continuing discussion over the nearly 10 years since FMIT cancellation has been focused by the IEA Fusion Power Coordinating Committee on studies for an International Fusion Materials Irradiation Facility (IFMIF)[2] that would hopefully provide larger flux and test volume than FMIT would have, within a similar cost boundary, by using recent technical advances. In the near term at least, the D-Li approach is the only approach with a sufficiently demonstrated technology to proceed quickly to an operating facility. Indeed, advances during the last decade in accelerator technology allow the confident proposal of an IFMIF based on 250-mA, 35-MeV accelerator/target modules.[3] Two such modules, oriented at 90^o relative to the test volume, are shown to provide a test volume 18 times larger than FMIT (for the same average uncollided neutron flux).

The cost of such an IFMIF and the complications of international funding have led to serious planning in Japan[4] for a nearer-term low- to intermediate-fluence facility that would address many areas of basic materials research as well as aspects of fusion materials development. The strategy[5] proposes an Energy Selective Neutron Irradiation Test Facility (ESNIT), coupled with a highly modernized test laboratory using modular-type hot cells (MODULAB) and the Small Specimen Test Technique (SSTT). Although the deuteron current of the ESNIT might be only 20-40 mA (to reduce costs), the combination of MODULAB and SSTT is expected to offset some of the disadvantage of reduced flux.

ESNIT, or the larger IFMIF, would be configured to provide a more flexible experimental facility than earlier designs.[6] Some of the capabilities that could be provided might suggest new experimental techniques to materials researchers. As its name implies, ESNIT will provide energy selectivity, typically in discrete steps. Neutron intensity can also be varied. The target chamber could be irradiated by more than one beam, from different angles, providing many possibilities for tailoring the flux distribution. The density distribution of the deuteron beam at the target could also be tailored using advanced techniques in magnetic optics, affording further control of the target chamber distribution. Finally, the accelerator and associated beam-transport elements are all essentially electronic devices and therefore can be controlled and modulated in time-varying patterns under computer control, opening the possibility for study of rate-dependent effects.

The cited sources provide many details of the materials research needs and facility requirements. We discuss briefly here some aspects of the deuteron linear accelerator system.

Accelerator Issues

While detailed design work has not been funded, ESNIT and IFMIF requirements fall within the envelope of extensive work at Los Alamos during the 1980s on the neutral particle beam program and recently on design studies for Accelerator Production of Tritium (APT) and Accelerator Transmutation of Waste (ATW). These latter two applications require cw proton currents of up to 250-300 mA at 1.5 GeV. Detailed conceptual design work on the accelerator for APT/ATW has been completed, and APT was stringently reviewed by the Energy Research Advisory Board of the US Department of Energy.[7] Their findings include the following:

- The continuous-wave RF linac approach is the most advanced accelerator technology for application to the production of tritium,
- The continuous-wave RF linac approach for APT is technically sound. While an integrated accelerator system has never been built and operated at APT conditions, the accelerator feasibility and engineering development issues could be solved with an adequate research, component and systems development, and engineering demonstration program.
- Beam transport is a mature discipline. The high-energy transport system requires some component development and testing. However, beam transport is not expected to be a significant problem in an APT development program.
- An initial 4-year period would be required for activities including R&D, system optimization, conceptual design, and design of the first sections (up to 60 MeV) of the accelerator system, with parallel activities such that construction of an engineering demonstration could be completed in 2-2.5 more years.

This review is of major importance in assessing the present state of the art of high-brightness, low-loss accelerator design. What are some of the key features?

High-Intensity Linacs With Very Low Particle Loss

Stray beam losses along a linac produce radioactivity in the beamline elements that can severely complicate maintenance. One of the most critical requirements for a high-intensity linac factory environment is that beam losses along the accelerator be kept low

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enough that "hands-on" maintenance† is possible over the life of the facility. At deuteron energies up to 35-40 MeV, this means that no more than a few mA/m of beam loss (or a fractional loss of $\sim 10^{-4}$/m for a 30 mA linac) can be tolerated.

Our design principles insure that high-current operation is combined with excellent beam quality based on fundamental beam physics.[8] We must start with a high quality 75-100 keV ion source having low emittance, and preserve that emittance through the following acceleration and transport to the target. Up to about 2 MeV, we use a radio-frequency quadrupole (RFQ) for bunching and initial acceleration. The RFQ[9] is a superb preaccelerator for maintaining beam quality under high-current, space-charge-dominated conditions. Following the RFQ, we use a drift tube linac (DTL) or short sections of separate cavities up to the 35-40 MeV final energy. Both the RF frequency and the transverse/longitudinal focusing strengths are kept as high as possible, within other constraints. This minimizes the charge per bunch with given phase advance per focusing period, and keeps the beam size small. (While space-charge forces are increased in a small beam, the spatial extent over which the beam thermal energy is distributed is smaller, and the latter dominates.) In the DTL or separate cavity section, we design for large ratios of aperture to transverse-beam size and longitudinal bucket size to beam phase length, and may use a ramped accelerating gradient to help insure this. We insist on good alignment, good closed-loop control of accelerator field amplitude and phase, and extensive diagnostics for beam control and maintenance of the operating regime. Even so, some halo and spill may occur, but activation effects can be limited in a variety of ways, including use of rad-hard electromagnet quads (this sets an upper limit on the DTL frequency) and localizing losses at selected spots using emittance filters. Our facility design work has also addressed many details of the operational, maintenance, failure mode, and safety requirements of accelerator-based factory installations.

We have also carefully compared the expected performance of our 250-mA cw/1.5 GeV-class proton linac designs with the experience of LAMPF, presently the most intense operational facility at 1 mA average/0.8 GeV. The detailed comparison is beyond the scope of this paper, but is summarized in Table 1.

Table 1. Detailed Comparison of LAMPF vs APT

	LAMPF (Actual)	APT (Design Goal)
Average current	1 mA	250 mA
Peak current	17 mA	250 mA
Particles per bunch*	0.5×10^9	2.2×10^9
RF buckets filled (in high-energy section)	1/4	all
Activation (mRem/hr)	4**	≤ 100
Beam loss (nA/m)	0.2	≤ 5
Fractional loss/m***	2×10^{-7}	$\leq 2 \times 10^{-8}$
Aperture/rms beam size	6.3	20

* The extrapolation of ~4.4 in particles per bunch is the meaningful extrapolation in terms of fundamental beam physics, rather than the apparent factor of 250 in average beam current.

** Except for a few hot spots. APT has a factor of 2-3 advantage because it is not a pulsed machine. An additional factor of about 5 is needed; by using large aperture/rms beam size ratio, we believe much larger factors will be attained.

*** APT needs 10 times lower fractional loss/m than LAMPF to retain hands-on maintenance. A factor of 100 should be achievable.

† "Hands-on" vs remote maintenance: $\leq$ 10 mRem/hr--unconstrained hands-on; 100 mRem/hr---hands-on, limited access time; 1 Rem/hr--hands-on with carefully controlled, very limited access; $\geq$10 Rem/hr--remote maintenance required.

Having this firm basis for relation to an existing factory (and to other machines such as the high-brightness 100-mA/7-MeV Los Alamos ATS and the CERN linac) is important in establishing the credibility of the present state of the art.

ESNIT Features

Energy Selectivity

ESNIT neutron peak energy selection should be possible in at least three steps, e.g., 5, 10, and 14 MeV, with corresponding deuteron energies in the range of 10 to 35-40 MeV.[10] Such steps, or more if desired, would be made by splitting the accelerator structure into appropriate sections. This is usually done anyway to accommodate to the RF amplifier system. The beam would be accelerated to the desired energy and transported through the remaining deactivated sections. We have decided to use electromagnets in our high average current applications, rather than permanent magnets that are rather easily radiation-damaged. Electromagnets are particularly appropriate for the energy-selective feature because their strengths can be computer-controlled for optimum focusing at different beam energy and current levels.

Beam Distribution at the Target

The deuteron beam density distribution at the molten Li target is important for target design and will also influence the test volume characteristics. To distribute heat through the target depth, an energy dispersion cavity could be added at the linac exit as in FMIT, to rapidly sweep the beam energy over a small range. A more complex system using two or three harmonically related RF frequencies could be used if higher uniformity were needed.

The addition of higher-order nonlinear elements to the transverse beam-transport system could provide more uniform or tailored beam distribution over the target and test volumes. Using a combination of quadrupoles, octupoles and duodecapole electromagnets, a peaked distribution can be transformed into a rectangular uniform distribution in two dimensions.[11] The method "wraps back" the tails of a Gaussian distribution into the central core. Containment of seven standard deviations of the initial gaussian has been achieved in simulation studies.

The distribution tailoring system requires further detailed design to be able to handle the wide energy range discussed above.

Multiple Beam Exposure

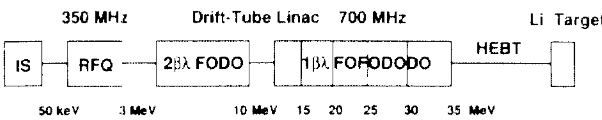
In a modularized IFMIF system, or similar scaled-down smaller ones, it would be natural to deliver the neutrons from separate targets to the test chamber from different directions, affording various options for the dose distribution in the chamber. Separating a 20-40 mA ESNIT-scale machine into modules would introduce probably unwarranted expense, but other methods of providing multiple beams are possible and would be studied specifically for this application.

Electronic Variation of Neutron Beam Characteristics

The accelerator and associated beam-transport elements are all essentially electronic systems, and can be controlled and modulated on a time-cycle basis. Therefore, the beam energy, intensity, and distribution could be varied in possibly complex patterns under computer control. This may open further experimental approaches for studying various time-dependent effects.

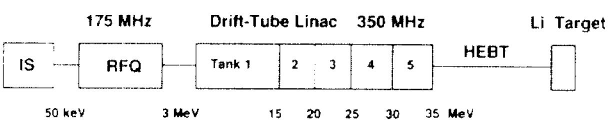
Beam Current Upgradeable Design

Figure 1 shows one conceptual design for an ESNIT optimized at the design current of 25 mA. The use of higher frequency components would result in some cost saving and somewhat less length and RF power requirement than the current-upgradeable concept shown in Fig. 2, which is essentially a partial IFMIF module capable of 125 mA. We would recommend the current upgradeable approach.



Parameters	RFQ	DTL
Emittance (n, rms, T)	0.10 π mm-mrad	0.11 π mm-mrad
Emittance (n, rms, L)	0.21 π mm-mrad	0.21 π mm-mrad
Accelerating gradient		2.0 MV/m
Structure length	4.0 m	20.9 m
RF power (beam)	80.0 kW	0.8 MW
RF power (copper)	224.0 kW	1.4 MW
RF power (total)	304.0 kW	2.2 MW

Fig. 1. Conceptual variable-energy 25-mA D+ linac optimized for design current.



Parameters	RFQ	DTL
Emittance (n, rms, T)	0.10 π mm-mrad	0.11 π mm-mrad
Emittance (n, rms, L)	0.19 π mm-mrad	0.20 π mm-mrad
Accelerating gradient		1.5-2.0 MV/m
Structure length	4.1 m	26.0 m
RF power (beam)	83.5 kW	0.8 MW
RF power (copper)	109.2 kW	1.7 MW
RF power (total)	192.7 kW	2.5 MW

Fig. 2. Conceptual variable-energy 25 mA D+ linac upgradeable to 125 mA.

Summary

The technical design of an ESNIT deuteron linac neutron source with a flexible range of energy variability and perhaps attractive density distribution tailoring is feasible. The facility could be current upgradeable. Detailed design work could begin immediately to flesh out the concepts and to determine the cost. An energy-selective intense neutron source, embodied in the ESNIT proposal, is an attractive capability for materials researchers, and it should be possible to provide this capability within reasonable cost and time constraints.

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