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FMIT-THE FUSION MATERIALS IRRADIATION TEST FACILITY*

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Summary

One of the major problems facing future fusion reactor designers will be the choice of materials with which to build the containment vessel. Although hundreds of millions of dollars are being invested in fusion research around the world, and optimism exists that fusion power will become available by the end of the century, we cannot today build a practical power plant because we cannot positively specify a material that will withstand the irradiation of high flux, 14-MeV neutrons for adequate lengths of time. High rates of helium and hydrogen production, transmutation, and extensive irradiation damage all result when materials are subjected to 14-MeV neutrons. It is essential now that we build a machine that can produce these neutrons by means other than fusion and at flux levels sufficiently high so that material assessments can be made in time periods substantially shorter than projected end-of-life spans under normal operating conditions. Such a machine can be used to support all facets of the fusion energy program, whether it be magnetic or inertial confinement that eventually proves to be most effective. This machine must be put into operation by the mid-1980's so that preliminary materials data can be made available by 1990 to confirm reference material choices and provide a basis for development of advanced materials.

A joint effort by the Hanford Engineering Development Laboratory (HEDL) and Los Alamos Scientific Laboratory (LASL) has produced a preliminary design for a Fusion Materials Irradiation Test Facility (FMIT) that uses a high-power linear accelerator to fire a deuteron beam into a high-speed jet of molten lithium. The result is a continuous energy spectrum of neutrons with a 14-MeV average energy which can irradiate material samples to projected end-of-life levels in about 3 years, with a total accumulated fluence of 10^{21} to 10^{22} n/cm^2.

Introduction

Figure 1 shows an overview of the FMIT facility with the accelerator in the foreground and an active test cell at the left end of the near leg of the High Energy Beam Transport (HEBT) line. At the of 10 cm^3, with a 14-MeV average neutron energy. A considerably larger volume at reduced flux surrounds the hot core. To meet these goals, a 100-mA continuous duty deuteron beam at 35-MeV is required to be focused on a lithium target with a 3-cm by 1-cm spot size (FWHM). LASL is designing the accelerator to produce this beam and HEDL is developing the lithium target. Table I gives the principal accelerator and target specifications.

The designs from the three major contractors, HEDL, LASL, and the architect-engineer, Ralph M. Parsons Co., will be brought together at HEDL and assembled into a facility that will become fully operational in 1985, after one year of testing

TABLE 1
ACCELERATOR AND TARGET SPECIFICATIONS

Particle	Deuterons
Duty Factor	100%
Frequency	80 MHz
Output Energies	20 & 35 MeV
Maximum Beam Current	100 mA
Average Energy Gain	1 MeV/m
Injector Energy	100 keV
Low-Beta Accelerator (RFQ) Output	2 MeV
Number of Linac Tanks	2
Number of Drift Tubes	72
Inner Diameter of Linac Tanks	2.48 & 2.40 m
Length of Linac Tanks	35 m
Total Length of Accelerator	42.7 m
Total RF power	5.5 MW
Operating Pressure	10^{-6} torr
Max E-Field (Kilpatrick)	10.6 MV/m
Shunt Impedance	37 MΩ/m
Target Material	Lithium
Jet Velocity	1660 cm/s
Jet Thickness	1.9 cm
Max Beam Power Deposition	2 MW/cm^3
Average Inlet Temperature	220°C
Average Outlet Temperature	270°C

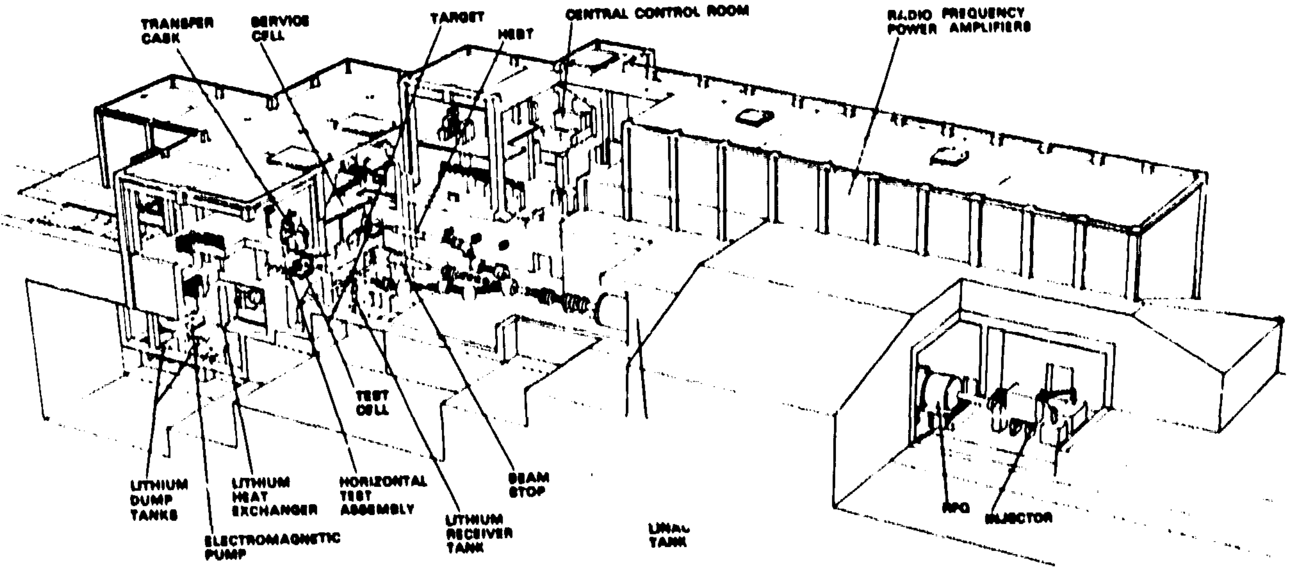

Fig. 1. Facility layout at HEDL - view is looking SW.

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*Work performed under the auspices of the U.S. Department of Energy.

and tune-up. Such a cooperative effort with such a high-power system requires that all possible design and fabrication problems be anticipated in advance. For this reason, a 5-MeV prototype of the FMIT has been designed for installation and test at LASL. The energy selected reflects the view that most accelerator design problems occur at the low-energy end of the machine. The prototype, which will operate with a continuous duty beam power of 500 kW, also will provide a base for instrumentation and control software development and operator training. Simultaneously, an experimental lithium-target system will be tested at HEDL. Marriage of the two systems will not occur until the FMIT is assembled at HEDL.

Beam Targeting

A sketch of a representative lithium target design is shown in Fig. 2. Despite the problem of interfacing with an accelerator vacuum system, molten lithium was chosen as the target material for FMIT for several sound reasons. When used in a stripping reaction to release neutrons from the deuteron beam, the neutron field primarily is that a moving liquid metal allows the target itself to be passive, with high mechanical reliability. Other factors are the low vapor pressure of lithium, its low density, high volumetric heat capacity, and its high heat transfer coefficient. No film barrier can isolate the HEBT from the lithium surface because of the beam's high power density and short range. To aid the integrity of the lithium surface, the jet moves in a curved path through the beam at a velocity of ~1660 cm/s. In passing through the beam, a thermal stripe of superheated lithium reaches a peak temperature of over 800°C at the Bragg peak. Some lithium vapor is expected to move back into the HEBT (~2-3 g/yr) as well as larger quantities because of spallation and possibly bulk quantities if target failure occurs. The impact of such interactions is one of the major interface problems still under assessment.

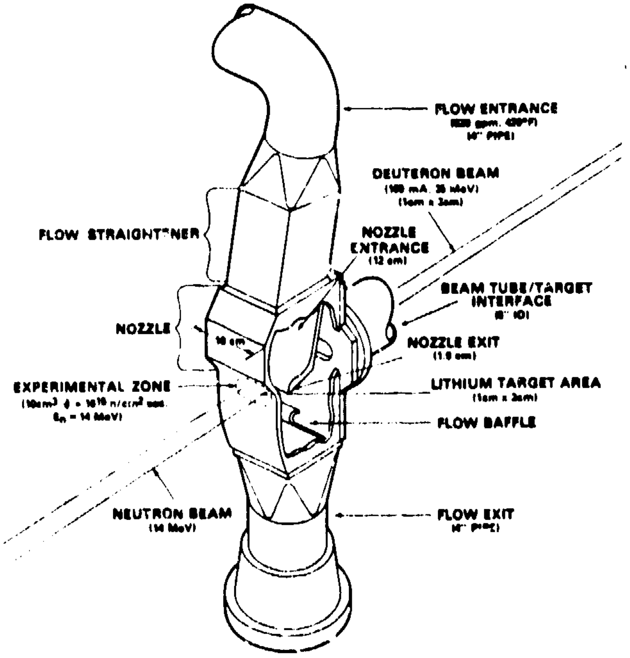

Fig. 2. FMIT lithium target.

The HEBT can deliver the beam to either of two test cells by a bipolar bending magnet at the beamline junction.

The Accelerator System

Figure 3 shows the accelerator system. High reliability and high availability guide the design of the accelerator, because the facility must operate essentially as a factory for neutrons to meet the materials testing goals set up by the experimentors. Therefore, the injection voltage is kept low, around 100 kV, which enhances the ion source and accelerating column reliability. In fact, tests are underway to determine the effectiveness of the source at even lower voltages, 50-75 kV. Normally, such low injection voltages, coupled with the massive deuteron beam pose a serious mechanical design problem for the linac because the cell-length $\beta\lambda$ is so short. In addition, the capture efficiency of a drift tube linac operating directly off such low-injection voltages would be extremely poor. This problem is circumvented by use of an intermediate low-beta linac, the new Radio-Frequency Quadrupole (RFQ), which efficiently captures over 90% of the low energy injected beam and raises its energy to 2 MeV where $\beta\lambda$ = 17.3 cm. This greatly simplifies design of the first drift tube, as well as allowing more effective capture of the beam by the linac. The RFQ is a revolutionary accelerator concept, first proposed by the Russians, and designed and tested in this country for use in FMIT by LASL researchers.

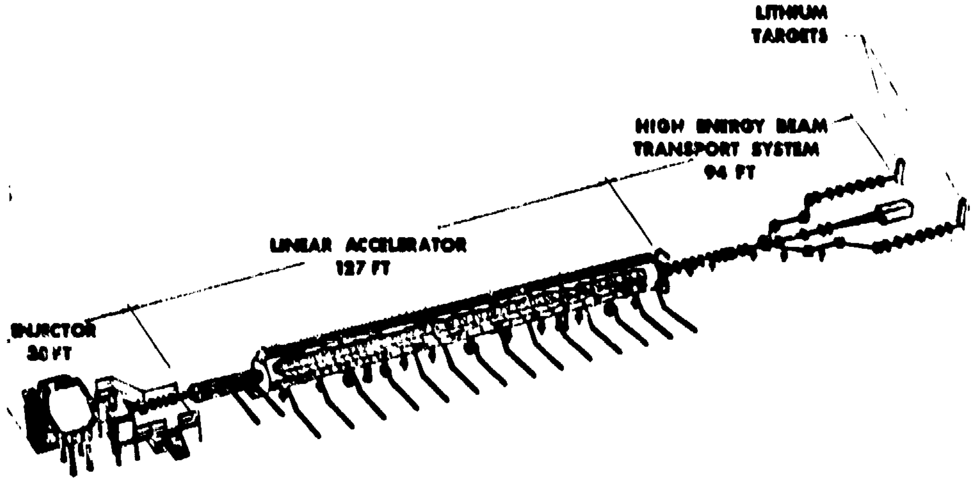

Fig. 3. FMIT Accelerator System.

The outstanding advantage of the RFQ is the fact that it focuses the beam with electric fields that vary at radio-frequencies; this allows effective focusing at low energies. By machining the structure's vane tip low-energy focusing can be blended with longitudinal accelerating field components to provide two additional operations: bunching and acceleration. The RFQ's output beam displays low emittance growth and is well bunched; it is ideally suited for matching into a drift-tube linac. A 425-MHz proof-of principal (POP) working model of the RFQ was tested at LASL in early 1979; it met or exceeded all design expectations in accelerating a proton beam. Figure 4 shows a drawing of this device, enclosed in an RF manifold tank. The 80-MHz FMIT RFQ is physically much larger than the POP model and must carry away several hundred kilowatts of RF power dissipation; it is similar in all beam-dynamical respects to the high-frequency experiment, and is expected to perform well in the FMIT. One of the major mechanical differences between the two is that POP waveguide coupling is not practical in the FMIT because of the low frequency; therefore, coaxial drive-loop coupling is required. However, an RF manifold, operating in TEM mode, to cross-couple through angled slots into the TE_{210}-like mode required by the RFQ cavity itself, is a sound approach.

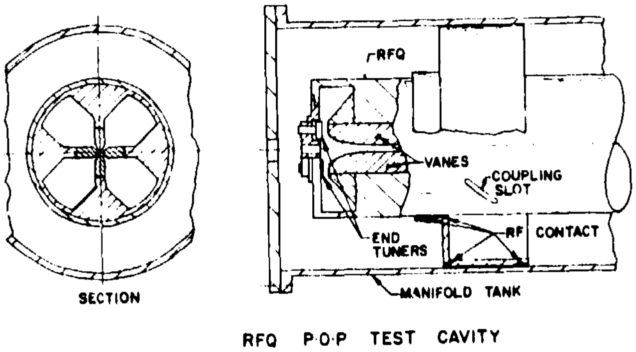

Fig. 4. RFQ POP Test Cavity.

The drift-tube linac accelerates the beam from 2 MeV to 35 MeV with an intermediate energy of 20 MeV, obtained by turning off the downstream tank RF power. The tank shell is steel, sheathed in 0.5-cm-thick copper for ease of fabrication and for good thermal properties. The linac operates at 80 MHz, a compromise between such factors as the large drift-tube bore diameters required (5-8 cm) availability of RF amplifiers for high-power cw operation, and the desire to reduce the physical size of components. The tanks are post-coupler stabilized and the drift tubes are assembled into girder-supported modules for ease of maintenance and alignment. Because of activation of the drift tubes due to beam spill, manned entry into the tanks is prohibited after deuteron beam operation begins. Therefore, the design approach is to weld all RF joints where possible, to avoid all components at the RF surface of the tank that are difficult to service (such as water-cooled vacuum grills), and to fabricate the tanks as two complete assemblies 18 m and 15 m long, joined by an intertank spacer. All peripheral components, including the drift-tube girders, can be removed from the outside. Beam steering is provided by steering coils superimposed on the quadrupole magnets in the front-end drift tubes, but excessive use of such steering introduces sextupole field distortions. The best way to avoid steering is precision alignment. This is handled as shown in Fig. 5. Each girder assembly is prealigned and checked out in an alignment dock. The entire assembly is then installed in the tank, where it is supported on kinematic mounts. Optical alignment of each girder relative to other girders then assures accurate alignment of the drift-tube quadrupoles.

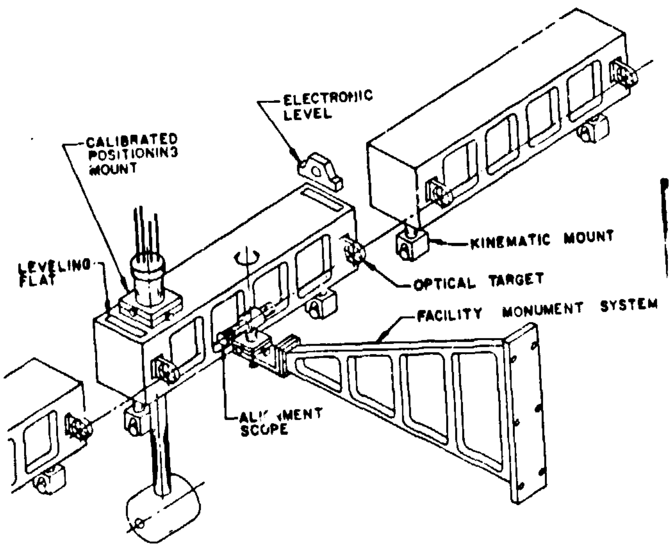

Fig. 5. Drift-tube module-to-module alignment.

The RF power demand of the linac is 5.5 MW, delivered by 13 drive loops. The RF loops are driven simultaneously, delivering the required power under the control of amplitude and phase servos. Difficulties with multi-loop drive at high power will be assessed in the prototype program at LASL. Although the FMIT is rated for continuous-duty operation, pulsed operation is also possible to assist in checkout and tuneup at full current but at low average-beam power.

Beam Losses and HEBT

Many accelerators, which typically operate in pulsed mode, deliver high peak currents for short periods. No machine today operates cw at the average beam current of the FMIT. Some beam must inevitably be lost to the structure of the linac and the beam transport system. Activation in the FMIT is due to direct deuteron interactions, which are short range, as well as to neutron production, which activates the structure of the accelerator, and the walls of the facility. Russian studies of such a facility assumed a loss model of 10 μA/m. LASL estimates, based on LAMPF and other high current machines, allow about 0.1% beam loss or about 3 μA/m with "hot-spots" at the matching section from the RFQ and at the switching and bending magnets in the HEBT. Some of the immediate results of power loss and activation considerations appear in the FMIT design as water-cooled bore tubes in the first few linac drift tubes following the RFQ, gold plating and lead shielding of the linac bore tubes from 10 MeV to 35 MeV, and use of water-cooled aluminum beam tubing in the HEBT. Other passive measures taken are the provision of beam scrapers at various points in the HEBT and lead sheathing of the HEBT components to reduce residual gamma fields. Some components in the HEBT, such as beam-line valves and certain diagnostic equipment, may still require remote maintenance; therefore, the HEBT is being designed with adequate accessibility to allow for such maintenance. Bridge cranes are provided for both the linac and HEBT.

Upstream of the HEBT is the Energy Dispersion Cavity (EDC), which disperses the essentially monoenergetic linac beam sufficiently to aid the target in limiting beam-power deposition to 2 $\mathrm{MW/cm^2}$. The HEBT is a periodic transport system that can accept a