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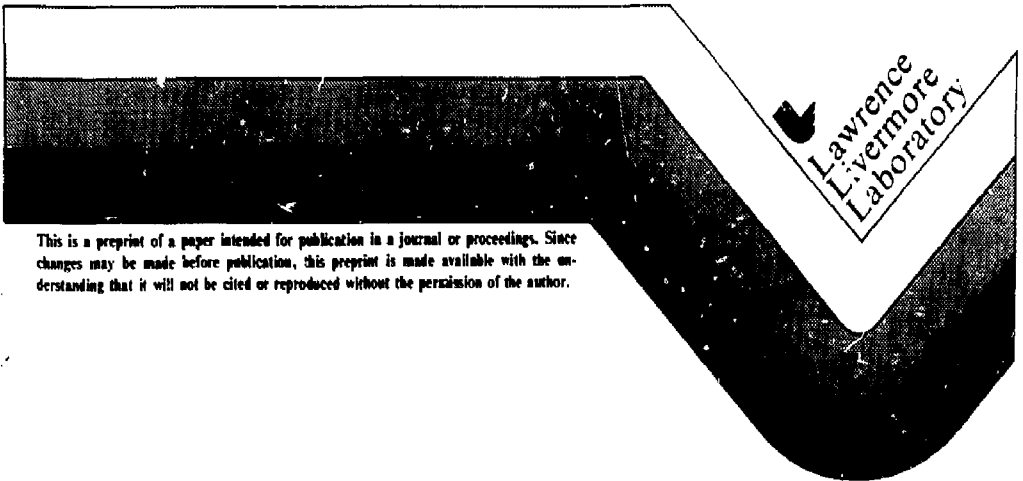
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TECHNOLOGY FOR LARGE TANDEM MIRROR EXPERIMENTS*

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ABSTRACT

Construction of a large tandem mirror (MFTF-B) will soon begin at Lawrence Livermore National Laboratory (LLNL). Designed to reach break-even plasma conditions, the facility will significantly advance the physics and technology of magnetic-mirror-based fusion reactors. This paper describes the objectives and the design of the facility.

1. INTRODUCTION

For the past three years we have been constructing a Mirror Fusion Test Facility (MFTF) based on a single-cell minimum-B mirror [1]; its completion was scheduled for March 1982. That device would have improved the confinement time of single-cell mirrors an order of magnitude beyond that demonstrated in 2XII-B [2]. In addition, its superconducting magnet, neutral beams, vacuum system, and control system all advanced the technology of fusion devices.

With the invention of the tandem mirror confinement scheme [3,4], modifications to MFTF were considered. The simultaneous occurrence of good experimental results [5] from our first Tandem Mirror Experiment (TMX) and the invention of the thermal barrier improvement [6] to tandem mirrors led LLNL to propose [7] that MFTF be modified, rather than completed in that configuration, to a tandem machine, MFTF-B. This reconfiguration will begin in October 1980, and should be completed late in 1984.

2. OBJECTIVES

Scaling laws for electrostatically confined plasmas in tandem mirrors are fundamentally different than those for magnetically confined plasmas in single-cell mirrors. Figure 1 shows how the confinement product n_c improves with ion energy for single-cell mirrors having a mirror ratio $R = 2$ and for tandems with a confining potential $\phi_c = 2 T_c$ (central-cell ion temperature T_c). For MFTF-B, we expect operation at $n_c \sim 5 \times 10^{13}$ with a 10-keV ion temperature. While TMX performance improvement with variations in ϕ_c/T_c gave us confidence in this scaling law, the scaling to "break-even" regimes and the demonstration of thermal-barrier operation are major objectives of MFTF-B. The incorporation of a thermal barrier in an upgrade of TMX will allow an exploration of that idea.

The physics objectives of MFTF-B are largely contained in the above goal. Table 1 elucidates them, as well as the technology objectives which should be fulfilled by the

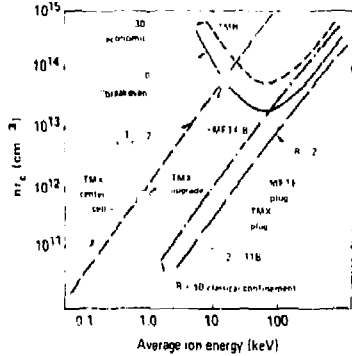


Fig. 1. Variation of the plasma confinement parameter n_c with ion energy in single-cell and tandem-mirror machines.

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TABLE I
NETF-B OBJECTIVES

Physica objectives

- (i) To demonstrate the improvement in Q with increasing potential-well depth, in the range of $0.1 < Q < 1$
- (ii) To explore radial transport in the central cell and determine its influence on confinement
- (iii) To explore microinstabilities in the end plugs and means of controlling them
- (iv) To explore the β -limits imposed by magnetohydrodynamic (MHD) stability

Technology objectives

- (i) To gain experience in constructing and operating a large Nb-Ti superconducting magnet system
 - (ii) To learn to construct and operate reliable, long-pulsed, high-current, high-voltage neutral beams
 - (iii) To maintain high-vacuum conditions in the presence of interactions between the plasma and the walls equilibrium
 - (iv) To handle, without deleterious effect on the plasma or materials of construction, the intense particle and plasma-energy deposition on surfaces in the vacuum vessel
-

time this facility is constructed and in operation. The technology objectives are the main topic of this paper.

3. TANDEM MIRROR OPERATION

Before describing the components and systems which compose the conceptual design of the machine a brief description of how the plasma will be created and maintained is in order. From this operating scenario and the magnetic configuration of fig. 2(a), the major machine features are derived. With this magnet set we produce the fields, densities, and potentials depicted in fig. 2(b-d). The magnetic field is variable from 1/2 to 1 T in the solenoid, making a transition to a 2:1 mirror ratio yin-yang magnet. The peak mirror field there is 4 T. Thermal barriers are created with an auxiliary coil at each end in the magnetic well created by the outer field peak of the yin-yang and the auxiliary coil. The coil pinches the plasma fan in its narrow dimension as it exits the yin-yang and channels the fields to a 6.5 T peak.

As the plasma fans out of the auxiliary coil it expands toward the end wall of the vacuum tank and intercepts an elliptical area on the end wall. Within this ellipse are mounted plasma streaming guns which inject an initial target plasma into the machine. To sufficiently cover the cross section, 30 guns, each firing for 10 μ s, are spread over this elliptical surface at each end. Simultaneously, 20-kV neutral beams of 100 A each (power supply current) are injected into the yin-yang mirror to build the plasma density and raise the average ion energy. Ten beams are injected in each end. To raise the energy further and sustain the plasma through the startup regime, a total of 16 beams at 80 kV, 80 A are injected into the central cell and end mirrors for 1/2 s. During this time, the thermal barrier is established and the configuration can be maintained by 3D-a-injection sources, both neutral beams and rf.

The thermal barrier is established by the injection of a beam in the A-cell which produces sloshing ions, and hence a density minimum, in the mirror midplane. [See fig. 2(c)]. The density minimum is accompanied by a potential minimum according to a prescribed relation.

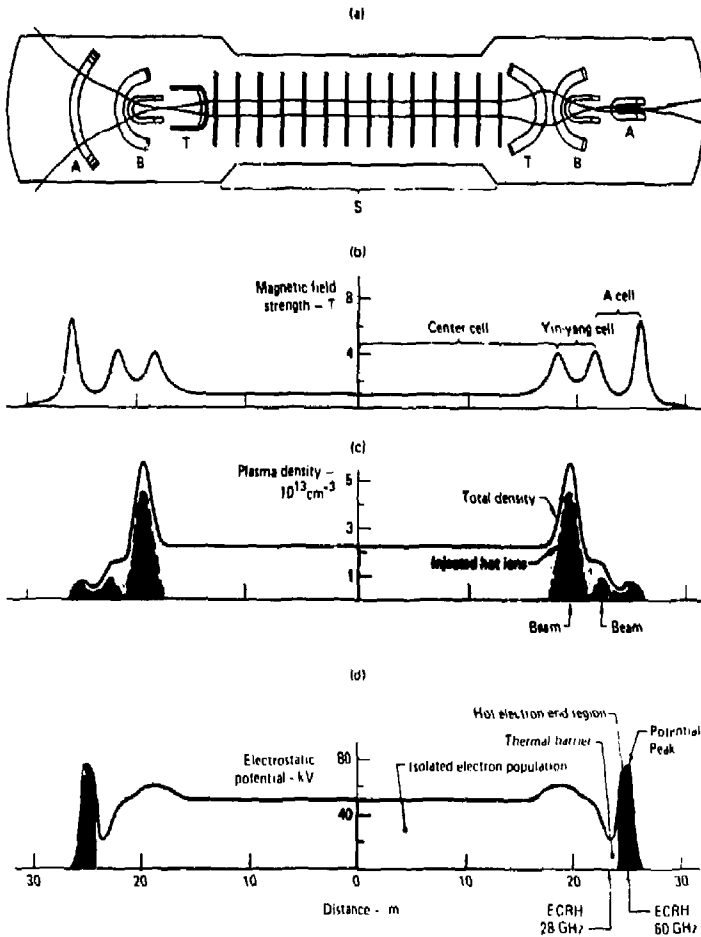


Fig. 2. MFTF-B profiles: (a) magnet configuration in MFTF-B, and (b) the fields magnets produce. The machine will be operated so as to produce the density (c) and potentials (d) which create a thermal barrier.

This potential minimum [see fig. 2(d)] is an electron potential hill which partially separates the electrons in the center from those where the large positive potential is to be built. Other 30-s beams are injected into the central cell and Yin-yang to maintain the plasma in those regions. Finally, to create the large potential, we heat the electrons to a temperature well above those in the central cell by rf power at the electron cyclotron resonant frequency (56 GHz).

Three other injectors are required, one to deepen the potential well and the others to sustain it. We can deepen the well by magnetically trapping electrons in it, which we do by increasing their perpendicular energy with ECRH power at the mirror minimum (28 GHz). Maintaining the well requires that ions which scatter in velocity space and become trapped by the magnetic and/or potential well be pumped out. A 30-s beam injected axially from the end of the machine pumps these ions out by charge exchange as they pass through that region.

This pumping is augmented by a 2-kV neutral beam passing radially through the narrow dimension of the plasma fan at an appropriate axial position. That position is on the rising potential slope within the A cell, at a point where the potential just exceeds that in the yin-yang (call that point I). Most ions trapped in the A cell are magnetically trapped on the rising field of the outer yin-yang coil and electrostatically trapped on the rising potential slope, passing point I before being reflected. Consequently, a low-voltage pump beam exchanges a low-energy ion (2-kV for penetration into the fan) for one with much higher perpendicular energy, and can therefore traverse the A cell and get to the central cell over the yin-yang potential.

4. MACHINE DESCRIPTION

The superconducting magnet set in fig. 2(a) has 14 solenoid coils, transition coils to the yin-yang pairs, and C-coils at each end to form the A cells. All coils use NbTi superconductor, with peak fields of 8 T at the yin-yang and C-coil conductors. Peak fields in the transition coil are ~5 T, and those in the solenoids are 2 T. The 2-m spacing and 5-m bore of the solenoids were chosen to limit the field ripple to 1% at the plasma surface ($r = 0.56$ m). The slot in the A cell is minimized to make the highest possible mirror ratio (6.5 here) in the A cell consistent with beam access and plasma-fan size. The yin-yangs have a 2.1:1 mirror ratio and a 3.6 m length from peak to peak.

This magnet array is supported structurally within the vacuum vessel. Individual magnets also have their own structural cases to support the rather large magnetic forces. Each yin-yang, for example, has case stresses of up to 80 thousand psi. A force of 22 million pounds is exerted on the yin-yang magnet faces, tending to open the slots which pass the plasma. The nested configuration of this magnet pair allows for some mutual assistance in supporting these forces, since each magnet acts as a clamp for the other. The C-coil in the A cell, by contrast, requires a large box-beam support to prevent it from being pried open. The general tendency of the magnet set to collapse axially also requires the structural support which is inside the vessel.

Figure 3 shows the MFTF-B facility, featuring the vacuum vessel inside of a 2-m-thick concrete vault. The vessel supports not only the magnets, but also the cryopanel, beam and rf ports, stream gun and diagnostic ports, gettering mechanisms, and cryopumps. With an 8-m-diam. modular center section, the vessel has an overall length of 64 m and encloses ~3000 m³ of volume. Between shots, a base pressure of 8 μ Pa is maintained by means of cryocondensing pumps having 4.5-K surfaces and cryosorption pumps with argon condensed on 2.7-K surfaces. During plasma shots, some 1500 m² of cryopanel surfaces maintain low background pressures and minimize surface reflux as the equivalent of ten litres of gas at atmospheric pressure is injected from all sources.

Liquid nitrogen and helium refrigeration systems, both closed-loop systems, are employed for vacuum pumping, for magnet cooling, and in nitrogen liners on the magnets. The nitrogen refrigerator is a 214-kW (cold) unit while the helium system is 8-kW.

While the 10-ms startup beams (20 kV) and 500-ms, 80-kV beams were developed for MFTF and are now being built, the 7 beams producing 60 A at 80 kV for 30 s are yet to be developed. Water-cooled grid sources are being developed at both ORNL and LBL. A 1/4-scale version of a rectangular-grid source has been constructed by LBL [8] and is currently undergoing tests.

Approximately 1 MW of rf power is required for electron heating in MFTF-B, and to supply this power at 28 and 56 GHz we expect to use 200-kW gyrotron tubes. Two 28-GHz units and six 56-GHz units should supply the required power. While the CW operation of the 28-GHz

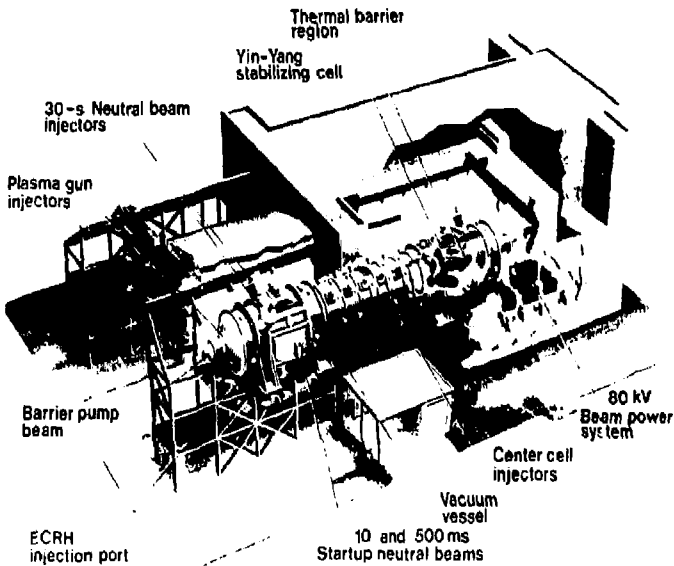


Fig. 3. Artist's rendition of the MFTF-B facility with the vacuum vessel inside of a large concrete vault. Neutral beam and rf ports are shown on the vessel.

tube at 200 kW has been demonstrated by Varian Associates [9], the 56-GHz tubes are now being developed.

To handle the 30-s neutral-beam power on ion dumps and beam dumps, we intend to develop beam dumps capable of handling 2 kW/cm^2 on a continuous basis. For incident power levels of $\sim 7\text{--}8 \text{ kW/cm}^2$, this requires the dump surfaces to be inclined to the direction of the incident power in the usual fashion.

A final feature of note in MFTF-B is the machine's control, diagnostics, and data acquisition system. A set of supervisory control consoles form a hierarchical system which interfaces to the machine through local control systems. There are LSI-11 microcomputers for local control, and communication between the facility and control area is via digital signals on fiber-optic data links to CAMAC instrumentation. The CAMAC units interface the data links with local control panels that are hard-wired to sensors, switches, and controls on the machine. Plasma data acquisition and diagnostic-instrument control is handled by the same supervisory control system through diagnostic local-control systems similar to the machine's local-control system.

5. CONCLUSION

With the construction and successful operation of MFTF-B, the mirror program will have made a long step toward demonstrating fusion-power feasibility by the tandem approach. In addition, it will have generally furthered the technology of fusion by demonstrating very advanced engineering systems relevant to nearly all fusion approaches.

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