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THE MIRROR FUSION TEST FACILITY (MFTF-B)--STATUS

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ABSTRACT

The Mirror Fusion Test Facility (MFTF-B), now under construction at Lawrence Livermore National Laboratory, represents more than an order-of-magnitude step up from earlier magnetic mirror experiments on the way to a future mirror fusion reactor. In fact, when the device begins operating in 1988, it will be capable of achieving plasma performance approaching scientific breakeven for D-T equivalent operation. We have taken major steps to develop MFTF-B technologies for tandem mirrors. In the machine, we will use steady-state, high-field, superconducting magnets on reactor-elevant scales. The 30-s beam pulses, ECRH, and ICRH will also introduce near steady-state technologies into those systems.

INTRODUCTION

The Mirror Fusion Test Facility (MFTF-B) is a large, near-reactor scale experimental device to test advanced plasma-confinement concepts in tandem configuration.

The MFTF-B has evolved from a minimum "B", single-cell device to an axicell, thermal-barrier, tandem mirror configuration.[1,2] The creation of the thermal-barrier concept, offers the possibility that the plasma-confinement performance of the tandem mirror will be competitive with the tokamak by the end of the decade. Furthermore, the device may be superior to tokamaks in the long run because of its relatively simple magnet geometry and steady-state operation.

In its present configuration, MFTF-B is capable of operating very near the scientific breakeven point for deuterium and tritium (D-T) fuel. Current plans call for operation only with deuterium. Construction of the MFTF-B configuration began in 1980, and the device will be operational in 1988, although delayed because of funding limitations.

PERFORMANCE GOALS

The major physics goal is to reduce end losses so that confinement in the central cell would allow us to approach the energy breakeven point for an equivalent D-T plasma. To do this, MFTF-B must do the following:

- Achieve axial ion-confinement times in excess of 1 second (axial $n\tau_c = 5 \times 10^{13}\ \mathrm{cm}^{-3}\cdot\mathrm{s}$).
- Generate maximum, central-cell, ion-confining potentials ($\phi_c \approx 30$ kV) sufficient for confinement, i.e., equivalent to achieving $Q \approx 0.5$ with D-T.
- Achieve plasma temperatures sufficiently high to test the physics of thermal barriers and of radial transport, both in appropriate collisionless reactor regimes.
- Demonstrate high beta, magnetohydrodynamic (MHD) equilibrium and stability $\beta_c \approx 0.5$.
- Achieve microstable sloshing ions and thermal barriers in the MFTF-B yin-yang magnets (based on theoretical models).

The axicell MFTF-B outperforms previous designs because it produces equivalent values of $n\tau_c$, T_{ic}, and T_{ec} at a much higher density in the central cell, and hence yields a much higher fusion-power output per unit volume (Table 1). It is this latter property, traceable to the high magnetic fields possible with the circular axicell coils, that is so attractive for a reactor.

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*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

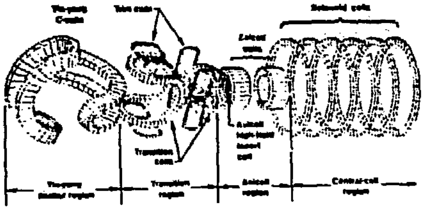

Fig. 2. The axicell MFTF-B magnet array in the west half of the vacuum vessel. The whole array includes this half plus a reflected and rotated duplication for the east half.

principally through the 12-T magnets on the outer side of the axicells. The principal confinement time for fusion reactions occurs in the central cell with spiraling deuterium ions bouncing back and forth between the inner axicell magnets at the 6-T point.

Figure 3 shows the magnetic field related to the magnet coils and vessel locations. The primary experimental mode is the MARS reference mode. Also illustrated are potential ϕ and density n shown as a function of axial position relative to the center of the vessel. These depict the plasma-confinement modes most related to advanced-reactor concepts. The thermal barriers peak in the axicell and in the anchor regions, thus aiding ion confinement.

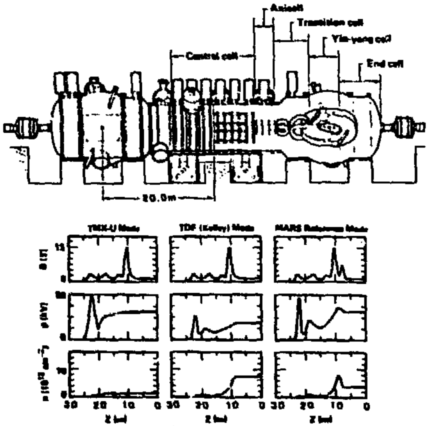

Fig. 3. Configuration of MFTF-B axicell magnets and vessel (a). Profiles of magnetic field strength B, plasma potential ϕ, and plasma density n for three of the MFTF-B operating modes (b).

VACUUM CONDITIONS

The plasma internal pressure is established by densities from 2×10^7 to 5×10^9 particles/cm^3. The end-cell background pressure has a base value of 10^{-8} Torr but rises to 10^{-6} Torr during experimental operations. The vacuum system features (1) high-volume cryocondensing pumps with 1500 m^2 of 4.5-K surfaces to pump all condensable gases and (2) cryosorption pumps with 2.7-K surfaces on which argon is condensed to pump helium. The cryopanels are regenerated periodically.

PLASMA HEATING

The MFTF-B central cell has ten 80-kV, 80-A, 0.5-s neutral beams to provide added gas density with six additional 0.5-s neutral beams in the anchor and axicell regions. The 400-kW central plasma heating is achieved through ICRH at frequencies of 6 to 20 MHz. Specifically, the machine runs at durations up to 30 s with six 80-kV, 35-A neutral-beam injectors to fuel, heat, and pump various regions of the confined plasma. The 80-kV high-energy pump beams (HEPB) are aimed axially from each end dome. To raise the electron temperature in each yin-yang anchor and thus minimize ion cooling, we use ECRH at frequencies of 28, 35, and 56 GHz. Ten 200-kW gyrotrons will be required. In addition, a closed-loop feedback-control system is incorporated in the ECRH system to allow individual, simultaneous, or staggered operation of these ten gyrotrons. This flexibility of operation permits the complex spatial and temporal applications of ECRH needed for a wide range of plasma-physics experiments.

All beams, except the one 0.5-s beam in the yin-yang region, are housed in external beamlines equipped with magnetic shielding, cryopanels, and ion dumps. The ion dumps will be capable of handling power fluxes up to approximately 5 kW/cm^2 on the surface perpendicular to the beam axis.

The absorbed heat is removed during each shot by cooling water in the high-temperature beam dumps and warm liners. Liquid-nitrogen shields (at 80 to 85-K) protect the 4.5-K magnets and the 4.7-K cryopanels. For 4.35-K liquid helium, a 10-kW cryogenic helium refrigerator/liquefier is used. There is also a 500-kW, liquid-nitrogen, closed-loop system to provide reliquefaction of nitrogen for cooling.

DIAGNOSTICS AND MACHINE CONTROL

The MFTF-B control room is housed in a separate building hundreds of feet from the actual machine. Fiber optic bundles link the control room and the facility. Following an experimental shot, both the machine and plasma diagnostics data are sent through the computer system's shared memory to the distributed database in the nine supervisory computers, including two diagnostic data processing minicomputers. The operation is verified and data transferred between shots; this can occur as frequently as once every five minutes.

The plasma diagnostics measure the specific plasma parameters, that is, determine energy balance, monitor densities, measure potential profiles, monitor plasma-wall interactions, determine particle and power flows, and characterize the plasma buildup in various regions. The initial diagnostics set will consist of 12 instruments with 222 data channels.

All the systems are operated by an hierarchical control and data handling system (Fig. 4). The system is projected to collect 8×10^6 bytes of data per shot. Seven consoles are included--five for subsystems, one for injectors, and one for the overall systems operation. All control functions are directed and executed through touch panels on the operating console. The subsystem diagram with control blocks is first displayed; then all levels are adjusted, switches are thrown, and ranges set from the control touch panels.

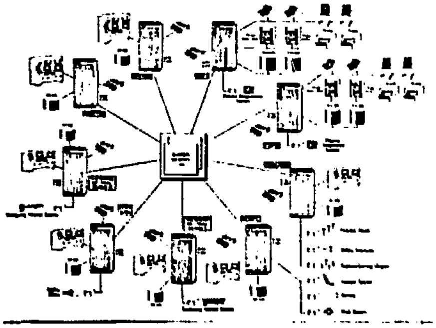

Fig. 4. Supervisory and local control and diagnostics system of MFTF-B.

The supervisory minicomputers interface with local control computers through standard serial communication links. The local control computers (LSI-11) communicate through fiber-optic links to Computer-Automated Measurement and Control (CAMAC) crates for local control, monitoring, and data communication. There are 75 subsystems to handle 35,000 diverse devices. The parameters are set before each shot, verified back to the systems control console, and time-sequenced for each element before the shot is initiated by the 3-MHz master timer.

STATUS

MFTF-B consists of two elements: first, design and construction of a facility (PACE) to be completed by June 1986 at a cost of $246.6 M and, second, expense-funded items covering research and development, design and fabrication, and auxiliary components, such as those for plasma heating, diagnostics system, experimental preparation, and maintenance. The operational budget was reduced for FY85 and FY86. As a result, operational readiness will be delayed from January 1987 to June 1988. Total estimated cost at completion for the above operational activities is $198.5 M.

TECHNOLOGY DEMONSTRATION

By the end of 1981, construction of the original single-cell mirror machine (MFTF) had progressed substantially to allow integrated tests of several key systems to demonstrate the technology. This series of system tests was formulated to provide the principal data necessary to confirm the technology objectives. At the cornerstone of the Technology Demonstration was the 500-MJ yin-yang magnet test. The magnet operated at its full design current; the peak fields, case stresses, and conductor strains matched their calculated values very accurately.

For testing, the liquid helium required to cool the magnets was supplied by the 3075-W helium refrigerator; this device can produce helium at a rate of over 600 litres per hour. During the test of the external and internal vacuum systems, vacuum pressures of 10^{-8} Torr were achieved. (The vacuum systems employ both liquid helium and liquid nitrogen to achieve the low vacuum pressure demanded in a large vessel.) Also meeting test objectives were the system cryopanels; while maintaining a hard vacuum, they were able to pump added deuterium from the vessel housing the magnet.

Tests of the Supervisory Control and Diagnostic System (SCDS) were successful in validating the hierarchical structuring of controls and data handling from the machine's local control panels to the SCDS for operating and monitoring. The SCDS is used to test the operation of all the integrated test systems.

Design and construction activity is 95% complete. The design of major elements for the construction project is essentially completed. We are entering the assembly, installation, and acceptance test phase. The auxiliary components activity is 50% complete.

The main building housing the facility is finished (Fig. 5), and many systems are in the final stages of installation. The vacuum vessel has been fabricated and acceptance tested (Fig. 6). Solenoids have been installed in the vessel modules (Fig. 7), and lines and piping are being leak checked. Both yin-yang assemblies are installed in their respective vacuum-vessel sections. Transition and trim coils are fabricated and ready for installation. The external vacuum system is installed. The cryogenic system is fabricated, and installation is complete with the exception of the vault piping. Reliquefication compressors have been tested.

The 80-kV prototype and preproduction neutral-beam power supplies were operated successfully with a 0.5-s, 80-kV, 80-A source. All components on the remaining 20 supplies were fabricated and installed, except the controls which are in fabrication (Fig. 8). All eight channels of the ECRH power supply have been installed and tested. One channel was tested with 28, 36, and 56 GHz, 200-kW gyrotrons into a dummy load (Fig. 9).

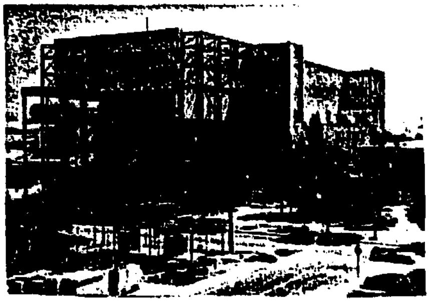

Fig. 5. Building 431, showing the western extension of the crane and building structure to house the MFTF-B vault (7-ft-thick-concrete walls) and major systems components.

Fig. 6. Vacuum vessel in place in the vault. The nearest component is the West End Vessel and the East Vessel is shown with the 8-m-diameter test head attached to the transition cylinder for vacuum test.

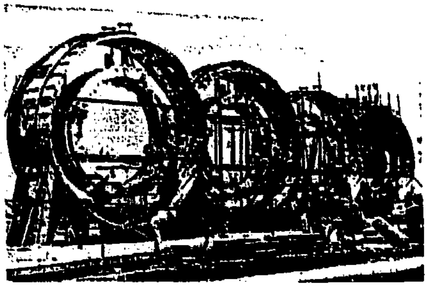

Fig. 7. The Center Vessel is made up of six modules with two 5-m-diameter superconducting solenoid coils housed in each module. This illustration shows four of the six modules with coils and LN-shield assembly underway in the LLNL magnet assembly yard in Livermore, California.

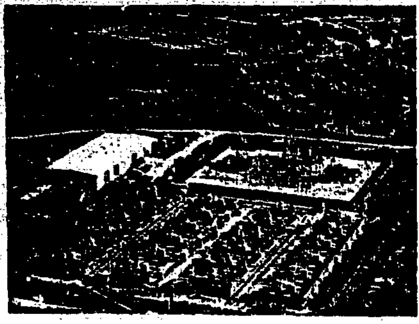

Fig. 8. This aerial view shows the 250 kV, 250 MW ac power line with two main transformers providing 13.8 kV or to the Accel DC power supplies. Twenty-four of the dc power supplies to supply 24 Neutral Beam Injection Ion-Source. Modules at 80 kV, 50-80 A each are in the foreground with 4 rows of 6 each individual units.

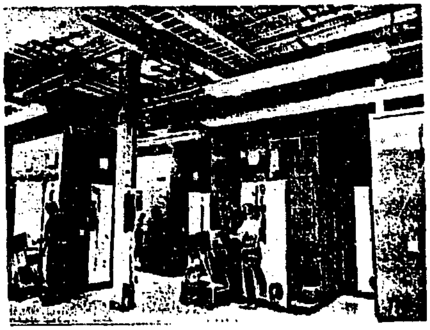

Fig. 9. The ECRH power supply system modulator/regulators manufactured by Universal Voltronics Corporation (UVC). Each of these cabinets have been recently installed on the first floor of Bldg. 431 and will provide regulated high voltage for a gytotron positioned under the west MFTF-B vessel.

The Supervisory Control and Diagnostics Systems hardware was installed and is operational. Software for it is 75% complete. Local control computers are 90% installed. Integrated system test of PACE items is scheduled for September 1985, and the test of the remaining auxiliary components will begin in January 1986.

The MFTF-B project continues to achieve its technical baseline on schedule (budget permitting) and within cost.

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