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Mirror Fusion Test Facility Status

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This note discusses the current status of the Mirror Fusion Test Facility under construction at Livermore, funded by the Office of Fusion Energy in DOE. First authorized in FY78 as a single mirror device, in FY81 the project was rescoped to a tandem mirror configuration (MFTF-B) in response to promising technical developments in the program that have made the tandem mirror concept the leading alternative to the tokamak in the U.S. magnetic fusion program. It has long been thought that mirror reactors would have two distinct advantages; namely, steady-state rather than pulsed operation, and a simpler shape - a straight tube as compared with the doughnut-shape of the Tokamak. But first, formidable physics problems associated with the loss of plasma out of the ends of the tube had to be overcome. The tandem mirror appears to solve these problems. During 1979-80, results from the TMX experiment at Livermore, corroborated by experiments in Japan, confirmed the basic principles of the tandem mirror concept. It was on the basis of these results and a promising theoretical outlook that the Department of Energy approved proceeding with the MFTF-B. The MFTF-B, scheduled to begin operating in 1985, is the tandem mirror companion to the TFTR tokamak, scheduled to operate in 1982. If it meets theoretical expectations, the MFTF-B will bring the tandem mirror on a par with the tokamak, scientifically, and lay the groundwork for the engineering development of a tandem mirror reactor.

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In proceeding with the MFTF-B project, DOE had the endorsement of three prestigious groups of advisors: The Mirror Senior Review Panel, the Fusion Power Coordinating Committee, and the Fusion Review Panel of ERAB. At the time of these reviews, nearly 2 years ago, it was recognized that the MFTF-B goals were ambitious and that the tandem mirror concept was still evolving. For these reasons, the review panels recommended that the MFTF-B construction schedule accommodate further data input from an intermediary experiment, TMX-Upgrade, and that the MFTF-B design be made flexible enough to incorporate in the future improved magnet configurations then being explored theoretically. Both recommendations are being followed. The TMX-Upgrade will soon begin experimental operation, and considerable progress has been made in identifying promising configurational improvements and in assessing their impact on the MFTF-B design.

II. PHYSICS STATUS

A. MFTF-B Goals

MFTF-B is designed to reduce end losses to the point that, barring excessive radial transport, the center cell confinement would approach "energy breakeven" in an equivalent DT plasma (actual experiments will use pure deuterium plasmas). Specifically, MFTF-B is designed to achieve axial confinement times of 15 keV ions in excess of 1 s (axial $n\tau_e = 5.10^{13} \text{ cm}^{-3} \text{ s}$). We propose to accomplish this by isolating the center cell electrons from the microwave-heated end plug electrons which create the confining potential. The thermal barrier isolating these electron populations is an essential feature of the machine, as it allows high

performance to be achieved with modest magnetic field strengths and relatively low energy neutral beams.

B. Primary Physics Processes

To achieve our stated goals we rely on the MHD stability of a high- β equilibrium, the startup and establishment of thermal barriers, and microstability of the end regions to minimize the power required to sustain the ends. Having accomplished this, we expect to achieve axial confinement times sufficient to examine radial transport phenomena. Estimates of resonant transport due to quadrupole fields in the end plugs have been improved to include the effect of parallel currents (see below), but remain uncertain because of extreme sensitivity to the radial potential profile. The present worst-case estimate corresponds to a lifetime of 0.25 s.

Models of finite-beta corrected equilibria used for stability analyses and transport calculations now incorporate quadrupole-driven axial currents which can extend into the center cell. These axial currents are driven by pressure gradients where field curvature causes particles to drift off of magnetic flux surfaces. Correcting magnet designs to minimize distortion of the equilibria by zeroing axial currents simultaneously corrects drift orbits, so that they now coincide with flux surfaces. This analysis was developed while finalizing the magnet shape in the MFTF-B A-cell, and it resulted in better equilibria and more nearly coincident drift surfaces.

Stability of these equilibria to short wave-length ballooning modes has been examined and our earlier optimism that kinetic

effects would have a major stabilizing influence proved to be correct. With proper design, ballooning instabilities no longer limit the maximum β one can achieve in tandem mirrors. The long perpendicular wave-length mode ($m=1,2$) should be flute-like in character. Using a strict interchange criterion, machine designs with a β limit exceeding 50% are possible. Experimental results in Phaedrus and at high β in TMX support these calculated interchange results. At present we do not have a complete theory for low m modes in quadrupole geometry.

Turning to the question of startup, we now find that we can start up MFTF-B by operating it first in the standard tandem (or two-component) mode, in the same way that TMX operated successfully. The resulting performance ($n_r \sim 10^{12}$, $T_e \sim 0.5-1$ keV) can safely and conservatively be assumed. This method of startup provides the flow of plasma at relatively low density and modest temperature out of the yin-yangs into the A-cell (free of gas sources into the A-cell) as is needed for the ECRH and pumping to be effective in forming thermal barriers.

MFTF-B was designed for microstable operation and depends on it to minimize the power requirements to sustain the end cells. Microstability and other such issues of detailed mirror physics are important in the A-cell end plug. Historically, advances in mirror devices have relied on understanding such issues and designing operating scenarios accordingly. Figure 1 is a testimony to the success of this experimental and theoretical enterprise, showing increases in performance through a sequence of machines in which, after other processes were brought under control, the plasma

confinement closely approached the ideal, classical collision limit for mirror devices ($nT \propto E_i^{3/2}$). There is a reasonable basis in experience to believe that this performance pattern will continue in MFTF-B. As noted by the Mirror Senior Review Panel "... many of the classical processes required for successful plasma operation have already been demonstrated in some degree ...". The ERAB panel noted that "The use of warm plasma streams to fill the loss cones in 2x11-B experiments, as well as the partial suppression of rf in TMX, indicate at least qualitative understanding and mastery of high frequency instabilities". Further examinations of ion and electron microstability since the machine was proposed show no change in the outlook.

C. The Timing of MFTF-B

In order to optimize the chance for early success in thermal barrier operation in MFTF-B, the ERAB panel recommended that "the construction of MFTF-B should be paced to accommodate results from the TMX Upgrade program". These results could quantitatively alter certain of the parameter settings assumed in creating the thermal barrier scenario, thereby requiring a certain flexibility in machine operations. Examples of the flexibility one might require concern the ability to launch, aim, and locate the beams and ECRH; to control neutral gas flow; to select ECRH frequencies (within a range of 5-10%); to time and sequence the turn-on of all injection systems; and to vary the beam and ECRH power. No changes in the magnets or vessel appear necessary.

Most of this flexibility exists in the machine as constructed. Each beam and microwave source has variable output, beams can be

aimed 4^0 from their mounting locations with ease, and a master timing system allows arbitrary sequencing. These are normal operational variables, but one can also move beams to different locations, alter the aiming beyond 4^0 , move ECRH antennas, add baffles and apertures to control gas, and add gettering to additional surfaces for relatively little cost.

Extra beam ports, an extra pair of beamlines in the center-cell, additional diagnostic ports, and access to the vessel have been provided so that the cost associated with these re-configurations is within the normal budget for operations.

An important margin of power density is available by reducing the plasma radius. A factor of 2-3 in power density is plausible and should not change the plasma performance to any major extent. Beyond that, the beams cannot be focused as required to continue increasing the power density.

One of the TMX-U milestones is to "demonstrate the existence of thermal barriers and the improvement in center-cell confinement due to the barrier", by December 1982. The auxiliary systems involved in these flexibility discussions are constructed in FY83 and FY84 in the operating budget for MFTF-B. No impact is foreseen on items in the PACE budget except the possible adjustment of some port locations. These are movable later at little cost. Information from TMX-U may influence the final location of beams and ECRH antennas and give useful design data for the waveguide systems. In the operational phase of MFTF-B understanding of the detailed mirror physics issues gained in TMX-U should shorten the time needed to realize the optimum thermal barrier performance.

Experience in TMX-U will help to focus the diagnostic requirements and to select those instruments which will augment the initial set installed on the machine.

Since startup of thermal barrier operation in MFTF-B begins with the standard, two-component mode which is already well understood from TMX results, top priority in the project is given to completing the base facility necessary for the initial experiments in the standard mode; namely, the vessel, magnets, 80 kv power supplies, cryo-system, etc. that comprise most of the PACE budget. Operation in the standard tandem mode will provide considerable engineering and operational experience and the results will contribute to the success of the thermal barrier operation. This period of time is also available to further distill the results of TMX-U before proceeding with thermal barrier formation.

III. PROJECT STATUS

One of the goals of MFTF is to advance the technology of mirror systems, so as part of the proposal to rescope to MFTF-B the key technologies of MFTF are to be demonstrated. This technology demonstration is in progress and to date the vacuum vessel has been pumped down and much of the cryogenic system has been operated by computer control. Using local control panels the 3000 W helium refrigerator passed all the detailed acceptance tests and has liquified helium for the cryopanel and magnet cooldown now in progress. A full field test of the 500 MJ superconducting yin-yang magnet will begin in late November.

Power supplies for the 1/2 s neutral beams are in final checkout and the test of an 80 kv source from our industrial supplier with

this power supply is scheduled for next spring. Four of these sources have been delivered and their arc-chamber tests completed successfully.

The funding required to maintain the present schedule is as follows (millions of \$):

<u>Item</u>	<u>Prior Years</u>	<u>FY82</u>	<u>FY83</u>	<u>FY84</u>	<u>FY85</u>	<u>Totals</u>
PACE(B/A)	107.6	41.5	46.5	30.5	0	226.1
Operating(B/O)	28.9	9.0	24.5	39.0	23.9	124.3

As of October 1981, the PACE items are 49% costed and 74% committed, while the operating funds for R&D and auxiliary components are 27% complete and committed (no liens). During FY81 contracts totaling \$39M were let to industry for the superconducting magnets, and \$12.4M for extending the vessel. In the first quarter of FY82 another \$17M will be committed, completing the awards of all major contracts in the PACE budget.

The PACE funds include the items in the base facility such as magnets, vessels, cryogenic systems, power conditioning apparatus, and conventional facilities such as buildings, utilities, and site work. The operating budget has components of a more changeable nature for plasma preparation, heating, and diagnostics. Supporting technical staff as well as machine specific research and development are also included. The major components provided in the operating budget are the neutral beams, gyrotrons for ECRH power, plasma diagnostics, beamlines, and plasma stream guns.

Major developments were required in both the gyrotrons and neutral beams to achieve respectively the high frequency power and optics for the MFTF-B 30 s requirements. Developments in these

areas in programs elsewhere have been impressive. Gyrotrons now produce cw power at more than 200 kw per tube at 28 GHz, and a 56GHz cw tube is under construction.

Both LBL and ORNL have operated 1/4 scale models of actively-cooled-grid sources and have full scale sources in assembly for tests at their respective labs for pulses of ~ 1 s. A 30 s test capability at LLNL will be available April 1982 for comparative evaluations of these sources.

At this time the contingency use on the project is reasonable and the schedule is being maintained. Good management of the project has been a hallmark since its inception.

IV. FUTURE FLEXIBILITY

In the MFTF-B design, the thermal barrier is created in an A-cell attached to a yin-yang magnet that provides MHD stability. At the time of the DOE decision to proceed with MFTF-B, there were already under theoretical consideration various axisymmetric plug geometries, also suitable for thermal barrier operation, which might ultimately represent an improvement over the A-cell design in reactor applications. In endorsing the DOE decision, both the Mirror Senior Review Panel and the ERAB Panel considered this question. To quote the ERAB panel: ". . . It would not be prudent to proceed now on the MFTF-B scale with axisymmetric plugs. Nor is a delay of the MFTF-B of two or three years warranted while these plugs are assessed because they can be included later. . . . The MFTF-B design should be sufficiently flexible to permit, without excessive cost or delay, a future conversion to alternate end-plug designs should these become desirable."

During the past two years, much effort has gone into evaluating axisymmetric end plug ideas. Most of this effort has focused on the axi-cell design consisting of an end plug with circular coils at a high field, followed by a low-field yin-yang MHD anchor outboard of the plug. The DOE now plans to fund a small experiment of this design called TARA, at MIT. Preliminary studies have shown the feasibility of implementing the axi-cell design in the MFTF-B, as a later modification at moderate cost, and at this writing consideration is also being given to implementing the axi-cell design from the start. Initially the axi-cell design was considered mainly as a way to gain experimental data on axisymmetric center cells while retaining the conservative yin-yang approach to MHD stability. More recently, a reactor study at LLNL has concluded that, together with recent developments in the technology of high-field circular magnet coils, the axi-cell is a particularly promising reactor candidate. Further evaluation of the axi-cell design is in progress.

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