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THE FLEXIBILITY OF MFTF-B FOR THERMAL-BARRIER
MODIFICATIONS AND AXISYMMETRIC UPGRADES

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March 25, 1981

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INTRODUCTION

Following a favorable recommendation by the Fusion Review Panel of the Energy Research Advisory Board (ERAB), the Department of Energy (DOE) has approved a major rescoping of the Mirror Fusion Test Facility (MFTF) to a tandem mirror geometry (MFTF-B), and initial funding has been provided in the FY 1981 budget.

In their recommendation, the ERAB panel made two observations concerning the construction schedule and design philosophy. Their first observation concerned thermal barriers. In order to obtain $Q = 1$ conditions, the MFTF-B design incorporates the new thermal-barrier concept that will first be tested experimentally in the TMX Upgrade facility now under construction. Although the panel agreed with this aggressive strategy, it cautioned that "the construction of the MFTF-B should be paced to accommodate results from the TMX Upgrade program." The second observation concerned the use of conservative quadrupole end-plug magnets in the MFTF-B, whereas it is hoped that simpler axisymmetric plugs may eventually prove feasible. On this point, the panel agreed that "it would not be prudent to proceed now on the MFTF-B scale with axisymmetric plugs" but urged that "the MFTF-B design be sufficiently flexible to permit, without excessive cost or delay, a future conversion to alternate end-plug designs should these become desirable." Since the panel's recommendation was written, construction has actually begun on TMX Upgrade, with a projected completion date of November 1981, and we have analyzed further the flexibility afforded by the MFTF-B design. This additional work essentially confirms our earlier assurances to the panel. At the time of the panel review, we indicated that we believed that the MFTF-B and TMX Upgrade schedules were compatible, and that it would be feasible to add axisymmetric end plugs at a later date.

Concerning the TMX Upgrade experiments, further examination shows that aside from a general confirmation of the thermal-barrier concept, the most important information for MFTF-B is quantitative data on neutral-beam currents, ECRH power and frequencies, control of neutral gas, aiming of beams and ECRH,

and other such control parameters that might help to optimize MFTF-B design details.

he TMX Upgrade should begin providing this data by the fall of 1982, in time to affect the final choice of beam-port location, surface materials, cryopanel locations, waveguide geometry, etc., in the MFTF-B vessel on the presently planned MFTF-B construction schedule (completion January 1985).

As we indicated earlier to the panel, it appears relatively easy to modify the MFTF-B magnet set to include axisymmetric mirrors at each end of the solenoid. There is one form that could be incorporated in MFTF-B from the start, from an engineering viewpoint. This scheme would involve insertion of an axisymmetric cell (axi-cell) between the yin-yang mirror and the central cell. The result would be a machine in which MHD stability is provided either by hot electron rings in the barriers or by the quadrupole end plugs serving as "anchors" (see Fig. 1). Preliminary studies have shown that this approach appears to be especially adaptable to MFTF-B, although more work is needed to fully assess this and other potential future modifications of the facility.

This document then addresses each of the above issues: (1) the ability to accommodate changes resulting from information from TMX Upgrade experiments, and (2) the ability to readily modify the facility to incorporate axisymmetric options. To properly address the first issue, we must guess what adjustments might be required when thermal-barrier operation is better understood. We therefore include a summary of the physics contributions expected from TMX Upgrade experiments. We also summarize the MFTF-B baseline configuration in order to assess the impact of changes on that baseline. Axisymmetric options that can easily be added to MFTF-B are discussed and the axi-cell configuration is singled out on the basis of its promise and ease of adoption in the machine.

PRESENT MFTF-B PROGRAM

The facility and components of MFTF-B allow the exploration of tandem operation with or without thermal barriers. As a standard tandem without barriers, both normal and two-component operation are possible, and differ only by the amount of beam power in the yin-yang. Each of these operating modes has different requirements for cold gas feed, injected-beam and ECRH power, and diagnostic locations, all of which can be accommodated in our design.

FIG. 1. Coil geometry and field profile for an axisymmetric tandem mirror (axi-cell) anchored by the MFTF-B yin-yang mirror.

Figure 2 summarizes the beam requirements for each mode of operation and assumes that the 1/2-s 80-kV beams deliver 50 A of neutrals (all species) to the plasma while the 30-s beams deliver approximately 30 A. There are 20 of the former and 7 of the latter. All of the 20 beams at 80 kV, 1/2 s, are required in the two component mode but only 16 of them can be used in the thermal barrier mode, since some of the power supplies are needed for 30-s beams. Figure 3 shows the beam locations for the two-component and thermal-barrier modes. We plan that 8 of the 12 central-cell beam ports will have beamlines (shields, bending magnets, ion dumps, beam dumps, and cryopanel), thus providing a small margin over the 6 beams calculated to be necessary. The additional ports may be needed later to explore higher beta in the machine. To use these ports, additional beamline components and source cables, not included in the project, must be built.

Operating mode	Central cell (total)	Yin-yang cell (each end)	A cell (each end)	End region (each end)
1. Standard tandem Simple	500-8000 A_A cold gas	500 A, 15 keV, 10 ms 600 A, 50 keV, 500 ms	up to 50 A, 50 keV, 500 ms	streaming plasma sources ($\bar{n}_s r_s^2 \geq 7 \times 10^{15} \text{ cm}^{-1}$)
Two component	500-8000 A_A cold gas 300 A, 50 keV, 500 ms	500 A, 15 keV, 10 ms 300 A, 50 keV, 500 ms	up to 50 A, 50 keV, 500 ms	streaming plasma sources ($\bar{n}_s r_s^2 \geq 7 \times 10^{15} \text{ cm}^{-1}$)
2. Thermal barrier	20-1000 A_A cold gas 300-400 A, 50 keV, 500 ms 25 A, 60 keV, 30 s	500 A, 15 keV, 10 ms 200-300 A, 50 keV, 25 A, 60 keV, 500 ms 25 A, 60 keV, 30 s	50 A, 50 keV, 500 ms 30 s 5 A, 2 keV, $\perp$ 30 s (LEPB)	streaming plasma sources ($\bar{n}_s r_s^2 \geq 7 \times 10^{15} \text{ cm}^{-1}$) 25 A, 60 keV, 30 s (HEPB)**
220 kW for mag- netically trapped electrons				
350 kW for electro- statically confined electrons				

NOTE: Neutral beam currents are specified as required incident on the plasma.

* A_A = atomic amperes

+ LEPB = low-energy pump beam

**HEPB = high-energy pump beam

FIG. 2. Summary of the machine configuration for MFTF-B.

FIG. 3. MFTF-B sustaining neutral-beam source location.

Consider first the thermal-barrier mode of operation, which has both startup and equilibrium phases. Startup, during the first 1/2 s, should bring the plasma to the conditions listed in Table 1, at which time the 1/2-s beams are turned off and the plasma is maintained by seven beams and 1140 kW of ECRH power for 30 s. The beam locations and calculated required currents are listed in Table I and shown in Fig. 2.

Figure 4 gives more detail on the end-region injection, with 30-s beams in the yin-yang for maintaining pressure there and in the A cell at B_a , for establishing the sloshing-ion distribution. Point B_a is the conjugate turning point to B_a ($B_a = 2$ T) and depends on the potential profile in the A cell. Consequently, this beam requires some aiming flexibility. The axial pump beam is the third beam in the end region and a central-cell beam is the seventh 30-s beam required for equilibrium. ECRH is used at B_a (350 kW) and B_b (220 kW) to create the confining potential peak and to lower the potential minimum in the barrier.

Table 1. Approximate parameters for MFTF-B operating scenarios.

Parameter*	Two-component standard tandem mode	A-cell barrier; improved 80-kV beams [†] (Ref. case)
Q_c (central cell)**	(0.04) ^{††}	0.57
Q (overall)**		0.50
$n\tau_c$ (cm ⁻³ · s)	1.1×10^{12}	5.0×10^{13}
n_c (cm ⁻³)	4.3×10^{13}	2.08×10^{13}
τ_c (s)	3.4×10^{-2}	2.4
T_{ic} (keV)	0.15	15
T_{ec} (keV)	0.68	9
ϕ_c (keV)	0.43	28
ϕ_b (keV)	--	40
$\phi_c + \phi_e$ (keV)	4.6	85
β_c	0.17	0.2
β_p	0.3	0.4
β_b	--	0.3
P_{fusion}^c (kW)**	0.53	915
P_{fusion}^p (kW)**	--	176
P_{ECRH} , 28 GHz (kW)	--	292
P_{ECRH} , 56 GHz (kW)	--	680
I_{inj}^c (A)	211	3.0
I_{inj}^p (A)	123	8.8
I_{inj}^a (A)	--	1.3

*Definitions of the super- and subscripts in this column: a = A cell, b = thermal barrier, c = central cell, e = electron, i = ion, p = yin/yang cell, ECRH = electron cyclotron resonance heating, inj = injected.

[†]Improved beams: 30-s, 80-kV, 80% D⁺.

**As if D-T; actual experiments will use pure deuterium.

^{††}This value of Q_c is limited by the temperature dependence of $\langle\sigma v\rangle_{DT}$. For example, if 150-kV beams were injected, rather than 80 kV, Q_c would rise to 0.1 without significantly changing other plasma parameters.

FIG. 4. Profiles of field B , potential ϕ , and density n versus distance z at one end of MFTF-B operated with A-cell-type thermal barriers.

Eight gyrotrons with 200-kW output each are provided to meet the ECRH requirement. At each location there is 400 kW of rf output from two tubes, so that the margin at B_b is perhaps 50%, depending on waveguide, launching, and propagation losses and on absorption efficiencies, and there is no margin at B_a .

For startup, ten 20-kV beams in each yin yang and sixteen 80-kV beams are turned on simultaneously. The 80-kV beams (1/2 s) are located as in Fig. 1, one in each A cell, four in each yin yang, and six in the central cell. The total of 16 is determined by the number of available power supplies--of the 24 supplies available, 1 is used for ECRH and 7 for the 30-s beams. Startup calculations now being developed determine whether the necessary plasma conditions are obtained at the end of 1/2 s.

The current required for both startup and equilibrium depends on the radial density profile. Table 2 lists the minimum and maximum currents required in the 30-s beams, assuming, respectively, a parabolic and a flat-top profile with a 40-cm plasma radius at the yin-yang midplane. The minimum and maximum beam currents given for the 2-kV and 80-kV 30-s beams are based on optimistic and pessimistic assumptions of grid, aperture, neutralizer, and reionization losses in the beamlines. Generally, there appears to be some margin of current in each beam.

Because the power requirements depend on the plasma volume created and sustained, one can use the plasma radius as a control to match the plasma volume with the available power, if the requirements differ from those calculated in the baseline design. One can envision volume reductions of 25%-50% before radial effects might affect performance. Also, one could imagine a smaller radius during startup than would be maintained in equilibrium. In equilibrium, the 30-s beams penetrate the plasma completely (10%-20% trapping fractions), so the plasma may expand from an initially smaller radius to one limited by the footprint of the axial pump beam that maintains the potential barrier.

Gas pumping in MFTF-B is designed to accommodate the quantities of gas given in Table 3. The location of gas sources, proximity of sources and surfaces to the plasma, and the natural flow of gas to the end of the machine, all determine the gettering scheme and cryopanel layout. Flow rates are the same in both modes but more gas is injected in the thermal-barrier operation. Since the major source of gas is from the beams, baffles and apertures in the

Table 2. 30-s beam requirements for thermal barrier operation of MFTF-B.

Beam location	Beam energy, kV	Expected neutral- beam output, A		Required neutral beam current, A	
		min	max	min	max
Central cell	80	28	38	16	32
Yin-yang cell (per cell)	80	28	38	11	22
Sloshing ions (per cell)	80	28	38	12	24
HEPB (per cell)	80	28	38	12	24
LEPB (per cell)	2	9	13	5	10

Table 3. Sources of gas during MFTF-B operation.

Source	Number	Duration, s	Flow rate/source, Torr · litre/s	Total flow, Torr · litre
<u>Stream-stabilized</u>				
20-kV neutral beams	20	0.01	30	6
Stream guns	60	0.01	15	9
80-kV neutral beams	23	0.5	30	345
Gas injection	1	0.5	100	50
				<u>410</u>
<u>Thermal-barrier mode</u>				
20-kV neutral beams	20	0.01	30	6
Stream guns	60	0.01	15	9
80-kV neutral beams	16	0.5	30	240
Gas injection	1	30	10	300
80-kV neutral beams	5	30	30	4500
Ion-pump beams (80 kV)	2	30	30	1800
Ion-pump beams (2 kV)	2	30	20	1200
				<u>8055</u>

beamlines are important in controlling the flow to the chamber, and these are easily modified. Gettering on surfaces is important to the proper startup of a plasma, and additional gettering or the relocation of the getter mechanisms is not a major change.

The above systems have an inherent flexibility which will allow them to meet changing requirements, and it will also be possible to rearrange existing equipment (move beams to different ports, relocate ECRH, move getter mechanisms, modify baffles and apertures, etc). These flexibilities will be exercised in normal experimental operations by parameter variations and through normal experimental modifications. These should be sufficient to demonstrate the expected performance, and information from TMX Upgrade will likely expedite this process.

Modest changes in the configuration of the machine as presently designed (such as changing a few port locations, adjusting beam aiming beyond the $\pm 4^\circ$ design range, or adding another pair of gyrotrons) can be accommodated during construction with minimal impact until such a time as the system in question is to be built. The magnetic field profile and beam energy being fixed, flexibility comes mainly from the control of particle currents, rf power, and neutral gas.

The MFTF-B construction schedule (Fig. 5) shows the key dates for design, bid and award, and construction. The magnet and vessel are controlling features in the schedule, since the ability to relocate components depends largely on interfaces with the vessel and the magnet structure and supports. Table 4 picks out key construction dates in the magnet and vessel systems. Construction of auxiliary components will generally not begin until FY 1983.

FLEXIBILITY FOR CONFIGURATION CHANGES

Experiments in TMX Upgrade should confirm the essential features of thermal-barrier configurations. We review here the information expected from TMX Upgrade and its timing, in order to evaluate the options available to us and to assess their impact. The timing is based on the TMX Upgrade milestones given in Table 5.

FIG. 5. MFTF-B project schedule.

Table 4. MFTF-B key construction dates.

MAGNETS

Order yin-yang conductor	October 1980
Award contract for A-cell, transition, solenoid	January 1981
Award contract for A-cell winder	February 1981
Order case steel (for all magnets)	March 1981
Order all other conductors	April 1981
Preliminary design review	July 1981
Start fabrication of steel cases	September 1981
Final design review	January 1981
Start winding A-cell	February 1982
Start winding solenoid	July 1982
Modify LLNL winder for transition coil	October 1982
Start winding transition coil	January 1983

VESSEL

Award contract for east vessel	May 1981
Award contract for central and west vessels	May 1981
Steel order due at vendor	May 1981
Start fabrication of east vessel	December 1981
Final design review for both contracts	January 1982
Start fabrication of central and west vessels	February 1982
Cut ports in east vessel	August 1982
Cut ports in central and west vessels	October 1982
Final design review for cryogenic systems	January 1983
Start fabrication of cryopanel	January 1983

Table 5. TMX Upgrade milestones.

1. Submit TMX Upgrade experimental plan	July 1981
2. Begin checkout of TMX Upgrade	November 1981
3. Produce initial plasmas in TMX Upgrade	March 1982
4. Demonstrate end-plug sloshing-ion distribution with 1-MW neutral-beam power per plug	May 1982
5. Submit plan for incorporation of axisymmetric end plugs in TMX	May 1982
6. Submit report on initial TMX Upgrade experimental results	July 1982
7. Demonstrate electron heating with 200-kW wave power per plug	September 1982
8. Submit report on TMX Upgrade ECRH results	November 1982
9. Demonstrate existence of thermal barrier and improvement of central-cell containment due to barrier	December 1982
10. Complete radial transport measurements	March 1983
11. Submit report on radial transport in TMX Upgrade	June 1983
12. Submit final report on TMX Upgrade results	August 1983

INFORMATION FROM TMX UPGRADE

The creation of a thermal-barrier tandem can be viewed in terms of a number of fundamental processes whose physics should be verified in TMX Upgrade. Theory shows that the plugs can be stable to microinstabilities, depending on the spatial distribution of trapped ions and warm plasma in the magnetic well. The key to achieving stability is the proper injection of the sloshing-ion beam and the detrapping of ions at the potential minimum (thermal barrier) by pump beams. The sloshing-ion distribution should be demonstrated by May 1982. With the proper distribution of sloshing ions established, the barrier must be pumped to maintain the potential minimum. Trapping by collisions, fluctuations, and charge-exchange penetration of surface neutrals

must be balanced by pumping with the axial pump beam. Demonstration of the existence of a thermal barrier by December 1982 will verify that the trapping processes have been correctly calculated.

Electron heating by ECRH is important in establishing the potential profile at the end of the machine. Heating of potential-trapped electrons at the outboard peaks of the sloshing-ion distribution creates the confining potential maximum. Heating the magnetically trapped electrons at the magnetic field minimum (thermal-barrier region) slows their loss rate and reduces the potential there, deepening the thermal-barrier well and improving performance significantly. Many variables are involved in these heating processes. A successful demonstration will probably require an experimental learning process on launching structures, propagation (ray-tracing theory is a guide), absorption (distribution functions may depend on frequency and parallel-wave number choices), and other such physics issues. Further, experience in running the system will show how to avoid mode-conversion losses and breakdown in the waveguides, and will show compatibility of ECRH power with other experimental components, diagnostics, and material surfaces. This experience from TMX Upgrade is expected to be available by September 1982.

Startup is another area where the learning experience from TMX Upgrade will be very valuable. In steady state the processes that maintain the density and potential profiles can be examined to determine the required particle and energy input and control. However, the transient response to beams, rf, and gas input during the first 500 ms must be such as to evolve from initial particle and energy distributions with poor confinement to the desired final state. ~~Calculational models have been coded to determine working scenarios,~~ but the solutions are not yet optimized. The proper timing of beams, rf, and gas feed to control density and temperature profiles during buildup in various regions will probably be determined experimentally on TMX Upgrade between March 1982 and December 1982.

Stability to ballooning and interchange requires that the central-cell pressure be limited. Theoretical limits based on ideal MHD theory using the energy principle to predict the onset of instability are presumed to give a lower bound on this limit. Both TMX Upgrade and MFTF-B are designed to operate up to this limit, even though kinetic effects are thought to permit higher limits. In TMX Upgrade, operation at the ideal MHD limit, and some exploration beyond, will be demonstrated between July 1982 and December 1982.

Finally, there are many different spatial regions in a thermal-barrier tandem, with complex particle-distribution functions in each region. Diagnostics to understand these phenomena completely could be prohibitively expensive without an intelligent selection of measurements and of instruments to choose for a particular measurement. Again, the experience from TMX Upgrade will be valuable in making these choices for MFTF-B. This information should be in hand by December 1982.

EXAMPLES OF IMPACTS ON MFTF-B

Modifications to MFTF-B in response to the above information should be viewed in terms of the beams, rf, and gas control systems. Aside from changes in these particular systems themselves, our ability to accommodate the concomittant changes in the vessel and magnet system should be examined. Changes in the magnet system, given that the profile is fixed, have an impact only insofar as the structures and supports between the magnets and to the vessel restrict access to the desired region.

Figure 6 shows the magnet system with structures and linkages in place. The region where access is most difficult is in the A cell, where only limited changes in beam access are feasible. Nonetheless, beam steering is possible from the existing ports in the A cell, and ECRH relocation is not a problem. Both the schedule and design constraints on the magnet system dictate an early freeze on the configuration, so changes can simply be examined in view of their impact on the vessel with the magnet structure and linkages fixed.

To visualize potential changes, we have picked a few examples concerning the thermal-barrier processes described earlier (stability, pumping, ECRH control, startup, and diagnostics). Table 6 describes various issues and ways we can respond to them. Under "Inherent flexibility," we include only those things which can be changed from the control room or by minor adjustments on the machine. The "Configuration changes" range from a rearrangement of base-line hardware to minor modifications of the facility. Costs for making the configuration changes are minimized if the changes are made early. In the estimates given below, the timing between TMX Upgrade information and MFTF-B schedule was considered, and most changes would come at an early stage.

FIG. 6. Magnet structures and linkages in MFTF-B.

Table 6. Some physics issues of thermal-barrier tandems and their potential impact.

Issue	Inherent flexibility	Configuration changes
MHD β -limits cannot be tested.	(1) Reduce plasma volume to give more power density. (2) Lower the yin-yang field to the theoretical limit.	(1) Shift some yin-yang beams to the central cell. (2) Add ICRH to the central cell.
MHD β -limits may be raised by wall stabilization.		Add a flux-conserving shield in the transition region.
Insufficient warm plasma to stabilize '1' DCLC in the A cell.	Change the relative beam current amounts in the sloshing and pump beams.	Control the neutral-gas density at the barrier surface with apertures, gettering, or added cryo-surfaces.
Thermal barrier allows higher than expected electron conduction--more 56 GHz ECRH power required.	Reduce plasma volume.	Add 2 ECRH tubes to the system.
ECRH at 28 GHz is ineffective in reducing barrier potential.		(1) Adjust aiming of ECRH antenna. (2) Change frequency or frequency mix. (3) Add ECRH power. (4) Change antennas, polarization.
Barrier filling rate is higher than expected from either ion two-stream instability, scattering by fluctuations, or neutral gas penetration.	Adjust beam aiming.	(1) Change beam aiming. (2) Vary pump-beam currents. (3) Add gas-control apparatus.
Radial losses too high.	Lower the central-cell field so the 1,2-T step mirrors more particles.	(1) Use gas boxes rather than gas feed to the central cell. (2) Control the profile with pellet injections or low-energy central-cell beams.
Impurity collection in the barrier or center.	More source conditioning before installation.	(1) Choice of materials on critical surfaces. (2) Added gettering, pumping.
Plasma startup does not lead to plasma parameters assumed for steady-state barrier operation.	(1) Program densities by gas and beam injection. (2) Timing of beam and ECRH turn on. (3) Program stream gun turn on. (4) Adjust beam aiming.	(1) Change beam and ECRH aiming. (2) Move stream guns. (3) Different frequency mix. (4) More gas control.
Secondary electrons from end wall cool the electrons in the machine.		(1) Different surface materials and treatments. (2) Added baffles, apertures, pumping in end region.

The changes listed in Table 6 are not major ones and their associated costs are modest in terms of either the initial project contingency or a normal budget for operations. Consider first the changes involving beams. Aiming with a $\pm 4^\circ$ adjustment is provided in the base design. Wedges on mounting flanges will permit further swings, but apertures would need to be moved and beam dumps relocated. In regions where we need to change the aiming rather than adjust it, one could design for a range of dump locations to allow a more rapid reconfiguration. Moving a given beam port (the least likely change) is more serious, since it requires a vessel alteration. But the currently planned ports will not be cut in the vessel until late 1982, so such changes could still be made. A large 80-in. port costs approximately \$25,000, so the impact is not large if the beamline is not already mounted to it and filled with its internal parts. Once the beamline is mounted, redesign and relocation becomes a major undertaking, but the beamlines will not be mounted until FY 1984.

The impact of moving beams from the yin-yang to the central cell is modest if only two beams are shifted, since there are two available ports with beam accessories (shielding, neutralizer, cyropanels, bending magnets, dumps). The costs are simply the cable costs of approximately \$100,000 per source. Moving additional sources to the central cell requires the construction of beam-injector accessories (about \$300,000 per set). Alternatively one might add an ICKH system (at about \$3 per watt). In steady state, the central-cell beam injects 150 kW, so doubling this power would cost about \$500,000.

Modifications to the ECRH system are relatively easy. Vessel penetrations and waveguide locations are easy to change at very low cost. Waveguide components, such as couplers and antennas, are relatively inexpensive and TMX Upgrade experience will be available before the design of these components is finalized.

Gyrotron orders will be placed in August 1982, with the first and last tubes delivered in July 1983 and May 1984. Our present choice of frequencies is 26 and 28 GHz for the tubes at the barrier and 56 and 60 GHz for the tubes at the potential peak. Possible changes include using a different mix of frequencies or adding a third tube to each potential maximum region, where there is no margin on power. The frequency choices are (1) using a single frequency in each location, (2) having a smaller frequency separation at a given location (say 59 and 60 GHz), or (3) using mixtures of fundamental and

second harmonic heating. These choices can be made at no cost until the order is placed, and that timing is consistent with the timing of expected TMX Upgrade results.

Adding a pair of gyrotrons, associated components, and power-conditioning apparatus would add about \$1.5 million, including \$350,000 for the tubes. Further additions would be more expensive since the 80-kV power supply (which now handles 8 tubes) can accommodate a maximum of 10 tubes.

Changes in the gas-feed system and the control of neutral-particle flows in the machine are more likely to come from experience in operating MFTF-B than from TMX Upgrade because of physical differences in the machines. These differences include the use of cryopumping in MFTF-B, differences in the energy spectra of flux on vacuum vessel and magnet liner surfaces, spacing differences between the plasma and surfaces, and the physical shape (thin) of the A cell plasma in MFTF-B. In short, the need for design modifications may be machine dependent and best made as a normal part of the experimental operations.

Nonetheless, the location and geometry of baffles and apertures can be optimized in FY 1983 without much cost impact if TMX Upgrade sheds light on physics processes that we can translate to design changes. Processes involving surface preparation, like gettering and glow-discharge cleaning, can be optimized in MFTF-B in FY 1983 with little cost impact. Finally, cryo-panels can be added in various regions until early FY 1983 with some cost impact, about \$2000 per square meter of panel up to the reserve capacity of the refrigerator. Each square meter uses about 1.5 W, and some of the 1500-W reserve capacity may be available. If refrigeration is added, the system and panels cost \$4000/m². There is a total of 1500 m² of cryosurface area in the base design, but local pumping problems could be handled with perhaps 10-100 m², space permitting.

We should be able to accommodate modifications indicated by new information from TMX Upgrade with the changes contemplated in Table 6. Furthermore, even if most of these changes must be made, the total cost is only a modest fraction of the contingency.

AXISYMMETRIC UPGRADES TO MFTF-B

We are exploring a number of options for incorporating axisymmetric coils in the end plugs, at least in the region of high magnetic fields and plasma

pressure. An important criterion in selecting among these options is MHD stability with respect to the interchange of plasma and flux in long-wavelength radial displacements. This property, which the minimum-B yin-yang mirror provides for present-day tandems, is missing from simple axisymmetric mirrors. To recover this property, the axisymmetric coils must be formed in cusp geometry, contain internal rings, or have Elmo-Bumpy-Torus-(EBT)-type electron rings driven by rf power.

A number of ideas have emerged during our search. One of the more promising ones can be added to MFTF-B rather easily, perhaps even during the construction of the machine on its present schedule. This option, the axi-cell scheme, will be evaluated more thoroughly during the next 6 months and an LLNL recommendation will be made in August 1981.

THE AXI-CELL SCHEME

In the axi-cell scheme shown in Fig. 1, only a simple axisymmetric mirror is introduced at the end of the central-cell and the yin-yang plug is retained for MHD interchange stability. A thermal barrier and the confining potential are created in the simple mirror and the yin-yang is operated at half-strength with a reduced ion pressure, just enough to provide stability when averaged over the machine length. Ballooning in the region where the plasma fans out of the 6-T mirror into the central cell will set a limit on the allowable pressure in the confined plasma.

Accommodating an NbTi magnet in the MFTF-B vessel and magnet set requires careful attention to beam access for sloshing ions and barrier pumping. Figure 7 shows a pumping beam at 45° to the machine axis, aimed at the 3-T point (mirror ratio of 2:1 to the 6-T peak), and a sloshing-ion beam aimed so that the conjugate ion density peak (nearest the yin yang) occurs at the 2-T point. ECRH heating at that conjugate point produces the confining potential, while ECRH at the 1-T mirror minimum depresses the potential dip that is the thermal barrier. A 2-kV pump beam (not shown) is also used, in the same way we now operate one in the A cell, to augment the barrier pumping. The layout in Fig. 7 requires optimization in both physics and engineering, and the detail necessary to evaluate the impact on the present design must evolve.

Incorporating the axi-cell design into the existing MFTF-B configuration would require certain vessel modifications and construction of additional

FIG. 7. Layout of pumping and sloshing beamlines in the axi-cell scheme.

beamlines and magnets. A very preliminary estimate of the additional cost is \$20 million (for completion by January 1985).

If a decision could be made soon enough, vessel modifications could be carried out from the start to permit ready later incorporation of magnets and beamlines. If later retrofitting of the vessel were necessary, costs would be higher, perhaps by \$2-3 million. An LLNL recommendation on this question will be included in our August, 1981, assessment.

The other long-lead item requiring a decision is the magnets. We conclude that the thermal-barrier magnets could be constructed and installed by 32 months after a decision to proceed, including 8 months for design time. Then the required schedule of decisions to incorporate the axi-cell design in MFTF-B from the start, based on the present MFTF-B schedule, would be as follows:

1. Assessment--decide to modify vessel or retrofit later, August 1981
2. Begin magnet design, April 1982
3. Let magnet contract, January 1983
4. Complete MFTF-B, including axi-cell configuration, December 1984.

Evidently, any slip in this decision schedule would delay operation in the axi-cell configuration accordingly. If initial experiments were carried out in the presently designed configuration, a later switchover to the axi-cell configuration would probably require about 6 months downtime.

OTHER POSSIBILITIES

There are other axisymmetric options possible, and these too are being assessed. LLNL has established the Advanced Mirror Systems group under the leadership of Grant Logan to carry out this assessment. The cusp, internal ring, and EBT-ring schemes are among those under study. It is interesting to note that should the axi-cell scheme be built into MFTF-B at an early date, one could still replace the coils outboard of the symmetric mirror with other MHD stabilizing coils, such as a cusp, in a later upgrade.

Finally, more extensive plug modifications than the scheme in Fig. 6 will likely have to wait until FY 1987, when experimental results from axisymmetric experiments are available.

SUMMARY

Flexibility in MFTF-B will be achieved partly by using the margins in particle and energy control designed into the machine and partly by making modest changes based on results obtained in TMX Upgrade. This latter flexibility is permitted by the schedule for vessel construction and component fabrication. The changes we might expect were determined by an examination of the processes involved in creating a thermal barrier and by speculating on the range of outcomes from TMX Upgrade experiments.

The schedule fit is based on milestones for achieving results in TMX Upgrade, on the MFTF-B vessel construction schedule, and on the FY 1983-84 schedule for constructing all auxiliary components. It is also based on the recognition that, with the magnetic field profile and magnet structural system fixed, flexibility is limited to that determined by the injection and control of beams, gas, and ECRH, and by the impacts on the vessel when these systems are modified.

In searching for axisymmetric options for end plugs in MFTF-B, we have identified the axi-cell scheme as the one which should seriously be considered for early incorporation in MFTF-B. We expect to have the information necessary for making a timely decision by August 1981. The information we develop will be based on a fairly detailed physics and engineering examination of this option.