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The Tandem-Mirror Program -
Status and Projection

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The basic tandem mirror consists of a long, axisymmetric central mirror cell stabilized against interchange instabilities by minimum-B cells at both ends. The escape of ions out the ends of the central cell is inhibited by the higher plasma potential (higher plasma density and temperature) maintained in the end cells (Dimov et al., 1976; Fowler and Logan, 1977). Loss-cone instability modes in the end cells are suppressed by the warm plasma flowing out both ends of the central cell, consistent with theoretical expectations (Rosenbluth and Post, 1965; Post and Rosenbluth, 1966) and with experiment results on 2XIIB (Simonen et al., 1978).

The validity of the basic tandem-mirror concept was effectively demonstrated in experiments conducted in the Tandem Mirror Experiment (TMX). The experimental results may be summarized as follows (Coenggen et al., 1980a and 1980b):

- 1) Finite-beta, central-cell plasmas were produced and maintained by neutral-atom-beam injection with plasma beta up to 0.1 without central-cell beam heating and up to 0.4 locally with central-cell beam heating.
- 2) The confinement of the central-cell plasma was improved by the higher (> 200 V) electric potential of the end-cell plasmas (up to 9-fold increase in attained n_i).
- 3) The electron temperature achieved in the TMX end cells was higher than that observed in the single-cell 2XIIB experiments (T_e up to 260 eV, three times the value obtained in 2XIIB with comparable injected neutral-beam current).

An improvement to the basic tandem-mirror idea, the use of thermal barriers to insulate the electrons in the central cell from those in the end cells, was proposed (Baldwin and Logan, 1979) as a means of enhancing central-cell plasma confinement with reduced plasma parameters in the end cells. The plasma potential in the end cells can then be increased by microwave (ECRH) heating of the electrons locally without affecting significantly the electron temperature in the central cell.

The thermal barrier can be created in the low-magnetic-field region in the midplane of a tandem-mirror end cell by maintaining a low ion density in that region. By injecting neutral-atom beams at an angle (e.g., 45°) to the axis such that they predominantly oscillate between well-separated mirror reflection points on both sides of the midplane of the end cell a double-hump, "sloshing-ion" distribution can be maintained. This type of ion distribution (Kesner, 1973) has two properties of interest: (1) in a mirror cell of high mirror ratio and adequate length both a thermal barrier for electrons and a potential maximum to inhibit ion loss can be created, and (2) the sloshing-ion distribution is far more stable to loss-cone instabilities than that having the typical density maximum at the midplane field minimum (Baldwin et al., 1980). In order to prevent collisional relaxation of the double-hump distribution, ions that are scattered to large pitch angles and therefore concentrate near the midplane must be removed. This can be done, for example, by injection of neutral-atom beams aimed at a small angle relative to the axis within the loss-cone. The plasma potential at the thermal barrier can be further reduced by creating a

population of energetic, anisotropic electrons that are magnetically trapped near the midplane by application of ECRH microwave power at the gyrofrequency of the magnetic-field minimum. These energetic trapped electrons will depress the thermal-electron density near the midplane below the ion density in that region.

The plasma-potential peak that forms the final plug for inhibiting ion loss from the central cell is created in the outer lobe of the double-hump ion distribution by heating the electrons trapped in that region by microwaves at the gyrofrequency corresponding to the stronger magnetic field in this region. Because of the thermal barrier between this region and the central cell, the central-cell electrons are insulated from the hot electrons in producing the potential peak.

The maximum achievable center-cell plasma beta in a tandem-mirror system is thought to be limited by ballooning modes due to the presence of regions of bad magnetic-field curvature. Theoretical studies (Baldwin et al., 1980) indicate that in a tandem-mirror system with thermal barriers, stability to ballooning modes depends upon the plasma betas in three regions, the central cell, the thermal-barrier and the potential-peaks. The details of the magnetic-field configuration are important, and good progress has been made in shaping the magnetic field to increase the plasma-beta limit imposed by ballooning modes.

The first test of thermal-barrier enhancement of central-cell plasma confinement will be conducted in an upgrade of the TMX, the TMX-U, toward the end of 1981. The end cells of TMX-U are elongated minimum-B cells with mirror ratio of 4 and will accommodate the combination of thermal barrier and potential peak as described above.

The design objectives of the TMX-U are to achieve parameters that will:

- 1) Permit an early evaluation of the thermal-barrier tandem-mirror concept as already incorporated in the design of the much larger MFTF-B design,
- 2) Improve the performance of the TMX by about an order of magnitude, and
- 3) Operate with the central-cell plasma in the collisionless-diffusion regime appropriate to the MFTF-B and tandem-mirror reactors.

Selected machine design and anticipated plasma parameters for TMX-U are given in Table 1.

The end-cell arrangement of the Tandem Mirror Fusion Test Facility (MFTF-B) now under construction, will consist of a yin-yang coil set at each end of the central-cell solenoid with an outer C-shaped coil beyond the yin-yang coils at each end to form additional exterior mirror cells (A-cells). All magnetic coils of MFTF-B will be superconducting and can operate continuously. The NbTi multifilamentary, copper-stabilized superconductor is rated in this design for 5775 A in a transverse magnetic field of 7.68 T at a temperature of 4.5 K. The first set of superconducting yin-yang coils have been wound and encased, and will be mounted in the end-cell vacuum vessel for testing scheduled to begin in July, 1981. Some of the MFTF-B machine parameters are given in Table 2.

Because of the double-end-cell arrangement, the MFTF-B can be operated in any of several modes:

- 1) The two component mode without A-cells characterized by

stabilization of the end-cell plasmas by warm plasma streaming out both ends of the central cell and by no thermal barriers (basic tandem-mirror mode).

- 2) Tandem with A-cells, stream-stabilized or possibly inherently microstable, without thermal barriers.
- 3) Tandem with inside thermal barriers in the yin-yang cells.
- 4) Tandem with combination A-cell-thermal barrier, the reference case that is expected to achieve equivalent $Q = 0.5$ to 1.

Construction of MFTF-B is scheduled for completion in 1985.

Results of experiments in TMX-U and MFTF-B will permit the design of the D-T burning tandem-mirror next-step facility (TMNS) in which physics issues will not be at issue. TMNS will be a facility for engineering research and development. The end cells of TMNS are expected to be appropriate for a tandem-mirror demonstration fusion reactor (TMR), construction of which should begin about 1986 for operation in the 1990's.

Table 1. Summary of Selected TMX-U Parameters

Parameter <u>Central Cell</u>	With thermal barriers	Without thermal barriers
Density (H^+)	$23 \times 10^{12} \text{ cm}^{-3}$	$5 \times 10^{12} \text{ cm}^{-3}$
Ion temperature	0.9 keV	0.33 keV
Electron temperature	0.6 keV	0.5 keV
Plasma beta	0.25	0.06
Plasma potential	2.6 kV	1.6 kV
Ion confining potential	2.2 kV	0.35 kV
Neutral-beam current (H^+)	180 A equiv.	40 A equiv.
Average neutral-beam energy	10 keV	10 keV
Magnetic-field strength	0.3 T	0.3 T
Cell length (mirror to mirror)	8 m	8 m
<u>End Cells</u>		
Density (H^+)	$7 \times 10^{12} \text{ cm}^{-3}$	$10 \times 10^{12} \text{ cm}^{-3}$
Confinement	$5 \times 10^{10} \text{ cm}^{-3} \text{ s}$	$7 \times 10^{10} \text{ cm}^{-3} \text{ s}$
Magnetic-field strength		
Mirrors	2.0 T	2.0 T
Barrier	0.5 T	0.5 T
Barrier ECRH power	40 kW	0
Barrier electron energy	50 keV	0.50 keV
Potential peak ECRH power	40 kW	0
Peak electron temperature	1.4 keV	0.54 keV
Ion density at potential peak	$8 \times 10^{12} \text{ cm}^{-3}$	$10 \times 10^{12} \text{ cm}^{-3}$

Table 2. MFTF-B Magnet Parameters

Location	Parameter	Value
A-cell C-coils	Field strength at the coils	8 T
	Barrier-well field strength	1.0 T
	Mirror ratio	6.5
	Length, mirror to mirror	4.2 m
Ying-yang plugs	Midplane field strength	2 T
	Mirror ratio	2.1
	Length, mirror to mirror	3.6 m
	Plasma radius	0.4 m
Transition coils	Field strength at the coils	3.5 T
Central cell	Field strength	1 T
	Field uniformity	1%
	Length of uniform field	30 m
Machine length yin-yang center to yin-yang center		40 m
Overall length of vacuum vessel		64 m

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