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TANDEM MIRROR THERMAL BARRIER EXPERIMENTAL PROGRAM PLAN

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ABSTRACT

This report describes an experimental plan for the development of the Tandem Mirror Thermal Barrier. Included is: 1) a description of thermal barrier related physics experiments; 2) thermal barrier related experiments in the existing TMX and Phaedrus experiments; 3) a thermal barrier TMX upgrade; and 4) initiation of investigations of axisymmetric magnetic geometry. Experimental studies of the first two items are presently underway. Results are expected from the TMX upgrade by the close of 1981 and from axisymmetric tandem mirror experiments at the end of 1983. Plans for Phaedrus upgrades are developing for the same period.

INTRODUCTION AND SUMMARY

Incorporating thermal barriers[1] into tandem mirror reactor designs[2] improves projected performance and reduces magnet and neutral beam technology, as shown by Table 1. Thermal barriers can be incorporated into tandem mirror designs in numerous ways, as illustrated in Fig. 1.

The thermal barrier region thermally isolates the electrostatic end plugs from the reacting solenoid. With such a thermal barrier, electrons in the end plugs can be heated to temperatures above those in the solenoid. The potential well, confining central cell ions, is then increased and center cell ion confinement is increased.

The basic principles involved with the thermal barrier concept can be calculated on the basis of theoretical models.[1,3] While many features of the barrier concept have been experimentally studied in other contexts, they have not been tested in a compound experimental configuration nor at thermonuclear temperatures. A report describing technical considerations for such tandem mirror experiments was written by Drake.[4] This report presents an experimental plan for the development of the tandem mirror thermal barrier. The plan presented herein proceeds in parallel with the construction of MFTF-B, in which we propose to incorporate thermal barriers.

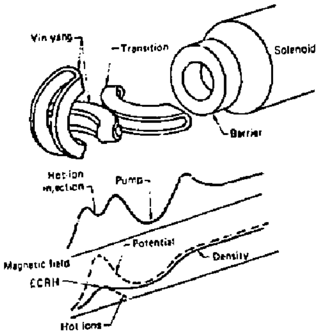
A summary of the experimental plan to develop the thermal barrier concept is outlined in Fig. 2. Physics issues can be investigated during these periods on several University facilities. Also in the near term, present TMX and Phaderous tandem mirror experiments can investigate, to a limited extent, certain issues such as barrier filling rates, thermal insulation, ECRH, and E-beam heating.

A thermal barrier TMX upgrade will allow barrier physics experiments and a test of a complete thermal barrier system to gain experience before operation of MFTF-B.

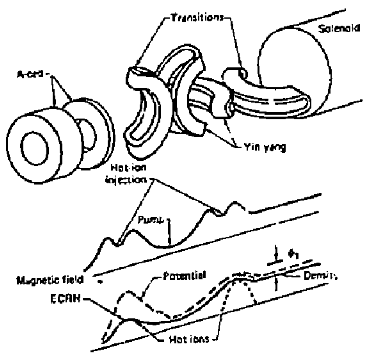
Further improvement in center cell plasma confinement properties can be gained by using axisymmetric magnetic coils. These experiments will require replacing the TMX magnet system in 1983.

TABLE 1. Improvement in tandem mirror reactor designs[5] with addition of direct electron heating and thermal barriers.

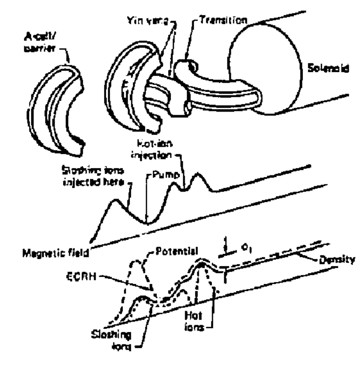
	Preliminary design	A-cells and center cell electron heating	A-cells and plug electron heating	Thermal barriers
Neutral beam energy, keV	1200	600	350	200
Max. magnetic field, T	17	19 to 21	15 to 17	12
Neutral beam power, MW	530	80	42	10
Direct electron heating, MW	0	130	250	57
Fusion power, MW	2500	2100	3000	1500
Center cell length, m	100	240	320	50
Q	4.8	10	10	23



ORIGINAL THERMAL BARRIER DESIGN



A-CELL DESIGN



IMPROVED A-CELL DESIGN

Fig. 1 Various thermal barrier configurations.

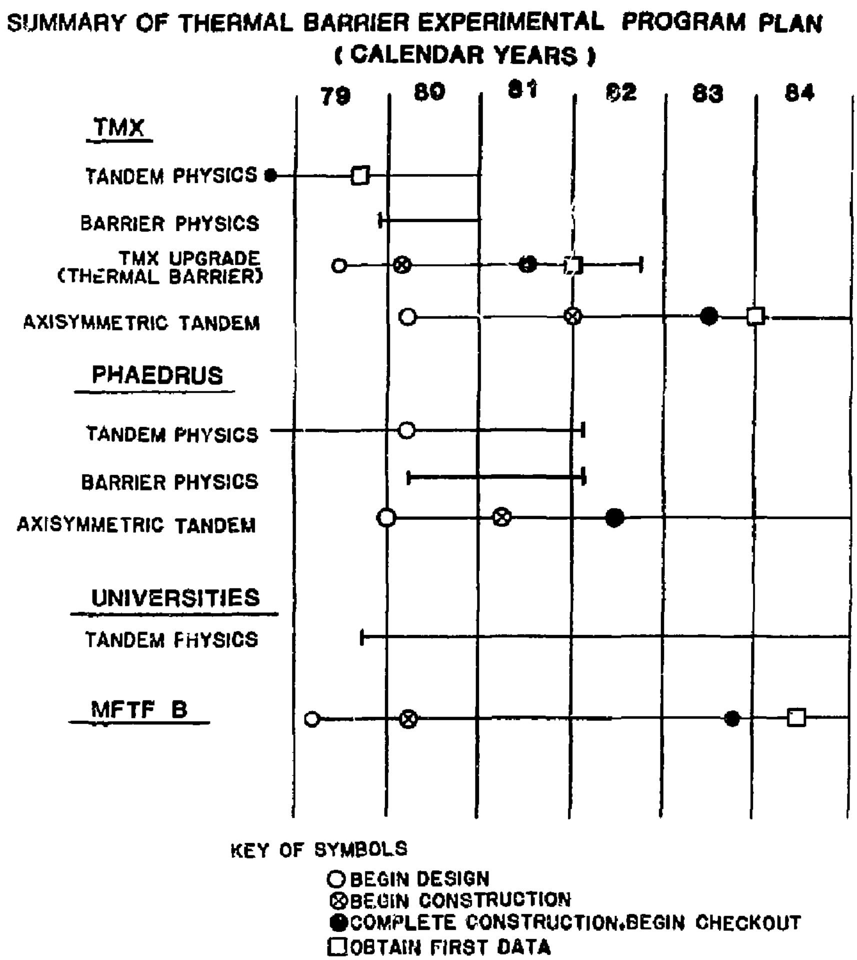


Fig. 2 Summary of thermal barrier experimental program plan.

THERMAL BARRIER RELATED PHYSICS EXPERIMENTS

Many individual aspects of thermal barrier physics principles have been observed in prior experiments, as summarized in Table 2. In this section we summarize these experimental results and indicate possible further experiments that could be carried out. Following the outline developed at the Workshop on Thermal Barriers in Tandem Mirrors, held at LLL October 10-12 1979, we divide these experimental issues into four broad categories: barrier region physics, MHD, electron heating, and microstability.

BARRIER REGION PHYSICS

ELECTRON TEMPERATURE GRADIENTS IN 2XIIB

We formerly thought that electron temperature profiles along magnetic field lines *must be uniform in other than highly collisional plasmas.* Measurements[6] in 2XIIB, shown in Fig. 3, indicate that electron temperature gradients exist even in a more collisionless regime. These measurements spurred theoretical considerations to emphasize such gradients in tandem mirrors and led to the present thermal barrier concepts. The 2XIIB results could be modeled by a Monte Carlo electron code.[7] Another characteristic thermal barrier feature showed up in 2XIIB, a density depression separating two higher density regimes. In this case the density depression shown in Fig. 4 occured naturally, presumably by ion coupling to ion cyclotron fluctuations. Although the tandem mirror reactor will operate in a more collisionless regime, these 2XIIB measurements nevertheless indicate that both electron temperature and density gradients can be maintained along field lines. Diagnostics are being prepared to look for similiar barrier effects in TMX.

TABLE 2. Summary of experiments relating to Tandem Mirror Barrier Physics.

Category	Existing data	Possible experiments on existing facilities	Possible experiments with new/modified facilities
• Barrier physics			
-Thermal insulation	Iowa triple plasma device ΔT_e in 2XIIB	Detailed measurements at Iowa TMX solenoid Thomson scattering TMX ΔT_e experiments Phaedrus heat pulse Experiment	Gridded or pulsed tandem Config. TMX-upgrade T_e scaling
-Barrier filling	Quiescent Filling Rate Q-Mach. (Kessner 1971)	Double-ended chopped Q-machine TMX Phaedrus center cell filling	TMX upgrade
-Barrier pumping	Density dip at 2XIIB mirror	Pondermotive potential TMX	TMX neutral beam pumping Non-omigenous drifts Phaedrus
• MHD			
-Ballooning	U Wis. Octupole TMX center-cell	U.C. Berkeley multiple mirror Achieve higher beta in TMX	TMX upgrade
-Axisymmetric mirror	U C. Irvine blanket Hot electron rings OGRA feedback stabilization	Irvine Higher temp-core TRW ECRH mirror U. C. Berkeley	Phaedrus TMX
• Electron heating			
-ECRH	High efficiency, many exps.	TRW ECRH mirror TMX 200-kW ECRH	TRW tandem mirror 0.8 MW on TMX upgrade
-E-beam	10% efficiency, many exps.	Constance I and II TMX E-beams	TMX high power E-beams
-ICRF	Phaedrus end plug experiments	Phaedrus	Phaedrus
• Microstability	PR6 ECRH stability DECA sloshing ions Streaming ion experiments	DCLC studies on TMX/Phaedrus TMX sloshing ion Phaedrus ion-ion mode experiments	TMX and Phaedrus TMX Upgrade sloshing A-cell

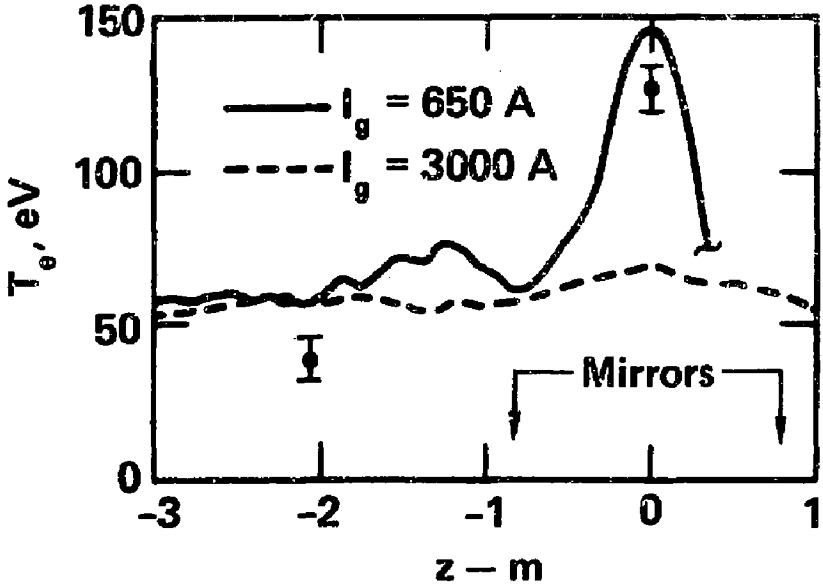


Fig. 3 Electron temperature axial profiles for typical 2XIIB gas box current. The curves are Monte Carlo calculations.

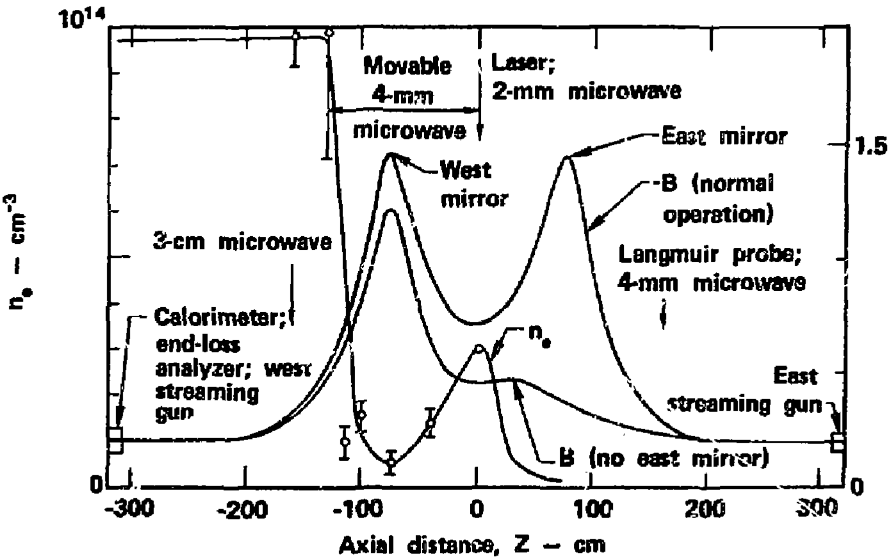


Fig. 4 Axial density profiles measured in 2XIIB.

THERMAL INSULATION IN DOUBLE LAYERS

A double layer is a standing electrostatic shock, or sheath, with a monotonically changing potential between two regions of uniform poteniai. Laboratory double layers can be used to study electron thermal insulation provided by potential barriers along field lines. Experiments at the University of Iowa[8] using a triple plasma device allow detailed, steady-state, low noise measurements of electron distribution functions throughout potential barriers with $\Delta\phi/T_e > 20$. These experiments were carried out in unmagnetized plasmas and with uniform axial magnetic field. Mean-free paths can be made large compared to the device, and ionization plays no role. Existing data indicate temperature differences across double layer potential barriers and the possibility of deviations from a Boltzman dependence at potentials much larger than T_e. These experiments can be extended to study ΔT vs. $\Delta\phi$ over a wider range of T_e and B field, using even more detailed diagnostics.

BARRIER FILLING

Measurements of the mirror filling rate in a single-ended cesium Q-machine were carried out by Kesner.[9] A rotating wheel was used to chop the plasma flow through a mirror machine. The mean free path was varied between collisional and collisionless regime. These experiments with a relatively quiescent plasma showed that the mirror filled at the classical coulomb collision rate.

Further experiments could be carried out in more detail with a double-ended Q-machine, such as at the University of California, Irvine.[10] At $t = 0$ sources could be pulsed, and the buildup of density, fluctuations, and potential could be monitored using steady sources and pulsed grids. The grids can be pulsed at a high rep-rate and box car techniques used to detail the time evolution of density, fluctuations, and velocity distribution by laser-fluorescence diagnostics. By deliberately unbalancing the plate temperatures, axial transport can be investigated.

This configuration could also be used to demonstrate neutral beam techniques for pumping out the ions.

The observation of the classical relaxation of a sloshing ion distribution in the DECA experiment[11] also provides a calibration of the theoretical calculation of barrier filling by Fokker-Planck codes.

BARRIER PUMPING

The presently favored method of pumping is by neutral beams. Neutral beams are injected into the velocity space loss cone and charge-exchange away ions trapped in the barrier cell. Such neutral beam interaction is well understood and is the basis of mirror plasma production, except, of course, that beams are not presently aimed into the loss cone. Neutral beam pumping has been observed in the ISX tokamak experiment. We consider neutral beam pumping physics to be straight-forward. The main issues are the amount of neutral beam current required (set by the barrier filling rate) and how to maintain a high vacuum environment near the barrier cell.

MHD STABILITY EXPERIMENTS

BALLOONING

Most implementations of thermal barriers involve average min-B stabilization, wherein regions of unfavorable magnetic curvature are stabilized by regions of good curvature. This concept is demonstrated in the TMX device[12], where the center cell plasma is stabilized by the good magnetic curvature in the end cells. Such stabilization has been observed in the Wisconsin Octupole,[13] which achieved betas of 8%, slightly above ideal theoretical limits. Finite gyro radius effects are thought to aid stability. These experiments are ongoing with more energetic plasma sources to attain still higher beta.

Along the line of MHD stability is the Sarmac idea under study at the University of California at Los Angeles.[14]

Related experiments are underway at the University of California, Berkeley[15] using a 10-m, multiple-mirror confinement device, stabilized by linked quadupole coils. In the Berkeley experiments injection from Marshall gun and conical theta pinch sources have already achieved in a single mirror cell betas greater than 10%. Future experiments expect to achieve betas up to 30%. These experiments will be performed to look for instabilities both under optimized field shapes when connection lengths for ballooning modes are minimized and when a single high beta cell is purposely destabilized. Observations of low order modes will be made both with a plasma camera and a probe array. The main experimental difficulty is to distinguish effects of high m-number ballooning modes from other sources of radial diffusion.

AXISYMMETRIC MIRRORS

Experiments at University of California, Irvine have been carried out with an external plasma blanket to stabilize MHD flutes.[10] These experiments are being extended to the stabilization of a hotter plasma and to measurements of thermal transport.

A second method to stabilize a simple mirror, using high beta electron rings, is under study at TRW.[16] These experiments will investigate issues beyond those examined in earlier ECRH mirror studies.

ELECTRON HEATING OF TANDEM MIRROR THERMAL BARRIERS

Electron heating using ECRH or E-beams has been employed in numerous mirror experiments. Tests of these techniques are presently planned. ECRH has several possible applications to the tandem mirror thermal barrier concept:[17] first, as a method to heat electrons; second, as a way to stabilize an axisymmetric mirror; and third, as a way to reduce electron heat flow. Early ECRH experiments have successfully heated a high beta annulus region of mirror plasmas. Electron beams have also been successfully employed to heat mirror plasmas and could be employed on tandem mirrors.[18]

TRW MIRROR

Experiments using multiple microwave frequencies are under construction at TRW[16] to heat a uniform plasma cross section as required in the tandem mirror thermal barrier concept. These first experiments will be carried out with a single mirror; however, the experiment could be expanded to produce a tandem mirror magnetic field configuration.

TMX ECRH

A 200-kW ECRH experiment is underwoood for TMX. This experiment will employ a 28 GHz gyrotron. Higher power experiments are planned in the TMX thermal barrier upgrade.

ELECTRON HEATING ON CONSTANCE I AND II

Electron heating experiments using E-beams[19] and ECRH[20] have been performed on the Constance I and II experiments. Electron beam (75 kW, 0.5 ms) heating has been demonstrated to have heating efficiencies of as high as 10%. ECRH (200 kW, 0.05 ms) has demonstrated even higher efficiencies.

A program is currently under way in Constance to maximize the heating efficiency of the E-beam injection by increasing the perpendicular energy of the electron beam. This is believed to be important in exciting electron cyclotron modes of the beam plasma interaction.

The Constance I electron heating experiments to date have been performed on over-dense plasma ($1 < \omega_{pe}/\omega_{ce} < 3$) with results indicating bulk electron heating, rather than high energy tail heating. The higher magnetic fields of Constance II should allow studies over a greater range of plasma parameter. The Constance I and II program will continue to study electron heating techniques and their effects on stabilizing ion cyclotron instabilities.

ELECTRON BEAM HEATING ON TMX

Electron beam heating experiments have been initiated on TMX. In initial experiments with 2.5 MW of power extracted from the electron guns, an increase of electron temperature from 94 eV to 142 eV was measured. Ongoing experiments will attempt to increase the heating efficiency and power.

PHAEDRUS ICRF

There are some indications of electron heating on Phaedrus[21] using ICRF. These experiments are continuing.

MICROSTABILITY

Thermal barriers introduce several advantages to tandem mirror microstability as well as introducing possible new two-stream instability modes. The outside A-cell barrier should stabilize the inner main plug due to the accumulation of warm plasma backing each end of the ion plug. It is further expected that the sloshing ions in the outside barrier cell will be stable due to the warm plasma held by a depression in the potential at the midplane of the barrier region. Two stream instabilities are expected to limit parameters that can be achieved. Theoretical consideration of these advantages and limitations, introduced by the thermal barrier concept, has been initiated.[3] Some relevant experimental investigations are summarized here.

SLOSHING ION DISTRIBUTION

Experiments on the DECA mirror device[11] demonstrated that a sloshing ion angular distribution could be created. Calculations by Kesner[22] indicate that one can create and sustain even larger density depressions using neutral beams than were achieved in DECA.[23] Since DECA was a pulsed experiment, the distribution relaxed toward a mirror normal mode distribution. The relaxation was at the classical coulomb rate indicating the absence of enhancement due to microinstability.

Experiments in 2XIIB showed that microinstabilities could lead to rapid relaxation of the angular distribution.[24] Thus quiescent buildup must be maintained through startup.

WARM PLASMA DCLC STABILIZATION

The DCLC mode can be stabilized by a flowing streaming plasma [25, 26] and by the ions injected by neutral beams.[27] These methods reduce the electron temperature. Recent ECRH experiments[28] on PR6 have shown that the DCLC mode can also be stabilized when a critical amount of plasma is confined in a potential depression in the region of the mirror midplane. These experiments showed a sharp pressure threshold for stability with the introduction of background gas. The sloshing ion A-cell will provide a potential well to confine such low energy ions.

THERMAL BARRIER RELATED EXPERIMENTS ON THE EXISTING TMX AND PHAEDRUS FACILITIES

This section describes thermal barrier related experiments, which are under consideration on TMX and are being planned for Phaedrus. The purpose of these experiments is to investigate several fundamental thermal barrier physics principles within the next 6 to 12 months.

TMX BARRIER FILLING AND TEMPERATURE GRADIENT EXPERIMENTS

The existing TMX magnetic field configuration is similar to one-half of an A-cell/barrier system and can be used to explore a number of aspects of thermal barrier physics. The apparatus indicated in Fig. 5 is being used in the initial investigations. Diagnostic information can be obtained at the locations shown. The basic regions may be summarized as follows:

- The center cell plasma is simulated by a plasma gun augmented by gas puffing at the end well.
- One of the TMX end plugs serves as the main plug.
- A thermal barrier should be created by the center cell on a transient basis since it will fill slowly due to its large volume. Gas feed can be used to vary the barrier density.
- An A-cell is created in the other TMX end plug and auxiliary electron heating can be applied with E-beams.

The thermal barrier density plays a critical role in barrier performance, the rate at which ions fill the barrier determines the barrier pumping rates. Data from such a TMX barrier filling experiment are shown in Fig. 6. East stream guns are on during the period of 5 to 15 ms. The west end loss analyzer shows that this plasma flows through the entire system. The east plug density builds up within 10 msec. The center cell is seen to fill with a 4-to 5-ms time constant. This filling rate is not inconsistent with our present knowledge of the mean ion energy, although further analysis is needed.

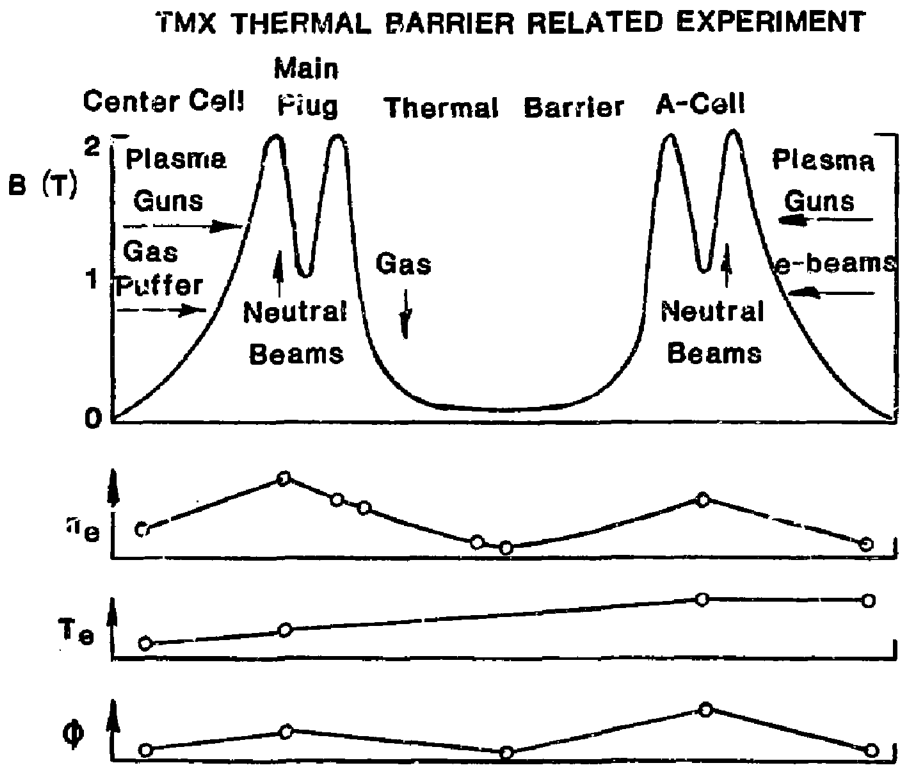


Fig. 5 TMX thermal barrier related experiments with schematic illustration of possible diagnostic measurements.

TMX THERMAL BARRIER DATA

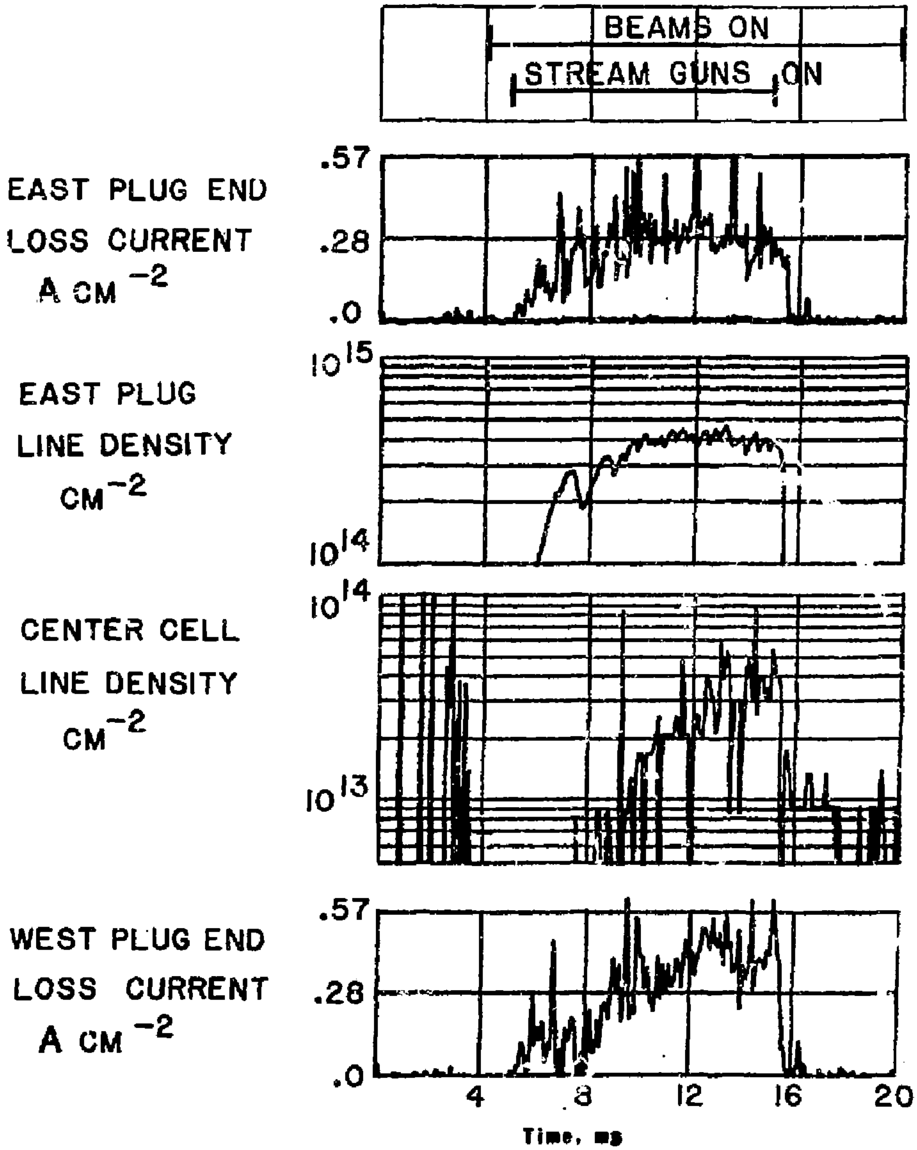


Fig. 6 Example of TMX thermal barrier related experimental data.

The next step in these thermal barrier experiments is to establish an electron temperature gradient along the magnetic field lines by heating one end plug with more beam power and electron beams and cooling the other with gas feed. Experiments in 2XIIB have shown that such gradients are possible at high density where axial heat flow is limited by collisional processes. The present TMX experiments are aimed at obtaining such electron temperature gradients by inhibition of heat flow by the low density barrier region, a technique more suitable for reactor applications. To measure an electron temperature difference between the A-cell and the main plug with only one Thomson scattering system, we will reverse the roles of the ends of the machine. The temperature difference should be controllable by the density of the plasma gun that simulates the center cell; and by the barrier density, the A-cell neutral beam and electron beam heating power.

PHAEDRUS LOW-DENSITY THERMAL BARRIER FILLING AND THERMAL CONDUCTION EXPERIMENTS

When the Phaedrus tandem mirror configuration is operational, it can be used to carry out thermal barrier-related experiments. These Phaedrus experiments would be carried out in the low-density collisionless regime using probe and gridded analyser diagnostics. The central cell will be employed as a barrier, as in the TMX previously experiment described. The advantage of these low-density experiments over barrier magnet modifications is that these experiments cause less disruption of the initial tandem studies to be carried out on Phaedrus.

End plug plasmas will be generated using either longitudinal or transverse plasma gun injection. The decaying end plug plasma will flow through the center cell and fill this region. The rate of fill will yield the velocity-space-averaged flux, of particles into the trapped region of the central cell. This filling rate can be compared to the collisional filling rate for stable plasmas. Probes can be used to detect any two-stream instabilities. The measured fluctuating electric fields can be used to compare the observed filling rate with Fokker-Planck type transport coefficients for a turbulent plasma.

If the end plugs are sufficiently stable, electron thermal conduction experiments can be carried out using ECRE in one end plug. Measurements of the electron temperature rise of one plug relative to the other plug will be used to determine heat conduction through the barrier. Since these experiments would be carried out at low density, only a very small amount of microwave power is needed; and again probe diagnostics are possible. For these experiments to succeed, it will be necessary to develop means for low energy gun injection, control microstability, and control neutral gas pressure.

TMX THERMAL BARRIER UPGRADE

The purpose of the TMX upgrade is to demonstrate a complete tandem mirror barrier system that will also improve the performance of TMX as rapidly as possible. To accomplish this there are four physics objectives that must be achieved:

- Demonstrate microstability of the ion plug and outer A-cell.
- Demonstrate MHD stability of the compound configuration.
- Demonstrate electron heating of the outer A-cell.
- Demonstrate the establishment of an electron temperature difference across the thermal barrier region.

We have completed the preliminary analysis of three possible ways to modify TMX to investigate the thermal barrier concept. Magnetic field profiles are given in Fig. 7. The relative advantages and disadvantages of these three cases are given in Table 3. We have selected case 3, the stable sloshing A-cell/barrier, and are now carrying out the detailed design. It was the only design where we could expect DCLC stable plugs; and thereby this case would achieve the best performance. This configuration is similiar to the MFTF-B design, so experience gained on TMX will be transferable to MFTF-B operation.

An outside mirror is added to each end of TMX to form the A-cell barrier. Neutral beams inject into the outer A-cell at an angle to create a sloshing ion density distribution[22], which holds warm ions to stabilize the DCLC mode. The hot density peaks and warm density drops at a location where the magnetic field is not to flat discourage the remnant DCLC mode from being established.[3] ECRH power is applied at the outer A-cell density peaks to raise the electron temperature. ECRH is also applied at the A-cell

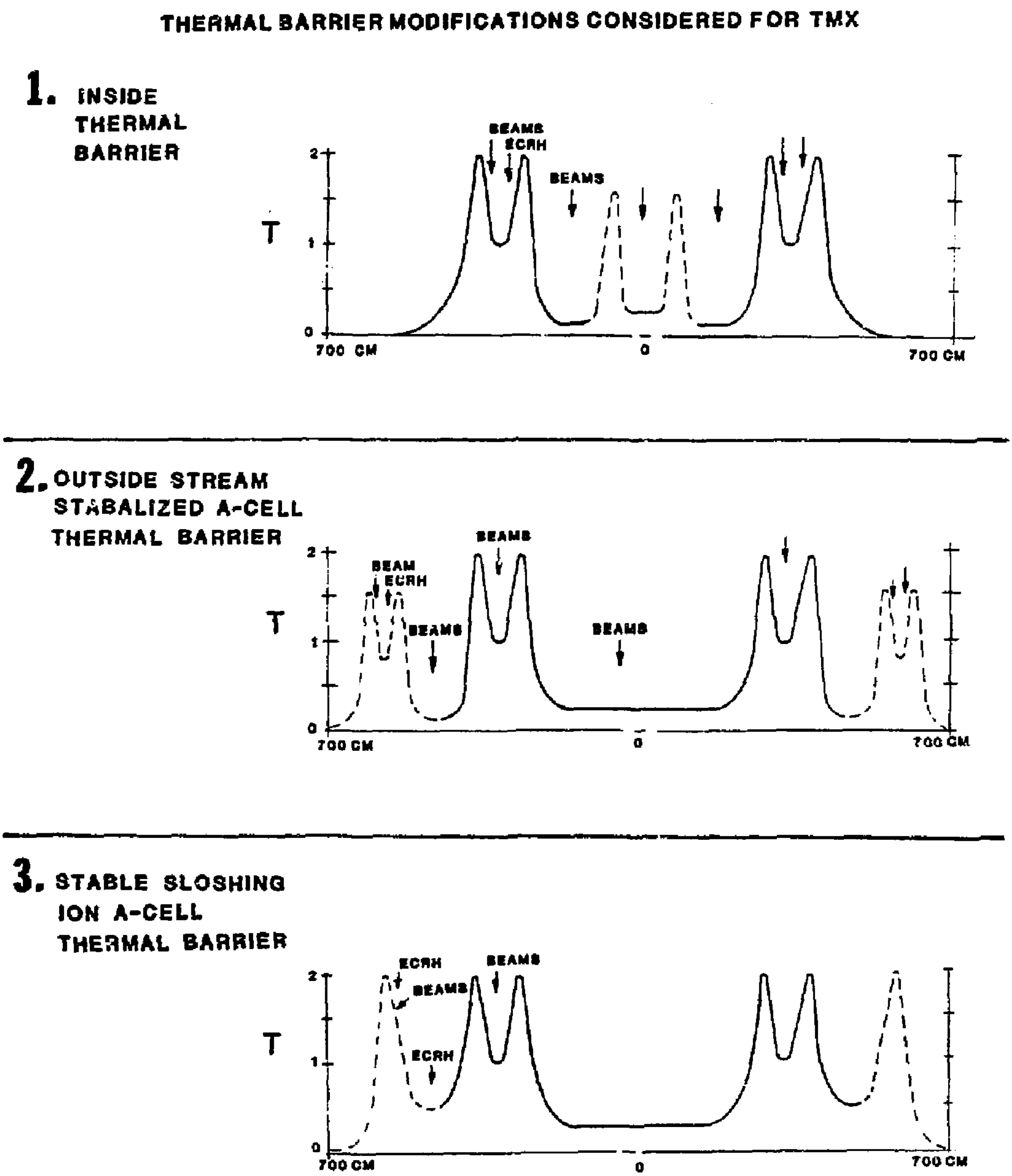


Fig. 7 Three thermal barrier modifications considered for TMX.

TABLE 3. Comparison of thermal barrier modifications considered for TMX.

1. Inside thermal barrier:

Advantages	Disadvantages
• Simplest magnet modification	• Center cell volume very small
	• Requires inordinate pump power
	• Little parameter improvement

2. Stream stabilized A-cell thermal barrier:

Advantages	Disadvantages
• Very flexible physics experiment	• High field at end wall
	• Modest parameter improvement
	• Susceptable to microinstability
	• Low adiabatic energy limit.

3. Stable sloshing ion A-cell thermal barrier:

Advantages	Disadvantages
• DCLC mode stable	• High field at end wall
• Maximum performance	• All functions integrated in one cell so independent control and measurements of individual functions is difficult
• Same beam can pump and fuel A-cell	
• Looks like MFTF-B design	

minimum to create magnetically trapped electrons to create a thermal barrier by inhibiting electron thermal transport. Neutral beams remain in the present plug and in the center cell. The main plug is stabilized by warm plasma penetrating both ends from the center cell and A-cell.

A design is being considered for incorporating thermal barriers and an axisymmetric central cell into Phaedrus is being developed at Wisconsin. This axis symmetric cell is used to develop both the positive barrier for central cell ions as well as the thermal barrier. This design will probably involve axisymmetric mirror coils between the center cell and the end plug as suggested by Kesner.[22] Such a design would involve major modifications to the Phaedrus facility, including a considerable increase in neutral beam power. Supplemental heating would be by ICRH and possibly also by ERCH.

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