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OVERVIEW AND DIRECTION IN THE
TANDEM MIRROR PROGRAM

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ABSTRACT

There are two main thrusts to the tandem mirror program at the present time. One is to gather the experimental data base to verify the axicell thermal-barrier concept and the other to improve the end plugs for tandems. With such improvements one might approach the ideal fusion reactor, a simple solenoid of modular elements whose ends are but a modest perturbation on the configuration from both a cost and technological view point. Progress toward these two goals is discussed here, and the directions to be taken in the immediate future are described.

INTRODUCTION

The tandem mirror is a young concept, but is rooted in a very old concept with a considerable experimental base, the magnetic mirror cell. In minimum-B single cell mirrors impressive performance was achieved--the near classical containment of hot plasmas at more than 10 keV energy at β values approaching 100%. Unfortunately the classical containment times one can

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expect in such reactors leads to values of Q (energy gain) in the range of 1-2, so that approach was abandoned in favor of tandems. The data base is nonetheless transferable, and in fact the key feature of a tandem comes from the ambipolar potential of a single cell mirror, namely the plugging potential at each end of the machine.

Other features observed in single cell mirrors are also adopted, including the creation of hot electron populations with ECRH, warm ion populations for microstability, and MHD stability from pressure-weighted good curvature.

In the first tandem, TMX, the plugging potential was erected by beam injection in the end cells to raise the density relative to that in the central cell. Confinement was improved over single cell values and tandem scaling laws were verified.⁽¹⁾ For improved reactor performance it is desirable to create the plugging potential by raising the local electron temperature in the end plug relative to the temperature in the central cell. Such a feat requires a thermal separation of these two populations, a thermal barrier. Our upgrade TMX-U was constructed primarily to demonstrate that such barriers could be made and that the plugging potentials could be erected by ECRH heating of those electrons isolated to the ends of the machine.

Initial results on TMX-U confirmed two of the ideas central to thermal barrier formation, the establishment of a sloshing ion population⁽²⁾ and the production of a large fractional hot electron population⁽³⁾ (more than 50% hot electrons at the plug midplane). Further, the sloshing distribution led to much improved microstability as one would expect from theory and from earlier experiments⁽⁴⁾ in PR-6,7 in which a local potential minimum at the midplane of the mirror was created (as it is in the TMX-U plug by sloshing). Warm ions that collect in this local minimum are stabilizing to microinstabilities of mirror trapped ions.

AXICELL TANDEMS

Thermal barrier tandems are an improvement over the standard tandem because the ratio of densities between the end plug and central cell is lower. Both plug losses and plasma pressure are thereby decreased, improving both the system Q and the technological outlook for the end cells. Further improvements were made with the invention of axicell geometries, that is with simple mirror cells at the ends of the tandem.

In MFTF-B these axicells, located at each end of the central cell, are used to reduce the density in the end plugs to about 5% of the central cell density (compared to 30-50% in previous thermal barrier designs). A further gain in Q and reduction in end plug complexity accrues from this change. Viewed another way, one can increase the central cell density while lowering the end plug density somewhat. Higher density in the central cell leads to higher fusion power density so another choice can be made in the axicell configuration--the plasma radius can be reduced and still achieve a respectable wall loading ($\sim 5 \text{ MW/m}^2$ in a reactor). The smaller plasma in the central cell means a smaller plasma in the quadrupolar end plug (MHD anchor). Consequently, the yin yang magnets in a reactor can be smaller. In MARS (Mirror Advanced Reactor Study) they are comparable in size (about 30% larger) to the MFTF yin yang magnet, even with shielding between the plasma and magnet surface.

In the TARA experiment at MIT the axicells will be used to construct the thermal barrier and confining potential. With the confining potential in the axicell only the plasma leaking from the tandem reaches the outboard yin yang anchors, so the density reduction between the central cell and the quadrupole anchors can be a thousand-fold. Should this configuration prove to be MHD

stable to trapped-particle modes (theory says it won't be) it would approach our ideal reactor configuration. All the plasma confined in the tandem would be within an axisymmetric, linear machine.

Both TARA and the MFTF-B axicell configuration benefit from improved radial confinement because most (or, in TARA, all) passing ions avoid the fan-shaped plasma regions in the transitions from axisymmetric cells to minimum-B cells. In these transitions there are large geodesic curvatures of the magnetic field lines, and particles passing such regions make excursions off the flux surface they are following. These excursions play the dominant role in determining radial transport in tandems.

I.e. MFTF-B, Baldwin and Bulmer⁽⁵⁾ have designed "double-fan" transitions (see Fig. 1) to minimize transport. A double-fan transition is one in which the flux fan, made by gathering the expanding flux bundle from the yin yang anchor, is followed by a similar fan in a plane rotated 90° from the first one. From the second fan a transition to a circular flux bundle is made before reaching the first axicell coil. With this second elliptical fan, geodesic curvature of equal magnitude but opposite sign to the curvature of the first fan is produced. Ions passing this double-fan region integrate these two peaks of curvature and see essentially cancelling effects, leading to small excursions from the flux surface.

Both MFTF-B (Fig. 2) and TARA, will test the axicell configuration to determine how much improvement in end plugs can be made and, in MFTF-B, whether radial confinement times of a second can be reached. Should the TARA mode of operation be successful MFTF-B can be operated in this mode by moving the sloshing beams and ECRH from the yin yang anchor plug to the axicell. As presently configured, MFTF-B uses the axicell only for density reduction and that can be done with a simple high field "choke" coil. (The MFTF-B axicell

consists of a 12 T choke coil and a 6 T coil to complete the mirror cell). In TMX-U, plans have been made⁽⁶⁾ to install a choke coil late this year to take advantage of the higher central cell density and improved performance on an axicell tandem.

The current MARS reactor design⁽⁷⁾ uses a choke coil, double-fan transitions, and recircularizing coils outboard of the yin yang plugs to reduce the volume of the end tanks. Further, it makes use of the double-fan region of the transition to improve MHD anchoring. A double-fan is created most easily by a yin yang coil pair, and a yin yang makes a minimum-B field. In MARS, the double-fan is formed with a yin yang in the transition (the plug is also a yin yang) and plasma pressure is put in this region by ICRH to heat the ions there. This pressure in a good curvature region adds to the stability provided by a hot electron pressure in the (good curvature) plug to give a configuration which will hold a central cell plasma having an average B of 40% in a 4.7 T field.

NEXT GENERATION TANDEMS

Following successful operation of MFTF-B LLNL would begin construction in FY 90 of the first phase of a Fusion Power Demonstration (FPD). Described elsewhere in these proceedings,⁽⁸⁾ FPD would be patterned after the current MARS design but with a shorter central cell. One of the attractive features of a tandem is that the physics and engineering can be developed on short machines to hold down costs. In FPD full scale MARS end plugs would be used with the full confining potential required for a reactor.

This theme of short central cells can be combined with another idea, the Kelly mode of operation, to allow very attractive upgrade options⁽⁹⁾ in

MFTF-B. For example, Logan⁽¹⁰⁾ has worked out operating scenarios for a short axisymmetric mirror cell (4 m in length) inserted in MFTF-B, a cell with a 4.5 T field and 12 T mirrors. By injecting beams into this cell, a hot, mirror trapped ion population is created--one which produces a fusion power density of $\sim 35 \text{ w/cm}^3$. Warm plasma at a density of $\sim 10\%$ of the hot ion density (this is the Kelley mode, the inverse of a two component mode that has a minority hot species) is confined by the plug potential at the ends of the tandem. MHD stability of the plasma in the insert section for average β values of 20% is also provided by the anchors in the tandem. This option has been termed MFTF-B+T.

With new MARS-like end plugs replacing those in MFTF-B, and with the same reactor insert, one can operate the upgrade in two different modes--a high Γ (wall flux) mode and a high Q mode. The high Q (~ 2) is possible because the new end plugs would have twice the field of MFTF-B and one would use a 200 kV sloshing beam to produce twice the potential of MFTF-B. This option, called MFTF- α T, is pictured in Fig. 3. In the high Γ mode the "reactor insert" would be beam driven by higher current than in MFTF-B+T to produce $\sim 55 \text{ w/cc}$ of fusion power (twice that in MARS). The higher power density than was quoted earlier is the result of a higher average β (40%) that is allowed by the better stability in the new end plugs.

These MFTF-B upgrade options using a reactor insert, with or without new end plugs, have been described in a recent LLNL report⁽¹¹⁾ and are described elsewhere in these proceedings⁽¹²⁾. Performance in these upgrades is summarized in Table 1, with FPD and MARS included for comparison.

SUMMARY

While the experimental basis for the tandem mirror is being pursued in TMX-U, TARA, MFTF-B, and other supporting facilities in the mirror program, new ideas for concept improvement are continually being sought. Preparations for a reactor engineering step in FPD are being made and options to upgrade MFTF-B for early support of such a step are being developed.

Table 1. Parameters in the reactor-like insert in MFTF-B Upgrades compared with central cell parameters in FPD (phase II) and MARS. Comparison is made on a 1 m length.

Parameter	MFTF-B+T	MFTF- α +T ^(a)	FPD-II ^(b)	MARS
Plasma radius(m)	0.15	0.15	0.54	0.49
Plasma density $\times 10^{14} \text{cm}^{-3}$	4.2	4.75	1.5	3.26
Average β (%)	20	31	47	28
Magnetic field (T)	4.5	4.5	2.5	4.7
Fusion power density (w/cc)	36.8	55.2	5.8	26.5
Fusion power (MW/m)	2.6	3.9	5.3	20.0
Wall loading (MW/m ²)	1.3	2.0	0.96	4.24
First wall radius (m)	0.25	0.25	0.7	0.6

(a) Parameters for high neutron flux mode.

(b) Conceptual design in early stages of definition. Parameters may change.

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FIGURE CAPTIONS

- Fig. 1. The "double-fan" transition regions developed by Baldwin and Bulmer for MFTF-B to minimize radial transport. A variation of this idea is used in the MARS reactor design.
- Fig. 2. Axicell magnetic configuration in MFTF-B. The end plug coils, starting from the right, are the two yin yang plug and anchor coils, two transition coils, and the 12 T and 6 T axicell coils.
- Fig. 3. MFTF- α +T, an upgrade of MFTF-B which uses improved MARS style end plugs and a reactor-like central cell insert. Operating on DT, it can reach $Q \sim 2$ in a physics mode and $\Gamma = 2 \text{ MW/m}^2$ in the insert in an engineering mode with ~ 10 hour experimental runs.

K. I. Thomassen - Figure 1

K. I. Thomassen - Figure 2

K. I. Thomassen - Figure 3