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PLASMA ENGINEERING CONSIDERATIONS FOR AN INSIDE-BARRIER TANDEM MIRROR TEST FACILITY

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Summary

The effects of technology limitations on the design of a tandem mirror, aimed at testing materials and pertinent reactor technology on a 1990's time scale, are presented. Parameters for a reference case device and parametric variation of some important quantities are exhibited. Particularly important considerations are magnetic field limits, neutral beam injection angles, ECRH and ICRH systems, alpha particle removal, fueling, and stability criterion.

Overview of an Inside-Barrier Tandem Mirror

The classical tandem mirror contains plasma in a solenoidal magnetic field which is electrostatically plugged in separate, minimum-B end cells. This idea was independently proposed by Fowler and Logan[1] and by Dimov, et al.[2] The plug electrostatic potentials are maintained by using neutral beam injection to drive plug density, n_p, much higher than central cell density, n_c, which gives a plug electrostatic potential, ϕ_c, since ϕ_c is proportional to the plug electron temperature, T_{ep}, times the log of the density ratio. Because fusion power is proportional to n_c^2, it is difficult to make an economical reactor based on the classical tandem mirror.[3]

Baldwin and Logan[4] then conceived the idea of the thermal barrier, a region between central cell and plug where the potential dips, thermally insulating plug electrons from central cell electrons. A relatively small amount of power is then needed to keep T_{ep}, and therefore ϕ_c, high. The potential dip in the barrier, ϕ_b, follows from a density depression caused chiefly by flux tube expansion and maintained by "pumping" out ions which become trapped in the barrier potential and would otherwise soon fill the dip. The most straightforward method of barrier pumping is by charge exchange off of a neutral beam injected into the barrier loss cone. The resulting ion joins the central cell population, while the resulting neutral quickly leaves the plasma. This method is applied here; evaluation of other pumping schemes is beyond the scope of this paper.

Generic axial profiles for magnetic field and electrostatic potential for an inside-barrier tandem mirror are shown in Fig. 1. A schematic view of the magnetic field coils and input power points is also given. Not shown is a low energy pump beam of 2 keV, 0.2 MW, injected slightly outside of the point of electron cyclotron resonance heating. This configuration is being used for TASKA[5], a joint tandem mirror engineering and materials test facility study by the University of Wisconsin and the Kernforschungszentrum Karlsruhe, FRG. Parameters for the TASKA reference case are given in Table 1. Specific details are discussed in sections to follow, but some general comments are in order.

The goal of the TASKA study is to model a tandem mirror test facility on the 1990's time scale. To this end, technology is required to be either in hand or available with moderate development. The chief exception is that plug neutral beams are assumed to utilize negative ion technology to achieve 250 keV energies for protons; this will require a major developmental program. Cost goals are set at approximately $750 million capital costs; the main impact of this goal on plasma engineering is to restrict total input power to the order of 100 MW. Neutral beams and ICRH are costed at $2/watt while ECRH is costed at $5/watt. A trade-off exists between neutron wall loading and input power, as shown in Fig. 2. A wall loading of 1.5 MW/m^2 is taken as a reasonable value for materials testing.

Other configurations besides the inside-barrier tandem mirror are under investigation by various people. The TMX-U[6] experiment will use a configuration where the plug and barrier are in the minimum-B cell and the MFTF-B[7] experiments will use A-cell configuration; both of these will use sloshing ion distributions. We restrict our investigation to the inside-barrier cases.

Magnets

Magnets are limited by both technology and cost considerations. In general, superconducting magnets are required in order to avoid prohibitive powers for running the magnets. A schematic view of the magnet

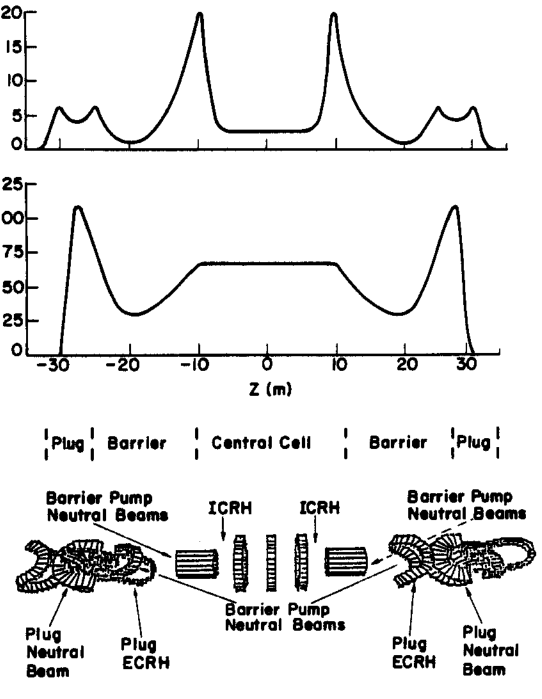

Figure 1 Axial profiles of magnetic field and potential, plug coil configuration and power deposition.

Table 1

Machine, Power, and Plasma Parameters for the Reference Case. These were used in the TASKA base case.[5]

CC wall load	1.52 MW/m^2
Fusion power	86 MW
Total input power	117 MW
Elect. line power	164 MW
Central cell length	19 m
Central cell wall radius	0.46 m
Central cell plasma radius	0.32 m
Barrier length	14.5 m
Maximum barrier plasma radius	0.50 m
Plug length	5.1 m
Plug midplane plasma radius	0.28 m
Neutral Beams	
Plug: power	5 MW
Energy	250 keV
Angle	60°
Species	p
Barrier: power	50 MW
Energy	50 keV
Angle	25°
Species	D/T
Barrier: power	7 MW
Energy	76 keV
Angle	20°
Species	D
Barrier: power	0.2 MW
Energy	2 keV
Angle	45°
Species	D
ECRH	
Plug: power	15 MW
Frequency	56 GHz
ICRH	
CC: power	40 MW
Frequency	21 MHz

Table 1 (Column 2)

Magnetic Fields	
Central cell	2.7 T
Barrier Maximum	20 T
Barrier minimum	0.8 T
Plug maximum	6.25 T
Plug minimum	4 T
Plasma Parameters	
Central Cell	
Density	$1.9x10^{14}cm^{-3}$
Ion temperature	30 keV
Electron temperature	11.5 keV
Potential, ϕ_e	66 keV
Beta	0.5
Barrier	
Minimum density	$6.8x10^{12}cm^{-3}$
Potential, ϕ_b	38 keV
Beta	0.05
Plug	
Density	$6.3x10^{13}cm^{-3}$
Avg. ion energy	388 keV
Electron temperature	59 keV
Potential, ϕ_c	43 keV
Beta	0.64
Ion species	p

design for an inside-barrier tandem mirror is shown in Fig. 1. Three superconducting central cell solenoids, giving an average field on axis of 2.7 T, are used. Since barrier pumping power varies approximately as n_b^2, and barrier density, n_b, varies as 1/B because of flux tube expansion, supplementing the peak barrier field by a few Tesla, added through a copper insert in the superconducting barrier coils, is a useful technique for reducing the required neutral beam power. For the reference case, about 15 MW per coil in the copper inserts adds 6 T to the peak field, giving an overall power savings on the order of 80 MW. The superconducting part of the coil provides 14 T to give a peak field of 20 T.

A transition coil is then used to map the circular flux tube into the minimum-B configuration generated by the Yin-Yang set. The Yin-Yang magnets are limited by coil forces to a peak field on the coils of about 8 T. This translates to an on-axis maximum of about 6.25 T. Now, for a given operating point, there tends to be a maximum allowable value for the ratio n_c/n_p in order to satisfy relationships between potentials and temperatures. A high plug minimum field is thus desirable, since fields and densities are related through limits on beta, the ratio of plasma pressure to magnetic field presure. For the reference case, a plug minimum field of 4 T has been chosen, giving a vacuum mirror ratio of 1.56.

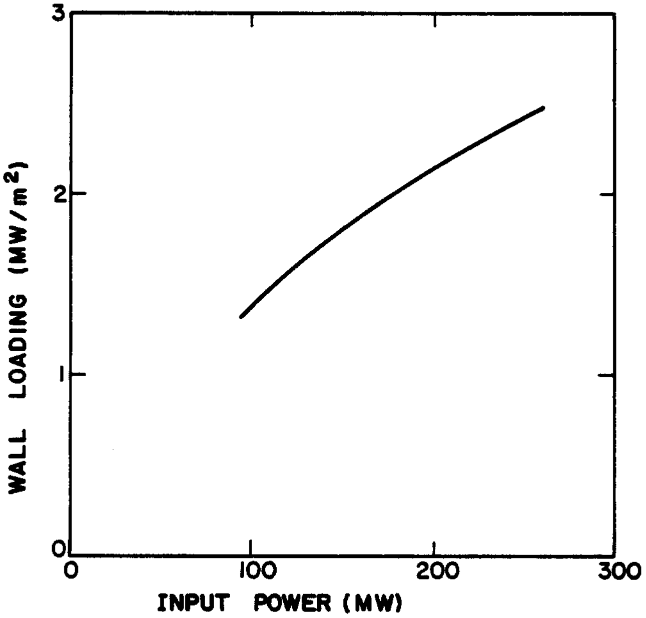

Figure 2 Trade-off between neutron wall loading and input power.

Neutral Beams

Three types of neutral beams are used to pump the barrier. Most of the pumping (97.5%) is done by 50 keV beams injected at 25° to the axis and aimed at a point where the barrier potential has dropped only 4 keV; the principle behind this beam is that it is most efficient to pump those ions which have just barely trapped. The ions which filter through and become trapped near the bottom of the potential wall are pumped in two stages: 1) A beam of 76 keV ions injected at 20° is aimed at the bottom of the barrier. The ions resulting from charge exchange and ionization move along the axis to a point about 5 keV above the central cell potential. 2) At that point, a 2 keV beam is injected; the resulting charge exchange ions have almost no perpendicular energy and thus simply fall down the potential hill with enough parallel momentum to reach the central cell, having felt little effect from the magnetic field.

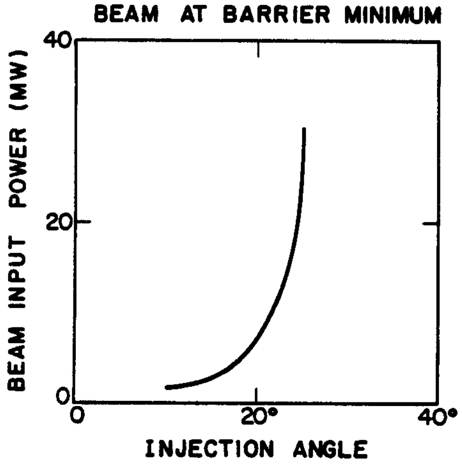

Figure 3 High energy barrier pump beam power versus injection angle.

Beams of these energies pose few problems in construction beyond development to steady state operation. Fitting the beams into the system at the required angles, however, is a difficult problem.[5] In particular, the beam at 20° at the bottom of the barrier has almost no flexibility in its operating point. Fig. 3 shows the variation of beam input power versus injection angle. Powers become prohibitive beyond 20°, while mechanical considerations limit the angle to at least 15° and, more conservatively, 20°.

The plug beam, 250 keV protons injected at 60°, will require a strong developmental program for negative ion technology. Present day neutral beam systems use positive ion technology, but this is limited to about 100 keV for protons. Deuterium or tritium could be used in the plugs, but this would increase the neutron source in the plugs and require more shielding and, therefore, size and cost for the Yin-Yangs. The 60° injection angle aids microstability, as discussed in that section.

Electron Cyclotron Resonance Heating

Maintaining the plug electron temperature necessary to give a high ϕ_c requires some auxiliary heating of plug electrons. The present front-running candidate for this task is electron cyclotron resonance heating (ECRH). For the reference case, this is assumed to be applied at the 2 T point on the plug side of the barrier. Since the plug electrons are essentially potential-confined, heating sufficiently far down the slope of the potential will heat the bulk of the electron population.

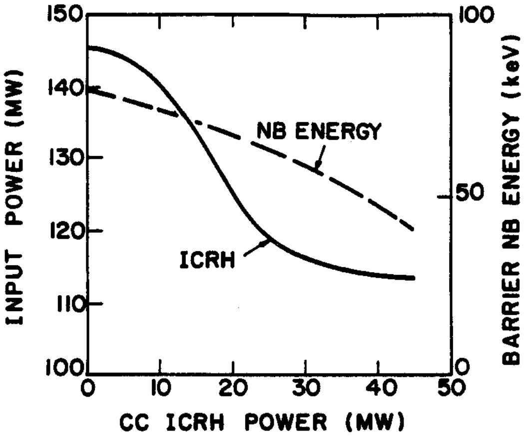

Figure 4 Total input power and main pump beam energy versus central cell ICRH power.

Development of steady-state gyrotrons for the high frequencies required for ECRH (56 GHz for the reference case) is in progress. High absorption efficiencies appear possible, but much theoretical work on the problem is still in progress.

The possibility also exists for using ECRH at the bottom of the barrier to create a hot, magnetically-trapped, barrier electron population. Since total electron density must equal ion density, the hot electrons reduce the total allowed passing electrons, requiring an enhanced ϕ_b. However, this use of ECRH mainly saves plug ECRH and, since the reference case uses only 15 MW of ECRH, the introduction into the barrier of one more source of free energy to drive microinstabilities does not seem justified.

Low ECRH power is desirable since the present estimate of capital cost is about $5/watt.

Ion Cyclotron Resonance Heating

Using ion cyclotron range of frequencies heating (ICRF) in the central cell takes the burden of satisfying central cell power balance from the barrier neutral beams which must also provide particle balance and pump the barrier. This allows flexibility in finding a good operating point and saves, for the reference case, about 30 MW of total input power, as shown in Fig. 4. In particular, using 40 MW of central cell ICRF replaces approximately 70 MW of 50 keV pump neutral beams, greatly easing the problem of fitting those beams into the system. The ICRF antennas, however, do create a problem in that they complicate the design of blanket modules and hinder accessibility. If the ICRF antennas must be placed very near the plasma, they may intersect a significant number of alpha particles and antenna surface heating may become a problem.

A major benefit of central cell ICRF is that it greatly eases the problems of plasma start-up. Because neutral beams are poorly attenuated by low density plasmas, start-up with neutral beams alone is very difficult. Central cell ICRF greatly facilitates the start-up process and will also be useful for control of the plasma burn.

Fueling

A fusion reactor will require fueling by gas puffing or pellet injection. Some fueling for a tandem mirror is also accomplished when the barrier pump beams undergo ionization. Because the reference case uses a large amount of barrier pumping relative to total fusion power, operating points can be found where ionization of the neutral beams does all of the fueling required. This negates the need for a major developmental program on this time scale, since pellet injection requires extremely high pellet velocities and the physics of both gas puffing and pellet injection in the reactor regime of temperatures is unclear.

Care must be taken also to avoid over-fueling by the neutral beams since this would build up plasma density and quickly cool the plasma.

Alpha Particles

A major problem for fusion reactors is the removal of alpha particle ash resulting from burn-up of deuterium and tritium. For a test facility, however, Q, fusion power/input power, is not required to be large. Indeed, the reference case is a highly driven system, with Q = 0.74. For this case, the central cell confining potential ϕ_c = 43 keV while the central cell ion (and thermal alpha) temperature T_{ic} = 30 keV. Although ion confinement increases with the charge of the ion, the low potential to temperature ratio and small fusion power (86 MW) give an equilibrium alpha particle population of only about 1% of the central cell density. This is not a significant fraction.

Questions remain, however, of the possiblility of the alpha particles accumulating in the barrier region. A possible scheme for pumping alpha particles using a charge exchange resonance between deuterium and helium has been proposed by Hamilton and Logan.[8]

MHD Stability

Tandem mirrors are designed for average minimum-B MHD stability. That is, good curvative overcomes bad curvature in an average sense when plasma pressure weighting is taken into account.

A central cell beta (plasma pressure/magnetic field pressure) of β_c = 50% has been chosen for the reference case. Large beta is desirable since efficient use is then made of the magnetic field available. Present thinking tends to place maximum beta limits at about 70%, set by the interchange mode. Zero Larmor radius ballooning mode theory give beta limits of only about 20% for the referene case configuration, but finite Larmor radius effects raise this value above the interchange mode limit. We have chosen to be relatively conservative and taken the 50% value.

Microstability

Because the plug consists of ions magnetically confined while a potential tries to thrust them from the plug, the ion population is strongly peaked in $v_\perp$ and is far from a Maxwellian. Thus, sources of free energy exist which can drive modes termed microinstabilities. The most troublesome of these appear to be the drift cyclotron loss cone mode, the axial loss cone mode, and the Alfven ion cyclotron mode.[7]

For the reference case, the plug would be unstable if ions were simply injected perpendicular to the magnetic field. Therefore, we inject at about a 60° angle which gives the bulk of the plug ions trajectories which bounce at points away from the plug midplane. This sets up a "sloshing ion" distribution and, therefore, a dip in potential at the midplane of the plug. If relatively cool ions fill this dip, either from RF diffusion or by beam injection, the ion distribution will be much closer to a Maxwellian and a microstable operating point should be attainable.

Work on the problem is in progress, and we rely on this method for microstability of the plugs.

Conclusions

A tandem mirror can make an excellent materials and technology testing device on the 1990's time scale. The chief development needs are the high field superconducting/copper hybrid coil, gyrotron source for ECRH, and steady state positive and negative ion neutral beams. The primary physics uncertainties are the use of the sloshing ion plug to achieve plug microstability, the operation of the thermal barrier, and strong heating by ECRH and ICRF. Some aspects of all of these will be tested in various tandem mirror and tokamak experiments in the 1982 - 1986 period. If the results are positive, then there will exist a good experimental physics basis for proceeding with TASKA.

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