REACTOR ISSUES FOR TANDEM MIRRORS OPERATING IN THE NEGATIVE POTENTIAL MODE

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INTRODUCTION

During 1985, interest has been revived at LLNL in tandem mirrors operating in the negative-potential mode. The negative tandem is formed by combining ECRH-sustained hot electron and cell plasmas with pumping mechanisms to remove trapped ions from the end cells. No sloshing ions are required. The resulting negative potential in the end cells confines the central cell electrons. The requirement of charge neutrality causes the ambipolar potential of the central cell to become negative relative to the end wall (hence, the name "negative" tandem mirror), thereby providing central cell ion confinement. This potential distribution is shown later in Fig. 5(a) and is the exact inverse of the axial distribution for the conventional (positive) tandem mirror without thermal barriers. In the negative tandem mirror, central cell electrons are confined electrostatically, end cell electrons are confined magnetically, and ions are confined electrostatically everywhere. In this report, we briefly assess the reactor issues pertinent to the operation of the tandem mirror in the negative mode.

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Before proceeding with the negative tandem mirror, it is instructive to briefly review MINIMARS, a tandem mirror reactor with thermal barriers operating in the positive mode.^{2,3} MINIMARS is a small compact machine with octopole end plugs, having a net electric output in the range 250-600 MW_e. A cross-section of the interim baseline design at 30 MW_e is shown in Fig. 1. A schematic of the plasma/magnet configuration is shown in Fig. 2, while a corresponding axial distribution of the magnetic field and plasma potential is shown in Fig. 3. MHD stabilization is achieved by means of the octopole coil and a mirror-confined hot electron mantle surrounding the end cell plasma.⁴ The coil set is shown in Fig. 4. Table 1 lists the principal operating parameters for MINIMARS at 600 MW_e.

It is important to note from Fig. 2 that, although the octopole plug results in a small compact reactor, there are a number of systems which must be integrated into the compact plug region for this positive mode tandem. These systems include two drift pump coils,⁵ a sloshing ion neutral beam, a barrier ECRH system, a potential peak ECRH system, and a mantle ECRH system. Accordingly, in view of the requirement for the perception of "simplicity" for future fusion reactors, important advantages for the negative-mode of operation would be evident if it allowed us to reduce or eliminate some of this complexity in the end cells.

⁵or, possibly, a single coil system with multi-frequency capabilities.³

FIG. 1. MINIMAR-1: A Fusion-Mission Reactor with net power gain, and the use of the positive potential mode.

Fig. 2. A schematic of the end cell plasma/magnet configuration for a positive mode tandem mirror reactor. The complexity of systems integration is evident.

Fig. 4. Axial distribution of magnetic field (B_z) and electrostatic potential (ϕ) for an axisymmetric positive-mode tandem mirror reactor. The potential distribution should be compared with that for the negative-mode of operation shown in Fig. 5(a) and (b).

Fig. 4. A typical octopole end cell magnet set for MINIMARS. A negative-mode tandem has the same MHD stability requirements.

Table 1. Principal physics parameters for MINIMARS at 600 MW₀
(interim baseline, Oct. 1991)^a

<u>General</u>	
Fusion power (MW)	1237
β	33.6
Neutral wall loading (MW/m ²)	3.88
Cost of electricity (mills/kWhr)	-34
Mass utilization (kg ₀ /tonne)	-104
<u>Magnetic fields</u>	
Central cell (T)	3.46
Choke coil (T)	24.0
End cell midplane (t)	24.0
Outer mirror (T)	3.98
<u>Central cell</u>	
Length (m)	30
Plasma radius (m)	0.367
Ion temperature (keV)	26.7
$\langle \alpha \rangle$	0.6
<u>End cell</u>	
$\langle \beta \rangle$	0.333
Core BORH power ^b (MW)	15.5
Mantle BORH power ^b (MW)	19.9
NBI power ^b (MW)	1.35
α_0 (keV)	147
α_1 (keV)	-192
α_2 (keV)	-158

^aAbsorbed, both ends.

ADVANTAGES OF THE NEGATIVE MODE

The reactor advantages of the negative mode over the positive mode are as follows:

1. **No sloshing ion beam required.** Since plug sloshing ions are not required in the negative tandem,¹ we have no need for a high energy sloshing beam. This clearly reduces end cell hardware requirements and eases access constraints on other systems. Note from Table 1 that, in the positive mode, we require a trapped sloshing beam power of 1.35 MW, or accounting for trapping fraction, an injected power of ~ 7 MW. Thus, elimination of the beam has only a small effect on total reactor recirculating power requirements, but a large impact on end cell simplification.
2. **Sloshing ion adiabaticity criterion eliminated.** Adiabaticity of sloshing ions sets a lower limit on both the mirror-mirror length and the midplane field of the end plug in the positive-mode. Since there are no sloshing ions in the negative mode, we can further reduce the end cell volumes and fields, minimum values now being determined by passing ions having energies a factor of

$$= [E_{\text{slow}} + (4\pi \cdot 10^{-19} / (T_0 \cdot 4)) \cdot 4] = [425 + 833] / (27 + 332) = 3.2 \text{ lower.}$$

Reduction of end plug volumes and fields has two big advantages: First, the end cell core and mantle SCRH powers are reduced; from Table 1 we can see that this represents a large amount of recirculating

power. Second, the minimum length of the central cell for ignition is determined by the end cell volume; smaller end cell volumes mean that we can achieve smaller reactors more economically (see ref. 2 for further discussion of this).

3. **No potential peak required.** The negative mode of operation does not require the maintenance of a potential peak by way of an ECRH-sustained warm electron distribution. This saves on the hardware and complexity of one plug ECRH system. Unfortunately, the power required for the warm electron distribution is small (typically $< 10\%$ ^{*}) compared with that for either the hot barrier electrons or the hot mantle electrons, so this represents only a small saving on recirculating power or system Q. We should also note here that some form of ECRH-sustained warm electron feed may be needed in the negative mode (see next section), which would mean that we have eliminated one ECRH system only to replace it with another.
4. **No pumping of deeply trapped sloshing ions required.** In the positive mode of operation, we have to provide for drift pumping of two species of trapped ions in the end cell, namely: (i) passing ions which pitch angle scatter in the end cell and become trapped between the choke coil magnetic field peak and the potential peak; and (ii) sloshing ions which become deeply trapped at the bottom of the barrier. This pumping can be effected either by two distinct drift pump coils or one coil displaying multiple frequencies tuned to the bounce frequencies of the

^{*}This assumes that there are no cold electron sources at point "a".

different species. In the negative mode, we have no sloshing ions and thus require only one drift pump for the ions which trap from the central cell passing population. This considerably simplifies the coil system design. Although we still have to remove deeply trapped central cell ions from the bottom of the barrier, it should be noted that one coil located over a relatively narrow region of B may be sufficient to pump the whole region,⁵ i.e., uniform pumping throughout the end cell may not be required.

DISADVANTAGES OF THE NEGATIVE MODE

Disadvantages of the negative mode of operation compared with the positive mode are:

1. **Warm electron feed to hot population.** Hot electrons at the potential minimum will probably be sustained by ECRH at the second harmonic.⁶ Since the potential is at its maximum negative value, any cold electron feed from the central cell will be effectively cut off. Accordingly, an ECRH-sustained feed of warm electrons may be required on the central cell side of the minimum. This may require a separate ECRH system analogous to the potential peak ECRH system on the outboard side of the positive mode operation. Besides requiring extra hardware, the warm electron feed ECRH system would be located in the same region envisaged for placement of the drift pump coils in MINIMARS and may cause a

⁶ This will not be the case if strong ECRH models (and, therefore, very high ECRH powers) apply - see 4. below.

possible interference problem. However, in view of the fact that the ion-confining potential rise occurs nearer the outboard mirror than in the positive mode, we may be able to position the drift pump coil on the outboard side of the potential minimum. One ameliorating effect on the requirement for the warm electron feed is the possibility of cavity-mode heating. Reflection and subsequent reabsorption of the second harmonic ECRH on the inboard side of the potential minimum at a field value corresponding to the fundamental, may provide sufficient warm electron feed to the hot population.

2. **Longer (in z) or deeper (in ϕ) distribution of hot electrons.** A longer axial extent of the hot electron distribution may be required in the negative mode.¹ A longer hot electron distribution clearly implies more volume, and therefore higher ECRH powers. However, this increase may be ameliorated for two reasons: (i) negative mode end cells can be shorter in total length (see above); (ii) the flux tube necks down as it approaches the mirrors, so an increase in axial length of the distribution is not matched by a proportional increase in volume. In addition, it is suggested¹ that, for TMX-U at least, a deeper potential well would be required compared with the thermal barrier in the positive mode, since the former is the only electron confining potential in the machine. Deeper wells imply greater ECRH powers and harder pumping requirements. Now for MINIMARS in the positive mode, ϕ_0 is almost as large as ϕ_e (~ 132 keV compared with ~ 158 keV - see Fig. 2); therefore, we would not expect a significant increase in the

equivalent ϕ_p in the negative mode. We might expect then that overall core ECRH powers in the negative mode will be less than or of the same order as those in the positive mode (see, however, 4. below).

3. **Higher plug beta.** If enhanced potential minima are required compared with the positive mode (see above), then the higher $T_{e, \text{plug}}$ will result in higher plug betas. This has two implications: (i) larger beta-depression of the radial field profile across the plug, resulting in a changing resonance zone with radius; (ii) higher mantle beta for MHD stabilization of the pressure-weighted bad curvature in the plug.
4. **Strong ECRH heating characteristics in plug.** In the negative mode, we lack the outboard electron confining potential ϕ_p present in the positive mode. Accordingly, second harmonic heating of the hot distribution in the strong ECRH limit leads to all heating characteristics connecting to the loss boundary, with the result of very large ECRH losses. Clearly, a reactor would not be viable under these circumstances due to the prohibitive ECRH power required.

Accordingly, the ECRH heating characteristics in this region certainly require further investigation before any conclusions can be drawn. Indeed, this is probably the most significant outstanding issue for the negative tandem. Heating at the fundamental at the inboard feed point might be a possible solution to this problem.

5. **Loss of direct converter.** In both the positive and negative mode of operation, the dominant loss of ions occurs through trapping and subsequent drift pumping in the end cell. The resulting induced radial transport moves pumped ions out to the unplugged halo where they are

swept to grounded halo dumps at the ends of the machine. We can recover the ion thermal energy at some low efficiency (20-30%) by using the end dump coolant water as feedwater heating to the main steam cycle. By contrast, although the electron loss in both modes of operation is axial, it is here that the difference can be seen in the two modes. In Fig. 2 we can see that for the electron to be collected axially at the end of the machine in the positive mode, it has to climb through a high negative potential ϕ_e . We can, therefore, directly convert the electron kinetic energy ($T_e + \phi_e$) to electric potential energy at some reasonably high efficiency (~ 63%⁵). In the negative mode, however, the opposite is true [see Fig. 5(a)], i.e., the electrons fall through some reasonably large positive potential ϕ_{co} which means that only thermal conversion to electric power is possible, with its attendant low efficiency.

One possible solution to the negative mode direct converter is shown in Fig. 5(b). Here, the end cell potential ϕ_{co} is maintained not by the end wall plate as it is in the normal mode of operation in Fig. 5(a), but by a grid which is more or less transparent to electrons. The end wall plate can then be positioned beyond the grid and biased at ϕ_e , where $\phi_e = \phi_b + \delta\phi$ and where $\delta\phi$ is small. The large fraction of electrons (> 95% by suitable grid design) which pass through the grid can then be collected by the end plate with direct conversion of a significant fraction of their kinetic energy. The big problem here is the electron power density on the grid wires. A simple

Fig. 5(a). Axial field (B) and potential (ϕ) distributions for a negative-mode tandem with no direct conversion.

Fig. 5(b). Potential distribution for a negative-mode tandem reconfigured with a potential control grid for direct conversion.

calculation for MINIMARS yields, for 95% transparency, a grid power density of $\sim 4\text{--}8 \text{ kW/cm}^2$ which presents a formidable heat transfer problem (see, for an analogous situation, the MARS Interim Design Report).⁷

An estimate of doing away with direct conversion and operating with the conventional negative configuration shown in Fig. 5(a), allowing only thermal conversion of electron end loss power, shows that the cost of electricity for MINIMARS would rise by $\sim 10\text{--}15\%$, i.e., an appreciable penalty.

CONCLUSIONS

In conclusion, without a more detailed study, we certainly cannot make a clear case for the superiority of the negative mode tandem mirror reactor.

Advantages relative to the positive mode are: (a) a reduction in end cell volume; and (b) a reduction in end cell systems (i.e., neutral beams and ECRH injection requirements) providing we can sustain the potential minimum without deleterious increases in ECRH power. The disadvantages include: (a) the large uncertainty in ECRH heating powers due to the validity of the strong ECRH model when so many characteristics intersect the loss region; and (b) the loss of the electron direct converter or, alternatively, the reconfiguration to a significantly larger gridded structure. Certainly, a successful near term experiment in the negative mode will serve to stimulate considerable interest in further study of a negative-potential tandem mirror reactor.

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