UCRL--86845

DE82 004762

UCRL- 86845
PREPRINT

CONF - 811203 -- 5

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This Paper was Prepared for Submittal to
2nd Workshop on Hot Electron Ring Physics,
San Diego, CA
December 1 - 3, 1981

November 30, 1981

Lawrence Livermore National Laboratory

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ABSTRACT

A tandem mirror configuration can be created by combining hot electron end cell plasmas with neutral beam pumping. A region of large negative potential formed in each end cell confines electrons in the central cell. The requirement of charge neutrality causes the central cell potential to become negative with respect to ground in order to confine ions as well as electrons. We discuss the method of producing and calculating the desired axial potential profile, and show the calculated axial potential profile and plasma parameters for a negative configuration of TMX-Upgrade.

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*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

1. THE NEGATIVE TANDEM CONFIGURATION

1.1 SIMPLE TANDEMS

The tandem mirror machines confine plasma in a large volume central cell by creating a difference in potential between the central cell and small volume end cells. In TMX,[1] it was shown that a mirror confined ion population in each end cell produced an end cell potential that was positive with respect to the central cell. Ions were therefore confined in the central cell, and the plasma potential of the central cell was positive in order to confine electrons equally as well as ions.

The negative machine is also possible, i. e. a machine in which end cell electron rather than ions are mirror confined. This option has been considered earlier by Fowler. In this machine, the hot electron density in the end cells exceeds the central cell density; since the lifetime of the end cell electrons is enhanced by mirror confinement, the end cell plasmas develop a negative potential in order to enhance the ion lifetime by potential confinement and maintain charge neutrality. It was found, however, that the central cell to end cell potential difference required to confine central cell electrons demanded that the density difference between the central cell and end cells be large. As a consequence, the end cell density was found to be excessive in terms of power loss and required microwave frequencies.

1.2 PUMPED TANDEMS

A later development enabled the construction of a large negative end cell potential without employing hot electron end cell plasmas much denser than the central cell. It was found that if ions were removed (pumped) at a sufficient rate from the region of the mirror confined, hot electrons, a large negative potential could be produced even in end cell plasmas having densities less than the central cell density.[2] The negative potential develops as a response of the plasma to maintain charge neutrality in the end cells. Thus, if the end cell electron lifetime is enhanced by mirror confinement, and ions are removed from the end cells by a pumping mechanism described below, the loss of ions by scattering from the region is reduced by the formation of a deep potential well untill the charge flows are equal. This mechanism can be employed to create the thermal barrier for positive tandems,[3] and it can be employed to create the electron confining potential of a negative tandem mirror. An example is shown in Fig. 1.

One method of pumping ions out of a potential well is by passing a beam of energetic neutral atoms through the plasma. If the conditions for magnetic and potential confinement are not satisfied for ions that are produced by charge exchange of the neutrals with potential trapped ions, the net effect is the removal of trapped ions from the potential well. The neutrals that are produced by neutralization of the trapped ions escape the plasma across the field lines.

The density of the end cells in which the negative potentials are located can be substantially less than the density of the central cell. It is this feature that makes the negative tandem attractive from the point of view of making a fusion reactor. The lower density of the hot electron end cell plasma decreases the power and frequency requirement for the microwave heating. In the experimental design discussed below, the density of the hot electron plasma is less than the central cell plasma. Increasing the end cell mirror ratio and decreasing the ratio of the thermal electron temperature to the ion temperature further decreases the end cell density and the ECRH power requirement.

2. AXIAL POTENTIAL PROFILE AND CONFINEMENT

2.1 DETERMINATION OF THE POTENTIAL PROFILE

The axial confinement of the negative tandem is determined by the confinement of the thermal central cell electrons by the negative potential in each end cell. The shape and magnitude of the axial potential is determined by the quasi-neutrality requirement and the dependence of the ion and electron densities on the electrostatic potential and the magnetic field. In calculating the axial potential profile, it is convenient to identify four separate populations of ions and electrons:

a. Thermal, Maxwellian ions in the central cell having temperature T_i; this population flows through the inner mirror into the low potential region of each end cell, is reflected, and returns to the central cell. This is the passing ion population, with a local density n_p depending on both the potential ϕ and the magnetic field B.

b. A fraction of the passing population becomes trapped by collisions in the end cell potential well. This is the trapped ion population. Its local density n_T depends upon the potential ϕ, the magnetic field B, the temperature T_i, and the rate of removal ν of the trapped ion population from the well. It is the dependence of this population on the pumping strength ν that enables the formation of large negative potentials in end cell regions with densities less than the central cell density. The dependence has been found through extensive Fokker-Planck calculations[4] and has been modeled in analytic form.[5]

c. The thermal electron population, assumed to be Maxwellian with temperature T_e within the regions of potential confinement. Outside of this region, the electrons accelerate rapidly, and their density decreases and becomes negligible compared to the mirror confined electron density.

d. The mirror confined electron population, with density n_H assumed to depend only on the magnetic field strength.

The functional dependence, except for the electron and ion temperature, can be written

$$n_H(B) + n_e(\phi) = n_p(\phi,B) + n_T(\phi,B,\nu)$$

It is seen that the potential ϕ is a function of the magnetic field and the pumping strength ν. The axial distribution of the electrostatic potential $\phi(z)$ is obtained through the axial distribution of the magnetic field intensity B(z). The axial profile shown in Fig. 1(a) and (b) are similar to those of TMX-Upgrade. The magnitude relative to the central cell of the positive potential near the outer mirror points is determined by requiring the loss of ions to equal the total outflow, thermal and hot, of electrons. The axial loss of thermal electrons is determined by a Pastukhov relation.[6] The ion loss is the sum of Pastukhov loss, radial transport, and pumping losses. The density profiles of ions and electrons are shown in Fig. 2 and 3, respectively.

2.2 TMX-UPGRADE PARAMETERS

The TMX-Upgrade confinement device can be operated in a "negative" mode. This mode employs the pumping beams and central cell heating beams only, with no sloshing beams. The calculations are done for an axial $(n\tau)_p = 10^{12}$ cm^{-3} s. The plasma parameters are given in Table I. Cases A and

B correspond to different estimates of the radial transport. Case C shows the effect of heating the central cell plasma with ICRH rather than neutral beams. A diagram of the power flow is given in Fig. 4. We note that the axial $(n\tau)_p$ can be increased considerably by increasing the depth of the electron confining potential. This can be accomplished by increasing the neutral beam pumping or increasing the end cell mirror ratio.

3. SUMMARY

Our calculations show that an effective tandem mirror confinement configuration with hot electron end cell plasma densities of 2 to 5 x 10^{12} cm^{-3} can be constructed. Two primary issues in the design of an experiment or a fusion reactor are discussed elsewhere in this workshop: (1) The power required to support the hot electron density, and (2) the MHD stability of the plasma. Initial analysis of both the microstability[7] and MHD stability[8] is encouraging, and detailed work is in progress.

4. ACKNOWLEDGMENT

We acknowledge the work of G. Logan, T. K. Fowler, and D. Baldwin in conceiving the ideas and doing much of the detailed work, and F. H. Coensgen for initiating this work.

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Table I. TMX upgrade parameters.

Parameter	TMX-U (positive)	TMX-U (negative)		
	Thermal barrier (reference case)	Case A	Case B	Case C
Central cell				
Density, n_c (10^{12} cm^{-3})	23	20	16.4	10.6
Ion density, n_{ic} (bulk) (10^{12} cm^{-3})	16.7	10.6	10.6	10.6
Ion temperature, T_{ic} (keV)	0.90	1.0	1.0	1.0
Electron temperature, T_{ec} (keV)	0.60	0.45	0.43	0.24
Beta, β_c ($\perp$)	0.25	0.18	0.12	0.05
Ion confining potential, ϕ_i (keV)	2.2	2.5	2.5	2.5
Electron confining potential, ϕ_e (keV)	2.6	2.4	2.4	1.3
Axial confinement, $(n\tau)_{c\parallel}$ (10^{11} cm^{-3} s)	10	10	10	10
Radial confinement, $(n\tau)$ (10^{11} cm^{-3} s)	5	2	∞	∞
Beam ionization fraction, f^c_{ion}	0.15	0.13	0.11	-
Beam charge-exchange fraction, f^c_{cx}	0.30	0.28	0.22	-
Beam current, I^c_{beam} (incident) (A)	180	162	107	-
Gas feed, I_{gas} (H equiv.) (A) (ionized)	42	67	35	46
ICRH power (absorbed) (kW)	-	-	-	250
Plugs (per plug)				
Density, n_p (10^{12} cm^{-3}) (at electron feed)	7	7	7	7
Confinement, $(\tau n_a)_p$ (cx) (10^{10} cm^{-3} s)	5	-	-	-
Perpendicular beta, $\beta_\perp$	0.33	0.32	0.32	0.32
Parallel beta, $\beta_\parallel$	0.01	0.08	0.08	0.08
Barrier electron energy, E_{eh}(b) (keV)	50	50	50	50

FIGURE CAPTIONS

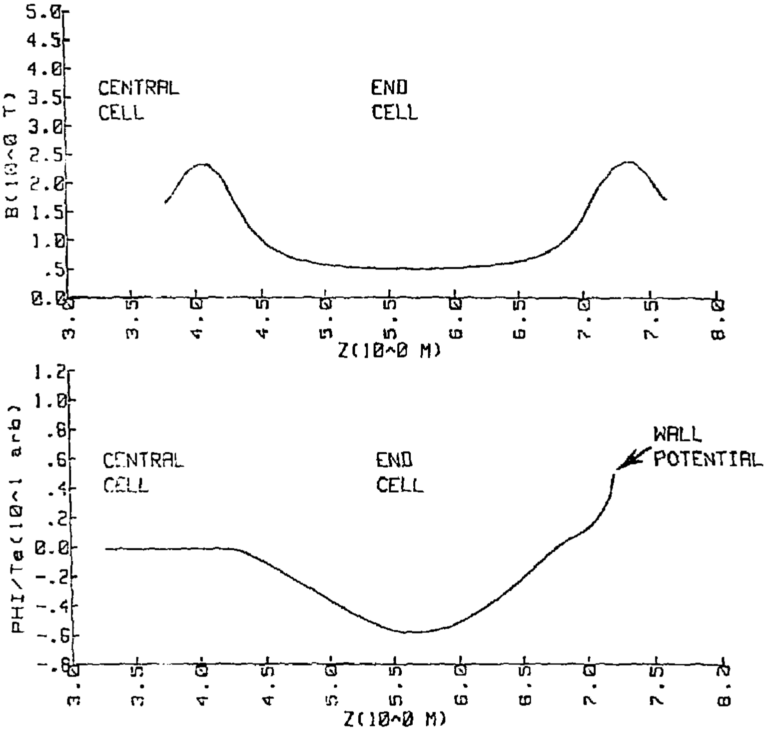
Fig. 1. Axial profiles of magnetic field (top figure) and electrostatic potential (bottom figure). The field and potential models TMX-Upgrade operated in a negative mode.

Fig. 2. Axial profiles of n_p, the density of passing ions in the end cell, originating from the Maxwellian central cell ion population (top figure), and n_T, the density of ions trapped in the potential well as a consequence of ion-ion collisions (bottom figure).

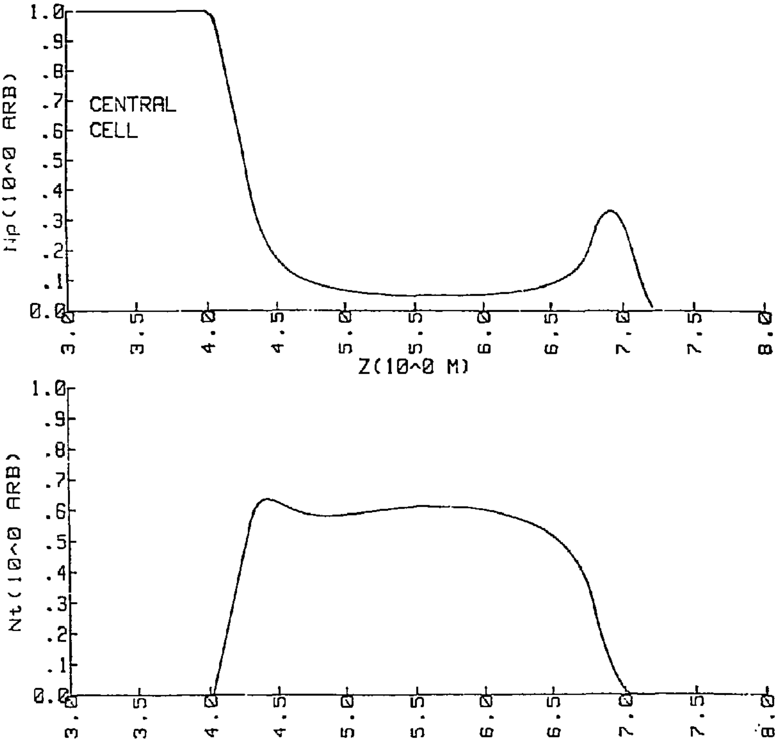
Fig. 3. Axial profiles of n_e, the density of Maxwellian electrons confined between the low potential end cells (top figure), and n_H, the density of energetic, mirror confined electrons in the end cell (bottom figure).

Fig. 4. The power flow in TMX-Upgrade operated in the negative mode (corresponds to Case A, Table I).

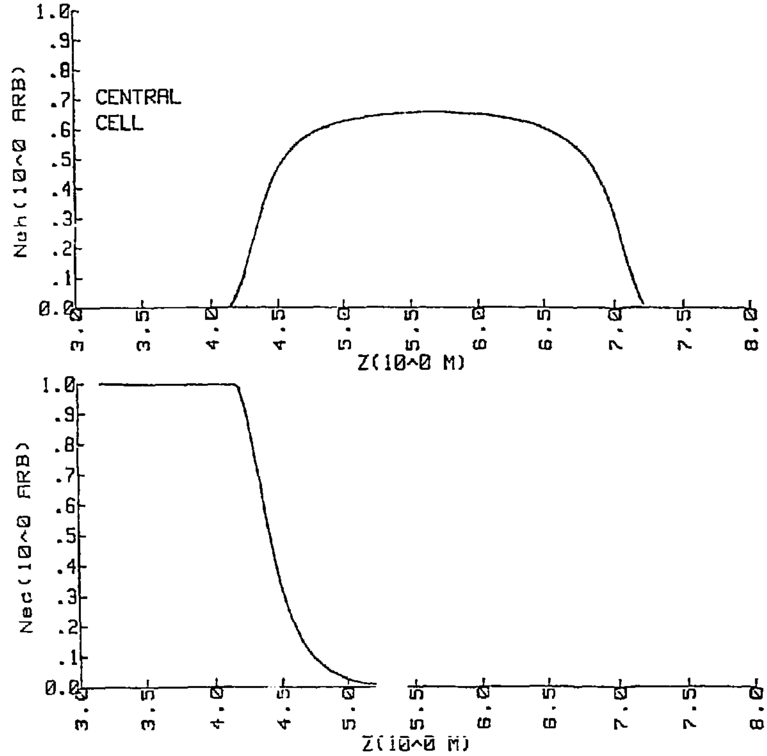
Poulsen et al. - Fig. 1



Poulsen et al. - Fig. 2



Poulsen et al. - Fig. 3



Poulsen et al. - Fig. 4