γ

UCRL-84221
PREPRINT

CONF-800409--5

INITIAL RESULTS OF THE TANDEM MIRROR EXPERIMENT (TMX) AT THE LAWRENCE LIVERMORE LABORATORY

MASTER

D. P. Grubb, C. A. Anderson, T. A. Casper,
J. F. Clauser, F. H. Coensgen, D. L. Correll,
W. F. Cummins, J. C. Davis, R. P. Drake,
J. H. Foote, R. J. Fortner, A. H. Futch,
R. K. Goodman, G. A. Hallock, R. S. Hornady,
A. L. Hunt, C. V. Karmendy, B. G. Logan,
R. H. Munger, W. E. Nexsen, P. Poulsen,
T. D. Rognlien, T. C. Simonen, D. R. Slaughter,
B. W. Stallard, O. T. Strand

This paper was prepared for inclusion in the Proceedings of the International Conference on Plasma Physics--1980, to be held at the Institute of Plasma Physics, Nagoya University, Nagoya, 464 Japan, April 7-11, 1980

April 2, 1980

Lawrence Livermore Laboratory

Initial Results of the Tandem Mirror Experiment (TMX) at the Lawrence Livermore Laboratory*

D. P. Grubb, C. A. Anderson, T. A. Casper, J. F. Clauser, F. H. Coensgen,
D. L. Correll, W. F. Cummins, J. C. Davis, R. P. Drake, J. H. Foote,
R. J. Fortner, A. H. Futch, R. K. Goodman, G. A. Hallock,† R. S. Hornady,
A. L. Hunt, C. V. Karmendy, B. G. Logan, R. H. Munger, W. E. Nexsen,
P. Poulsen, T. D. Rognlien, T. C. Simonen, D. R. Slaughter,
B. W. Stallard, and O. T. Strand**
Lawrence Livermore Laboratory, University of California
Livermore, California 94550 USA

Abstract: Initial experimental results from the Tandem Mirror Experiment (TMX) are presented. Axial profiles of the plasma density and potential necessary for electrostatically enhanced confinement of the central-cell ions have been generated and sustained for the duration of neutral-beam injection. The resulting central-cell ion confinement against axial loss is improved by a factor as large as 9 above that given by magnetic confinement alone. The plasma exhibits gross magnetohydrodynamic stability and microstability. Under some conditions, a residual level of ion cyclotron fluctuations in the end cells heats the central-cell ions and degrades their confinement.

1. Introduction

The Tandem Mirror Experiment (TMX) at Lawrence Livermore Laboratory (LLL) was designed[1] to test the principle that an axial electrostatic well could be created in a linear mirror experiment which would significantly improve the axial confinement of the ions in that well above that provided by a magnetic mirror alone. This "tandem mirror" concept was proposed independently by Dimov[2] and Fowler and Logan.[3] In the devices proposed by these authors, a high-density plasma is sustained in a minimum-B magnetic well at each end of a

---

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

†Renssalear Polytechnic Institute, Troy, New York 12180.

**Johns Hopkins University, Baltimore, Maryland 21218.

lower density, solenoidal, central-cell plasma (Fig. 1). Due to its higher density, the plasma in the minimum-B mirror rises to a higher ambipolar potential than that of the central cell. In this fashion, a potential well of depth

$$\phi_c = T_e \ln \left(\frac{n_p}{n_c}\right) \tag{1}$$

forms, where T_e is the electron temperature, n_p is the density in the minimum-B mirror, and n_c is the density in the central cell. These end cell plasmas ("plugs") are also necessary to provide pressure-weighted, average minimum-B stability to the tandem device.

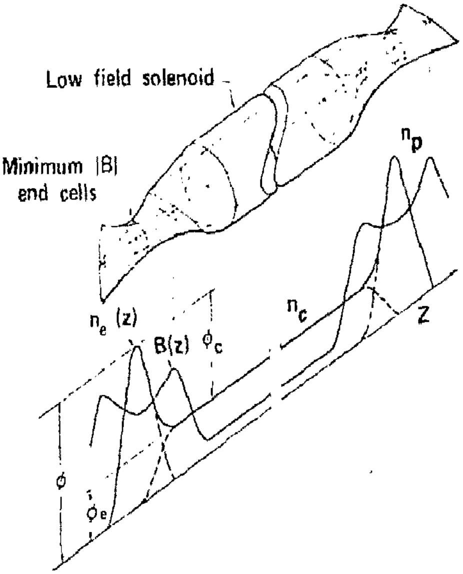


Fig. 1. Tandem mirrors with ambipolar barriers at the ends.

Early experiments in the Gamma-6 device at Tsukuba[4] used streaming-plasma guns to establish plugs with densities larger than those in the central cell and, thereby, to produce a potential well. Langmuir probe measurements indicated that the magnitude and scaling of the potential-well depth were consistent with theoretical predictions.

2. The TMX Device

TMX is shown schematically in Fig. 2. The vacuum chamber is 14 m long and 4.3 m in diameter. The vacuum is maintained by mercury charged diffusion pumps. For experiments, the pumping is augmented by sublimating layers of fresh titanium onto the walls and by filling baffles with liquid nitrogen. Nominal operating pressure is 2 x 10^{-8} Torr.

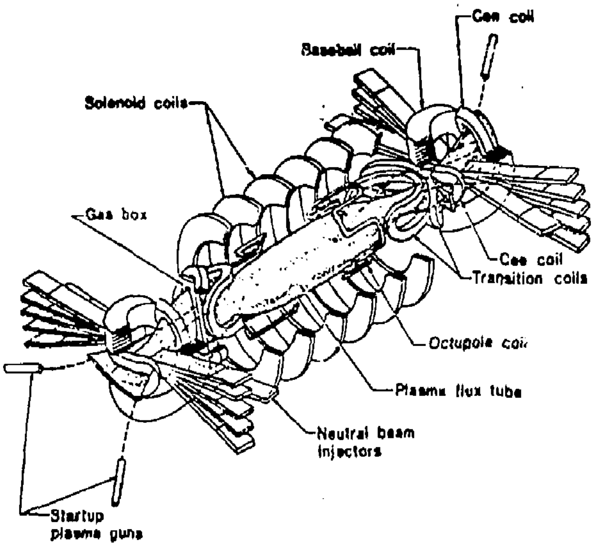


Fig. 2. The tandem mirror device: TMX.

The magnetic field is created by 18 water-cooled, quasi-dc (2- to 3-s duration) magnets. During the shot the currents in the coils are held constant by silicone-controlled-rectifier-switched power supplies. For the bulk of the data reported here, the plugs had a minimum field strength of 1.0 T with a 2:1 mirror ratio. The central-cell magnetic field was 0.1 T.

A total of 24 neutral beams is available for heating and fueling the end plugs. Nominally, 23 beams are distributed between the two plugs and one beam is used in the central cell for diagnostic purposes. Peak neutral-beam currents in excess of 200 equivalent atomic amperes per plug have been injected with an average accelerating voltage of 17 keV and a mean energy per atom of 13 keV. This corresponds to an injected power of 2.6 MW per plug. Of this, approximately 400 kW has been trapped in the end plugs.

The central cell of TMX is fueled by gas introduced on the plasma periphery either by gas boxes at each end of the central cell or by a puffer valve at the midplane of the central cell. The diagnostic neutral beam is aimed so that energetic particles from the beam are not trapped in the plasma.

3. Plasma Parameters and Electrostatic Confinement

The plasmas in TMX are generated as follows: the magnetic fields are sequenced on; then when the fields have reached a steady-state level, four startup plasma guns (Fig. 2) are fired for 5 ms to provide an initial target for the neutral beams. At this time, the beams are turned on and plasma begins to build up in the plugs. Approximately half way through the pulse from the streaming-plasma gun, gas is introduced into the central cell to create the central-cell plasma. At the time the gun is turned off, the central-cell plasma is well established and the loss-cone modes in the plugs are maintained at a marginally stable state by the warm plasma stream from the central cell. The plugs are sustained in this fashion for the duration of the neutral-beam pulse.

Table 1 presents maximum (i.e., not all from the same shot) plasma parameters and those for a typical shot. For comparison, the results from a self-consistent, classical, point model code for axial power balance, TAMRAC,[5] is shown for this shot. A factor of two agreement is obtained.

In Fig. 3(a) a sample axial density profile is shown. According to Eq. (1) the measured density ratio of factor three between the central cell and the plug with an electron temperature (in this shot) of 100 eV gives rise to a confining potential well depth of approximately 100 eV. The central-cell potential as measured by a heavy-ion-beam probe (HIBP) and the plug potential as determined from the energy spectrum of end-loss ions are shown in Fig. 3(b). Within the errors in the measurements, the well depth is 100 to 300 eV.

It is the existence of this potential well that enhances the confinement of the central-cell ions above that which would be achieved simply by flow-through magnetic mirrors alone. Mathematically, this relationship can be expressed as

TABLE I. Maximum TMX parameters and comparison of values obtained on a shot with those predicted by the Tandem Rate Code (TAMRAC).

Parameter	TMX maximum[a]	Shot 56 (3/26/79) TMX data	Shot 56 (3/26/79) TAMRAC[b] calculations
n_p (10^{13} cm^{-3})	4	2.5	-
j_{end} (A/cm^2)[c]	1	0.9	-
T_{ep} (eV)	260	140	105
n_c (10^{13} cm^{-3})	3	1.0	1.7
T_{ic} (eV)	250	52	29
ϕ_i (V)	100 to 300	128[d]	42
$n\tau_c$ (10^{10} cm^{-3}·s)	7	3.1	2.7
$n\tau_c/n\tau_{ii}$	9	2.9	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

[a] Deuterium; gas box; R_c = 0.1 [illegible].

[b] TAMRAC input: observed n_p and j_{end}; W_i in plug = 13 keV.

[c] Current density referenced to end-plug midplane.

[d] T_e ln n_p/n_c consistent with [illegible] diagnostics.

[e] 50% with neutral-beam injections into the central cell.

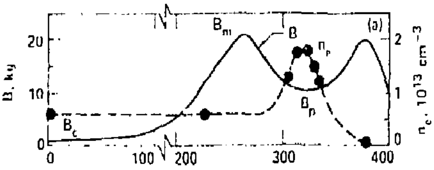


Fig. 3(a). Measured axial density profile.

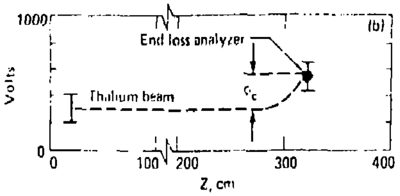


Fig. 3(b). Measured axial potential profile exhibiting potential well.

$$(n\tau) = (n\tau_F + n\tau_M)\ \exp\ (e\phi_c/kT_{ic})\quad , \tag{2}$$

where

$$n\tau_F = \frac{n_c\ L_c\ R_c}{(8kT_{ic}/\pi M_i)^{1/2}}\quad , \tag{3}$$

$$n\tau_M = n\tau_{ii}\ g\ (R_c/2)\ (e\phi_c/kT_{ic})\quad . \tag{4}$$

In these expressions, kT_{ic} is the temperature of the central-cell ions , and $e\phi_c$ is the confining electrostatic potential. The central-cell mirror ratio is R_c = 20, and M_i is the ion mass. The ion-ion 90° scattering time is τ_{ii}, and $g(R) = \sqrt{\pi}\,(2R+1)(4R)^{-1}\ln(4R+2)$. By including both terms ($n\tau_F$ and $n\tau_M$), Eq. (2) correctly models end losses in both collisional and collisionless regimes.

Experimentally, we determine the axial confinement parameter of the central-cell ions from the measured central-cell density and end losses according to

$$(n\tau)_c = e\, n_c^2\, L_c / j_c \quad , \tag{5}$$

where n_c is the central-cell density, j_c is the end-loss current density, and L_c is the equivalent cylindrical length of the central cell (314 cm). By using the experimentally measured parameters to evaluate Eq. (3) and (5) we can determine the electrostatic enhancement factor $n\tau_c/n\tau_F$ (Fig. 4) during the steady-state phase of operation. As noted in Table 1, enhancement factors as large as 9 have been measured.

In addition, we can obtain direct evidence (Fig. 4) of the plugging efficiency when we turn off the neutral beams in one of the plugs. The plug without neutral-beam injection decays on a time scale of a few milliseconds. The central-cell ions are then confined only by the magnetic mirror on that end of TMX. The ratio of the end-loss current out the unstoppered end to that out the plugged end is a measure of the plugging efficiency of the end with neutral-beam injection.

4. Instability Measurements

As noted earlier, TMX exhibits gross magnetohydrodynamic (MHD) stability and microstability. However, a residual level of plug ion cyclotron fluctuations persists, not only in the plugs but also in the central cell. The presence of the plug oscillations in the central cell appears to lead to heating of some of the ions, which degrades their confinement. By resonant interaction with the ion cyclotron fluctuations, these ions gain energy

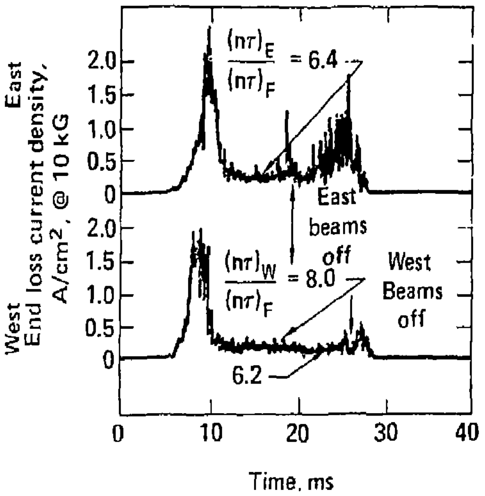
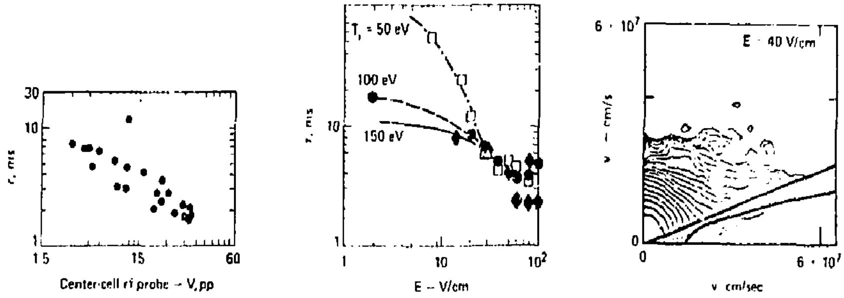


Fig. 4. Evidence of electrostatic plugging in TMX. The subscripts E and W refer to the east and west end plugs, respectively.

greater than the confining potential. They are then lost by pitch-angle scattering into the loss region of phase space.

Monte Carlo code modeling of the instability interaction as a resonant heating process occurring where the field strength in the central-cell transition region is equal to the minimum field strength in the plug shows that the tail of the central-cell ion energy distribution is heated (Fig. 5). The Monte Carlo code also shows qualitative agreement with the experimental result that nearly classical central-cell axial confinement is measured for low instability levels (rf) but that a degradation of the confinement occurs at high fluctuation amplitudes. We are presently investigating the hypothesis that the plug instability arises because the flow of plasma stream from the central cell through the plugs is insufficient. The instability level, therefore, increases to increase the available stream of plasma.



a. Measured confinement time if near classical at low rf, degrades with higher rf.

b. Calculated confinement time agrees if $k_\perp = 3.6$ cm^{-1} and $\tilde{\phi}_{\parallel\lambda} = 5\,\tilde{\phi}$ probe.

c. Calculated velocity space shows ions heated at resonance point providing stream for drift-cyclotron loss-cone (DCLC) mode.

Fig. 5. Comparison between measured and calculated central-cell confinement time, ϕ_c held constant.

5. Conclusion

During the initial operation of TMX, we have established and maintained in equilibrium axial density and potential profiles that lead to the enhanced axial confinement of the central-cell ions.

6. References

1. F. H. Coensgen, Lawrence Livermore Laboratory Report, LLL-Prop-148, January, 1977.

2. G. I. Dimov, V. V. Zakaidakov, and M. E. Kishinevsky, Fiz. Plasmy 2, 597 (1977).

3 T. K. Fowler and B. G. Logan, Comments on Plasma Phys. 2, 167 (1977).

4. K. Yatsu et al., Phys. Rev. Lett. 43, 627 (1979).

5. R. Cohen, Nucl. Fusion 19, 1295 (1979).