Electrostatic Plasma-Confinement Experiments in a Tandem Mirror System

F. H. Coensgen, C. A. Anderson, T. A. Casper, J. F. Clauser, W. C. Condit, D. L. Correll, W. F. Cummins, J. C. Davis, R. P. Drake, J. H. Foote, A. H. Futch, R. K. Goodman, D. P. Grubb, G. A. Hallock,[a] R. S. Hornady, A. L. Hunt, B. G. Logan, R. H. Munger, W. E. Nexsen, T. C. Simonen, D. R. Slaughter, B. W. Stallard, and O. T. Strand[b]

Lawrence Livermore Laboratory, University of California, Livermore, California 94550

(Received 15 January 1980)

Results from the tandem mirror experiment are described. The configuration of axial density and potential profiles are created and sustained by neutral-beam injection and gas fueling. Plasma confinement in the center cell is shown to be improved by the end plugs by as much as a factor of 9. The electron temperature is higher than that achieved in our earlier 2*X*II*B* single-cell mirror experiment.

PACS numbers: 52.55.Mg, 52.55.Ke

This Letter reports the first results obtained from the tandem mirror experiment (TMX) at the Lawrence Livermore Laboratory. Steady-state tandem-mirror plasmas have been produced and an electrostatic barrier that improves plasma confinement has been observed. The tandem-mirror configuration[1,2] can enhance the performance of a magnetic-mirror thermonuclear reactor. Such a reactor would produce power in a cylindrical, high-β, magnetic solenoid. End losses from this center cell are reduced by electrostatic end-plug barriers of positive potential, which turn back those low-energy ions which escape through the magnetic mirror. These potential barriers are established on both ends of the center cell by high-density, high-temperature, mirror-confined plasmas, which have a larger ambipolar potential than does the center-cell plasma.

Earlier tandem-mirror experiments,[3] in which plasma guns were used to establish end-plug densities larger than those in the center cell, have produced potential wells. Langmuir-probe measurements indicated that the magnitude and scaling of the potential-well depth is consistent with theoretical predictions. Our results demonstrate that we can produce and sustain a tandem-mirror plasma configuration by use of neutral beams to fuel the end plugs and gas to fuel the center cell. This method can be extrapolated to continuously operated systems. Our experiments further demon-

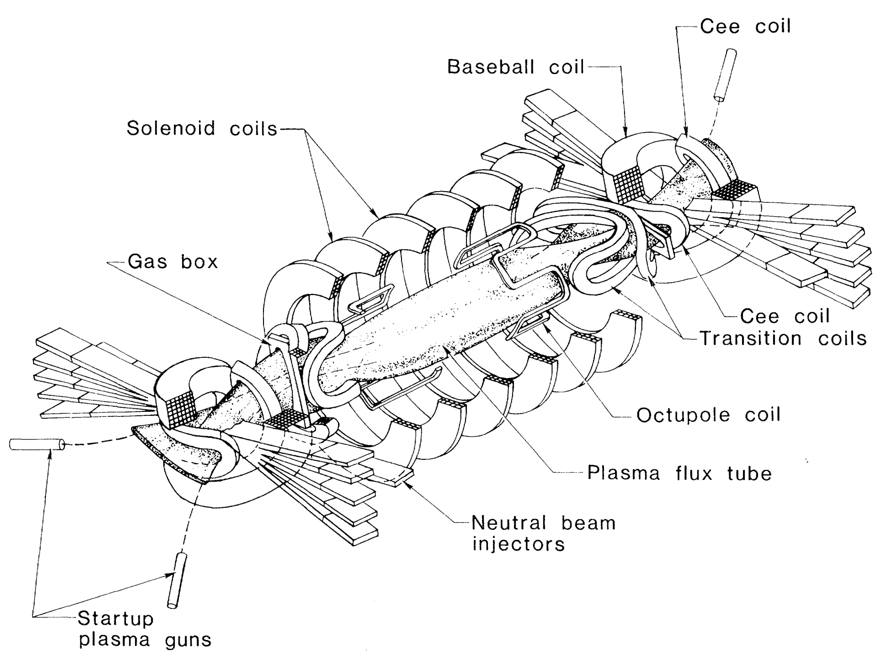

FIG. 1. Schematic diagram of TMX magnet and neutral-beam system.

strate that the confinement of the center-cell plasma is enhanced by electrostatic plugs.

The TMX magnet and neutral-beam systems are shown in Fig. 1. Eighteen water-cooled magnets produce the magnetic field profile shown in Fig. 2(a). The finite-β, center-cell plasma is stable against magnetohydrodynamic instabilities because along a magnetic field line the minimum-B plugs provide a favorable pressure-weighted curvature.

The TMX plasma is heated and sustained by 24 neutral beams. Peak neutral-beam currents in excess of 200 equivalent atomic amperes per plug have been injected with an average accelerating voltage of about 17 keV and a mean energy per atom of 13 keV. About 400 kW have been trapped by the end-plug plasmas

To trap the neutral-beam atoms and initiate buildup of plasma in the plugs, a target plasma is produced by a 5-ms pulse from four deuterium-loaded titanium-washer plasma guns of the type used in 2*X*II*B*.[4] These guns are located outside the plugs. After startup, low-energy plasma from the center cell is required to maintain the plug plasmas. The center cell is fueled by a gas feed.

Sample TMX axial-density-profile data are plotted in Fig. 2(a). The densities are derived from the measured attenuation of neutral beams and by microwave interferometry. The tandem-mirror density profile shown in Fig. 2(a) has been maintained in steady state for the duration of the neutral-beam pulse, which indicates that no gross instability precludes the production of a tandem-mirror plasma configuration.

On the basis of extensive experience with 2*X*II*B* and neutron measurements, we estimate the TMX end-plug ion energy to be about 13 keV, equal to the mean injection energy. A Thomson scattering system in the east end plug has measured electron temperatures as high as 260 eV—three times the characteristic value obtained on 2*X*II*B* (Ref. 4) with comparable beam current. The mean energy of the center-cell plasma is estimated from the plasma diamagnetism and the density profile. If we assume a Gaussian radial temperature profile of the same scale length as the density, the mean temperature (electron plus ion) is characteristically 140 eV during gas-box feed and 60 eV with the gas-puffer feed. We assume the center-cell ion and electron temperatures are equal, $T_{ic}=T_{ec}$. Center-cell β values as high as 10% are observed at present levels of trapped beam power.

The key to tandem-mirror confinement is to es-

TABLE I. TMX plasma parameters with deuterium and center-cell field strength of 0.1 T.

		Puffer valve, Shot No. 57			Gas box, Shot No. 46		
	TMX max	TMX	TAMRAC	RF TAMRAC	TMX	TAMRAC	RF TAMRAC
Plug density n_p (10^{13} cm^{-3})	4	1.35	1.35[a]	1.35[a]	2.5	2.5[a]	2.5[a]
Total center-cell loss current density out both ends. j_c (mA/cm^2) at center-cell midplane	~200	44	44	44	180	180[a]	180[a]
Plug electron temperature T_{ep} (eV)	260	103	115	130	140	106	121
Center-cell density n_c (10^{13} cm^{-3})	3	0.52	0.82	0.54	1.0	1.7	1.1
Center-cell ion temperature T_{ic} (eV)	250	27	27	69	52	29	78
Center-cell confining potential ϕ_c (V)	100 to 300	b	57	119	b	42	101
Center-cell confinement parameter $n\tau_c$ (10^{10} cm^{-3} s)	7	3.0	7.5	3.2	3.1	7.7	3.1
Electrostatic enhancement in confinement, $n\tau_c/n\tau_T$	9	4.1	7.6	4.7	2.9	4.0	3.2
Center-cell β $\hat{\beta}_c$ (%)	10	1.4	5	4	4.2	9	9

[a]Specified code input parameter.

[b]Sufficiently accurate direct measurements of ϕ_c have not yet been made. Calculation of ϕ_c, in the presence of thermal barrierlike effects ($T_{ep}\neq T_{ec}$), requires measurements not now available. See, for example, D. E. Baldwin and B. G. Logan, Phys. Rev. Lett. 43, 1318 (1979).

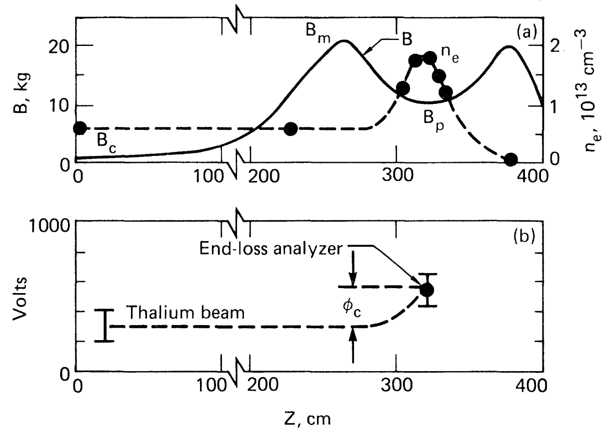

FIG. 2. TMX density and potential measurements. (a) The TMX magnetic field profile and the measured density profile shows that a tandem-mirror density profile is created and sustained by neutral beams. (b) Measurements of plug and center-cell potential with end-loss analyzer and thallium beam probe show the presence of a tandem-mirror potential well.

tablish an electrostatic well. The center-cell potential is measured by a thallium-ion-beam probe. For the data plotted in Fig. 2(b) the center-cell potential, φ_e, is 300 ± 100 V. The potential of the end plug, φ_p, is taken as the minimum energy of escaping ions as determined with use of electrostatic energy analyzers located on the axis at each end of the vacuum chamber. The potential well ($\varphi_c = \varphi_p - \varphi_e$) is believed responsible for the enhanced confinement described below.

TMX has operated over a wide range of conditions. The maximum deuterium-plasma parameters achieved with a 0.1-T central-cell field are listed in Table I. These maximum parameters were not all achieved on the same shot nor under the same conditions. Table I includes data from two specific shots, one using the gas puffer and the other using the gas box to fuel the solenoid. Both cases have been compared with the point-model TAMRAC code[5] and RF TAMRAC, a version in which rf heats the center-cell ions. This rf heating is intended to simulate coupling of end-plug, ion-cyclotron fluctuations to center-cell ions. Measured center-cell parameters are in factor-2 agreement with TAMRAC.

End-loss measurements show that most of the power trapped in the end plugs is deposited on the end wall. The flux of these ions is much greater than the neutral-beam trapping could provide, indicating that the trapped beam power is in large part flowing through the plasma to the end wall, suggesting the absence of large, anomalous, ra-

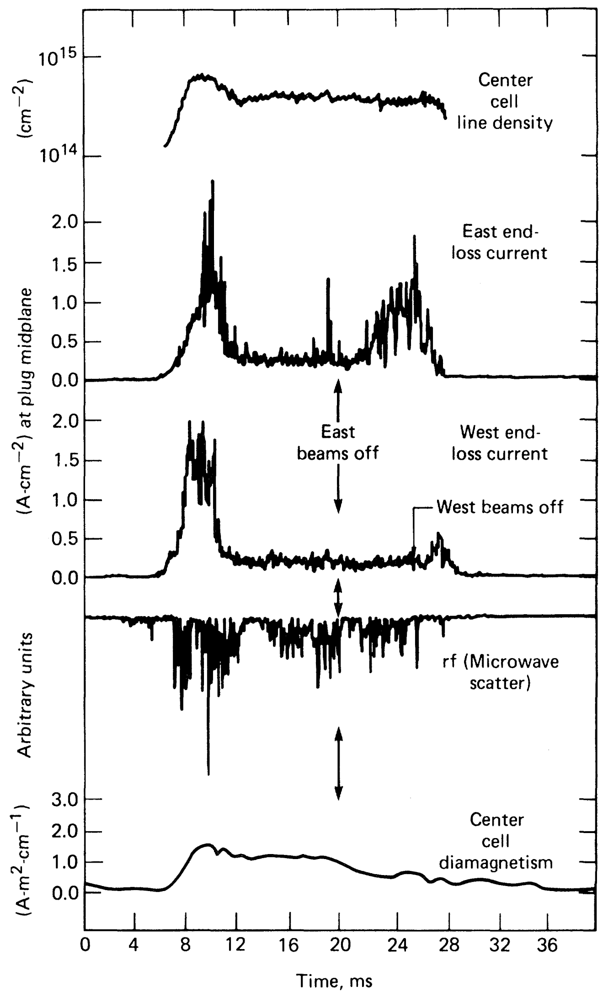

FIG. 3. The time development of several key TMX parameters during a typical shot. (Shot No. 57; $B_c = 0.1$ T, $I_b = 110$ A per plug). Current buildup initiated by stream-gun beams is followed by a steady state. When the beams are turned off at 20 ms, the east-end loss current increases relative to the west end, which indicates that the east end was electrostatically confining center-cell plasma.

dial losses of energy.

Figure 3 shows time histories of some parameters corresponding to the first shot listed in Table I. Plasma buildup is observed while the plasma guns are on. Then a steady state is established with comparable losses out both ends of the machine. The east beams are turned off at 20 ms, and by 24 ms the east-plug plasma has decayed and a new steady state has been established. At this time, the east-end losses are several times the west-end losses. Because the collision rate into the loss cone of the center-cell plasma is quite high in this shot, the fluxes entering each plug should be equal. The fact that much less current reaches the west-end wall than the east shows that the west plug is turning back much of the flux from the center cell. This is direct evidence that the end cells plug the center cell. The observed plugging is believed to be electrostatic, but an alternate explanation is that ion-cyclotron waves excited within the end plugs provide rf plugging. However, when TMX is operated with high levels of rf fluctuation, the plasma in the center cell is less well confined. Therefore it appears that rf does not plug in this device but rather that it degrades confinement.

We can use our data to evaluate the extent to which two plugs enhance confinement during the steady state. The center-cell particle-confinement parameter is given by

$$(n\tau)_c = en_c^{\,2}L_c/j_c.$$

In this formula, e is the electronic coulomb charge, n_c is the central density in the center cell in inverse cubic centimeters, and j_c is the total center-cell loss-current density out both ends in $A \cdot cm^{-2}$ at the center-cell midplane. The effective center-cell length is $L_c = 314$ cm. The theoretical confinement parameter $(n\tau)_c$ is[6]

$$n\tau = (n\tau)_T \exp(\varphi_c/T_{ic})$$
$$= \left[10^{11}T_{ic}^{\,1/2}\varphi_c + \frac{n_c L_c R_c}{(8KT_{ic}/\pi M_i)^{1/2}}\right]\exp(\varphi_c/T_{ic}).$$

In these expressions T_{ic} is the center-cell ion temperature in kiloelectronvolts, and φ_c the confining electrostatic potential in kiloelectronvolts. The center-cell mirror ratio is $R_c = B_m/B_c = 20$, M_i is the ion mass in grams, and $K = 1.6\times10^{-9}$ ergs/keV. Many TMX plasmas are collisional so that confinement is dominated by the second term, which characterizes plasma flow out of a magnetic nozzle. At higher temperatures the collisionless first term becomes important. For the shot represented in Fig. 3, the ratio $(n\tau)_c/(n\tau)_T$ is calculated to be 4. Values of this parameter as high as 9 have been obtained, as Table I indicates.

In conclusion, a tandem-mirror plasma has been created and sustained in TMX by use of neutral-beam injection and gas fueling. Tandem-mirror density and potential profiles have been measured. In TMX, the electron temperature is significantly greater than that achieved in the single-cell mirror experiment, 2XIIB. Finally, the end plugs enhance the plasma confinement in the center cell, apparently because a potential well is established.

We thank the engineering and operations staff who built the TMX facility, the Lawrence Livermore Laboratory theory group, and the Lawrence Berkeley Laboratory neutral-beam group. D. Boyd, A. Gardner, W. Getty, and T. Kawabe helped us in our early physics runs. This work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore Laboratory under Contract No. W-7405-ENG-48.

[a]Permanent address: Rensselaer Polytechnic Institute, Troy, N. Y. 12181.

[b]Permanent address: Johns Hopkins University, Baltimore, Md. 21218.

[1]G. I. Dimov, V. V. Zakaidakov, and M. E. Kishinevsky, Nucl. Fusion 3, 177 (1977).

[2]T. K. Fowler and B. G. Logan, Comments Plasma Phys. Controlled Fusion 2, 167 (1977).

[3]K. Yatsu *et al.*, Phys. Rev. Lett. 43, 627 (1979).

[4]W. C. Turner *et al.*, Nucl. Fusion 19, 1011 (1979).

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

[6]T. D. Rognlien and T. A. Cutler, in Proceedings of the Ninth European Conference on Controlled Fusion and Plasma Physics, Oxford, England, 17–21 September, 1979 (to be published).