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ABSTRACT

TMX experimental data on ambipolar potential control and on the accompanying electrostatic confinement are reported. New results on the radial dependence of the central-cell confining potential are given. Radial and axial particle losses as well as scaling of the central-cell axial confinement are discussed.

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1. INTRODUCTION

A year ago the THX group reported¹ that the tandem mirror^{2,3} configuration of axial density and potential profiles was created and sustained by central-cell gas fueling and end-cell neutral-beam injection. Axial central-cell particle confinement improved because of the the confining ambipolar potential. In a subsequent publication,⁴ end-cell stability requirements (rising from microinstabilities near the plug ion-cyclotron frequencies) were shown to reduce the central-cell confinement below classical Coulomb values when the end cell to central-cell density ratio roughly exceeded three.

This paper expands the data set supporting these original conclusions, documents measurements of the radial dependence of the ambipolar potential, discusses the relative radial to axial confinement of the central cell, and demonstrates that for low, constant values of RF fluctuations the central cell axial confinement scaled with end-cell injection energy according to implied values of the confining potential.

Effects, other than confinement, due to large ambipolar potentials,⁵ and the next generation tandem experiment at LLNL (THX Upgrade),⁶ are examined in accompanying papers in this workshop. More detailed information from the THX experiment on power balance, fluctuation studies, and axial and radial transport will be reported in individual journal publications.

The four main points of this paper are:

- By controlling end-cell and central-cell densities, ambipolar potentials were formed in THX.
- Confining potentials of 150 V on axis and within the central core have been measured (up to 300 V on some shots).

- Radio frequency fluctuations near ion-cyclotron frequencies of the end cells can degrade enhancement on axis. Radial losses near the edge of the plasma can be of the same order as axial losses.

- When end-cell injection energy was increased, central-cell confinement on axis increased.

11. AMBIPOLAR POTENTIAL FORMATION

Figure 1 shows the TMX magnet and neutral-beam injector systems. The four deuterium-loaded titanium-washer startup guns supply a plasma target for neutral-beam buildup within the plugs. They are turned off after 5 ms and the central cell is fueled either by gas injection into two gas boxes in the transition regions between the plugs and central cell or by feeding gas into the central region of the solenoid vacuum vessel (gas puffing). Steady-state density conditions are reached within 10 ms and are sustained for the entire 25-ms pulse length of the neutral beams. Typical axial plasma density, potential, and magnetic field profiles are plotted to scale in Fig. 1. The inside mirrors on both ends are located 265 cm from the midplane of the central cell with the outside mirrors at 375 cm. The plug midplane is at 320 cm. The plug magnetic field had a midplane strength of 1 T with a 2-to-1 mirror ratio. The central-cell field strength, which could be varied from 0.05 to 0.2 T, was usually 0.1 T. The values of plug and central-cell density (n_p and n_c) are controlled by the amount of neutral-beam current and central-cell gas fueling. However, day-to-day variations in other key plasma parameters, such as electron temperature, T_e , can have a minor effect. The value of the central cell potential, ϕ_c , is established by the required equality of electron and ion losses. The plug potential, ϕ_p , is predicted to be higher than ϕ_c by the confining ambipolar potential of the central cell, $\phi_c = T_e \ln(n_p/n_c)$ for T_e constant along field lines. This positive

Fig. 1. THX Geometry: schematic of experiment and axial profiles to scale of magnetic field, plasma density, and plasma potential.

electrostatic potential, ϕ_c , augments the central-cell magnetic confinement by turning back ions of parallel energy less than ϕ_c .

A thallium heavy-ion beam probe (HIBP) was used to measure the central-cell space potential, ϕ_e .⁷ The potential is determined from the energy of doubly ionized thallium ions. The experimental time sequence and the measurement of ϕ_e at a central-cell radius of zero are given in Fig. 2. After a sufficient hot mirror-confined plasma density is reached within the plugs, the plasma guns are turned off and the central cell is fueled by gas injection and the end plugs by the neutral beams. Steady-state values of ϕ_e are reached within 10 ms and are maintained for the entire length of neutral beam injection. If we turn off the neutral beams in one plug before the other, as we did with the west plug for this shot, we find that ϕ_e falls to a lower steady-state value because of the reduction in the central-cell electron temperature, T_{ec} , and in ion particle confinement. When the remaining east-plug neutral beams are turned off, the central-cell potential is observed to fall until it reaches the lower sensitivity limit of the HIBP. To measure the radial dependence of ϕ_e , the HIBP can be radially incremented shot-to-shot by adjusting the beam voltage or, if there is sufficient signal to noise, a single-shot radial scan can be accomplished by using a set of beam deflection plates.⁷

The plug potential, ϕ_p , is measured by the four swept-voltage end-loss analyzers (two per end cell with one movable on the west plug). These electrostatic end-loss ion analyzers (ELA's) have ion-repeller grids biased positively with respect to ground. Ions with energies less than the ion-repeller-grid voltage do not reach the collector plate. Because the ELA's are located in the escaping plasma fan regions at the end wall where the magnetic field strength is 0.007 T, the ion end-loss current has most of its energy converted to parallel motion. Since all the escaping ions must pass

Fig. 2. Central-cell space potential, ϕ_e , on axis (measured by HIBP) vs time. The timing sequence of plasma fueling and heating is shown as well.

through the plug to leave the central cell, the end-loss current will not be attenuated unless the ion-repeller voltage exceeds the potential drop from the plug to the end wall, ϕ_p . In Fig. 3(a), we show the ion end-loss current vs time along the magnetic axis ($r_c = 0$) for the west end. The current density in mA/cm^2 is referenced to the central-cell midplane. The current spike near 8 ms is due to stream plasma from the start-up guns which reflected from the plasma being built up within the plugs. Turning the west neutral beams off before the east neutral beams resulted in a dramatic increase in measured west-end losses at 22 ms. In Fig. 3(c) and (d), we plot the current-voltage characteristics of the ion end-loss current density, J , measured by the west ELA at two different repeller sweep times, one near 16 ms (representative of steady-state operation) and one near 25 ms (representative of a single plug tandem). The ion end-loss current is not reduced until the ion repeller voltage exceeds ϕ_p . At higher repeller voltages, the curvature of the I-V curve is a measure of the energy distribution of the ion end losses. During steady-state operation the west plug was measured to have a shot-to-shot average value for ϕ_p at $r = 0$ of 480 V. When either plug is turned off before the other (as the west plug was for the data in Fig. 3) the measured value of ϕ_p is near that of ϕ_e ; that is, there exists only one end of the machine with any electrostatic stoppering. These points are illustrated in Fig. 3(b), where measured values of ϕ_p are plotted vs time, including the 16 and 25 ms data of Fig. 3(c) and (d).

The central-cell potential, ϕ_e , and the end-cell potential, ϕ_p , are plotted in Fig. 4 as functions of central-cell radius, r_c , for the two times discussed earlier, 16 and 26 ms. These measurements were taken under constant machine conditions of magnetic field strength, neutral-beam injection current, and central-cell fueling. The plug magnetic field had a midplane strength of 1 T with a 2-to-1 mirror ratio and the central-cell field strength was 0.1 T.

Fig. 3. End loss current density, J , and end cell potential, ϕ_p , vs time for the same shot as Fig. 2. I-V characteristics of the end loss analyzer (ELA) at two distinct times (16 and 25 ms) are given to illustrate ϕ_p measurements.

Fig. 4. ϕ_p and ϕ_e vs central-cell radius, r_c , for $t = 16$ ms ($n_p/n_c \approx 5$) and $t = 26$ ms ($n_p/n_c \approx 1$). Data for $n_p/n_c \approx 1$ is used to check the calibration of the HIBP and ELA against each other.

The neutral-beam injection current per plug was 150 ± 20 A equivalent of atomic deuterium. To fuel the central cell, we used a standard LBL neutral-beam gas valve located on the middle bottom port of the central cell. The deuterium gas input was 1580 equivalent atomic A. The selection criteria were that the neutral-beam current was near 150 A and that the on-axis potential was reproducible.

That the two diagnostics (HIBP and ELA) measured similar potentials at 26 ms when $n_p \approx n_c$ testifies that there is no systematic offset in the determination of ϕ_c and ϕ_p . Therefore, we conclude that the data in Fig. 4 at 16 ms, when $n_p/n_c \approx 5$, can be used to give the central-cell confining potential by simple subtraction, $\phi_c = \phi_p - \phi_e$. These results are shown in Fig. 5 where the error bars represent (as in Fig. 4) the statistical fluctuations from shot to shot. We have estimated the systematic error in the HIBP and the ELA to be ± 20 V and ± 30 V, respectively.

The data of Fig. 5 shows the existence of a central-cell confining potential on axis of 150 V. We see that ϕ_c remains near the on-axis value to a central-cell radius of 15 cm. In this region ($0 \leq r_c \leq 15$ cm), there is agreement between the measured values of ϕ_c and the predicted values based on the ambipolar potential well established by quasi-neutrality,

$$\phi_c = T_e \ln (n_p/n_c).$$

The range of predicted values of ϕ_c represents the uncertainty in determining the values of electron temperature, T_e , plug plasma density, n_p , and central-cell density, n_c . The electron temperature in the east plug, T_{eE} , was measured by Thomson scattering techniques at three radial positions which map into r_c values of 0, 15.8, and 31.6 cm by flux conservation [$r_c = r_p (B_p/B_c)^{1/2}$]. The electron temperature in the west plug was estimated as $T_{eW} = T_{eE} \phi_{pW}/\phi_{pE}$. The radial values of n_p and n_c were determined by inverting line-integral densities measured using beam attenuation

Fig. 5. Comparison of $\phi_c = \phi_p - \phi_e$ at 16 ms to the predicted value $T_e \ln (n_p/n_c)$, both as functions of r_c .

techniques.⁸ We found that using second-order polynomial inversions of f_{nd1} gave densities that were in good agreement with electron density measurements by Thomson scattering in the east plug and central cell. The predicted values of ϕ_c in Fig. 5 were therefore generated using the following experimental values: $T_{eE} = 87[1 - (r_c/38.6)^2]$ eV, $\phi_{pE} = 540$ V, $\phi_{pw} = 480$ V, $n_{pw} = 1.7 \times 10^{13}[1 - (r_c/38.6)^2]^{1/2}$ cm⁻³, and $n_c = 3.5 \times 10^{12}[1 - (r_c/38.6)^2]^{1/2} [0.77 + 0.91(r_c/38.6)^2]$ cm⁻³. Two electrically grounded limiters at $r_c = 38.6$ cm were spaced 54 cm on either side of the central-cell midplane.

The last experimental point, according to our present calibrations and error analysis, changes sign from a positive confining potential to a negative repelling potential for central-cell ions. From a diagnostic viewpoint, the ELA should determine the highest potential within the plasma, whether it be ϕ_p or ϕ_c , unless the axial central-cell losses become mirror-trapped within the end cells or undergo charge-exchange events before reaching the end wall. Although there exists no experimental evidence for significant azimuthal asymmetries, such asymmetries could alter the off-axis evaluation of ϕ_c ; the machine geometry required the radial dependence of ϕ_p and ϕ_e to be measured in different directions, horizontal (z) and vertical (y), respectively. We are investigating how thermal-barrier effects,⁹ non-Maxwellian electron distributions, edge fueling of neutrals, and radial losses of electrons might modify theoretical predictions for ϕ_c .

III. CENTRAL-CELL POTENTIAL CONFINEMENT

Figure 6 summarizes the axial and radial particle losses of the central cell for the same experimental data that generated Fig. 5. Ion flux Faraday cups and net electrical current detectors were mounted in arrays across the narrow dimension of the magnetic flux bundle at both ends of the machine to determine central-cell particle losses. All total current values are

$r_c = 30$ cm	Axial		Radial Ion	
	Ion	Electron	Nonambipolar	Ambipolar
Total current (A)	95	180	80	<260
Lifetime (ms)	4.8	2.6	5.7	>1.8
$\left(\frac{eN}{I}\right)$				

Fig. 6. Total central-cell axial and radial ion losses vs r_c . Ion and electron lifetimes for various processes are given in terms of total number of particles divided by total particle current within a 30-cm radius.

integrated assuming axisymmetric profiles with symmetry points at the peak of the end cell potential. The axial electron current to the end walls was determined by adding in absolute magnitude the net electrical current (found to be negative or zero) to the Faraday-cup measurements of ion axial current. The nonambipolar radial ion losses were arrived at by subtracting the predicted end-cell electron losses (on the order of 10 A per end) from the net electrical current at the end wall. The ambipolar radial losses in the central cell were estimated from the difference between the total electron end losses predicted from central-cell fueling codes and measured values of the axial electron current. Because of uncertainties in central-cell electron-temperature profiles, the fueling codes can only be used to put an upper bound on currents and a lower bound on lifetimes for ambipolar radial losses. The volume average lifetime in Fig. 6 is defined as the total number of particles within a 30-cm-radius, 314-cm-long cylinder, divided by the particle current associated with each of the losses.

The data of Fig. 6 shows that within a 30 cm radius, the central-cell ion axial losses are less than the nonambipolar radial losses. The nonambipolar losses can be predicted by resonant-neoclassical radial transport arising from radial drifts enhanced by azimuthal components of nonaxisymmetric magnetic fields.^{10,11} The global axial confinement time of the ions, 4.8 ms, is a factor of 3 higher than the magnetic confinement time of the central-cell ions without potential barriers. What is surprising is the fact that the radial dependence of the confinement parameter in the region $20 \leq r_c \leq 30$ cm does not show any adverse effects near the radial position where we believe the confining potential has reversed sign (see Fig. 5).

In Fig. 7, we discuss how, near the magnetic axis of the central cell where radial losses are small compared to axial losses and where there is good agreement between measured and predicted values of ϕ_c , additional effects

Fig. 1. Ratio of end-cell to central-cell plasma density, n_p/n_c , and central-cell axial ion-confinement parameter, nr , plotted against RF levels of end-cell ion-cyclotron fluctuations within the central cell.

due to RF fluctuations can degrade central-cell axial confinement. We begin by defining four expressions describing the axial particle-confinement parameter of the central cell.

During steady-state operation we determine the experimental ion confinement parameter $n\tau_c$ ($\text{cm}^{-3}\cdot\text{s}$) by evaluating the expression

$$n\tau_c = en_c^2 L_c / j_c \quad (1)$$

where e is the electronic Coulomb charge (1.6×10^{-19}), n_c is again the central-cell density in cm^{-3} , L_c is the effective solenoidal length (314 cm), and j_c is the total central-cell loss-current density out both ends in A/cm^2 (evaluated at the central-cell midplane).

The unstoppered ($\phi_c = 0$) mirror confinement of the central cell predicted by theory is given by

$$n\tau_o = n_c \tau_{ii} \log R + 2n_c L_c \left(\frac{\pi m}{8T_c} \right)^{1/2} R \quad (2)$$

where T_c is the central-cell ion temperature. The two terms are: (1) the ion-ion scattering time for an empty loss cone with mirror ratio R (mean free path $\gg RL_c$), and (2) for a filled loss cone (mfp $\ll RL_c$), the product of the density and the losses due to flow $(8T/\pi m)^{1/2}$ out both ends of a magnetic bottle with mirror ratio R .¹²

The Coulomb confinement of the central cell, $n\tau_\phi$, in the presence of a potential, $\phi_c = T_e \ln (n_p/n_c)$ is increased according to the following expression:

$$n\tau_\phi = \left[n_c \tau_{ii} g(R) \frac{\phi_c}{T_c} + 2n_c L_c \left(\frac{\pi m}{8T_c} \right)^{1/2} \frac{R}{2} \right] \exp (\phi_c / T_c) \quad , \quad (3)$$

where for $\phi_c \geq T_c$, $g(20) = 3$. Both terms of Eq. (3) are enhanced over Eq. (2) by $\exp(\phi_c/T_c)$ because only ions with energy exceeding the confining potential,

ϕ_c , can escape axially. The additional enhancement of the first term by ϕ_c/T_c can qualitatively be explained by the modification of the ion-ion collision frequency term due to collisions among particles with energy less than ϕ_c in determining the rate of diffusion into the loss cone. The function $g(R)$ takes into account that the confining potential is peaked at the end-cell midplane, not at the mirror point of the central cell. This same effect changes the mirror-ratio dependence of the flow term from R to $R/2$ for an end-cell midplane field strength half of the mirror point.

The equation

$$n_{RF}^* = n_{\phi} \left(1 + \frac{E^2}{E_c^2} \right)^{-1} \quad (4)$$

describes the degradation of central-cell ion confinement by the distortion of the ion-velocity distribution (assumed initially to be Maxwellian) due to oscillating electric fields, E , at the ion-cyclotron frequencies of the end cells. Due to the magnetic geometry (see Fig. 1), there exist 10-kG zones resonant with the plug midplanes within the central cell. Rognlien and Matsuda¹³ developed the theory that led to Eq. (4) and discussed the critical electric field strength, E_c , required for such effects to occur.

The diamond and circle data points in Fig. 7 (Ref. 4) represent a neutral-beam current scan of the end cells to vary the ratio of n_p/n_c and the shaded ellipses are the accompanying data to Figs. 5 and 6. We see that as the magnitude of the RF fluctuations within the central cell (at the end-cell ion cyclotron frequencies) increased, the experimental n_{ϕ}^* degraded. At low levels of RF, there was good agreement between n_{ϕ}^* and the Coulomb value n_{ϕ_0} . At the higher levels of RF, the measured enhancement of n_{ϕ}^* over n_{ϕ_0} decreased. The predicted value of n_{RF}^* is seen to agree well with the overall dependence of n_{ϕ}^* vs RF. The critical electric field, E_c , can be taken as a one-point fit between n_{ϕ}^* and n_{RF}^* .

To test the scaling of electrostatic enhancement of central-cell axial confinement, we carried out an experiment in which we varied the energy of the injected neutral beam. Our results are shown in Fig. 8. We were able to vary the neutral-beam injection voltage on the east end cell of the experiment without changing the total injected-beam current, by operating 20 kV and 40 kV neutral-beam injectors at various levels. The west end cell was operated with a constant neutral-beam injection level similar to case B for all three cases (A, B, and C) of the east end cell. The value of ϕ_c was determined from $T_e \ln(n_p/n_c)$.¹⁴ In all three cases we have normalized the experimental value n_{rc} to the "flow" term of Eq. (3). The values of n_c and T_e justify this approximation. We find that the normalized experimental value of the central-cell ion confinement agrees with the theoretically implied scaling one would describe for mirror confinement enhanced by a confining electrostatic potential.

IV. SUMMARY

The experimental data of this paper verifies the formation and control of ambipolar potentials in TMX and the accompanying electrostatic enhancement of the central-cell ion confinement. In Fig. 5, we expanded upon earlier on-axis measurements¹ of ϕ_c and discussed its central cell radial dependence. In the core of the central cell ($0 \leq r_c \leq 15$ cm), the experimentally determined value of ϕ_c is in good agreement with the expected value, $T_e \ln(n_p/n_c)$. Near the edge ($20 \leq r_c \leq 30$ cm), ϕ_c is lower, and may even reverse at the edge.

Central-cell axial and radial particle losses are given in Fig. 6. We find that the ion axial and nonambipolar radial confinement within a 30-cm radius are of the same order. Radial losses do not become significant until $r_c \geq 20$ cm. In Fig. 8, we show that under conditions where the RF effects

Case	A	B	C
V_{inj} (kV)	11	16	27.5
I_{inj} (A)	70 A	70	50 A @ 32 kV 20 A @ 16 kV
E_{plug} (keV)	5.7	9.2	14.6
T_e (eV)	96 ± 21	121 ± 35	133 ± 20
n_p (10^{13} cm^{-3})	1.1	1	0.84
β_p (%)	3.5	5.1	6.8
J_c (mA/cm ²)	32	28	14
n_c (10^{12} cm^{-3})	3.9	4.8	3.7
T_{ic} (eV)	62	44	48
Central cell RF (V_{pp})	7.0	9.5	8.5

$$\frac{n\tau_c}{n\tau_{Flow}} = \frac{en_c^2 L_c (2J_{CE})^{-1}}{2n_c L_c \sqrt{\frac{\pi m}{8T_c}} \frac{R}{2}}$$

$$\frac{n\tau_\phi}{n\tau_{Flow}} = \exp^{\phi_c/T_{ic}} = \left(\frac{n_p}{n_c}\right)^{T_e/T_{ic}}$$

$$\text{for } \phi_c = T_e \ln n_p/n_c$$

Fig. 8. Central-cell ion confinement for three cases of end-cell neutral-beam injection voltage (case A: 11 kV; case B: 16 kV; and case C: 27.5 kV) compared to implied ϕ_c enhancement.

on central-cell ion confinement (as discussed in Fig. 7) can be ignored, the on-axis n_{c} was observed to scale according to the implied values of ϕ_{c} . The electrostatic confinement associated with $\phi_{\text{c}} > 0$ was enhanced above the $\phi_{\text{c}} = 0$ central-cell mirror confinement from 4 to 8 as the end-cell neutral-beam injection voltage was increased from 11 to 27.5 kV.

TMX generated data which demonstrated that electrostatic confining potentials in magnetic mirror systems can significantly improve central-cell plasma confinement and which provided the impetus for the TMX Upgrade.⁶

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14. The HIBP used to evaluate ϕ_e was at an early stage of its development and was not able to make accurate enough measurements to verify the scaling phenomenon. Nevertheless our data from Fig. 5, where we could use the HIBP to measure ϕ_e , supports our using $\phi_c = T_e \ln (n_p/n_c)$ along the magnetic axis.

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