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# PLASMA CONFINEMENT IN THE TANDEM MIRROR EXPERIMENT*

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ABSTRACT. Plasma confinement in the *Tandem Mirror Experiment* (TMX) is described. Axially confining potentials are shown to exist throughout the central 20-cm core of TMX. Axial electron-confinement time is up to 100 times that of single-cell mirror machines. Radial transport of ions is smaller than axial transport near the axis. It has two parts at large radii: nonambipolar, in rough agreement with predictions from resonant-neoclassical transport theory, and ambipolar, observed near the plasma edge under certain conditions, accompanied by a low-frequency, m = 1 instability or strong turbulence.

INTRODUCTION. The demonstration of successful enhancement of axial plasma confinement by ambipolar potentials in the TMX end cells[1,2,3] has led to a study of the total plasma confinement. Near the axis, plasma axial losses from the central cell exceed the radial losses; near the outer edge radial losses are comparable or dominant.

AXIAL ION CONFINEMENT. Here we demonstrate that confining potentials are generated throughout the cross section of TMX. The central-cell-to-ground potential, $\phi_e$, was determined from the energy of secondaries caused by plasma ionization of a heavy-ion beam.[4] The plug-to-ground potential, $\phi_p$, was determined from the minimum energy of ions which escape through the plugs to the end walls. The difference, $\phi_c$, is in approximate agreement on axis with the potential predicted from the Boltzmann relation, $T_e \ln(n_p/n_c)$, where subscripts p and c refer to the plug and central-cell values. Good agreement is seen, out to a radius of 15 cm, in the radial potential profile shown in Fig. 1. Beyond 15 cm the comparison is poor, although the uncertainties are large. Central-cell ion confinement is found to be enhanced above that of magnetic mirrors by this potential, approximately as predicted by the Pastukov formulas applied to the tandem system.[5,6] Detailed calculation yields good agreement with measurement when the heating of ions by rf generated in the end plugs at the ion-cyclotron frequency is taken into account.[3]

AXIAL ELECTRON CONFINEMENT. The electron energy confinement time in TMX was a factor of up to 100 above that obtained in 2XIIB[7]--from 60 to 600 μs as compared to 3 to 7 μs. The confinement time was calculated as the ratio of stored electron energy to input power to

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the electrons; the input power arises from collisional drag with the energetic plug ions.

The body of the electrons in TMX was isolated from the end walls to ensure that secondary processes at the wall were small. This was achieved by decreasing the magnetic field at the wall by a factor of 300 from that at the plug mirrors, so that the electron density dropped from $1 \times 10^{13}$ $cm^{-3}$ in the plug midplane to $10^9$ to $10^{10}$ $cm^{-3}$ near the wall. In addition, the electron temperature dropped from 50 to 150 eV in the plug and central cell to 5 to 10 eV near the wall.

A comparison of the total energy reaching the end wall (measured by calorimeters) with the ion energy (measured by end-loss analyzers) showed that ions accounted for almost all of the energy reaching the end wall (Fig. 2), and thus that the energy flowing directly in electrons was small. The ion energy included $e\phi_p$ ($\approx 5T_e$) originating from the electrons; nevertheless, secondary electron processes (secondary emission, arcs) were of negligible importance. Secondary emission coefficients were measured by hot-wire probes near the wall; the ratio of secondary electrons to incident ions ranged from 0.3 to 0.9, in good agreement with predicted values. No evidence of unipolar arcs was found on the end walls.

The reflux of gas from the wall provides a source for cold-plasma generation. The measured density of this plasma, $\gtrsim 10^9$ $cm^{-3}$, is in agreement with a model[8] that includes cold-gas recycling, secondary electron emission, and ionization. The cold ions are isolated from the main plasma by the electrostatic potential. As the rate of generation of electrons by ionization is much less than the loss rate from the tandem-confined plasma, the additional power drain on the confined plasma by end-wall processes is at most about 1 to $2T_e$ times the end-loss current: typically 10 to 30 kW. This compares to a typical input power to the central cell of 100 to 400 kW. Processes in the end regions and at the end walls of TMX were thus reduced to a minor role in the power balance.

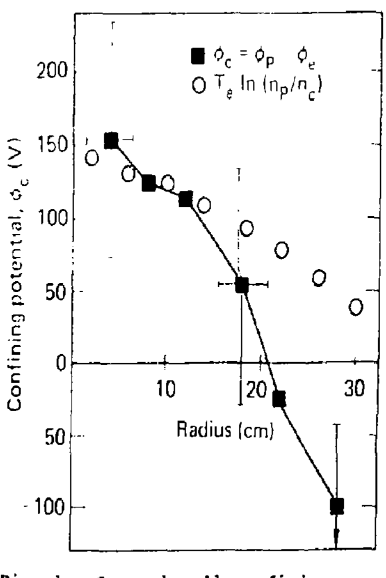


Fig. 1. Central-cell confining potential.

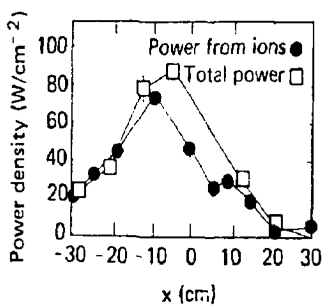


Fig. 2. Measured end-loss power referred to the central cell.

RADIAL TRANSPORT. Radial transport in the central cell of TMX is predicted to have a nonambipolar component arising from resonant-neoclassical transport due to the quadrupole fields in the transition regions.[9,10] Charge neutrality is maintained by a balancing electric current to the (metal) end walls. The net radial nonambipolar ion transport can then be related to the end-loss electron current by radial integration of the current-conservation equation.

The end-loss electron current density was determined from the difference between the net current density to the end wall (measured by collectors at the wall) and the ion current density (measured by Faraday cups). Azimuthal symmetry is assumed. Figure 3 compares measured ion transport with predictions based on theoretical diffusion coefficients.[9] Near the axis the measured electron current density includes that originating in the plugs from radial transport caused by charge exchange with the neutral beams. This current was calculated and subtracted from the measured value before integration. Its effect is large inside a 15-cm radius, but negligible outside that radius.

The errors in the predicted flux arise primarily from uncertainties in the radial electric field. The measured and predicted fluxes are comparable although large uncertainties exist in both. Resonant transport contributes substantially to, and may be the whole cause of, the radial nonambipolar ion transport.

Ambipolar processes were determined by comparing ion end-loss current density with ion sources predicted from gas-deposition codes. For low gas input into the central cell, the density is strongly peaked on axis and the measurement and prediction agree to within their uncertainty, indicating that radial ambipolar transport is weak compared with the nonambipolar transport.

As the gas input is raised, however, the calculated ion source and measured end losses differ by a factor of 3 or more at large radii (>20 cm in central-cell coordinates). This difference lies outside the estimated uncertainties in calculation and measurement, indicating an ambipolar flux comparable to the nonambipolar flux. The onset of this transport is accompanied by a low-frequency instability. At moderate gas inputs, an $m = 1$ mode is observed in the plasma with an azimuthal phase velocity approximately the same as the $E \times B$ velocity. The radial eigenfunction, Fig. 4, is largest in the region in which the large ambipolar transport is observed. At high gas inputs, the plasma edge becomes more turbulent. Although direct evidence is absent, it seems plausible that the observed ambipolar transport is due to this instability.

TMX UPGRADE. Because of the success of TMX, an improved tandem mirror, TMX Upgrade, is being constructed. TMX Upgrade is expected to yield improved axial and radial central-cell confinements. Axial confinement will be increased by using thermal barriers[11] to permit a difference in electron temperature between the plug region and the central cell. Radial confinement will be improved by a stronger magnetic field (0.3 T instead of the 0.1 T in TMX) and by a weak mirror within the axisymmetric part of the central cell; as a result the number of particles that undergo resonant transport will be reduced. The better confinement is predicted to yield increased central-cell temperatures ($T_e \simeq 0.6$ keV, $T_i \simeq 0.9$ keV).

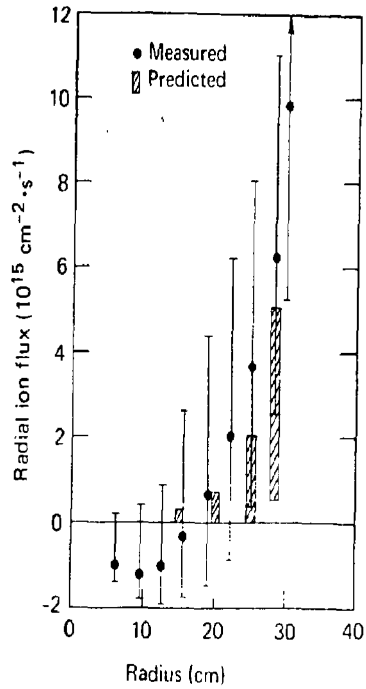


Fig. 3. Nonambipolar radial transport.

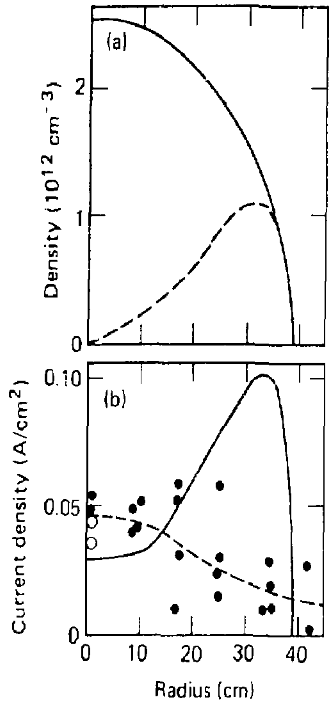


Fig. 4. Ambipolar radial transport: (a) average (solid line) and rms-oscillation densities, (b) ion end losses (data points and dashed line) and calculated ion source.

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