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ABSTRACT

Central cell plasmas in Tandem Mirror Experiment-Upgrade (TMX-U) are heated with 100 kW of ICRF transmitter power to ion temperatures of 1.5 keV at densities of 2×10^{12} cm^{-3}. We have used two Faraday-shielded antennas: the first had one 90^0 loop; and the second, in current use, has two 170^0 loops connected in an m = 1 configuration. We are also installing a slot antenna. Optimum heating for wave launching occurs below the cyclotron frequency, consistent with slow wave heating. In TMX-U, we observed a power threshold, which is consistent with computed end-loss power balance. The measured loading resistance varies with density and frequency in agreement with McVey's antenna-plasma coupling code.

INTRODUCTION

TMX-U is designed to study the formation of thermal barriers and their effect on plasma confinement /1/. Thermal barriers /2/ enhance the axial electrostatic confinement of a tandem mirror by insulating central cell electrons from potential peak electrons, which can then be heated to higher

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temperatures. This increases the confining potential, and provides confinement of central cell densities that exceed the end cell densities. TMX-U is designed to confine isotropic ions in the central cell with temperatures up to 0.9 keV. Achieving these temperatures and reducing the ion collision frequency requires ICRF /3/ and/or neutral beam heating in the central cell.

In Fig. 1a, we show the locations of the ICRF antennas on TMX-U. The loop antennas were used to obtain the results described here. The slot antenna /4/ is being installed; its low inductance of 0.5 μH, and higher predicted loading resistance /5/, should provide a loaded $Q \approx 20$ with low voltage.

Each antenna is driven by a Class C power amplifier, capable of 200 kW /6/. The matching network, located within the vacuum, covers the range of 1.7 to 4.0 MHz /7/. Network analyzer processing of the forwaro and reflected power provides data for tuning the matching network and for computing the loading resistance and reactance /6/.

HEATING

The first antenna that we used on TMX-U was a 5.5-turn loop subtending 90^0 (Fig. 1b). The heating efficiency, which is the fraction of the radiated power that appears in the rate of rise of the diamagnetism, was a maximum of 10% for $\omega/\omega_{ci} < 1$ and near zero for $\omega/\omega_{ci} > 1$. However, the density always decreased during the ICRF pulse. These data are consistent with convective radial losses that could be driven by nonuniform electron heating of the ICRF. Based on this model, we designed an m = 1 antenna with two-170^0 loops to provide more symmetric heating.

We are currently using two-170^0 antennas that consist of three turns each and are connected in a series to cover the 1.7- to 4.0-MHz range (Fig. 1c). Our results were obtained using an optically opaque Faraday shield between two nonsegmented limiters, similar to the JET antenna shield /8/. Several of the shield bars are shown in Fig. 1c to illustrate their design.

Using the two-170^0 antennas, the heating efficiency is about 40% at a density of 2×10^{12} cm^{-3} and less at lower densities. The central cell

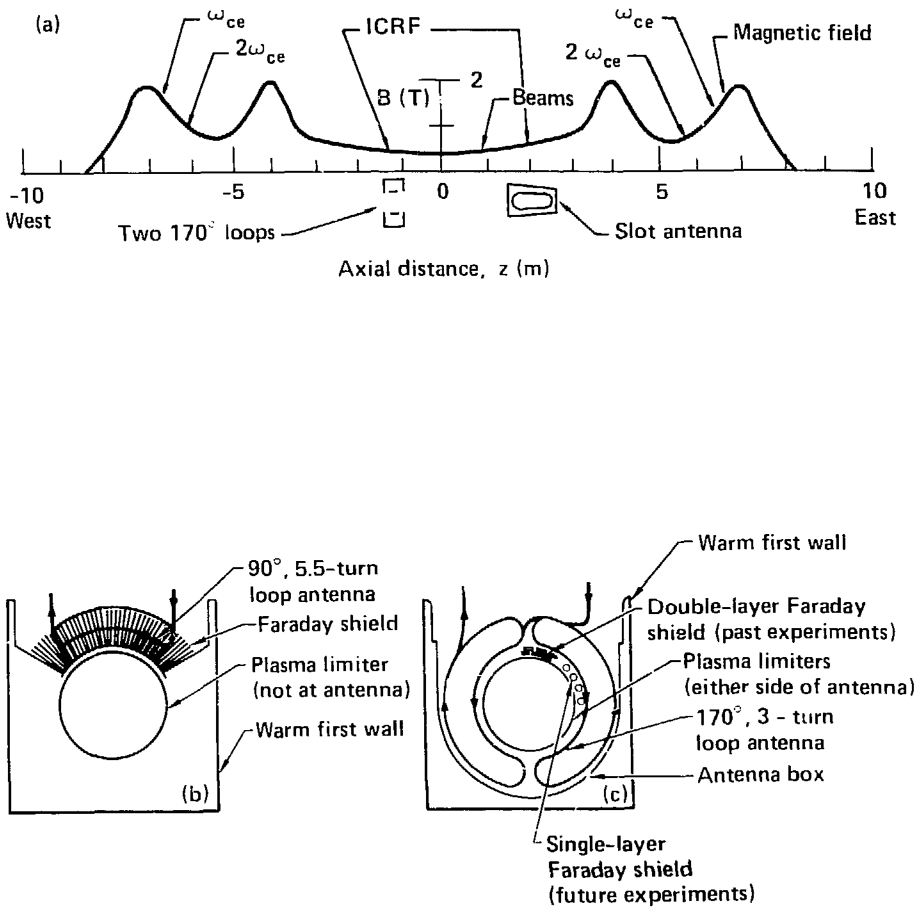

Fig. 1. The TMX-U axial magnetic-field profile is shown with the location of the loop and slot antennas (a). Two loop antennas have been used: (b) one-90^0 loop with 5.5 turns, and (c) two-170^0 loops of 3 turns each (several bars, from sets that completely encircle the plasma, are shown to illustrate two shield designs).

density increases slightly with these antennas during the application of ICRF power (Figs. 2a and 2b). Average ion temperatures of up to 1.5 keV, perpendicular to the magnetic field, are measured with diamagnetic loops (Fig. 2c).

The ion temperature $T_{ic\parallel}$ (Fig. 2d), parallel to the magnetic field, is measured at the ends of TMX-U with retarding-potential end-loss analyzers /9/. $T_{ic\parallel}$ increases during the heating pulse to 0.15 keV at 50 ms. This measurement, combined with an axial array of diamagnetic loops, indicates that the ion velocity distribution is anisotropic. Ions heated at the cyclotron resonance have a pitch angle of 16^0 from normal to the magnetic field, referenced to the midplane. Broadening of the angular distribution by ion-ion scattering is limited by charge exchange (τ_{cx} 10 ms) and electron drag ($\tau_d \approx 5$ ms) to pitch angles of less than 35^0 at 50 ms for the shot in Fig. 2.

A threshold is observed in the power that is required to achieve plasma heating (Fig. 3). We associate the threshold with the power that is required to heat the plasma beyond the collisional flow regime, where increasing the temperature increases the end-loss current proportional to the ion velocity. Once the ion temperature exceeds about 100 eV in TMX-U, the ions become mirror confined, the end-loss current decreases with increasing temperature ($\tau_{ii} \propto T_{ic}^{-3/2}$), and the end-loss power decreases as $T_{ic}^{-1/2}$. We divide the ion end-loss power by the ion heating efficiency ϵ, to obtain the radiated power required to heat the ions. At low ion temperatures, this is given by

$$P_0 \approx \frac{1}{\epsilon} \frac{qn^2 T_{ic} \pi r^2 L}{n\tau_{flow} + n\tau_{ii} \log R} \quad ,$$

where we use typical values for the plasma parameters: r = 20 cm, L = 200 cm, $\epsilon = 0.2$, the mirror ratio R = 7, and $\tau_{ii} = 90^0$ ion-ion scattering time. The measured density is $n = 1.7 \times 10^{12}$ cm^{-3}.

As the ion temperature increases, additional power-loss mechanisms become significant. We include the largest additional effects in the term P_1: electron drag with a fixed electron temperature of $T_e = 50$ eV and charge exchange on the gas required for fueling. These effects determine a limit to T_{ic},

$$P_1 = \epsilon^{-1} qnT_{ic} \pi r^2 L \ (\tau_d^{-1} + \tau_{cx}^{-1}) \quad .$$

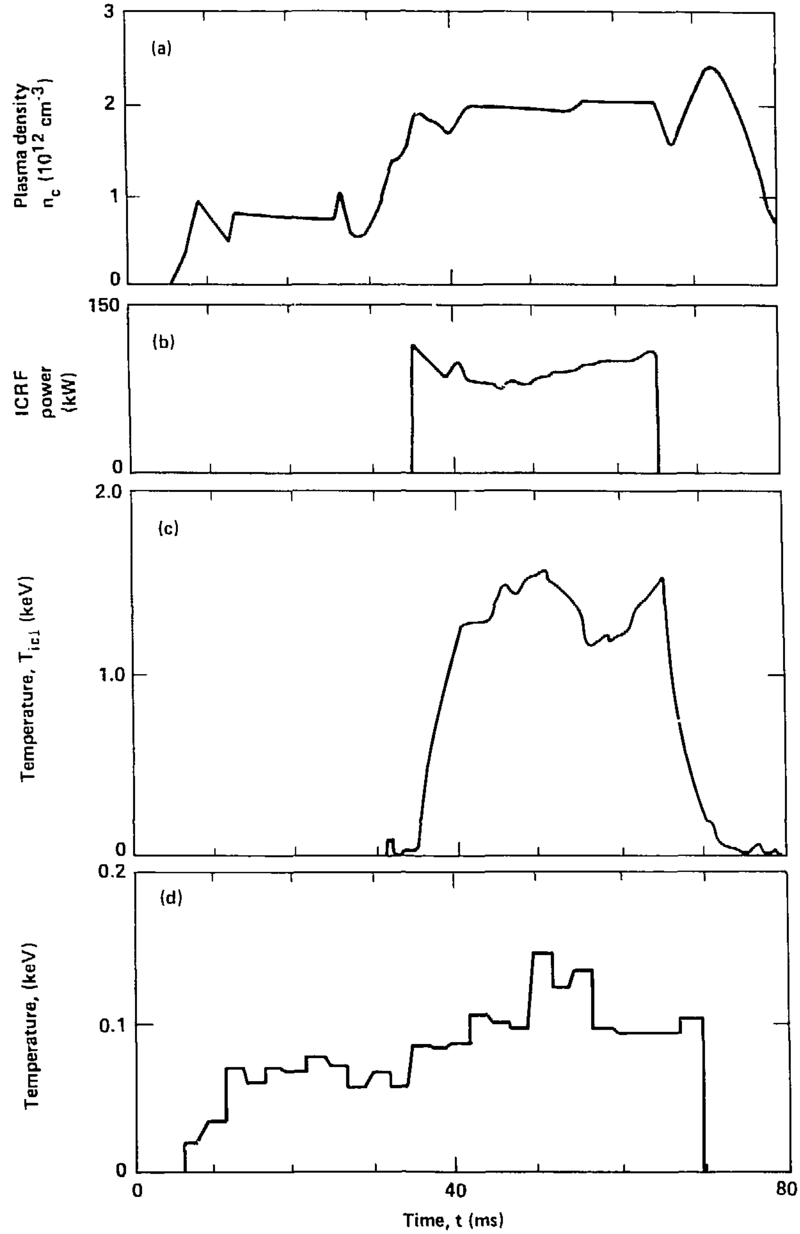

Fig. 2. With two-170^0 loop antennas, the plasma density (a) increases slightly during ICRF heating (b), and the temperature increases both perpendicular (c), and parallel (d) to the magnetic field.

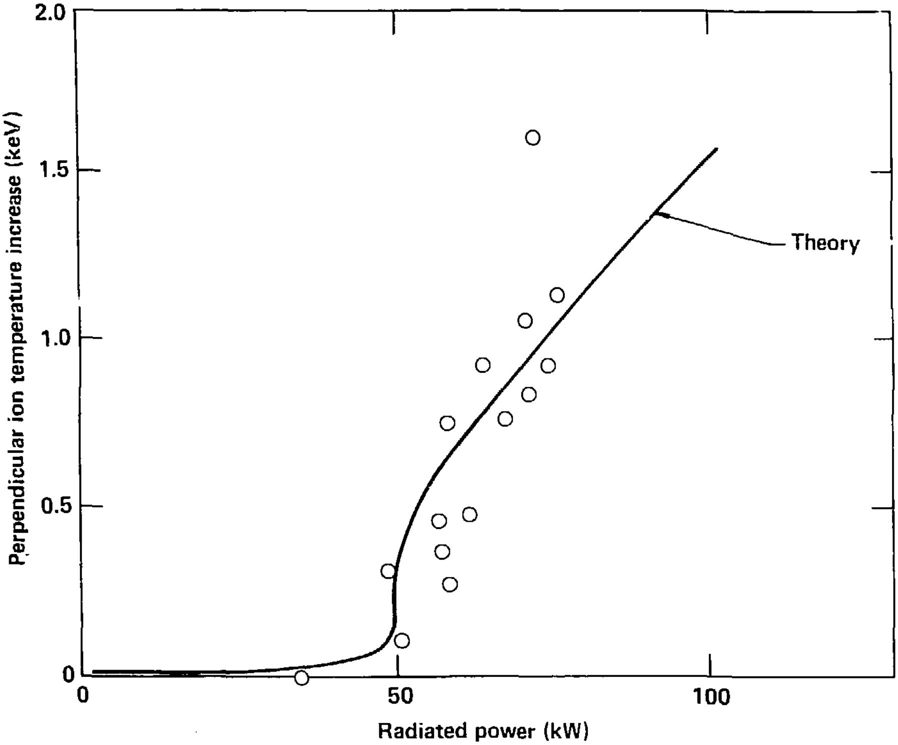

Fig. 3. Ion heating exhibits a threshold that is consistent with the line computed for the end-loss power balance, which is discussed in the text.

The total power is given by $P = P_0 + P_1$ and is plotted in Fig. 3. Further details of this model are discussed in Ref. /3/.

COUPLING

Faraday shields have been used on both TMX-U loop antennas. The purposes of these shields include both electrostatic shielding, and environmental shielding of the antenna and matching network from charge-exchange neutrals, uv radiation, and titanium gettering. Environmental shielding requires optically opaque shields that reduce the rf magnetic field reaching the plasma /10/. The power, which can be coupled at the voltage holding limit of the antenna relative to the maximum power without the shield, is reduced to 0.46 for the U-shaped shields used with the 90^0 antenna, and to 0.3 for the straight shields used with the two-170^0 antennas.

The parasitic loading, which we observed earlier when limiters allowed plasma to flow along the magnetic field into the shield, has been eliminated by reducing the radius of the limiters. Our computations show that the power dissipated on the shield by flowing plasma is comparable to the radiated power. This finding is consistent with our measurements of increased loading resistance with little or no ion heating.

We find that the measured loading resistance vs density in Fig. 4 agrees with predictions of McVey's antenna-plasma coupling codes /5/ for over an order of magnitude variation in both the plasma density and the loading resistance. The code prediction, as plotted, is corrected to a multiturn Faraday-shielded antenna by multiplying the square of the number of turns times the attenuation of the rf power by the shield (i.e., $6^2 \times 0.46 = 17$ for the 90^0 antenna).

We also find agreement between the measured and predicted loading resistance vs frequency (Fig. 5). The decrease in resistance just above the cyclotron frequency is consistent with launching slow waves for $\omega/\omega_{ci} < 1$ at the antenna. These can damp on a magnetic beach near the midplane for $\omega/\omega_{ci} > 0.8$. In this case, the multiturn correction of the loading resistance is $3^2 \times 0.3 = 2.7$.

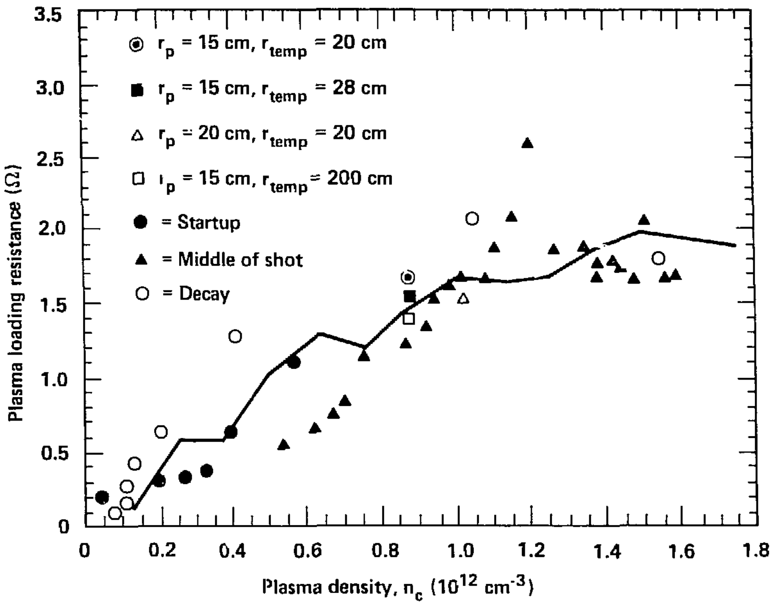

Fig. 4. The computed loading resistance vs density agrees with measurements at 2.48 MHz (ω/ω_{ci} = 0.85). The data are from the 90^0, 5.5-turn antenna.

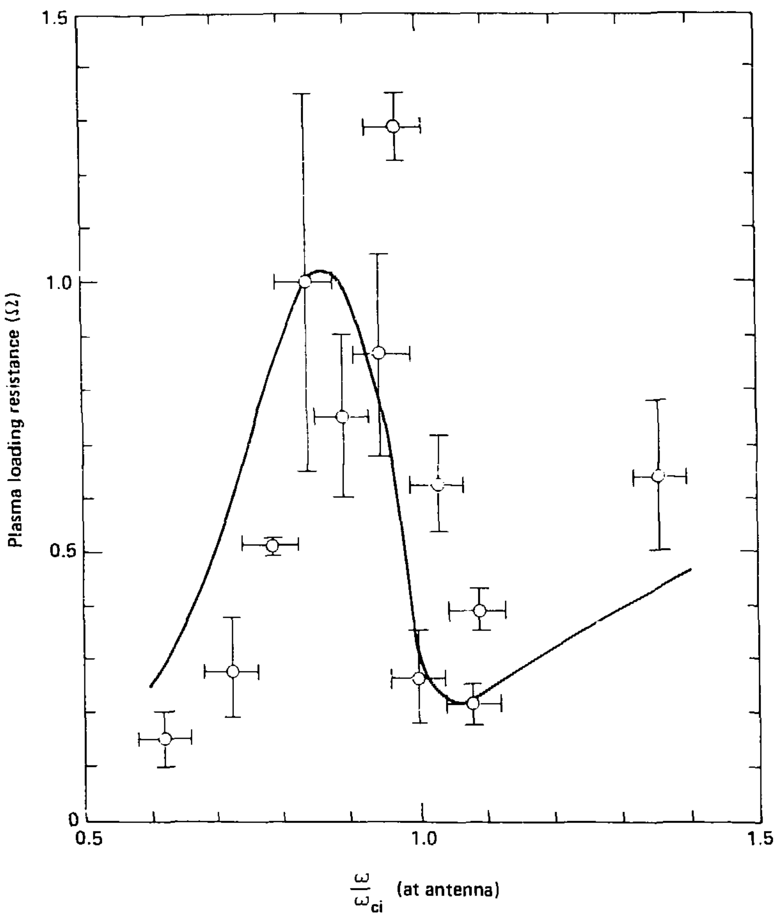

Fig. 5. The computed loading resistance of the two-170^{0} antennas vs frequency agrees with measurements at a density of 1 x 10^{12} cm^{-3}. The vertical bars indicate the shot to shot variation, and the horizontal bars the variation of the dc magnetic field within the near field of the antenna.

PLANS

Our next sequence of ICRF heating experiments include two new elements: the slot antenna, described above, and a new Faraday shield for the two-170^0 loop antennas. Both types of antennas are designed to handle 200 kW. A 50% transparent shield for the loop antennas has been constructed using 1 cm diameter tubes, four of which are shown in Fig. 1c. This transparent shield will provide electrostatic shielding with little environmental shielding; we predict an increase in transmission by a factor of three, producing a similar increase in the loading resistance. These two antenna types, operating simultaneously with separate transmitters, will increase the radiated power from the present maximum of 70 kW to as much as 300 kW in our next experiments.

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