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ABSTRACT

An ion-cyclotron range of frequencies (ICRF) heating system has been installed in the Tandem Mirror Experiment-Upgrade (TMX-U) central cell. Our initial objective is to heat low density ions in the near field of the antenna. This heating reduces the collisionality of central cell ions, which decreases the filling rate of the thermal barrier by passing ions from the central cell. From power- and particle-balance calculations, we determined that 60 kW of absorbed power is sufficient to heat plasma densities of up to 2×10^{12} cm^{-3}. These power requirements are consistent with ion heating results from the Phaedrus tandem mirror.[1] Based on this, we have installed a 200-kW oscillator/power amplifier, tunable to as low as 1.5 MHz. It drives a 110^{o}, 9 1/2-turn loop antenna that has a commercially built Faraday shield and matching network.[2] The system has been tuned with plasma and is being used for the initial heating studies at the ion-cyclotron frequency ω_{ci}.

INITIAL EXPERIMENTS

The first application of ICRF in TMX-U will be to aid in the formation of thermal barriers.[1,2] Two other possible applications in the central cell are to heat the boundary of the plasma to sustain a halo that shields the hot core plasma from neutrals, and to bulk heat the central cell as a supplement to or substitute for neutral beams. We have used results from the Phaedrus tandem mirror experiment[3] as the empirical basis for planning these ICRF experiments.

Formation of thermal barriers in TMX-U requires heating the central cell ions to reduce collisional filling of the thermal barrier to a level that can be pumped. The bulk of the ion distribution is heated more effectively by ICRF at ω_{ci} than by neutral beams.[1] This has been evaluated in detail[2] and is summarized below. Figure 1 shows the power balance for central cell ions--with and without a thermal barrier. Without a thermal barrier, the ion confinement is due only to magnetic mirrors in the computation, as shown by the upper solid line (a). With a thermal barrier, the axial confinement is enhanced by electrostatic stoppering that reduces end losses by more than an order of magnitude, as shown by the lower solid line (b). The solid lines depict the power required to maintain the plasma at the indicated density. The ion temperature is related to the density by the requirement that the filling rate of the barrier be low,[2] T_{ic} (eV) = $(n_c/6.3 \times 10^{8}$ cm$^{-3})^{2/3}$. Losses due to radial diffusion become significant at higher temperatures, as shown by the bend in line (b). Charge-exchange losses are included, from the gas required to fuel the plasma.

We also need to determine the maximum power that can be coupled into the plasma with ICRF and compare with the required powers. The lower edge (d) of the cross-hatched region indicates the approximate power absorbed by the central cell plasma in the Phaedrus tandem mirror. The upper edge (c) scales the power by $r^2 = 4$ to indicate the higher power absorption expected with the larger radius of the plasma in TMX-U. The ICRF heating in Phaedrus is believed to be due to an evanescent fast wave,[3] and we expect empirical scaling from Phaedrus to fail near a deuteron density of 8 x 10^{12} cm^{-3} because fast waves will propagate above this density in TMX-U.

An ICRF heating system, based on the above requirements, was installed in TMX-U in November 1982. The transmitter is an AN/FRT-86, operated in Class C, yielding an output power of up to 200 kW. The output stage has been revised to lower the minimum frequency to 1.5 MHz to provide the ω_{cd} resonance at a 2-kG midplane, central-cell magnetic field. A 110°-partial-turn antenna, Faraday shield, and network to match the antenna impedance to a 50-Ω line were designed and built commercially.[4]

A change from hydrogen to deuterium operation, and a reduction in the minimum central-cell magnetic field from 3 to 2 kG decreased the frequency for midplane resonance from 4.5 to 1.5 MHz, shortly before the antenna system was delivered. The frequency change was incorporated into the antenna system by replacing the partial-turn loop with a 39-μH, 9 1/2-turn loop that fits within the same Faraday shield and mounts to the same supports. We find that this produces a radio frequency (rf) magnetic field that is equivalent to that of the 110° half-turn loop; we measured the rf field near the antenna in air at a 56-MW power level. These measurements agree to within 30% with computations of the vacuum field of a 9 1/2-turn coil[5] as well as with computations[6] using 10 times the current in a 110° 1/2-turn coil. From this we have concluded that the multiturn approach is viable.

The ICRF system in TMX-U has been operated at 1.5, 1.7, and 2.3 MHz with the multiturn antenna. The maximum power at 2.3 MHz was 1.5 kW--above which we observed break down. This power corresponds to about 5 kV on the matching capacitors. Although this power is insufficient to produce observable heating at higher densities, by following line (a) of Fig. 1 and operating at a central cell density of about 1 x 10^{11} cm^{-3} the ICRF heating was sufficient to increase the density of one end plug by a factor of two and to decrease the axial end losses of ions relative to electrons. This effect may be due either to direct electron heating or to excitation of a slow wave that heats ions on the magnetic beach at the central cell midplane, 1.3 m for the antenna.

These experiments will be continued at higher power levels after making appropriate alterations to the antenna system. We are evaluating the present 110° antenna, pairs of 180° antennas, and slot antennas with McVey's antenna code.[6] Our goals are to uniformly heat the entire plasma cross section and to maximize the loading resistance. We have used the code to investigate heating from a single 110° antenna, operated at several times the cyclotron frequency with propagating fast waves as in the Elmo Bumpy Torus (EBT) experiment.[7] We find that the heating is both azimuthally uniform and radially uniform except for a null near the axis with the lowest radial eigenmode. However, measurements on EBT show that only the tail of the ion distribution is heated at cyclotron harmonics--rather than the bulk heating that is required in TMX-U and which we expect from ICRF near ω_{ci}. We are also using the code to investigate heating by the near field evanescent waves near ω_{ci} as well as by slow waves that would damp on the beach near the central cell midplane.

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REFERENCES

1. Molvik, A. W., F. E. Coffield, S. Falabella, D. Griffin, B. H. McVey, W. L. Pickles, P. Poulsen, T. C. Simonen, and J. Yugo, Initial TMX Central-Cell ICRH Experiments, Lawrence Livermore National Laboratory, Livermore, CA, UCID-18866 (1980).

2. Molvik, A. W. and S. Falabella, Use of ICRH for Startup and Initial Heating of the TMX-U Central Cell, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19342 (1982).

3. McVey, B. D., R. A. Breun, S. N. Golovato, A. W. Molvik, D. L. Smatlak, D. K. Smith, and L. Yujiri, "Ion Cyclotron Resonance Heating Studies in the Central Cell of the Phaedrus Tandem Mirror"; to be published.

4. Mullen, J. H. and T. L. Owens, "ICRH Antenna System Designs and Configurations for EBT-S, TMX-U, and TFET," Bull. Am. Phys. Soc. 27, 1045 (1982).

5. Myer, R., J. Luine, A. W. Molvik, S. Falabella, and T. L. Moore, Paper A-1.3 for this conference.

6. McVey, B. D., Excitation Theory of the Inductive Drive, TRW, Inc., Redondo Beach, CA, Task II Report-2740 (1980).

7. Owens, T. L., J. H. Mullin, F. W. Baity, W. A. Davis, D. C. Eldridge, and D. L. Hillis, "Heating Experiments in the Ion-Cyclotron Range of Frequencies on EBT-S," Nucl. Fusion 23 (1983).

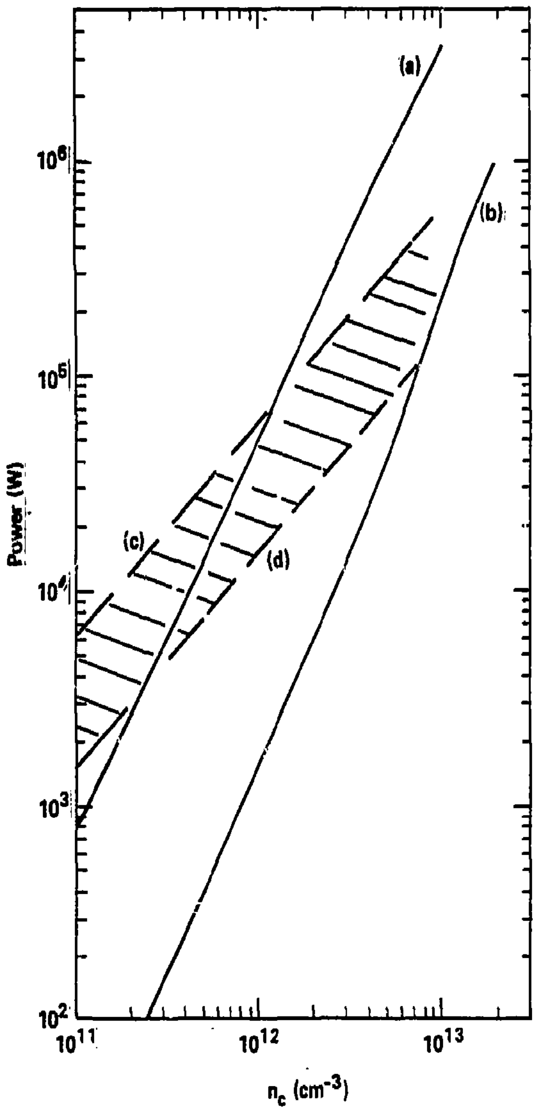

Fig. 1. The power required to heat ions in the TMX-U central cell to a pumpable temperature before (a) and after (b) thermal barrier formation (Φ_i/T_{ic} = 2.44) versus density (n_c). The power that can be coupled with ICRF is shown for Phaedrus data (d) and scaled to TMX-U (c).