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ICRF HEATING OF PASSING IONS IN TMX-U*

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ABSTRACT

By placing ion-cyclotron resonant frequency (ICRF) antennas on both sides of a midplane gas-feed system in the central cell of the Tandem Mirror Experiment-Upgrade (TMX-U), our results have improved in the following areas:
(a) The end losses out both ends show a factor of 3 to 4 increase in passing-ion temperatures and a factor of 2 to 3 decrease in passing-ion densities.
(b) The passing-ion heating is consistent with Monte Carlo predictions.
(c) The plasma density can be sustained by ICRF plus gas fueling as observed on other experiments.

I. SYMMETRIC PASSING-ION HEATING

We introduced ICRF heating into the TMX-U experiment to reduce the collisionality of passing ions and, thereby, keep the thermal-barrier collisional filling rate below the pumping rate [1]. This is one of the necessary conditions for successful operation of a thermal-barrier tandem mirror. A thermal barrier is a depression of the plasma potential in each end cell that isolates central-cell electrons from the warmer electrons at the positive potential peak, which provides axial plugging [2]. ICRF heating can reduce filling both by heating the passing ions and by reducing their density through trapping in the central cell.

The locations of ICRF antennas and resonances, electron-cyclotron resonant heating (ECRH) resonances, and gas fueling are shown in Fig. 1. The ICRF system is discussed in greater detail elsewhere [3,4].

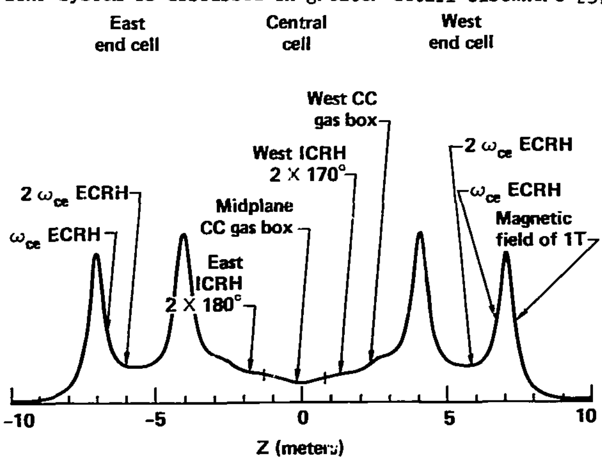

Fig. 1. TMX-U fueling and rf heating locations with a magnetic-field strength that reaches a maximum of 2.3 T. Lines between the antennas and the midplane CC (central-cell) gas box indicate the ion-cyclotron resonance locations.

Previous experiments in TMX-U used gas fueling 2.25 m west of the central-cell midplane, and a double half-turn loop 1.26 m west of the midplane [3]. These experiments demonstrated efficient perpendicular heating of trapped ions, and good agreement between plasma loading and the predictions of the code [5] ANTENA. Figure 2 shows measurements with a new diagnostic: the end-loss ion spectrometers (ELIS) [6]. The ELIS measures: the plasma potential from the low energy cutoff of the ion distribution, the parallel ion temperature (which we equate with the passing-ion temperature) from the slope below the high energy cutoff, and the end-loss current density from the integral of all the channels. For the east-end losses that passed through ICRF resonances, the bulk of the ion-energy distribution was heated; whereas, for the west-end losses that did not have to pass through a resonance, the bulk of the ion distribution was much colder although a tail was heated to similar energies as the bulk in the east end. The west-end loss current (Fig. 2) was larger by a factor of 2 to 3.

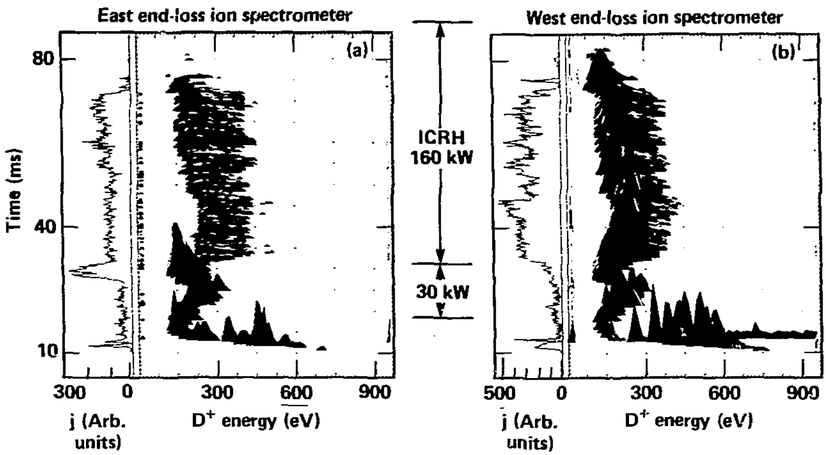

Fig. 2. Fueling from the West CC gas box results in heating toward the east end, but less toward the west because ions can flow to the west end without passing through an ICRF resonance where they would be heated or trapped. The currents and ion-energy distributions are from the ELIS. (3/12/86 Shot 29.) (Note that the current scales are different on each graph.) The CC density is 3 to 4 × 10^{12} cm^{-3}.

Present experiments use a more symmetrical arrangement, with gas fueling near the central-cell midplane (0.25 m east) and double half-turn antennas toward both ends of the central cell. The frequencies, 2.88 MHz east and 2.55 MHz west, are selected to provide an ion-cyclotron resonance that will damp slow waves between each antenna and the gas box. Newly ionized particles must make a minimum of one pass through a resonance before reaching an end cell. The disadvantage of midplane gas fueling is that the energy confinement time is reduced because, on each bounce, the central-cell ions pass through the gas box, where they have a finite probability of being lost by charge exchange.

The results from the new arrangement are similar at both ends as predicted [7]: the end-loss bulk-ion temperature is increased by a factor of 3 to 4, and the end-loss current is reduced by a factor of 2 to 3 (Fig. 3). The collisional filling of the thermal barriers is proportional to $n_p T_p^{-1.5}$ [see Ref. 1], the passing-ion density and temperature. This filling rate is reduced by a factor of more than 10 for the data shown here. However, despite the reduction in passing-ion collisionality, the maximum density at which thermal-barrier operation is obtained has not increased significantly, indicating that other effects are limiting operation.

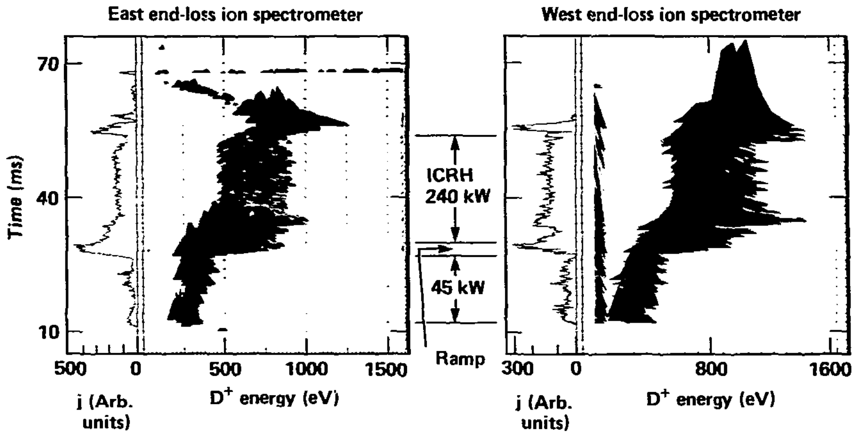

Fig. 3. Fueling from the midplane CC gas box results in similar increases in temperature and decreases in current for both ends.

II. COMPARISON WITH MONTE CARLO PREDICTIONS

We believe that the passing-ion heating occurs in a single pass through the resonance because only the temperature at the nearest end is affected substantially when one ICRF system turns off earlier. Based on this observation, we plot the passing-ion temperature (measured by the east ELIS) vs the ICRF power radiated from the east antenna (Fig. 4) and find a nearly linear relationship. Similar results are obtained at the west end.

Figure 4 shows the predictions of a Monte Carlo code [8] by a line through three computed points. The code used the following parameters: central-cell density $n_e = 3 \times 10^{12}$ cm^{-3}, the data varied from 0.7 to 3.5 $\times 10^{12}$ cm^{-3}; electron temperature $T_e = 42$ eV compared with the data from 20 to 80 eV; a radial confinement time of 26 ms; and 0.5 of the radiated power absorbed by ions, compared with typical experimental efficiencies of 0.2 to 0.5. This agreement between code and experiment is quite good considering

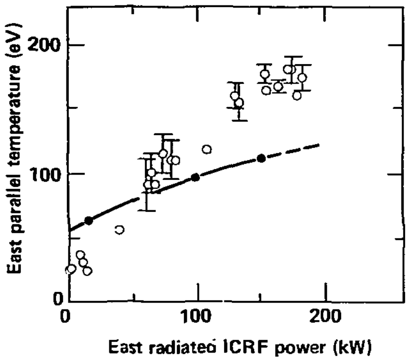

Fig. 4. The parallel ion temperature to each end, with midplane gas fueling, increases with the radiated power from the ICRF antenna nearest that end. The line is the Monte Carlo prediction described in the text. The CC density is 0.7 to 3.5 × 10^{12} cm^{-3}.

that the code has not been iterated with the data. For example, better agreement would be obtained by increasing T_e proportionally to the ICRF power in the Monte Carlo code as observed in the experiment.

III. ICRF-SUSTAINED OPERATION

Operation with the midplane central-cell gas-box fueling and ICRF power can sustain the plasma density and temperature in TMX-U as previously predicted [9] and demonstrated in other tandem mirrors [10], but which did not occur with the west gas-box fueling of TMX-U. We now typically sustain plasma densities of 1 to 3 × 10^{12} cm^{-3} for the duration of the ICRF and midplane gas.

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