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ICRF HEATING OF PASSING IONS IN A THERMAL BARRIER TANDEM MIRROR*

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Introduction

Ion heating is used in the central cells of tandem mirrors to reduce the collisional trapping of passing ions in the end cell thermal barriers. In this paper, we reevaluate ICRF heating of the TMX-U central cell in two limits. The first we term isotropic heating, because we impose the condition that ions heated in the perpendicular direction be confined for at least one 90° scattering time, thereby heating the passing ions. The second we call anisotropic heating. It uses higher ICRF power to mirror trap a majority of the ions near the midplane, thereby reducing the density and collisionality of passing ions. Anisotropic heating has the advantage of increasing with ICRF power, whereas isotropic heating is limited by ion collisionality. Both techniques require gas fueling near the central cell midplane, with an ion cyclotron resonance toward each end cell to heat the cold ions.

I. Isotropic ICRF Heating

Isotropic heating depends on ion-ion collisions; therefore it will be limited by the ion density and temperature that determine the collision frequency, rather than by the available ICRF power. The ion-ion collision time τ_{ii} determines maximum fueling rate ν for which warm central cell ions can be heated to pumpable temperatures, given by

$$\nu(sec^{-1}) \le \tau_{ii}^{-1} = \frac{n_w}{10^6 A^{1/2} T_i^{3/2}(eV)}.$$

The atomic mass is A. The minimum ion temperature T_i is determined from equating barrier filling and pumping rates:[1] $T_i(eV) = (n_w/\mathbf{P})^{2/3}$. The pumping rate is proportional to **P**. It is in the range $2 \times 10^8 \le \mathbf{P} \le 6 \times 10^8$, for which we obtain $\nu = 140$ to 435. Gas fueling in excess of this rate will cause warm passing ions to be lost by charge exchange before reaching the required temperature.

Ionization of the fueling gas sustains the plasma density with axial and radial losses and provides for build up of the density. The total fueling rate ν, including charge-exchange losses associated with fueling, is defined as

$$\nu(sec^{-1}) = (\nu_\parallel + \nu_\perp + \frac{1}{n}\frac{dn}{dt})\frac{<\sigma v>_{tot}}{<\sigma v>_i}.$$

The present gas fueling rate for a cold flowing plasma without axial plugging is $\nu \approx 2000\ sec^{-1}$.

Isotropic heating requires improved radial and axial confinement in order to be able to fuel at reduced values of ν. Such improvements have been demonstrated, the first by electrically floating the end walls,[3] and the second by formation of a thermal barrier.[4] Also, since the maximum allowed fueling rate is directly proportional to the pumping rate, improved pumping can reduce the requirements on confinement or allow faster buildup of density.

The minimum power requirements for isotropic ICRF heating are given by

$$P(W) = \nu_E q n (3/2) T_i V = \nu_E q V (n^{5/3}/\mathbf{P}^{2/3}),$$

where the perpendicular temperature is heated only to the required passing ion temperature in order to maximize collisionality. The volume is $V = 5 \times 10^5\ cm^3$. The results are shown in Fig. 1 for the two pumping rates **P**. We have taken the energy loss rate ν_E to be equal to the warm ion loss rate ν. The capability of heating at higher fueling rates is desirable because thermal barrier conditions can then be established, even with poorer global confinement, or maintained during faster build-up rates of density.

II. Anisotropic ICRF Heating

Anisotropic ICRF heating provides a technique to reduce the passing ion collisionality at higher fueling rates. It requires using higher ICRF power to heat and trap ions between magnetic mirrors, thereby reducing the density at the mirror[2,5] as shown by the data in Fig. 2. This technique has the advantage that, even if $T_{\parallel}$ increases only slowly with ICRF power, the passing ion collisionality can be reduced sufficiently, as indicated by heating trajectories A to B or C in Fig. 3.

The power threshold for anisotropic heating was discussed by Molvik, et al.[2] The scaling of the power threshold versus density is shown by the data points in Fig. 1. The power requirement is given approximately by

$$P(MW) = \alpha n^2(10^{13}cm^{-3})E_{\perp}(keV),$$

where $\alpha \approx 2$ for gas box fueling outside of the ICRF resonances fits the measured threshold for anisotropic heating in TMX-U, and $\alpha \approx 6$ is predicted from Fokker-Planck studies for midplane gas fueling.[5]

III. Selection of Fueling and Heating Locations

The location of the gas fueling is chosen to be near the central cell midplane, between ICRF resonances from two antennas, as in Fig. 4a. This is similar to the arrangements used successfully in the Phaedrus[7] and TARA[8] tandem mirrors. It has the advantage that cold ions make at least one pass through a resonance, rather than being prevented from reaching a resonance by a potential peak formed near the resonance during anisotropic heating. A corollary is that cold ions are not preferentially lost out one end. Midplane gas fueling is also predicted to produce higher $T_{\parallel}$.[5] The parallel heating will be aided by any potential peak in the central cell that will add to the parallel energy of passing ions. These advantages counteract the disadvantage of higher ICRF power requirements, that as shown in Fig. 1, still allow heating densities up to $2 \times 10^{12} cm^{-3}$ with 200 kW absorbed power.

The axial location of the ICRF antennas is selected to satisfy the following conditions: a) Launch slow waves that will damp at resonances outside of the gas box, i.e., above 3 kG. For densities up to 3×10^{12} cm^{-3} in near-term running, this requires that the antenna be at fields of ≥ 4 kG; b) Minimize radial transport by placing the resonance below 4.3 kG[6]; c) Provide no resonance in the end plugs that could deeply trap passing ions. Including Doppler shifts, this requires that the central cell resonance be at a field no greater than 3 to 4 kG; d) Locate the antennas and resonance in moderately small magnetic field gradients; and e) Minimize interference with other systems.

The antenna design selected is the two-half-turn loop, that has functioned well in tandem mirrors.[2,7,8] One antenna can be the existing two-170° loop antenna,[2] Fig. 4b,c, located at 3.85 kG west of the midplane. For the second, we are designing a new, higher power, two-half-turn antenna[9], to be installed near 5 kG on the east end of the central cell. The higher power capability is obtained by using low inductance, single strap antennas rather than the present three-turn design, and by placing the matching network outside of the vacuum where there is room to add the capacitance necessary to operate at frequencies as low as 2.3 MHz.

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Figure Captions

Figure 1. The power, required to be coupled to the ions, is shown versus the central cell density. Anisotropic heating is labeled by the value of α for $E_i = 1$ keV. Isotropic heating is labeled by **P**.

Figure 2. Ratio of plasma density at the inner mirror to the midplane of the central cell versus the average perpendicular ion energy for constant midplane density ±20%.

Figure 3. Anisotropic ion heating can reduce collisional barrier filling sufficiently either by only reducing the inner mirror density, *line A-B*, or *by a combination of reducing the density and increasing* $T_{\|}$, *line A-C*.

Figure 4. The TMX-U axial magnetic-field profile is shown with the location of the ICRF antennas and the gas fueling (a). A two-170° loop antenna of 3 turns each is shown (b,c) with two designs of Faraday shield.

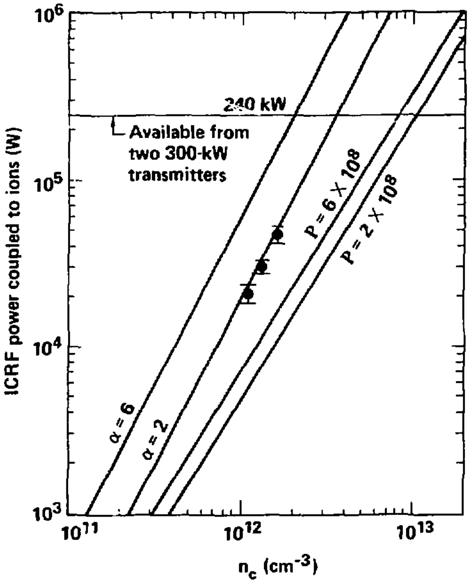


Figure 1.

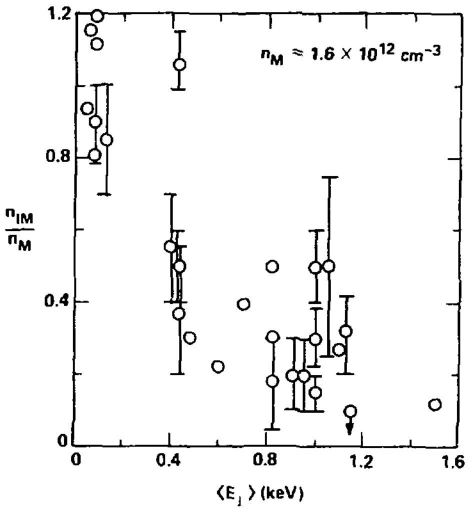


Figure 2.

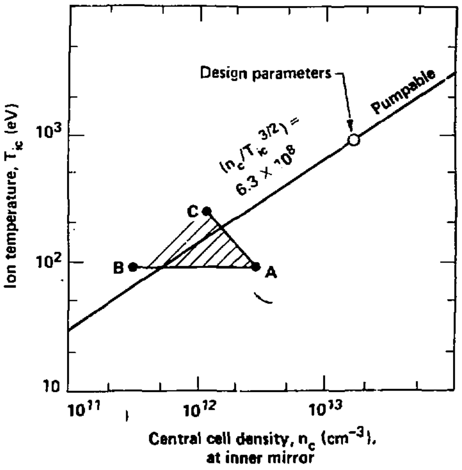
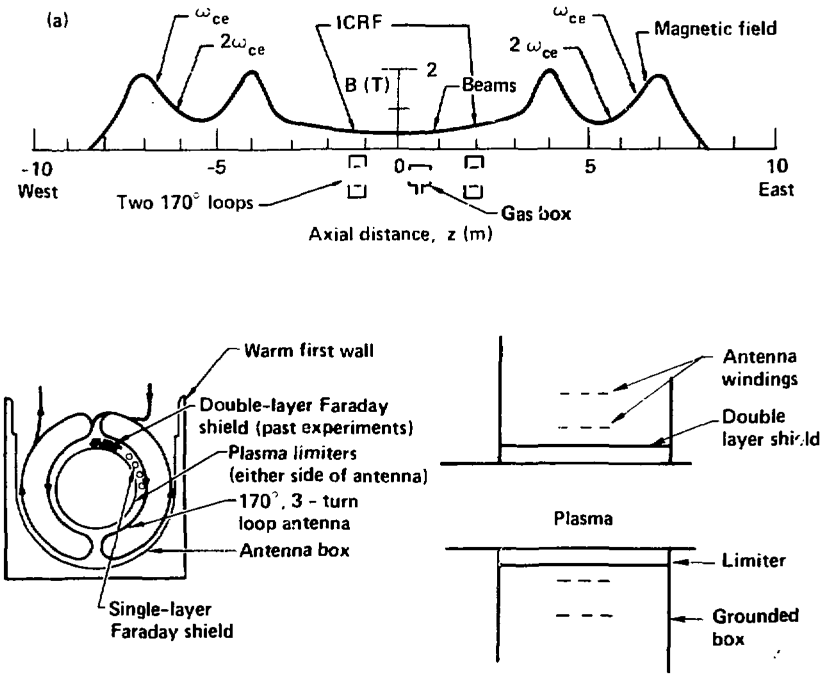


Figure 3.



(b) Cross-sectional view

(c) Axial view

Figure 4.