Ion Cyclotron-Resonance Heating in a Toroidal Octupole

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(Received 10 February 1975)

rf power near the ion cyclotron-resonance frequency has been used to produce a hundredfold increase (from $\lesssim 1$ to ~ 100 eV) in the ion temperature in a toroidal octupole device. The heating produces no noticeable instabilities or other deleterious effects except for a high reflux of neutrals from the walls. The heating rate is consistent with theory and the limiting ion temperature is determined by charge-exchange losses.

Ion cyclotron-resonance heating (ICRH) has previously been used in the Model-C stellarator,[1] in a turbulently heated magnetic mirror,[2] and in the ST tokamak.[3] We report here the first experiments in which high-power ICRH has been used to raise the ion temperature significantly (a hundredfold) in a toroidal multipole device. The ICRH agrees with theoretical calculations,[4] produces no noticeable instabilities or other deleterious effects except for a high reflux of neutrals from the walls, and is limited to ~100 eV by losses due to charge exchange with the background neutrals. The advantages of studying ICRH in a toroidal multipole are that density, electron temperature, poloidal field, and toroidal field can all be adjusted independently from zero up to values approaching those used in present tokamak devices.

The experiments were performed on the small Wisconsin toroidal octupole,[5] part of which is shown in Fig. 1. The poloidal magnetic field is produced by the currents in the four solid copper hoops which encircle an iron transformer core (not shown). The poloidal magnetic field pulse is normally a half sine wave of 5 msec duration. A toroidal magnetic field of up to 1 kG can be added, but for most of the experiments described here no toroidal field was used.

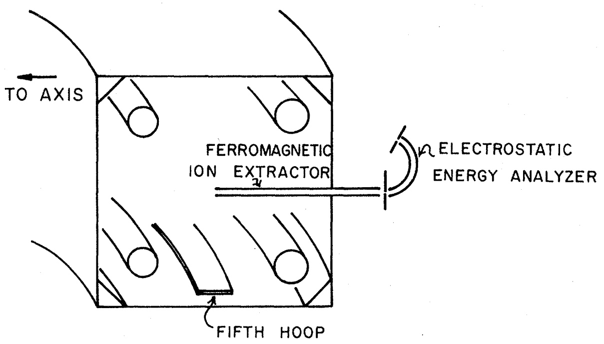

FIG. 1. Cross section of toroidal octupole showing fifth hoop (shielding not shown) and electrostatic ion energy analyzer.

The rf power is introduced by means of a single-turn, flat copper, electrostatically shielded, fifth hoop located near the bottom wall of the device. The fifth hoop is the inductor of the tank circuit of an oscillator tuned to ~1 MHz and capable of supplying up to 500 kW of rf for 1 msec. This system produces a toroidal electric field which is everywhere perpendicular to the confining magnetic field and which falls rapidly with distance from the coupling hoop. The resonance zone for protons (~700 G) is an approximately circular cross-section toroidal surface which comes within ~6 cm of the fifth hoop at its closest point. The resonance zone can be moved by changing the magnetic field strength or by changing the oscillator frequency, but the ion heating is observed to be a maximum at the values chosen. When the resonance zone is moved closer to the minor axis, the electric field decreases sharply, and when the resonance zone is moved closer to the wall, the resonance surface comes within an ion gyroradius of the limiter.

Plasmas with $kT_e \sim 3-5$ eV are produced either by electron cyclotron-resonance heating (ECRH) at 2.45 GHz ($n \lesssim 10^{11}$ cm^{-3}) or by gun injection ($n \lesssim 5\times 10^{12}$ cm^{-3}). Ion distribution functions are measured by an electrostatic energy analyzer[6] which extracts particles from the zero-field region near the axis through a ferromagnetic pipe.[7] The rf power absorbed by the plasma can be determined by measuring the change in Q of the oscillator tank circuit. The rf electric field in the plasma is measured using magnetic probes. These probes show that even at the highest densities available (6.7×10^{12} cm^{-3}), the electric field at the resonance zone nearest the hoop is hardly affected by the plasma, whereas the rf field on the $B=0$ axis is depressed by about a factor of 30 because of lack of accessibility in regions where the wave frequency exceeds the

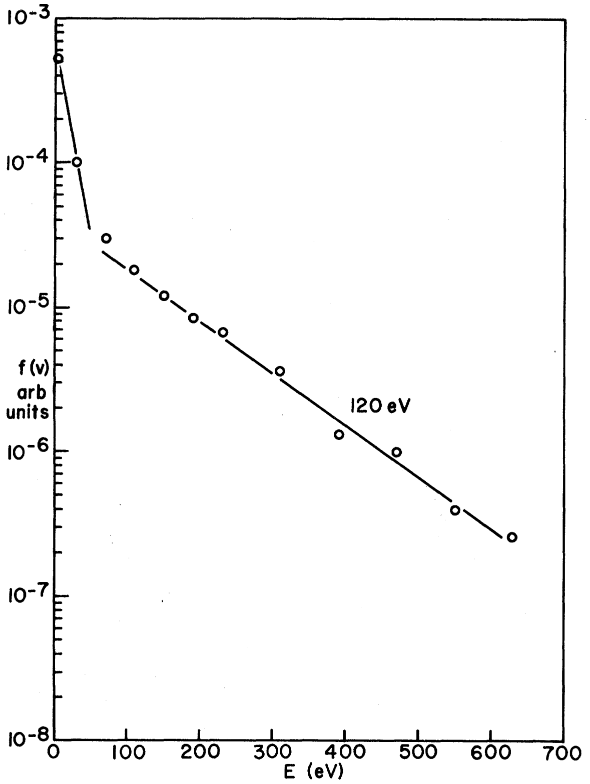

FIG. 2. Ion energy distribution with two-temperature Maxwellian fit for $n \simeq 6\times10^{10}$ cm^{-3}.

lower-hybrid-resonance frequency.

When the rf power is applied, the ion temperature rises from <1 to ~100 eV in ~100 μsec and then remains nearly constant until the rf is turned off. Thus an equilibrium is achieved between ICRH and charge-exchange losses. Figure 2 shows that the ion energy distribution function for a typical case is reasonably Maxwellian except for a cold component of comparable density that probably represents ions which never reached a resonance zone. Roughly half the ions are mirror trapped and never cross the resonance zone provided their magnetic moment is conserved. For those ions which do cross the resonance zone, the distribution function is predicted to be Maxwellian[8,9] and to remain so even in the presence of weakly velocity-dependent losses.

The power absorbed by the plasma is plotted in Fig. 3 versus plasma density. Applied voltages on the hoop are typically 3 to 7 kV, zero to peak. The absorbed power is determined from the loading of the oscillator tank circuit (crosses) and by the observed rate of rise of ion temperature (circles) when the rf is turned on. The absorbed power is proportional to plasma density in agreement with single-particle cyclotron-resonance-heating theory[4]:

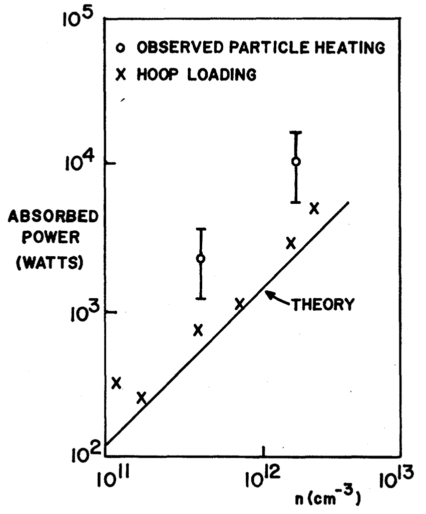

FIG. 3. Absorbed power versus plasma density.

$$P_{\mathrm{abs}} = \tfrac{1}{2}\pi \int neE_{\perp}^{2}\delta(B - B_{\mathrm{res}})\,dV, \qquad (1)$$

where $E_{\perp}$ is the measured toroidal rf electric field and the integral is taken over the volume of the toroid.

The ion temperature is limited by charge-exchange losses:

$$P_{cx} = n_0 \int n\langle\sigma_{cx}\rangle(2kT_i/M_i)^{1/2}kT_i\,dV, \qquad (2)$$

where $\langle\sigma_{cx}\rangle$ is the charge-exchange cross section[10,11] for protons in cold H_2 appropriately averaged over a Maxwellian ion distribution. Over the energy range of interest $\langle\sigma_{cx}\rangle$ (in cm^2) can be approximated by

$$\langle\sigma_{cx}\rangle \cong 5\times10^{-17}[1+5.85\times10^{-3}(kT_i)^{3/2}]$$
$$\times\exp[-5.82\times10^{-2}(kT_i)^{1/2}],$$

where kT_i is in eV. Equating Eqs. (1) and (2) allows one to calculate the equilibrium ion temperature as a function of neutral density n_0, and this result is shown in Fig. 4 along with the experimental results. These neutrals are due in part to reflux from the walls as evidenced by an upward kick in the ion-gauge pressure reading when the machine is pulsed with rf power. We have succeeded in significantly reducing the wall reflux by a variety of discharge cleaning techniques.

The penetration of the electric field into the plasma results from the propagation of the extraordinary wave across a magnetic field that is

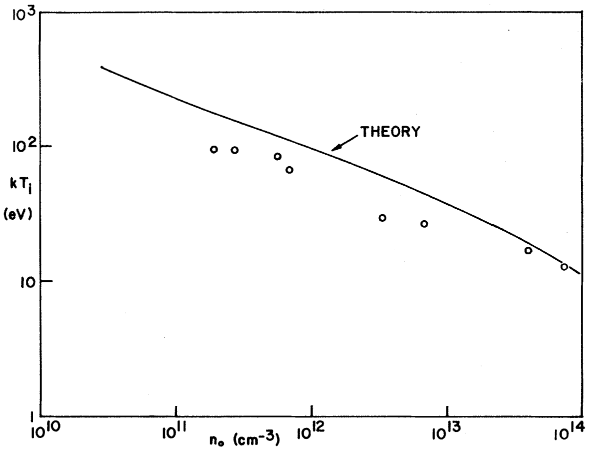

FIG. 4. Ion temperature versus neutral hydrogen density.

everywhere perpendicular to $\vec{E}$. When a toroidal magnetic field (B_T) is added, conductivity along field lines tends to short circuit the electric field. The conductivity is reduced from the Spitzer value,[12] however, because (1) the frequency ω is much above the collision frequency ν, (2) the rotational transform increases the distance that currents must flow, and (3) most electrons are mirror trapped and do not contribute to the conductivity. With a toroidal field, the penetration depth is estimated to be

$$\delta \cong \frac{\pi c}{\omega_{pe}} \frac{B_{\max}}{B_{\min}} \left(\frac{2\omega}{\nu} \frac{\langle B \rangle}{B_T} \right)^{1/2},$$

which for a plasma denisty of 10^{11} cm^{-3} ($\omega_{pe} = 1.8 \times 10^{10}$ sec^{-1} and $\nu = 1.8 \times 10^5$ sec^{-1}) gives $\delta \cong 44$ cm even for the worst case of $B_{\max}/B_{\min}$ and $\langle B \rangle / B_T$ equal to unity. Measurements of the electric field in the presence of a toroidal magnetic field do in fact show an attenuation that is consistent with the above estimate and that scales in the proper direction with variations of n and B_T. Unfortunately it has not been possible to measure ion temperature in the presence of a toroidal magnetic field because the energy analyzer requires a zero magnetic field at the entrance aperture of the extractor pipe. Langmuir probes do show evidence of decreased ion heating and increased electron heating as the toroidal field is increased.

For the same reason, it has not been possible to measure the spatial dependence of T_i which would have provided convincing evidence that the heating mechanism is ICRH. However, spatial measurements of the floating potential show a positive peak at the resonance zone which moves in space as the magnetic field is varied. A similar negative peak is observed at the ECRH resonance zone and is believed to be caused by an increase in the ratio of trapped particles produced by the anisotropic heating.

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