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ION CYCLOTRON RESONANCE HEATING IN A TOROIDAL OCTUPOLE

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ABSTRACT. : A 1 MW, 2 msec pulse of rf power at the ion cyclotron frequency (2.6 MHz) has been used to heat the ions from < 1 eV to ~ 350 eV in a toroidal octupole device. The ion temperature is limited by charge exchange loss and agrees quantitatively with theoretical predictions. No parametric decay waves, enhanced diffusion, or other deleterious effects except for a high neutral reflux are observed to accompany the heating.

Ion cyclotron resonance heating is a promising technique for raising the ion temperature in a Tokamak reactor above the level that can be achieved with ohmic heating alone. Many of the Tokamak-related problems can be studied on toroidal multipole devices which can operate over a wide range of parameters. The small toroidal octupole[1] at the University of Wisconsin has been used to study ICRH for a number of years, and we previously reported[2] ion temperatures of about 100 eV with 500 kW of 1 MHz for 1 msec. We have recently upgraded the oscillator to 1 MW of 2.6 MHz for 2 msec and redesigned the coupling structure in an attempt to increase the ion temperature above 100 eV. We report here experiments in which ion temperatures of about 350 eV are observed with no deleterious effects except for a high neutral reflux which limits the ion temperature by charge exchange.

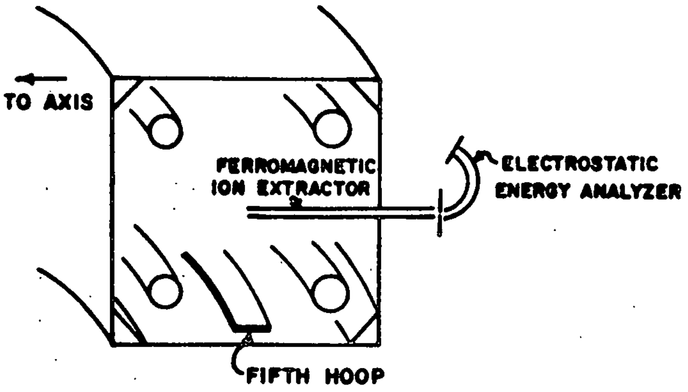

Figure 1

A cross section of the toroidal octupole device is shown in Fig. 1. The magnetic field in the experiments to be described is purely poloidal and is produced by the currents in four solid copper hoops which link an iron transformer core (not shown). The field pulse is a half sine wave of 10 msec duration and the ICRH is done near peak field. Plasmas with $kT_e \sim 3\text{-}5$ eV and $n \sim 3\times10^{10} cm^{-3}$ are produced by 5 kW cw ECRH at 2.45 GHz. Ion energy distribution functions are measured by an electrostatic energy analyzer[3] which extracts particles from the zero-field region near the axis through a ferromagnetic pipe.[4]

The rf power is introduced by means of a single-turn, flat copper hoop located near the bottom wall of the device. The hoop is the inductor of the tank circuit of a single tube, self-excited, triode oscillator fed from a pulse forming network which provides 20 kV at $\lesssim$ 100 amps. RF voltages up to 20 kV zero-to-peak across the gap in the hoop have been achieved. The previous hoop was insulated, electrostatically shielded, and had an adjacent toroidal limiter. The present hoop was installed initially without an insulator, shield, or limiter but was so heavily loaded by electrostatic plasma surface effects that the oscillator would not work. Then a glass insulator was installed over the structure giving satisfactory operation except for a modulation of the plasma potential of ~ 100 volts at the rf frequency and a high neutral reflux due presumably to ions which are accelerated from the edge of the plasma and strike the glass with energies ~ 10 keV. The inductive electric field is purely toroidal and hence is everywhere perpendicular to the magnetic field. Its spatial dependence has been measured and in the vicinity of the cyclotron resonance surface is not significantly changed by the low density plasma. The resonance zone for protons (1800 G) is an approximately circular cross-section toroidal surface with a radius only slightly less than the minor radius of the machine. Nearly all the field lines intersect the resonance somewhere.

A typical ion energy distribution function is shown in Fig. 2. The distribution consists of a cold component that appears much hotter than it actually is because of the 100 volt oscillations of the plasma potential at the pump frequency, and an approximately equal density Maxwellian component with $kT_i \sim 350$ eV with a cutoff at ~ 700 eV caused by the lack of confinement of large gyroradius ions.

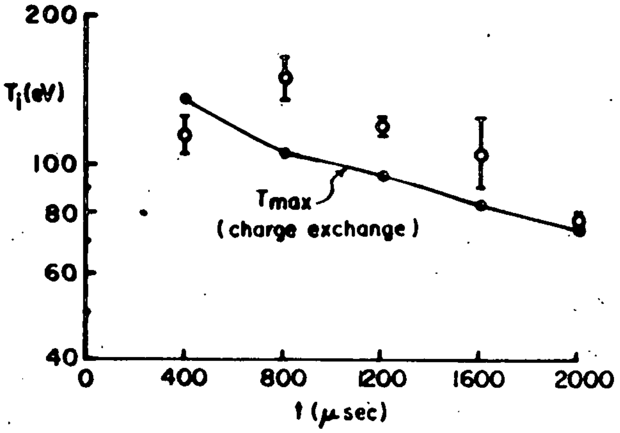

Figure 3

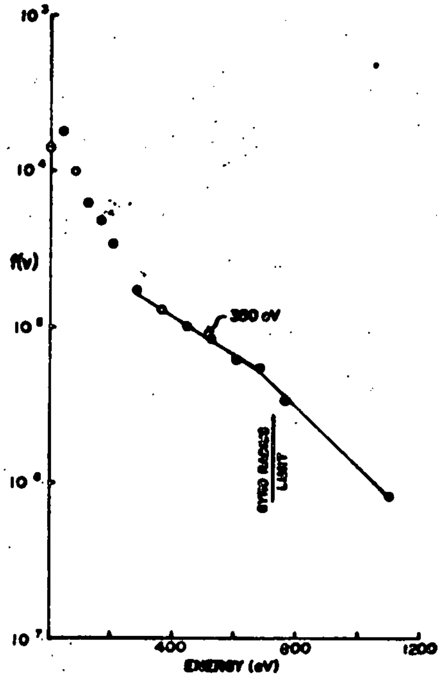

Figure 2

The ion temperature vs time after the beginning of the heating pulse as shown in Fig. 3 is observed to rise in a few hundred μsec and then to fall slowly as the neutral pressure rises due to reflux hydrogen neutrals. Also shown in Fig. 3 is the theoretical steady state ion temperature calculated from the theoretical heating rate[5] and charge exchange losses from published cross-section data[6] using the measured neutral pressure. The neutral pressure rises by about a factor of five during the pulse due to wall reflux.

Shown in Fig. 4 is the maximum ion temperature obtained vs time after initial pumpdown of the ICRH hoop and insulator. The insulator was still cleaning up when the machine was let up to dry nitrogen 12 days later. After a few weeks of operation the insulator cleaned up and ion temperatures were consistently ~ 350 eV. We estimate that the neutral reflux is given in terms of the plasma flux by $\Gamma_n/\Gamma_{ei} \simeq 0.0083\sqrt{kT_e(\mathrm{eV})} + 0.28\sqrt{kT_i(\mathrm{eV})}$ depending upon the history of the vacuum.

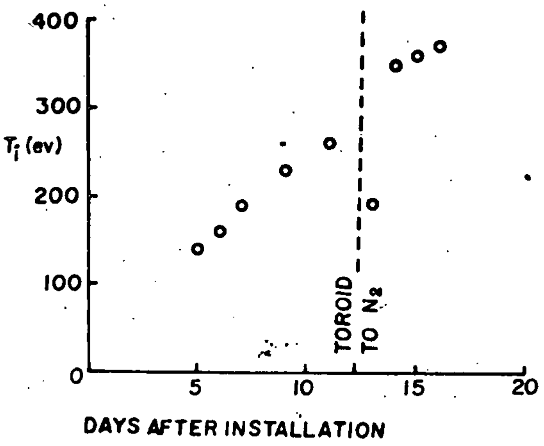

Figure 4

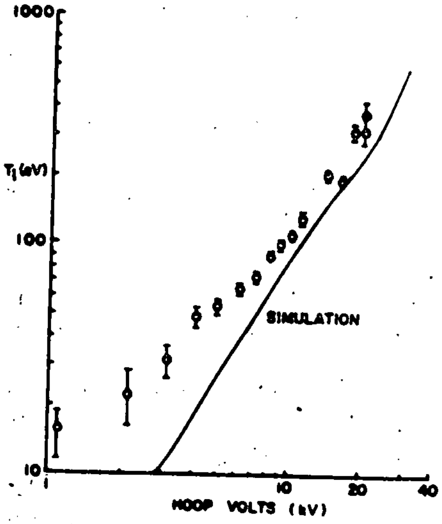

Figure 5

The ion temperature vs the zero-to-peak rf voltage on the hoop is plotted in Fig. 5 along with the prediction of a computer simulation[7] which considers the theoretical heating rate and all known loss mechanisms. The agreement is seen to be quite good except at low levels of ICRH where some anomalous ion heating accompanies ECRH. There is a further systematic error of about a factor of two because the computer simulation assumes a Maxwellian ion distribution whereas only the hot component is measured in the experiment. We have plans for doubling the hoop voltage in the next few months to 40 kV which should give $kT_i \sim 800$ eV.

In a search for parametric decay waves, the spectrum of floating potential fluctuations was measured over the range 10 kHz to 1 MHz and all signals in that range associated with the ICRH had an amplitude < 1% of the 2.6 MHz pump wave signal. There was also no evidence of enhanced diffusion in the presence of the large rf electric fields.

Fig. 6 shows a power flow diagram obtained from the computer simulation. The heating efficiency is rather low because of the low densities. The efficiency increases at higher densities, and plasmas with $n \sim 6 \times 10^{12} cm^{-3}$ have been heated by ICRH, but the temperature is lower because of the high neutral pressure that accompanies the production of such plasmas by gun injection. At densities above $\sim 10^{12} cm^{-3}$, toroidal eigenmodes ought to exist and we plan to measure the spatial variation of the rf electric fields and to test whether the oscillator will track these modes.

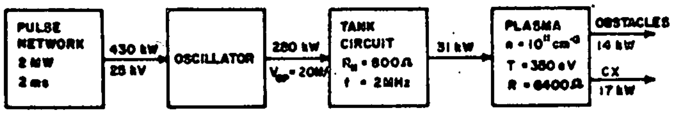

Figure 6