ICRH EXPERIMENTS

IN A TOROIDAL OCTUPOLE

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ABSTRACT

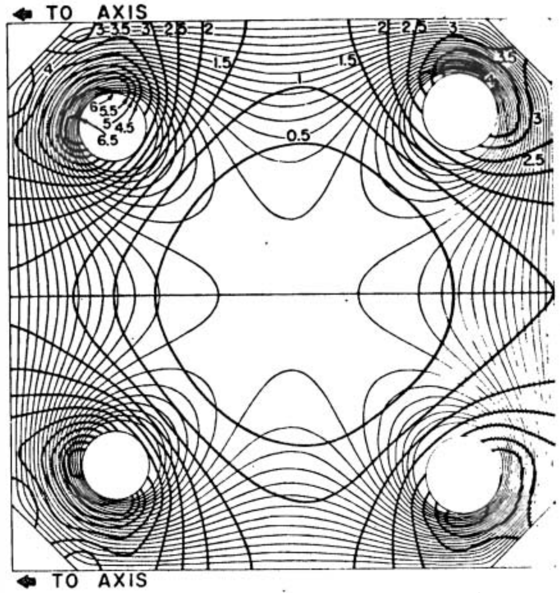
A 100 kW, 144 μsec pulse of 1.4 MHz rf is used to heat plasmas with densities $\lesssim 3\times10^{12}$ cm^{-3} at the ion cyclotron frequency in a toroidal octupole. The rf is coupled to the plasma by a single turn, electrostatically shielded hoop coaxial to the four main hoops and located near the wall. Absorbed power is inferred from plasma loading of the hoop and measured directly with an electrostatic ion energy analyzer and compared to single particle resonance heating theory.

Introduction

For a number of years we have been studying ion cyclotron resonance heating of plasmas in the toroidal octupoles at the University of Wisconsin.[1-3] We have previously reported significant increases in ion energy (exceeding ten-fold) for low density ($\lesssim 10^{10}$ cm^{-3}) plasmas. In the work to be described here, we have extended the measurements to higher densities (3×10^{12} cm^{-3}) and observed good agreement between the measured heating rates and a single particle heating model[4] identical to that used to interpret the electron cyclotron resonance heating results.[5]

Experimental Apparatus

Since the field in the octupole is predominantly poloidal, an rf coupling loop in the toroidal (θ) direction and parallel to the main hoops is required to provide an $\vec{E}$ field perpendicular to $\vec{B}$. This may be compared to the tokamak configuration where $\vec{B}$ is predominantly in the θ-direction requiring a coupling loop in the poloidal direction following the minor circumference.[6] From wave propagation considerations, the hoop must be placed in a higher field region than the resonance zone to allow propagation into the resonance zone. In the tokamak this indicates the inner side of the minor cross-section, while in the octupole with magnetic well, any peripheral position should be satisfactory.



CONSTANT B SURFACES IN THE WISCONSIN TOROIDAL OCTUPOLE

Fig. 1

Fig. 1 shows a cross-sectional view of the small (supported) toroidal octupole at Wisconsin. The axis of toroidal symmetry is to the left with copper hoops placed as shown. The surfaces of constant ψ are indicated in "lower case" lines while surfaces of constant B ($|\vec{B}|$) are indicated in boldface lines. Two ψ surfaces should be noted. ψ_s is the separatrix which passes through the B = 0 region on the minor axis. ψ_{crit} is the last MHD stable flux surface. The rf coupling loop (or fifth hoop) is mounted near the lower wall, concentric with the main hoops, and centered in the minor cross-section. The resonance zone corresponding to the frequency used is a $|\vec{B}|$ surface ≅ .83. Since the rf electric field falls off rapidly with distance from the fifth hoop, we expect most of the heating to be done in the lower portion of the resonance zone nearest the hoop. The $\vec{E}$ field has been measured experimentally as a function of position in the mid-cylinder, vertically above the hoop.

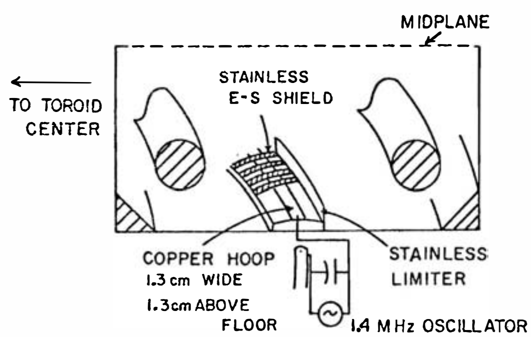


Fig. 2

Fig. 2 gives some detail on hoop construction and shielding. The hoop is a copper strip 1.3 cm wide mounted 1.3 cm from the lower wall. The hoop is electrostatically shielded with 1-mil stainless steel leaves about .6 cm wide with gaps about .3 cm between leaves. A stainless limiter 1.9 cm high is also employed (outside ψ_{crit}) to lower plasma density near to the hoop. The fifth hoop is a single turn inductor in parallel with resonating capacitors which form the tank circuit of a 1-tube regenerative oscillator. In this manner, the oscillator frequency tracks any change in resonance frequency due to reactive plasma loading and insures an optimum match between the oscillator and the load. The unloaded Q of the circuit is typically 100 and drops to ~ 87 at densities of 3×10^{12} cm^{-3}. The electrostatic analyzer samples velocity distributions of ions extracted from the zero field region through a high - μ tube.

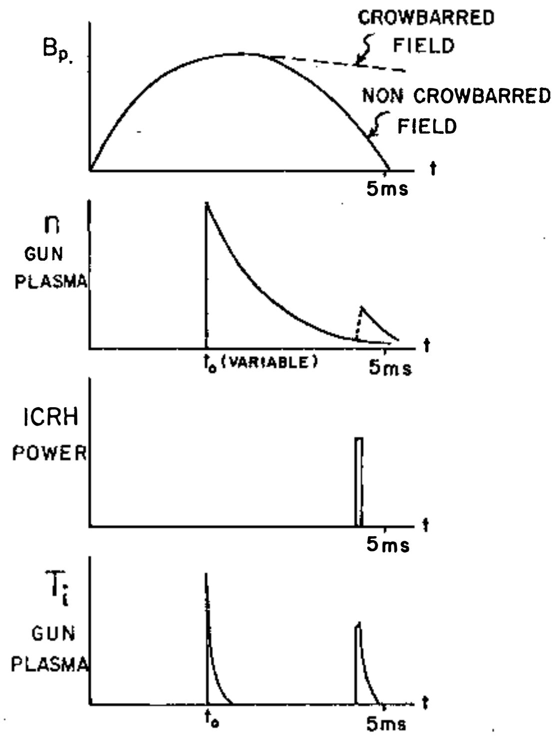


Fig. 3

Experimental Results

The time evolution of a typical experiment can be seen in Fig. 3. The top graph depicts the poloidal B field which can be operated in two modes. In the half-sine mode the half period is 5 msec. Or the field can be crowbarred at maximum field to extend the field lifetime. The crowbarred mode was used for this experiment. The next graph shows injection and heating of a plasma produced by a gun mounted directly on the wall of the vacuum chamber. The 144 μsec rf pulse is shown in the third graph and plasma ion temperatures in the last graph. The rapid decay of ion temperature is a result of charge exchange on the dense neutral background that accompanies this kind of gun injection. This figure is meant only to indicate the timing sequence. The magnitude of the quantities will be indicated in subsequent figures.

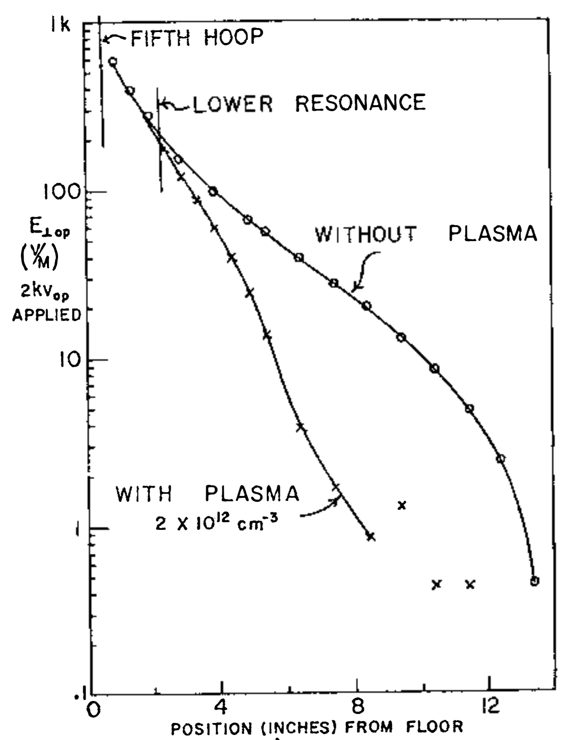


Fig. 4

The measured $\vec{E}$ field of the fifth hoop as a function of position in the vertical mid-cylinder is shown in Fig. 4. The field without plasma is indicated with o's, the field with a 2×10^{12} cm^{-3} plasma with x's. Recall that the confinement B field is strong at the left and right (the lower and upper walls) and is zero in the center (7"). The fifth hoop position is shown at the left. Note that the field penetrates well to the nearest portion of the resonance zone and is attenuated beyond the resonance zone ($B < B_{resonance}$). The $\vec{E}$ field at the near portion of the resonance zone and at the B = 0 axis are plotted in Fig. 5 to give an indication of the penetration of the rf field.

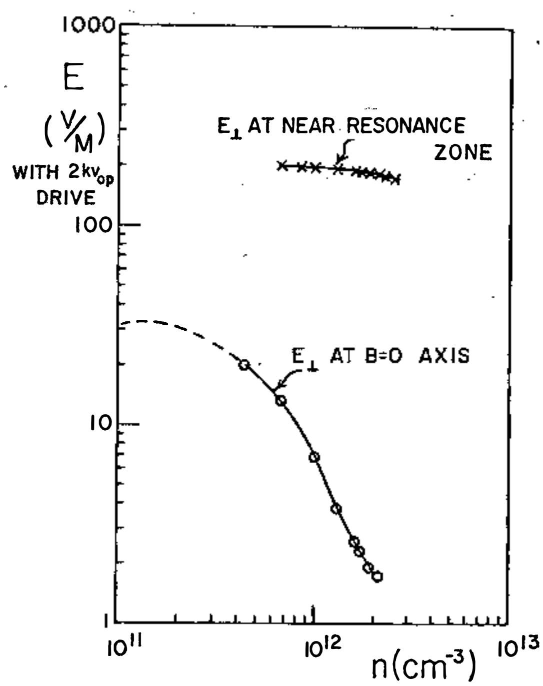


Fig. 5

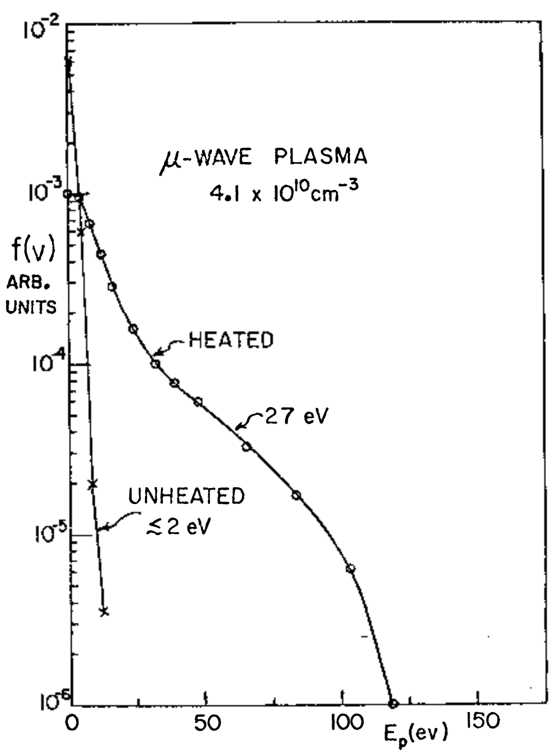


Fig. 6

Fig. 6 shows a distribution function of a heated μ-wave produced plasma. ln[f(v)] is plotted vs. energy for the cold plasma and after the rf pulse is applied. A μ-wave produced plasma was chosen for display because the neutral background density is much lower than for the gun injected plasma. Consequently the cooling (via charge exchange) is much weaker and the final temperature is higher. Typical heated temperatures observed with gun injected plasmas of densities ~ 3×10^{12} cm^{-3} are ≃ 8 eV. The distribution function is somewhat non-Maxwellian and has a cutoff at ≃ 100 eV due probably to the poor confinement of large gyroradius ions.

Measurements were made of the resistive loading presented by the plasma to the fifth hoop. To do this we monitored the voltage across the tank circuit and the drive current. For convenience the difference of these was taken and the deviation from a null condition was calibrated experimentally.

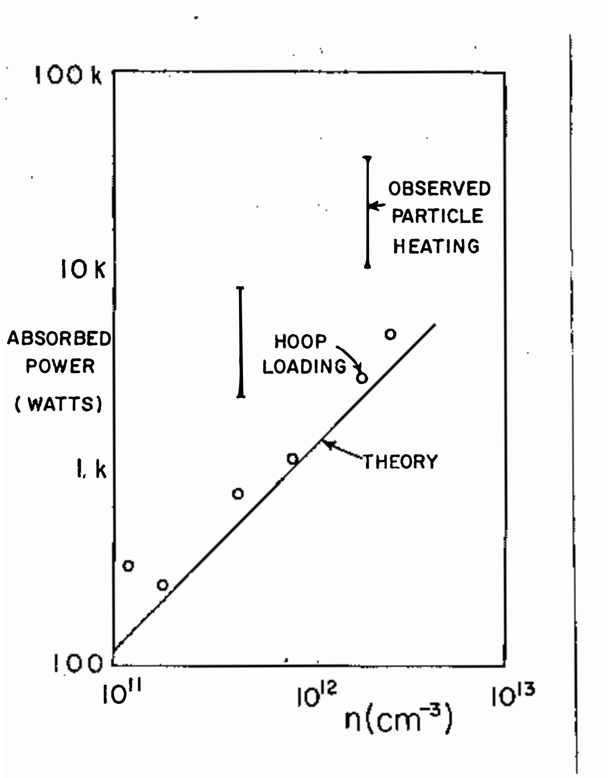


Fig. 7

Fig. 7 shows some results of this method with gun injected plasmas. The single particle heating theory is plotted assuming constant (unperturbed) $\vec{E}$ field at the resonance zone. This is not the case but because of the spatial dependence of $\vec{E}$, the heating should occur primarily in the portion of the zone nearest the fifth hoop where the electric field is nearly independent of density. The loading data show power absorbed by the plasma after correcting for the slight depression of electric field at the near portion of the resonance zone. The disparity between points inferred from ion velocity distributions and coil loading points may indicate inadequacy of the assumptions of spatially uniform temperature distributions and uniform density filling the toroid. Uncertainties in measurement of density may also contribute. However, both the loading measurements and the direct ion heating clearly show a linear variation of absorbed power with density that is in good agreement with the prediction of resonance heating theory.

Summary

In summary, ion heating with rf fields near the ion cyclotron frequency has been found to scale properly with density and is in good agreement with single particle resonance theory. Also good penetration of the $\vec{E}$ field has been observed in densities as high as $3x10^{12}$ cm^{-3} and significant increases in ion energy are observed.

Acknowledgement

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