ECRH EXPERIMENTS IN A TOROIDAL OCTUPOLE

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May 1974

PLP 570

Plasma Studies

University of Wisconsin

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ABSTRACT

Electron cyclotron heating rates have been measured for low density plasmas ($\omega_p^2 << \omega^2$) in a toroidal octupole by the sweep method with resonance zones situated near the minor axis of the toroid. The energy absorbed by the plasma from the 100 mW frequency sweep oscillator is determined from the broadening of the cavity modes. The heating rate is measured for different magnetic field strengths, electron temperatures, electron-neutral collision frequencies and plasma densities. The scaling of heating rate with plasma density is different from previous results of high frequency (10 GHz) cavity mode measurements. The difference is explained by the different positions of the resonance zones.

Introduction

A detailed quantitative comparison between ECRH theory and experiment has been reported elsewhere.[1] In that experiment, the resonance zones were situated near the hoops of the small (supported) toroidal octupole. In this paper, we describe another method of measuring the heating rate with the resonance zones near the center of the octupole. The experiment consists of measuring the Q of a microwave cavity in which various plasmas can be produced and confined by a toroidal octupole magnetic field. The low frequency cavity modes of several hundred MHz are excited by a 100 mW frequency sweep oscillator. The cavity Q with and without plasma are measured from the widths of the cavity modes and the energy absorbed by the plasma can thus be calculated.

Let $\langle E^2\rangle_{res}$ = E^2 averaged over the resonance zones

$\langle E^2\rangle_{cavity}$ = E^2 averaged over the cavity volume V.

$\alpha^2 = \langle E^2\rangle_{res}/\langle E^2\rangle_{cavity}$

Q_o = cavity Q without plasma $\equiv \frac{\omega_o}{\delta\omega_o}$

Q = cavity Q with plasma $\equiv \frac{\omega}{\delta\omega} \simeq \frac{\omega_o}{\delta\omega}$

$B_o = m\omega/e$

The rf power absorbed by the plasma is:

$$P = \frac{nVe\langle E^2\rangle_{res}}{B_o} G \equiv \frac{1}{Q_p} \varepsilon \langle E^2\rangle_{cavity} V\omega$$

$$\therefore \quad \frac{1}{Q_p} = \frac{\omega_p^2}{\omega^2}\frac{\varepsilon_o}{\varepsilon} \alpha^2 G \simeq \frac{\omega_p^2}{\omega^2} \alpha^2 G \qquad (1)$$

Also

$$\frac{1}{Q_p} = \frac{1}{Q} - \frac{1}{Q_o} = \frac{\delta\omega}{\omega} - \frac{\delta\omega_o}{\omega_o} \simeq \frac{\delta\omega - \delta\omega_o}{\omega_o} = \frac{1}{Q_o}\frac{\delta\omega - \delta\omega_o}{\delta\omega_o} \qquad (2)$$

Equate Eq. (1) and Eq. (2) to get

$$\alpha^2 G = \frac{1}{Q_o}\frac{\omega^2}{\omega_p^2}\frac{\delta\omega - \delta\omega_o}{\delta\omega_o} \qquad (3)$$

So $\alpha^2 G$ can be experimentally determined by measuring Q_o, ω_p^2, ω^2 and the cavity mode widths ($\delta\omega_o$, $\delta\omega$) with and without plasma. G is the dimensionless heating rate which can be predicted theoretically. When a particular cavity mode is chosen and the positions of the resonance zones are fixed, α^2 is a constant and we can investigate the scaling of G with plasma electron temperature, electron-neutral collision frequency and plasma density. It should be noted that the variation of $\alpha^2 G$ with resonance zone positions can differ from that of G if there is a spatial dependence in α^2.

Experimental Apparatus

The experimental set up is schematically shown in Fig. 1. The plasma is produced by the 2.45 GHz magnetron whose output power controls the plasma density. The magnetic field is crowbarred at peak field (at 2.4 ms) with a decay time of about 50 ms. The magnetron is turned off at peak field and the electron temperature of the afterglow decays from 10 eV to 0.5 eV in 2 ms which is short compared with the magnetic field decay time. This allows us to study plasmas at different electron temperatures with negligible change in the magnetic field. A toroidal magnetic field B_o can be added by pulsing a current through an eight turn coil wound around the torus. The frequency sweep oscillator can sweep through a cavity mode within 50 μs in which the changes of the plasma parameters are negligible. The plasma density fluctuations have very little effect on the cavity mode width since it is a low Q cavity ($Q_o \lesssim 500$). The plasma density is measured by a Langmuir probe

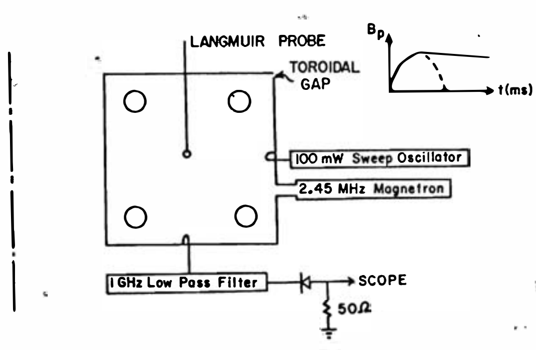

Fig. 1

placed near the center of the octupole. The electron temperature before the magnetron is turned off is measured by sweeping the Langmuir probe and the electron temperature of the afterglow is measured by an admittance probe.[2]

Experimental Results

Three cavity modes (325 MHz, 420 MHz, 598 MHz) are used to study the ECRH heating rate. Fig. 2 shows the variation of $\alpha^2 G$ as a function of resonance zone position (B_o/B_{wall}), B_{wall} being the octupole field at the outside wall on the mid-plane. The data points for the 325 MHz cavity mode are almost a factor of ten lower than the theory, and the variation with B_o/B_{wall} is quite similar to the theory. This is probably because it is the lowest frequency cavity mode and α^2 has a weak spatial dependence. The data for the 420 MHz cavity mode varies markedly from the theory. The rf signal of this mode pick-up by an antenna probe shows a strong peak at about two inches from the center of the octupole. This indicates that there is possibly a strong spatial dependence in α^2.

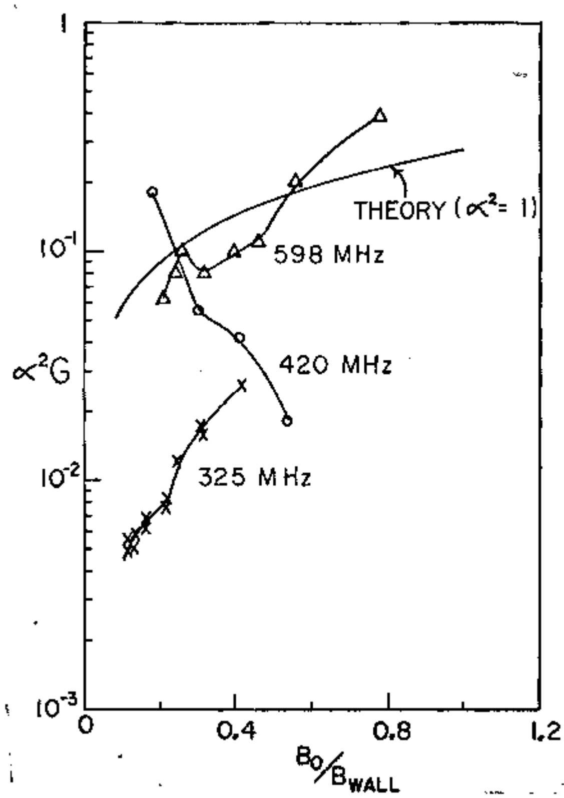

Fig. 2

Fig. 3 shows the variation of $\alpha^2 G$ as a function of the toroidal magnetic field B_θ for the 420 MHz cavity mode. Theory predicts that the heating rate peaks before the resonance zones are driven out of the machine. This peak is found in all the three modes used in the experiment. For

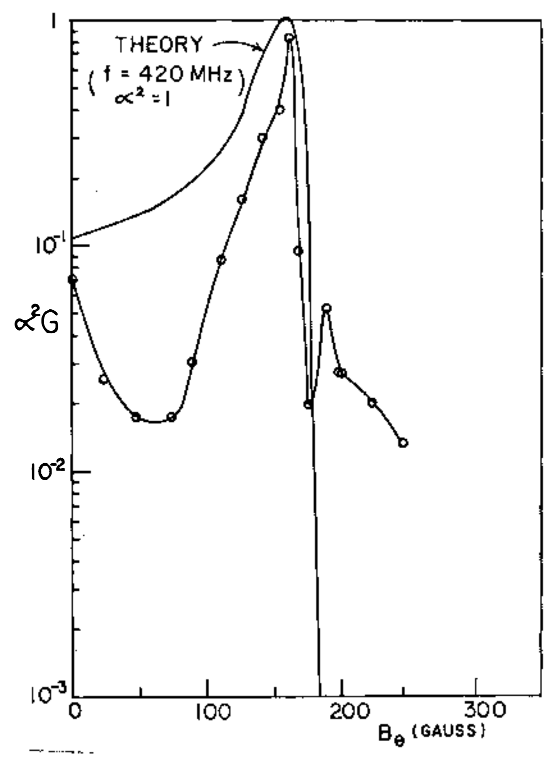

Fig. 3

the two higher frequency modes, $\alpha^2 G$ dip before they peak up. This is again probably due to the spatial dependence of α^2.

Fig. 4 shows the heating rate as a function of electron temperature. The heating rate is found to be independent of the electron temperature as expected. The electron-neutral collision frequency is varied by changing the neutral hydrogen pressure. Theory predicts that G should be independent of ν_{en}/ω for $\nu_{en}/\omega < 0.1$, but experimental data in Fig. 5 show a slow rise of G with ν_{en}/ω. Theory also predicts G to be independent of plasma density and the data in Fig. 6 show a slow increase of G with density. It is still not clear whether this is real or due to some systematic erros in the measurements.

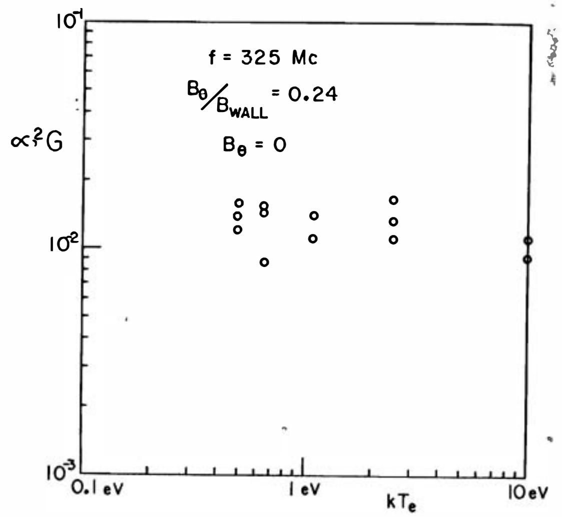

Fig. 4

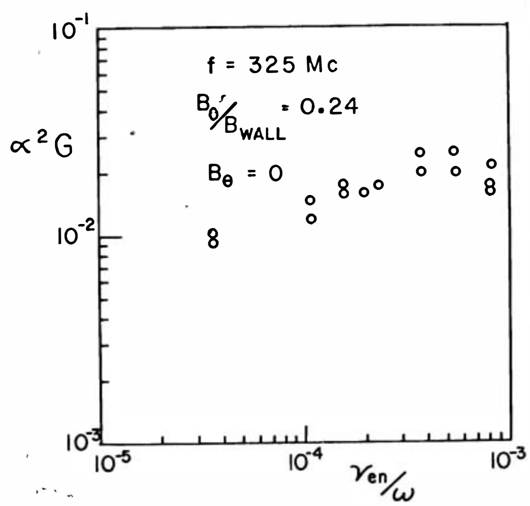

Fig. 5

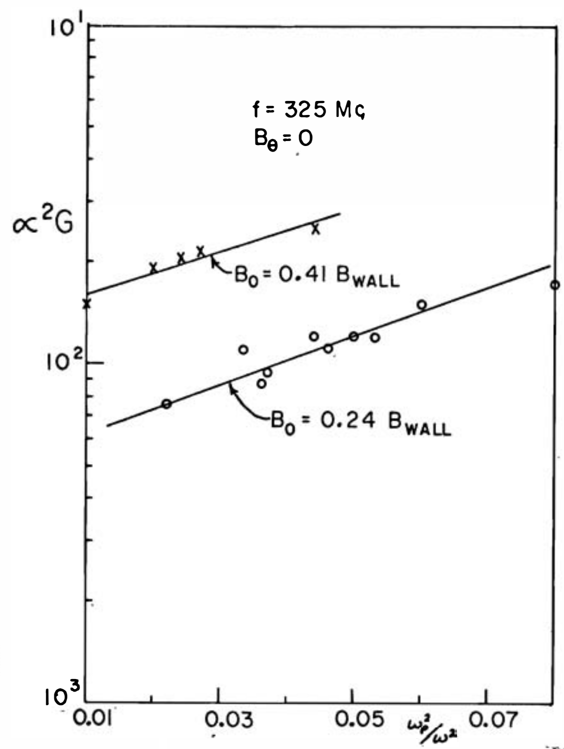

Fig. 6

In the previous experiment[1] with resonance zones near the hoops of the octupole, G was found to be independent of density for $\omega_p{}^2/\omega^2 < 0.01$ and to fall rapidly for $\omega_p{}^2/\omega^2 > 0.01$ as shown in Fig. 7. In the same range of $\omega_p{}^2/\omega^2$, we don't see this anomalous falloff when the resonance zone is near the center of the octupole. This can be explained by the difference in the resonance zone positions. When the resonance zones are near the hoops, the microwaves have to propagate from a low magnetic field to a high magnetic field in order to reach the resonance zones. The right hand circularly polarized wave which is responsible for the electron cyclotron resonance heating has to tunnel through an opaque region. Assuming r.c.p. wave propagating along straight field lines with uniform magnetic field gradient, the transmission coefficient can be approximately calculated to be $\exp\left(-4\pi^2 \frac{B_o}{\lambda|\nabla_{\parallel}B|} \frac{\omega_p{}^2}{\omega^2}\right)$. Since the heating rate is proportional to the square of the electric field, the scaling with density becomes

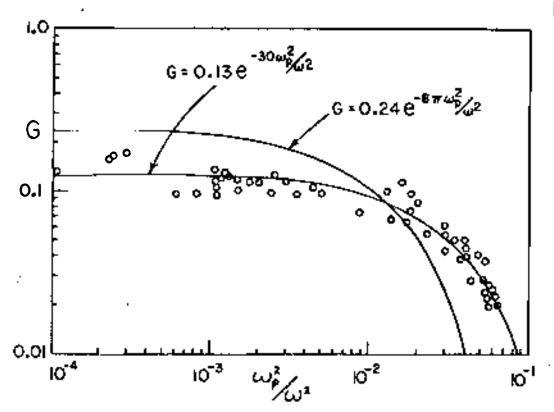

Fig. 7

$$G = G_o \exp\left[-4\Pi^2 \frac{B_o}{\lambda|\nabla_{\parallel}B|} \frac{\omega_p{}^2}{\omega^2}\right] \quad (4)$$

where G_o is the theoretical heating rate with a uniform, isotropic electric field. In the experiment, $B_o = 3.24$ kG, $\lambda = 3.2$ cm, $|\nabla_{\parallel}B| \sim 0.5$ kG/cm, $G_o = 0.24$, so

$$G = 0.24 \exp(-8\pi^2 \omega_p{}^2/\omega^2) \quad (5)$$

This curve is shown in Fig. 7. We don't expect a very nice fit to the data points since the assumptions made in obtaining the transmission coefficient are not true in the experiment. However, it gives a qualitative behavior of the heating rate as a function of electron density. The curve which has the best fit to the data is $G = 0.13 \exp(-30\ \omega_p{}^2/\omega^2)$ as shown in Fig. 7. It should be noted that if the density measurements are a factor of two too high, then the corrected data points will fit the curve $G = 0.26 \exp(-60\ \omega_p{}^2/\omega^2)$ which is very close to Eqn. (5). In the experiment described in this paper, the resonance zone is near the center of the octupole. The microwaves are launched on a magnetic beach. They have no problem in reaching the resonance zones and so the heating rate does not fall off with plasma density.

Acknowledgement

This work was supported by the U. S. Atomic Energy Commission.

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