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University of Wisconsin, Madison, Wisconsin 53706

ABSTRACT

Electron cyclotron heating rates have been measured for plasmas in a toroidal octupole magnetic field over a wide range of magnetic field strength, electric field strength, plasma density, and neutral density. The results agree with single particle heating theories at low densities but show a decreased heating rate as the density increases.

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Electron cyclotron heating has been a standard technique for producing hot electron plasmas for a number of years. The heating rate for such plasmas can be calculated in a remarkable variety of ways[1-6] and the result is

$$\frac{d\langle W\rangle}{dt} = \pi \int neE^2 \ \delta(B-B_o)dV/2\int ndV, \tag{1}$$

where n is the electron density, E is the rms electric field strength at frequency ω perpendicular to $\vec{B}$, B_o is the magnetic field strength at resonance ($B_o = m\omega/e$), $\langle W\rangle$ is the average electron energy, and the integrals are over the volume of the plasma.

Despite the existence of a theory and the abundance of experimental data, there has never been a detailed quantitative comparison between the theory and experiment over a range of parameters. The reason is the difficulty of making accurate temperature measurements and the fact that poorly understood cooling and loss processes are usually present. We present here the first such comparison made in a large scale plasma confinement device which exhibits most of the complications which might render the theory inapplicable. The results are in good agreement at low densities but deviate markedly as the density increases.

The experiment consists essentially of measuring the perturbed Q of the large multimode microwave cavity in which various plasmas can be produced and confined by a toroidal octupole magnetic field.[7] Plasmas with $kT_e \sim 5$eV are produced by a 2.45 GHz, ≤ 2kW, cw microwave source. The Q measurements use a 9.6 GHz, ≤ 100 W, cw carcinotron which can be frequency swept over 1 GHz in < 25 μsec to excite a spectrum of ~ 300 cavity modes. A 24.0 GHz, 100 mW microwave system is used to measure plasma density. The octupole magnetic field is highly non-uniform, and regions of cyclotron resonance exist up to frequencies of about 18 GHz.

If the microwave cavity is sufficiently large compared with the rf wavelength, and if the cavity Q is not too low, the electric field is homogeneous and random, and equation (1) can be written

$$\frac{d\langle W\rangle}{dt} = \pi e\langle E^2\rangle \int n\delta(B-B_o)\,dV/3\int n\,dV = \frac{e\langle E^2\rangle}{B_o}G, \tag{2}$$

where G is a dimensionless quantity which depends only on the magnetic field shape, the position of the resonance zone, and the spatial distribution of plasma density. The quantity G has been calculated by computer as a function of B_o for the toroidal octupole assuming a density profile which is constant in space.

Since the cavity Q for $\omega_p^2 \ll \omega^2$ is given by

$$Q = \varepsilon_o \omega \langle E^2\rangle V/P,$$

where V is the cavity volume and P is the input microwave power, G can be written as

$$G = \frac{\omega^2}{Q_o\omega_p^2}\left[\langle E_o^2\rangle/\langle E^2\rangle - 1\right] . \tag{3}$$

The quantity G can thus be experimentally determined by measuring the cavity Q without plasma (Q_o), the plasma frequency ($\omega_p^2 = ne^2/\varepsilon_o m$), and the ratio of the average unperturbed to perturbed electric field $\langle E_o^2\rangle/\langle E^2\rangle$. It is necessary to monitor the forward and reflected power to insure that any variation in electric field is due to plasma absorption rather than to a change in input power. The purpose of the frequency swept microwave source is to excite many cavity modes so that the average field can be measured with an antenna at a fixed position in the cavity. It was determined experimentally that this average is the same within about 20% as that obtained by using a fixed frequency and varying the antenna position. The experiment consists of comparing the measured value of G given by equation (3) with the theoretical value calculated from equation (2).

Figure 1 shows the measured and calculated values of G as a function of plasma density. The density was adjusted by varying the 2.45 GHz microwave power and measured using a Langmuir probe which line-averages the density across the plasma midplane and a 24.0 GHz multi-mode cavity perturbation technique[8] which gives a volume-averaged density. The two methods generally agree within about 50%. Langmuir probes show the density to be constant to within about a factor of two across the plasma. The theory predicts no density dependence since it is based on a single particle model. There is an implicit density dependence in the heating rate since the electric field decreases with increasing density, but this effect is normalized out when G is plotted. The experiment agrees with the theory at low densities, but falls well below the theory as the density increases. At high densities the experiment gives $G \propto 1/\omega_p^2$ as if there is a lower bound on the perturbed Q at a value of ~ 500. It is important to realize that although the heating rate is below the theoretical value at high densities, the absorption is still nearly 100% since the perturbed Q is well below the unperturbed Q ($Q_o \simeq 3000$).

Figure 2 shows the variation of heating rate as a function of resonance zone position (B_o/B_{MAX}). These data were taken at low plasma density by varying the magnetic field strength at constant B_o. B_{MAX} is the maximum value of field in the machine. For $B_o/B_{MAX} > 1$, there is no region of resonance in the machine, and both the theoretical and the experimental heating rates drop to zero. The agreement is within about a factor of two over the range, and the discrepancy is probably a result of the fact that in order to apply the theory, the density is assumed to be constant in space. With considerably more effort, it would be possible to recalculate the theoretical curve using the experimentally measured density distribution.

The variation of G with the electric field strength was measured by varying the carcinotron power from 1 watt to 100 watts corresponding to electric fields of $E/cB_o \sim 10^{-6}$ to 10^{-5}. The theory predicts a heating rate that varies as E^2, and hence the quantity G should be constant as indeed is the case experimentally.

The variation of heating rate with collision frequency was also measured by varying the neutral hydrogen pressure from 10^{-6} torr to 10^{-3} torr corresponding to a collision frequency change from $\nu/\omega \sim 10^{-7}$ to 10^{-4}. No variation of heating rate was noted over this range confirming that the heating is a resonant rather than a collisional process. Collisional heating should give $G = \nu/\omega$.

In summary, the experiment confirms the single particle theoretical prediction of equation (1) over a range of parameters provided the density is low. At higher densities the discrepancy probably results from the assumption that the electric field is constant throughout the volume, even in the vicinity of the resonance. The electric field cannot be constant when the thickness of the resonance region exceeds the wave penetration depth which occurs when

$$\frac{\omega_p^2}{\omega^2} > \frac{\lambda \nabla B}{2\pi B_o} \quad .$$

The quantity ∇B varies considerably over the resonance surface, but it is possible to place an upper limit on G by assuming the resonance surface to perfectly opague, in which case the minimum Q is

$$Q_{MIN} = 2\pi V/\delta S \quad ,$$

where V is the cavity volume and S is the area of the resonance surface. The corresponding maximum G is

$$G_{MAX} = \frac{\lambda S}{2\pi V} \frac{\omega^2}{\omega_p^2} \quad . \tag{4}$$

which is plotted as a dotted line in Figure 1. The shape agrees with the observation, but the magnitude is high by a factor of 10, suggesting that a more refined theory is necessary to explain the density dependence.

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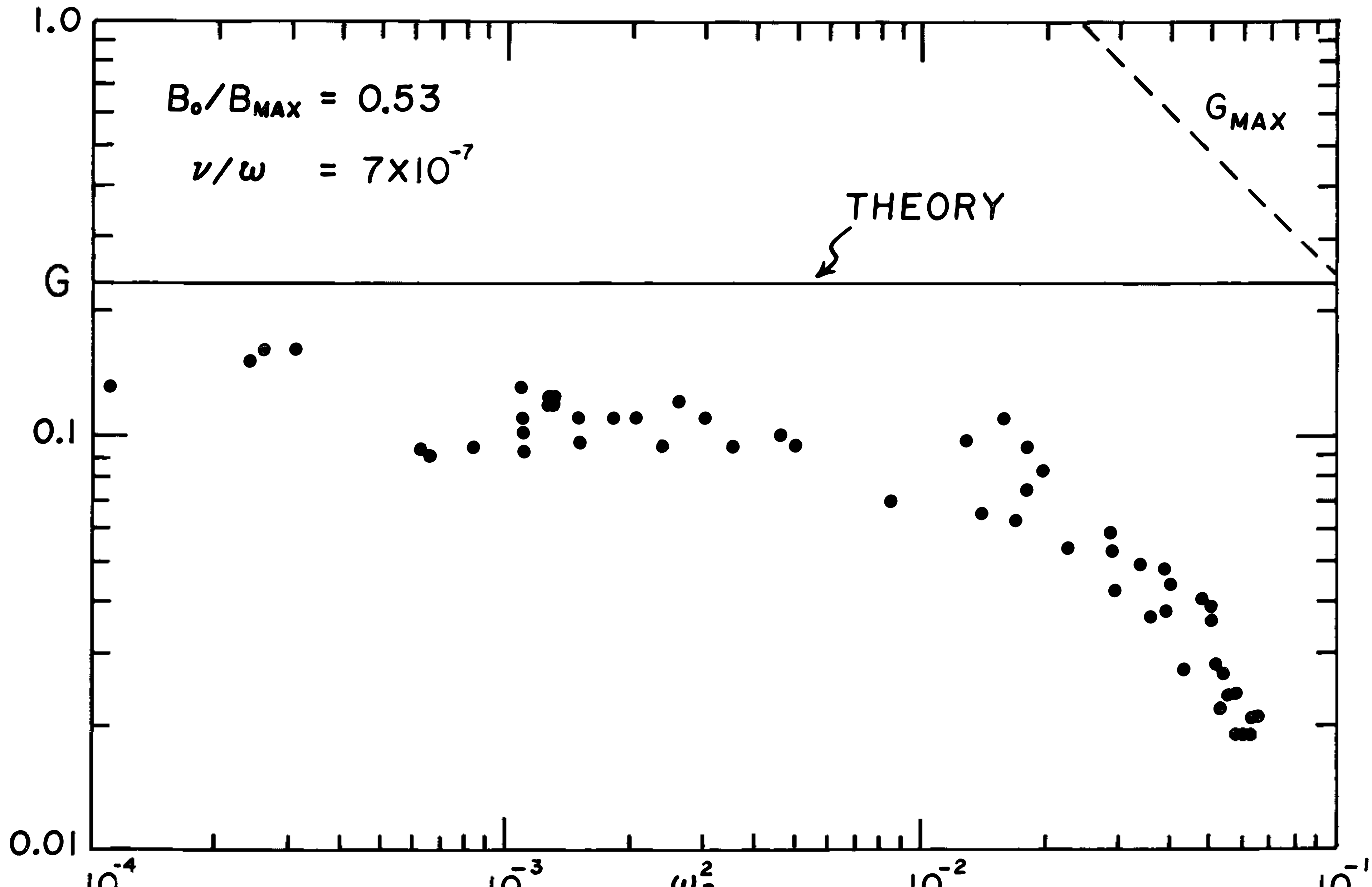
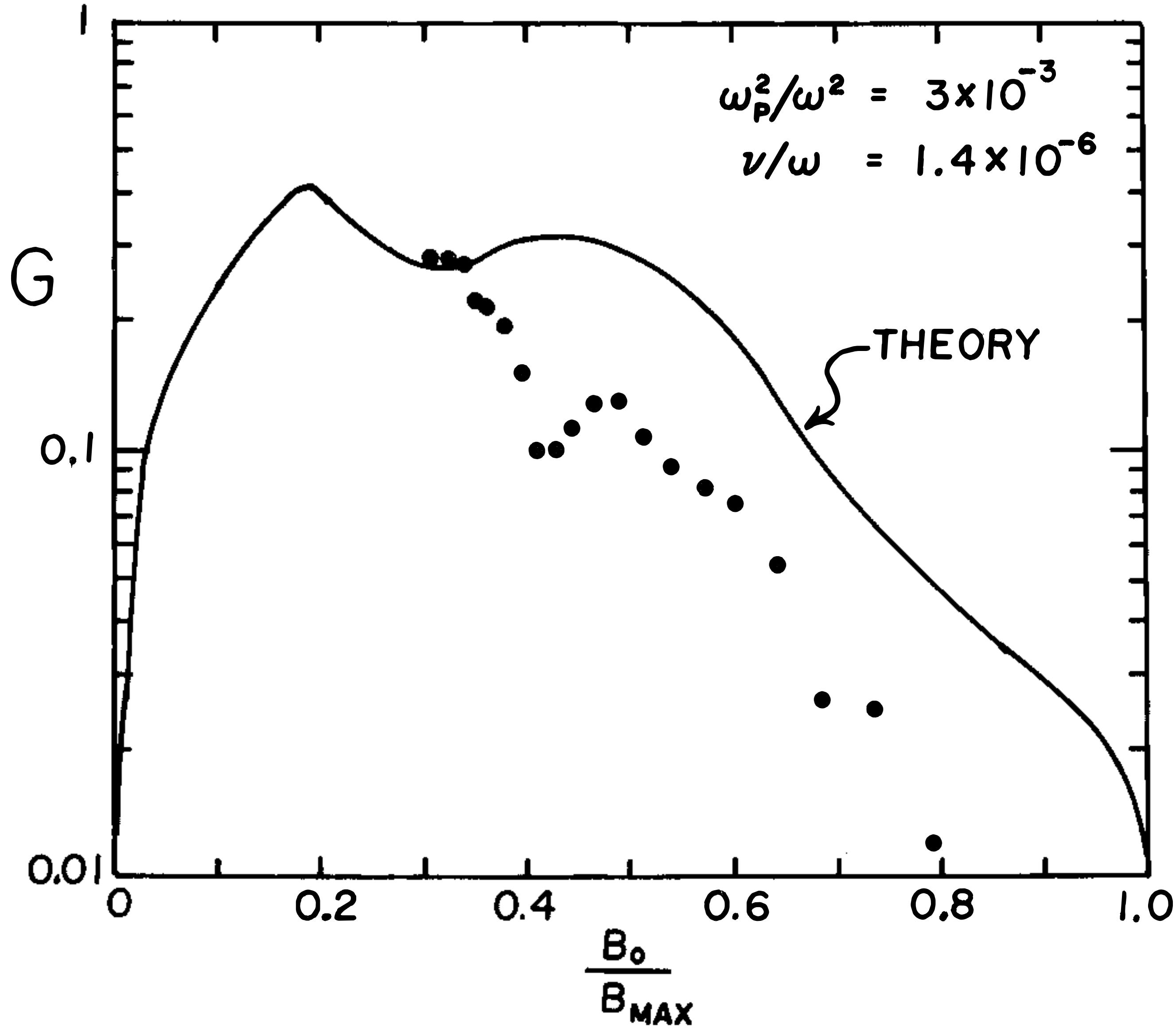
Figure Captions

1. Heating rate as a function of plasma density.
2. Heating rate as a function of resonance zone position.



1.0
G
0.1
0.01
$B_o/B_{MAX} = 0.53$
$\nu/\omega = 7 \times 10^{-7}$
THEORY
G_{MAX}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$\frac{\omega_p^2}{\omega^2}$



1
$\omega_p^2/\omega^2 = 3\times10^{-3}$
$\nu/\omega = 1.4\times10^{-6}$
G
THEORY
0.1
0.01
0
0.2
0.4
0.6
0.8
1.0
$\frac{B_0}{B_{MAX}}$