Measurements of electron-cyclotron heating rates

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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.

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

$$d\langle W\rangle/dt = \pi \int neE_\perp^2\, \delta(B - B_0)dV/2 \int n\,dV, \qquad (1)$$

where n is the electron density, $E_\perp$ is the rms electric field strength at frequency ω perpendicular to $\mathbf{B}$, B_0 is the magnetic field strength at resonance ($B_0 = m\omega/e$), $\langle W\rangle$ 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, detailed quantitative comparisons between the theory and experiment over a range of parameters are lacking. The reason is the difficulty of making accurate temperature measurements and the fact that poorly understood cooling and loss processes are usually present. Here, we present such a 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] The toroid has a major radius of 43 cm and a minor radius of 18 cm which is sufficiently large compared with the microwave wavelength so that the mode structure is very complicated and hence approximately random. In this way, the heating rates inferred from the absorption measurements, although indirect, are insensitive to any loss or cooling processes. Plasmas are produced and heated by a 2.45-GHz, $\leq$ 2-kW, cw microwave source. The Q measurements use a 9.6-GHz, $\leq$ 100-W, cw carcinotron (or backward wave oscillator) 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 nonuniform, and regions of cyclotron resonance exist for frequencies from zero to about 18 GHz. The densities ($\lesssim 10^{10}$ cm^{-3}) and temperatures ($kT_e \sim 5$ eV) are well below those of interest in fusion reactors, although the ratio of plasma frequency to cyclotron frequency (ω_p/ω_c) resembles that in a reactor, and the theory predicts no dependence on temperature. The 100-W, 9.6-GHz microwave power used to measure the heating is negligible compared with the 2 kW, 2.45 GHz used to produce the plasma, and hence only slightly perturbs the total plasma energy.

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 Eq. (1) can be written

$$d\langle W\rangle/dt = \pi e\langle E^2\rangle \int n\delta(B - B_0)dV/3 \int n\,dV = (e\langle E^2\rangle/B_0)G,$$

where

$$G = \pi B_0 \int n\delta(B - B_0)dV/3 \int n\,dV \qquad (2)$$

is a dimensionless quantity which depends only on the magnetic field shape, the position of the resonance zone, and the spatial distribution of the plasma density. The quantity G has been calculated numerically as a function of B_0 for the toroidal octupole assuming a density which is constant in space.

The input microwave power P from the 9.6-GHz source is absorbed by the cavity walls and by the plasma so that

$$P = (\varepsilon_0\omega\langle E^2\rangle V/Q_0) + nV(d\langle W\rangle/dt),$$

where V is the cavity volume and Q_0 is the cavity Q in the absence of plasma. Using the fact that

$$P = \varepsilon_0\omega\langle E_0^2\rangle V/Q_0,$$

and substituting the value of $d\langle W\rangle/dt$ from Eq. (2), G can be written as

$$G = (\omega^2/Q_0\omega_p^2)(\langle E_0^2\rangle/\langle E^2\rangle - 1). \qquad (3)$$

The electric field E_0 is the 9.6-GHz electric field in the absence of plasma. The quantity G can thus be experimentally determined by measuring the cavity Q without plasma, the plasma frequency ($\omega_p^2 = ne^2/\varepsilon_0 m$), and the ratio of the spatially averaged unperturbed to perturbed electric field $\langle E_0^2\rangle/\langle E^2\rangle$. 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 microwave signal from the antenna is passed through a high pass filter that removes the 2.45-GHz component and thence to a diode square law detector whose output is proportional to

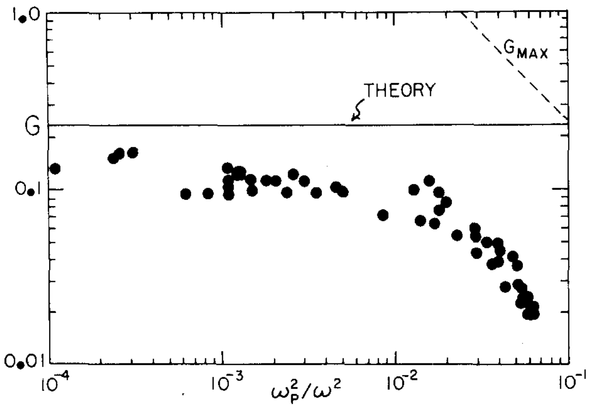

FIG. 1. Heating rate as a function of plasma density for $B_0/B_{max} = 0.53$ and $\nu/\omega = 7 \times 10^{-7}$.

$\langle E^2 \rangle$. The experiment consists of comparing the measured value of G given by Eq. (3) with the theoretical value calculated from Eq. (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 multimode cavity perturbation technique[8] which gives a volume-averaged density. The two methods generally agree within 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 $Q(Q_0 \simeq 3000)$.

Figure 2 shows the variation of heating rate as a function of resonance zone position (B_0/B_{max}). These data were taken at low plasma density by varying the magnetic field strength at constant B_0. B_{max} is the maximum value of field in the machine, and this maximum occurs at the surface of the hoops where the density is low. For $B_0/B_{max} > 1$, 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, but other uncertainties render the comparison unreliable to better than a factor of two.

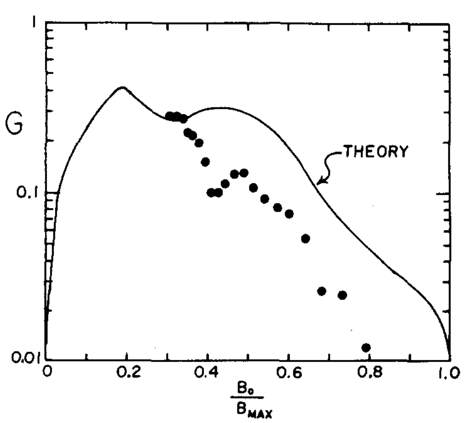

FIG. 2. Heating rate as a function of resonance zone position for $\omega_p^2/\omega^2 = 3 \times 10^{-3}$ and $\nu/\omega = 1.4 \times 10^{-6}$.

The variation of G with electric field strength was measured by varying the carcinotron power from 1 to 100 W corresponding to electric fields of $E/cB_0 \sim 10^{-6}$ to 10^{-5}. The theory predicts a heating rate that varies as E^2, and hence the quantity G should be constant as is indeed the case experimentally as shown in Fig. 3.

The variation of heating rate with electron–neutral collision frequency was also measured by varying the neutral hydrogen pressure from 10^{-6} Torr to 10^{-3} Torr corresponding to collision frequencies from $\nu/\omega \sim 10^{-7}$ to 10^{-4}. Figure 4 shows that 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 $G = \nu/\omega$, and hence no effect would be expected.

In summary, the experiment confirms the single-particle theoretical prediction of Eq. (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

$$\omega_p^2/\omega^2 > \lambda \nabla B/2\pi B_0 .$$

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 be perfectly opaque, in which case the minimum Q is

$$Q_{min} = 2\pi V/\lambda S,$$

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

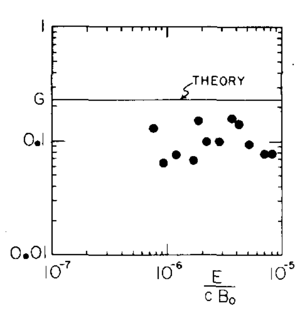

FIG. 3. Heating rate as a function of electric field strength for $B_0/B_{max} = 0.53$ and $\omega_p^2/\omega^2 = 7 \times 10^{-8}$.

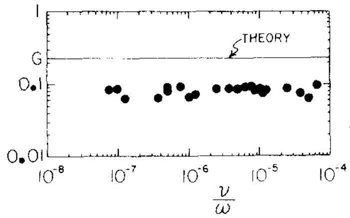

FIG. 4. Heating rate as a function of electron-neutral collision frequency for $B_0/B_{\max} = 0.53$ and $\omega_p^2/\omega^2 = 5 \times 10^{-3}$.

$$G_{\max} = (\lambda S/2\pi V)(\omega^2/\omega_p^2), \tag{4}$$

which is plotted as a dotted line in Fig. 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.

In a subsequent series of experiments a swept 1-GHz 1-W microwave source was used to excite an isolated low-order cavity mode, and the heating rate was determined from the broadening of this mode when a plasma is introduced. The results are similar to those obtained at 9.6 GHz in being typically a factor of three below the theory except that the decrease at large ω_p^2/ω^2 was not observed.

In addition to understanding the density dependence of G, we hope to extend the measurements over a wider range of parameters, including electron temperature, looking particularly for off-resonance effects and anomolous absorption due to parametric instabilities.

ACKNOWLEDGMENT

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