$q_a \simeq 1.5$ and it follows that the required intensities would be $\bar{S}_2^{\,in} = 5.5\times10^{11}$ W cm^{-2} and $\bar{S}_1^{\,in} = 1.1\times10^{13}$ W cm^{-2}. Such power densities are presently available.[9,10]

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Experimental Investigation of Plasma Heating by a High-Frequency Electric Field near the Electron Cyclotron Resonance in the FM-1 Spherator*

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Plasma heating due to a high-frequency electric field near the electron cyclotron resonance is investigated in a toroidal plasma confinement device, the FM-1 spherator. It is observed that electrons and ions are heated "anomalously" when the incident high-frequency field exceeds a threshold value. Above the same threshold the parametric decay instability of upper and lower hybrid waves takes place. We investigate the effect of the decay instability and plasma heating on the confinement time.

Plasma heating by high-power, high-frequency electric fields near the electron cyclotron frequency have been investigated in a number of experiments.[1-4] Recently, similar experiments have been also performed in toroidal devices such as the TM-3[5] and the Lawrence Livermore Laboratory Levitron.[6]

In this Letter we report results of detailed experimental studies of plasma heating and confinement properties when a high-frequency electric field with high power is applied near the electron cyclotron frequency (i.e., the upper hybrid frequency) in a toroidal device, the FM-1 spherator. The main subjects of the present investigation are as follows: (a) Anomalous ion heating is studied by measuring the ion temperature with the Doppler-broadening method. Above a threshold of incident rf power an anomalously fast heating of the main body of ions is observed. (b) This threshold is shown to correspond to excitation of the parametric decay instability of upper and lower hybrid waves.[7-9] The presence of such an instability is observed experimentally, and it is proposed that parametrically excited lower hybrid waves are responsible for the observed ion heating. (c) The effect of decay instability and plasma heating upon particle confinement is also investigated. (d) Since the experiment can be carried out with much lower neutral pressure than in linear devices, it is possible to calculate accurately the distribution of input energy in the plasma. To the best of our knowledge this is the first time that the foregoing points (a) and (c) have been demonstrated experimentally.[10]

The FM-1 spherator has a superconducing ring levitated magnetically to produce closed magnetic surfaces for confining the plasma.[11,12] The superconducting ring is excited with $I_p = 275$ kAt, and the ratio of the ring current I_p to the toroidal field current I_T is 0.94. In this magnetic field configuration the fluctuation level is minimum.[11] The average magnetic field is about 2 to 4 kG. Plasmas are produced by using 10.5-GHz microwave power with a filling helium gas of 4×10^{-7}

to 1×10^{-6} Torr. The same microwave source is also used to produce plasma heating. The plasma volume is 7×10^5 cm^3, and the vacuum tank volume is 5×10^6 cm^3. The electron cyclotron resonance surface for 10.5 GHz is located around the internal ring. About one third of the magnetic surface has the resonance magnetic field strength.

The electron plasma density is measured by an 8-mm microwave interferometer. The electron temperature is obtained by swept Langmuir probes and by using a calibrated monochromator to measure the absolute light intensity of the 4686- and 5876-Å spectral lines. The ion temperature is obtained from the Doppler-broadening measurement of the 4686-Å line with a pressure-swept Fabry-Perot interferometer. The minimum resoltuion of this equipment corresponds to $\Delta T_i = 0.1$ eV.

Figure 1 shows the experimentally measured temperatures when the incident microwave power level is varied. By changing the preionizing power level the initial plasma density was adjusted to $n_e = 1\times10^{11}$ cm^{-3}. The initial electron temperature was 0.5–1 eV and that of the ions 0.1 eV. The ion heating rate was obtained by measuring the ion temperature with a time interval of 1 msec. In Fig. 1(a), the observed ion heating rate is shown as a function of power. Below the incident power of 0.7 kW the ion temperature stayed the same as without heating. Above that threshold a sharp increase in the ion heating rate was observed. The estimated electric field inside the vacuum tank is $E_0 \simeq 5$ V/cm at $P_{inc} = 1.0$ kW, assuming that the vacuum tank works as a multicavity[12] with a Q value of 1000. The electron temperature, which is shown in Fig. 1(b), also shows a sudden increase of heating rate around $P_{inc} = 0.7$ kW.

The increase of ion temperature during the heating pulse is compared with numerical calculations. In this numerical code the measured time dependence of the electron temperature $T_e(t)$ and plasma density $n_e(t)$ is used to evaluate the charge-exchange, ionization, and recombination rates. The ion temperature is increased rapidly at the initial phase and tends to saturate around 2.7 eV. The measurement by the Doppler-broadening technique should reflect the bulk ion temperature and should not be sensitive to the tail of the velocity distribution. The electron temperature, which increased to ~20 eV initially, was gradually reduced to 8–10 eV at $t = 10$ msec because of ionization (resulting in an increase of the plasma density to $n_e = 1.3\times10^{11}$ cm^{-3}).

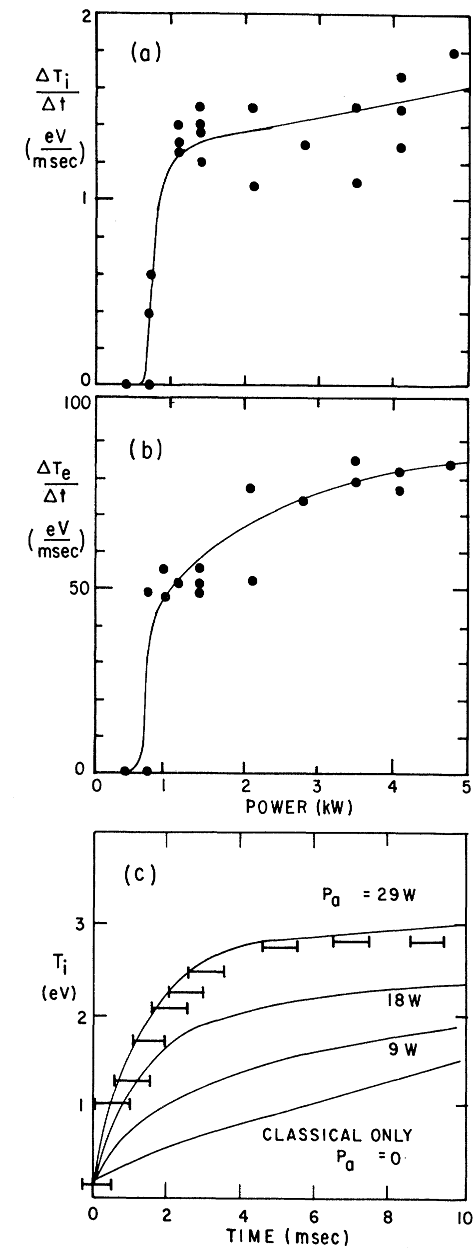

FIG. 1. (a) Heating rate of ion temperature versus input power. (b) Heating rate of electron temperature versus input power. (c) Comparison of time dependence of T_i with numerical calculations.

These results indicate that the plasma in the spherator is not fully ionized (about 50% ionization), so that the quasistationary state is determined by the energy balance between input power and loss due to ionization and charge exchange. Thus, in order to avoid the ambiguity due to energy loss by these processes, the heating rate at the initial stage was investigated to determine the power input to particles [as is shown in Figs. 1(a) and 1(b)]. The time constant of ionization is 2–4 msec and that for charge exchange is 5–10 msec under the present operating conditions. The comparison shows that a power input to ions of 30 W, in addition to the classical energy transfer from electron to ions, is required to explain the initial increase of ion temperature. This additional power input is higher than that of classical process by a factor of 7–9. The value of $P_a \sim 30$ W also seems to explain the ion temperature at later time. The average power input to the electrons at the initial phase was about 500 W. These results indicate that the ratio of energy input to ions and electrons at the initial phase is about 5%.

Suspecting that the anomalously fast plasma heating may be due to parametric instabilities, we have investigated the frequency spectrum in the plasma volume by coaxial probes. Above the threshold power level of $P_{\rm th} \sim 0.5$ kW, a typical parametric decay instability spectrum is present in the plasma. The measured spectrum shows both the low-frequency decay spectrum peaking at $\omega_1 \simeq \omega_{pi}$, and the high-frequency lower sideband peaking at $\omega_0 - \omega_1 \sim \omega_{UH}$ (where $\omega_{pi}/2\pi$ is the ion plasma frequency, $\omega_0/2\pi$ the pumping frequency of 10.6 GHz, and $\omega_{UH}/2\pi$ the upper hybrid frequency). The dependence of the low-frequency spectrum on the input power is shown in Fig. 2(a). It is noticed that as the incident power was increased, the peak of the decay spectrum shifted from 30 to 40 MHz ($\omega_{pi}/2\pi = 25$–30 MHz). In addition, at higher power levels second-harmonic generation also occurs. The dependence of the primary peak of the spectrum upon incident power level is shown in Fig. 2(b). It is clearly seen that the threshold is $P_{\rm th} \sim 0.5$ kW, which corresponds to $E_{\rm th} \sim 3.5$ V/cm. From Fig. 2 it can be concluded that plasma heating takes place above nearly the same threshold power as the decay instability. The spatial dependence of the decay spectrum was also studied. By varying the magnetic field the upper hybrid layer was moved to different radial positions, and the decay spectrum peaked near the new hybrid layers. These experimental results indicate that ions as well as electrons are heated by the parametric decay process; presumably, the electrons are heated by absorption of upper hybrid waves (Bernstein waves) and the ions by absorption of lower hybrid waves.[13]

The theoretical estimate of the threshold for the parametric decay of the extraordinary mode

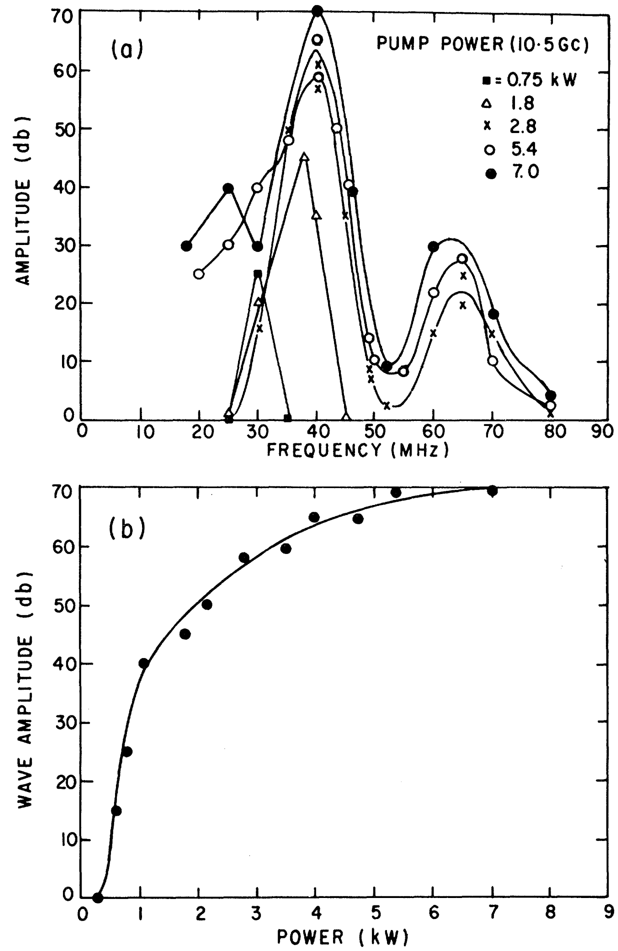

FIG. 2. (a) Frequency spectrum for different input rf powers. (b) Wave amplitude versus input power.

near the upper hybrid frequency[9] yields $E_{\rm th} \simeq 3$ V/cm, which is in good agreement with the experimental results. The perpendicular wavelength for the most unstable mode, $\lambda_\perp \approx 10^{-2}$ cm, was obtained from the usual frequency-matching conditions. However, it must be noted that the agreement between theory and experiment may be somewhat fortuitous since density and magnetic field gradients have not been taken into account in the threshold calculations.

The effect of the heating on the plasma confinement time is investigated during the heating period by measuring the loss rate Γ with loss detectors located just inside the most outside magnetic surface. The plasma confinement time can be estimated by $\tau = \int n\,dV/\Gamma$. The electron temperature monitored by light intensity showed $T_e \sim 8$–10 eV, almost independent of the input power level with higher power (see Fig. 3). In this stage

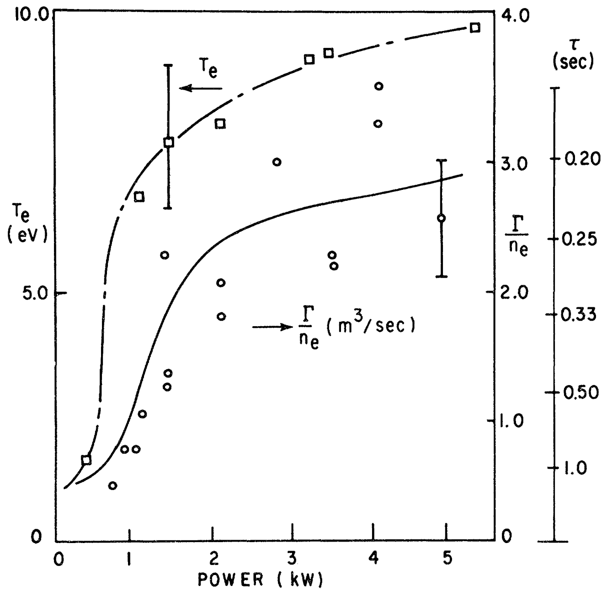

FIG. 3. Electron temperature and loss rate versus input power (bar shows typical experimental error).

the final electron temperature is determined by energy balance between the heating power input and the ionization energy loss. The plasma confinement time is reduced with an increase of power input. Thus, a question arises whether this decrease of confinement time with an increase of power input is essentially related to the parametric instability. As is reported elsewhere,[11] the magnetic field configuration of the spherator has a tendency to yield $\tau \sim (150-300)\tau_B$ in the high-electron-temperature regime ($T_e = 1-30$ eV).[14] (The Bohm time τ_B is 9 msec at $T_e = 1$ eV.) By using the electron temperature observed in the present experiment, it is possible to estimate the confinement time τ_0 corresponding to the condition where no parametric heating takes place. The value of τ_0 is 0.2–0.4 sec for $T_e = 8-10$ eV. (In the low-electron-temperature regime, $T_e < 1$ eV, the confinement time is increased with an increase of T_e. However, in the present experiment the electron temperature is higher than 1 eV so that the high-electron-temperature regime is used for the estimate.[11]) This number is close to the one obtained in the present experiments. Although there is still an ambiguity of a factor of 2, in these experiments the fully developed parametric decay process did not produce deleterious effects on the plasma decay time. This may be because of the localization of the maximum decay amplitudes well within the plasma body, and of the very short wavelengths.[7]

In conclusion, significant electron and ion heating has been observed in a toroidal device, the FM-1 spherator, above a threshold X-band microwave power, and it was shown to be associated with the simultaneous occurrence of a parametric decay instability. The effect on the plasma confinement due to the parametric instability is not significant for the power levels used in these experiments.

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