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ABSORPTION AT DOWN-SHIFTED FREQUENCY IN THE PLT TOKAMAK

By

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EXPERIMENTAL INVESTIGATION ON ELECTRON CYCLOTRON ABSORPTION AT DOWN-SHIFTED FREQUENCY IN THE PLT TOKAMAK

MASTER

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ABSTRACT

The absorption of 60 GHz electron cyclotron waves, with the extraordinary mode and an oblique angle of propagation, has been investigated in the PLT tokamak in the regime of down-shifted frequencies.

The production of energetic electrons, with energies of up to 300 - 400 keV, peaks at values of toroidal field (≈ 29 kG) for which the wave frequency is significantly smaller than the electron cyclotron frequency in the whole plasma region.

The observations are consistent with the predictions of the relativistic theory of electron cyclotron damping at down-shifted frequency. Existing rf sources make this process a viable method for assisting the current ramp-up, and for heating the plasma of present large tokamaks.

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1. INTRODUCTION

Recent theoretical investigations [1] on the damping of electron cyclotron waves (ECW) in tokamaks have shown the advantages of using the extraordinary mode with an oblique angle of propagation (with respect to the magnetic field) and frequency below the electron cyclotron frequency. Compared to the more conventional method of using the ordinary mode with perpendicular propagation from the lower field side of the equatorial plane, one advantage is the possibility of operating at higher values of magnetic field. This allows the use of existing wave sources in present large tokamaks at values of toroidal field close to their maximum, like, for instance, in JET at $B \approx 35$ kG and $f = 70$ GHz, or in TFTR at $B \approx 45$ kG and $f = 83$ GHz, and for an initial central electron temperature in the range of 3–4 keV.

The second advantage is that wave absorption occurs via the electron tail of the velocity distribution, which makes the new method suitable for assisting the inductive tokamak discharge in all its phases of operation, i.e., from the low density cold plasma current ramp-up to the high density hot plasma regime. In fact, one can show that strong wave damping is expected in the two phases of a tokamak discharge with the same value of the parallel refractive index, $N_{\parallel}$, and frequency shift. In the case of a low density plasma, the electron distribution has a slide-away tail in the direction of the inductive electric field, which provides the electron population required for strong wave damping [2]. In the high density hot plasma phase, the effect of the electric field is negligible and the tail is Maxwellian. Nevertheless, at high values of plasma density and temperature, the number of electrons resonating with the cyclotron wave can still be sufficient for strong wave damping [1].

In general, absorption of electron cyclotron waves at velocities above the thermal speed results both in bulk heating and generation of an energetic tail. This is true at any value of plasma density, but the relative magnitude of the two effects is a sensitive function of the parallel velocity of resonant electrons. Heating of the main body of the electronic population results from the collisional relaxation of resonant with colder electrons, while the runaway production depends on pitch angle scattering and the decreasing resistance of resonant electrons caused by the perpendicular cyclotron heating. Thus, for resonant velocities too high compared with the thermal speed, the absorbing electrons are nearly collisionless and the runaway production is favored. On the other hand, for resonant velocities near the thermal speed, Coulomb collisions are very efficient and the wave energy is rapidly converted into bulk heating.

In this paper, we present some experimental results on the absorption of 60 GHz ECW at down shifted frequency and on the production of energetic electrons in the PLT tokamak. The experimental set-up is described in Sect. II, and the results are presented in Sect. III. Section IV is devoted to a discussion of the collected data, and the conclusions are in Sect. V.

2. EXPERIMENTAL SET-UP

The output of a 60 GHz gyrotron, capable of delivering 200 kW of microwave power in pulses of 100 msec, was launched into the PLT plasma through a port located on top of the vacuum vessel. The wave was polarized in the extraordinary mode, with an initial direction of 30° with respect to the local toroidal magnetic field.

As in a previous experiment on electron cyclotron heating in PDX [3], the rf power from the gyrotron in the TE_{02} mode was converted to the less lossy TE_{01} mode for transmission to the PLT tokamak. On the machine side, the TE_{01} mode was converted first to the TM_{11} mode, and then to the HE_{11} mode for launch into the PLT plasma from an open waveguide. The initial wave direction was determined by a flat mirror located in front of the launching waveguide. The wave had a radiation pattern with a full width, at the plasma center, of ≈ 10 cm between the 10 db points.

In order to couple to the extraordinary mode, the wave was launched into the plasma with the proper elliptical polarization. This was achieved with an elliptically deformed section of circular waveguide propagating the TM_{11} mode, located just before the HE_{11} mode converter [4]. The polarizer was adjusted to compensate both for the birefringence of a corrugated bend propagating HE_{11} , and for the flat mirror inside PLT which reverses the polarization sense of rotation.

Since it was not possible to position the gyrotron close to the PLT device, the use of a very long and tortuous transmission line became necessary, with a total of seven 90° bends in addition to three mode converters and one polarizer. This resulted in a very lossy transmission line, which limited the launched rf power to a maximum of 40-50 kW.

3. EXPERIMENTAL RESULTS

The experiment was carried out in a typical low density PLT discharge, with minor radius $a \approx 40$ cm, major radius $R_0 = 135$ cm, line average electron density $\bar{n}_e = 1.3 \times 10^{13} \text{ cm}^{-3}$, central electron temperature $T_{e0} = 1.8 - 2.0$ keV, toroidal magnetic field $B_0 = 26 - 33$ kG, and plasma current $I = 500$ kA. The wave was injected during the discharge steady state, typically 400 msec after its beginning.

Figure 1 shows the poloidal projection of the wave trajectory obtained with a ray tracing code [1]. Here, the plasma density has a parabolic profile, the initial propagation angle is 30° with respect to the toroidal magnetic field ($=27$ kG), and the plasma current flows in the same direction of $\vec{B}_0$, as in the experiment.

The relevant resonant condition, for $N_{||} > 0$, is [1]

$$\frac{p_{\parallel}}{mc} = \frac{N_{\parallel} f_c / f - (N_{\parallel}^2 - 1 + f_c^2 / f^2)^{1/2}}{1 - N_{\parallel}^2},$$

where $p_{\parallel}$ is the momentum component parallel to the magnetic field, c is the speed of light, m is the electron rest mass, f_c is the electron cyclotron frequency, and f is the wave frequency. From this equation, we can derive the energy of resonant electrons which is shown in Fig. 2 for three values of B_0 (27, 29, and 31 kG).

For the lowest value of toroidal field of Fig. 2 the resonant energy is not very large, so that, even in a Maxwellian plasma with a relatively low electron temperature, the wave can be totally absorbed in a single pass. This is shown in Fig. 3 which contains the power deposition profile given by the relativistic theory of electron cyclotron absorption [1] for a Maxwellian PLT plasma with the electron temperature profile $T_e = 2.0(1 - r^2/a^2)^{3/2}$. In these calculations, the effect of the antenna radiation pattern has been simulated with a weighted average over 96 rays.

At higher values of B_0 (> 27 kG), the resonant energy increases, and wave absorption becomes rapidly small in an ohmic PLT plasma if it is Maxwellian. For instance, we find negligible absorption when $B_0 = 29$ kG and $T_{e0} = 2$ keV. Wave absorption is then possible only at higher electron temperatures or through a suprathermal tail.

The main diagnostic used in our experiment was the measurement of plasma emission in the electron cyclotron range of frequencies (ECE) and in that of hard X-ray (30-700 keV). The electron cyclotron radiation was measured with a ten-channel polychromator [3] which detected second harmonic X-mode plasma emission at the lower field side of the equatorial plane. For PLT plasmas in the density range of the present experiment, this is a blackbody emission. Under normal conditions, the electron cyclotron frequency is determined by the local toroidal magnetic field $B_t = B_0 R_0 / R$ (where R is the local major radius), so that from a measurement of the ECE intensity at a known frequency, we derive the value of T_e at the various plasma positions.

Figure 4 shows the time evolution of an ECE signal with frequency corresponding to a major radius of 200 cm. Since no plasma was present at this location, the signal is within the instrumental noise level before the rf pulse. On the contrary, during the rf pulse the signal increases rapidly and reaches a maximum at the end of the pulse. After the rf is turned off, the signal at first decreases slightly in a time scale of 10-20 msec, and then remains constant or slightly increases up to the discharge end.

This ECE signal could only have been emitted by relativistic electrons at a down-shifted frequency, because its nominal radius corresponds to a location which is outside of the vacuum vessel. Since its direction of propagation was perpendicular to the toroidal magnetic field, the value of $\gamma = [1 + p^2/(mc)^2]^{1/2}$ of the emitting

electrons is simply the ratio of the ECE nominal position to their real major radius.

Figure 5 shows line integrated hard X-ray signals measured with a vertical array of detectors at the end of the rf pulse. These data clearly indicate that the rf generated energetic electrons were located in a central plasma core with a minor radius of ≈ 10 cm. From this, we conclude that the value of γ of the energetic electrons responsible for the signal of Fig. 4 was in the range $1.38 \leq \gamma \leq 1.60$ (that is $\gamma \approx 200/(135 \pm 10)$), which corresponds to an electron energy of 200-300 keV. Figure 6 shows the amplitude of several ECE signals with different values of the nominal major radius. The most down-shifted signal corresponds to an electron energy of 300-400 keV.

The large values of electron energy deduced from the ECE signals indicate that they could not have been produced by the rf wave alone. As described earlier, the launched wave interacts directly with electrons of smaller energy (Fig. 2) than the values derived from ECE measurements. The immediate conclusion is that the tokamak dc electric field must have played a fundamental role in the production of energetic electrons.

The ECE signals measured at the frequency that corresponds to a nominal major radius of 200 cm are shown in Fig. 7 as a function of the toroidal magnetic field. Both ECE signals with different frequency, and the plasma emission of X-ray (Fig.8) exhibit a similar behavior. These data indicate that the production of energetic electrons peaks in a very well defined and narrow range of magnetic field, where the wave frequency is much smaller than the electron cyclotron frequency.

4. DISCUSSION

The experimental data support the following scenario: in the absence of ECW, the effect of a dc electric field is that of extending the electron tail beyond the thermal energy. The features of this electron tail are the result of a balance between the effect of the dc electric field and the collisional pitch angle scattering and parallel slow-down. Since in a typical tokamak plasma the ratio of the parallel electric field, $E_{\parallel}$, and the Dreicer field, $E_d \propto n_e/T_e$, is usually less than 10^{-1} , the electron tail does not develop into a runaway tail. An upper limit of its maximum energy, E_0 , is obtained from the observation that, in the absence of ECW, the measured ECE signals are negligible for $R > (R_0 + a)$. For PLT, this corresponds to a value $E_0 < 150$ keV. The effect of ECW is to increase the perpendicular energy of resonant electrons, which reduces the collisional slow-down and increases the effect of the dc electric field. In the present experiment, the optimum conditions are found for $B_0 \approx 29$ kG (Figs.7,8) when the resonant electrons have energies of ≈ 20 keV and a fast tail develops to energies $E \gg E_0$. These are the conditions of interest

for the current ramp-up phase of a tokamak discharge. At smaller values of B_0 , this tail rapidly disappears because the energy of resonant electrons decreases and collisional effects dominate that of the electric field. These are the conditions for plasma bulk heating. Unfortunately, in the present experiment the power level was too small to produce a significant temperature increase in a plasma torus with the size of PLT.

We found that the energetic tail disappeared at larger values of B_0 as well. This is because the energy of resonant electrons in this range of magnetic fields was too large for the pre-existing ohmic tail, and the ECW absorption was impaired.

In terms of the Dreicer critical velocity, this qualitative picture can be described by saying that perpendicular cyclotron heating increases the production of runaway electrons by reducing the critical parallel velocity. The reduction of the Dreicer velocity is more effective in the high energy side of the initial tail, and the runaway production increases for decreasing values of the resonant velocity (i.e., B_0). This trend reverses at velocities for which collisions prevent a strong enhancement of the perpendicular energy ($B_0 < 29$ kG).

This qualitative description of the PLT experiment is supported by numerical results obtained with a quasi-linear Fokker-Planck code [5].

5. CONCLUSION

The absorption of electron cyclotron waves at down-shifted frequencies has been investigated in the PLT tokamak. It has been shown that the extraordinary mode with oblique propagation can be absorbed by energetic electrons. This is of interest for ECW assistance of the current ramp-up of low density tokamaks, where the wave is absorbed by a suprathermal ohmic tail. At higher values of plasma density, the wave can also be absorbed by a Maxwellian tail, if the electron temperature is sufficiently large. This is the regime for heating the main body of the electron distribution.

It is possible to imagine a scenario where a tokamak discharge starts at low density and its current ramp-up is assisted by ECW. As collisions transfer some of the energy from fast to slower electrons, the plasma temperature increases to values of 3-4 keV. At this point the plasma density is increased, and the absorption of ECW proceeds via the Maxwellian tail, with further increase of the plasma electron temperature. It is important to note that the switching from one phase to the other can be accomplished without change in the launching geometry.

In conclusion, the experimental observations are consistent with the predictions of the relativistic theory of electron cyclotron damping at down-shifted frequency. Existing rf sources make this process a viable method for assisting the current ramp-up, and for heating the plasma of present large tokamaks.

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FIGURE CAPTIONS

- Fig.1 Poloidal projection of a wave ray trajectory with $f=60$ GHz in a PLT plasma with $n_e = 2 \times 10^{13}(1 - r^2/a^2) \text{ cm}^{-3}$, and $B_0 = 27$ kG.
- Fig.2 Energy of resonant electrons along the ray path for $B_0=27$ kG (a), 29 kG (b), and 31 kG (c). Other conditions are those of Fig. 1.
- Fig.3 Power deposition profile (for 1 MW of rf power) in a Maxwellian PLT plasma with the conditions of Fig. 1, and $T_e = 2.0(1 - r^2/a^2)^{3/2} \text{ keV}$.
- Fig.4 Time evolution of an ECE signal with nominal radius $R=200$ cm for $B_0 = 29$ kG.
- Fig.5 Line integrated hard X-ray signals measured with a vertical array as a function of $r = (R - R_0)$ for $B_0 = 29$ kG.
- Fig.6 Amplitude of ECE signals as a function of nominal major radius R for $B_0 = 29$ kG.
- Fig.7 ECE signal ($R=200$ cm) as a function of B_0 at the end of the rf pulse.
- Fig.8 Hard X-ray signal (central chord) as a function of B_0 at the end of the rf pulse.

Fig.1 Poloidal projection of a wave ray trajectory with $f=60 \text{ GHz}$ in a PLT plasma with $n_e = 2 \times 10^{13}(1 - r^2/a^2) \text{ cm}^{-3}$, and $B_0 = 27 \text{ kG}$.

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