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Observation of Cyclotron Waves Resonantly Excited under Electron Cyclotron Resonance Heating at Magnetic Beach

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Abstract

Frequency analyses are made for cyclotron radiations emitted from electrons under electron cyclotron heating in a magnetic beach. In addition to a broad spectrum due to incoherent emissions a new spectrum is observed that is attributed to coherent emissions from spatially bunched electrons triggered by velocity space modulation by ECH and enhanced by magnetic-mirror effect.

Keywords:

ECH, cyclotron radiation, collective motion, bunching, magnetic mirror

1. Introduction

An electron cyclotron wave propagating toward a magnetic beach experiences two resonances, namely, one is the wave-particle cyclotron resonance and the other is a singular increase of the parallel wave-number that is associated with strong reduction of the wave's phase velocity. If the wave is monochromatic and of a large amplitude, we expect non-stochastic acceleration of resonant electrons which remain in phase with the wave. Then, the spectrum of the cyclotron radiation emitted by the electrons may bear characteristic features in addition to the normal spread associated with the velocity distribution.

We report about an experimental trial to observe such emissions at the fundamental cyclotron resonance and examine the observed radiation. The experiment is carried out at one mirror cell of a tandem mirror where electrons are resonantly heated by an electron cyclotron wave (ECH). Associated with the ECH, a several dB of enhancement in the radiation level is observed over a wide frequency range around the fundamental resonance. In addition, a much stronger radiation is observed in a narrow frequency range near the fundamental resonance.

The organization of the paper is as follows. The experimental setup is given in Sec. 2, and the results are given in Sec. 3. After the discussion in Sec. 4, we conclude the paper in Sec. 5.

2. Experiment Setup

The experiment is carried out at the east plug/barrier cell of GAMMA10 as illustrated schematically in Fig. 1. We take the machine axis as z-axis running from the east to the west with $z = 0$ at the mid-plane of the central cell. At the east plug/barrier cell, a high power microwave, generated at 28GHz up to 150kW by a gyrotron, is launched from the high field side to the resonance layer of 1T in shape of a beam of an x-mode cyclotron wave. The electrons are heated to reach collisionless regime (several hundred eV, $\approx 10^{17}\mathrm{m}^{-3}$) where the mean-free-pass is about 10^3 times larger than the machine length.

The observation system is illustrated in Fig. 2. The

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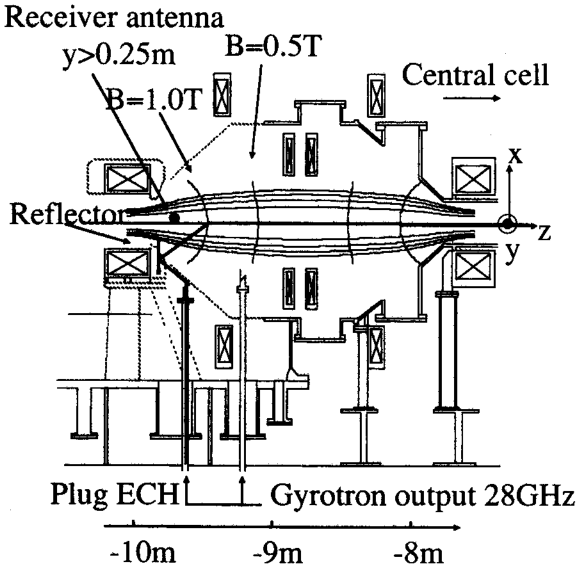

Fig. 1 A schematic view of the plug/barrier cell of the GAMMA10 tandem mirror.

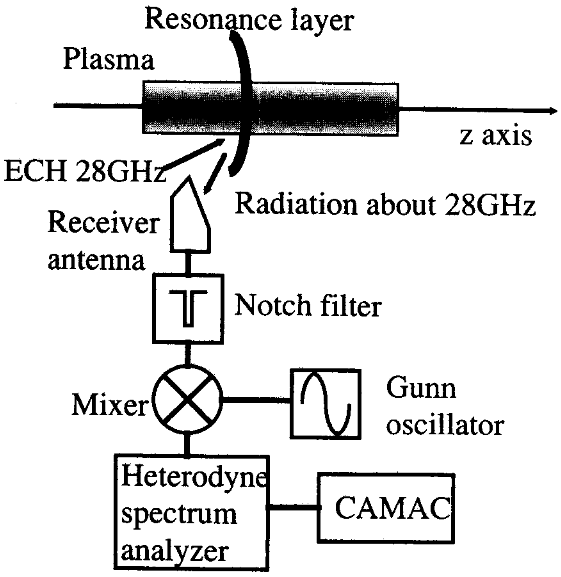

Fig. 2 A schematic diagram of the observation system. It consists of a movable receiver antenna, a notch filter, a balanced mixer, a gunn diode local oscillator and a heterodyne type spectrum analyzer.

microwave emissions are collected on a receiver antenna that is radially movable at z = –9.77m. The received microwave is propagated through an over-size circular waveguide, and converted to TE_{10} mode to be guided through a rectangular waveguide system which includes

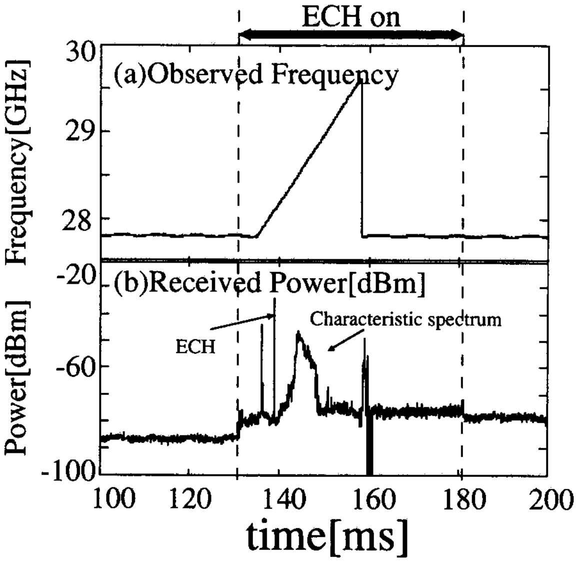

Fig. 3 Time sequence of the frequency analysis (a) Frequency as a function of time. (b) The received power as a function of time.

a notch filter with a 30dB rejection band from 28.0 to 28.1GHz equipped for the protection of the system from gyrotron output power. The signals are converted to below 1.8GHz through a heterodyne circuit that consists of a gunn diode local oscillator (27–29.5GHz) and a balanced mixer, and finally frequency-analyzed on a heterodyne-type spectrum analyzer.

3. Experimental Results

Fig.3 illustrates the experimental scheme of the spectrum analysis. The plasma is produced by a discharge from 50 to 230ms, and the ECH is applied from 130 to 180ms with a gyrotron power of 140kW. The frequency of the analyzer window 5MHz width is varied from 27.8 to 29.6GHz starting at 135ms and completing at 155ms as indicated in Fig. 3(a). The power level of the tuned microwave signal is plotted in Fig. 3(b). It is experimentally confirmed that the signal level of each frequency component in the swept domain does not appreciably change during the time of the frequency scanning. Therefore Fig. 3(b) shows the frequency spectrum averaged over the time interval. Associated with the application of ECH, an enhancement of the signal level is observed by several dB above the level detected before ECH. This component is observed over a wide frequency range around the fundamental resonance (26–30GHz). A further enhancement of more than 30 dB is observed at

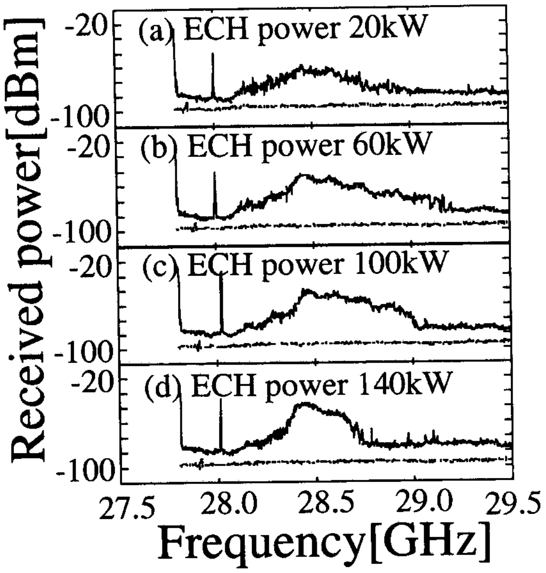

Fig. 4 Frequency spectra for different powers of ECH, (a) 20kW, (b) 60kW, (c) 100kW and (d) 140kW. The solid (dashed) line represents the spectrum with ECH (without ECH).

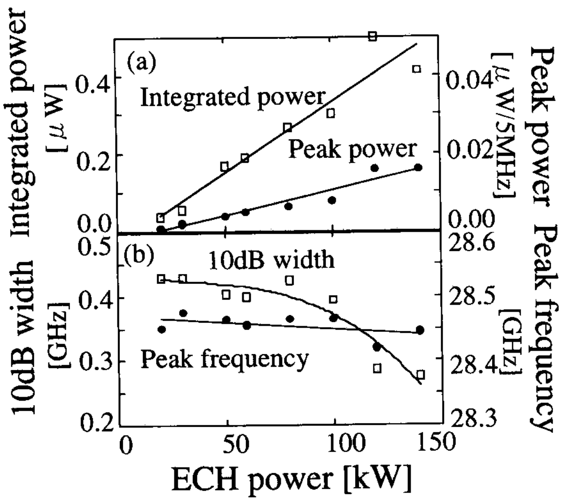

Fig. 5 The characteristics parameters of the narrow component vary with the ECH power. (a) The peak power and the integrated power. (b) The 10 dB width and the peak frequency.

142ms (corresponding to 28.4GHz). The 10dB frequency width of this component is quite narrow (0.4GHz). The spike at 135ms (27.8GHz) is due to the instrumental output associated with the initiation of the frequency sweep and at 137ms (28.0GHz) corresponds to the heating wave. The narrow component of the emission is close to but still well separated from the heating wave frequency. Time evolutions of the two components are different. The amplitude of the narrow component decreases down to the level of the broad component as soon as the ECH power is turned off. The broad component remains observed after the ECH power is turned off. The total power of the broad component is evaluated by correcting for the frequency-response of the whole system of detection and by integrating over the space with an approximation of isotropic emission. The result is nearly equal to the power of the cyclotron radiation summed over individual electrons in the plug region. Therefore this component is attributed to thermal motion of heated electrons including the bulk component and hot tails in the velocity distribution. The latter is the dominant source of radiation for hundreds of ms after the turn-off of ECH. The narrow component shows features different from the broad component. To study the mechanism of the generation of this component, we examine changes of this component by varying the ECH power. Some results are shown in Fig. 4, in which we plot the frequency spectrum of the received signal detected at increasing ECH power (20, 60, 100, 140kW). In each plate the dotted line represents the spectrum without ECH in the presence of the plasma. As mentioned above the spike at 28GHz may be discarded from the discussion. It is observed that the power level of this component increases and its width decreases with increasing power of ECH. It is noticed that the spectral tail in the high frequency side shrinks as the heating power is increased. These characteristics in the frequency spectrum are summarized in Fig. 5. Fig. 5(a) shows the peak level (closed circles) of this component and the frequency-integrated power (open squares) as functions of the ECH power. The integration is made from 28.1 to 29.5GHz. It is observed that the both power levels increase almost linearly with the heating power. So far we have not found any threshold value in heating power. Fig. 5(b) plots the 10dB width of this component (open squares) and the frequency of the peak power (closed circles) as functions of the ECH power. The 10dB width is about 0.4GHz and decreases with the increased ECH power. The peak frequency remains around 28.4GHz showing a slight decrease with the heating power.

4. Discussion

It is experimentally confirmed that the frequency spectrum does not change appreciably for different locations and orientations of the receiver antenna. However, it is beyond the capability of the present experiment to exclude a possibility that the narrow component is observed as a result of a selective transparency of the plasma against a wider frequency spectrum of emissions originally generated deep inside the plasma. To examine whether the narrow spectrum represents the spectrum of the actual emission, we study the path and the degree of absorption of each frequency component reaching the receiver antenna by using a ray-tracing code [1]. The ray-tracing calculation is based on geometric optics. Following assumptions are made for the present calculation. The electron velocity distribution function is a bi-Maxwellian. The density exponentially decreases as square of the radial coordinate and also with increasing external magnetic field. These simplifying assumptions are not very contradictory to the observed results of GAMMA10 plasma. As a result, we have confirmed that each frequency element of cyclotron waves in a wide range (27–30GHz) reaches the receiver antenna without severe damping as long as it is generated in the plasma. Therefore, From the comparison between the observation and the ray-tracing, we conclude that the strong radiations are generated only within the narrow frequency range. Because incoherent emission should generate a wider frequency spectrum, we expect that the narrow component is attributed to collective motion of electrons. Among several candidates wave-wave processes is not a dominant process because the frequency separation from the heating wave does not depend sensitively on the heating power and other plasma parameters. We also exclude the possibility of induced radiation from electrons during the acceleration by the heating wave because this component is largely separated from the heating wave. These considerations are consistent with our experimental confirmation that any characteristic peaking structures are not observed in the second harmonic range (around 56GHz). A plausible candidate remaining at hand is as follow: When the monochromatic ECH wave is applied to the plasma at the magnetic beach, the electrons are accelerated or decelerated depending the phase difference between the electrons and the wave. The modulation of the momentum is accompanied by a modulation in the gyration phase. The modulation in the velocity space results in the spatial bunching along the gyration orbit [2]. Since the heated electrons run along the increasing magnetic field, they are axially decelerated by the mirror effect. This effect contributes to localize the axial position where the azimuthal bunching appears. The coherence of cyclotron emissions under the bunching increases and the contributions from many electrons add up to higher level at the frequency that is also determined by the local magnetic field of the bunching. The shrinking tail at the high frequency side of the spectrum as observed in Fig. 5(b) can be understood in terms of the stronger mirror effect against electrons which have acquired larger transverse energy at a higher ECH power resulting in axial stagnation at a lower magnetic field.

5. Conclusions

Under the magnetic beach heating of collisionless electrons with a monochromatic cyclotron wave, we have observed a radiation spectrum that is composed of two components. One is a broad component that is attributed to incoherent cyclotron emissions of heated electrons. The other is limited in a narrow range in the upper side of the heating frequency but much stronger than the other component. The generation mechanism of this component is examined experimentally and theoretically. The most plausible mechanism is the spatial bunching of the electrons under the mirror effect after phase modulations by the heating wave. Phase modulation of gyrating particles has been discussed in relation to cyclotron echo [2]. It also plays an important role in a intermediate process of cyclotron heating [3,4].

Acknowledgments

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