Delayed Emission of Cyclotron Harmonics Triggered by a High-Power Microwave Pulse

N. Ohyabu, S. Sasaki, and N. Kawashima
Institute of Space and Aeronautical Science, University of Tokyo, Komaba, Meguro-ku, Tokyo, Japan
(Received 29 April 1974)

We study the interaction of high-power microwaves with a magnetized plasma. Delayed emissions at cyclotron harmonics are observed after the termination of the pumping wave when the frequency of the pumping wave is equal to one of the harmonics of the cyclotron frequency and is near the plasma frequency.

There has been much interest recently in the interaction of intense electromagnetic waves with plasma concerned with laser-induced fusion and nonlinear plasma wave phenomena in the magnetosphere.[1,2] Such an interaction can produce numerous nonlinear phenomena.[3-10] Here we will present interesting experimental results of the interaction of high-power microwaves with a magnetized plasma in which delayed emissions at cyclotron harmonics are observed after the termination of the pumping wave when the frequency of the pumping wave is equal to one of the harmonics of the cyclotron frequency and is near the plasma frequency.

The experimental layout is shown in Fig. 1. A helium plasma is produced in the steady state by ionization due to electrons which are emitted from an oxide-coated cathode and accelerated by the electric field between anode and cathode. The plasma density is around $10^{12}/\mathrm{cm}^3$ and the neutral-gas pressure P_0 is 1×10^{-4} Torr. The plasma is confined in a magnetic mirror field produced by coils I-IV and the radius of the plasma column is about 1 cm. High-power microwaves at $f_0 = 9.36$ GHz are transmitted transverse to the plasma column from an open-ended wave guide. The maximum power and the duration time of the pumping microwaves are 10 kW and 5–20 μsec, respectively. Microwave emissions from the plasma are measured by a spectrum analyzer (EMA 910) with a frequency range from 1 to 10 GHz.

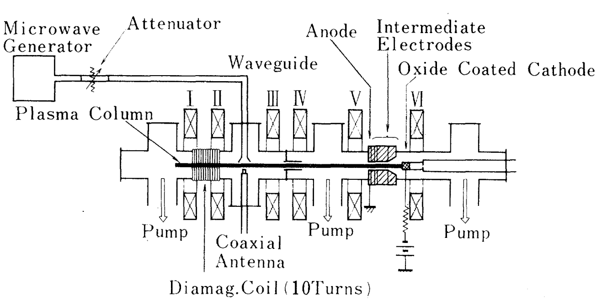

FIG. 1. Schematic layout of the experiment.

An output signal of microwave emissions from the plasma is shown in Fig. 2, in which the pumping frequency is 5 times the electron-cyclotron frequency ($f_0 = 5f_{ce}$) and the measured frequency is tuned to the second harmonic of the electron-cyclotron frequency. A strong microwave emission is observed simultaneously with the microwave pumping (between t_1 and t_2 in Fig. 2). After the termination of the pumping, pulsating microwave emissions appear with a maximum delay time of up to 50 μsec.

Such delayed emissions appear only when the resonance condition $f_0 = nf_{ce}$ ($n = 2, 3, 4, 5, \ldots$) is satisfied; the frequency spectrum of the delayed emission for $n = 4, 5$ is shown in Fig. 3. From Fig. 3, the following rule about the spectrum of the delayed emission is obtained: (i) spectra have peaks at the cyclotron harmonics (mf_{ce}) ($m = 2, 3, \ldots, n-1$); (ii) the emission at the second harmonic is the strongest; (iii) emissions at frequencies f_{ce} (fundamental) and nf_{ce} (i.e., the pumping frequency f_0) are so weak that they are difficult to distinguish from the noise level of the receiver.

The delayed emission is quite different from

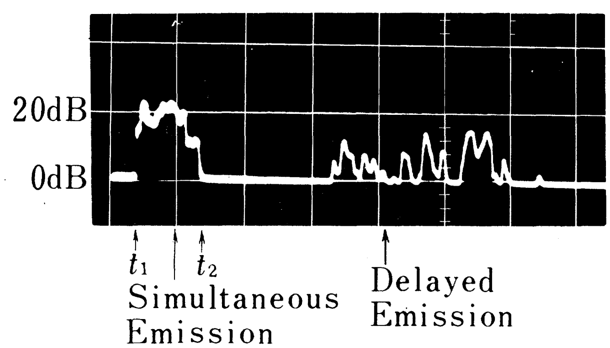

FIG. 2. Signal of the microwave emission at the second cyclotron harmonic from the plasma. The frequency of the pumping wave is 5 times that of the cyclotron frequency and the pumping wave is applied from the the time t_1 to the time t_2; 12.5 μsec/div.

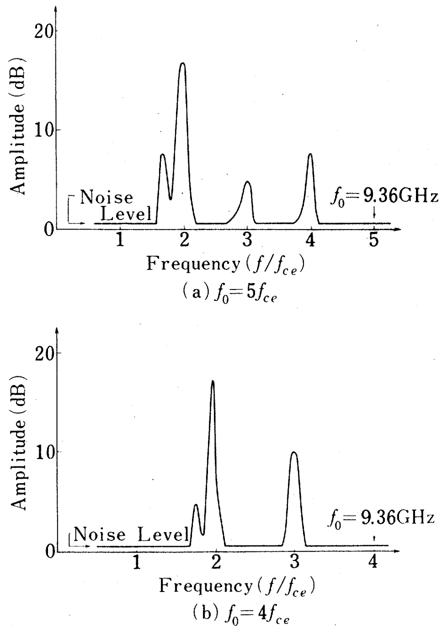

FIG. 3. Frequency spectrum of the delayed emission for (a) $f_0=5f_{ce}$, and (b) $f_0=4f_{ce}$.

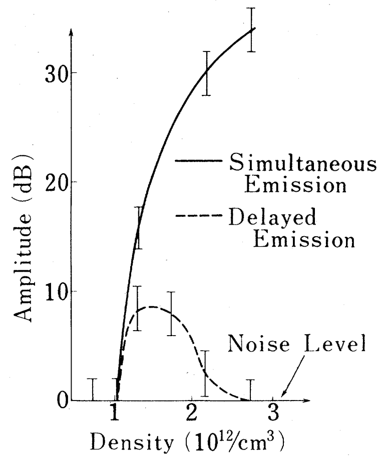

FIG. 4. Dependence of the delayed emission and simultaneous emission on the plasma density; $f_0=3f_{ce}$.

the simultaneous emission that is observed during the pumping time. First, the width of the resonance ($f_0=nf_{ce}$) for simultaneous emission is very broad (15%), but the delayed emission requires a much more severe resonance condition; the magnetic field strength should be tuned within 3% of the resonant-field strength in order to obtain the delayed emission. Second, the delay emissions appear only when the pumping frequency is near the plasma frequency ($f_0 \simeq f_{pe}$), while the simultaneous emission increases as the plasma density is increased (Fig. 4). Third, the power of the simultaneous emission increases almost linearly with that of the pumping wave in the measurable microwave power region of our receiver, but for the delayed emission there exists a clear threshold level of the pumping wave power (5 kW). When the pumping power is increased above this critical level, the delayed emission appears and increases sharply. Fourth, the simultaneous emission does not change very much even when the mirror ratio of the magnetic field is varied. The delayed emission, however, decreases as the mirror ratio is decreased and does not appear at all in a straight magnetic field. This implies the existence of hot electrons heated by the pumping wave; these should play an important role in the delayed-emission mechanism. Diamagnetic-signal and x-ray observations also support this possibility, although the magnetic field strength at which the diamagnetic signal, the total amount of x-ray emission, and the power of simultaneous emission show their maximum values is slightly, but definitely, different from the magnetic field strength where the delayed emission appears. The electron heating at electron-cyclotron harmonics has been observed in a number of experiments[11,12] and it is reasonable to believe that the pumping microwave power is converted into the energy of hot electrons confined in the magnetic mirror field and by some triggering mechanism, the stored energy is abruptly released accompanying the delayed emission.

Although the relation between the delay time of the delayed emission and the experimental conditions is important in order to clarify its mechanism, no definite correlation has been observed within the present experimental accuracy and reproducibility. The polarization of the incident and emitted wave cannot be specified because our experimental apparatus is a multimode system due to the reflection from the metal wall.

Including the above problems a more detailed mechanism is now under investigation.

[1]C. F. Kennell, F. L. Scarf, R. W. Fredricks, J. H. McGehee, and F. V. Coroniti, J. Geophys. Res. 75, 6316 (1970).

[2]H. Oya, J. Geophys. Res. 75, 4279 (1970).

[3]S. Tanaka, R. Sugaya, and K. Mizuno, Phys. Lett. 28A, 650 (1969).

[4]R. A. Stern, Phys. Rev. Lett. 22, 767 (1969).

[5]M. Porkolab and R. P. H. Chang, Phys. Rev. Lett.

22, 826 (1969).

[6]H. Eubank, Phys. Fluids 14, 2551 (1971).

[7]H. Dreicer, C. Ingraham, and D. Henderson, Phys. Rev. Lett. 26, 1616 (1971).

[8]A. Y. Wong and R. J. Taylor, Phys. Rev. Lett. 27, 644 (1971).

[9]R. P. H. Chang, M. Porkolab, and B. Grek, Phys. Rev. Lett. 28, 206 (1972).

[10]M. Porkolab, Nucl. Fusion 12, 329 (1972).

[11]H. Ikegami, S. Aihara, and M. Hosokawa, Phys. Fluids 15, 2054 (1972).

[12]B. Grek and M. Porkolab, Plasma Physics Laboratory, Princeton University Report No. Matt-953, 1973 (unpublished).

Heating of a Fully Ionized Plasma Column by a Relativistic Electron Beam*

C. Ekdahl, M. Greenspan, R. E. Kribel,† J. Sethian, and C. B. Wharton
Laboratory of Plasma Studies, Cornell University, Ithaca, New York 14850
(Received 10 June 1974)

A magnetized plasma column ($n_p \leq 6\times10^{13}$ cm^{-3}) is heated by the injection of an intense relativistic electron beam along the magnetic field. The energy per electron-ion pair transferred to the plasma increases linearly with the beam-to-plasma density ratio n_b/n_p. The electron heating is attributed to the electron-electron beam-plasma interaction while the energetic ions are produced by an electrostatic acceleration. After heating, the plasma column oscillates radially at a frequency proportional to $B/n_p^{1/2}$.

Advances in electron-beam technology have made possible the production of very intense relativistic electron beams with power levels as high as 10^{13} W. With the capability of delivering several megajoules of energy in a time less than 100 nsec, these beams have several applications in fusion research. One of the more promising is in their use for rapid heating of plasma to thermonuclear termperatures. The coupling between relativistic electron beams and plasmas of thermonuclear interest via Coulomb collisions is rather weak, but collective interactions can result in very significant energy transfer. Two collective interactions are expected, the electron-electron two-stream instability[1] involving the high-energy beam electrons streaming through the plasma, and the electron-ion streaming instability driven by the induced return currents flowing within the beam.[2] There have been several experimental studies of plasma heating by relativistic electron beams in which significant heating has been observed,[3-7] but as yet the dominant heating mechanism has not been positively identified. Most of the experiments were complicated by the presence of wall effects, un-ionized gas, or uncertainties in beam or plasma parameters which made comparison with theory difficult.

In the experiments described here, the plasma column is fully ionized and confined in a hard vacuum ($p \leq 2\times10^{-6}$ Torr) away from the vacuum chamber walls. The relativistic electron beam is produced in a diode having a foil anode which isolates the diode from the plasma, thus decoupling the beam parameters from those of the plasma. The latter feature eliminates the ambiguity that existed in earlier experiments using foilless diodes.[6] Recent observations of very weak x-ray production and paramagnetic signals indicate that only a weak beam, if any, was present in the foilless diode experiments and the observed heating was due to plasma currents driven by large axial electric fields within the plasma column.[8]

The experiments have been performed on the Cornell turbulent heating machine (THM) modified by the addition of a relativistic electron-beam accelerator.[6] A plasmoid is injected into a magnetic mirror trap where a plasma column is formed having a length of 1.8 m, a mean diameter of 6–10 cm, and a density that can be varied from 10^{12} to 6×10^{13} cm^{-3} on axis. It is confined by a 2.6-kG magnetic field in a cylindrical vacuum chamber of 40 cm. The device has the capability of heating the plasma column by the axial injection of a relativistic electron beam and by the application of a large axial electric field which produces current-driven turbulent heating.[9] The beam heating experiments are the subject of this paper.

The electron-beam accelerator consists of a Marx generator driving a 5.8-Ω, water-filled, coaxial pulse line which feeds a diode. It is capable of producing an 80-kA pulse of 500-keV elec-

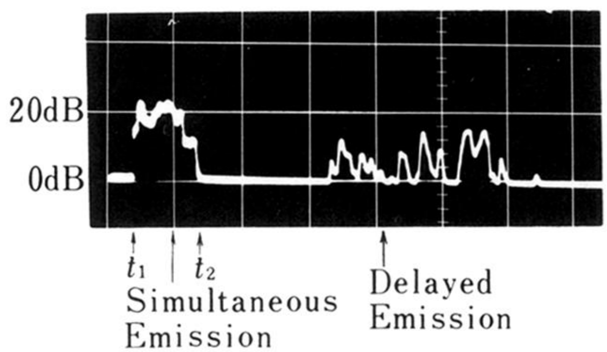

FIG. 2. Signal of the microwave emission at the second cyclotron harmonic from the plasma. The frequency of the pumping wave is 5 times that of the cyclotron frequency and the pumping wave is applied from the the time t_1 to the time t_2; 12.5 μsec/div.