High-Power Microwave Radiation from an Intense Relativistic Electron Beam-Plasma System

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HIGH-POWER MICROWAVE RADIATION FROM AN INTENSE RELATIVISTIC ELECTRON BEAM-PLASMA SYSTEM

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Abstract : High-power microwave radiation generated when an intense relativistic electron beam was injected into a plasma with an axial density gradient was observed in two frequency ranges of 30.7-35.7 and 40-60GHz, which were above the maximum plasma frequency in the drift tube. The observed radiation was classified into two types. One of them was observed both in the direction perpendicular to the beam propagation and in the direction of the beam propagation, while the other was observed only in the latter direction. Some characteristics of these two types of radiation were examined. The maximum power observed in the frequency range of 30.7-35.7GHz was about 12kW/cm^2 in the direction of the beam propagation.

Introduction

Generation of high-power microwave radiation from interactions between an intense relativistic electron beam (IREB) and a plasma is an interesting subject for research concerning plasma turbulence and high-power microwave sources. Unstable longitudinal electrostatic waves excited when an IREB is injected into a plasma are converted into electromagnetic radiation. However, conversion mechanisms are not well established yet. Only a few experiments have been carried out on this subject with different results. Recently, G. Benford *et al.* have reported that the generated radiation had a broad and nearly flat spectrum above the plasma frequency, the upper edge being out of their observing window, and the maximum radiation intensity in the broad spectrum region was one order higher than that at the plasma frequency. The weak and the strong turbulence theories could not explain these results and a model has been proposed for explanation of the observed spectrum and powers. In this model, a strong electrostatic wave is generated by the beam-plasma instability. Then, relativistic beam electrons collide with this in a coherent fashion. This interaction boosts the electrostatic wave up in frequency by the

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Compton effect and simultaneously converts the electrostatic wave to an electromagnetic one.1) A group of Lawrence Livermore National Laboratory, however, could not reproduce these results, and obtained a spectrum with an exponential decay.2)

This paper describes a preliminary experiment which is the first step of our research program to investigate generation mechanisms of the microwave radiation from an IREB-plasma system. In this experiment emphasis was put on detection of high-power microwaves. The experimental apparatus was almost the same as used for previous collective ion acceleration experiments3,4,5). Microwave emissions were measured in frequency ranges 30.7-35.7 and 40-60GHz when an IREB was injected into a plasma with an axial density gradient.

Experimental Apparatus

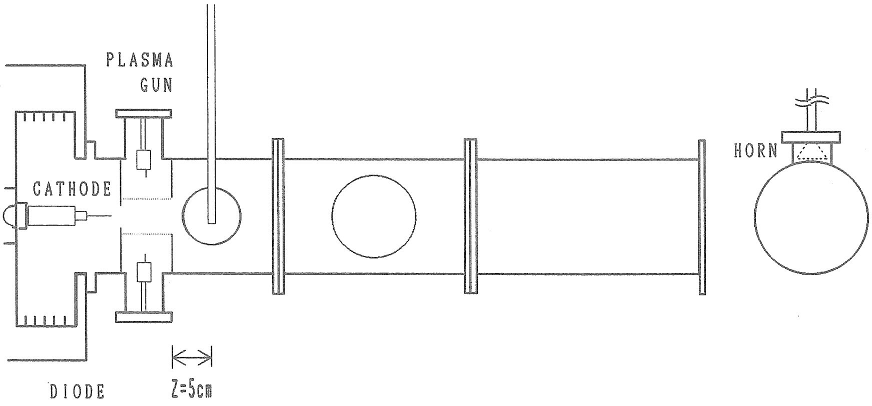

Figure 1. A schematic diagram of the experimental apparatus.

A schematic diagram of the experimental apparatus is shown in Fig. 1. The IREB generator used was a modified Pulserad 110A produced by Physics International, which generates a 1.5 MV-27 kA-30 ns pulse in a conventional diode. A 3mm-diam. tungsten rod was used as a cathode. There was a partitioned space called the anode space in front of the cathode, into which a carbon plasma was injected. The distance between the partition walls, made of aluminum, was 5cm, and the upstream wall and the downstream wall had a 2cm-diam. hole and a 5cm-diam. hole in the axis, respectively. The distance between the cathode and the upstream wall was typically 8mm.

The plasma was produced by two rail-type plasma guns set opposite to each other. The distance between the electrodes which were made of carbon was about 6 mm and their length was about 3cm. A 16μF capacitor bank was connected to each gun. The delay time between the firing times of the gun and the IREB, τ, was variable.

Typical values of the diode voltage, V_D and the diode current, I_D were 1.4MV and 28kA, respectively, when the charging voltage of the Marx generator of the IREB generator was 50kV.

The drift chamber was 16 cm in diameter and 71.5 cm in length. The base pressure was kept below 5×10^{-5} Torr.

The plasma filled in the anode space flowed out through the hole in the downstream wall. In this experiment the plasma density on the axis at $z=5$cm was measured by a Langmure probe and monitored by a plane probe located near the tube wall. Here z is the axial distance from the downstream wall. Density measurements in previous experiments on collective ion acceleration[4,5] showed that the plasma density decreased nearly exponentially and that the density at $z=5$cm was nearly a quarter of the density at $z=0$cm.

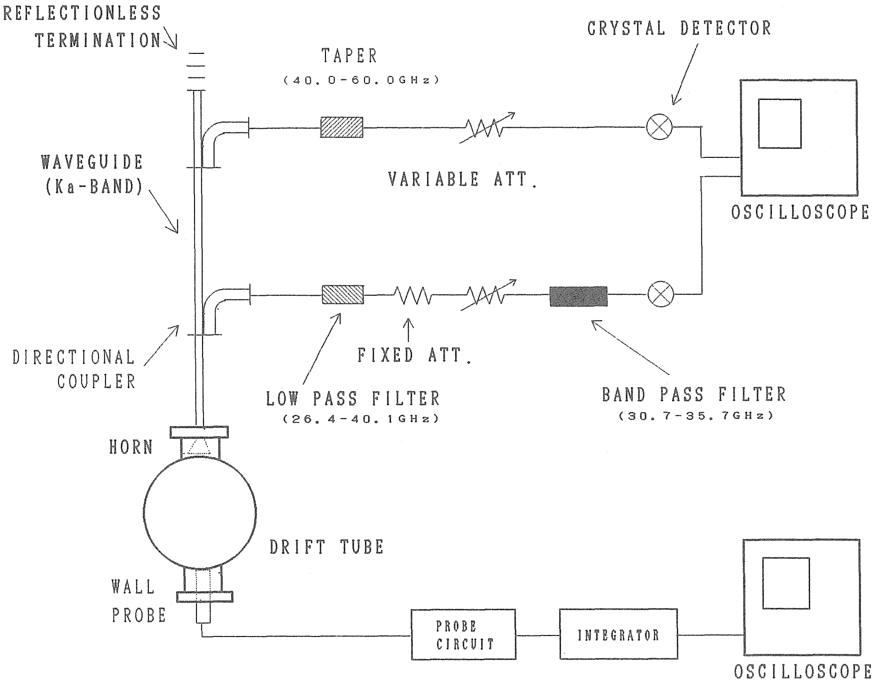

Figure 2. A schematic diagram of the microwave receiving system.

Figure 2 shows a schematic diagram of the microwave receiving system used in this experiment. A Ka-band horn (26.5-40GHz) was located either at $z=5$cm in radial orientation with the E polarization fixed parallel to the drift tube axis, or at the end of the drift chamber with a glass end plate covered with carbon coating except just in front of the horn. The signal received by the horn was transmitted through an assembly of waveguides to the measuring room. Then, a part of the signal was sent by a 20dB directional coupler into one leg, and, after passing through a 40.1GHz low-pass waveguide filter, a fixed and a variable attenuators and a 30.7-35.7GHz bandpass filter, it was detected by a Ka-band crystal detector. This detector was calibrated by a standard procedure. By an another 20dB directional coupler a part of the remaining signal was led into an another leg, and through a tapered transition from the Ka-band waveguide to the U-band (40.0-60.0GHz) waveguide and a U-band variable attenuator, sent to a U-band crystal detector. This detector was uncalibrated. Outputs of both detectors were displayed simultaneously on a dual-beam oscilloscope Tektronix 7844 with 7A19 amplifiers and photographically recorded.

Experimental Results and Discussions

High-power microwave emissions were always observed when the plasma density on the axis at $z=5$cm was varied, by changing τ, from about 1×10^{11} to 1.5×10^{12}cm^{-3}.

The radiated power per unit area in the frequency range of 30.7-35.7GHz was calculated from the output of the detector using the calibration curve of the detector, attenuation by the attenuators, insertion loss of the components in the assembly and the effective area of the horn. There was no change in signal strength when the receiving horn was rotated 90° about its axis, so the calculated power (W/cm^{-2}) was doubled. The peak value of the doubled is called as the microwave output (1) and denoted as $P_{33.2}$. As for the radiated power in the frequency range of 40-60GHz, only rough estimation was made because calibration of the detector could not be done. The peak value of the power twice the estimated one is called as the microwave output (2) and denoted as P_{50}.

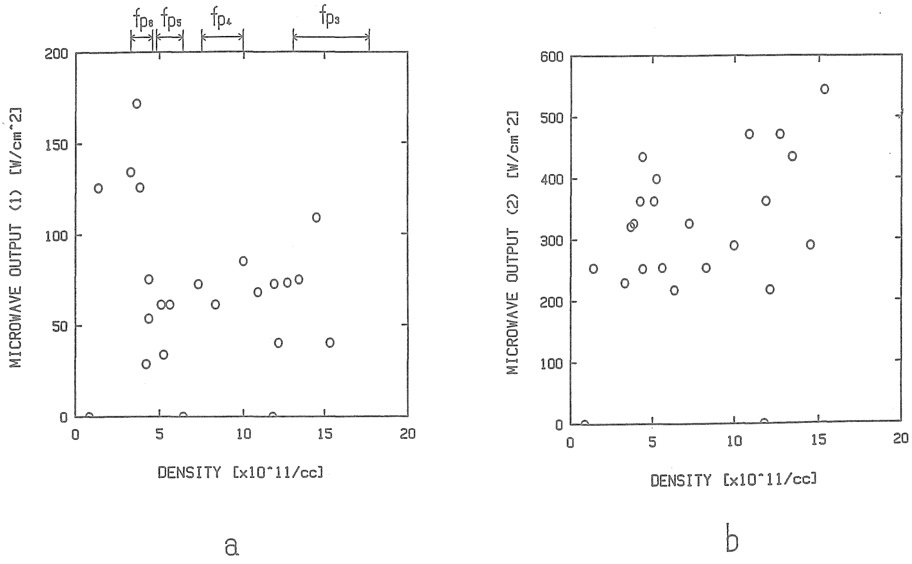

Figure 3. $P_{33.2}$ and P_{50} radiated in the radial direction at $z=5$cm as a function of the plasma density on the axis at this point, the charging voltage of the Marx being 40kV. a) $P_{33.2}$. b) P_{50}.

$P_{33.2}$ and P_{50} radiated in the perpendicular direction to the beam propagation (the radial direction) at $z=5$cm are plotted in Fig's 3a and 3b, respectively, as a function of the plasma density on the axis at this point, the charging voltage of the Marx being 40kV. The center frequencies 33.2GHz of the frequency range of 30.7-35.7GHz and 50GHz of 40-60GHz were about 3 times or more and 4.5 times or more higher than the local plasma frequency, respectively. Moreover, these frequencies were higher than the plasma frequencies at $z=$

0 which were estimated to be nearly twice as large as that at $z=5$cm. Although spectrum of the emitted microwave was not measured in this experiment, these Figures seem to show that the emitted radiation had a broad spectrum above the plasma frequency.

In order to obtain some informations on the spectrum, relation between $P_{33.2}$ and P_{50} was examined. Figures 4a and 4b show, respectively, plot of P_{50} versus $P_{33.2}$ in the radial direction at $z=5$cm and in the direction of the beam propagation (the forward direction) measured at the end of the drift tube, at the charging voltage of the Marx of 40 and 50kV. The parameter varied was τ. The observed radiation was classified into two types as shown in the Figures.

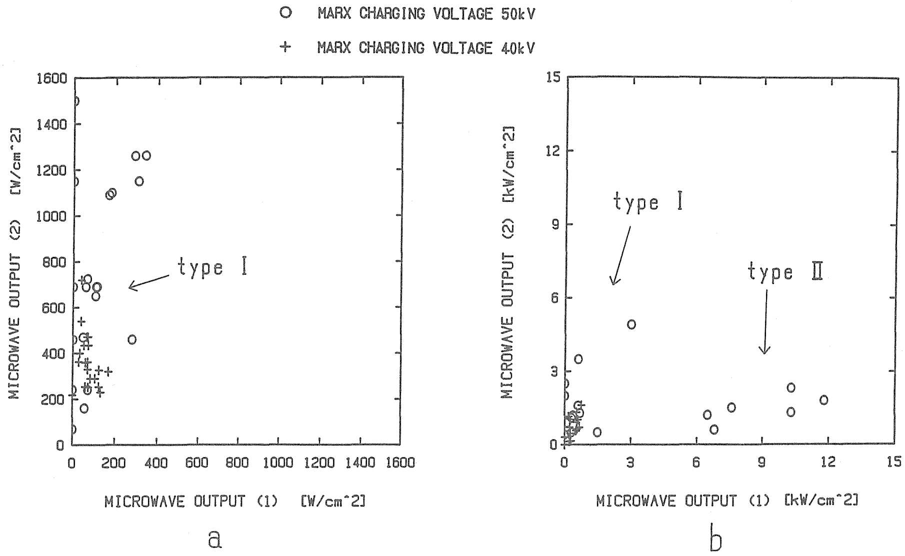

Figure 4. Plots of P_{50} versus $P_{33.2}$; a) in the radial direction at $z=5$cm, b) in the forward direction measured at the end of the drift tube, the charging voltage of the Marx being 40and 50kV.

The type I radiation was observed both in the radial direction and in the forward direction. The ratio P_{50} to $P_{33.2}$ seems nearly constant over the density range covered experimentally. The maximum output power observed in the forward direction was several times higher than that in the radial direction.

The scaling of the radiated power of the type I radiation in the radial direction and the peak of diode power, $V_D I_D$ at a fixed value of τ is shown in Fig. 5. The dependence of the radiated power on the diode power was steeper than linear for higher diode power.

The type II radiation was observed only in the forward direction, and only at the charging voltage of the Marx of 50kV. The ratio P_{50} to $P_{33.2}$ seems also nearly constant, and it was lower than that for the type I, that is, the type II radiation was low-frequency-component rich as compared with the type I radiation. This radiation was apt to appear when τ was so short that the plasma density was low. The type II radiation in the frequnecy range of 30.7-35.7GHz was stronger than the type I radiation in the same range in the forward direction. The maximum power observed in this frequency range was about 12kW/cm^2.

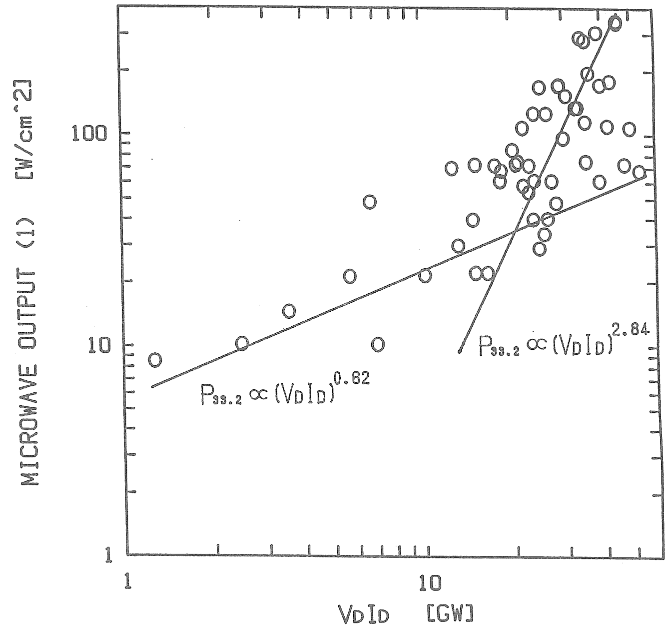

Figure 5. $P_{33.2}$ in the radial direction as a function of the diode power $V_D I_D$, τ being 8μs.

Forward beaming of both types of radiation, although beaming was stronger for the type II radiation, implies that they were produced by the relativistic beam electrons themselves. High power and broad spectrum above the plasma frequency imply bunching of the beam electrons. The existence of two types of radiation suggests that the bunched beam electrons interacted with different configurations of electric fields in the plasma. One model existing at present for the high-power radiation with a broad spectrum above the plasma frequency is the Compton-boosting model proposed in Ref. 1, a brief explanation of which is given in Introduction. There is another model which has a possibility for explanation of the observed radiation.[6] This model says that radiation can be produced by the scattering of the beam electrons by dipolar "solitons", regions of intense, localized electrostatic fields in the plasma. Further experimental and theoretical investigations are necessary to determine what physical processes really take place in this experimental configuration. Especially, it should be made clear what role the density gradient play over the whole process.

Summary and Concluding Remarks

High-power microwave emissions above plasma frequencies were always observed when an IREB was injected into a plasma with an axial density gradient. The observed radiation was classified into two types. The type I radiation was observed both in the radial and in the forward direction, with the axially radiated power several times higher than the radially radiated power, while the type II radiation was observed only in the forward direction. The type II radiation was richer in lower frequency components than the type I radiation. The type II radiation was observed only at high Marx charging voltages and apt to be emitted at rather lower plasma density. The power radiated in the frequency range of 30.7-35.7GHz of the type II radiation was higher than that of the type I radiation in the forward direction and the maximum was about 12kW/cm^2. The dependence of the radiated power of the type I radiation on the diode power was steeper than linear for higher diode power.

Common characteristics of both types of radiation, that is, forward beaming, high power and broad spectrum above the plasma frequency suggest that bunched beam electrons were responsible for radiation. Existing theories, however, deal with the case of axially uniform plasma, and cannot be directly applied to the present experiment in which the plasma had an axial density gradient.

Now, as the next step of the research program to investigate generation mechanisms of the microwave radiation from an IREB-plasma system, a 5-channel microwave spectrometer covering a frequency range from 18GHz to 40GHz are being prepared in order to investigate the detailed spectrum of the radiation. Also, some new methods for plasma production are being developed in order to widen the range of the plasma density and to produce an axially uniform plasma.

Acknowledgement

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