Normal Doppler Effect in Experiments on the Interaction of Relativistic Electron Beams with Plasma. Plasma Relativistic Microwave Amplifier

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Abstract— The Cherenkov interaction of a high-current relativistic electron beam with a spatially bounded plasma has been studied experimentally. An important role in the generation of electromagnetic radiation is played by a backward propagating plasma wave, which arises as a result of reflection from the end of the plasma column. Experiments revealed that normal Doppler effect occurs at the resonant values of the magnetic field, in which case the amplitude of the backward wave decreases. This phenomenon was used to create a plasma relativistic microwave amplifier in which an electron beam transfers 10% of its power to radiation. The radiation frequency was 9.1 GHz, and the relative radiation spectrum width, ±0.17%, was determined by the duration of the beam current pulse. The maximum radiation power was equal to 100 MW, the amplification coefficient being 32 dB.

1. Introduction

A constant challenge in creating high-power microwave amplifiers is how to reduce the feedback factor in order to prevent the amplifier from functioning as an oscillator. In vacuum microwave electronics, the feedback factor is often lowered by placing a microwave absorber inside the device. Here, we present experimental studies on the possibility of reducing the amplitude of the backward wave under the resonant conditions of the normal Doppler effect.

An electron beam propagating through the plasma along the lines of the external magnetic field can be subjected to instability, during which a slow beam space charge wave with the frequency $\omega = k_z u - \omega_b/\gamma^{3/2}$ interacts with a slow plasma wave. Here, ω is the frequency of the excited waves, ω_b is the Langmuir frequency of the beam electrons, k_z is the longitudinal wave vector component, u is the electron beam velocity, and γ is the relativistic factor. Figure 1 shows a qualitative pattern of the dispersion curves of the forward and backward plasma waves and of the space charge waves of an electron beam with a low current such that $\omega_b/\gamma^{3/2} \ll \omega$. As $k_z \to \infty$, the frequency of the plasma wave approaches the Langmuir frequency of the plasma electrons, ω_p. At the point of intersection of the dispersion curves of the beam wave, $\omega = k_z u$, and the forward plasma wave ($k_z > 0$), a beam instability develops that has the frequency ω^* and the wavenumber k^*. The wave reflected from the end of the plasma waveguide ($k_z < 0$) satisfies the relationship $\omega^* = -k_z^* u$. In the presence of a magnetic field, a fast cyclotron wave with the frequency $\omega = k_z u + \omega_H/\gamma$ (where ω_H is the electron gyrofrequency) can propagate along the beam. At the resonance point $-k_z^* u = k_z^* u + \omega_H/\gamma$, there exists normal Doppler effect. The resonance condition has the form

$$\omega^* = \omega_H/2\gamma \qquad (1)$$

Under this condition, the electric field of the backward wave raises the energy of the beam electrons [1, 2]. As a result, the amplitude of the backward wave decreases and the microwave generation process can be suppressed.

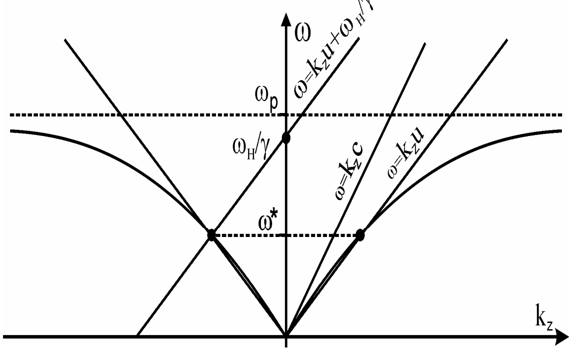

Fig1. Dispersion curves of the forward and backward plasma waves and of the space charge waves of an electron beam.

We stress again that the aforesaid is true only for electron beams of low density such that $\omega_b/\gamma^{3/2} \ll \omega$. For beam currents in the experiments to be reported below, the beam-plasma instability can occur in a broad frequency range from 0 to $1.2\omega^*$. At a frequency close to ω^*, the instability grows at the fastest rate. For an electron beam of finite density, cyclotron absorption occurs not only at the resonant frequency (1) but also in a certain band around it [2]. The frequency band of resonant absorption can be further broadened by applying a nonuniform external magnetic field, in which case the resonance condition for the normal Doppler effect is satisfied in a certain frequency band at different points along the plasma column.

In order for the electron beam to absorb the backward plasma wave, it is necessary that not only condition (1) be satisfied but also that the backward wave have a high-frequency electric field component perpendicular to the magnetic field lines. If the plasma and the beam are infinite in the transverse direction, then the beam generates only a longitudinal electric field, so that absorption is impossible. In a transversely bounded plasma, surface waves can be excited whose electric field has both longitudinal and transverse components. This was just the case in our experiments.

In vacuum relativistic microwave electronics, the effect of attenuation of the power of a microwave oscillator (a backward wave tube, BWT) in a certain range of magnetic field strengths was first observed in [3]. In [4], it was shown that this phenomenon is attributed to the normal Doppler effect. Our experiments are the first study of the development of a beam--plasma instability under the conditions of the normal Doppler effect.

2. Experimental device [5]

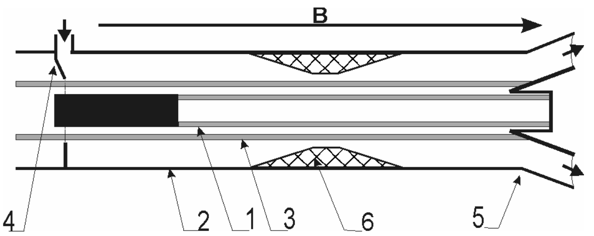

Fig.2 Experimental device. 1.- plasma, 2.-metall waveguide, 3.-electron beam, 4.- microwave power input, 5.-output microwave horn, 6.-absorber.

A schematic of the device is shown in Fig. 2. A 28 cm-long cylindrical annular plasma column *1* with a mean radius of 8 mm and a thickness of 1 mm was produced in a smooth cylindrical waveguide *2* with a radius of 22 mm. The waveguide system was in a strong longitudinal magnetic field *B*. An annular relativistic electron beam (REB) *3* was injected into the waveguide through its left end. The electron accelerator operated in the single-pulse mode. The REB parameters were as follows: the electron energy was 500 keV, the beam current was 1 or 2 kA, the mean beam radius was 10 mm, and the beam thickness was 1 mm. The duration of the beam current pulses was 100 ns. During this time interval, an REB produced a plasma with a density hundreds of times lower than that of the pre-produced plasma.

The device just described was investigated in two operating modes: as an oscillator and as a microwave amplifier. The device was made an amplifier by equipping the plasma waveguide with a ceramic microwave absorber 6 and was excited by a signal transmitted through waveguide *4* from one of the two pulsed magnetrons with a frequency of 9.1 and of 13.0 GHz and a controllable power of 20 to 60 kW. The microwaves generated were recorded at the exit from the dielectric window of a coaxial horn 5.

3. Techniques for measuring microwave radiation parameters

The microwave pulse energy was measured by a calorimeter, and the envelope of a microwave power pulse was measured by semiconductor detectors.

The microwave radiation spectra were recorded by three methods. First, a calorimetric spectrometer permitted measurements of the energy spectrum of individual radiation pulses in absolute units with a frequency resolution of ≈ 3 GHz. The second method made it possible to determine the fraction of microwave pulse energy in the frequency band 9.1 GHz ± 2.5%. And third, the radiation spectra from the microwave amplifier were measured by a heterodyne method with a high frequency resolution (≈ 3 MHz). In the ideal case, for a 9.1 GHz signal at the entrance to the plasma amplifier, and for a 9.35 GHz heterodyne frequency, a sinusoidal signal with a frequency of 0.25 GHz is to be detected.

4.Experimental results. Microwave oscillator

During the injection of an REB, the device in which the microwave absorber is removed from the plasma waveguide operates as an oscillator. Earlier, we investigated the microwave generation process in a strong magnetic field of ≈ 20 kG, for which the condition $\omega < \omega_H/2\gamma$ was satisfied [6]. In the experiments reported here, we reduced the magnetic field strength, while keeping the plasma density fixed, and measured the energy of the microwave pulses.

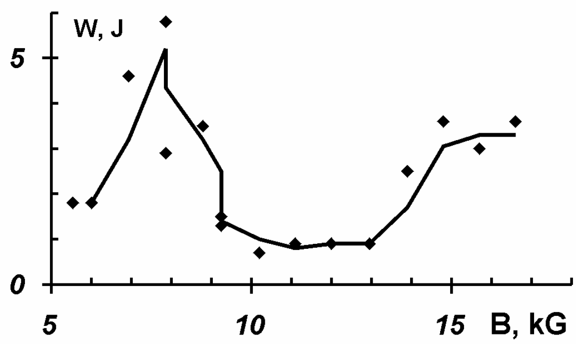

Fig.3. Microwave pulse energy on magnetic field.

We found that, in a range of magnetic field strengths of 9—13 kG, the radiation power level was low. This can be attributed to feedback suppression in the microwave oscillator due to the normal Doppler effect, under the additional assumption that, in the above range of magnetic fields and at the above fixed plasma density, the excited backward waves have the same spectrum with a mean frequency of $f = f_H/2\gamma \sim$ 8.5 GHz (B = 11 kG, γ = 1.8). The hypothesis proposed here allows us to qualitatively explain the change in the radiation spectrum when the magnetic field was varied (Fig. 4) at a fixed plasma density.

The spectrum was measured by a calorimetric spectrometer. In Fig. 4, the arrows indicate the frequency band in which the exact resonance condition (1) for the magnetic field in question is satisfied. That the resonance occurs not at a single frequency but in a frequency band stems from the fact that the magnetic field in our experiments was nonuniform. For B = 8 kG ± 9% (the upper plot in Fig. 4), the resonant frequency is $f_H/2\gamma$ = 6.2 GHz ± 9%, in which case no radiation at low frequencies is emitted and the spectrum contains only the frequencies f > 9.3 GHz.

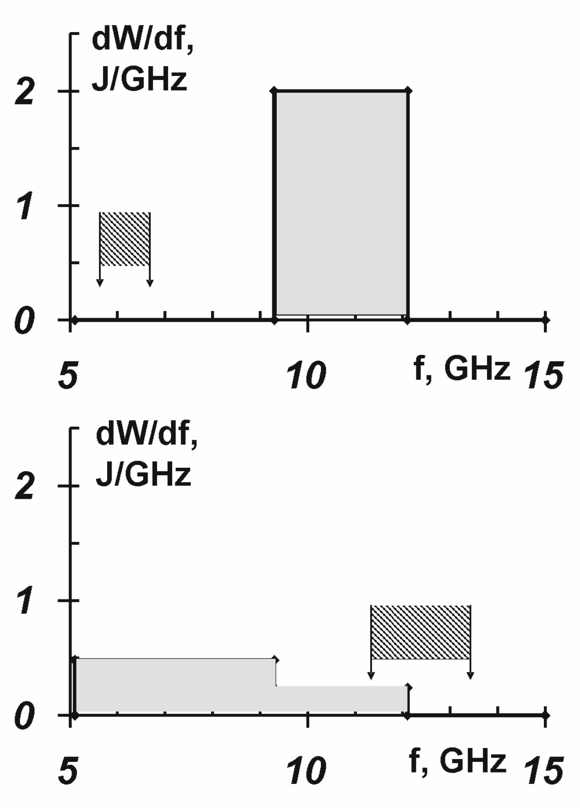

Fig.4. Frequency spectrum of microwave pulse energy, up - B = 8 kG ± 9%, down - B = 16 kG ± 9%

For B = 16 kG ± 9% (the lower plot in Fig. 4), the resonant frequency is equal to $f_H/2\gamma$ = 12.4 GHz ± 9%; in this case, the radiation energy at frequencies f > 9.3 GHz is substantially lower and microwaves are also emitted at frequencies f < 9.3 GHz. Hence, the change in the spectrum that was observed when the magnetic field was varied can be qualitatively explained as being due to feedback suppression at frequencies close to the resonant frequency.

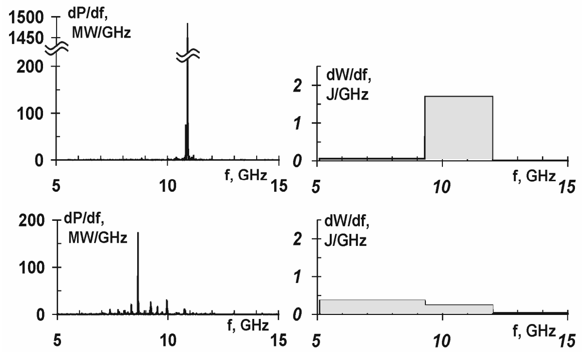

Fig.5. Frequency spectrum of microwave pulse power and energy, up - B = 8 kG ± 9%, down - B = 16 kG ± 9%, (computer simulation).

Since we were unable to measure the radiation spectra from individual microwave pulses in a frequency band around 10 GHz as fully and precisely as desired (this is clearly seen in Fig. 4), we carried out numerical simulations of the operation of a plasma microwave oscillator by using the KARAT computer code [7]. Our numerical experiments were done for magnetic fields of B = 8 kG ± 9%, by choosing the minimum plasma density in such a way that all the frequencies exceeded 9.3 GHz. The upper spectrum in Fig. 4 was found to be reproduced at $n_p = 10^{13}$ cm^{--3}. Using this density value, we calculated the pulse-integrated microwave power spectra for B = 8 kG ± 9% (the top-left plot of Fig. 5) and B = 16 kG ± 9% (the bottom-left plot of Fig. 5). The right plots of Fig. 5 show the energy spectra calculated from the power spectra. The energy spectra in Fig. 4 are seen to agree well with those in the right plots of Fig. 5.

Note that the spectrum shown in the bottom-left plot of Fig. 5 consists of several lines in the frequency band in which, according to linear theory, the beam--plasma instability grows at the fastest rate. This indicates that the spectrum resembles that expected for an infinitely strong magnetic field. At weak magnetic fields, microwave generation at frequencies of ~ 8 GHz is suppressed and radiation is observed to be emitted at a frequency of 10.9 GHz (see the top-left plot of Fig. 5), which corresponds to the upper instability boundary. The numerical experiments just described prove that microwave generation is suppressed at nearly resonant magnetic fields.

5. Plasma microwave amplifier

In creating amplifiers, we utilized the phenomenon of suppression of the backward wave by the normal Doppler effect. This was done by choosing the optimum profile of the magnetic field and its optimum strength and by installing broadband microwave absorbers in the plasma waveguide. Below, we will present the data from measuring the spectra and shapes of microwave signals as well as the dependence of the output power on the input power of a microwave amplifier at a frequency of 9.1 GHz.

The experiments were carried out under the following conditions: the plasma density was ~ 1.0×10^{13} cm^{-3}, the input signal frequency was 9.1 GHz, the REB energy was ≈ 500 keV, and the REB current was 1.1 and 2 kA. The typical oscillograms of a plasma amplifier at a beam current of 1.1 kA are illustrated in Fig. 6. Figure 6a shows an oscillogram of the voltage at the accelator cathode. The duration of the plateau in the pulse is ≈70 ns and the pulse amplitude is 500 kV. Figure 6b shows oscillograms of the microwave signals. The solid curve is for the signal over a broad frequency band, and the dotted curve is for the signal in the frequency band 9.1 GHz ± 2.5%. That the two oscillograms nearly coincide during the major portion of the pulse provides evidence that, during this time, the width of the output radiation spectrum did not exceed 5%. Figure 6c shows an oscillogram of the beating signal. An enlarged fragment of the signal, on a shorter time scale (from 50 to 110 ns), is shown in Fig. 6d. The beating oscillogram demonstrates that microwave radiation from a plasma amplifier is almost monochromatic and the beating frequency is 250 MHz.. We found that, as we reduced the input signal power, the output radiation power decreased linearly while the signal shape and the spectrum width remained unchanged. For an input microwave signal with a power of 60 kW, the spectrum width was equal to 15 MHz, the microwave pulse energy and output microwave power being 3 J and 40 MW, respectively

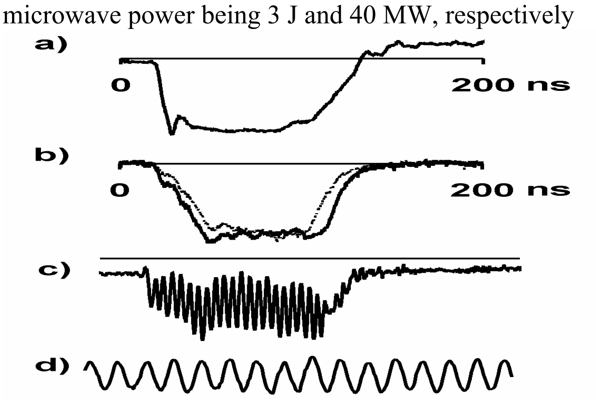

Fig.6.Typical oscillograms. a) accelerator cathode voltage, b) microwave pulses, c) beating signal, d) fragment of the same signal c) during 70 ns.

As the REB current was raised to 2 kA, the output power from the plasma amplifier increased to 100 MW but the radiation spectrum became wider. Figure 7 displays the spectra of two beating signals, recalculated for the frequency of the input signal. The dotted curve is the magnetron radiation spectrum (during a time interval of 70 ns), and the solid curve is the spectrum of the output radiation signal at a power level of 100 MW. We can see that the output radiation spectrum is far from being ideal. As for the output radiation spectrum at a power level of 40 MW (which corresponds to a beam current of 1.1 kA), it is indistinguishable from the spectrum shown by the dotted curve in Fig. 7. This indicates that, in the case at hand, the spectrum width, equal to 15 MHz, is determined only by the radiation pulse duration, 70 ns.

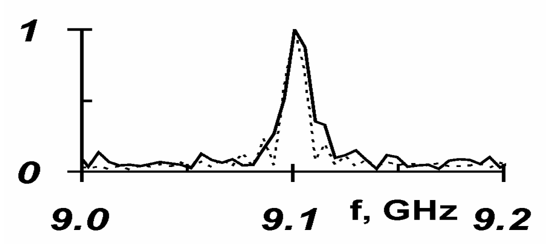

Fig.7.100 MW radiation spectrum – solid line, input radiation spectrum – dotted line.

By properly choosing the magnetic field profile, we succeeded in constructing a plasma microwave amplifier operating at two frequencies [5]. It is important to note that the amplifier can be tuned from one frequency to another by varying only one parameter---the plasma density. At this point, we briefly recall the results of [5]. For output signals at two frequencies, 9.1 and 13 GHz, the output power up to a level of 60 MW was found to depend linearly on the input power. The maximum power efficiency was 6%, the amplification coefficient being 30 dB. It was also shown that the width of the amplified signal spectrum does not exceed 5% of the mean frequency, which is equal to the frequency of the input signal.

Note that the plasma microwave sources considered above have different efficiencies. The efficiency of the plasma amplifier tuned to a frequency of 9.1 GHz is ≈ 10%, while the amplifier tunable to two frequencies, 9.1 and 13 GHz, has an efficiency of ≈ 6%.

6. Conclusion

Investigation of the radiation spectra from a plasma relativistic microwave oscillator at different strengths of the guiding magnetic field and different degrees of its nonuniformity led us to create an efficient plasma microwave amplifier based on the suppression of microwave generation by the normal Doppler effect. The output radiation power from the amplifier is 100 MW, which corresponds to an efficiency of 10% and an amplification coefficient of 32 dB. The width of the radiation spectrum from the plasma amplifier is 15 MHz (0.17% of the mean frequency); it is determined by the duration of the emitted microwave pulses (70 ns).

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