Plasma-filled gyrotron with a relativistic supervacuum electron beam

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An experimental investigation was made of a gyrotron utilizing a relativistic supervacuum electron beam (electron energy 320 keV and current 1.2 kA) in the form of pulses of 30 nsec duration. The space charge of the beam was compensated by a plasma generated earlier. This gyrotron emitted the expected TE_{13} microwave mode of $\lambda = 3 \pm 0.1$ cm wavelength and 60 MW power. The efficiency of conversion of the electron-beam energy into microwave radiation was 15%. The dependence of the microwave radiation power on the plasma density was determined.

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The feasibility of using relativistic electron beams for generation and amplification of electromagnetic radiation was considered many years ago in the well-known work of Veksler, Ginzburg, and Prokhorov. One of the most widely used oscillators based on the relativistic effects is a cyclotron-resonance maser (gyrotron) utilizing cyclotron (synchrotron) radiation emitted by relativistic electrons rotating in a magnetic field. The theory of these devices was developed and the devices themselves were implemented by the Gorkiĭ school of physicists headed by Gaponov.[1] Gyrotrons were first built for the weak relativistic range using electron beams of energies within a hundred kiloelectron volts and currents of a few tens of amperes.[2]

The recent development of the technology of high-current relativistic electron beams has provided a basis for a considerable increase in the gyrotron power.[3-5] However, the currents used in gyrotrons have been below the vacuum limit I_{vac}. As the current approaches the vacuum limit, the action of the space-charge field on electrons increases their velocity scatter and, consequently, reduces the gyrotron efficiency and thus limits the power.

These difficulties can be overcome by plasma neutralization of the electron beam: this is done by filling the electrodynamic system of a gyrotron with a plasma which is, on the one hand, sufficiently rare to have no significant influence on the natural frequencies of the gyrotron and not to screen the output radiation[1)] and, on the other, is sufficiently dense to neutralize the charge and magnetic field of the electron beam and thus increase the current transmitted by the system and reduce the electron velocity scatter in the current range $I > I_{vac}$ (Ref. 9). The problem of construction of plasma-filled relativistic generators of electromagnetic radiation has been considered in several theoretical papers.[10,11]

A preliminary experimental investigation of the use of cyclotron radiation of relativistic electrons in plasma-filled electrodynamic systems was described in Ref. 12. The work reported below involved experimental implementation of a plasma-filled gyrotron with a supervacuum relativistic electron beam. Our experiments were carried out using the Terek–II accelerator. A tubular electron beam of 320 keV energy, 1.2 kA current, and 30 nsec pulse duration was injected into a plasma-filled resonator. The measurement method was the same as that described in Ref. 5, reporting an investigation of the "vacuum" variant of the gyrotron.

Plasma was generated in advance by a plasma-beam discharge in which a weak tubular electron beam passed through xenon ($p \approx 10^{-4}$ Torr). The beam current was 0.1–1 A, electron energy was ~2 keV, and pulse duration was ≈20 μsec. The beam was generated in an electron gun located in the immediate vicinity of the accelerator anode. The plasma density was varied by altering the low-energy beam current and was recorded with a single probe producing a signal which was calibrated with the aid of an 8-mm microwave interferometer in the plasma density range $n_p = 10^{11}-10^{13}$ cm^{-3}.

The electrodynamic system comprised a resonator designed to generate the TE_{13} mode by electron beam currents of $I \approx 1-1.5$ kA, as used earlier in the "vacuum" gyrotron.[5] The beam potential was measured with a capacitative divider, which was a stainless-steel plate located in one of the slots cut along the resonator for mode selection. The method made it possible to measure the induced beam charge also when there was no flow of charged particles to a plate. This condition was satisfied in our case because electrons were known to be magnetized and the plasma ions could not reach the resonator walls in a time equal to the pulse duration of ~30 nsec.

As before,[5] the microwave emission spectrum was investigated with band-pass filters and the oscillation mode was identified by determining the field distribution across the aperture of an exit horn, which was done with a mobile receiving waveguide of 18 × 7 mm cross section. The total output power of the gyrotron was determined from the known field distribution making the assumption that the field structure in the aper-

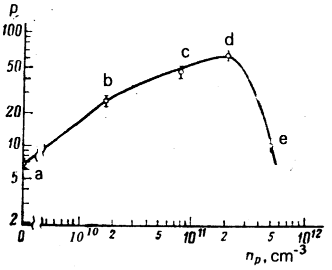

FIG. 1. Dependence of the maximum radiation power P(MW) per pulse on the plasma density for the following optimal parameters: a) $k=2.0$, $H=5.32$ kOe; b) $k=2.0$, $H=5.47$ kOe; c) $k=2.0$, $H=5.55$ kOe; d) $k=2.0$, $H=5.70$ kOe; e) $k=2.0$, $H=5.85$ kOe.

ture of the receiving horn was nearly a plane wave.

The field dependences of the maximum radiation power (per pulse) obtained for various mirror ratios $k=H_{res}/H_{coil}$ and several values of the plasma density but the same injection current $I=1.2$ kA$>I_{vac}$ indicated that stimulated emission occurred only in a fairly narrow range of magnetic fields characterized by $\Delta H/H \sim 0.05$, which was in agreement with the calculated width of the cyclotron resonance band. For each mirror ratio k there was an optimal field H_{opt} in which the radiation had its maximum power. When the plasma density was varied, the maximum radiation was obtained for $k=2.0=$ const.

Figure 1 shows the dependence of the total maximum radiation power on the plasma density. It is clear from this figure that increase of the plasma density to $n_p \approx 2\times 10^{11}$ cm^{-3} enhanced the microwave radiation power by a factor of 10 but in the range $n_p > 3\times 10^{11}$ cm^{-3} the power fell steeply. Each point in the figure was obtained by averaging the maximum power per pulse over several shots from the accelerator. The optimal parameters k_{opt} and H_{opt} were obtained for each point in the graph.

The plasma-density dependences of the beam current through the resonator and of the beam potential inside the resonator for $k=2$ and $H=5.50$ kOe are plotted on the same scale in Fig. 2. We can see that the vacuum current was $I_{vac}=640$ A and that the current increased with the plasma density, due to compensation of the space charge of the beam electrons. The maximum current was the injection current and it was limited by the emissivity of the diode. The beam potential fell on increase of the plasma density.

The results indicated that in the $n_p > 3\times 10^{11}$ cm^{-3} range the current did not vary greatly and the radiation power fell by a factor of about 10. This was clearly due to the fact that the plasma altered significantly the electro-dynamic parameters of the resonator or screened the radiation.

The maximum output power was 60 MW when the efficiency was about 15%. The wavelength was close to the calculated value of $\lambda = 3\pm 0.1$ cm and the radiation field structure was close to the TE_{13} mode, in agreement with the calculations. Thus, by plasma filling of the electrodynamic system it was possible to increase the output power of the gyrotron while still retaining the single-mode emission and to utilize currents exceeding the vacuum limit.

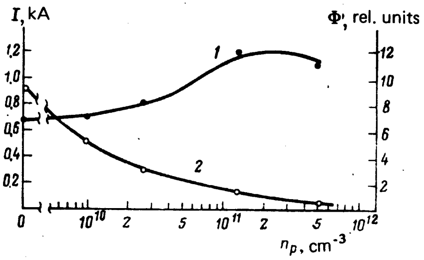

FIG. 2. Dependences of the beam current (1) and potential (2) on the plasma density for $k=2.0$ and $H=5.50$ kOe.

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[1)]It should be pointed out that when an electrodynamic system is filled by a dense plasma, a two-stream instability[6,7] may develop and this may be used in, for example, high-current Cerenkov generators utilizing relativistic electron beams.[8]

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