Effect of plasma density gradients on generation of terahertz radiation in magnetized plasma column during relaxation of kiloampere REB inside it

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Abstract. Generation of terahertz radiation in the magnetized plasma column due to the two-stream instability developing in the relativistic electron beam (REB) with a current of 10 kA is studied at the GOL-PET facility. In the first series of the experiments, at the regular transverse plasma density gradients, power of the generated terahertz radiation increased thirty times. At a frequency of the upper-hybrid oscillations (0.2–0.3 THz) and pulse duration of few microseconds, it reached 4 MWs. In the next experiments, when the additional longitudinal density gradients were created in plasma, the radiation power exceeded 10 MWs. These results are described in this paper.

1. Introduction
Generation of the electromagnetic (EM) radiation due to the collective electron beam-plasma interactions is a fundamental phenomena, which is important for both cosmic and laboratory plasmas. Often, such radiation is the only source of information about the wave processes occurring in the local plasma regions. On the other hand, the generation of terahertz electromagnetic radiation with a frequency in the range of 0.1–1 THz and the peak power exceeding hundreds of kilowatts is a problem important from the point of view of various applications. For example, with the help of the high-power THz radiation sources, new fields of physical research become available. The first experimental studies of mechanisms for the submillimeter wave generation (0.1–0.8 THz) due to the collective relaxation of the relativistic electron beam (0.8 MeV/20 kA/6 μs) in the plasma column with a density of (2–4) $10^{14}$ cm$^{-3}$ placed in the strong (~4 T) magnetic field were carried out at the GOL-3 facility [1]. Experiments showed that, at these experimental parameters, the spectrum of submillimeter-wave radiation of the beam-plasma system falls into the frequency range in the vicinity of the frequency of the upper hybrid plasma oscillations, as well as its doubled value [2–5]. Further, such experiments were continued at the GOL-3T facility at the plasma densities varying in the range of 5 $10^{14}$–3 $10^{15}$ cm$^{-3}$. At such plasma densities, the bulk of radiation power with a frequency in the range of 0.15–0.3 THz (near the upper hybrid plasma frequency) was emitted in the direction along the axis of the plasma column and the submillimeter radiation beam occurs. In the experiments on the beam-plasma interaction, currently conducted at the special-purpose GOL-PET facility [6–7], we study the properties of this submillimeter-wave beam. In this paper, the results of experiments on
the generation of the terahertz radiation at different plasma density gradients are presented and analyzed theoretically.

2. Experimental facility and diagnostics
The GOL-PET facility consists of the electron accelerator with particle energies of up to 0.8 MeV and the multi-mirror magnetic trap with a magnetic induction of 4.7 T (see [6–7]). In this magnetic field, the 250-cm-long plasma column with a diameter of 6 cm is confined, the density of which can vary in the range of $3 \times 10^{14} - 3 \times 10^{15}$ cm$^{-3}$ (see Fig. 1). The beam is characterized by a current density of 2–4 kA/cm$^2$ and a diameter of 4 cm. Its pulse duration is 6 μs. The beam propagates along the plasma column axis and is intercepted by the graphite collector in the decreased magnetic field at the chamber end. The submillimeter radiation escaping from the plasma column along its axis passes through a 180-mm-diameter aperture in the graphite collector, then it is reflected by the mirror (see Fig. 1) and, finally, the radiation beam escapes from the vacuum chamber into the air through the teflon window. In these experiments, we measured the local parameters of the beam and plasma. The submillimeter-wave radiation from the plasma column was recorded in both longitudinal and transversal directions of the beam-plasma system. The experimental studies were focused on measuring the spectral power density of the generated radiation beam. For the spectral measurements, the polychromator was used with ten frequency selective channels in the range of 0.1–0.8 GHz [2, 7].

![Schematic of experiments at the GOL-PET facility.](image)

3. Results and discussion
In the experiments on the beam injection into the plasma, the plasma density and its radial gradient across the plasma column were varied from shot to shot. The experiments have shown that, for the plasma densities higher than $5 \times 10^{15}$ cm$^{-3}$, the bulk of the generated terahertz radiation propagates along the axis of the plasma column, and its spectrum is in the frequency range near a frequency of 0.2 THz that is just the upper-hybrid frequency of plasma oscillations (see [5–6]). Figure 2 presents the spectra of the submillimeter radiation measured by the terahertz polychromator that was installed at a distance of 3 meters from the output teflon window of the vacuum chamber (see Fig. 1). These spectra correspond to two radial density distributions that are marked by two different colours. These two density distributions are shown in Fig. 2 in the upper right panel. Blue and red colours correspond to the uniform density distribution and the distribution with the strong radial density gradients, respectively. We note that the presented spectra are obtained by means of averaging the spectra measured by the polychromator in six shots with the same experimental parameters. The presented spectra were measured approximately in 1.5 μs after the beginning of the electron beam injection. One can see that the spectral power density of radiation in the vicinity of the upper-hybrid frequency (200–300 GHz) increases thirty times when we used the plasma column with the strong radial density gradients instead of the plasma column with the uniform radial density distribution. With allowance for the absolute sensitivity of the polychromator channels and geometry of the experiment, we calculated the submillimeter radiation power in the frequency range in the vicinity of the upper-hybrid frequency, which turned out to be approximately 4MW at pulse duration of up to 4 μs.
We explain an increase in the terahertz radiation power in the following way. In Fig. 2, one can see that the radial plasma density perturbations have the approximately regular periodic structure in the direction transverse to the magnetic field lines. If we assume the presence of the modulation instability of the dominant plasma wave, which is in resonance (the Cherenkov resonance) with the electron beam propagating along the magnetic field lines, then the resulting regular density perturbations will occur in the plasma, which will be directed at an angle to the magnetic field lines. These regular density perturbations result in the development of the linear instability of the electromagnetic waves propagating in the longitudinal direction. The instability development is pumped directly by the high-current electron beam. The growth rate of this instability is as high as that of the most unstable potential modes [7]. In our opinion, in the presence of the plasma density perturbations directed at an angle to the magnetic field, the development of the electromagnetic wave instability due to its direct pumping by the REB is the key mechanism for generation of the high-power electromagnetic beam with a frequency in the range near the upper-hybrid frequency.

![Graph](image)

**Figure 2.** Spectra of the terahertz radiation for two different radial density distributions of the plasma column. These two plasma density distribution are shown in the upper right panel.

To additionally increase the power of the waves escaping from the plasma column along its axis, we created the plasma gap with the strongly decreased density at the column end near the graphite collector intercepting the electron beam with the wide cross section. The experiment results presented in Fig. 3 show that, for such plasma column with the low density region, the submillimeter radiation power escaping from the plasma into the vacuum chamber through the 180-mm-diameter aperture becomes much higher. In the left panel in Fig. 3, the voltage pulses supplied to the accelerator diode ($U_{\text{diode}}$), the current flowing through the diode ($I_{\text{diode}}$) and the beam current at the end of the plasma column ($I_{\text{end}}$) are presented. The pulses of the terahertz radiation power inside the vacuum chamber $P_{\text{vac}}$ and the radiation power $P_{\text{atm}}$ outside the chamber after it escaped through the teflon window into the air are shown in the same figure (arb. units). The experiments show that when the terahertz radiation power inside the vacuum chamber increases several times, its pulse duration is still 4 μs, as it was for the low radiation power. But after radiation escapes through the window into the air, its pulse duration becomes less than 1 μs. This fact is confirmed by the $P_{\text{vac}}$ and $P_{\text{atm}}$ waveforms in Fig. 3. This discrepancy in the terahertz pulse durations can be explained by the electrical breakdown on the inner window surface (vacuums pulse facing surface) initiated by the high-frequency electromagnetic field.
Figure 3. Left panel presents waveforms of the \( U_{\text{diode}} \) voltage and of the \( I_{\text{diode}} \) and \( I_{\text{load}} \) currents as well as the \( P_{\text{osc}} \) and \( P_{\text{amp}} \) pulses of the terahertz radiation power. Right panel shows the cross section of the terahertz radiation beam.

Analysis of the output window surface after several shots of its exposure to terahertz radiation revealed that it was repeatedly damaged due to the electrical breakdown processes. In the right panel in Fig. 3, bright glow of the neon lamp array, installed at the distance of one meter from the teflon window, is shown, which occurred under the effect of terahertz radiation. It can be seen that the diameter of the glowing region on the neon lamp array at a distance of 1 m is approximately 20 cm (the window diameter is 18 cm).

4. Conclusions

The generation of terahertz radiation in the magnetized plasma column due to the two-stream instability developing in the relativistic electron beam with a current of 10 kA is studied at the GOL-PET facility at the plasma density varying in the range of \( 3 \times 10^{19} - 3 \times 10^{19} \, \text{cm}^{-3} \). In the first series of experiments, at the regular transverse plasma density gradients, the terahertz radiation power at a frequency of the upper-hybrid oscillations (\(-0.2-0.3 \, \text{THz}\)) was 4 MW and its pulse duration was several microseconds. This power is 30 times higher than the radiation power generated in plasma with the homogeneous radial density distribution. Theoretical interpretation of these experimental results is presented. To additionally increase the terahertz radiation power, in the last series of experiments, we created a low-density plasma gap between the end of plasma column and the graphite collector intercepting the electron beam. In this case, the power of the terahertz radiation escaping from the end of plasma column into the vacuum chamber increased to more than ten megawatts at pulse duration of 4 \( \mu \)s. But in the course of its further propagation, while the radiation escapes through the window into the air, its pulse duration becomes less than 1 \( \mu \)s. This discrepancy in the terahertz pulse durations can be explained by the electrical breakdown on the inner window surface (vacuum facing surface).

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