Properties of sub-THz Waves Generated by the Plasma during Interaction with Relativistic Electron Beam

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Abstract. In the paper, last experiment's results on sub-THz wave emission from the area of relativistic electron beam-plasma interaction in the GOL-PET device are described. A plasma column with the diameter of 6 cm, length of 2.5 m and electron density (0.2-2)×10^{15} cm^{-3} is confined by multiple-mirror magnetic field with mean value of 4 T. The relativistic electron beam injected into the column, has the following parameters: energy E_b ~ 0.8 MeV, current I_b ~ 30 kA, current density J_b ~ 2 kA/cm^2 in the mean magnetic field. Previous studies have shown that the beam pumps the plasma electron oscillations in a vicinity of the upper hybrid wave branch. These plasma oscillations can be converted in electromagnetic waves on regular or artificial plasma density gradients in a vicinity of upper hybrid frequency. The electromagnetic waves with the double upper hybrid frequency are also generated in the beam-plasma system due to coalescence of the plasma oscillations in case of high level of the oscillation energy density. The described experiments are devoted to measure the spectral properties of the generated radiation and the direction of the sub-THz plasma emission in depending on plasma and beam parameters. As results the wave emission with the specific power concentrated in the direction along the axis of the plasma column, in the frequency interval 0.25-0.5 THz has been obtained at the plasma density about of 10^{15} cm^{-3}.

INTRODUCTION

Creating tunable generators of high power sub-terahertz radiation at moderate size and weight can be considered as one of the most important tasks of vacuum electronics. Developed gyrotron generators based on the use of magnets with high field strength allows getting radiation at the frequency band 300-600 GHz. But the power and efficiency of such generators are not great. Its frequency adjustment is difficult as well. In view of these circumstances, we turned to the task on the generation of sub-terahertz radiation due to intense interaction of a high-current electron beam with plasma. Generation of powerful electromagnetic radiation in this frequency area under collective deceleration of high-current electron beam in plasma column was experimentally and theoretically studied at the Budker Institute of Nuclear Physics during last five years [1-5]. This generation is interpreted as result of high level power density of longitudinal (Langmuir) and/or oblique (upper-hybrid) waves excited by the strong electron beam. Currently, the issue of assessing the prospects for the practical use of sub-terahertz radiation generation in a beam-plasma system is shifted from the study of the fundamental characteristics of this phenomenon to the analysis of mechanisms of effective conversion of the plasma electron oscillations in an electromagnetic radiation flux and the output of the flux from plasma into open space. Study of dynamics of radiation output from different regions of an elongated plasma column in which high-current relativistic electron beam (REB) is decelerated, is of great importance for solving this task. Among the characteristics of the radiation which dynamics should be studied, one can select the following: specific spatial distribution of radiation, the spectral density of the radiation and the angular distribution of electromagnetic emission. This work is aimed at solving these tasks.

THE EXPERIMENTAL DEVICE

For study of the conditions related with generation of electromagnetic radiation, a specialized facility GOL-PET has been created. The facility consists of an open magnetic trap with a multiple-mirror or uniform magnetic field of mean value B = 4.5 T and length L = 2.4 m between the end mirrors. The end mirrors have a strong field up to B = 8 T. U-2 accelerator producing high current REB is mounted at one end of the trap. It produces the beam with current I ~ 10kA and the kinetic energy of electrons $E_e \approx 0.8$ MeV [6]. The duration of the electron beam is $\tau \approx 6$ μs, the beam diameter is 4.2 cm in the magnetic field 4 T. A plasma with a density $n_e \approx (0.2 \div 5)\times 10^{15}$ cm^{-3} and a diameter of 7 cm is created by the longitudinal high-current discharge. The REB is injected in the end of the discharge current. The discharge plasma current stabilizes simultaneously the beam injection process. Previous experiments have shown that the variation of the power value of the emitted electromagnetic waves correlates with the changes in the efficiency of plasma heating by the electron beam and the both wave generation and plasma heating processes lasts during the first half of the injection time [1-5]. It was decided therefore to maximize the number of diagnostics at the first meter of the plasma column (see. Fig. 1). Measurement of plasma density is carried out by mean of laser diagnostic complex [7]. The radial profile of the plasma density is measured at a distance z = 0.83 m from the entrance mirror by diagnostics based on Thomson scattering. Dynamics of the average plasma density is measured by Michelson interferometer at z = 1.16 m.

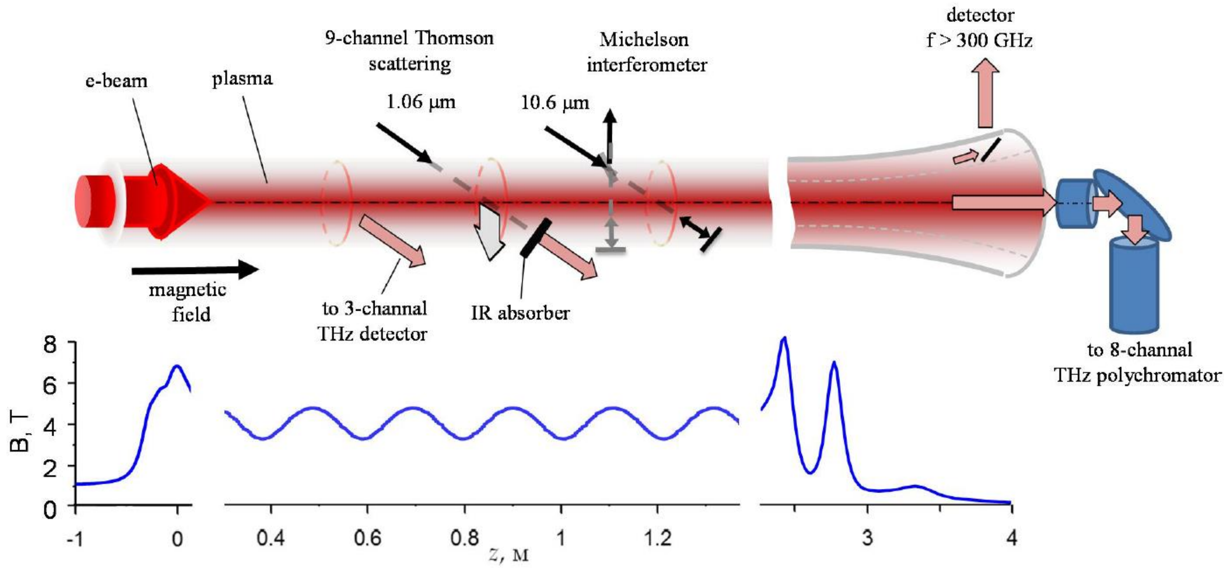


FIGURE 1. Layout of the GOL-PET device with the diagnostics (top). The longitudinal confining magnetic field distribution is presented on the bottom of figure. Here the multiple-mirror configuration is shown. In the uniform configuration the central part of the diagram one need to replace to flat curve.

The electron beam current at different axial points is measured by pulsed current transformers. Electron energy of REB is determined according with accelerator voltage in the U-2 diode. The transfer of energy from REB to plasma is calculated from measurements of diamagnetic probes mounted along the plasma column. 8-channel sub-mm polychromator [8], as well as a number of single detectors with bandpass filters at the entrance is utilized to study properties of radiation emitted by plasma.

EXPERIMENTAL DATA AND DISCUSSION

Before start measuring of the radiation spectrum at different plasma densities from 10^{14} up to 10^{15} cm^{-3}, a series of experiments on the simultaneous registration of radiation power emitted along the axis and in the perpendicular direction was carried out in separate experiments. The radiation power was measured by single detectors with spectral sensitivity above 300 GHz band. Measurements of the EM-wave power emitted in the transverse direction were done in a middle part of length of the plasma column. The power of EM-waves which propagate along the axis of plasma column was measured at the output expander of GOL-PET with usage a mirror reflector (see Fig. 1). The results of these measurements are shown in Fig. 2a. The radiation emitted across the confining magnetic field (in the central part of the plasma column) was observed only at relatively low plasma densities $n_e < 5\times10^{14}$ cm^{-3}. For higher values of plasma density, the emission in the band above 300 GHz is observed only along the axis of the device. Just as in the earlier experiments on the GOL-3, the EM-wave emission mainly exists simultaneously with the increasing of the plasma diamagnetism. The radial distribution of electron plasma density during process of EM-waves emission was measured by Thomson laser scattering system (see upper diagram in Fig. 2b). It showed that all conditions with different plasma density its profile in the beam area has almost constant value. Therefore for each shot one value of the electron density is given.

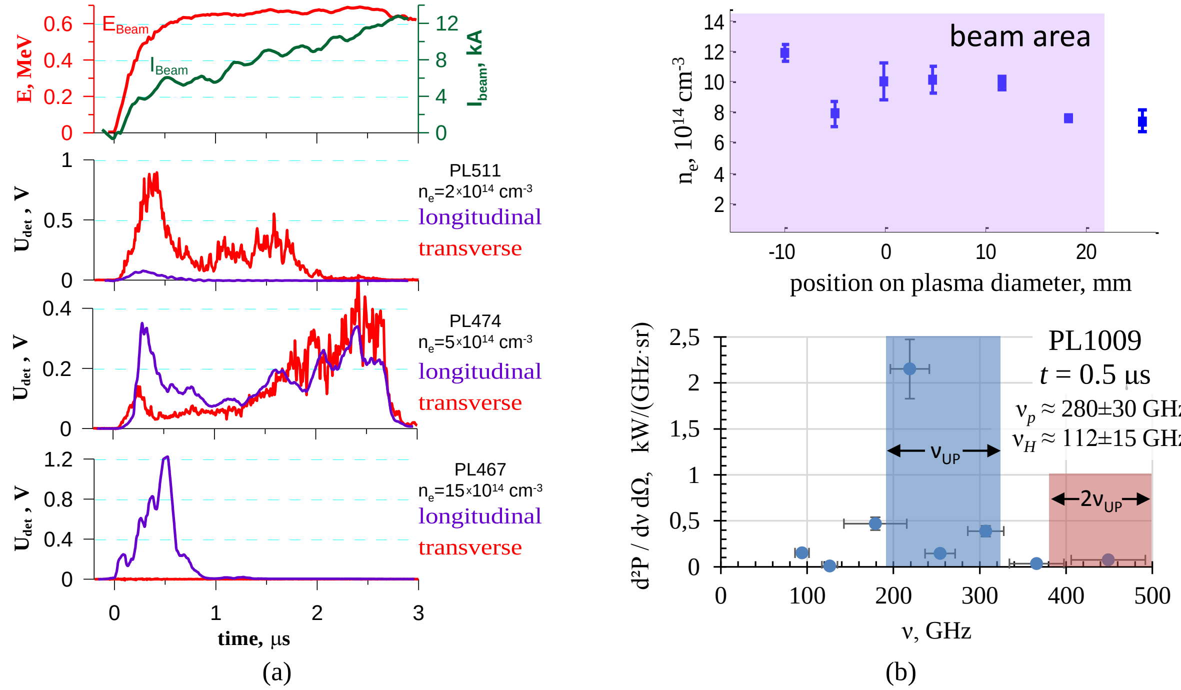
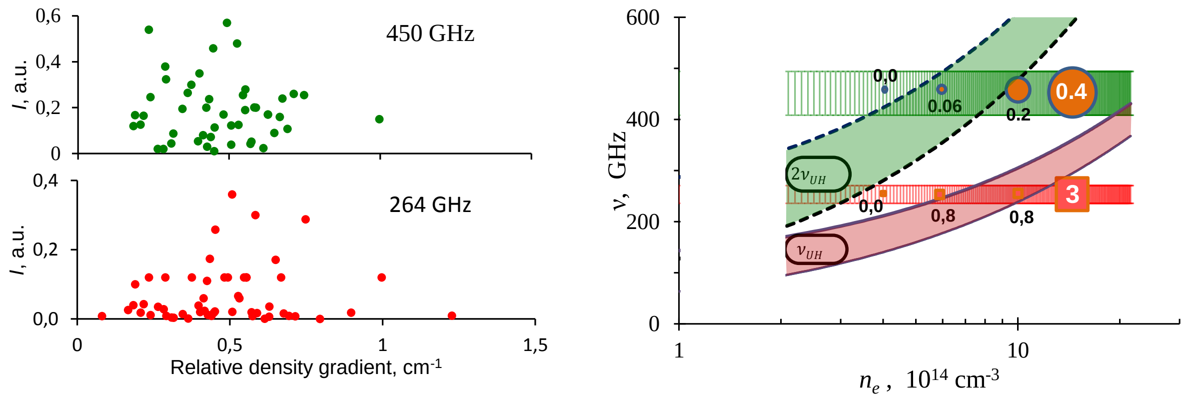


FIGURE 2. Dependence of transverse and longitudinal EM-wave power from plasma density in 300-500 GHz frequency band (a). Radial plasma density distribution on cross section of plasma column (b-top). Spectral power of axial propagated EM-waves, measured at the exit of GOL-PET facility (b-bottom) with plasma density, shown on top of the figure.

Taking into account the results of these experiments, measurement of the spectral power of the EM-wave emission along the system axis was carried out in at high plasma density $n_e \sim 10^{15}cm^{-3}$. In the Fig. 2b (bottom) the typical spectral power profile of EM-waves is shown. The spectrum contains three local peaks: the first is less than 100 GHz, the second - in the range from 150 to 330 GHz, and the third - in the frequency range 380÷500 GHz. At frequencies below 100 GHz radiation power is negligible in compare with radiation in 150÷330 GHz band. Since the frequency of radiation in the 100 GHz range does not change when we vary the plasma density, one can be assumed that this observed emission is due to the cyclotron movement of beam electrons. The signals in the frequency band 150÷330 GHz are interpreted by us as radiation near the upper-hybrid plasma frequency [8]. This frequency range for plasma density $n_e \approx (0.8\div1.2)\times10^{15}$ cm^{-3} and magnetic field B = 4.2 T occupies the interval of $\nu_{UH} \approx 190\div320$ GHz. Generation of such EM-waves can be realized due to the direct conversion of upper-hybrid plasma waves on plasma density gradients. This plasma gradient may be result density fluctuations caused, for example, by ion plasma waves. As to the high-frequency band 380÷500 GHz, this emission, on our opinion, is result of the coalescence of two upper hybrid plasma waves to electromagnetic one [9-11].

The physics of EM-wave generation in range of the upper-hybrid frequency assumes that the high enough gradients of plasma density exist. The dependency of EM-wave emission in the ranges of the upper-hybrid frequency and its double value on the relative gradient of the plasma density in radial direction of the plasma column was obtained in our experiments. The evolution of EM-wave power obtained by certain detectors is presented in Fig. 3. This figure shows that the optimal plasma gradient about of 0.5 cm^{-1} has to exist for effective generation of EM-waves in both spectral bands. However, the emission along the axis at the exit of the GOL-PET device depends on plasma density directly, see the numbers on Fig. 3b. It means that additional feature exists for conversion of upper-hybrid waves into electromagnetic ones with subsequent longitudinal redirection of them in the GOL-PET device.



(a) (b)

FIGURE 3. Dependence of EM-waves in two spectral band (450±50 and 260±20 GHz) emitted along the axis at the exit of the GOL-PET vs relative electron plasma density gradient (a). The gradient is calculated from Thomson scattering system data. The band of upper-hybrid plasma waves and its double value vs plasma density (b). In figure the spectral band of registered radiation on (a) is shown. The numbers near to (inside) squires or circles show the power in the detectors in watts.

CONCLUSION

The emission of electromagnetic radiation from the plasma is observed mainly at the stage of intensive beam-plasma interaction, as evidenced by a sharp increase in plasma diamagnetism in this time. The main power of radiation is in two spectral ranges corresponding to the upper-hybrid plasma frequency and its doubled value.

In a series of experiments on the interaction of high-current electron beam (~1kA/cm^2) with a plasma (n ≈ 10^{14}÷10^{15} cm^{-3}) in an external multiple-mirror magnetic fields the specific power of radiation in the frequency range of 150-330 GHz can reach values up to 10 kW/(sr·cm^2). For the frequency range of 400-500 GHz, the power density can reach a value of 1 kW/(sr·cm^2) at a plasma density $n_e \approx 10^{15}$ cm^{-3}.

Based on these results, for the future experiments we plan the adjustment of the electron accelerator diode geometry for the increase in the REB current density in accordance to the higher plasma density already achieved in our experiments. In the next series experiments, the detailed measurements of the spectra of electromagnetic radiation emitted both perpendicular and parallel to the magnetic field will be carried out and all emission from the beam-plasma system will be collected a united radiation beam.

ACKNOWLEDGMENTS

This research was financially supported by RSCF under Project #14-12-00610 for the investigation of sub-terahertz emission from plasmas. The upgrade of the radiometric system was funded by the Ministry of Education and Science of RF under the State Assignment Contract #3002.

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