Beam-Plasma System as a Source of Powerful Submillimeter and Terahertz Radiation
(Experimental and Theoretical Studies)

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Abstract. The processes of plasma wave transformation into electromagnetic radiation during strong interaction of a relativistic electron beam with magnetized plasma are studied in BINP in collaboration with NSU. Since 2010, experimental studies on such transformation processes were carried out on the GOL-3 facility by measuring the radiation emitted from beam-plasma system. Then after 2014 the GOL-PET device is used for these studies. Results of these experiments on emission in the frequency interval 0.1-0.5 THz from a long plasma column due to E-beam injection are described in the presented paper. The experimental results have been compared with theoretical ones obtained for EM-wave generation by the beam-plasma system.

INTRODUCTION

From one hand, beam-plasma systems widely exist in the outer space as sources of EM-waves. The EM-wave flows from such sources were measured and interpreted by astrophysics researchers since the middle of the last century [1, 2]. To verify astrophysical models of various mechanisms of the EM-wave generation in space plasma, supporting laboratory beam-plasma experiments are carried out. From other hand, such beam-plasma systems are very attractive for the development of generators of radiation in millimeter and submillimeter ranges [3, 4]. Motivated by these circumstances, we study the systems in laboratory experiments since 70-th of the past century [5]. Past five years this activity was concentrated on experiments to study electromagnetic wave emission from the beam-plasma system in the frequency interval 0.1-0.7 THz. The processes of transformation of plasma waves into electromagnetic radiation during strong interaction of a relativistic electron beam with magnetized plasma was initially studied the GOL-3 facility (see. [3]). Since 2014 these studies are continued at the GOL-PET device [4]. The experimental research is accompanied by theoretical investigations at appropriate the beam and plasma parameters [5, 6]. The presented paper describes results of the experiments for the EM-wave emission from the beam-plasma system in the frequency interval 0.1-0.5 THz and of the theoretical studies for the process of plasma wave transformation into electromagnetic radiation in a frame of analytical models and computer simulations for suitable beam and plasma parameters.

KEY RESULTS OF GOL-3 EXPERIMENTS

In the experiments at GOL-3 facility on the beam-plasma interaction, parameters of the injected beam were the following: the electron energy E_e = 0,6 to 0,8 MeV, the beam current I_e = 10 to 30 kA, the duration of the beam injection t~10 µs, the beam energy content in the beam pulse Q ~130 kJ [20]. A plasma column had a diameter about of 8 cm and a length about of 14 m. In the first series of the experiments carried out for the plasma density of a few units of 10^{14} cm^{-3}, it was found that emitted pulses of mm-waves and sub-terahertz radiation by the beam-plasma system continued 1-3 µs from the beam injection beginning, as a rule, and the most part of the emission was concentrated in the first two meters of the beam way along the plasma column [3].

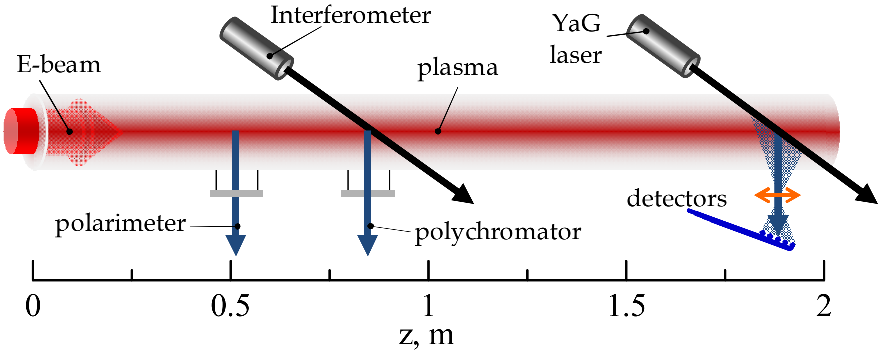

FIGURE 1. Schematic drawing of the GOL-3 experiments on emission of sub-mm waves and terahertz radiation

Taking into account these experimental results we placed main part of the diagnostics for measuring the plasma, E-beam and radiation parameters exactly along these two meters of the plasma column. Schematic of this part of GOL-3 facility exploited for the generation of sub-terahertz radiation due to beam-plasma interaction is presented in Fig. 1.

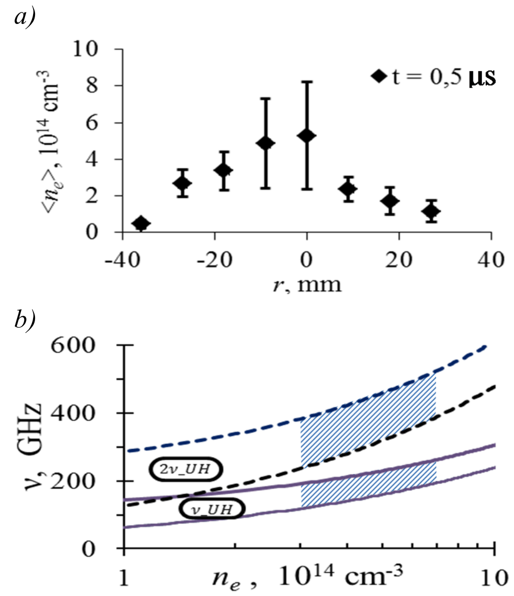

FIGURE 2. Plasma density distribution over the plasma column diameter (a) and ranges of the upper hybrid frequency and its doubled value for this density distribution (b). The frequency ranges are marked by shaded areas.

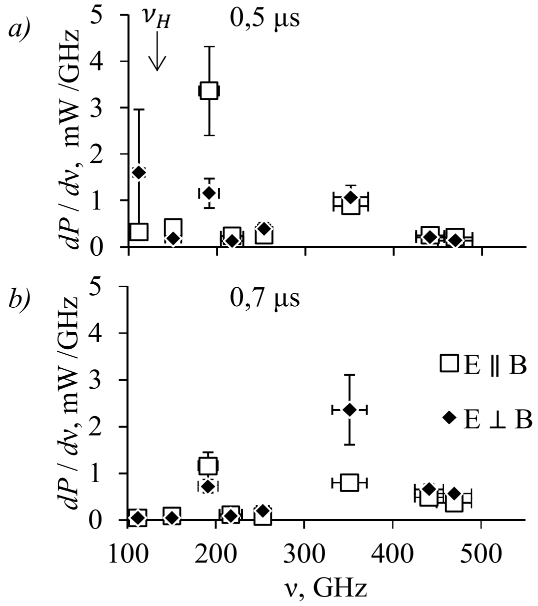

FIGURE 3. Radiation spectra measured for two times from starting the beam injection: (a) - for t=0.5 µs and (b) - for t=0.75 µs.

Measurements of plasma density were done by a Michelson interferometer on the wavelength l=10.6 µm at a distance of z_2 = 83 cm and by a Thompson scattering system with laser radiation on the wavelength l=1.06 µm at a distance of z_3 = 192 cm from the entrance of the beam into the plasma column. Registration of the sub-terahertz emission from the plasma was carried out in two cross-sections of the plasma column. To record the polarization of the radiation in this range a special device (a polarimeter) was installed at z_1 = 52 cm. At a distance of z_2 = 83 cm the measurements were carried out with the help of eight-channel polychromator covering the frequency range 90 – 400 GHz. The detail description of the eight-channel polychromator for terahertz frequency range was already done in [8]. The magnetic field in the cross section, which emission of radiation was registered from, had a value of B = 4.7 Tesla. Diameter of the plasma column, determined by diaphragms and the measured the laser diagnostics was d_p = 70 mm. In turn, the beam diameter was close to d_b = 43 mm and the beam current density had a value of 2 kA/cm^2. As demonstrated by Fig.2a, the plasma density in area of the beam cross section was (3-7) 10^{14} cm^{-3}. In accordance with the plasma density value, the calculated value of the upper hybrid frequency is in the range 110-200 GHz and the its doubled value has to be from 240 up to 400 GHz (see Fig.2b). Exactly, these frequency ranges were detected in spectral measurements with the usage of the polychromator (see spectra in right part of Fig. 3). The Figure 3 also demonstrates polarization of the plasma emission in these two spectral ranges. This experimental result has good coincidence with the result of a theoretical analysis given in [6, 7].

GOL-PET EXPERIMENTS WITH THE INCREASE OF PLASMA DENSITY

Essential progress in the experiments on generation of terahertz radiation by the beam-plasma system could was provided by increasing the plasma density of on plasma column. Taking into account this prospect we had deeply reconstructed our GOL-3 facility. The schematic of a new device called GOL-PET (Plasma Emission in Terahertz range) is presented in Fig.4.

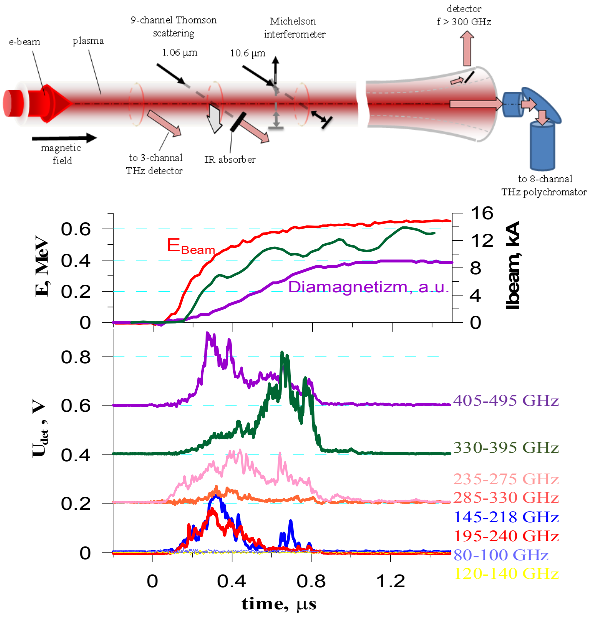

FIGURE 4. Schematic of the GOL-PET experiments and typical experimental shot data, U_{det} – signals from THz polychromator detectors.

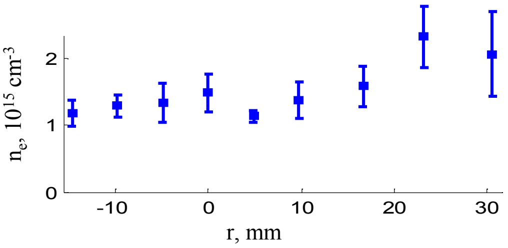

FIGURE 5. Plasma density distribution over diameter.

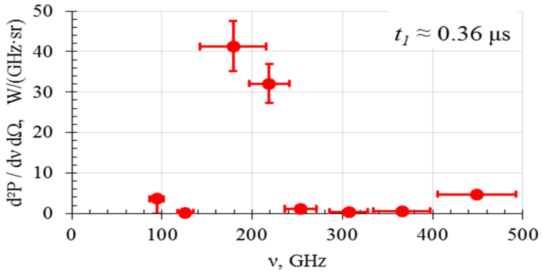

FIGURE 6. Spectrum of the radiation that goes out along the axis.

The main advantage of the GOL-PET experiment geometry is that the plasma column length is in three times less than it was in case of the GOL-3 facility. The GOL-PET experimental conditions allow us to increase the plasma density up to 5•10^{15} cm^{-3} and to measure the properties of the plasma emission along the axis of the device as it is demonstrated in Fig. 4. The GOL-PET experiments have shown if the plasma density is increased from pulse to pulse of the device operation in the interval from 5•10^{14} up to 1•10^{15} cm^{-3}, the direction of the terahertz emission is changed from transverse one to the longitudinal. For the plasma density upper than 1.5•10^{15} cm^{-3} (see in Fig.5 the plasma density distribution for the shot #472) the radiation flux is concentrated in the direction along the axis of the device and practically no emission in the transverse direction. Results of the spectral measurements of the radiation propagated along the axis is presented in Fig. 6 for the shot #472. One can see the spectral power density of the radiation is localized near the frequency 200 GHz that is approximately equal to the upper-hybrid frequency for the plasma density in this shot (see Fig. 2). But one can see the spectral power density for the range of the double value of the upper-hybrid frequency is lower in ten times. We suppose that the maximum of the spectral density for the doubled frequency is located in an area with higher frequency.

THEORETICAL ANALYSIS COMMENTS FOR EXPERIMENTAL RESULTS

It has been experimentally found that the EM emission near the doubled upper-hybrid frequency changes drastically its direction when the plasma density increases from 2•10^{14} cm^{-3} to 2•10^{15} cm^{-3}. The same tendency is predicted by the recently proposed theoretical model [6,7] in which this emission is produced by coalescence of long-wavelength upper hybrid waves. According to this model, the power pumping into upper hybrid waves by the electron beam is saturated at a constant level $P_{pump} \approx 1/3(\gamma_b - 1) n_b v_b m_e c^2 / L$ which is determined by beam trapping and does not depend on the structure of the pumoed turbulence. Here, the electron beam has the density n_b, velocity v_b and relativistic factor γ_b, and loses its energy at the length L. The power balance between different regions of turbulent spectrum allows to estimate the energy of resonant W_R and nonresonant W plasma waves,

$$W_R \approx 2W\sqrt{\frac{m_e}{m_i}}, \qquad \frac{W}{nT} \approx \left(\frac{m_e}{m_i}\right)^{1/4} \left(\frac{P_{pump}}{\omega_p nT}\right)^{1/2}, \tag{1}$$

and the characteristic size of the radiating source region in the wavenumber space, $k_M \approx \sqrt{W/nT}/r_D$.

Let us estimate these values in different experimental regimes for rarefied and dense plasmas. If the plasma with the density n = 2•10^{14} cm^{-3} is heated to the typical temperature $T = 1$ keV and confined by the strong magnetic field at which the electron cyclotron frequency equals to $\Omega_e/\omega_p = 0.8$, the turbulence energy reaches the level $W/nT \approx 0.01$ and the energetic long-wavelength part of turbulent spectrum is restricted by the wavenumber $k_M \approx 2.5c/\omega_p$. If we raise the plasma density up to n = 3•10^{15} cm^{-3} without changes in magnetic field and beam parameters, we transit to the regime of weaker magnetic field $\Omega_e/\omega_p = 0.2$ and less electron temperature $T \approx 100$ eV. In such a regime, the plasma turbulence is characterized by the same wave energy $W/nT \approx 0.01$, but is distributed inside the wider wavenumber region $k < k_M \approx 4c/\omega_p$. Using the theory [6, 7], we have calculated the angular distribution of radiation power of the doubled frequency that is presented in Fig. 7. This result demonstrates that the direction of the radiation can be changed from transverse to almost longitudinal one by the increase of plasma density.

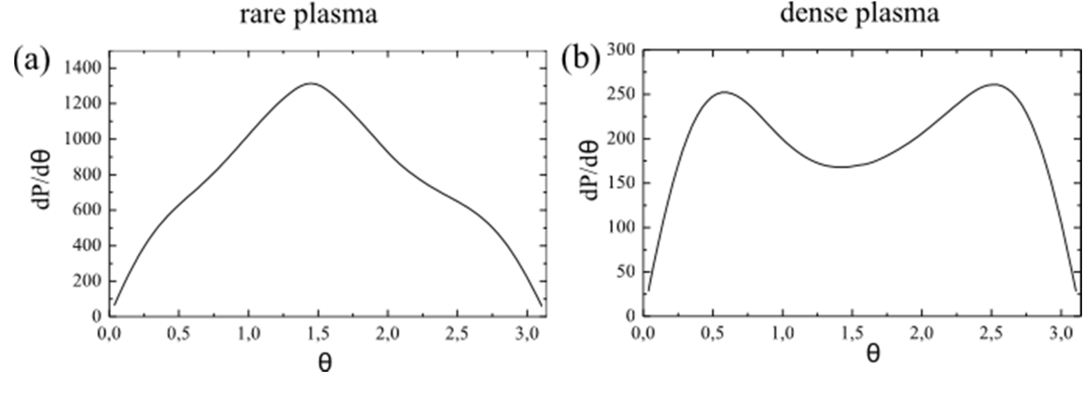

FIGURE 7. (a) The power of the second harmonic radiation $dP/d\theta$ emitted in a unit polar angle θ (in radians) as a function of this angle in the case of low-density plasma. (b) The power $dP/d\theta$ in the case of high plasma density.

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