

## Observation of the spectral and polarization dynamics of sub-THz emission from E-beam – plasma interaction area

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### Introduction

Studies of electromagnetic emission from beam-plasma interaction area have considerable interest for astrophysics, the fusion program based on long open traps and for creation of high power sub-terahertz generators on novel fundamental principles. In the case of strong plasma turbulence driven by an intense relativistic electron beam (REB) the plasma oscillations are transforming over the wave vector spectrum from the domain of resonance with the beam to the region of large wave vectors. At the same time, the scattering of Langmuir wave on strong gradients of plasma density and the coalescence of two plasma waves are possible. In the first case the electromagnetic wave can be generated with a frequency close to the upper- hybrid plasma frequency and at its double value.

The first experiments on observation of sub- terahertz electromagnetic emission from a laboratory plasma at injection of a high-current relativistic electron beam (REB) with microsecond duration were carried out on the GOL-3 facility in 2009-2010.<sup>1</sup> Results of measurements of the temporal dynamics of spectrum and polarization of sub-THz radiation at the GOL-3 facility are presented in this paper.

### Experimental set-up and diagnostics

The length of a plasma column in these experiments at the GOL-3 facility is about 12 m. Experiments on generation of sub-terahertz radiation in plasma were performed in the first two meters of REB passing in the plasma because there its main energy deposition in the plasma column was localized (see Fig. 1). In the described series of experiments the plasma density was about  $3 \times 10^{14} \text{ cm}^{-3}$  and the magnetic field was 3-4 T. The parameters of the beam injected into the plasma were as follows: the electron energy  $E_e$  and the beam

current  $I_e$  were increasing up to 0.6 MeV and up to 20 kA respectively during injection time. The total duration of the beam injection was  $t \sim 10 \mu\text{s}$  and the beam energy content in the beam pulse was  $Q \sim 130 \text{ kJ}$ .

The beam current was measured by pulse current transformers. The electron energy of the beam was determined from measurements of the voltage of an accelerator diode. Measurements of plasma density were carried out in two cross-sections along the plasma column with the usage of laser diagnostics (see Fig. 1): at the distance of  $z_1 = 0.8 \text{ m}$  from the entry of the beam into the plasma by a Michelson interferometer and at the distance of  $z_2 = 1.9 \text{ m}$  by the Thomson scattering system. Observation of the sub-terahertz emission from the plasma was carried out in the same cross-sections. At the distance of  $z_1 = 0.8 \text{ m}$  a polarimeter was installed and at  $z_2 = 1.9 \text{ m}$

an eight-channel polychromator was used. We applied band-pass quasi-optical filters for two frequency ranges which correspond to the spectral domains of fundamental plasma frequency and its second harmonic. To separate two components with orthogonal polarization the quasi-optical strip-grid polarizers were used. For measurements of radiation fluxes passed through the filters we applied Schottky detectors with temporal resolution about 2 ns. Detailed description of the diagnostic system for these experiments was published in Ref. 2. The spectral sensitivity of two channels of the polarimeter with the filters installed is presented in Fig. 2. Presented spectral characteristics demonstrate that the suppression of radiation out of the filter

bandwidths reaches four and even five orders of magnitude. Both polarimeter and polychromator use the quasi-optical sub-THz systems and have the input angle sensitivity width  $\Delta\alpha_{1/2} = 4^\circ$  which is determined by diffraction.

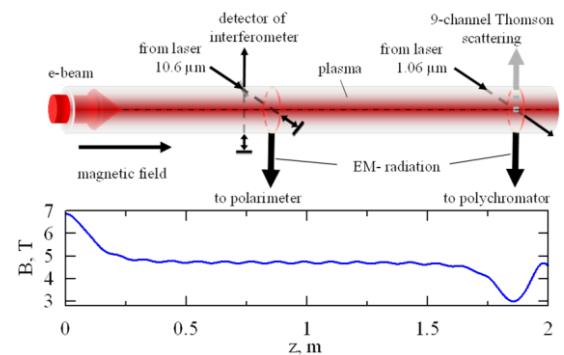


Fig.1. Schematic drawing of the experiment

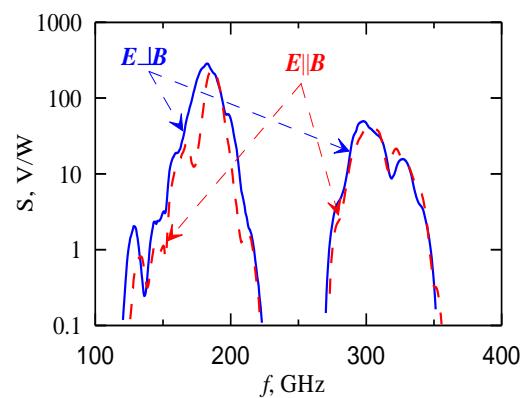


Fig.2. Spectral sensitivity of two channels of the polarimeter

## Results of experiments on spectral measurements

Measurements of the plasma density by the Thomson scattering diagnostics in eight locations along the plasma diameter have shown that without the beam injection the central part of the plasma column within diameter 40 mm had the density of about  $2 \cdot 10^{14} \text{ cm}^{-3}$ . During the beam injection the plasma density in the electron beam cross-section increased to the level of about  $4 \cdot 10^{14} \text{ cm}^{-3}$  with variation from one injection pulse to another one within 30%. Fig. 3 presents temporal dynamics of the spectral power density obtained by usage of polychromator when a polarizer at its input was in two different positions. The waveforms of the beam electron energy and the beam current are also shown. Presented results were obtained by averaging spectra data of seven shots of GOL-3 device when it operates with the same parameters of the beam and the plasma.

Measurements of the spectral power density demonstrate that the sub-terahertz emission exists during  $2\mu\text{s}$  from the beginning of the beam injection. In time duration about  $1\mu\text{s}$  this emission is clearly separated into three spectral domains: near 100 GHz and 190 GHz, and in the range of 270 – 400 GHz. In frequency gaps between these three domains the plasma emission has vanishing level of the spectral power density. The spectral power density in Fig. 3 can be recalculated into specific spectral intensity of THz radiation supposing uniform longitudinal distribution of the source. In the vicinity of 190 GHz the specific spectral intensity of radiation reaches a maximum  $50 \text{ mW}/(\text{GHz} \cdot \text{Sr} \cdot \text{cm}^3)$ . As the high-frequency region in the frequency interval 270 – 400 GHz is concerned, the maximum values of the specific spectral intensity of radiation  $34 \text{ mW}/(\text{GHz} \cdot \text{Sr} \cdot \text{cm}^3)$  is achieved. The

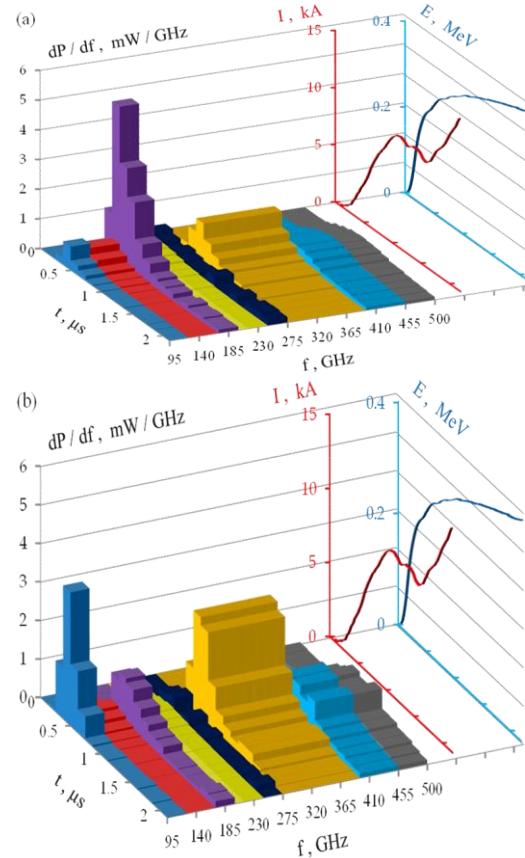


Fig. 3. Dynamics of the spectral power density of electromagnetic emission from the plasma with the polarization parallel, figure (a), and perpendicular, figure (b), to the magnetic field in the plasma.

specific spectral density of radiation with a frequency of about 450 GHz has an order of magnitude lower value  $-7 \text{ mW}/(\text{GHz}\cdot\text{Sr}\cdot\text{cm}^3)$ .

For the detailed investigation of polarization dynamics of the emission during the beam injection into the plasma column the radiometric polarimeter described above was used. The measurements showed that for the frequencies in the interval  $f_2 = 160 - 200 \text{ GHz}$  the polarization predominantly directed parallel to the magnetic field with the degree of the polarization approaching 30%. For the frequencies in the interval  $f_3 = 280 - 340 \text{ GHz}$  the polarization of this radiation is directed perpendicular to the magnetic field as well and the degree of the wave polarization exceeds 70%. The comparison of the values of the specific power for the two plasma cross section is presented in Tab. 1. There are presented sums of two orthogonal polarization signals measured by the polychromator and the polarimeter.

## Discussion

As measurements showed the vector of electromagnetic radiation has the primary direction perpendicular to the magnetic field for the frequency  $f_1 = 100 \text{ GHz}$ , and parallel to the magnetic field for the frequency  $f_2 = 190 \text{ GHz}$ . In this case, the most likely mechanism of electromagnetic wave generation is the linear conversion of the plasma oscillations into the electromagnetic waves on strong gradients of the plasma density.

Regarding the frequency interval  $f_3 = 280 - 340 \text{ GHz}$ , by varying the plasma density in these experiments we saw that this frequency band was approximately followed by changing the double of the upper-hybrid plasma frequency. Because of the polarization vector of this radiation was mainly directed perpendicular to the magnetic field we suggest that this emission is associated with the coalescence of two upper-hybrid plasma waves.

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