SUBTERAHERTZ EMISSION AT STRONG REB-PLASMA INTERACTION IN MULTIMIRROR TRAP GOL-3

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Investigation results for electromagnetic radiation emission induced by strong Langmuir turbulence driven by a microsecond relativistic electron beam are presented. The radiation is associated with a plasmon-plasmon merging process, which generates photons at a double plasma frequency in the range of few hundreds GHz. An original radiometric system for radiation spectrum and power measurements is described.

I. INTRODUCTION AND BACKGROUND

One of the key problems in investigating interaction of high current relativistic electron beams (REBs) with plasmas is to characterize the distribution of the energy losses of the beam between plasma electron and ion components and to characterize the beam-induced emission of electromagnetic radiation from a plasma volume.

In the experiments at the GOL-3 facility[1,2], wherein the plasma is heated by a 10 microsecond REB, the electron temperature reaches 1-2 keV at the bulk plasma density $n \approx 10^{14}$–10^{15} cm^{-3}. The mechanism of plasma heating at the GOL-3 facility is recognized as the excitation of strong Langmuir turbulence (LT) via a two-stream instability induced by the propagating high current REB[3]. Due to that mechanism of the plasma heating a significant fraction of the beam energy can be converted into the electromagnetic radiation emitted from the plasma column. Our long-standing plasma heating experiments with submicrosecond E-beams (1−10 kA/cm^2, $\tau_b \sim 100$ ns) showed that the LT energy density W_l at the strong beam-plasma interaction may reach a relatively high values (limited by nonlinear processes): $W_l / nT \sim 10^{-1}$, where nT is the energy density of the heated plasma electrons[3].

The detailed theoretical consideration of LT-induced electromagnetic emission from turbulent plasmas, verified by astronomical observations of solar radio-flares[4], distinguishes two main processes responsible for the electromagnetic radiation during the REB-plasma interaction at GOL-3.

First, plasmon scattering on plasma density fluctuations, yields electromagnetic emission at plasma frequency ω_p ("ω_p-process");

Second, plasmon-plasmon merging results in production of photons in the vicinity of a double plasma frequency $2\omega_p$ ("$2\omega_p$-process").

For plasma densities 10^{14}–10^{15} cm^{-3}, the output radiation frequencies associated with the aforementioned processes are located in the range of millimeter-submillimeter waves,

$$\omega_p/2\pi \cong 90-283\,\text{GHz},\quad 2\omega_p/2\pi \cong 180-566\,\text{GHz}.$$

In this paper, we present the first observation of LT-induced submillimeter-wave emission from GOL-3 plasma during injection of the 10μs-REB. The results are obtained with the use of an original radiometric diagnostics specially elaborated for spectral measurements in the band 250-430 GHz near the middle frequencies of the "$2\omega_p$-process". At the current stage of research, we intentionally focused on investigating $2\omega_p$-emission, since plasma is more transparence at the double plasma frequency compared to the ω_p-emission. In forthcoming experiments, the electromagnetic radiation both at plasma and double plasma frequencies is planned to be registered simultaneously. Simultaneous measurements carry important information on dynamics of plasma's density and temperature, as well as a spectrum and energy density of Langmuir turbulence that is considered to be important both for plasma diagnostics itself and for verification of theoretical models of plasma turbulence insufficiently studied in laboratory conditions.

II. EXPERIMENTAL SET UP

Experimental studies were carried out at the multimirror magnetic trap GOL-3, where a long (12 m) plasma column is confined in a strong corrugated magnetic field ($B_{max}/B_{min} \cong 4.8/3.2$ T). The electron beam with the current density up to 20 kA/cm^2 and the particle energy up to 0.8 MeV is injected during 10 μs through the left end of the plasma column as it is shown in Fig.1.

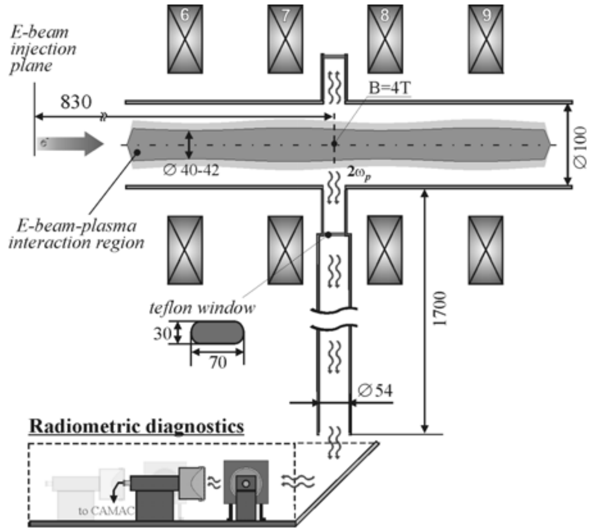

Fig.1. Schematic of the radiometric experiment at the GOL-3 facility. All dimensions are given in mms.

Measurements of the $2\omega_p$-emission were performed at the distance of about 80 cm from the beam injection plane (B ≅ 4 T) where the maximum efficiency for the beam-plasma interaction is identified from diamagnetic signals. The radiation output from the plasma chamber was carried out perpendicularly to the axis of the GOL-3 solenoid through a teflon window with the aperture size 70×30 mm joined with a quasi-optical transmission line. The latter was implemented as a hollow vertically mounted dielectric tube with diameter ∅ 54 mm and used for transporting the radiation to the radiometric system installed on a screened diagnostic bench. On the opposite side of the plasma chamber, an auxiliary teflon window was installed to minimize spurious re-reflections of submm-waves coming from the plasma regions beyond the direct "line of sight" of the radiometric system.

We developed an original 4-channel radiometric system capable of measuring power of submm-emission in four parallel frequency-shifted spectral bands[5]. The system employs a scheme with quasi-optical demultiplexing of the input radiation beam onto four spatially separated channels with subsequent frequency filtering by quasi-optical filters and spectral signal detection by calibrated Shottky-detectors matched with receiving horn-lens antennas, as shown in Fig. 2a. The incoming submm-wave beam passes through an auxiliary polarizer, which fixes the transmitted beam polarization in a vertical or horizontal direction and also used for studying a polarization state of $2\omega_p$-emission. The beam then undergoes 50%-splitting onto two cross-polarized beams by a polarization beam-splitter mounted at 45^0 to the incidence direction. The polarization axis of the splitter is oriented at 45^0 relative to the vertical line. Each of 45^0-polarized demultiplexed beams passes through a quasi-optical band-pass filter, which is designed such way that its frequency transmission bands for horizontal (X) and vertical (Y) components of the incident beam polarization are shifted on the frequency. In accordance to this peculiarity of the selective properties of such filters it is required only two hardware filters instead of four for the 4-channel radiometric system thus reducing the production costs. The filters are implemented on the basis of photolithographically-produced[6] self-resonant metal meshes with topology of anisotropic slots (Fig. 2b).

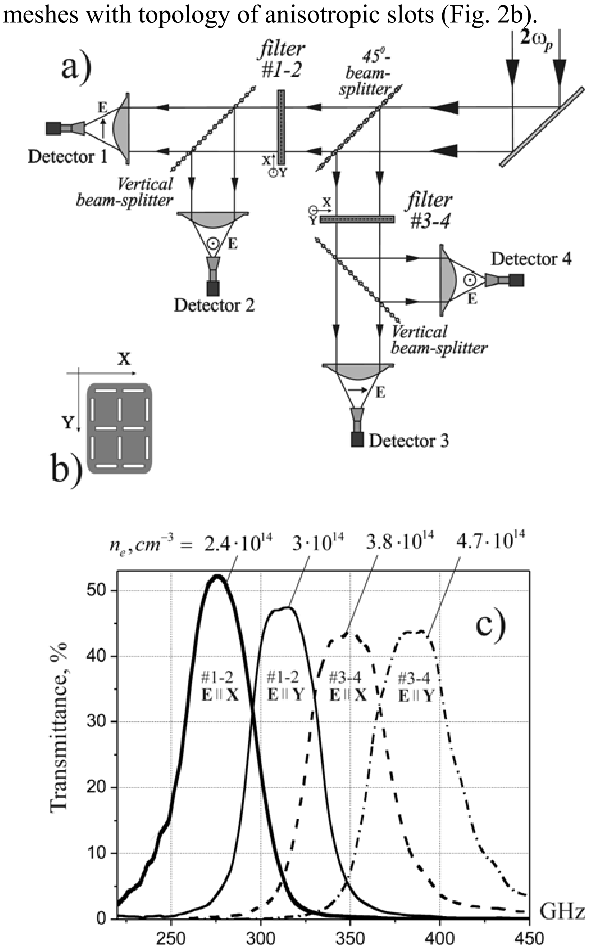

Fig. 2. a) Lay-out of the 4-channel radiometric system; b) topology of filter's meshes; c) frequency response of double-mesh filters (the data on the top indicate $2\omega_p$-related plasma densities corresponding to the frequency of transmission maximum for the respective filter: 275 GHz, 312 GHz, 350 GHz, 385 GHz). See also Ref. 5 for details.

They are embedded into polypropylene wafers to form the robust double-mesh configurations with a quarter-wavelength inter-mesh separation at ∅ 60 mm clear aperture diameter. We used the filters with bandwidth ~40 GHz and -20-30 dB out-of-band attenuation at 35-38 GHz frequency shift of adjacent transmission bands (Fig. 2c).

After passing through the filters, the X- and Y-polarized sub-beams undergo the final demultiplexing and are further focused by aspheric teflon lenses (f = 40 mm, CA ∅70 mm) into the receiving horn antennas of the Shottky-detectors units. The antennas are implemented as waveguide transitions from the outer oversized cross-section 3.6x1.8 mm onto the inner waveguide cross-section 0.72x0.36 mm of the detector. Detection of the submm-wave signal is provided by a beam-lead GaAs Shottky diode integrated into a microstrip line used for wideband "waveguide-diode" matching. Each detector, initially developed for operation at frequencies 210-450 GHz, is equipped with a built-in 900 MHz-band operational preamplifier and has the response time better than 2 ns. At 50 Ω loading resistance, the typical values of the detector volt-watt sensitivity and dynamic range precisely measured with calibrated 280 GHz-solid-state radiation-source are within 1000-4000 V/W and 50 dB, respectively. The broadband calibration of the detectors by means of a tunable backward-wave oscillator showed an acceptable level of their sensitivity up to ~530 GHz.

III. EXPERIMENTAL RESULTS AND DISCUSSION

For standard regimes of REB-plasma heating, a series of radiometric measurements of $2\omega_p$-emission from GOL-3 plasma was carried out. The experiments revealed a significant level of emission during the beam injection with total duration 7-10 μs (Fig. 3-5), which sometimes exceeded saturation level of Shottky-detectors. Retrieved via experiment geometry, a specific power of emission was estimated on the level of ~ 100 W/cm^3 that conforms to theoretical predictions[4]. The radiometric signals disappeared after termination of the REB injection into plasma. It also was at zero-level for the test experiments with REB injection into vacuum. Hence, a cyclotron emission from REB and plasma electrons can be ignored.

The experiments demonstrated a good concordance between the estimated value of the initial plasma density and the maximum of the power spectral density of emission associated with the "$2\omega_p$-process" (Fig. 3, 4). Inspection of the $2\omega_p$-emission polarization via a grid-polarizer mounted at the radiometry system entry showed predominance by a factor of 2-3 for radiation polarized transversely to the magnetic field. We also observed a phenomena of detuning and broadening of the $2\omega_p$-emission spectrum typically 4-5 μs after the beam injection start (Fig. 3). It occurs due to heating-induced modulation of the plasma density as established via Thomson scattering[7].

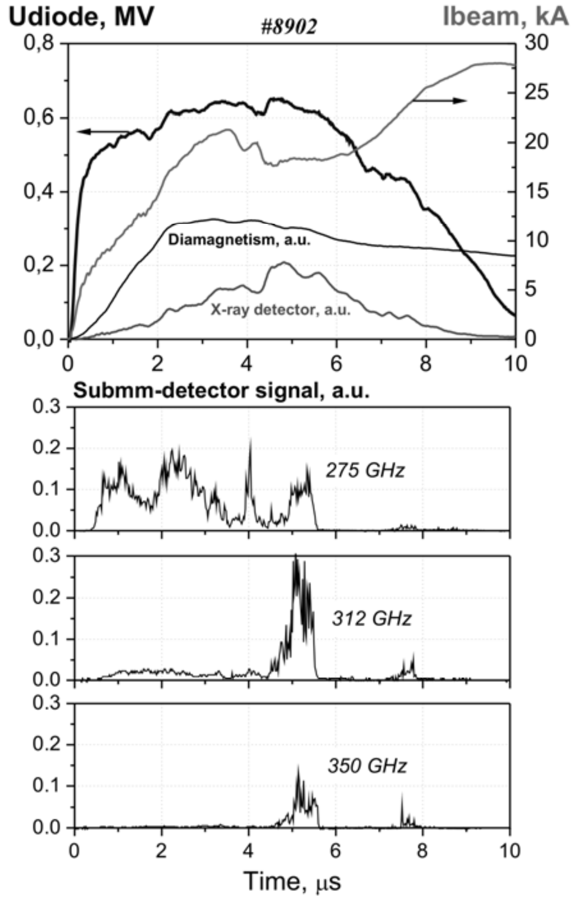

Fig.3. Typical waveforms of the REB-accelerator diode voltage, E-beam current, plasma diamagnetism and X-ray emisson (top), and spectral signals of submm-radiation (bottom) at initial plasma density $n_0 \approx 2.5\cdot10^{14}$ cm^{-3}. A signal at 385 GHz is zero-level and not shown. E-beam diameter in the plasma column is 4 cm.

The performed analysis of submm-signal in time domain revealed the presence of sharp spikes of emission with 2-10 ns duration against the 0.1-1 μs background envelope (Fig. 4, 5). The spikes exhibit fast spectral detuning and are admittedly associated with dynamic density dips (caverns) which emerge at the final stage of Langmuir turbulence. It is noteworthy that the fine temporal structure of the emission was distinctively enhanced for the experiments with decreased E-beam cross-section ∅ 1cm (Fig. 5), as compared to the case of a full-size beam (∅ 4cm, Fig. 4). This fact is associated with a smaller total number of caverns per a beam-plasma-interaction region that results on average in stronger amplitude excursion of submm-signals when caverns dynamically evolve.

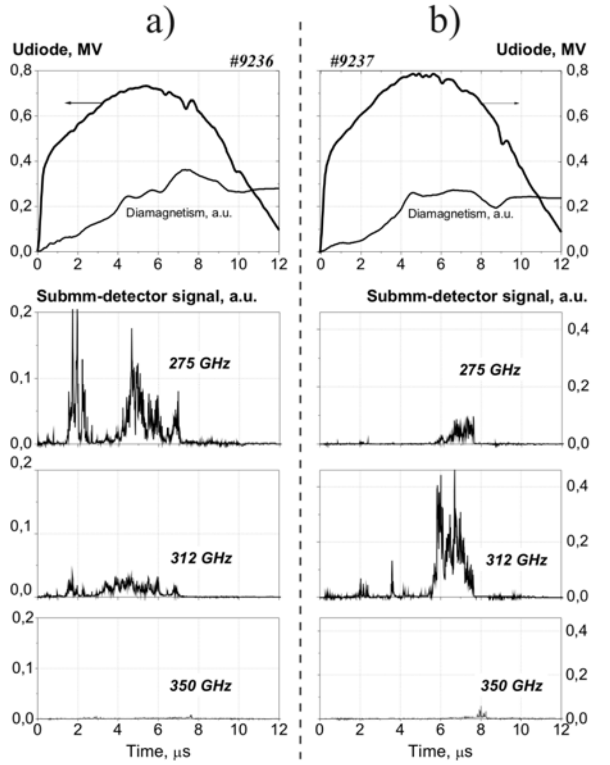

Fig.4. Illustration of the "blue shift" in the submm-emission spectrum due to increasing the initial plasma density: a) $n_0 \approx 2 \cdot 10^{14}$ cm^{-3}; b) $n_0 \approx 4 \cdot 10^{14}$ cm^{-3} (∅ 4cm).

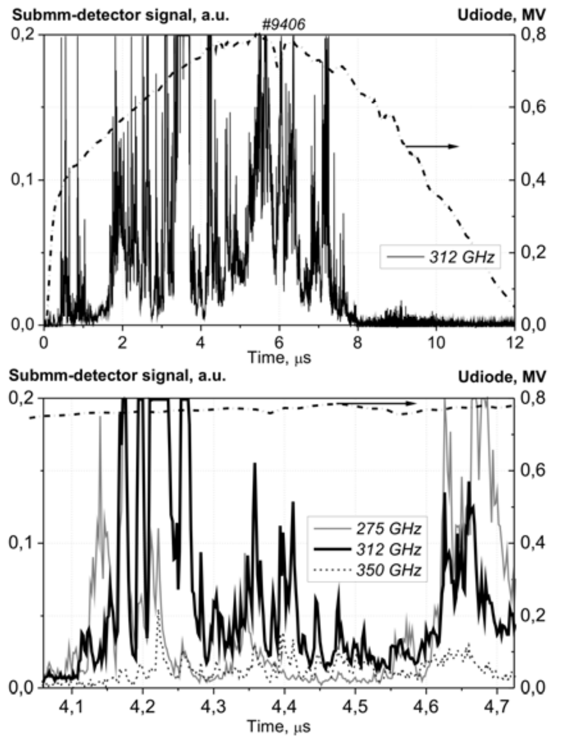

Fig.5. An example of the shot with a fine temporal structure of submm-emission obtained for the case of E-beam with decreased transverse cross-section (∅ 1cm). Top and bottom figures represent different time scales.

III. SUMMARY

In this paper the laboratory investigations of submm-wave emission produced at strong Langmuir turbulence driven by a high-current 10 μs relativistic electron beam were implemented realized for the first time. An original diagnostics was used for measuring power spectral density at frequencies 250-420 GHz. The emission associated with a plasmon-plasmon merging process is confirmed by means of the originally developed multichannel radiometric diagnostics. The experiments revealed a significant level of emission during the major part of beam injection time at a specific emission power value ~ 100 W/cm^3 and the prevailing component of polarization transverse to the magnetic field. Measurements showed presence of slow (0.1-1 μs) and fast (2-10 ns) spectral detuning associated with plasma density modulations.

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