Temporal Structure of ~2ω$_p$ Emission at Plasma Heating by Long-Pulse Electron Beam

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I. INTRODUCTION

Emission of the second and higher harmonics of plasma frequency ω_p from plasmas is a well known phenomenon that accompanies the Langmuir turbulence and beam-plasma interaction [1]. In this work dynamics of spiky microwave emission of a beam-heated plasma near the double plasma frequency in ~100 GHz band was studied. The plasma is heated by 80 keV, ~2 MW, sub-ms electron beam that is injected into the multiple-mirror trap GOL-3 with the typical density $n_e = (2.0\text{-}2.8)\times10^{19}$ m^{-3} in the observation point. In the discussed regime the spectrum was narrow at 94 GHz in the vicinity of the double plasma frequency. The special feature of this regime is small transverse size of the beam-heated plasma that was of the order of the emitted wavelength. Fine temporal structure of the microwave emission was studied. The microwave signal was spiky as before with the "thin" relativistic beam [2]. Details of the temporal behavior of spikes are discussed.

II. EXPERIMENT AND DIAGNOSTICS

The GOL-3 facility included the 12-m-long magnetic system, electron beam injector, and beam dump, see Fig. 1. Typical waveforms for the beam power of 1.7 MW are shown in Fig. 2. After the beam start, there was some transition period when the buildup of plasma occurred. The most part of the beam injection passed at quasi-stationary conditions. The magnetic field in the observation point was 1.24 T ($f_{ce} = \omega_{ce}/2\pi \approx 34.7$ GHz). We had special checks that ruled out cyclotron mechanisms for the radiation observed.

The plasma density was $n_e = (2.0–2.8)\times10^{19}$ m^{-3} with some growth during the shot. The plasma gained 100–150 eV diamagnetic energy per an electron-ion pair whereas the temperature of the bulk Maxwellian electron component was 40–80 eV. Further details of the regime can be found in Ref. 3.

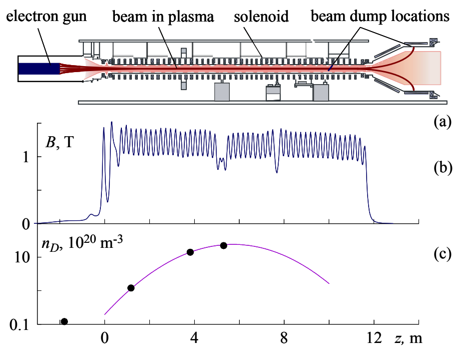

Fig. 1. Layout of the experiment (a). Axial dependencies of the magnetic field (b) and initial gas density (c) are shown.

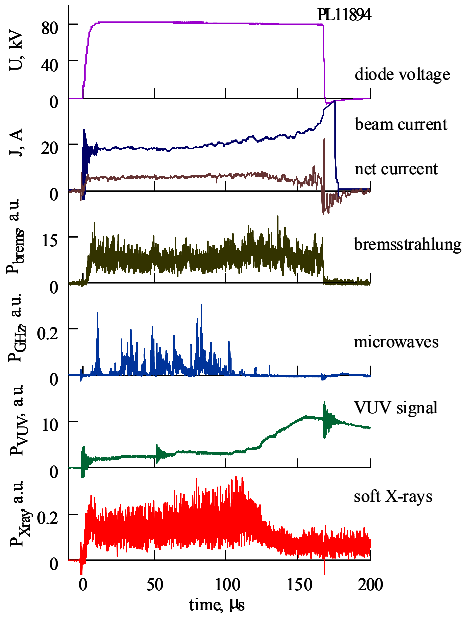

Fig. 2. Typical waveforms for 1.7 MW shot PL11894. The mean magnetic field is <*B*> = 1.24 T.

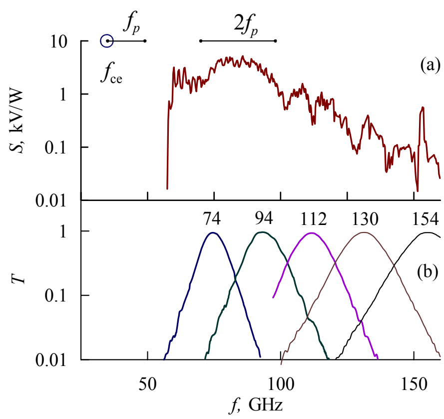

Fig. 3. Spectral sensitivities of single-channel Schottky detectors without selective filters (a) and transmittance curves of some filters (b). Numbers in (b) indicate frequencies of the maximal transmittance in GHz.

The microwave diagnostics consists of several movable detectors and a four-channel quasi-optical polychromator [4]. We controlled radial profiles of local plasma parameters by a Thomson scattering system. The spectral selectivity was provided by high-performance bandpass filters based on isotropic frequency-selective-structures (Fig. 3). Note that the cut-off of the detector sensitivity prevented both the $\omega_{\rm ce}$ and $\omega_{\rm p}$ from detection. In some experiments a 37 GHz detector monitored emission at $\omega_{\rm ce}$ and $\omega_{\rm p}$. Spectral measurements [5] show that in this particular regime most power was emitted near the maximum sensitivity of 94 GHz channel of the polychromator. Amplitudes of the nearby 74 and 112 GHz channels were typically close to values determined by the instrumental contrast.

III. TEMPORAL STRUCTURE OF RADIATION

Figure 4 shows the full waveform of the un-filtered microwave signal and its fragments. It has an irregular spiky nature with 0.3–2 μs bursts and peak-to-valley ratios exceeding 100:1. The beam and plasma parameters are quasi-stationary and change slowly. Some of the bursts of the same shot are smooth with slow variation of radiation intensity (see, e.g. interval at 29 – 31.5 μs), and some are not. Examples of the higher-frequency structures of plasma emission in the same shot are shown in Fig. 5. We observed three modulation types (smooth, chaotic and quasi-periodical) in a typical shot. A train of pulses can have modulation depth above 90%. Intervals between sequential pulses in the train vary in one series or between series in the same shot (see Fig. 6). The total number of modulation pulses can reach ~10^2 whereas the typical sequence is shorter.

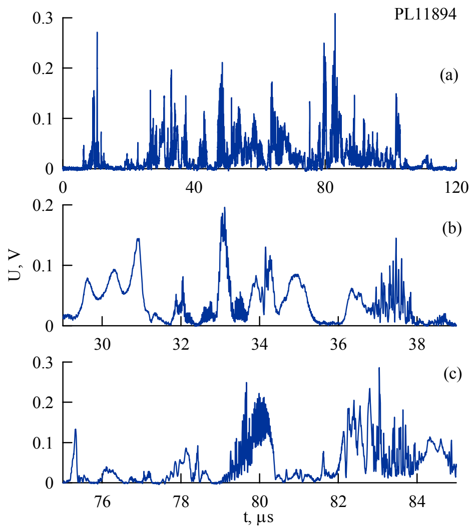

Fig. 4. Fine temporal structure of the microwave emission. Shown are: full microwave signal from the shot PL11894 (a) and its fragments from intervals 29 – 39 μs (b) and 75 – 85 μs (c).

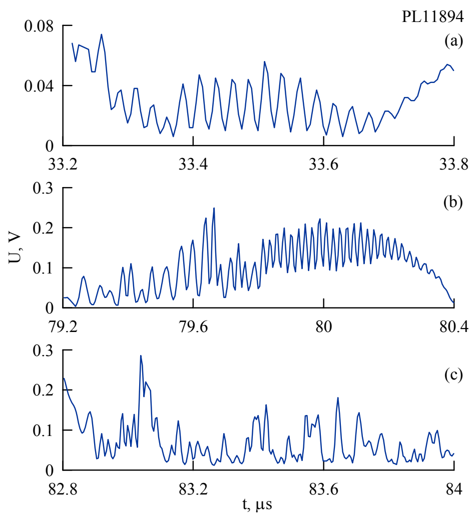

Fig. 5. Modulation of microwave pulses. Fragments of the waveform from the shot PL11894 are shown for 33.2 – 33.8 μs (a), 79.2 – 80.4 μs (b) and 82.8 – 84 μs (c).

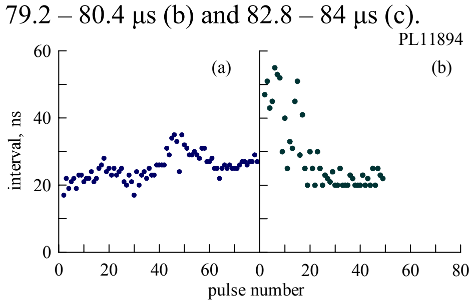

Fig. 6. The time interval between neighboring pulses in the modulation sequence. Part (a) corresponds to the modulation train shown in Fig. 5(a), part (b) is the same for Fig. 5(b). Typical readout errors are ~2 ns.

IV. DISCUSSION

In the discussed experiments, the cross-section of the beam-heated plasma that is of the order of the emitted wavelength. Therefore, one should expect an essential role of surface waves. The wave-induced periodic deformation of an emitting volume could lead to the observed modulation of a radiated spike. The peak-to-peak interval is close to the round-trip Alfvén time for a corrugation cell. In this case, the change of the peak-to-peak interval can probably be attributed to fast change of a length of a wave localization space along the magnetic field. Another explanation of this phenomenon is due to a fast change of local plasma parameters seems to be less probably because of different temporal evolution of modulation of different spikes.

The modulational instability of Langmuir waves can lead to formation of localized cavitons and then to the Langmuir collapse [6,7]. In our case, such cavitons can be the sources of spiky microwave emission. The estimate of characteristic duration of a wave collapse [8] is $\tau_c \sim (1.4\omega_p)^{-1}\sqrt{m_i/m_e}\,(nT/W)$ that gives $\tau_c \sim$ 10-15 ns at the turbulence level $W/nT \sim 0.01$. This time is much shorter than the observed duration of spikes in the discussed regime. This could mean either that the turbulence level W/nT is lower than that used in the estimate and corresponding characteristic wavelength of plasmons is therefore large, or that under these conditions some dissipation mechanisms were active before cavitons reach the stage of collapse. No direct experimental data on the turbulence spectrum in our experiments is available, so other mechanisms that can provide localization of emission zones are probably possible.

The mentioned spiky structure of the microwaves is observed under quasistationary conditions. The typical plasma time scale $\tau = 2\pi/\omega_p$ is five orders of magnitude shorter than the duration of an individual spike. Similar spiky plasma emission at $\sim 2\omega_p$ with millisecond time scales is routinely observed in Type III solar flares (see, e.g., Ref. 9).

V. SUMMARY

The experimental campaign of winter-2012 was done at GOL-3 in a completely new regime with the moderate-power long-pulse electron beam injection in $(2.0 – 2.8)\times10^{19}$ m^{-3} plasma (at the observation point). The beam injection lasts long enough providing quasi-stationarity. The beam current density was sufficient for pumping of the turbulence and generation of 75-200 GHz microwaves. In the discussed regime, the radiation spectrum was narrow at 94 GHz in the vicinity of $2\omega_p$. The special feature of this regime is the small transverse size of the beam-heated plasma. Fine temporal structure of the microwave emission was studied.

The microwave generation continued through the most part of the beam injection phase. The plasma radiated irregularly sequenced spikes of 0.3–2 μs duration. Modulation of individual spikes was observed. In some cases, this modulation was irregular. In other cases, trains of quasiperiodic pulses were observed. Some spikes had slow or no modulation. The modulation depth can reach 90%. Most probable interpretation of observation is that there was a small number of emitting cavitons within the field-of-view of the detector; the modulation can be provided by surface waves that periodically distort the emitting zone. We demonstrated that the spiky microwave emission occurs at steady plasma and beam parameters.

ACKNOWLEDGMENTS

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