Microwave generation in experiments on sub-relativistic electron beam relaxation in magnetized plasmas

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Introduction

Electromagnetic (EM) emission in the electron cyclotron and fundamental plasma frequencies bands is the well-known indicator of an intense electron beam-plasma interaction in space and laboratory plasmas. The frequency spectrum of the emission essentially depends on the spatial spectrum of plasma oscillation driven by the beam. In connection with the physical problem of excitation of the plasma oscillations we investigate the emission spectrum produced by the beam-plasma system in GOL-3 device [1]. These investigations can be of interest from practical point of view. They will give opportunity to create a powerful frequency-tunable source of mm and sub-mm radiation that can be useful for various applications.

The reported results were obtained at the multiple-mirror trap GOL-3 that operated with a sub-relativistic electron beam in a long-pulse configuration [2]. In the experiments, the beam with the following parameters: the electron energy of 70÷100 keV, the beam current of 15÷100 A at the current density of up to 1 kA/cm^2, the pulse duration of up to 300 μs was employed. A plasma column was created by the beam injection in deuterium puffed in the vacuum chamber. The plasma had the density of 10^{18}-10^{20} m^{-3} and the electron temperature of 20÷50 eV. The mean magnetic field was varied in the interval of 0.3÷4 T with corrugation factor 1.5.

MM-wave diagnostics

The microwave emission from the plasma column was studied in the 2÷8 mm band with a special spectrally- and polarization-selective radiometric system that uses a set of high-speed Schottky detectors covered by quasi-optical band pass filters [3].

Microwaves from the plasma are splitted by polarizing splitters into eight beamlets for the corresponding quasi-optical channels, see Fig. 1. Each beamlet passes through the quasi-optical frequency-selective filter and then it is detected by a detection section. The filters replacement in the separate channels is used for spectral tuning the registration systems.The detection section consists of fast Schottky detector with a preamplifier placed in the focal plane of hyperbolic Teflon lens with 70 mm aperture. All signals were digitized at 500 MHz, 12 bits

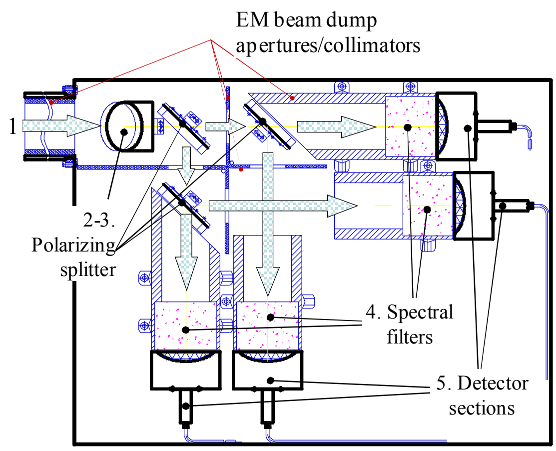

Fig. 1. The layout of eight-channel sub-THz quasi-optical system for spectrum analysing of EM-waves.

Directional pattern of the systems is determined on the level 4° by diffraction on apertures installed on the way of the EM wave flows and by a collimator at the entrance of the detection systems. This configuration enabled interchannel crosstalk up to 10^{-2}. The system is absolutely calibrated in full working diapason by special THz facility with BWO as a source and THz calorimeter.

EM-wave emission from plasma

The main parameters of the plasma and the beam were approximately constant during the EM-wave emission in the experimental shot. The EM-wave emission can last near the whole injection time of the sub-relativistic electron beam. But the temporal profile of the emission has the spiky structure [4, 5]. Examples of the temporal profile of the EM-wave emission for different experimental parameters are shown in fig. 2. These shots primarily differ by the magnetic field strength. To determine the plasma parameters a laser system of Thomson scattering was used. The system measured the plasma density profiles at up to 15 spatial points covering the plasma column diameter twice during in one beam injection shot. The system allowed measuring the plasma electron temperature in one local area in the central part of the column cross section. For the shot PL13578 that was carried out at magnetic field B=2.5 T the plasma had density $n_p=2\cdot10^{12}$ см$^{-3}$ during the EM wave emission, see fig. 2 (left column). For these parameters the fundamental plasma frequency is ν_p=13 GHz and the electron cyclotron frequency is ν_c=69 GHz. For the shot PL13729 (B=1.8 T, ν_c=50GHz) the plasma density varied during the beam pulse, so at t=15μs the density was $n_p=8\cdot10^{12}$ см$^{-3}$ (ν_p=25GHz) and at t=30 μs – $n_p=1.3\cdot10^{13}$ см$^{-3}$ (ν_p=32GHz).

Electron density distribution over the beam cross-section was measured by a soft gamma pin-hole camera which gave bremsstrahlung photograph of the beam dumper surface at exit of the trap with high temporal resolution. The distribution has a Gaussian profile with the width on half maximum of 6 mm at the magnetic field of 1.4 T.

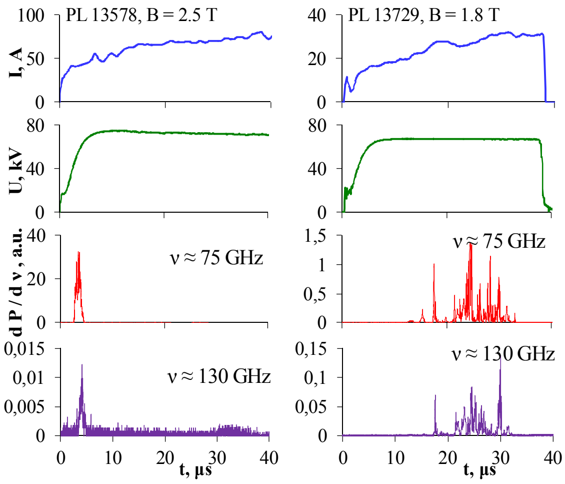

Fig. 2 Plasma shots with different parameters. Two upper diagrams show the parameters of electron beam. Two bottom ones show temporal dependence of EM wave emission in separate bands. The left column corresponds to a shot with confining magnetic field of 2.5 T and larger electron beam current in contrast to right column with magnetic field of 1.8 T.

Discussion

The electron beam drives the plasma waves due to two-stream instability. As results of the high level of plasma oscillation we observe the EM-wave emission in two frequency bands, see fig. 3. The high-frequency (near 120 GHz) band can be explained by nonlinear merging of two upper-hybrid waves into one electromagnetic wave. The first frequency band, at ~75 GHz, is in the vicinity of upper-hybrid of plasma oscillations and we explain it by the direct conversion of the plasma oscillations on strong plasma density gradients.

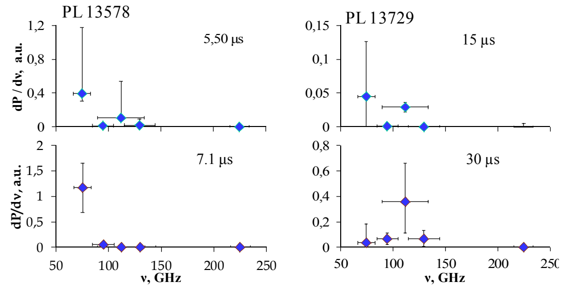

Fig. 3. Sub-THz spectrums of plasma EM-wave emission at the moments of Thomson scattering measurement for different shots corresponding to fig. 2.

These peaks cannot be associated with the harmonics of electron cyclotron oscillation, which, for example, can be emitted by maser mechanism, because their frequency position is not followed the variation of the value of the magnetic field strength (2.5 T in PL13578, 1.8 T in PL13729). Although this mechanism cannot completely be excluded.

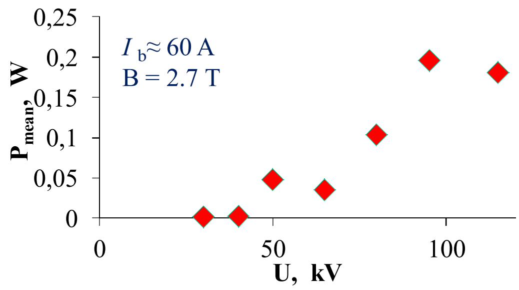

Fig. 4. Dependence of the total sub-THz power recorded within whole frequency band during the beam plasma interaction from voltage of electron beam accelerator.

The increase in the EM-wave emission when the energy of the beam electrons increases, that is demonstrated in fig. 4, can be explained by the dependence of the two-stream instability growth rate on the local beam parameters. The varying of the magnetic field (see fig. 5) affects the power of EM-wave emission through the influence on the growth rate as well. The growth rate in general depends on the ratio of the electron beam density to the plasma density and angular spread of electron beam velocities. So the angular spread increases with accelerating voltage reduction and during electron beam passing to the cross section of the EM-wave detection, about of 1.2 m from the entrance of the plasma.

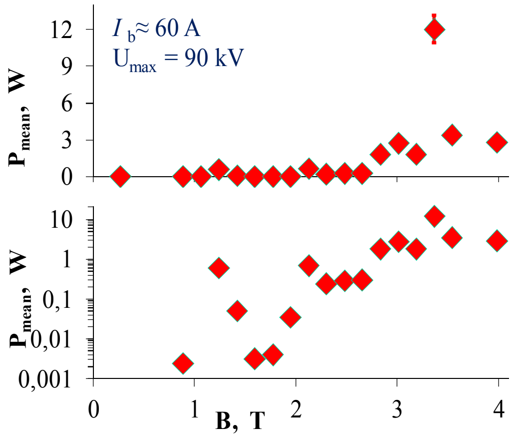

Fig. 5. Dependence of the total sub-THz power in the whole recorded band during the beam-plasma interaction from magnetic field.

In optimal regimes, the emission lasts for the full beam duration and has a quite narrow frequency spectrum. The spatial distribution of the emission and the radiation power depend on the experimental conditions. In particular, at the beam current of ~60 A, accelerating voltage of 90 kV and the magnetic field of 2.7 T the specific power of EM-wave emission from plasma achieves ~200 W/cm^3 (assuming isotropic emission of microwaves). These data agree with previous measurements [6].

Acknowledgments

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