Mechanisms of Enhanced Electromagnetic Emission in Laboratory Beam-Plasma Systems

I.V. Timofeev[1,2,a)], V.V. Annenkov[1,2] and E.P. Volchok[1,2]

[1]*Budker Institute of Nuclear Physics SB RAS, 630090, Novosibirsk, Russia.*
[2]*Novosibirsk State University, 630090, Novosibirsk, Russia.*

[a)]Corresponding author: timofeev@ngs.ru

Abstract. Using analytical theory and particle-in-cell simulations, we study two mechanisms of electromagnetic emission which can result in enhanced radiation of electromagnetic waves near the plasma frequency and its second harmonic in laboratory beam-plasma experiments at the GOL-3T open trap. The first mechanism works in a thin rippled density plasma with the thickness comparable with the radiation wavelength while the second one is based on the linear mode conversion and requires large plasma sizes in comparison with the typical wavelength of plasma oscillations.

INTRODUCTION

It has long been found that collective relaxation of an electron beam in a plasma is always accompanied by electromagnetic emissions near the plasma frequency ω_p and its second harmonic $2\omega_p$. In large-scale turbulent plasmas, efficiency of these emissions is usually very low, since most of the kinetic beam energy goes to excitation of a wide turbulent spectrum and subsequent plasma heating. For many years, the scientific program of the GOL-3 open trap was focused on mechanisms of turbulent plasma heating under the injection of high-power (10 – 20 GW) electron beams. Recently, it has been noticed that the parameters of such a powerful device are well suited for generation of terahertz radiation [1]. Even for the relatively low conversion efficiency 1 – 10%, the power of such a terahertz source could reach the gigawatt level (0.1 – 1 GW). Here, we propose two ideas how to achieve such radiation efficiency in a finite-size beam-plasma system.

The first idea is motivated by recent experiments with a thin electron beam that creates a plasma column with the diameter comparable with the radiation wavelength [2]. The crude estimates have shown that the radiation efficiency reaches the level of 1% in such a regime. To understand why radiation processes become more efficient in a thin plasma, let us consider the simplified problem in which the spectrum of beam-driven plasma waves is dominated by a single mode with the frequency ω and wavenumber $k_\parallel$ propagating along the guiding magnetic field. Such a narrow resonant spectrum is typical to the hydrodynamic regime of the two-stream instability. In this case, the wavenumber of the most unstable mode is determined by the Cherenkov condition $k_\parallel = \omega/v_b$ and its frequency is slightly shifted from the plasma frequency $\omega/\omega_p = 1 - n_b^{1/3}/(2^{4/3}\gamma)$ (here, ω_p is the plasma frequency, n_b is the relative beam density and v_b, γ are the velocity and relativistic factor of beam electrons). Inside a thick plasma, radiation can appear if this dominant potential wave produces the natural electromagnetic plasma modes due to scattering off density perturbations (ω_p-radiation) or nonlinear coupling with secondary quasi-potential waves ($2\omega_p$-radiation). Conditions for these three-wave interactions between plasma eigenmodes restrict sufficiently the phase volume of waves capable to produce radiation. For example, the most probable growth of longitudinal plasma density modulation in our system cannot result in generation of EM waves, since the scattered secondary waves must be also purely potential and their couplings with the primary beam-driven mode cannot produce the second harmonic emission. These processes, however, become possible in a thin beam-plasma system, where the backscattered wave can directly pump vacuum electromagnetic waves or can excite them via frontal coalescence with the primary mode, since the fields of these vacuum waves can penetrate into the plasma as forced oscillations. The only condition that should be satisfied for these processes is that the backscattered wave should have the superluminal phase velocity in order to get in resonance with these oscillations. In fact, a thin plasma column in which the beam can excite superluminal waves of electric current radiates EM waves as an ordinary antenna, that is why we refer this mechanism as a beam-plasma antenna. Since pumping of EM radiation due to this mechanism is localized inside the skin layers, the most efficient regime of emission is achieved when the plasma transverse size is comparable to the typical skin-depth. To check if this emission mechanism is able to provide high efficiency, we simulate the injection of an electron beam into a magnetized plasma using a 2D3V particle-in-cell code and propose an analytical theory predicting how the radiation power depends on different antenna parameters.

The second idea how to enhance radiation from the gigawatt beam-plasma system at the GOL-3T facility is to create large-scale gradients of plasma density which could transform the most unstable beam-driven waves to electromagnetic ones via the linear mode conversion. In fact, we consider the process that is inverse to the O-SX conversion used to heat the plasma by microwaves in tokamaks. Using the exact kinetic theory for the instability of a hot electron beam in a hot magnetized plasma, we find the most unstable mode in our beam-plasma system and calculate orientation of the density gradient to the magnetic field required for the complete conversion of this dominant plasma mode to electromagnetic radiation.

BEAM-PLASMA ANTENNA

Let us consider electromagnetic radiations produced by the injection of the electron beam into the magnetized plasma with the previously modulated density $n_i = n_0 + \delta n \cos(qx)$. If in the plane plasma layer with the thickness $2l$ the beam excites the longitudinal wave with the frequency ω and wavenumber $k_\parallel = \omega/v_b$, the scattering of this wave on the density perturbation with the number q produces forced plasma oscillations with $(\omega, k_\parallel - q)$. Such oscillations can have superluminal phase velocities and are able to get in resonance with vacuum electromagnetic waves traveling obliquely to the plasma layer. This resonant interaction becomes possible only if the period of plasma density modulation does not much differ from the wavelength of the beam-driven wave ($1 - v_b < q/k_\parallel < 1 + v_b$) (here, the beam velocity is measured in the speed of light c). The ratio between q and $k_\parallel$ inside this range fixes the unique radiation angle $\tan\theta = \sqrt{v_b^2 - (1 - q/k_\parallel)^2}/(1 - q/k_\parallel)$ [3]. In the particular case $q = k_\parallel$, radiation emerges from the plasma in the purely transverse direction and is polarized along the ambient magnetic field ($\mathbf{E}\|\mathbf{B}_0$). Since in the hydrodynamic regime of the beam-plasma instability the frequency of the dominant wave ω is less than the plasma frequency, the produced radiation can effectively interact with plasma currents only at the skin-depth. The total time-averaged power of EM emission in the realistic problem of beam injection is given by the expression [4, 5]

$$\frac{P_{rad}}{P_b} = \frac{\delta n^2 F(l)}{8(\gamma - 1) n_b v_b \sqrt{1 - \omega^2}} \int\limits_0^L E_0^2(x) dx, \tag{1}$$

where the factor

$$F(l) = \frac{\sinh^2(\varkappa l)}{\varkappa l \left[\omega^2 + \sinh^2(\varkappa l)\right]} \tag{2}$$

describes how this power depends on the plasma half-width l, $\varkappa = \sqrt{1 - \omega^2}$ defines the reciprocal skin depth, P_b — the power of the injected beam, $E_0(x)$ — the amplitude of the dominant beam-driven mode as a slowly varying function of the longitudinal coordinate x, and L — the length of radiating plasma region (here, all number densities are measured in units of n_0, frequencies in ω_p, scale lengths in c/ω_p, fields in $m_e c \omega_p / e$). The order of magnitude estimation for the integral in (1) gives the result: $\int \sim E_0^2 L$, where we assume that the amplitude of the dominant unstable wave is saturated at the level of beam trapping $E_0 \sim \gamma^3 \Gamma^2 v_b$ (Γ is the instability growth rate) and the radiating zone is limited by the typical length of the coherent wave packet $L \sim 3 v_b/\Gamma$ in which this trapping occurs.

These theoretical estimates are well confirmed by PIC simulations. To compare theoretical and numerical results, we chose the following parameters: $n_b = 0.02$, $v_b = 0.9$, $\delta n = 0.2$, $2l = 6.4$, $q = k_\parallel$. Figure 1 shows that the observed radiation is really directed across the plasma, localized near the injector and dominated by the O-polarization. The power of this radiation (after some transition processes) converges to the theoretical prediction (1) and constitutes the significant part of the total beam power ($5 - 10\%$). For the realistic cylindrical geometry of a plasma column, this theory is generalized in [4].

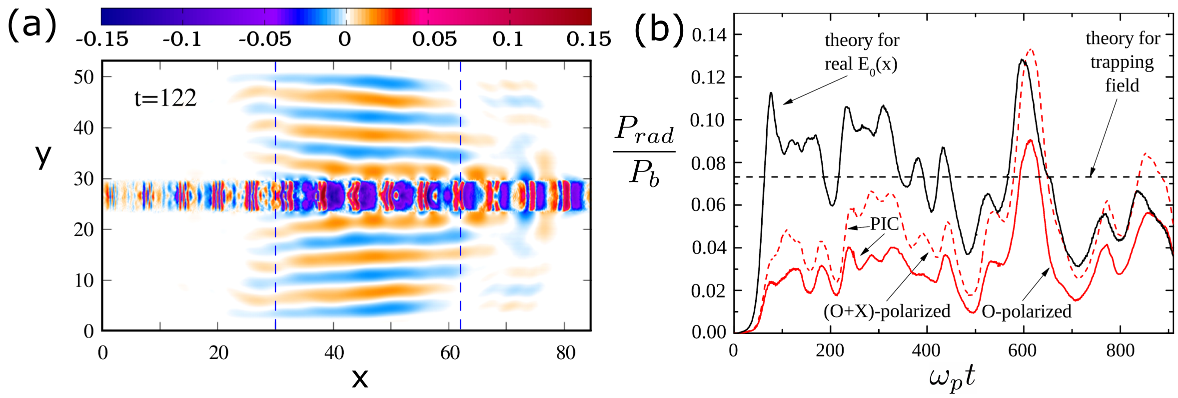

FIGURE 1. Simulation results: (a) the map of electric field E_x in the moment $\omega_p t = 122$; (b) the history of radiation efficiency in PIC simulations (red lines), in the theory (1) for real profiles $E_0(x)$ (black solid line) and in the theory for the uniform $E_0 = \gamma^3 \Gamma^2 v_b$ (black dashed line).

Thus, to generate radiation with the high efficiency, we need to create a small-scale longitudinal density modulation. Simulations [5] show that such a periodic perturbation of plasma density with the appropriate length appears self-consistently even in an initially homogeneous plasma due to the modulational instability of the dominant beam-driven mode. One more problem arising in the terahertz range for such a generating scheme is a small optimal transverse plasma size which should be comparable with the radiation wavelength. The more general theory for the oblique antenna emission [6] shows that, at certain angles, plasma can be transparent for generated waves and the whole plasma volume can be involved in their radiation. In this case, generation of EM waves remains efficient even in a relatively thick plasma when its diameter is an order of magnitude larger than the radiation wavelength.

SX-O CONVERSION

It is well known that electromagnetic waves launching in a nonuniform magnetized plasma as the ordinary modes (O mode) can be linearly converted at the critical surface ($\omega = \omega_p$) into the slow extraordinary modes (SX modes). This process is widely used to input the microwave energy into a plasma in different schemes of electron cyclotron heating. In Ref. [7] it was noticed that the inverse conversion process can be responsible for emission of electromagnetic waves from a turbulent plasma. If the turbulence is excited by an electron beam, the significant part of wave energy is usually concentrated in a very narrow spectral region near the wavevector of the most unstable resonant wave. Our idea is to create specifically oriented gradients of plasma density which will provide optimal conditions for the linear conversion of these most energetic beam-driven waves.

Let us consider a plane plasma slab in which the density gradient $\nabla n_i = (\nabla_\perp n_i, 0, \nabla_\parallel n_i)$ is directed at the angle χ to the uniform magnetic field $\mathbf{B} = (0, 0, B)$. In order to study how the wave with the fixed frequency ω and initial wavenumber $\mathbf{k} = (k_\perp, 0, k_\parallel)$ propagates through this nonuniform plasma, it is convenient to rotate the coordinate system in the (x, z)-plane in such a way as to align one of its axes with the density gradient ∇n_i. In the new system of coordinates (ζ, ξ), the transverse to ∇n_i component of refractive index is conserved, $N_\zeta = N_\parallel \sin\chi - N_\perp \cos\chi =$ const, where $N_{\perp,\parallel} = k_{\perp,\parallel} c/\omega$, c is the speed of light. If the wavelength is much smaller than the scale of plasma inhomogeneity, evolution of the longitudinal refractive index N_ξ can be found from the solution of the local dispersion equation $D(\omega, N_\zeta, N_\xi, \xi) = 0$. In the cold weakly magnetized plasma, when the electron cyclotron frequency Ω_e does not exceed the plasma frequency ω_p, the characteristic forms of dispersion curves $N_\xi(n_i(\xi))$ for different orientations of density gradient are shown in Fig. 2. It is seen that O and SX modes can intersect with each other only at the single value of χ

$$\chi_c = \arctan\left(\frac{N_\perp}{N_\parallel - \sqrt{\Omega_e/(\omega + \Omega_e)}}\right). \tag{3}$$

In this case (Fig. 2b) the resonant beam-driven SX wave that is indicated in the figure by the red square either propagates towards the low density region and reaches the upper-hybrid resonance, or is reflected from the denser region and then is completely converted into the O mode that can escape from the plasma. If the angle χ is significantly lower

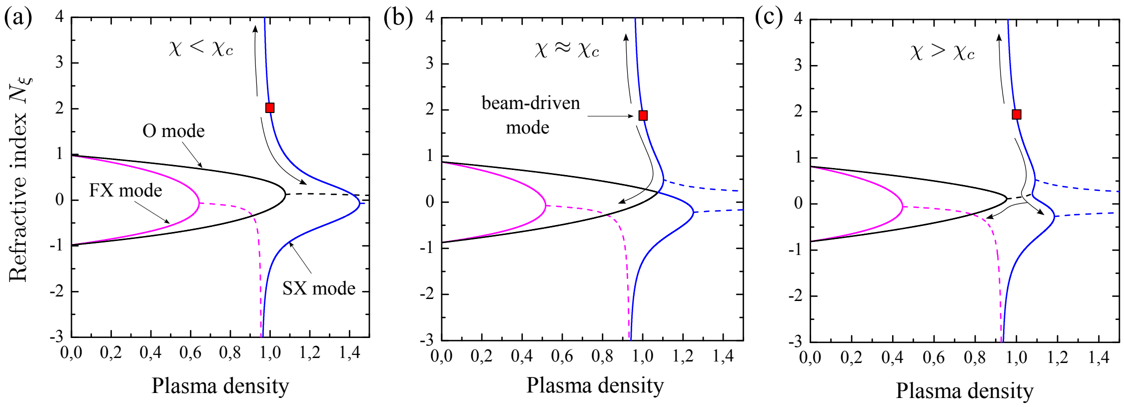

FIGURE 2. The refractive index N_ξ as a function of plasma density $n_i(\xi)/n_0$ for those plasma oscillations, which have the same frequency $\omega = 1.038\ \omega_p$ and refractive index N_ζ as the most unstable beam-driven mode starting from the point $n_i = n_0$ (Ω_e/ω_p = 0.4). Three cases with different orientations of ∇n_i are presented: (a) $\chi = 1 < \chi_c$, (b) $\chi = 1.15 \approx \chi_c$ and (c) $\chi = 1.2 > \chi_c$.

than χ_c (Fig. 2a), the SX mode has no any reflection points near the critical surface and is not coupled with the O mode even by complex decaying solutions (dashed lines). It means that the linear mode conversion becomes impossible in this case. In the opposite situation $\chi > \chi_c$, the beam-driven wave reflected from the denser region is still able to be converted into the O-mode, but the conversion efficiency strongly reduces with the increase of χ due to the need of wave tunneling through the evanescent region lying near the critical surface (Fig. 2c).

Let us find out what orientation of the density gradient provides the optimal conditions for the conversion of most unstable beam-driven waves to EM radiation. If we describe the monoenergetic relativistic beam (v_b/c = 0.93) with the typical angular spread $\Delta\theta = 0.1$ and the relative density $n_b/n_p = 0.01$ by the shifted Maxwellian distribution with the anisitropic temperature ($T_\perp$ = 12 keV and $T_\parallel$ = 25 eV), the maximal growth rate in the magnetized plasma with $\Omega_e/\omega_p = 0.4$ is achieved for the oblique modes driven by the anomalous Doppler effect ($N_\parallel = c/v_b\,(1 + \Omega_e/\gamma\omega)$, $k_\perp = 1.62\ \omega_p/c$). For the resonant wave with the frequency $\omega/\omega_p = 1.038$ starting from the point with the density $n_0 = 2 \cdot 10^{14}$ cm^{-3}, the possible orientations of the density gradient with the characteristic length $L = 2$ cm occupy the range $\chi = 66^0 \pm 1.7^0$.

Thus, in order to convert the part of the energy of beam-driven modes to electromagnetic radiation, near the point of the most intense beam-plasma interaction it is necessary to create the region of increasing plasma density with the gradient directed at the angle χ_c to the magnetic field. The most unstable waves propagating in the plane $(\nabla n_i, \mathbf{B})$ should be reflected from this region and then transformed to the O mode which, in the case of moving to the low density region, can escape from the plasma as an electromagnetic wave.

ACKNOWLEDGMENTS

This work is supported by the Russian Scientific Foundation (project 14-12-00610).

REFERENCES

[1] A. Arzhannikov and I. Timofeev, Plasma Physics and Controlled Fusion **54**, p. 105004 (2012).
[2] A. Burdakov, A. Arzhannikov, V. Burmasov, I. Ivanov, M. Ivantsivsky, I. Kandaurov, S. Kuznetsov, V. Kurkuchekov, K. Mekler, S. Polosatkin, S. Popov, V. Postupaev, A. Rovenskikh, V. Sklyarov, M. Thumm, Y. Trunev, and L. Vyacheslavov, Fusion Science and Technology **63 (1T)**, p. 286 (2013).
[3] I. Timofeev, V. Annenkov, and A. Arzhannikov, Physics of Plasmas **22**, p. 113109 (2015).
[4] V. Annenkov, E. Volchok, and I. Timofeev, Plasma Physics and Controlled Fusion **58**, p. 045009 (2016).
[5] V. Annenkov, I. Timofeev, and E. Volchok, Physics of Plasmas **23**, p. 053101 (2016).
[6] E. Volchok, I. Timofeev, and V. Annenkov, "Theory of electromagnetic wave generation via a beam-plasma antenna," in *11th International Conference on Open Magnetic System for Plasma Confinement* (2016).
[7] A. Timofeev, Plasma Phys. Reports **29**, p. 683 (2003).