Linear conversion of upper-hybrid to electromagnetic waves as a mechanism of sub-THz emission in laboratory REB-plasma experiments

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***Abstract*—We study the linear mode conversion between upper-hybrid and electromagnetic waves as a possible mechanism of sub-Thz emissions produced in laboratory magnetized plasmas penetrated by relativistic electron beams.**

I. INTRODUCTION AND BACKGROUND

IN laboratory REB-plasma experiments it was found that the most energetic electromagnetic (EM) emissions are basically concentrated near the plasma frequency ω_{pe} and its second harmonic [1]. Theoretical analysis showed that the second harmonic emission can be interpreted as a result of coalescence processes between the upper-hybrid (UH) waves generated in the long-wavelength part of the beam-driven strong plasma turbulence [2]. The fundamental emission in this scenario is associated with the conversion of these waves on randomly distributed density perturbations. Such a turbulent regime, however, is accompanied by strong plasma heating and is not best suited for generation of EM waves. In order to increase the radiation efficiency, one should create the conditions for the direct energy transfer between the beam-driven and EM modes. In the present work we propose to create specifically oriented regular gradients of plasma density, which can result in the linear mode conversion of the dominant beam-excited waves.

II. RESULTS

A. Large scale plasmas

We consider the case when the density gradient in a cold plasma is directed obliquely (angle χ) to the uniform magnetic field. The spatial scale of inhomogeneity is assumed to be large compared to the typical wavelength and allows to use the WKB approximation. The beam drives UH waves with the fixed longitudinal refractive index $N_\parallel = c/v_b$, where v_b is the beam velocity and c is the speed of light. These waves occupy the spectral range from ω_{pe} to $\sqrt{\omega_{pe}^2 + \Omega_e^2}$, and each frequency position is corresponded with its own propagation angle θ. For the typical plasma density $n = 5 \cdot 10^{14}$ cm^{-3}, magnetic field $B = 4.5$ T and beam velocity $v_b = 0.9\ c$, the wave frequency is always larger than the electron cyclotron frequency Ω_e. For each resonant wave in this case we can find the angle

$$\chi = \arctan\left(\frac{N_\perp}{N_\parallel - \sqrt{\Omega_e/(\Omega_e+\omega)}}\right), \qquad (1)$$

at which the dispersion curves of UH and ordinary EM waves are coupled [3]. If the dominant mode has the frequency $\omega = 1.01$, its propagation in the nonuniform plasma is described by the dispersion $N_\xi(n)$ shown in Fig. 1. It is seen that the conversion of this wave to the EM mode at the critical surface becomes possible only after its reflection from the higher-density region. Propagation to lower plasma densities results in the absorption of wave energy near the UH resonance.

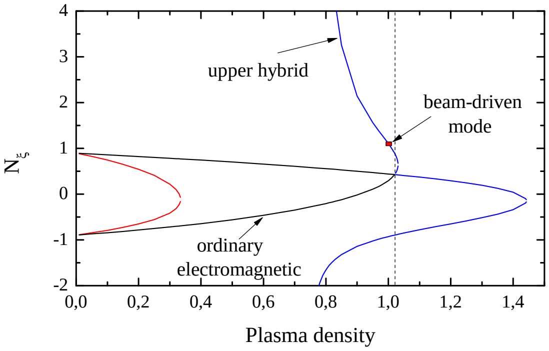

Fig. 1. The refractive index $N_\xi = N_\parallel \cos\chi + N_\perp \sin\chi$ as a function of plasma density for the case $\omega = 1.01$.

Thus, in order to convert efficiently beam-driven UH waves to EM radiation near the plasma frequency one should find the propagation angle θ for the most unstable mode in the beam-plasma system and then create the region of increasing plasma density with the gradient directed at the angle $\chi(\theta)$ to the magnetic field. Reflected waves propagating toward the region of lower density are able to escape the plasma as electromagnetic ones.

B. Small scale plasmas

When typical scales of plasma inhomogeneities become comparable with wavelengths of plasma oscillations, the WKB approximation is no longer valid and we have to use 2D3V particles-in-cells simulations. Since we are interested in diagnostics of those EM waves that can emerge from the plasma, the plasma in our simulation box is restricted in the transverse to the magnetic field direction and separated from

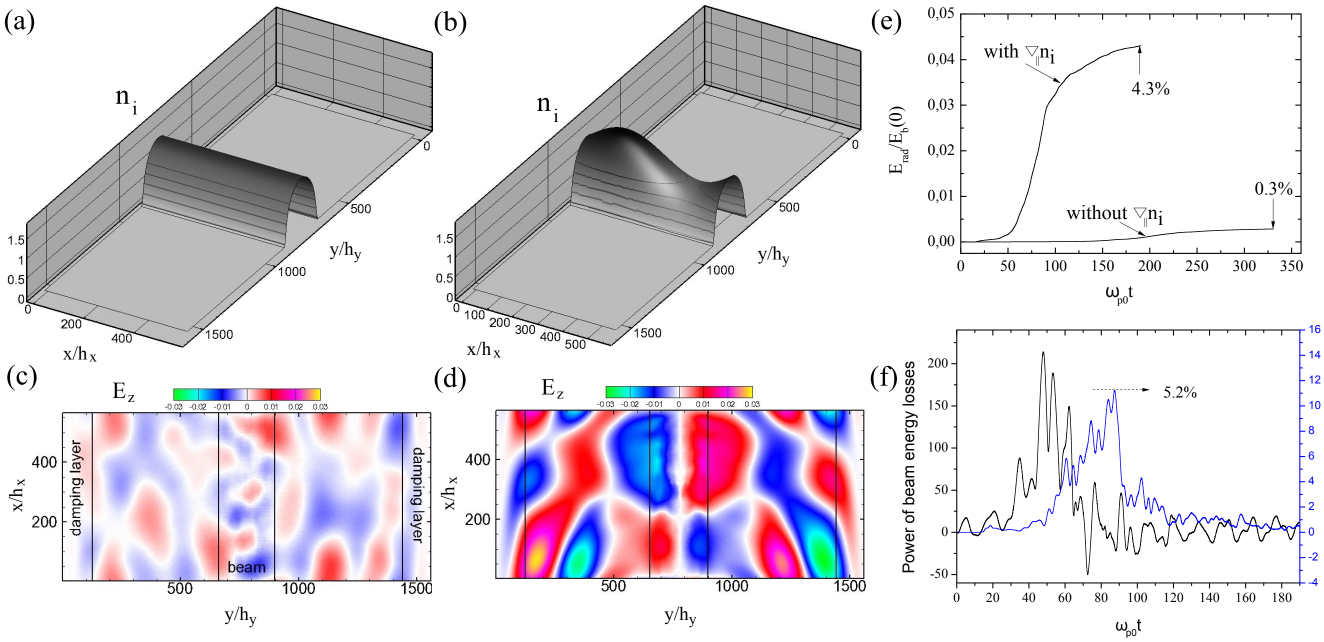

Fig. 2. (a)-(b) Initial density profiles of plasma ions $n_i(x, y)$ with and without $\nabla_{\|} n_i$. (c)-(d) The corresponding maps of electric field E_z in the moments of intense radiation. (e) The part of the total kinetic beam energy converted to EM waves and absorbed in damping layers in two different cases. (f) The histories of pumping and radiation powers.

the boundaries by the vacuum gaps. To prevent accumulation of EM waves in the system we construct the damping layers absorbing the radiation energy. Periodic boundary conditions are used along the magnetic field.

In such a closed system with the fixed energy content, the beam-plasma instability is excited during a short period of time and then saturated by beam trapping. Thus, in our simulations we can observe only a short pulse of pumping power that is followed by a similar pulse of radiation power (see Fig.2(f)). Comparison between the maximal pump power and the maximal radiation power indicates how efficiently EM radiation is generated in a beam-plasma system.

Simulations are performed for the parameters that can be achieved in the laboratory beam-plasma experiments [1]: the magnetic field is determined by the ratio $\Omega_e/\omega_{p0} = 0.6$, the drift velocity of beam electrons reaches the value $v_b = 0.9c$, the beam has the same density profile as ions $n_b/n_i = 0.05$, beam and plasma electrons have Maxwellian distributions with the temperatures $T_b = 10$ keV and $T_e = 80$ eV. The simulation box has the sizes $L_x \times L_y = 566h_x \times 1560h_y$ with the mesh $h_x = h_y = 0.02\ c/\omega_{p0}$ and 100 particles per cell.

Let us consider two different cases when the initial plasma density changes only in the transverse direction $\nabla n_i \perp \mathbf{B}$ (Fig.2(a)) and when the density gradient has a finite parallel component $\nabla_{\|} n_i \neq 0$ (Fig.2(b)). Fig. 2(c) and 2(d) show how the electric field E_z is distributed in the (x, y) space in the moments of the most intense radiation. It is seen that EM waves in vacuum regions are much more energetic in the case of mixed longitudinal and transverse inhomogeneities. It is quantitatively confirmed by Fig. 2(e), in which the radiation energy $E_{rad}(t)$ absorbed in the damping layers is shown as a part of initial beam kinetic energy $E_b(0)$. It is seen that, in the plasma with the parallel density gradient, about 4% of beam energy is converted to EM waves, which is 14 times higher than in the case of purely transverse inhomogeneity. Fig. 2(f) shows that the peak EM emission power in the regime with the finite $\nabla_{\|} n_i$ can reach 5% of the maximal power pumping by the beam in plasma oscillations. The most part of radiation energy in this case is concentrated near the typical frequency of beam-driven modes that is close to $0.9\,\omega_{p0}$.

III. CONCLUSION

It has been shown that the linear conversion of beam-driven UH modes to EM waves on the specifically oriented density gradients can be used in laboratory beam-plasma experiments for the generation of powerful sub-Thz and Thz radiation. Simulations of EM emission in small-scale plasmas have shown that the radiation power can reach 5% of the total power pumping by the beam into a plasma.

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REFERENCES

[1] A. V. Arzhannikov, A. V. Burdakov, S. A. Kuznetsov et al., “Subterahertz Emission at Strong REB-Plasma Interaction in Multimirror Trap GOL-3”, Fusion Sci. Technol., 59(1T), 74-77, 2011.

[2] I. V. Timofeev, “Second harmonic electromagnetic emission of a turbulent magnetized plasma driven by a powerful electron beam”, Phys. Plasmas 19, 044501, 2012.

[3] A. V. Timofeev, “Evolution of the electron Langmuir oscillations in an inhomogeneous magnetized plasma”, Plasma Phys. Rep. 29, 683, 2003.