Efficient electromagnetic emission from plasma with continuously injected counterstreaming electron beams

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Intoduction

Mechanisms of electromagnetic (EM) emission in plasma with electron beams have long been considered in the context of both astrophysical problems as well as laboratory experiments. One of suggested mechanisms is a three wave coupling process $\mathbf{k}_1^l + \mathbf{k}_2^l \to \mathbf{k}_3^t$ of two Langmuir waves with a frequency ω_p into EM radiation at the second harmonic of the plasma frequency. In the case of one electron beam propagating in plasma, such a process becomes possible only due to the interaction of a dominant beam mode and a backward propagating Langmuir wave driven by some nonlinear processes. Such a case is not quite efficient because most of the beam energy is spent on the excitation of turbulence and plasma heating. The enhancement of EM emission can be achieved in systems with counterpropagating beams when directly involved in the three-wave process are the most intense beam-driven plasma waves.

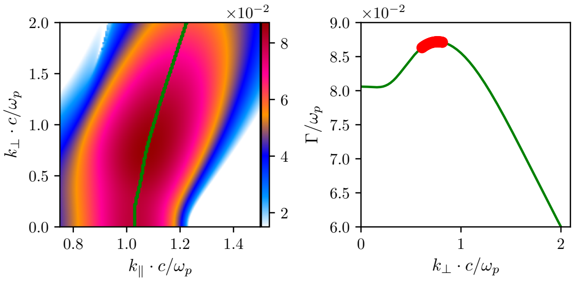

Figure 1: *The increment of two-stream instability for one beam with parametrs presented in Table 1. Left: growth rate map* $\Gamma\left(k_\parallel, k_\perp\right)$ *, green line* $k_\perp = k_\perp(k_\parallel)$ *corresponds to the maximum value. Right:* $\Gamma(k_\perp)$ *is on the line of the maximum (red points indicates the region of the three-wave interaction).*

For relativistic beams ($v_b \approx c$), the most unstable oscillations are oblique ones. This allows one to generate EM emission by plasma waves with maximal spectral energy density. It has been found [2] that using the exact kinetic theory for the instability of an electron beam in a hot magnetized plasma [1] it is possible to find the regime when an absolute maximum of the increment is in the area of the three-wave interaction (Fig. 1):

$$\left|\omega\left(k_\parallel, k_\perp\right) - \sqrt{k_\perp^2 + \frac{1}{4}}\right| \leqslant \Gamma\left(k_\parallel, k_\perp\right), \quad (1)$$

where $\omega\left(k_\parallel, k_\perp\right)$ is a wave frequency, $k_\parallel$ – a component of the wave number of plasma oscillations codirected with the axis of beams propagation, $k_\perp$ – a transverse component, $\Gamma\left(k_\parallel, k_\perp\right)$

– the growth rate of the beam-plasma instability. Using particle-in-cell (PIC) simulation in the model of infinite plasma (periodic boundary conditions) it has been shown that EM emission is efficiently generated even on a linear stage of beam-plasma interaction in this regime [2].

In the model with periodic boundary conditions, beam particles have a limited amount of energy. Thus this model allows one to study only the linear stage of beam-plasma interaction until the stage of beam trapping. A more realistic model is a model with open boundary conditions and continuously injected beam particles [3, 4]. The purpose of this work is to verify the possibility of efficient generation of EM radiation due to the three-wave interaction of oblique plasma waves driven by two counterpropagating beams continuously injected into plasma.

Results

In this work, we use our own parallel 2D3V particle-in-cell code for Cartesian geometry implemented on NVIDIA GPGPU. In our code, Maxwell's equations for EM fields are solved by the standard FDTD scheme of Yee. To calculate dynamics and currents of finite-size macro-particles with the parabolic form-factor we use the algorithm of Boris and the charge conserving density decomposition scheme of Esirkepov. A detailed description of open boundary conditions can be found in [4]. The computational domain consists of a plasma column with a length of $L_x = 52.8\ c/\omega_p$ and a width of $d_p = 32\ c/\omega_p$ separated in the transverse direction from boundaries by vacuum layers. Placed near all borders of the simulation box are damping layers for EM radiation. Electron beams with a width of $d_b = d_p$ are injected through the ends of the plasma column. The entire system is located in an external magnetic field B_x the value of which we characterize by the ratio of the electron cyclotron frequency to the plasma frequency $\Omega_e/\omega_p = 0.2$.

Parameter	run 1	run 2
n_b/n_0	0.05	
v_b/c	0.9428	
$T^{(e)}$	80 eV	
$T_\perp^{(beam)}$	64 keV	
$T_\parallel^{(beam)}$	64 keV	
Ω_e/ω_p	0.2	
Beam edge	sharp	smooth
L_x	$52.8\ c/\omega_p$	
$d_b = d_p$	$32\ c/\omega_p$	

Table 1: *System parameters.*

Given in Table 1 are parameters of all numerical calculations carried out in this work. Electron beams are considered to have an anisotropic Maxwell distribution:

$$f^{(b)}(p_x, p_y, p_z) \sim \exp\left(\frac{-p_z^2}{\Delta p_z^2} - \frac{p_y^2}{\Delta p_y^2} - \frac{(p_x - p_b)^2}{\Delta p_x^2}\right), \tag{2}$$

where p_b is a directed beam momentum, $\Delta p_y = \Delta p_z = \Delta p_\perp$, $\Delta p_x = \Delta p_\parallel$, temperature is defined as $T = \Delta p^2/(2m_e)$, where m_e – electron mass. The electron plasma temperature is assumed to be isotropic and equal to $T^{(e)} = 80$ eV. Ions are considered fixed.

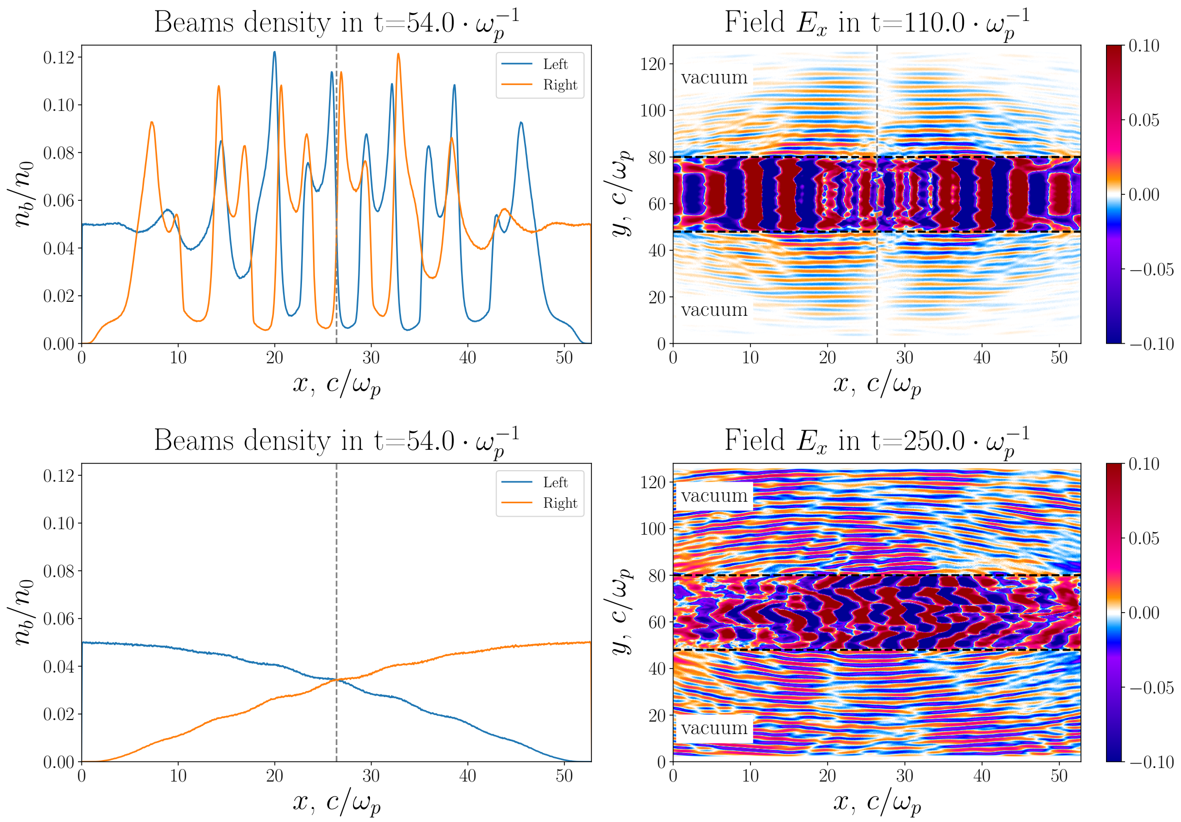

Figure 2: *Results of PIC simulations for run 1 (top) and run 2 (bottom). Left: averaged in transverse direction density of beams. Right: longitudinal electric field E_x in units $m_e c \omega_p / e$. The gray line indicates the middle of the system.*

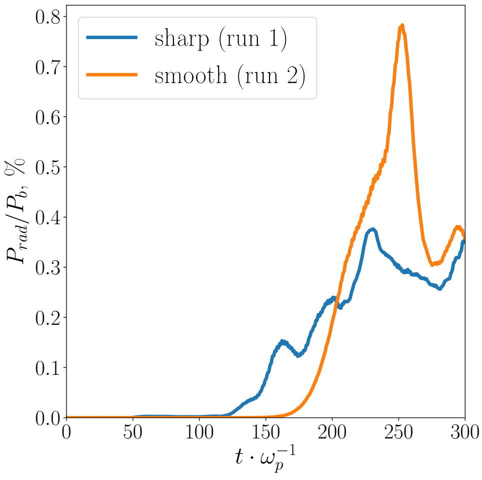

Figure 3: *The radiation power in units of the total injected beams power.*

Figure 2 (top) shows simulations results for the problem of two counterpropagating beams with parameters have been found in [2] and a sharp front (run 1). The linear theory predicts domination of oblique oscillations (Fig. [1]) in this regime. However, it has been found that such a beam profile creates a seed for buildup of longitudinal waves and significantly changes the dispersion of oscillations excited in the plasma. In this case, radiation is observed near the doubled plasma frequency due to the interaction of counterpropagating plasma waves with different transverse structures. The nonlinear interaction of these waves results in excitation of the longitudinal electric current which oscillates at the doubled plasma frequency and has a longitudinal wavenumber equal to $k_{\parallel}^{(3)} = k_{\parallel}^{(1)} - k_{\parallel}^{(2)}$. This current is able to radiate electromagnetic waves transversely to the propagation axis [4].

The effect of a sharp beam front can be suppressed by the smooth rise of the beam current over time. Usually, such a regime is realized experimentally during the generation of long electron beams. Figure 2 (bottom) demonstrates the simulation results of colliding beams, whose density increases from 0 to n_b during the time $\tau = 50 \cdot \omega_p^{-1}$. One can see intense EM emission at the doubled plasma frequency as well as radiation at higher harmonics, which is generated due to nonlinear processes. So, the three-wave process of EM emission can be studied more thoroughly in the case of beams with lower relative density which build-up less nonlinear plasma waves.

Figure 3 shows the efficiency of beams power conversion into EM emission as a function of time for both regimes considered in this paper. For a regime with a smooth beam front, the efficiency reaches the level of 0.8%. In these simulations, plasma ions were considered immobile and did not affect to the dynamics of the beam-plasma interaction and the generation of radiation. Due to the relatively high density of the beams ($n_b = 0.05 n_p$), the ion dynamics will be significant at the limiting times of these calculations ($300 \cdot \omega_p^{-1}$) and will induce the formation of longitudinal density modulation. This modulation can lead to a partial breakdown of the beam-plasma interaction, but it is also able to cause the generation of radiation by the mechanism of the beam-plasma antenna[5].

Conclusion

In this work, we show that derived from exact linear theory regime of beam-plasma interaction, in which the most unstable beam-driven plasma oscillations fall into the region of three-wave interaction, is also realized in plasma with continuously injected beams. We also observe a significant influence of the beam front on the spectrum of oscillations excited in the plasma.

Simulations were performed using the computing resources of the Center for Scientific IT-services ICT SB RAS (https://sits.ict.sc)"

This work is supported by Russian Foundation of Basic Research (grant No18-32-00107) and the Russian Science Foundation (grant No19-12-00250).

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