Powerful electromagnetic emission from a plasma with counterstreaming different-size electron beams

V.V. Annenkov[1,2], I.V. Timofeev[1,2], E.A. Berendeev[3], E.P. Volchok[1]

[1] *Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia*

[2] *Novosibirsk State University, Novosibirsk, Russia*

[3] *Institute of Computational Mathematics and Mathematical Geophysics, Novosibirsk, Russia*

Introduction

It has long been known that the second harmonic electromagnetic emission from a plasma with unstable counterstreaming electron beams can be sufficiently enhanced in comparison with the single beam case due to direct three-wave interactions between resonant beam-driven modes. To participate in such processes, these modes should propagate obliquely to the beam direction. The most efficient regime achieved via this radiation mechanism is realized when these three-wave interactions involve oblique modes growing with the maximal linear growth rate of the beam-plasma instability [1]. It is also well known that the frontal collision of potential plasma waves cannot produce EM radiation at the sum frequency if these waves are plane.

It has been found recently [2] that counterpropagating plasma wakefields driven by a pair of femtosecond laser pulses with different transverse structures can produce powerful and narrow-band EM emission near the doubled plasma frequency. Such a nonlinear process can proceed in a homogeneous plasma, does not require the creation of superstrong magnetic fields, and is not sensitive to the effect of plasma screening. Therefore, using this scheme, it is possible not only to significantly increase the power and energy of THz pulses (up to 1 GW and 10 mJ) but also to provide a small width of the frequency spectrum (1%).

In order to excite colliding plasma waves more efficiently and increase the duration of the intense THz generation, we proposed [3] to use kiloampere relativistic electron beams of picosecond and nanosecond duration instead of femtosecond laser drivers. Such beams can reach the high level of power (tens of GW) and are able to continuously pump plasma waves at ionic times via the two-stream instability.

Radiation mechanism

Two Langmuir waves propagating in a cold uniform plasma in opposite directions with equal phase velocities can be described by the potential

$$\Phi(t,\mathbf{r}) = \Phi_1(\mathbf{r}_\perp)e^{ikz-i\omega t} + \Phi_2(\mathbf{r}_\perp)e^{-ikz-i\omega t} + c.c. \tag{1}$$

Nonlinear interaction of these waves generates the longitudinal electric current

$$\mathscr{J}_{\parallel} = -(\delta n_1 v_{2\parallel} + \delta n_2 v_{1\parallel}) e^{-i2\omega t} + c.c., \tag{2}$$

which is able to radiate electromagnetic waves transversely to the propagation axis. Amplitudes of density and velocity perturbations for plasma electrons take the form:

$$v_{1\parallel} = -\frac{k}{\omega}\Phi_1(\mathbf{r}_\perp), \quad v_{2\parallel} = \frac{k}{\omega}\Phi_2(\mathbf{r}_\perp), \tag{3}$$

$$\delta n_{1,2} = \frac{1}{\omega^2}(\Delta_\perp - k^2)\Phi_{1,2}(\mathbf{r}_\perp). \tag{4}$$

Substituting these formulas in Eq. 2, we obtain the amplitude of radiating current

$$\mathscr{J}_{\parallel} = \frac{k}{\omega^3}\left(\Phi_1 \Delta_\perp \Phi_2 - \Phi_2 \Delta_\perp \Phi_1\right). \tag{5}$$

It is seen that this current disappears not only for plane waves (when $\Phi_{1,2}$ do not depend on $\mathbf{r}_\perp$), but also for waves with locally equal transverse profiles ($\Phi_1(\mathbf{r}_\perp) = \Phi_2(\mathbf{r}_\perp)$). In order to produce radiation in such a scheme, potential plasma waves should either have different transverse structures, or collide with a finite impact parameter.

Simulation results

Given in Table 1 are parameters of all numerical calculations carried out in this work. The computational domain consists of a plasma column with a length of L_x 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 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 Ω_e/ω_p.

Parameter	run 1	run 2	run 3
n_b/n_0	0.002	0.02	0.025
v_b/c	0.9		0.9428
$T^{(e)}$	40 eV		80 eV
$T^{(beam)}$	4 keV		1 keV
Ω_e/ω_p	0.3		0.1
L_x, c/ω_p	52.8		120
	diameter, c/ω_p		
Plasma	10		32
Left beam	5	10	32
Right beam	10		32
	immobile ions		

Table 1: *Simulation parameters.*

There are several ways how different amplitude profiles of excited plasma waves can be realized. First one is injection in plasma beams with different transverse sizes (Fig. 1). Our PIC simulations for the collision of low-density beams with different transverse sizes (run 1) show that the produced radiation is characterized by a narrow line-width ($\approx 1\%$), and its power enables reaching several percent of the total beams power (Fig. 3, top).

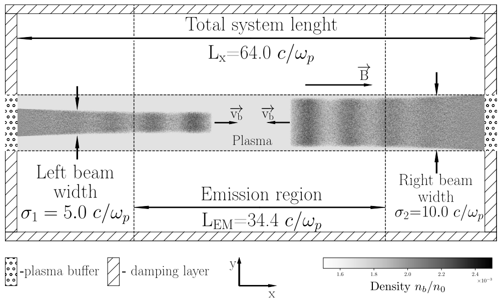

Figure 1: *Simulation layout (run 1).*

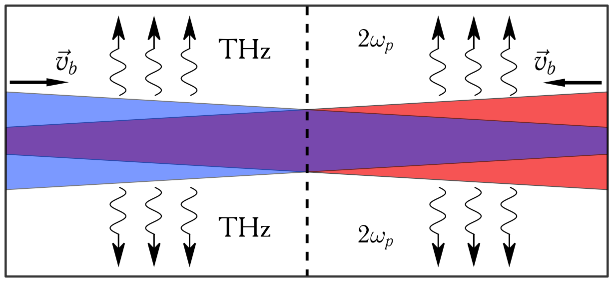

Figure 2: *Schematic illustration of beams filamentation and EM emission (run 2).*

It has also been found that the same radiation mechanism can work with the close efficiency in a system of dense electron beams with initial equal sizes. In such a system, different beam density shapes and different amplitude profiles of excited waves are automatically produced by the filamentation instability (Fig. 2 and Fig. 3, bottom).

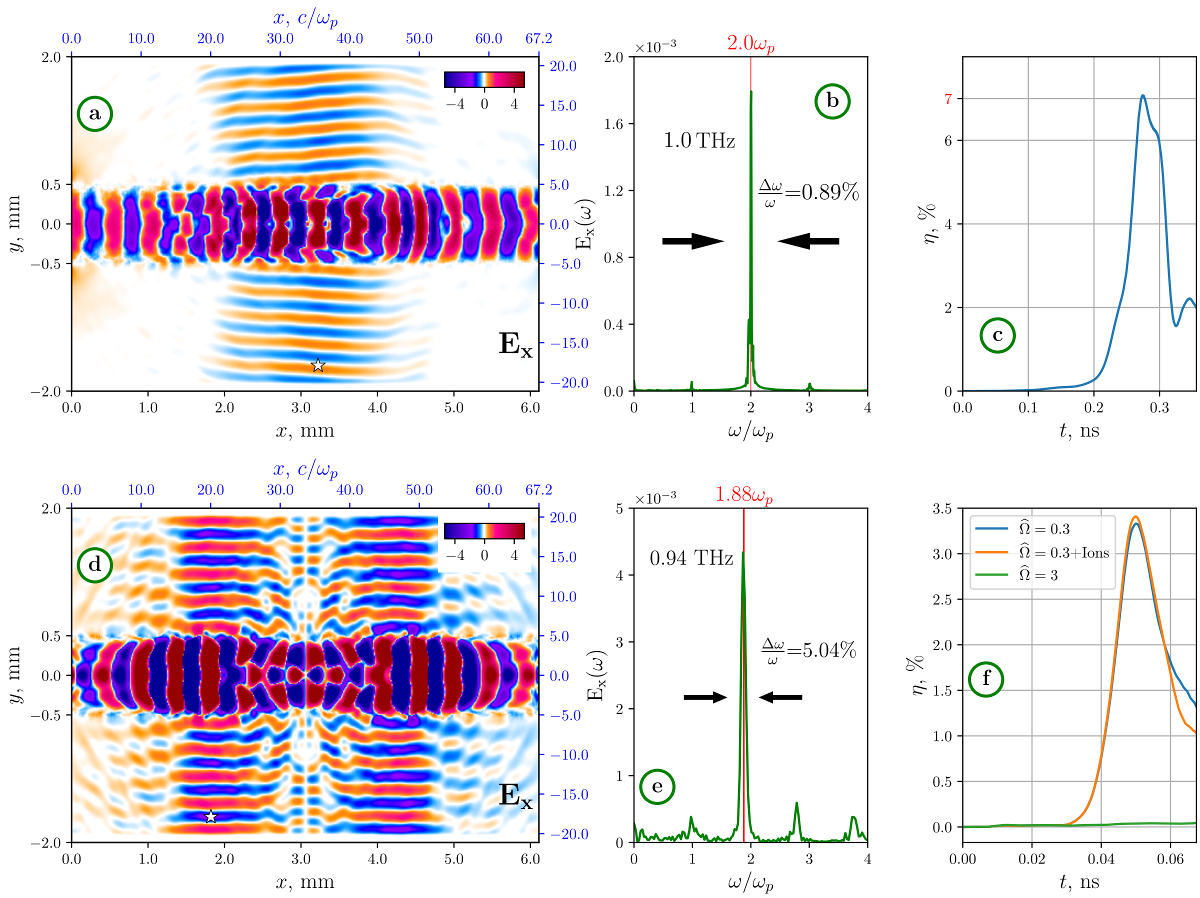

Figure 3: *Results of PIC simulations for run 1 (top) and run 2 (bottom). Left: maps of electric field E_x (in MV/cm) at the moment of highest EM emission. Middle: the frequency spectrum of radiation in the single point indicated by the white star. Right: the radiation power in units of the total injected beams power. All dimensional quantities correspond to the case $n_0 = 3.1 \cdot 10^{15}$ cm^{-3}.*

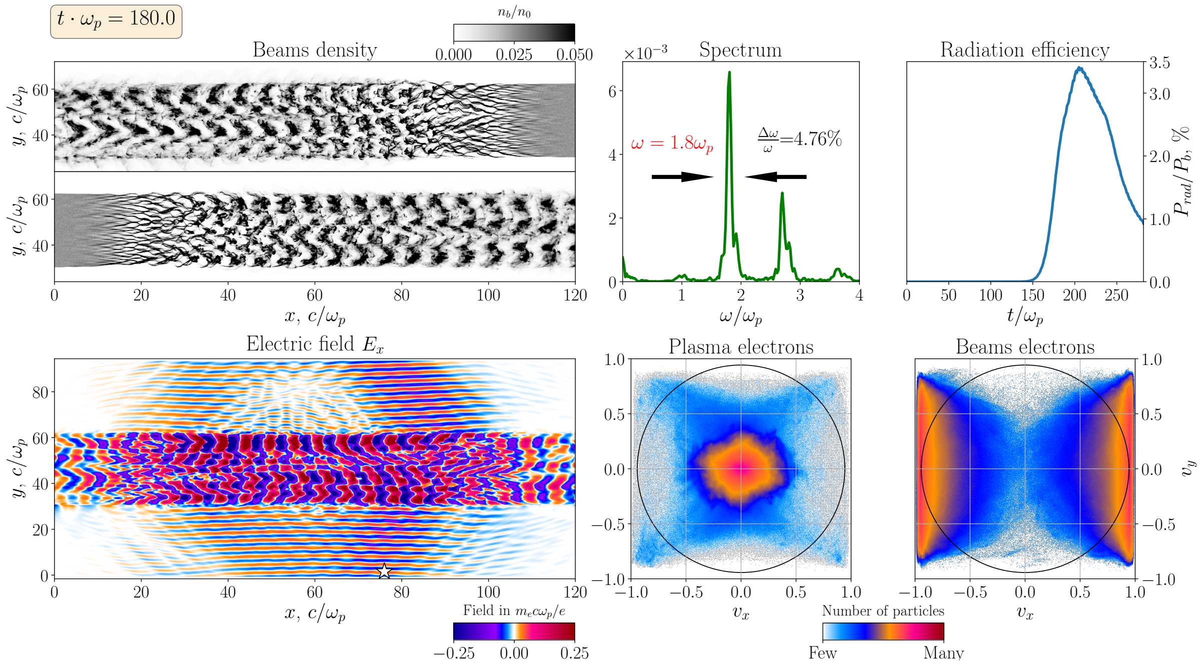

Figure 4: *Results of PIC simulations for run 3. Top: beams density n_b in units of unperturbed plasma density n_0; the frequency spectrum of radiation in the single point indicated by the white star; the radiation power in units of the total injected beam power. Bottom: maps of electric field E_x (in units of $m_e c\omega_p/e$) at the moment of highest EM emission; the phase space (v_x, v_y) of plasma and beams electrons. Black circle corresponds to the initial energy of the beams* (1.1 *MeV*).

Moreover, different transverse sizes of excited plasma waves can be realized in a case of small scale oblique instabilities, that is typical for relativistic beams (Fig. 4).

Conclusion

This new emission mechanism can produce gigawatt-class narrow-band THz radiation by multi-gigawatt electron beams typical for linear induction accelerators. Moreover, it can play the role in a natural beam and plasma environments such as type II and type IV solar radio-bursts in which emission regions may contain counterstreaming electron populations.

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 the RFBR grant 18-32-00107.

References

[1] Timofeev, I. V. & Annenkov, V. V. Phys. Plasmas, **21**, 083109 (2014).

[2] Timofeev, I. V., Annenkov, V. V., & Volchok, E. P. Physics of Plasmas, **24**(10), 103106 (2017).

[3] Annenkov, V. V., Berendeev, E. A., Timofeev, I. V., & Volchok, E. P. Physics of Plasmas, **25**(11), 113110 (2018).