SELF-FOCUSING AND WAKEFIELD-FOCUSING OF RELATIVISTIC ELECTRON BUNCHES IN PLASMA

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Abstract

The ratio of self-focusing due to the compensation of the space charge of bunches in plasma and of focusing by excited plasma wakefield is studied by numerical simulation. It is shown that this ratio is strongly depends on the parameters of the experiments. Verification of these parameters is performed by numerical simulation by code LCODE.

INTRODUCTION

Focusing of bunches of relativistic electrons is an important problem (see [1-15]). The intensity of this focusing on a few orders of magnitude larger than the intensity of used magnetic focusing [4]. However, the focusing, which occurs in the plasma at space charge compensation of bunches, are also not intense enough. The intensity of focusing can be increased significantly, for focusing in colliders, at use of excited transverse wakefield. Focusing by excited resonant wakefield was studied in [5, 16]. Also homogeneous focusing by excited wakefield was studied in [3, 5] for a relatively long bunches and in [16] for short bunches. The problem of ratio of self-focusing due to the compensation of the space charge of bunches in plasma or plasma focusing or self-focusing and of focusing by excited plasma wakefield is not fully investigated. Therefore, this ratio is studied in this paper by numerical simulation, using lcode in dependence on the parameters of the experiments.

THE RATIO OF SELF-FOCUSING AND FOCUSING BY EXCITED PLASMA WAKEFIELD

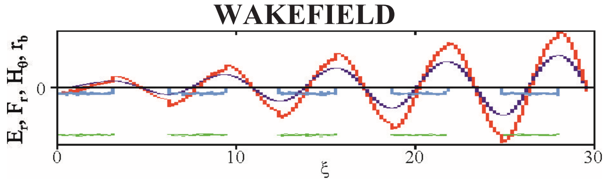

Figure 1: Longitudinal distribution of radius r_b (dashed line) of sequence of bunches, radial wake force F_r (oscillating line of smaller amplitude), radial wakefield E_r (oscillating line of larger amplitude) and magnetic field H_θ (train of rectangles), excited by sequence of resonant bunches before their focusing/defocusing.

In the resonant case $\omega_{pe}=\omega_m$ at injection of 1st bunch, the length of which is chosen to be equal to half of the wavelength, the plasma compensation increases in the 1st part of the bunch. ω_m is the repetition frequency of bunches, $\omega_{pe}=(4\pi n_{res}e^2/m_e)^{1/2}$ is the electron plasma frequency. The bunch focuses in the 2nd its part in addition by wakefield. The amplitude of this wakefield at the end of the bunch (the length of which is selected to be equal to $\xi_b=\lambda/2$) reaches the field of the space charge of the bunch. I.e. ratio of wakefield focusing and of self-focusing is achieved 50%:50%. Magnetic field H_θ in Fig. 1 shows the relative contribution of the intensity of the self-focusing in the overall intensity of focusing. Defocusing wakefield appears in the heads of further bunches, and in their tails - increasing focusing wakefield (see Fig. 1). Time is normalized on ω_{pe}^{-1}, distance - on c/ω_{pe}, density - on unperturbed plasma density n_0, fields – on $\omega_{pe}cm_e/e$.

This focusing/defocusing wakefield results in a strongly inhomogeneous focusing (see Fig. 2).

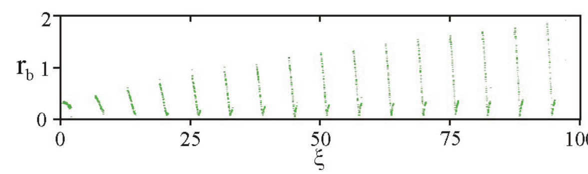

Figure 2: Longitudinal distribution of radius r_b of sequence of resonant bunches after their focusing/defocusing.

In the case of a longer sequence of non-resonant short bunches (see Fig. 3) the plasma compensation of space charge of short bunches do not have time to occur and focusing is determined by wakefield.

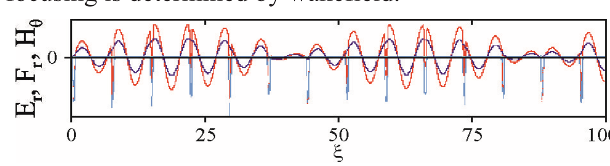

Figure 3: Longitudinal distribution of radius r_b (train of points), density n_b (vertical long lines) of sequence of nonresonant bunches, radial wake force F_r (oscillating line of smaller amplitude), radial wakefield E_r (oscillating line of larger amplitude) and H_θ (vertical short lines).

In the case of non-resonant bunches of finite length ($\xi_b=\lambda/4$) until to the end of 1st bunch the complete charge compensation is achieved (see Fig. 4). Consequently, the 1st bunch focuses due to the partial charge-screening. Following bunches get in growing wakefield. One can say that bunches, which are located near the fronts of the beatings, are focused due to the partial charge-screening. Others bunches get into growing wakefield. But focusing is periodically inhomogeneous.

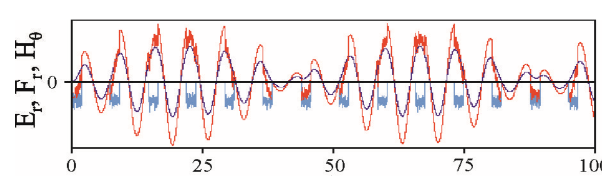

Figure 4: Longitudinal distribution of radial wake force F_r (oscillating line of smaller amplitude), radial wakefield E_r (oscillating line of larger amplitude) and H_θ (train of rectangles), excited by sequence of nonresonant bunches.

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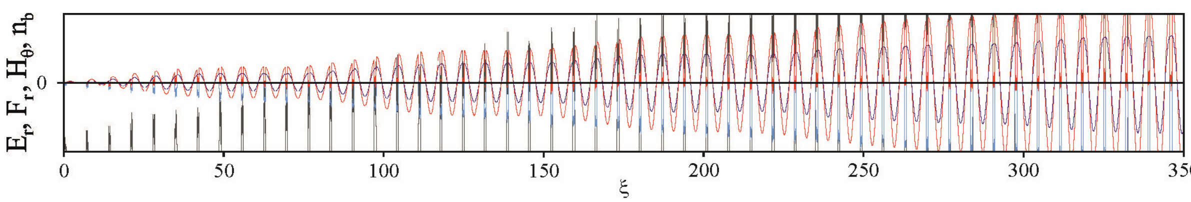

Figure 6: Longitudinal ξ distribution of density n_b (vertical long lines) of long linearly shaped along the sequence as well as along each bunch without precursor sequence of very short bunches relatively to E_r (oscillating line of larger amplitude), F_r (oscillating line of smaller amplitude), H_θ (vertical short lines).

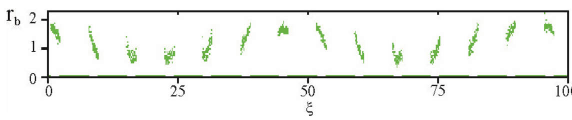

Figure 5: Longitudinal distribution of radius r_b

In the case of linear shaping along the sequence as well as along each bunch-thin-disc without precursor the plasma screening does not have time to occur (see Figs.5 - 7). The amplitude of the wakefield is approximately equal to the electric field of the space charge of bunches N>>1. In this case the wakefield focusing is much stronger than the plasma self-focusing.

Now we consider the ratio of self-focusing and wakefield focusing in dependence on the shape of short bunches.

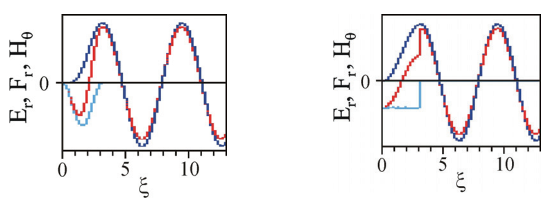

Figure 8: (left) E_r (oscillating line of smaller amplitude), F_r (oscillating line of larger amplitude), H_θ (curved line down), excited by Gaussian bunch; (right) E_r (oscillating line of smaller amplitude), F_r (oscillating line of larger amplitude), H_θ (rectangle), excited by rectangular bunch.

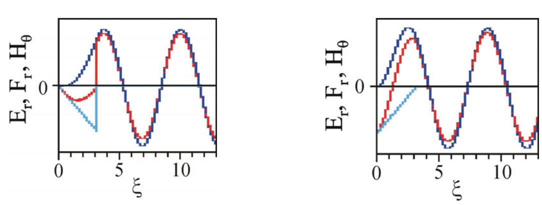

Figure 9: (left) E_r (oscillating line of smaller amplitude), F_r (oscillating line of larger amplitude), H_θ (triangle), excited by bunch, the charge of which increases linearly; (right) E_r (oscillating line of smaller amplitude), F_r (oscillating line of larger amplitude), H_θ (triangle), excited by bunch, the charge of which decreases linearly.

Almost on the entire length of Gaussian bunch $\xi_b=\lambda/2$ E_r is scattering (see Fig. 8, left) and only at the very end of the bunch it is wakefield focusing. But on the entire length of bunch F_r is focusing: on the first part of the bunch the shielding of the space charge of the bunch appears, and on the 2nd part of the bunch the wakefield focusing is still added.

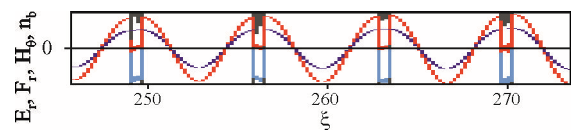

Figure 7: (part of Fig. 6) Longitudinal ξ distribution of density n_b (vertical lines) of linearly shaped along the sequence as well as along each bunch without precursor sequence of very short bunches relatively to E_r (oscillating line of larger amplitude), F_r (oscillating line of smaller amplitude), H_θ (vertical short lines).

In the middle of the bunch-uniform-cylinder with $\xi_b=\lambda/2$ (see Fig. 8, right) the compensation of its space charge is achieved, and in the 2nd half of the bunch the wakefield increases as a result of the electron inertia and its amplitude at the end of the bunch reaches the field of the space charge of the bunch. Thus, one can say that the ratio of self-focusing and wakefield focusing is approximately equal 50%:50%.

At the end of the bunch $\xi_b=\lambda/2$, the charge of which increases linearly (see Fig. 9, left), the resulting electric field vanishes and the focusing is determined by its own magnetic field.

In the 2nd half of the bunch $\xi_b=\lambda/2$, the charge of which decreases linearly (see Fig. 9, right), the role of the wakefield focusing increases and becomes large at the end of the bunch, where self-focusing

$$F_r \sim H_\theta = 2\pi e\, n_b (V_b/c) r \sim n_b(\xi)$$

is already small, and the wakefield focusing is large.

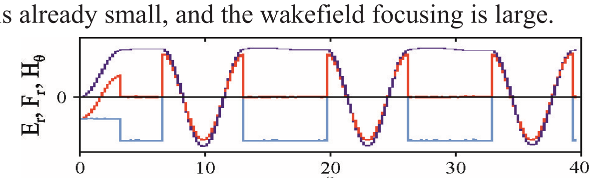

Figure 10: Longitudinal ξ distribution of E_r (oscillating line of smaller amplitude), F_r (oscillating line of larger amplitude), H_θ (train of rectangles), excited by sequence of long $\xi_b=\lambda$ bunches with a precursor of half charge density.

In the case of sequence of long $\xi_b=\lambda$ bunches with a precursor of half charge density in the first half of the precursor (see Fig. 10), the shielding of the space charge is performed, in the 2nd half of precursor the wakefield increases, reaching the value of the space charge field. This wakefield is compensated by increased field of increased volume charge. Focusing of bunches is determined only by self-focusing.

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Now we consider the ratio of self-focusing and wakefield focusing for a long bunch $\xi_b \gg \lambda$.

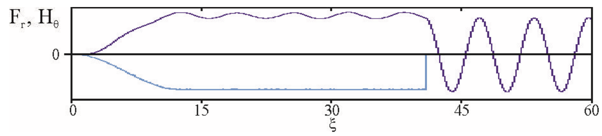

Figure 11: F_r (top oscillating line), H_θ (bottom line), excited by long $\xi_b \gg \lambda$ bunch with a smooth front.

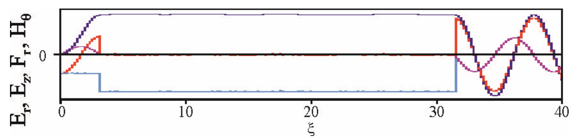

Figure 12: E_z (oscillating line of smaller amplitude), E_r (oscillating line of middle amplitude), F_r (oscillating line of larger amplitude), H_θ (two homogeneous intervals), excited by long $\xi_b \gg \lambda$ bunch with a bunch-precursor.

No matter how the smooth front of long bunch is used, still oscillating field generated by the front appears (see Fig. 11). And only if the corresponding precursor is used, ideal focusing (self-focusing) field is obtained. Shielding of the space charge (see Fig. 12) of precursor occurs on the first half, on its 2nd half the wakefield increases, reaching the value of the space charge field. This wakefield is compensated by increased field of increased volume charge. Homogeneous focusing of long bunch with precursor is determined only by self-focusing.

CONCLUSIONS

The ratio of self-focusing due to the compensation of the space charge of bunches in the plasma and of focusing by wakefield, excited in plasma, has been investigated by numerical simulation. It was shown that at the wakefield excitation by bunch, the length of which is equal to half of the wavelength, the ratio of wakefield focusing to self-focusing is large at the end of the bunch, the shape of which is such that its current decreases from the maximum value in the head of the bunch to zero at the end of the bunch. However, the ratio of the wakefield focusing to the self-focusing tends to zero at the end of the bunch, the length of which is equal to half of the wavelength, if the current increases along the bunch from zero at the head of the bunch to a maximum value at the end of the bunch. In the case of bunch of constant current with sharp edges, the length of which is equal to several plasma wavelengths, the self-focusing force F_s is constant along the bunch and the force of the wakefield focusing changes from $-F_s$ up to F_s, so that the overall focusing force varies from 0 to $2F_s$. In the case of bunch of constant current with precursor of half current and length, equal to half of the wavelength, the focusing of the bunch is determined by the homogeneous self-focusing and the wakefield focusing is equal to zero. In the case of a rectangular bunch, the length of which is equal to half of the wavelength, the ratio of the wakefield focusing and self-focusing is approximately equal to 50%:50%. In the case of a Gaussian bunch almost on the entire length of the bunch the radial electric field is defocusing and only at the end of the bunch, it becomes focusing. However, the entire bunch is focused due to self-focusing.

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