FOCUSING BY WAKEFIELD AND PLASMA FOCUSING OF RELATIVISTIC ELECTRONS IN DEPENDENCE ON PARAMETERS OF EXPERIMENTS

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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.

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Focusing of bunches of relativistic electrons is an important problem (see [1 - 4]). The intensity of this focusing on a few orders of magnitude larger than the intensity of used magnetic focusing [5]. 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 [1, 6]. Also homogeneous focusing by excited wakefield was studied in [4, 7] for a relatively long bunches and in [8] 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 relativistic 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 [9], in dependence on the parameters of the experiments.

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

In the resonant case at injection of the 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, and in the 2-nd part the bunch focuses in addition by wakefield, amplitude of which 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)%. Defocusing wakefield appears in the heads of further bunches, and in their tails – increasing focusing wakefield (Fig. 1), which result in a strongly inhomogeneous focusing (Fig. 2). The black bar shows the relative contribution of the intensity of the self-focusing in the overall intensity of focusing.

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

In the case of a longer sequence of non-resonant short bunches (Fig. 4) also the plasma compensation of space charge of short bunches do not have time to occur and focusing is determined by wakefield.

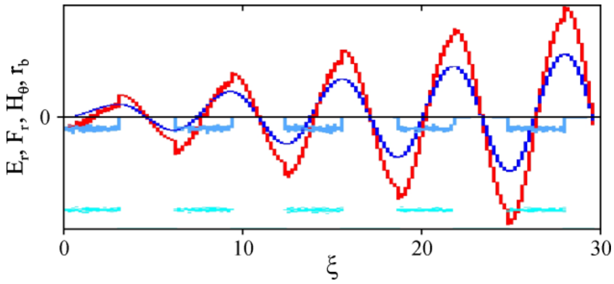

Fig. 1. Longitudinal distribution of radius r_b (dashed line) of sequence of bunches, of radial wake force F_r (oscillating line of smaller amplitude), of radial wakefield E_r (oscillating line of larger amplitude) and H_θ (train of rectangles), excited by sequence of resonant bunches before their focusing/defocusing. H_θ shows the relative contribution of the intensity of the self-focusing in the overall intensity of focusing

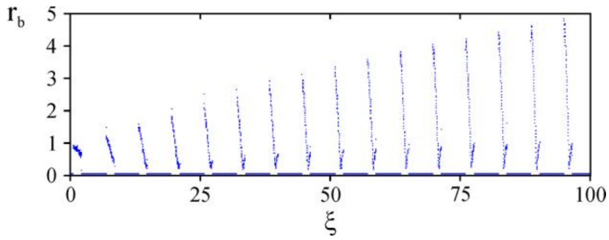

Fig. 2. Longitudinal distribution of radius r_b of sequence of resonant bunches after their focusing/defocusing

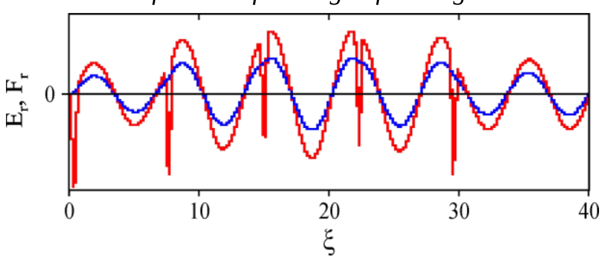

Fig. 3. Longitudinal distribution of radial wake force F_r (oscillating line of smaller amplitude) and of radial wakefield E_r (oscillating line of larger amplitude) in the case of sequence of nonresonant short bunches

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 (Fig. 5). Consequently, the 1st bunch focuses due to the partial charge-screening. Following bunches get in growing wakefield.

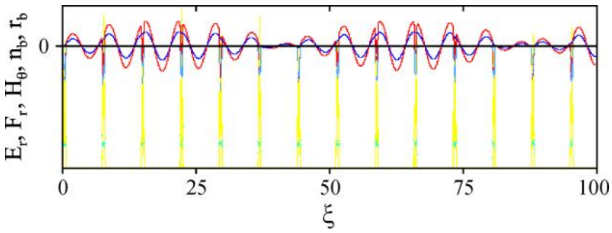

Fig. 4. Longitudinal distribution of radius r_b (train of points), of density n_b (vertical long lines) of sequence of nonresonant bunches, of radial wake force F_r (oscillating line of smaller amplitude), of radial wakefield E_r (oscillating line of larger amplitude) and H_θ (vertical short lines)

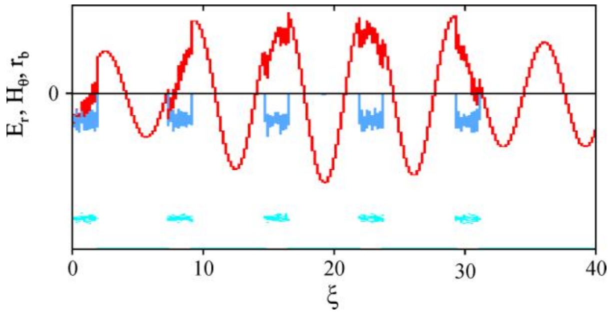

Fig. 5. Longitudinal distribution of radius r_b (dashed line) of sequence of bunches, of radial wakefield E_r (oscillating line) and H_θ (train of rectangles), excited by sequence of nonresonant bunches. H_θ shows the relative contribution of the intensity of the self-focusing in the overall intensity of focusing

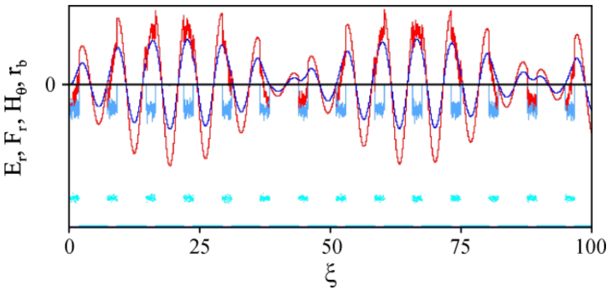

Fig. 6. Longitudinal distribution of radius r_b (train of points) of sequence of nonresonant bunches, of radial wake force F_r (oscillating line of smaller amplitude), of radial wakefield E_r (oscillating line of larger amplitude) and H_θ (train of rectangles), excited by sequence of nonresonant bunches. H_θ shows the relative contribution of the intensity of the self-focusing in the overall intensity of focusing

In the case of a longer sequence of non-resonant (Fig. 6) bunches of finite length ($\xi_b=\lambda/4$) 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 (Fig. 7).

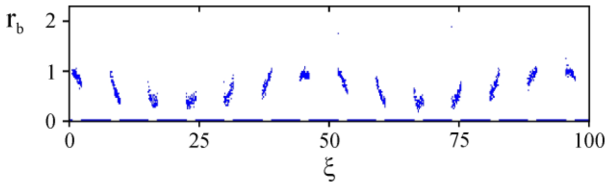

Fig. 7. Longitudinal distribution of radius r_b of sequence of nonresonant bunches after their focusing/defocusing

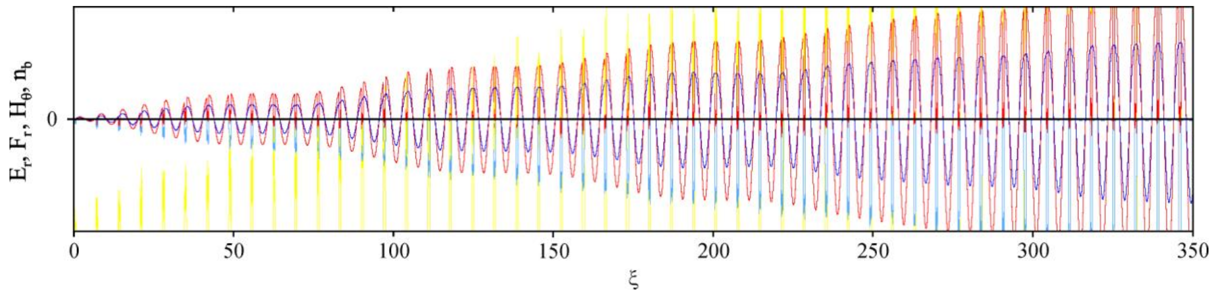

Fig. 8. Longitudinal ξ distribution of density n_b (vertical long lines) of long linearly shaped along the sequence as well as along each bunch without precursor sequence of very short bunches relatively to E_r (oscillating line of larger amplitude), F_r (oscillating line of smaller amplitude), H_θ (vertical short lines)

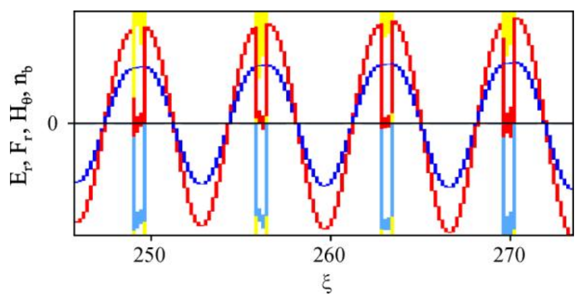

Fig. 9. (part of Fig. 8) Longitudinal ξ distribution of density n_b (vertical lines) of linearly shaped along the sequence as well as along each bunch without precursor sequence of very short bunches relatively to E_r (oscillating line of larger amplitude), F_r (oscillating line of smaller amplitude), H_θ (vertical short lines)

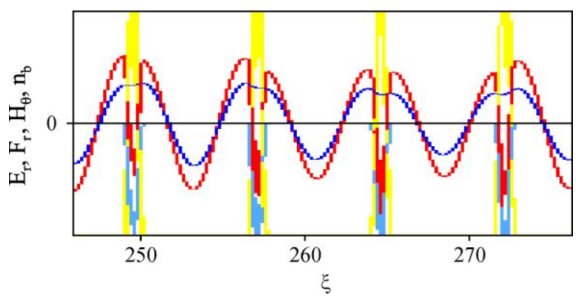

Fig. 10. Longitudinal ξ distribution of density n_b (vertical lines) of linearly shaped along the sequence as well as along each bunch without precursor sequence of very short Gaussian bunches relatively to E_r (oscillating line of larger amplitude), F_r (oscillating line of smaller amplitude), H_θ (vertical short lines)

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 (Figs. 8, 9). Therefore, the proper magnetic field almost completely suppresses scattering electric field of the space charge. 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 of relativistic focusing) focusing.

This happens in the case of such shaping of Gaussian bunches of finite small length (Fig. 10).

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

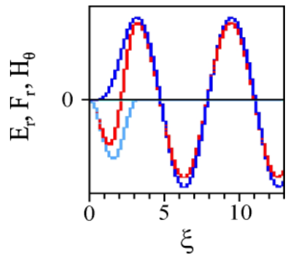

Fig. 11. E_r (oscillating line of smaller amplitude), F_r (oscillating line of larger amplitude), H_θ (curved line down), excited by Gaussian bunch

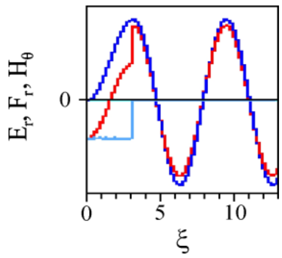

Fig. 12. E_r (oscillating line of smaller amplitude), F_r (oscillating line of larger amplitude), H_θ (rectangle), excited by rectangular bunch

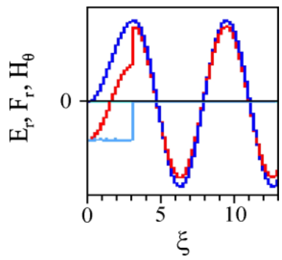

Fig. 13. E_r (oscillating line of smaller amplitude), F_r (oscillating line of larger amplitude), H_θ (triangle), excited by bunch, the charge of which increases linearly

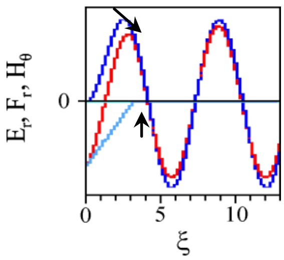

Fig. 14. E_r (oscillating line of smaller amplitude), F_r (oscillating line of larger amplitude), H_θ (triangle), excited by bunch, the charge of which decreases linearly

Almost on the entire length of Gaussian bunch $\xi_b=\lambda/2$ E_r is scattering (Fig. 11) 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 2-nd part of the bunch the wakefield focusing is still added.

In the middle of the bunch-uniform-cylinder with $\xi_b=\lambda/2$ (Fig. 12) the compensation of its space charge is achieved, and in the 2-nd 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 (Fig. 13), 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 (Fig. 14), 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.

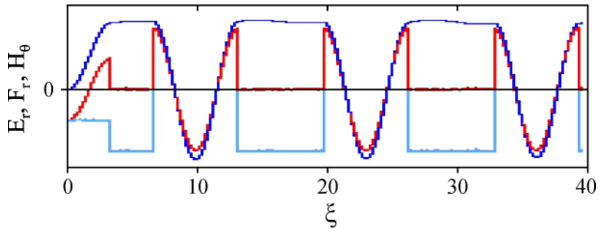

Fig. 15. E_r (oscillating line of smaller amplitude), F_r (oscillating line of larger amplitude), H_θ (train of rectangles), excited by sequence of long $\xi_b=\lambda$ bunches with a precursor of half charge density

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 (Fig. 15), the shielding of the space charge is performed, in the 2-nd 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.

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

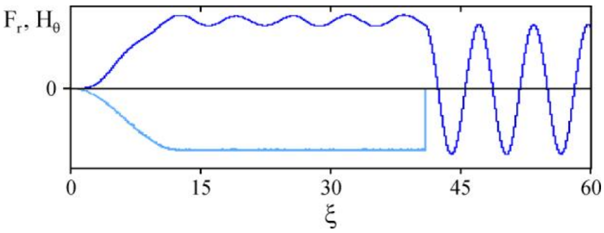

Fig. 16. F_r (top oscillating line), H_θ (bottom line), excited by long $\xi_b>>\lambda$ bunch with a smooth front

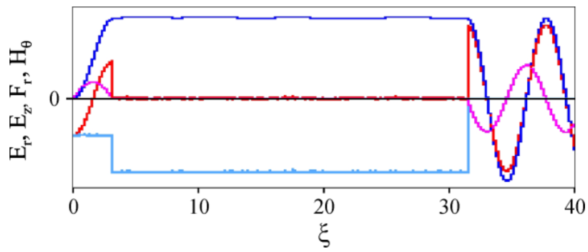

Fig. 17. E_z (oscillating line of smaller amplitude), E_r (oscillating line of middle amplitude), F_r (oscillating line of larger amplitude), H_θ (two homogeneous intervals), excited by long $\xi_b>>\lambda$ bunch with a bunch-precursor

No matter how the smooth front of long bunch is used, still oscillating field generated by the front appears (Fig. 16). And only if the corresponding precursor is used, ideal focusing (self-focusing) field is obtained. Shielding of the space charge (Fig. 17) of precursor occurs on the first half, on its 2-nd 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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КИЛЬВАТЕРНАЯ И ПЛАЗМЕННАЯ ФОКУСИРОВКИ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОНОВ В ЗАВИСИМОСТИ ОТ УСЛОВИЙ ЭКСПЕРИМЕНТОВ

И.П. Левчук, В.И. Маслов, И.Н. Онищенко

Численным моделированием исследуется соотношение самофокусировки за счет компенсации объёмного заряда сгустков в плазме и фокусировки кильватерным полем, возбуждаемым в плазме. Показано, что это соотношение сильно зависит от параметров экспериментов.

КІЛЬВАТЕРНЕ ТА ПЛАЗМОВЕ ФОКУСУВАННЯ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОНІВ У ЗАЛЕЖНОСТІ ВІД УМОВ ЕКСПЕРИМЕНТІВ

І.П. Левчук, В.І. Маслов, І.М. Оніщенко

Числовим моделюванням досліджується співвідношення самофокусування за рахунок компенсації об'ємного заряду згустків у плазмі і фокусування кільватерним полем, збуджуваним у плазмі. Показано, що це співвідношення дуже залежить від параметрів експериментів.