Focusing of a Sequence of Positron Bunches in Plasma*

Denys Bondar (reporter)[1,2]**,
prof., Dr. Sc., Vasyl Maslov[1,2]*,
prof., Dr. Sc., Ivan Onishchenko[1]

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[1]NSC "Kharkiv Institute of Physics and Technology"
Kharkiv, 61108, st. Akademicheskaya 1, Ukraine

[2]V.N. Karazin Kharkiv National University,
4 Svobody Sq., Kharkiv, 61022, Ukraine

**E-mail: vmaslov@kipt.kharkov.ua*

***E-mail: bondard12@gmail.com*

Plasma wakefield is important lens for focusing beams of electrons and positrons [1-8].

The wakefield lens in which uniform focusing of electron beam has been investigated in [8]. But in blow-out regime, according to investigations (see [4]) the positron bunch focusing is non-uniform unlike electron bunch.

Hence Gaussian positron bunches focusing is quantitatively researched in this article by particle-in-cell numerical simulation by 2.5D code LCODE [9].

The numerical code LCODE threats plasma as a cold electron fluid and the bunches as the ensembles of macro-particles.

The purpose of the investigation

- find and study the mechanism of focusing of a sequence of relativistic Gaussian positron bunches in plasma

The several cases are obtained for Gaussian bunches according to their length, the distance between them and charge ratio, when the investigated focusing is achieved.

It has been shown that bunches are focused by identical forces and the centres of bunches are focused more slower than their fronts.

Profiled sequences are also considered. A method for ensuring uniform focusing of a sequence of bunches is shown.

Cylindrical coordinate system (r, x) is used.

- **Wakefield** is normalized on $E_0 = cm\omega_p/e$, where m is the electron mass, e is the elementary charge, c is the speed of light, and $\omega_p = (4\pi n_0 e^2/m)^{1/2}$ is the plasma frequency;
- **Time** t is normalized on ω_{pe}^{-1}, longitudinal momentum of bunches P_z – on $mc\gamma_b$;
- **radius of bunches** on c/ω_p, beam current I_b – on mc^3/e, emittance of bunches σ - on c^2/ω_p;
- **plasma electron density** n_e and **bunch density** n_b are normalized on unperturbed plasma electron density n_0, radial r and longitudinal z coordinates - on c/ω_p.

Basic simulation parameters

- Plasma electron density is $n_e = 10^{11}\ cm^{-3}$
- Plasma wavelength is $\lambda = 10.6\ cm$
- Plasma frequency is $\omega_{pe} = 1.78 \cdot 10^{10}\ \frac{rad}{s}$
- $c/\omega_{pe} = 1.68\ cm$

The rest of the parameters can be found directly on the graphs and in the figure captions.

First type of the plasma lens

This type of the lens has the following set of parameters:

- **Bunches length equals $\lambda/2$.**
- **the charge of all bunches is in √2 times larger than the charge of the 1st bunch.**
- **The interval between the 1st and 2nd bunches is (n+1/8)λ, n=1, 2, …**
- **The interval between other bunches is a multiple of λ.**

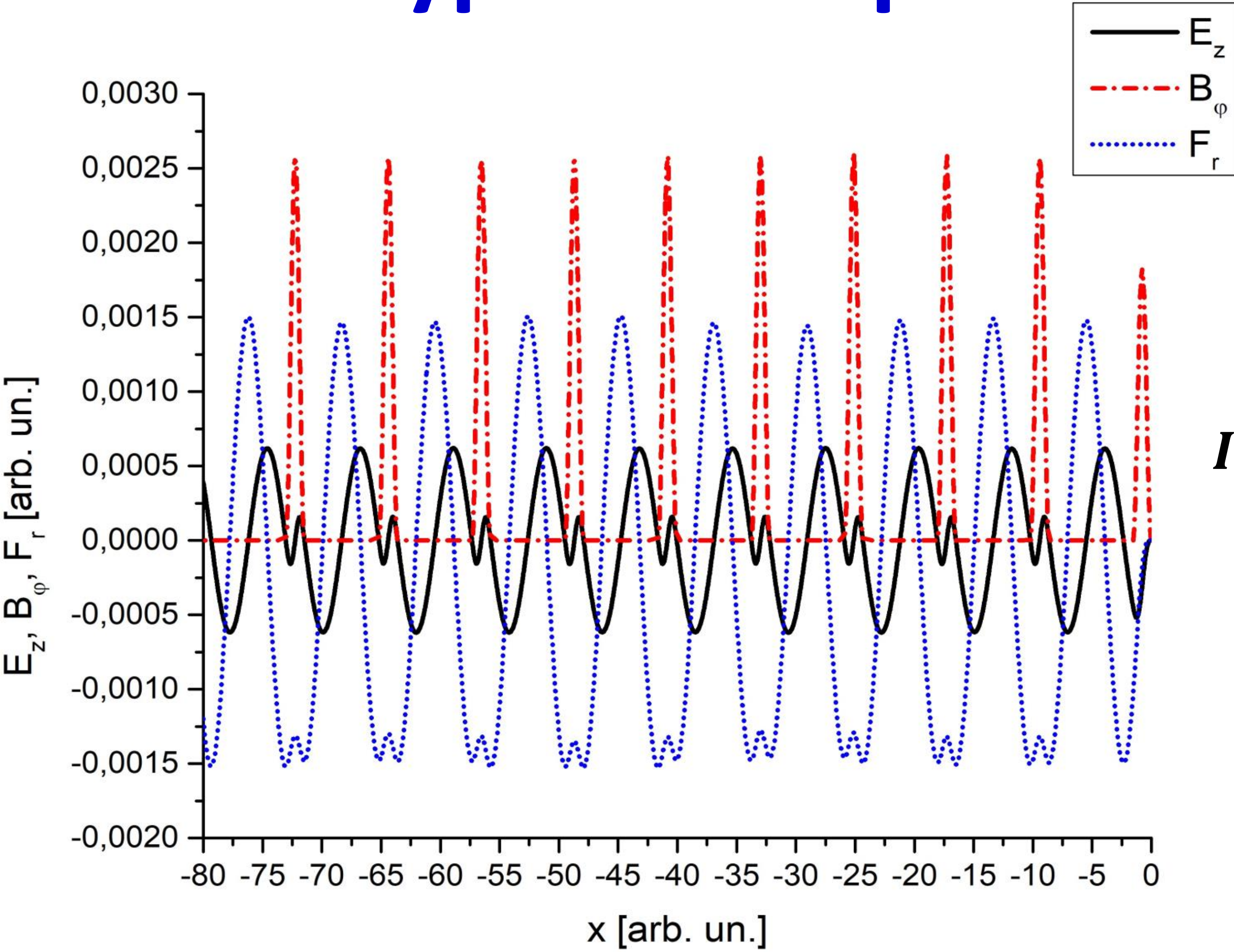
Only the 1st bunch is in the finite decelerating field. Other bunches are in the small longitudinal electric field. only the 1st bunch exchanges energy with the wakefield.

First type of the plasma lens

From Fig. 1 (slide 9) one can see that the fronts of the bunches are under a little higher focusing force than centers of the bunches. In this case, positron bunches are in wider regions with a plasma electron density exceeding the unperturbed $n_e > n_{0e}$ (see Fig. 2 (slide 10)). These regions are alternated with narrow regions with $n_e < n_{0e}$ (see Fig. 2 (slide 10)).

The bunches (except the first bunch) approximately do not exchange energy with wakefield, because they are in a small longitudinal wakefield (see Fig. 2 (slide 10)). Then only the first bunch exchanges energy with the wakefield, and the amplitude of the wakefield does not change along the sequence.

First type of the plasma lens



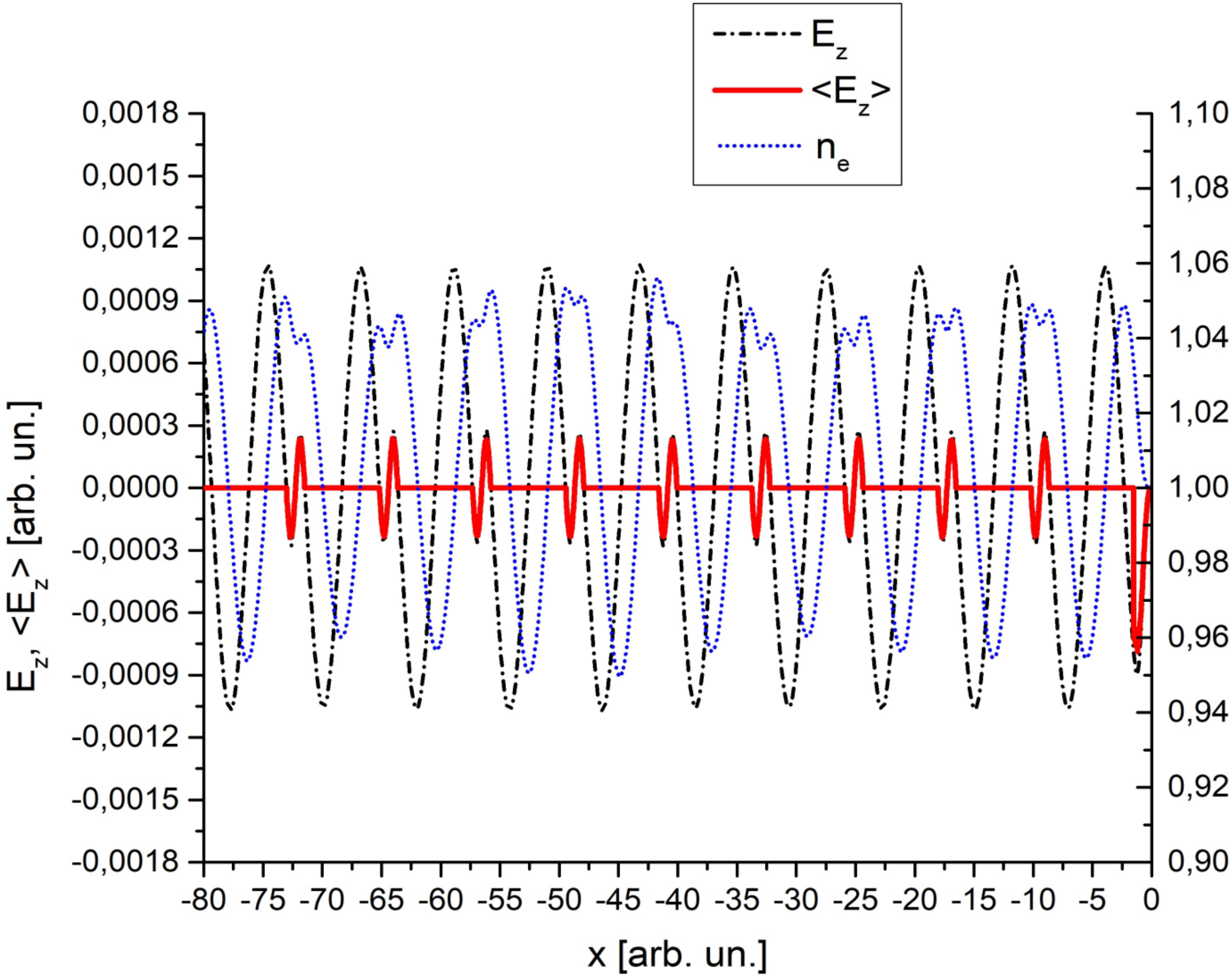
$\gamma_b = 5$

$I_b = 0.3 \cdot 10^{-3}$

$r_b = 0.1$

Figure 1: the off-axis radial focusing force F_r and off-axis magnetic field B_φ and also accelerating field E_z.

First type of the plasma lens



$$\gamma_b = 5$$
$$I_b = 0.3 \cdot 10^{-3}$$
$$r_b = 0.1$$

Fig. 2. The on-axis plasma electron density n_e, on-axis longitudinal wakefield E_z and $< E_z >$

Second type of the plasma lens

This type of the lens has the following set of parameters:

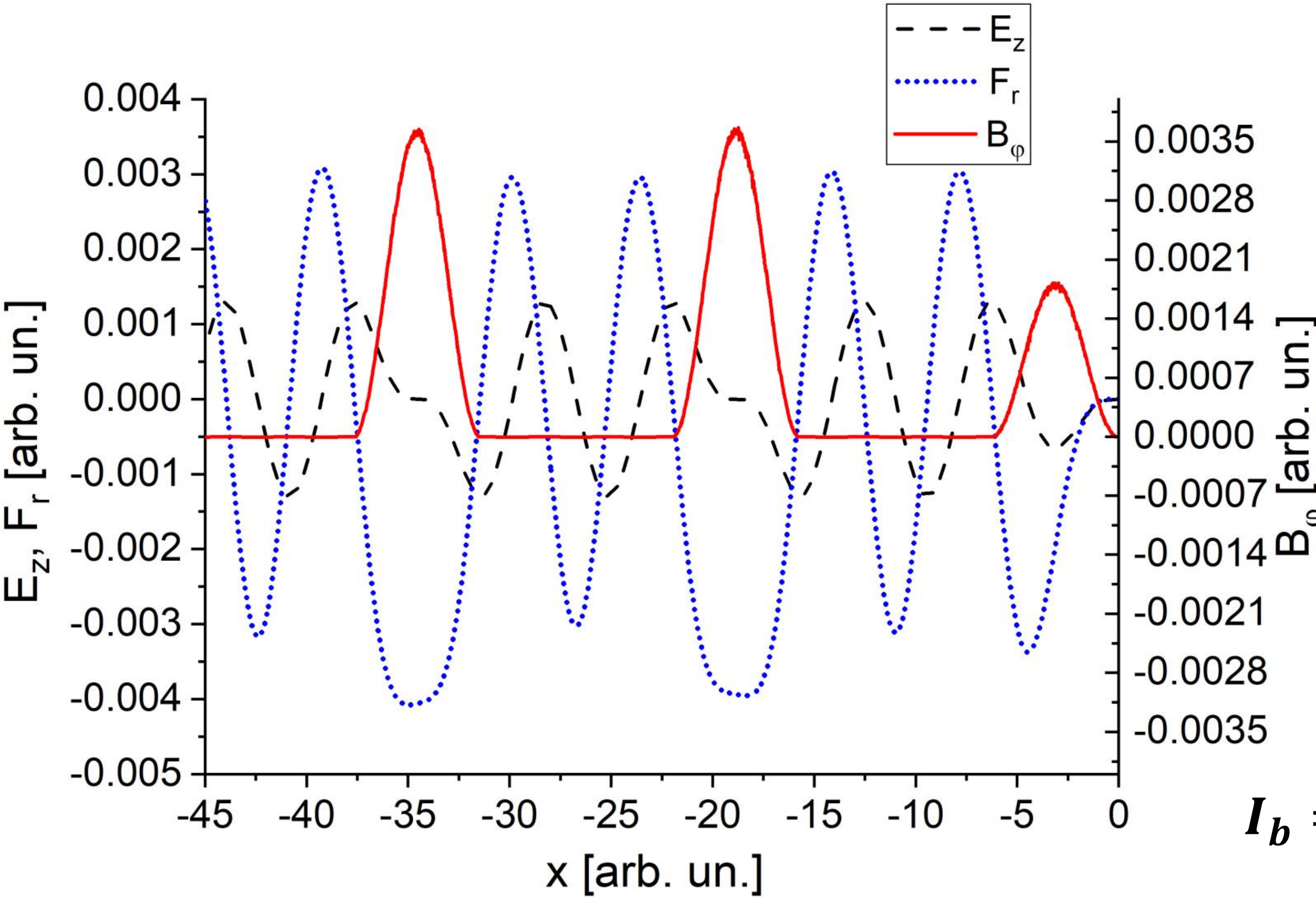
- **Bunches length equals $\lambda/_2$ (measured at half height).**
- **The charge of all bunches is in 2 times larger than the charge of the 1^{st} bunch.**
- **The interval between bunches is 2.5λ.**

Second type of the plasma lens

The center of only first bunch (see Fig. 3) (slide 14) is in non-zero longitudinal wakefield. Hence first bunch mainly forms focusing wakefield. Centers of back bunches of the sequence are in zero longitudinal wakefield and they do not form focusing wakefield. We see that wakefield does not change from one bunch to another.

After focusing the bunches are more uniform (except 1st bunch) than before focusing. Focusing is provided by the wide elevations of plasma electron density in regions of bunches (Fig. 4) (slide 14). In region of the 1st bunch, one can see strongly non-uniform elevation of density of plasma electrons. Similar wakefield distribution is formed also for seven Gaussian bunches with (Fig. 5 (a, b)) (slide 15).

Second type of the plasma lens



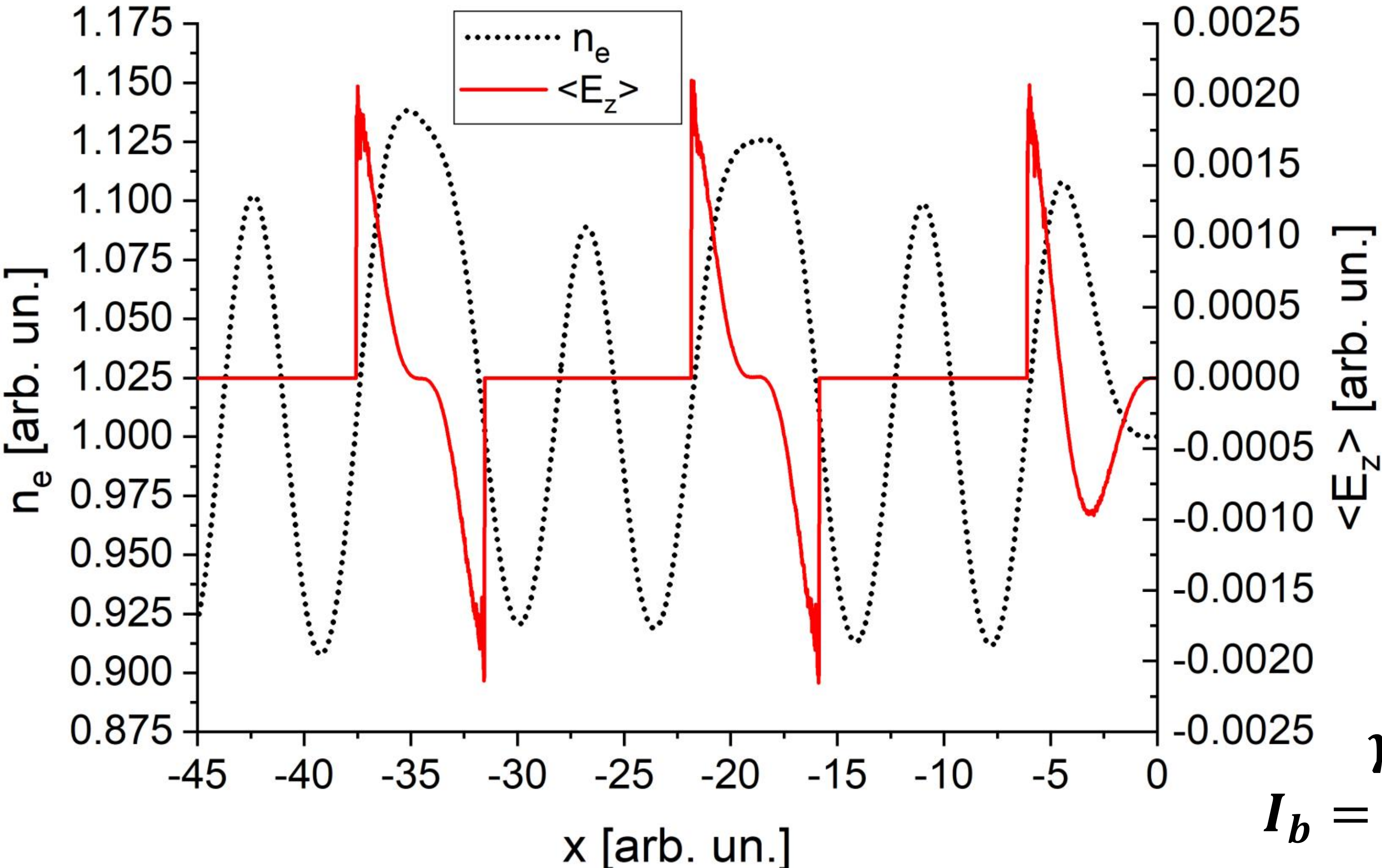
$\gamma_b = 5$

$I_b = 0.3 \cdot 10^{-3}$

$r_b = 0.1$

Fig. 3. Longitudinal wakefield E_z (off axis $r = r_b$), radial focusing force F_r and off-axis magnetic field B_φ

Second type of the plasma lens



$\gamma_b = 5$
$I_b = 0.3 \cdot 10^{-3}$
$r_b = 0.1$

Fig. 4. On-axis plasma electron density n_e and average value $< E_z >$ of the wakefield E_z into the plasma near the boundary of beam injection

Second type of the plasma lens

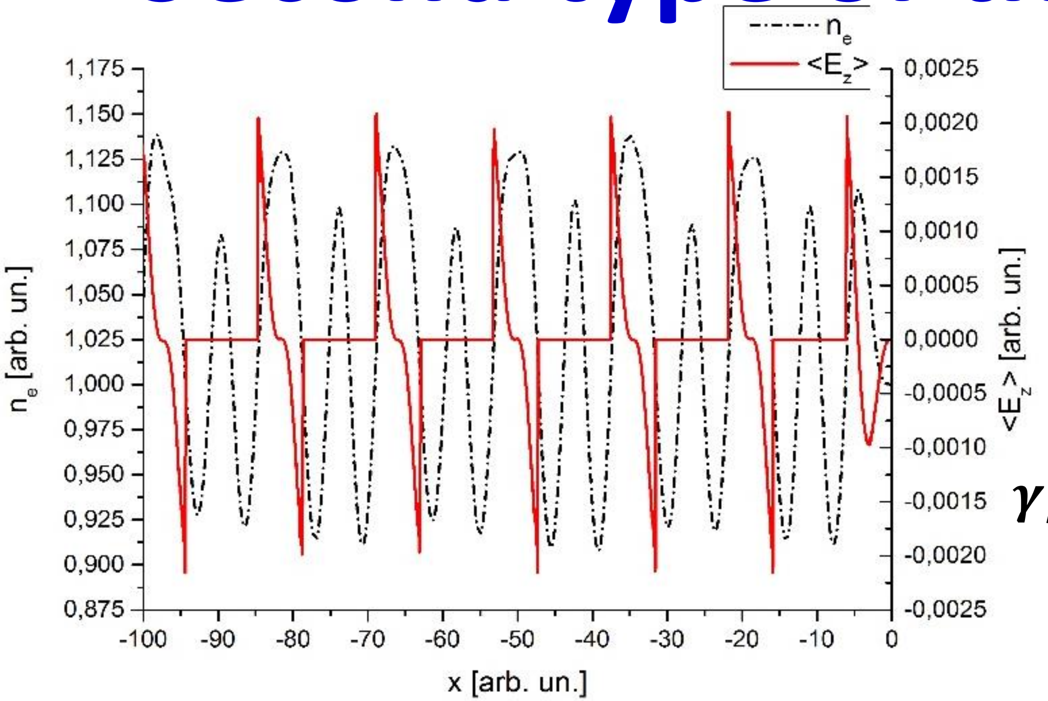


Fig. 5(a). Plasma electron density n_e on the axis and $< E_z >$ average value of the wakefield into the plasma (left picture)

$$\gamma_b = 1000, I_b = 0.3 \cdot 10^{-3}, r_b = 0.1$$

Seven bunches

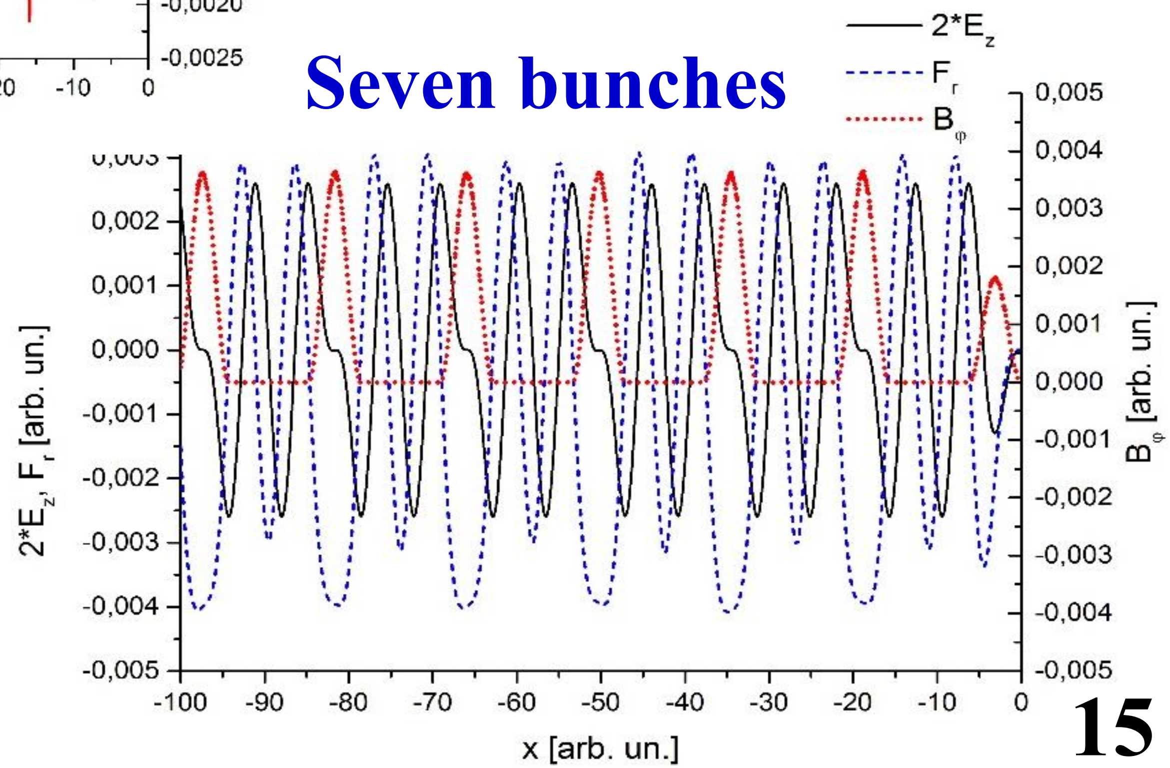


Fig. 5(b). The longitudinal wakefield E_z out of the axis, off-axis radial focusing force F_r (for $r = r_b$) and off-axis magnetic field B_φ for into the plasma (right picture)

The lens with more uniform focusing force distribution

This type of the lens has the following set of parameters:

- **Five Gaussian bunches in first front of sequence is shaped**
- **Bunches length equals $\lambda/_2$ (measured at bunches' base)**
- **The charges of first N=5 shaped bunches increase along sequence according to: 2k-1, k≤N**
- **The charges of next bunches equal 2N, k>N**
- **The interval between bunches is 1.5λ**

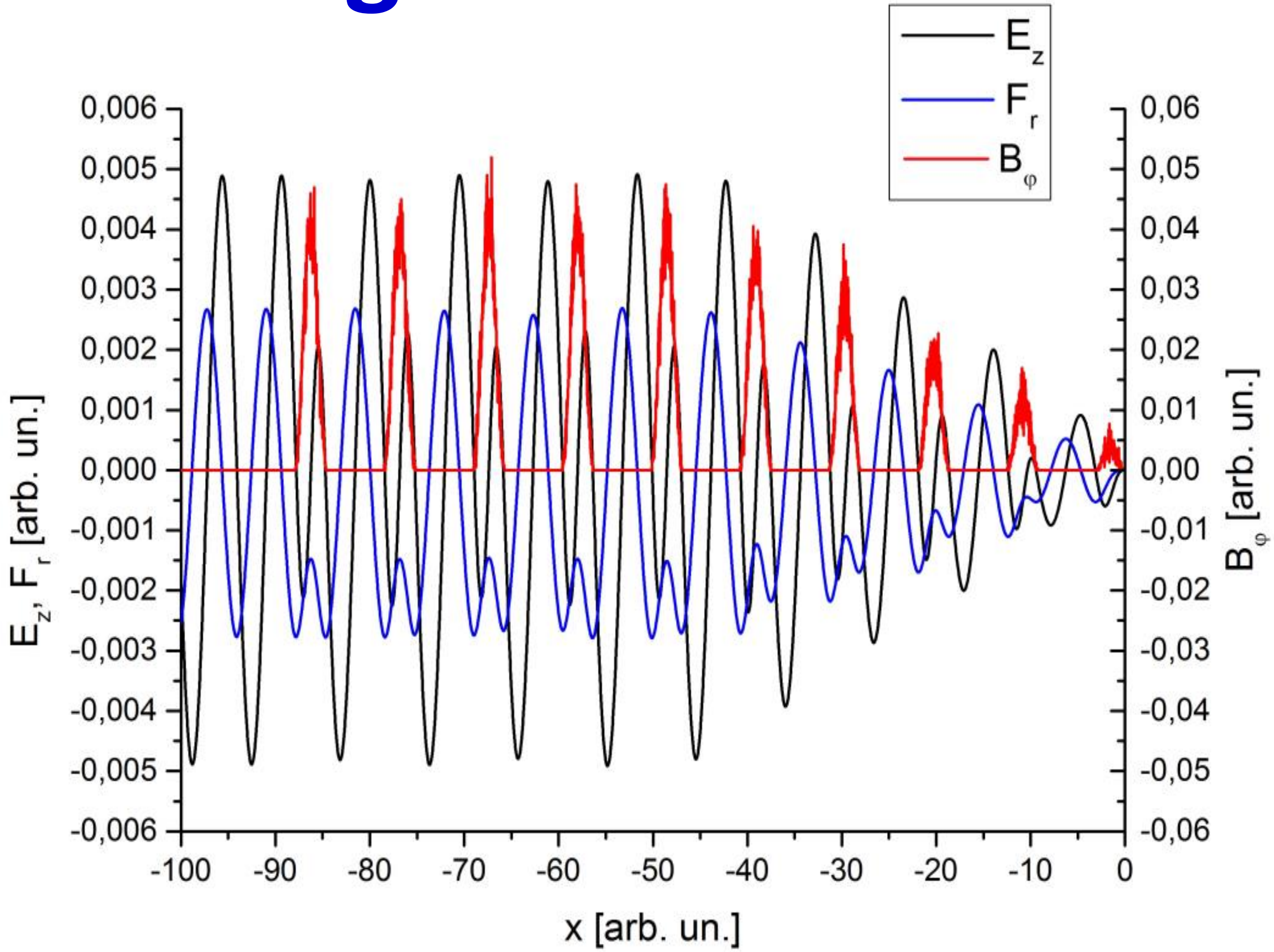
The lens with more uniform focusing force distribution

Because in Fig. 3-5 (slides 13-15) the focusing force is non-uniform, we consider wakefield lens with more uniform focusing force distribution (see Fig. 6) (slide 18).

The positron bunches have Gaussian profiles in the longitudinal and transverse directions. The charges of first . Gaussian bunches are shaped. One can see (Fig. 6) (slide 18) that radial wake force is identical for all bunches (after 5th bunch). But the centers of bunches are focused more slower than their fronts.

The profiling made it possible to provide the uniform focusing force. We considered several plasma positron lenses. Each of them has advantages and disadvantages and, at the same time, can be used to focus a sequence of bunches. In general, the first bunch of the sequence is defocused.

The lens with more uniform focusing force distribution



Off-axis (for $r = r_b$) longitudinal wakefield E_z, off-axis radial wake force F_r and off-axis magnetic field B_φ into the plasma

CONCLUSIONS

- **It has been shown that in proposed conditions all positron Gaussian bunches with exception of the first bunch (or several shaped bunches) of the sequence are focused identically but the centers of bunches are focused more slower than their fronts.**
- **To realize this kind of identical focusing of positron Gaussian bunches one need to consider the charges of all bunches are in $\sqrt{2}$ times larger than the charge of the first bunch. The interval between the first and second bunches is $(k + {}^{1}/_{8})\lambda$, k=1,2… The interval between other bunches is a multiple of excited wavelength λ.**
- **Another type of lens for positrons was considered in the article.**
- **Also this kind of identical focusing of positron Gaussian bunches is realized if the charges of first N shaped bunches increase along sequence according to: 2k-1, k≤N. The charges of next bunches equal 2N. The electron bunches, distributed through 1.5λ, have Gaussian profiles in the longitudinal and transverse directions. The length of the bunch (on the basis) is equal to ${}^{\lambda}/_{2}$.**

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Thank you

for your attention