SUPPRESSION OF BUNCH DESTRUCTION UNDER RESONANT EXCITATION OF THE PLASMA WAKEFIELD

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Acceleration by the wakefield in the plasma can provide compact sources of relativistic electron beams of high brightness. Free electron lasers and particle colliders, using plasma wakefield accelerators, require high quality bunches with predictable profile. Previous studies showed that the resonant sequence of electron bunches appears to be unstable due to the destruction of the bunches. In this paper we discuss the mechanism of this destruction due to the defocusing field phase shift in longitudinal direction which appears during this time evolution. We numerically and analytically showed the possible way of suppressing this instability, shifting all bunches by some distance relative to the first bunch.

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1. INTRODUCTION

High-efficiency acceleration of charged particle beams in the plasma wakefield accelerator in the blowout regime was studied experimentally and by numerical simulation in particular in [1–11]. In the case of a powerful driver, one driver is sufficient for self-injection of the accelerated bunch and/or for excitation of a sufficient accelerating field. At low intensity of a separate driver, self-injection of the accelerated bunch and/or acceleration of the self-injected bunch or of the bunch, injected from RF accelerator, to a sufficiently high energy can be achieved using longitudinally non-uniform plasma density [12–20] or by excitation of the accelerating wakefield by a short or long sequence of drivers [21–27]. In this case, it would seem that the most effective method of excitation should be resonant (see [21–22]). We present results of numerical simulation of plasma wakefield excitation by a sequence of relativistic electron bunches, made with 2.5D quasi-static code LCODE that treats plasma as a cold electron fluid and the bunches as ensembles of macro-particles.

Previous numerical simulations [28] and experiments [21–22] have demonstrated that a long resonant sequence of electron bunches develops instability. The heads of bunches begin to defocus and then destroy. In this paper we demonstrate that after the destruction of the bunch head, the new head begins to defocus. This effect occurs in the initial parts of the bunches and, increasing the amplitude of radial betatron oscillations for their back parts, leads to total destruction of the bunches. The primary cause of this effect is a phase shift of $\pi/2$ between the longitudinal field E_z and the focusing force F_r. Therefore, if the main part of the driver-bunch is located near the extremum of E_z, it is located in the vicinity of $F_r = 0$. From this follows that the head of the driver-bunch is located in the defocusing field. In this article we will investigate (numerically and analytically) the mechanism of this instability and possible ways to suppress it.

2. RESULTS OF NUMERICAL INVESTIGATION

Firstly, let us briefly consider the simulation results showing the longitudinal distribution of the fields (off-axis longitudinal wakefield E_z and off-axis focusing force F_r) and the temporal evolution of the bunch radius r. In all figures time is normalized on inverse electron plasma frequency $1/\omega_p$, distance – on c/ω_p, bunch current I_b – on the Alfvén current $I_A = 4\pi\epsilon_0 mc^3/e = 17kA$, electric field is normalized on $mc\omega_p/e$. e and m are the charge and mass of the electron, c is the light velocity, n_0 is the unperturbed plasma density. It is also important to note that in our modelling the frame moves with the speed of light, however the bunches move with speed $0.98c$ ($\gamma = 5$) and therefore the small shift of all values appears for times greater than the initial one.

As example, let us consider sequence of 8 resonant uniform bunches with length $l_b = \lambda/4$, where λ is the wavelength (the first bunch has length $\lambda/2$).

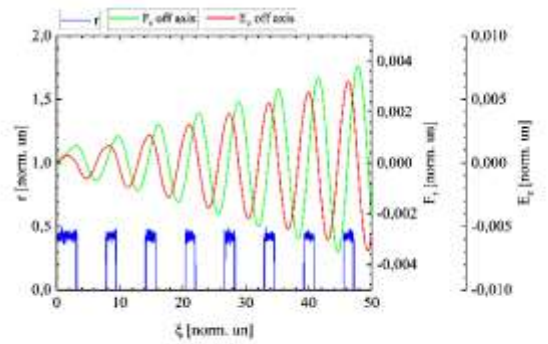

Fig. 1. E_z (red), F_r (green) and r (blue) for the resonant sequence of eight uniform bunches with length $l_b = \lambda/4$ (except the first one, which has length $l_b = \lambda/2$). This figure shows distribution at $z = 3$. Here and below, we use the axial coordinate system ($r, \xi = z - ct$). To demonstrate fast radial dynamics of bunches we chose the initial Lorentz factor of the electron bunches equal 5

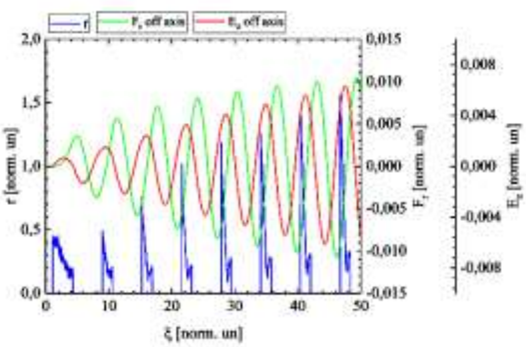

Fig. 2. E_z (red), F_r (green) and r (blue) for the resonant sequence of eight uniform bunches with length $l_b = \lambda/4$ (except the first one, which has length $l_b = \lambda/2$). This figure shows distribution at $z = 60$

From Figs. 1 and 2 one can see that front parts of the bunches, except the first one, are strongly defocused. However, the back parts are located in focusing field. After some period of time defocused front parts will leave the plasma channel created by the bunches. This means that this part will not further interact with the excited wakefield. This also happens in case of longer sequences [21, 22], [28]. This effect leads to the decreasing of the wakefield amplitude which means ineffective acceleration. Therefore, for this purpose and to have a predictable profile of the bunches one has to suppress this destruction.

Let us discuss the mechanism of this destruction. It appears that the defocusing field shifts into the bunch during the temporal evolution. This we can see on Fig. 3:

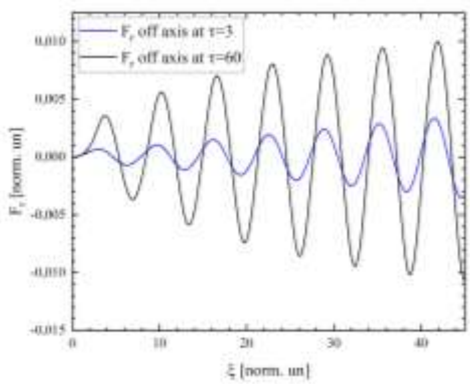

Fig. 3. Longitudinal distribution of $F_r(\xi)$ at $z = 3$ (blue) and $z = 60$ (black). Here $\tau = z/c$

From Fig. 3, one can see that during time evolution, as the front parts of the bunches defocus, the maxima of the focusing field shift relative to the bunches in the opposite direction of their motion. This may explain why bunches are destroyed so much. We can assume that after some time the defocused head of the bunch no longer interacts with the wakefield. This means that a new bunch with a smaller length must be considered. However, due to the phase shift of focusing field, the new head is also located in the defocusing field. This causes further destruction of the bunch.

Thus, to suppress bunch destruction, all bunches after the first must be shifted into a fully focusing field. Numerical investigation of shifted bunches with semi-cosine longitudinal profiles shows that indeed their destruction is suppressed.

3. RESULTS OF ANALYTICAL INVESTIGATION

As we mentioned in the previous section, to suppress the destruction of the bunches one has shift them into the fully focusing field. In this section we will consider analytical investigation of this problem and will show the exact value of the shift for uniform bunches.

Let us consider two resonance uniform bunches. The length of both bunches equals $\lambda/4$. Let us find the focusing field in linear regime inside the second bunch. For our problem one can get the radial force inside the second bunch [29]:

$$F_r(x) \propto 1 - 2\cos x + \sin x, \tag{1}$$

where $x = k\xi$ and $k = 2\pi/\lambda$.

The front of the second ($x = 0$) is located in defocusing field (for electrons $F_r < 0$). Therefore, the head of the bunch begins to defocus. Now let us find the length of the bunch's part which defocuses. To find it we have to solve the equation $F_r(x) = 0$. One can get easily that $x = 0.64$. Therefore, for $0 < x < 0.64$ the second bunch defocuses and for $0.64 < x < \pi/2$ the second bunch focuses.

Numerical simulations showed that after a certain time the head of the bunch becomes strongly defocused, as a result of which it ceases to interact with the wakefield. This fact means that we have to consider the second bunch without head:

$$F_r(x) \propto 1 + \sin x - \cos x - \cos(x - 0.64), \tag{2}$$

This is a model consideration under the assumption that at some point in time, the heads of all bunches, except the first one, expanded radially in the defocusing field so that they stopped interacting with the wakefield. For $F_r < 0$. It means that the new head of the second bunch also begins to defocus. These simple calculations show that the process of bunch destruction continues even after its head is removed. We can clearly observe this in the numerical simulation - the bunches become more and more defocused and destroyed over time.

Now our main goal is to shift the bunches to the fully focusing field. Let us consider the previous case, but now the distance between bunches equals $2\pi + l$. Let us find l:

$$F_r(x) \propto \sin x - \cos x + 1 - \cos(x - l). \tag{3}$$

To find l we have to set that $F_r(l) = 0$. After simple calculations one can get that $l = \pi/4$. And it is easy to see that for $\pi/4 < x < \pi/2 + \pi/4$ $F_r > 0$. Therefore, we shifted the second bunch into the fully focusing field, which grants that it will not become defocused and destroyed.

Using the same approach one can evaluate longitudinal distribution of accelerating field $E_z(x)$ and show that shifted bunch is located in decelerating field.

CONCLUSIONS

In this study, we investigated the mechanism of bunch destruction in plasma wakefield accelerators at wakefield excitation by resonant sequence of electron bunches and proposed a method to suppress it. Numerical simulations and analytical calculations demonstrated that the defocusing of bunch heads occurs due to their location in defocusing fields caused by a phase shift between the longitudinal electric field and the focusing force. This process leads to the sequential destruction of bunches over time. To suppress this instability, one can shift the bunches to fully focusing fields F_r. Numerical results confirmed that a semi-cosine-like bunch distribution, appropriately shifted, significantly reduces defocusing and stabilizes the bunches over time. This approach provides a viable path to improving the stability of plasma wakefield accelerators, contributing to the development of compact and efficient sources of high-brightness electron beams for advanced applications in particle accelerators and free-electron lasers.

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