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OBTAINING LONG ACCELERATED ELECTRON BUNCH OF GOOD QUALITY IN PLASMA WAKEFIELD ACCELERATOR AT HIGH TRANSFORMER RATIO*

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Abstract

The maximum energy of electrons accelerated by a wakefield, excited in a plasma by an electron bunch, is determined by the transformer ratio (see [1-11]). The transformer ratio is the ratio of energy acquired by the witness to energy lost by the driver. Approximately, the transformer ratio can be defined as $T_R = E_{ac}/E_{dec}$. Here E_{ac} is the maximum accelerating field after the driver bunch. E_{dec} is the maximum decelerating field inside driver bunch. T_R can be increased by shaping driver-bunch. In this paper, using a non-linear version of the 2d3v code LCODE [12], numerical simulation of excitation of a wakefield in a plasma in blowout regime by a shaped relativistic electron bunch was performed. There is also the problem of maintaining the small dimension and small energy spread of the accelerated electron bunch while maintaining sufficient values of the accelerating gradient and the transformer ratio. Also, the question arises about the values of the limiting dimension of the witness-bunch at which the acceleration process is stable. In this paper, the problem of the electron-bunch acceleration by a long shaped electron bunch is considered. Numerical simulation solves the problem of electron bunch acceleration of the high quality with simultaneous maximization of the transformer ratio and maximization of the witness-bunch length, at which the accelerating wakefield is uniform along witness-bunch.

INTRODUCTION

Despite the fact that wakefield accelerators, in theory, make it possible to reach very high accelerating gradient, which is extremely important for the development of modern physics, (since the current accelerators can no longer meet the demand of researchers), but to achieve these values into practice is difficult. A big problem is the emergence of dynamic electromagnetic fields in the plasma during the acceleration of the beam, since they defocus the beam. As a consequence, the control over the beam parameters becomes extremely difficult.

Now the idea of beam loading is actively developing to ensure a better acceleration process. The presence of some driver-bunch and some witness-bunch makes it possible to form accelerating fields of the same amplitude in the bunch-witness region. Such a field, in turn, provides acceleration of the beam as a whole. Hence, the question immediately arises of how long the accelerated bunches can be made so that it still forms a self-consistent accelerating wakefield of the plateau type. Also, it is necessary to figure out how to optimize not only the length of the witness bunch, but also the transformer ratio, which, in general, is responsible for the degree of acceleration of the bunch.

This paper demonstrates the results of numerical simulation obtained during the study of the dependence of the maximum length of the accelerated witness-bunch, which creates a self-consistent accelerating field, on the transformer ratio. The problem was considered for various driver-bunches.

We present results of numerical simulation of plasma wakefield excitation in blowout regime by a driver-bunch and of wakefield modification by witness-bunch, made with 2.5D code LCODE that treats plasma electrons and bunches as ensembles of macro-particles. We consider the bunch, electrons in which are distributed according to Gaussian in the transverse direction along the radius. We use the cylindrical coordinate system (r, z) and draw the plasma and beam densities and longitudinal electric field at some z as a function of the dimensionless time $\tau = \omega_p t$ or $\xi = V_b t - z$, V_b is the bunch velocity. Time, distance, bunch current I_b, fields are normalized to electron plasma frequency ω_{pe}, c/ω_{pe}, $I_{cr} = \pi mc^3/4e$, $mc\omega_{pe}/e$. e, m are the charge and mass of the electron, c is the light velocity.

INVESTIGATION OF THE DEPENDENCE OF THE MAXIMUM LENGTH OF THE WITNESS-BUNCH ON THE TRANSFORMER RATIO

Figures 1, 2 and 3 show the simulation results of witness-bunches with a maximum length, which create an accelerating wakefield of the plateau type, for different values of the transformer ratio. Due to the finiteness and continuity of the field, it can be understood that the transformer ratio is closely related to the distance between the witness-bunch and the driver-bunch. This is clearly seen from the data presented in these figures. Hence, it can be noted that with an increase in the transformer ratio, the maximum length of the studied witness-bunches should decrease. For comparison, let's look at the situation with a very long bunch-driver and a short bunch-witness (Fig. 4). It can be seen that under these conditions it is possible to achieve a significant transformer ratio.

To confirm this assumption, a series of numerical simulations were carried out for three different bunch-drivers (Figs. 5, 6, and 7). For different values of the transformer ratios, the witness-bunches with the maximum length were

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built. From the data obtained, it can be seen that, indeed, there is an inverse relationship between the value of the transformer ratio and the value of the maximum length of the witness-bunch. Also, it can be noted that with an increase in the size of the driver-bunch, the value of the maximum length of the witness-bunch increases, for the same values of the transformer ratio.

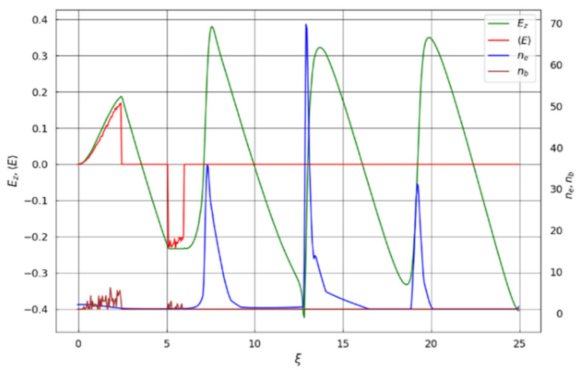

Figure 1: The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness, $\xi = z\text{-}V_b t$. Densities of bunches n_b on the axis are shown by brown. Average field $\langle E \rangle = \int E_z n_b r dr / \int n_b r dr$ is shown by red. Plasma electron density is shown to be blue as a function of the coordinate ξ along the plasma. The length of uniform bunch-driver is equal to 0.33 of nonlinear wavelength. The maximum current of bunch-driver is equal to $I_b = 2$ kA. The maximum current of bunch-witness is equal to $I_b = 0.9$ kA, $T_R = 1.2$.

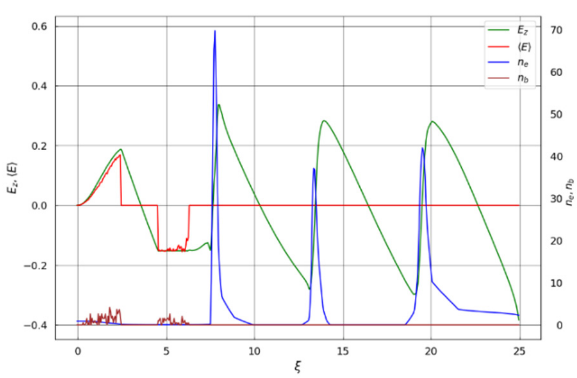

Figure 2: The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness, $\xi = z\text{-}V_b t$. The length of uniform bunch-driver is equal to 0.33 of nonlinear wavelength. The parameters of driver-bunch are the same as in Fig. 1. The maximum current of bunch-witness is equal to $I_b = 1.35$ kA, $T_R = 0.9$.

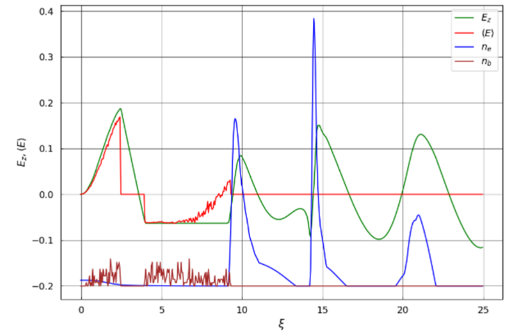

Figure 3: The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness, $\xi = z\text{-}V_b t$. The length of uniform bunch-driver is equal to 0.33 of nonlinear wavelength. The parameters of driver-bunch are the same as in Fig. 1. The maximum current of bunch-witness is equal to $I_b = 1.76$ kA, $T_R = 0.4$.

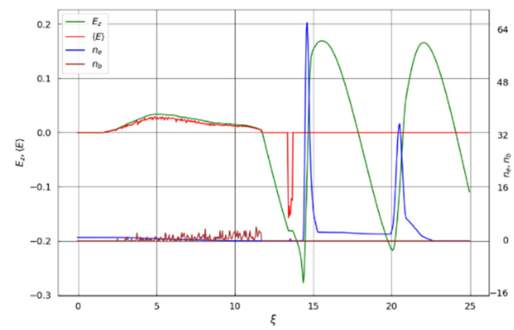

Figure 4: The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness, $\xi = z\text{-}V_b t$. Densities of bunches n_b on the axis are shown by brown. Average field <E> is shown by red. Plasma electron density is shown to be blue as a function of the coordinate ξ along the plasma. The length of uniform bunch-driver is equal to 2.5 of nonlinear wavelength. The maximum current of bunch-driver is equal to $I_b = 1$ kA. The maximum current of bunch-witness is equal to $I_b = 1$kA, $T_R = 5$.

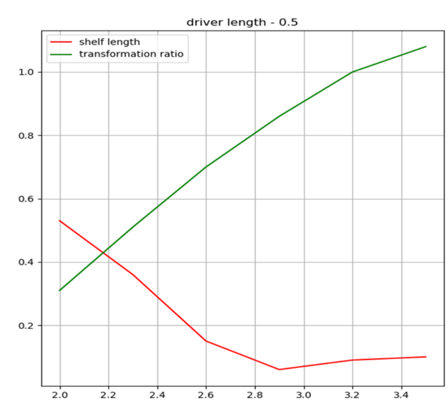

Figure 5: Dependence of the transformer ratio and the maximum length of the witness-bunch, depending on the distance between the witness-bunch and the driver-bunch. The driver-bunch length is 0.06 times the nonlinear wavelength.

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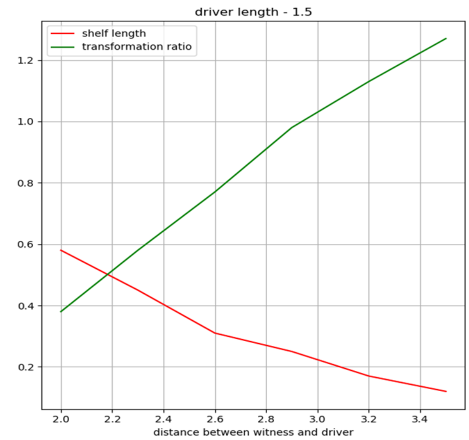

Figure 6: dependence of the transformer ratio and the maximum length of the witness-bunch, depending on the distance between the witness-bunch and the driver-bunch. The driver length is 0.23 times the nonlinear wavelength.

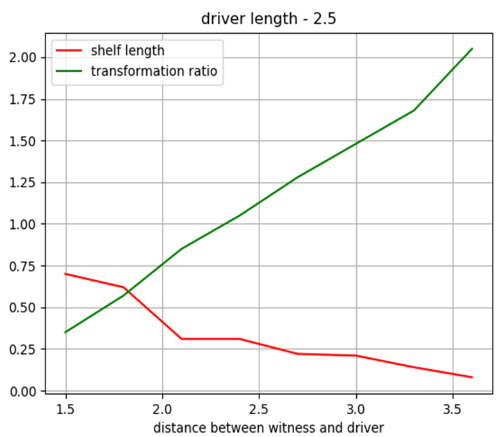

Figure 7: Dependence of the transformer ratio and the maximum length of the witness-bunch, depending on the distance between the witness-bunch and the driver-bunch. The driver length is 0.33 times the nonlinear wavelength.

CONCLUSION

By means of numerical simulations, the relationship between the transformer ratio and the maximum length of the witness-bunch has been demonstrated. The possibility of obtaining an accelerated bunch of good quality with a large transformer ratio is shown. The existence of the dependence of the values of the transformer ratio and the maximum length of the accelerated bunch on the dimensions of the bunch-driver is shown.

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