ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB155

OBTAINING ACCELERATED ELECTRON BUNCH OF HIGH QUALITY IN PLASMA WAKEFIELD ACCELERATOR*

R. Ovsiannikov†, V. N. Karazin, Kharkiv National University, Kharkiv, Ukraine
V. I. Maslov, I. P. Levchuk, I. N. Onishchenko,
National Science Center Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

Abstract

High-gradient plasma wakefield acceleration up to 100 GeV/m on the considerable length up to one meter has been already demonstrated experimentally [1, 2]. However producing accelerated electron bunch of high quality (charge, emittance, etc.) by plasma wakefield accelerators remains problematic.

In [3] optically triggered injection and acceleration of electron bunches, generated in a multi-component hydrogen and helium plasma, demonstrated. This 'plasma photocathode' decouples injection from wake excitation by liberating tunnel-ionized helium electrons directly inside the plasma cavity, where these cold electrons are then rapidly boosted to relativistic velocities. The injection regime is an important step towards the generation of electron beams with unprecedented low transverse emittance, high current and 6D-brightness.

To accelerate electron bunch of low energy spread, a method is usually used that involves the formation of the same accelerating gradient at the location of the bunch. The same accelerating gradient (plateau due to beam loading (see [4-7]) in the region of the accelerated bunch allow all its parts to move as a whole, and ensure the preservation of the spatial distribution of electrons over time, which, in fact, means an accelerated beam of high quality.

Also, the question arises about the limiting witness bunch length at which the accelerating wakefield is plateau-type. Beam loading has already been experimentally demonstrated in a beam-driven plasma accelerator (see [8]). In this report, the problem of the uniform accelerating wakefield (of plateau-type) formation due to witness-bunch loading is simulated in the cases of a short or long electron driver-bunch.

INTRODUCTION

High-energy particle physics requires more and more energy for research. For this, new accelerators are being built and old ones are being modernized. However, already now, the limits of energies to which particles can be accelerated are insufficient. And the only available way to increase the accelerated particles' energy to TeV value is to directly increase the size of the accelerator. This, in turn, entails an increase in the cost of the operating accelerators.

Conventional accelerators can provide accelerating gradients up to 100 MV/m. Such limitation is caused by the electrical breakdown. Obviously, in order to reduce the size and cost of the installation, it is necessary to increase accelerating gradient. Simulations and experiments show that there is a possibility of obtaining accelerating gradients up to 100 GV/m. In experiments [1] using front of 40 GeV bunch as a driver for plasma wakefield excitation the double energy of accelerated trailing edge of this bunch on one meter plasma length has been observed.

External injection of the bunch with a small size and a small energy spread, produced by a conventional accelerator, allows accelerating this bunch of high quality in high gradient plasma wakefield to high energy.

To compensate the energy spread of the accelerated electron bunch, it is possible to construct bunch of such a shape so that it forms a necessary self-consistent distribution of the accelerating wakefield. Such bunch should form an uniform accelerating wakefield in the region where the beam is located. This allows this bunch to be accelerated in the same way. Earlier it was shown [4-6] that in the case of acceleration of an electron bunch with external injection in a wakefield accelerator such self-consistent field of the plateau type can be obtained in a rather wide region of the excited wakefield. This raises the question of what maximum length of the accelerated bunch can be in order to form such a field.

In this paper, we report the results of numerical simulation on the problem of maximizing the length of the accelerated electron bunch, which creates a self-consistent field, which makes it possible to achieve minimum energy spread of the bunch. A mechanism for constructing such bunches was developed, as well as some dependences of their maximum length on the initial location of the bunch in the wakefield, excited by the bunch-driver, were obtained.

We present results of numerical simulation of plasma wakefield excitation in blowout regime by a driver-bunch and wakefield modification by witness-bunch using 2.5 D LCODE [9] that treats plasma electrons and bunches as ensembles of macro-particles. We consider the bunch, in which electrons are distributed according to Gaussian in the transverse direction along the radius. We use the cylindrical coordinate system (r, z, φ) 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 and fields are normalized to electron plasma frequency ω_{pe}, c/ω_{pe}, $I_{cr}=\pi mc^3/4e$ and $mc\omega_{pe}/e$. Here e, m are the charge and mass of electron, c is the light velocity.

*This work is supported by National Research Fundation of Ukraine "Leading and Young Scientists Research Support", grant agreement # 2020.02/0299.
† breakmannn@gmail.com

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB155

INVESTIGATION OF THE POSSIBILITY OF MAXIMIZING THE LENGTH OF THE BEAM FORMING THE DISTRIBUTION OF THE ACCELERATING WAKEFIELD OF THE PLATEAU TYPE

For convenience, we will build long accelerated beam from small longitudinal elements. Such small element, provided self-consistent plateau-type field in its area, do not distort field for neighbouring areas. That is, to build a long beam, which creates a self-consistent field, it is enough to alternately select the required charge of each small element of the beam, and, in the course of increasing the beam length, the field, in the already self-consistent region, remains so and does not change or changes extremely weakly.

We begin by considering a small bunch-driver. In Fig. 1 and Fig. 2, one can see the appearance of a self-consistent accelerating field, a plateau type. It is clearly seen that the sign of the accelerating field in these cases is opposite to the sign of the decelerating field of the bunch-driver, when, as in Fig. 3, due to the fact that the bunch-precursor is extremely close to the main bunch-driver, the signs of the decelerating fields for both bunches are the same. Also, it can be noted that the maximum dimensions of the accelerated beam depend on the proximity to the bunch-driver.

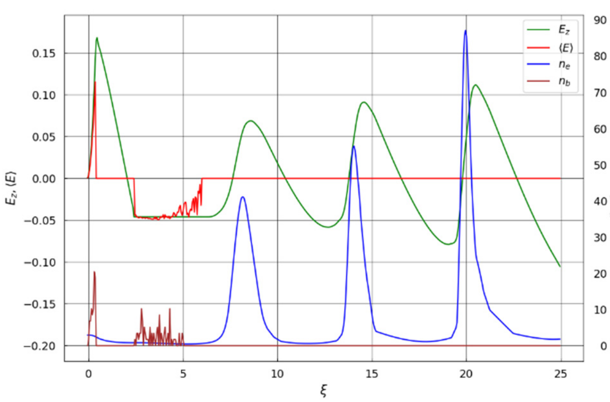

Figure 1: The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness, $\xi = z - V_b t$. Densities of bunches n_b on the axis are shown by brown. Average field $\langle E\rangle = \int E_z n_b r dr / \int n_b r dr$ is shown by red. Plasma electron density is shown to be blue as a function of the coordinate ξ along the plasma. The length of uniform bunch-driver is equal to 0.06 of nonlinear wavelength. The maximum current of bunch-driver is equal to I_b=5.015kA. The maximum current of bunch-witness is equal to I_b=0.9 kA.

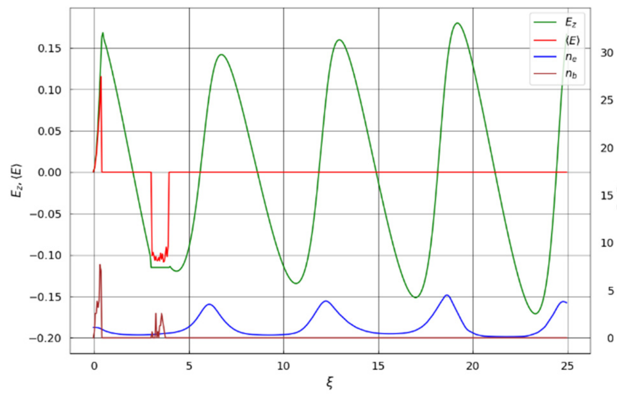

Figure 2: The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness, $\xi = z - V_b t$. Densities of bunches n_b on the axis are shown by brown. Average field $\langle E\rangle$ is shown by red. Plasma electron density is shown to be blue as a function of the coordinate ξ along the plasma. The parameters are the same as in Fig. 1. The maximum current of bunch-witness is equal to I_b=0.7 kA.

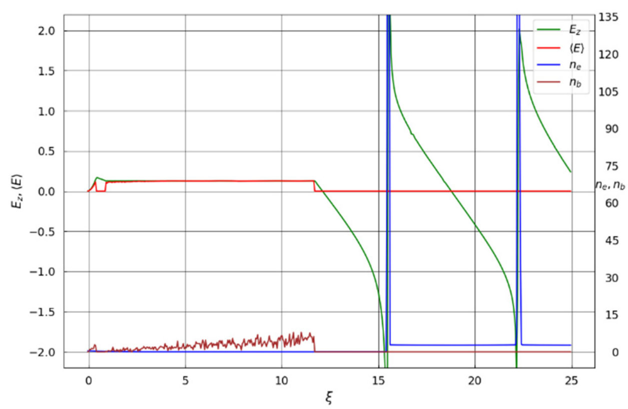

Figure 3: The on-axis wakefield excitation E_z by bunch-precursor and plateau formation on $E_z(\xi)$ by bunch-driver, $\xi = z - V_b t$. Densities of bunches n_b on the axis are shown by brown. Plasma electron density is shown to be blue as a function of the coordinate ξ along the plasma. The parameters are the same as in Fig. 1. The maximum current of bunch-driver is equal to I_b = 11 kA.

Figures 4 and 5 show the obtained beams of maximum length, which form an accelerating wakefield, such as a plateau. It can be noted that the longer bunch-driver is, the longer bunch-witness can be obtained.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB155

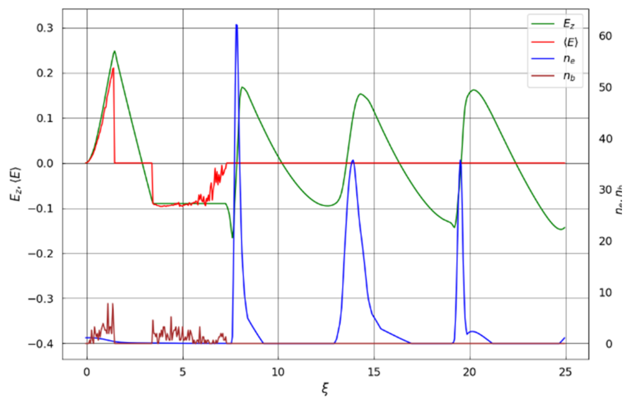

Figure 4: The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness, $\xi = z - V_b t$. Densities of bunches n_b on the axis are shown by brown. Average field <E> is shown by red. Plasma electron density is shown to be blue as a function of the coordinate ξ along the plasma. The length of uniform bunch-driver is equal to 0.23 of nonlinear wavelength. The maximum current of bunch-driver is equal to $I_b = 3$ kA. The maximum current of bunch-witness is equal to $I_b = 1.5$ kA.

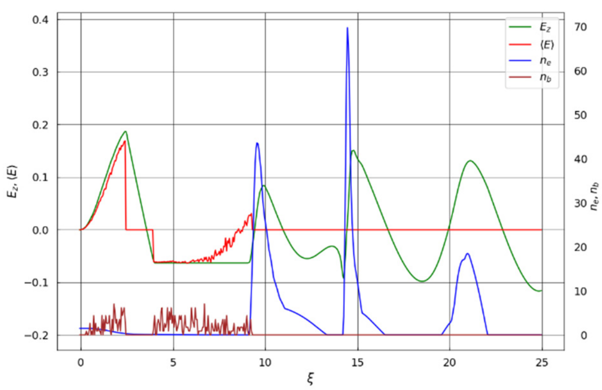

Figure 5: The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness, $\xi = z - V_b t$. Densities of bunches n_b on the axis are shown by brown. Average field <E> is shown by red. Plasma electron density is shown to be blue as a function of the coordinate ξ along the plasma. The length of uniform bunch-driver is equal to 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 $I_b = 1.76$ kA.

CONCLUSION

Numerical simulation was used to obtain such charge distribution of the witness-bunch, which makes it possible to obtain the longest section of a self-consistent accelerating wakefield of the plateau type. Such a field distribution makes it possible to reduce the energy spread in the beam. Some dependences of the length of such accelerated bunch on the relative position of the bunch-driver and its length are also shown.

ACKNOWLEDGEMENTS

This work is supported by National Research Fundation of Ukraine "Leading and Young Scientists Research Support", grant agreement # 2020.02/0299.

REFERENCES

[1] I. Blumenfeld *et al.*, “Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator”, *Nature*, vol. 445, pp. 741–744, 2007. doi:10.1038/nature05538

[2] A. J. Gonsalves *et al.*, “Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide”, *Phys. Rev. Lett.*, vol. 122, p. 084801, Feb. 2019. doi:10.1103/PhysRevLett.122.084801

[3] A. Deng *et al.*, “Generation and acceleration of electron bunches from a plasma photocathode”, *Nature Physic.*, vol. 15, no. 11, pp. 1156–1160, 2019. doi:10.1038/s41567-019-0610-9

[4] S. Romeo, M. Ferrario, and A. R. Rossi, “Beam loading assisted matching scheme for high quality plasma acceleration in linear regime”, *Phys. Rev. Accel. Beams.*, vol. 23, p. 071301, Jul. 2020. doi:10.1103/PhysRevAccelBeams.23.071301

[5] T. Katsouleas *et al.*, “Beam Loading in Plasma Accelerators”, *Particle Accelerators*, vol. 22, pp. 81–99, 1987.

[6] V. I. Maslov *et al.*, “Numerical Simulation of Plateau Formation by an Electron Bunch on the Distribution of an Accelerating Wakefield in a Plasma”, *Problems of Atomic Science and Technology*, no. 6, pp. 47–49, 2020. doi:10.46813/2020-130-047

[7] C. A. Lindstrøm *et al.*, “Energy-Spread Preservation and High Efficiency in a Plasma-Wakefield Accelerator”, *Phys. Rev. Lett.*, vol. 126, no. 1, p. 014801, 2021. doi:10.1103/PhysRevLett.126.014801

[8] M. Litos *et al.*, “9 GeV Energy Gain in a Beam-Driven Plasma Wakefield Accelerator”, *Plasma Phys. Contr. Fus.*, vol. 58, no. 3, p. 034017, 2016. doi:10.1088/0741-3335/58/3/034017

[9] A. P. Sosedkin and K.V. Lotov, “LCODE: A parallel quasistatic code for computationally heavy problems of plasma wakefield acceleration”, *Nucl. Instr. & Meth. In Phys. Res. A.*, vol. 829, pp. 350–352, 2016. doi:10.1016/j.nima.2015.12.032