Suppression of Emittance Growth of Externally Injected and Accelerated Electron or Positron Bunch due to Beam Loading

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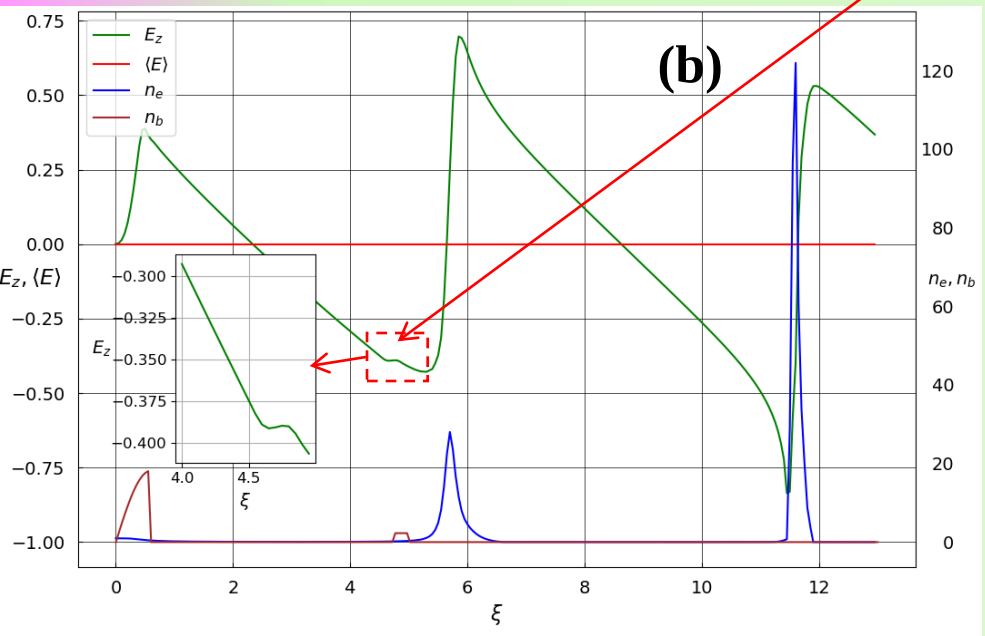
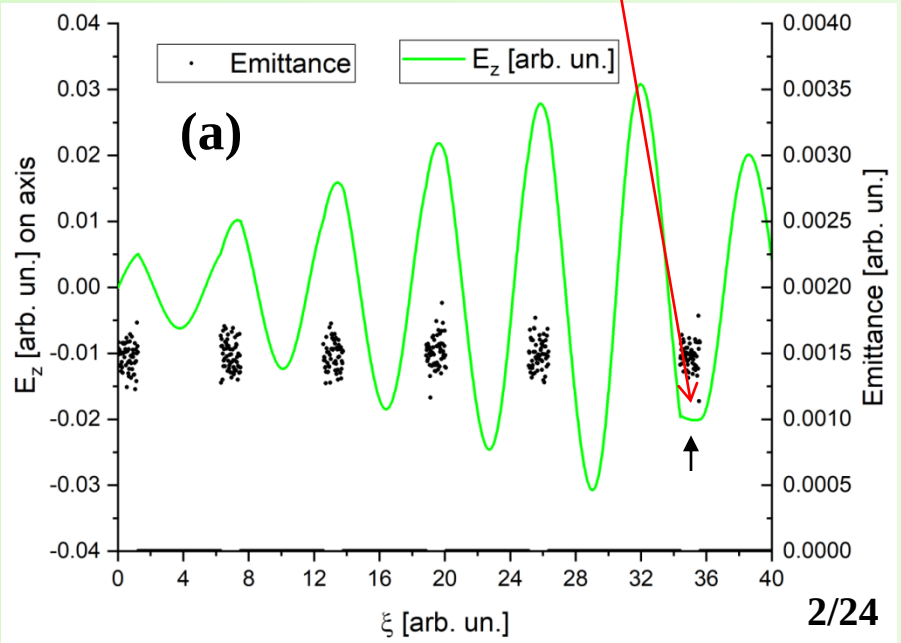
Aim

Plasma-wakefield acceleration promises compact sources of high-brightness relativistic electron and positron beams. Applications (particle colliders and free-electron lasers) of plasma-wakefield accelerators demand low energy spread beams and high-efficiency operation. Achieving both requires plateau formation on both the accelerating field for witness-bunch and the decelerating fields for driver-bunches by controlled beam loading of the plasma wave with careful tailored current profiles. We demonstrate by numerical simulation by 2.5D PIC code LCODE such optimal beam loading in a linear (a) and blowout (b) electron-driven and ion-driven plasma accelerator with RF generated low and high beam charge and high beam quality.



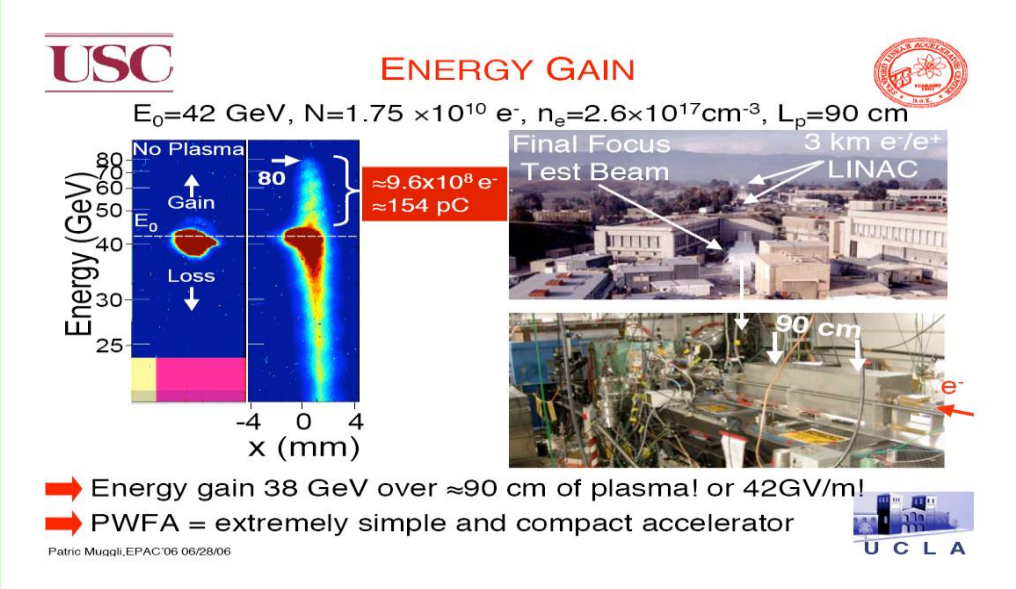


Introduction

Successful experiments on electron-bunch-driven wakefield acceleration have demonstrated acceleration of GeV-class electrons

Blumenfeld I., Clayton C.E., Decker F.-J. et al. 2007

and have therefore confirmed the relevance of this acceleration method.



Plasma-wakefield acceleration promises compact sources of high-brightness relativistic electron and positron beams. Because the plasma accelerators provide large accelerating gradients the plasma accelerators are intensively investigated:

Tajima T., Dawson J.M. 1979; Katsouleas T., Wilks S., Chen P., Dawson T.J.M., Su J.J. 1987;

Balakirev V.A., Onishchenko I.N., Sotnikov G.V. 1989;

Ayzatsky N.I., Dovbnya A.N., Kushnir V.A. et al. 1994;

Bulanov S.V., Pegoraro F., Pukhov A.M., A.S.Sakharov. 1997;

Tsakanov V.M. 1999; Esarey E., Schroeder C.B., Leemans W.P. 2009;

Lotov K.V., Maslov V.I., Onishchenko I.N. et al. 2010;

Kostyukov I.Y., Pukhov A.M. 2015; Shcherbinin M.A., Anisimov I.O. 2015;

V. Kubytskyi , C. Bruni, K. Cassou, V. Chaumat, N. Delerue et al. 2019;

Romeo S., Ferrario M., Rossi A.R. 2020 …

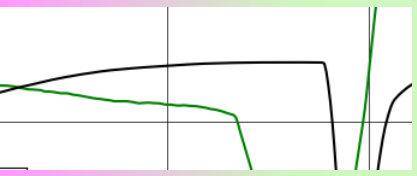
Parameters of Numerical Simulation

The results of numerical simulation of the excitation of the wakefield in the plasma in the linear regime, using the 2.5D LCODE code, which considers the electrons of the beam as ensembles of macroparticles, and the electrons of the plasma as a cold electron fluid, are presented. And the results of numerical simulation of the excitation of the wakefield in the plasma in the nonlinear regime, using the 2.5D LCODE code, which considers the electrons of the beam and the electrons of the plasma as ensembles of macroparticles, are presented. A bunches, in which electrons are distributed according to the Gaussian distribution in the transverse direction along the radius, is considered. A cylindrical coordinate system (r, z) is used. Plasma and beam density, longitudinal electric field at some z is calculated as a function of dimensionless time t or $\xi=z-V_b t$, where V_b is the bunch velocity. Time is normalized to the inverse electron-plasma frequency ω_{pe}^{-1}, distance - to c/ω_{pe}, beam current I_b - to $I_{cr}=\pi mc^3/4e=17$kA, fields are normalized to $mc\omega_{pe}/e$, momentum - to mc, where e and m - charge and mass of the electron, c is the speed of light. Spatial step equals $0.1c\omega_{pe}^{-1}$. Time step for plasma electrons equals $0.1\omega_{pe}^{-1}$.

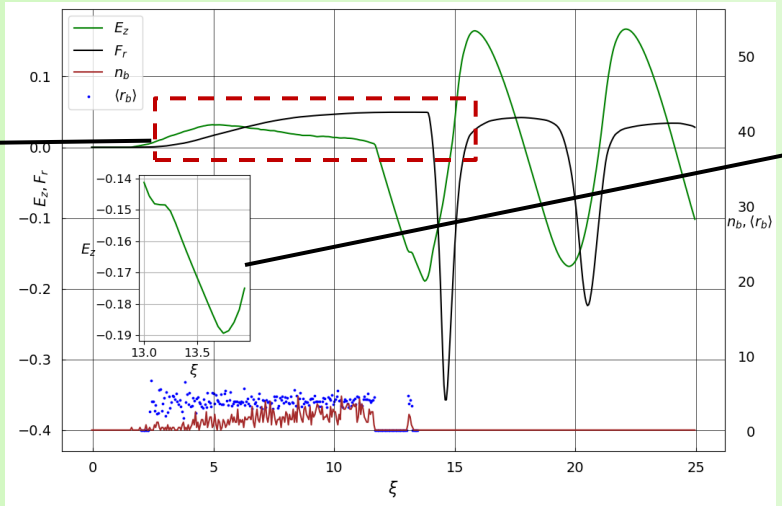
Time step for beam electrons - $0.1\sqrt{\gamma_b}\,\omega_{pe}^{-1}$.

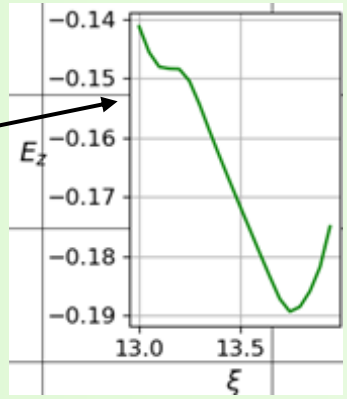
High-quality accelerated beams

At acceleration it is necessary $F_r(\xi)$=const, $E_z(\xi)$=const.



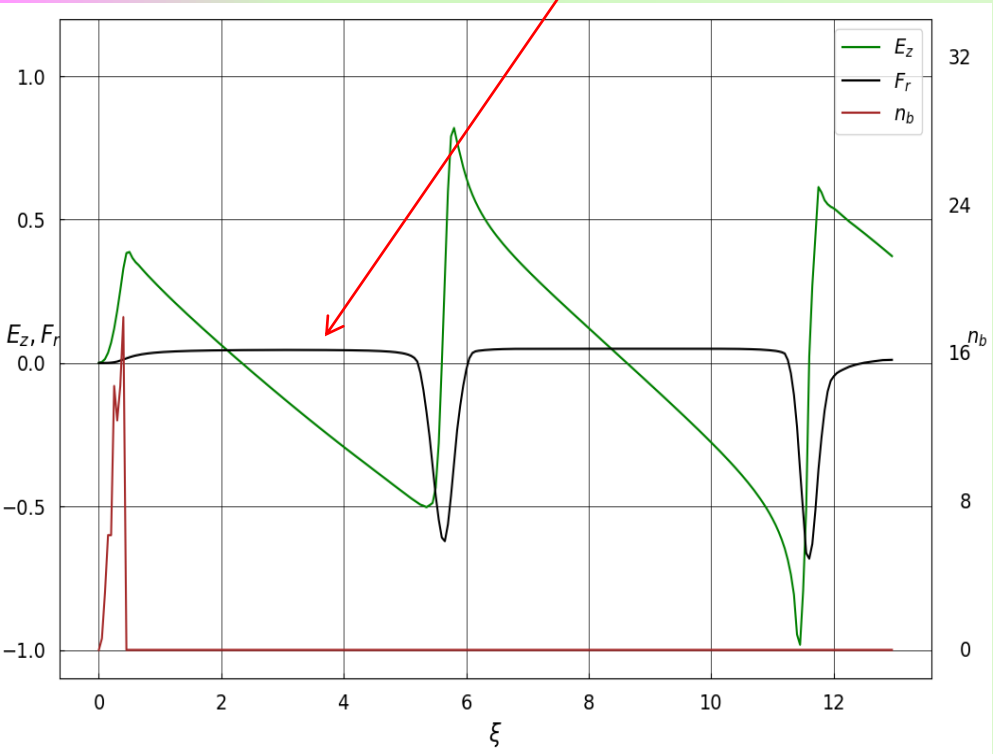
All electrons of the bunch are focused with the same force



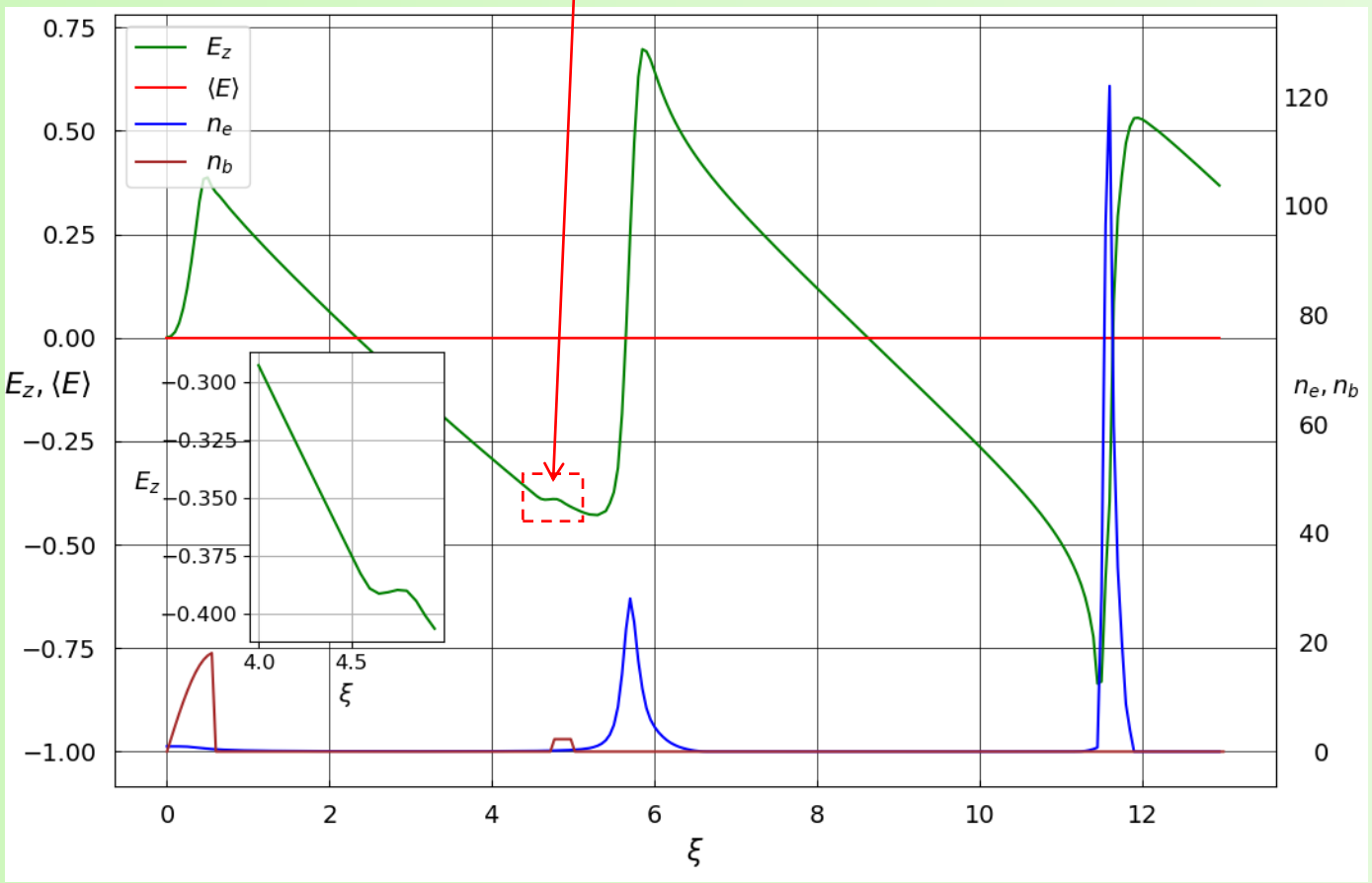


All electrons of the bunch are accelerated with the same force

Simultaneously with the creation of plateau for the accelerating and decelerating fields, it is important to ensure the focusing of the accelerated and exciting bunches. Earlier, we considered simultaneously focusing and excitation of the wakefield for the problem of the so-called transformer ratio, which characterizes to what energy particles can be accelerated at the same energy of the bunches, exciting the wakefield. Ensuring the focusing of driver bunches is important in the problem of excitation of the wakefield by driver-bunches. Ensuring the focusing of accelerated bunch of charged particles is important in the problem of their acceleration by an excited wakefield. We will try to ensure the simultaneous focusing of both the witness- and the driver-bunches in the problem of the excitation of the wakefield by the driver-bunches and the acceleration of the witness-bunch by this excited wakefield. In the case of small decelerating fields, in the problem of the so-called transformer ratio, we tried to ensure efficient excitation of the wakefield and, at the same time, focusing of the driver bunches.

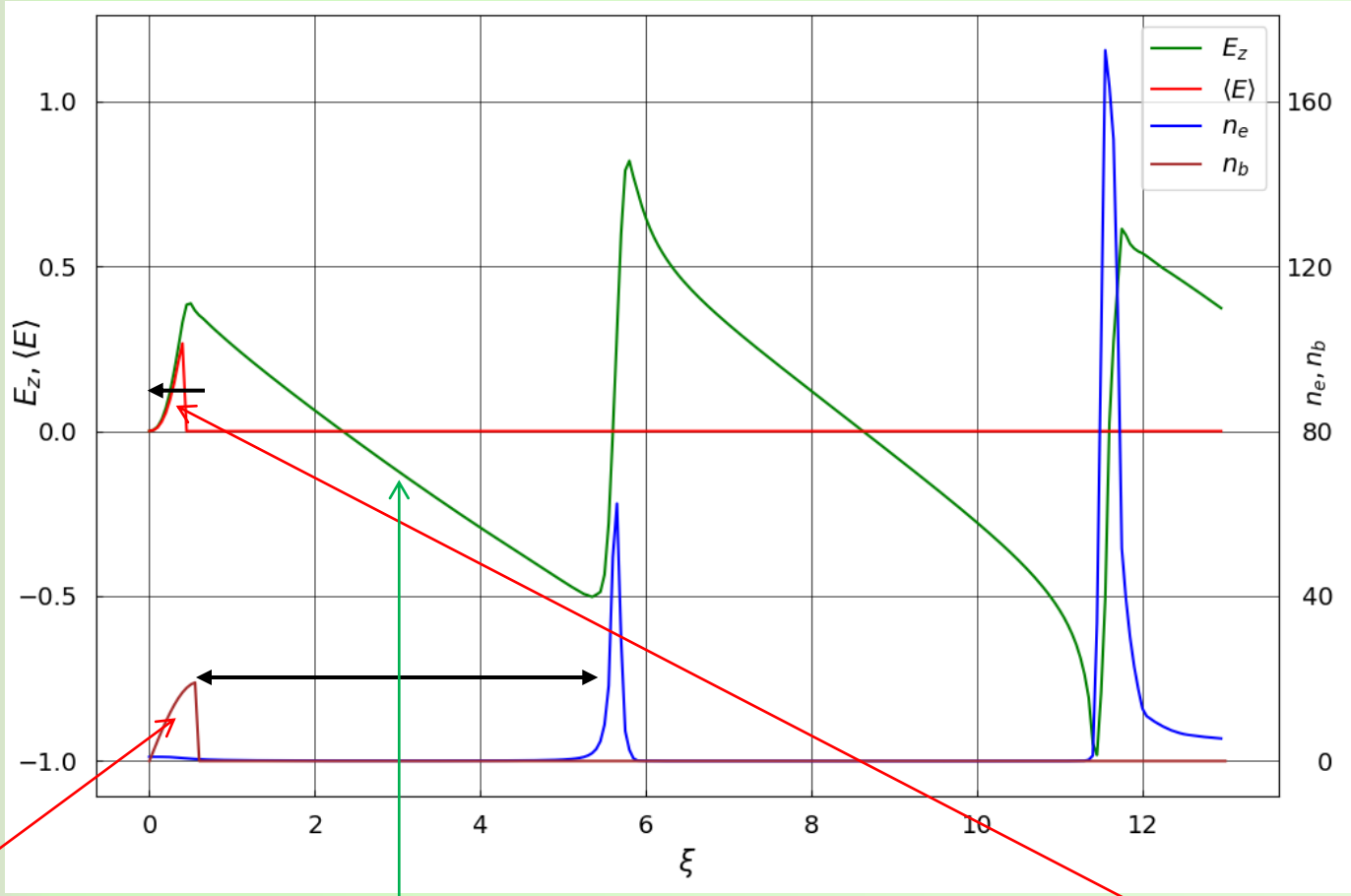


First, we developed procedure of a plateau formation for an accelerated (witness-) bunch for, in our opinion, more difficult conditions, namely, in the nonlinear case.



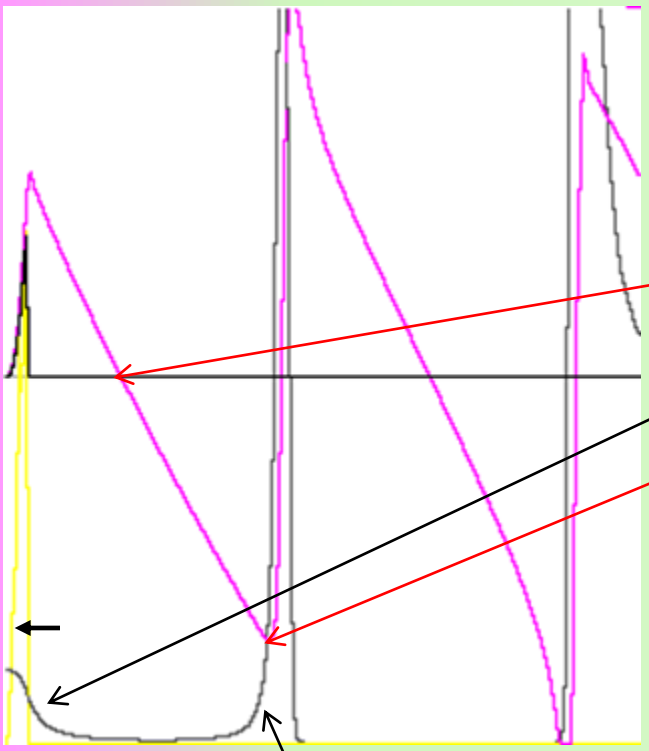
Plateau Formation on the Distribution of an Accelerating Wakefield in a Plasma by an Electron Witness-Bunch

To begin with, we consider the wakefield excitation in plasma in blowout regime by short electron bunch without witness-bunch.



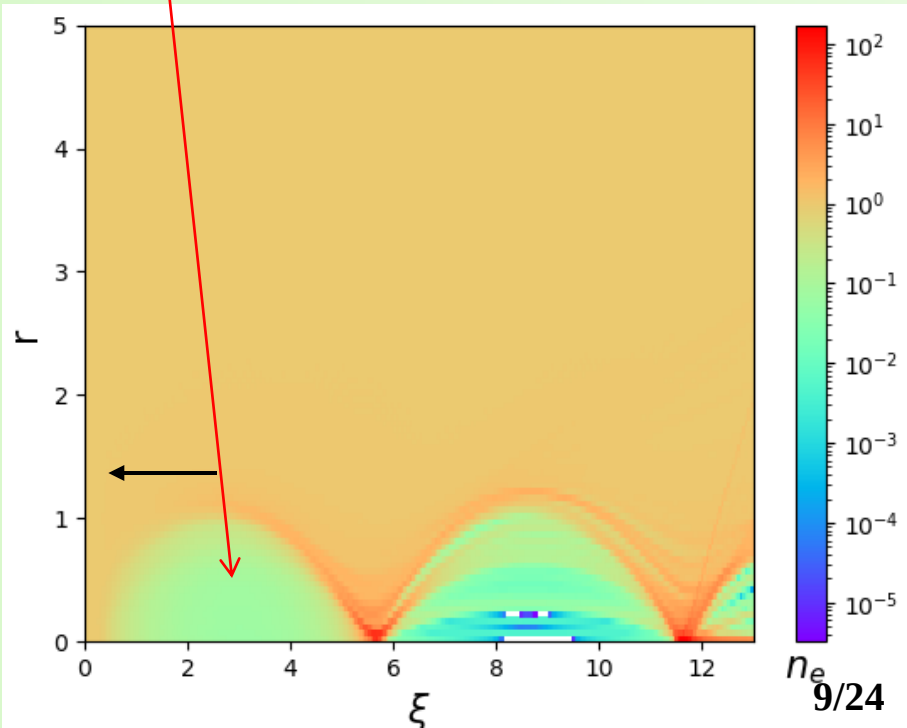
The on-axis wakefield excitation E_z by electron bunch-driver. The mean field E_0. Density of bunch-driver n_b on the axis. Plasma electron density n_e. The length of uniform bunch-driver is equal to 0.08 of bubble length. The maximum current of bunch-driver is equal to I_b=12.24kA. The direction of movement of the bunch-driver is shown by a one-way arrow. The area of 1st bubble is shown by a double-headed arrow.

Formation of Linear Dependence $E_z(\xi)$ at Wakefield Excitation by Short Driver-Bunch



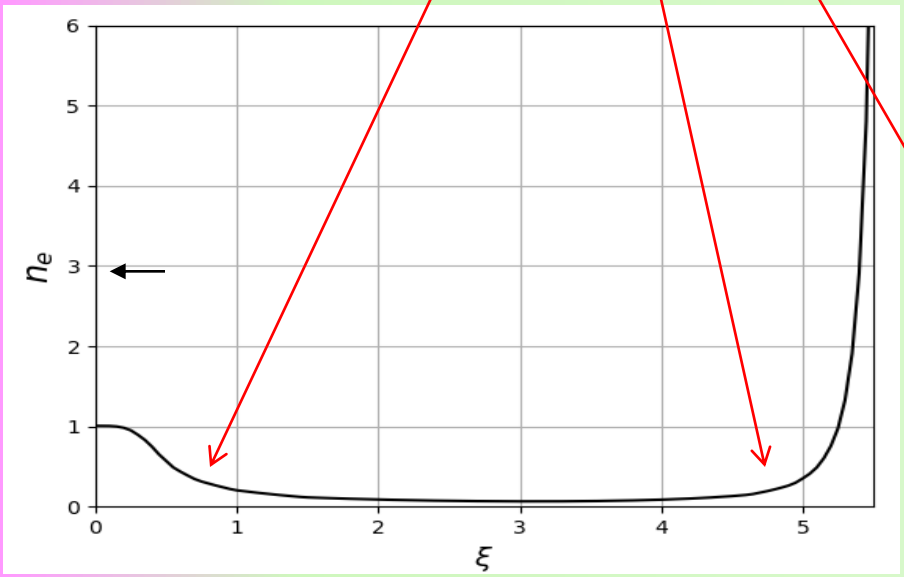
One can see that the plasma electrons have not completely left bubble. However, this case is good because on the acceleration interval, a linear longitudinal distribution of the accelerating wakefield $E_z(\xi)$ is observed. Then, if we achieve the formation of a plateau on $E_z(\xi)$ at some point ξ, then the plateau will be maintained at all points ξ in the process of witness acceleration and its shift inside the bubble.

The on-axis wakefield excitation E_z by electron bunch-driver. The mean field E_0. Density of bunch-driver n_b on the axis. Plasma electron density n_e.

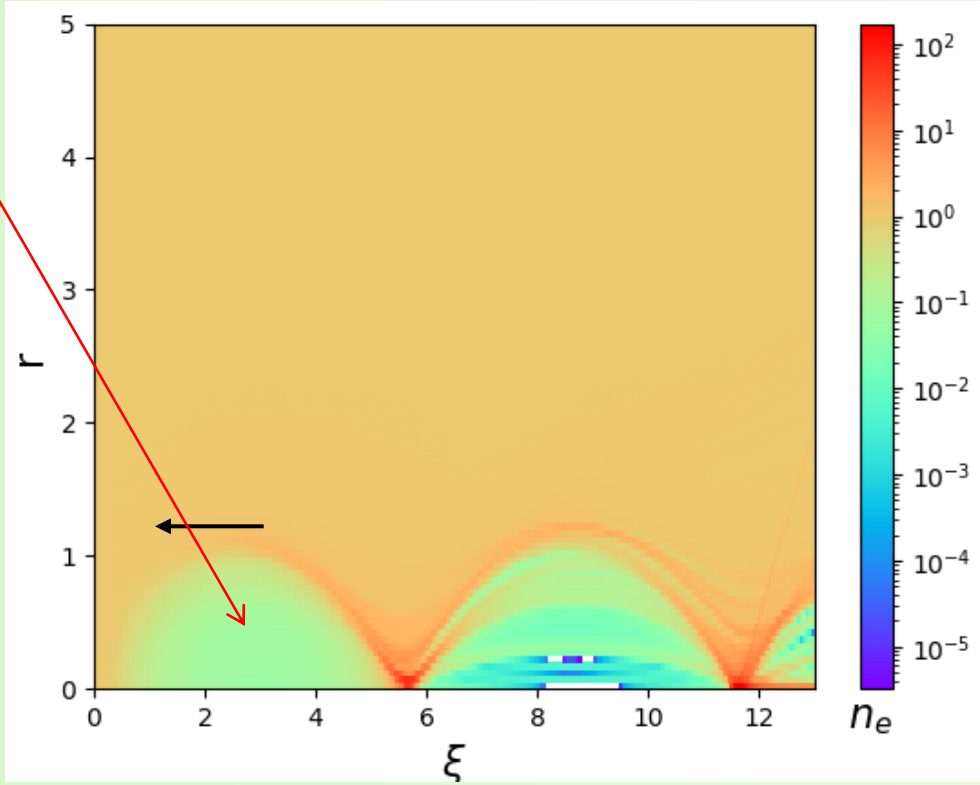


$n_e(\xi,r)$

Partially Filled Bubble at Formation of Linear Dependence $E_z(\xi)$ at Wakefield Excitation by Short Driver-Bunch

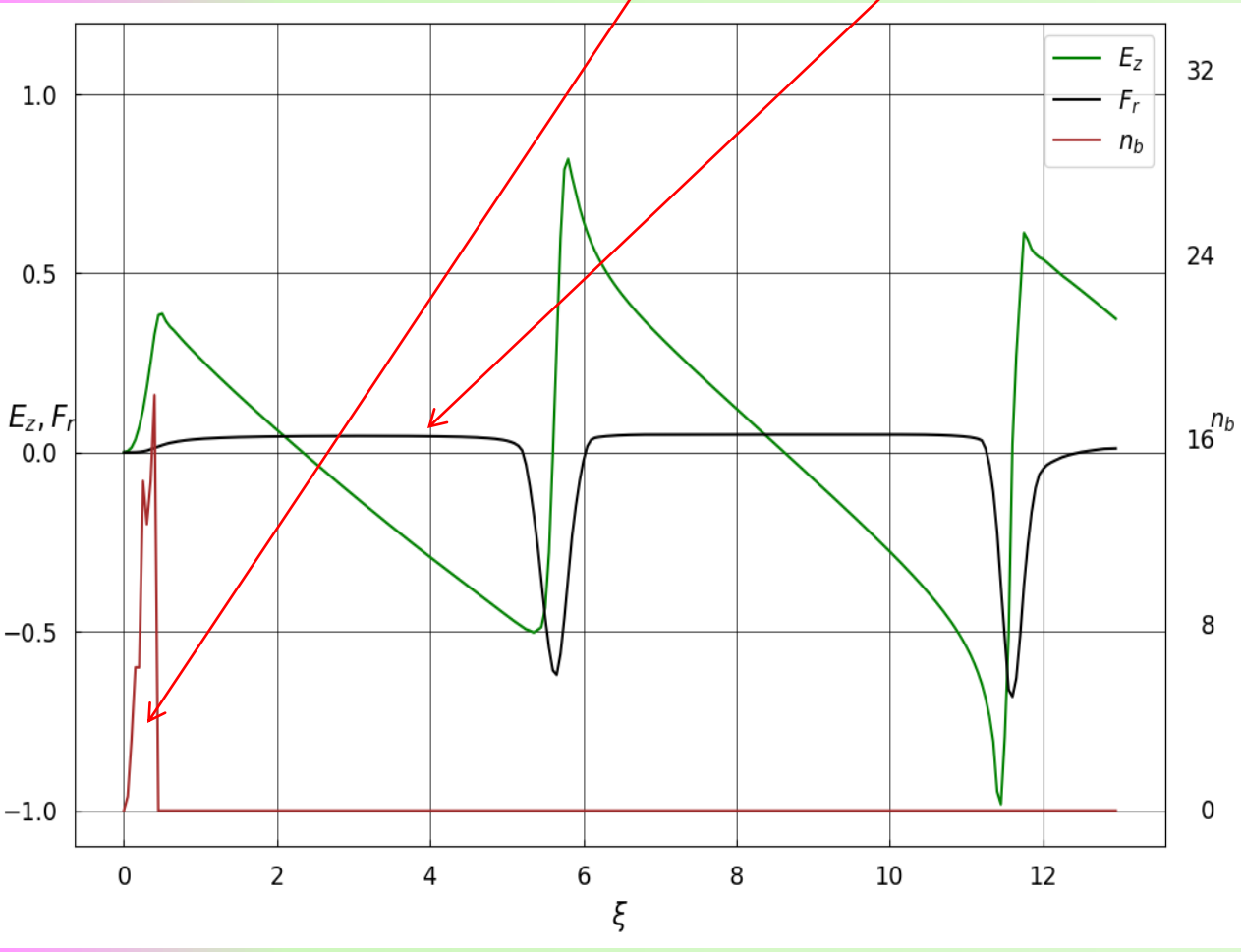


Plasma /electron density $n_e(\xi)$



$n_e(\xi,r)$

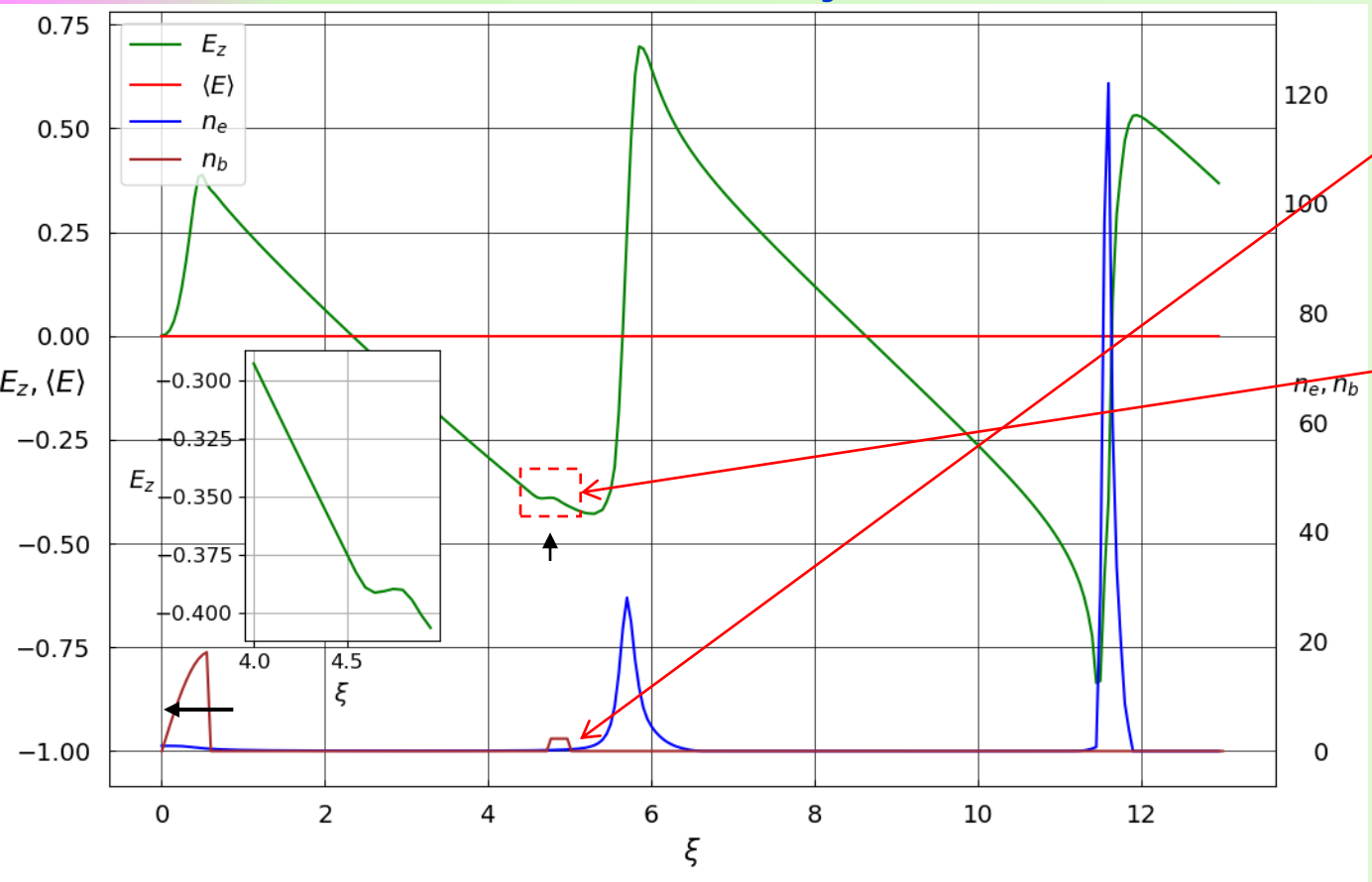
Formation of Linear Dependence $E_z(\xi)$ at Wakefield Excitation by Short Driver-Bunch and Uniform Focusing Field



At the same time on a considerable part of interval of acceleration the uniform focusing field is formed.

The off-axis wakefield excitation E_z by short driver-bunch. The off-axis densities of bunches n_b are shown by brown. The off-axis wake focusing force F_r is shown to be black as a function of the coordinate ξ along the plasma

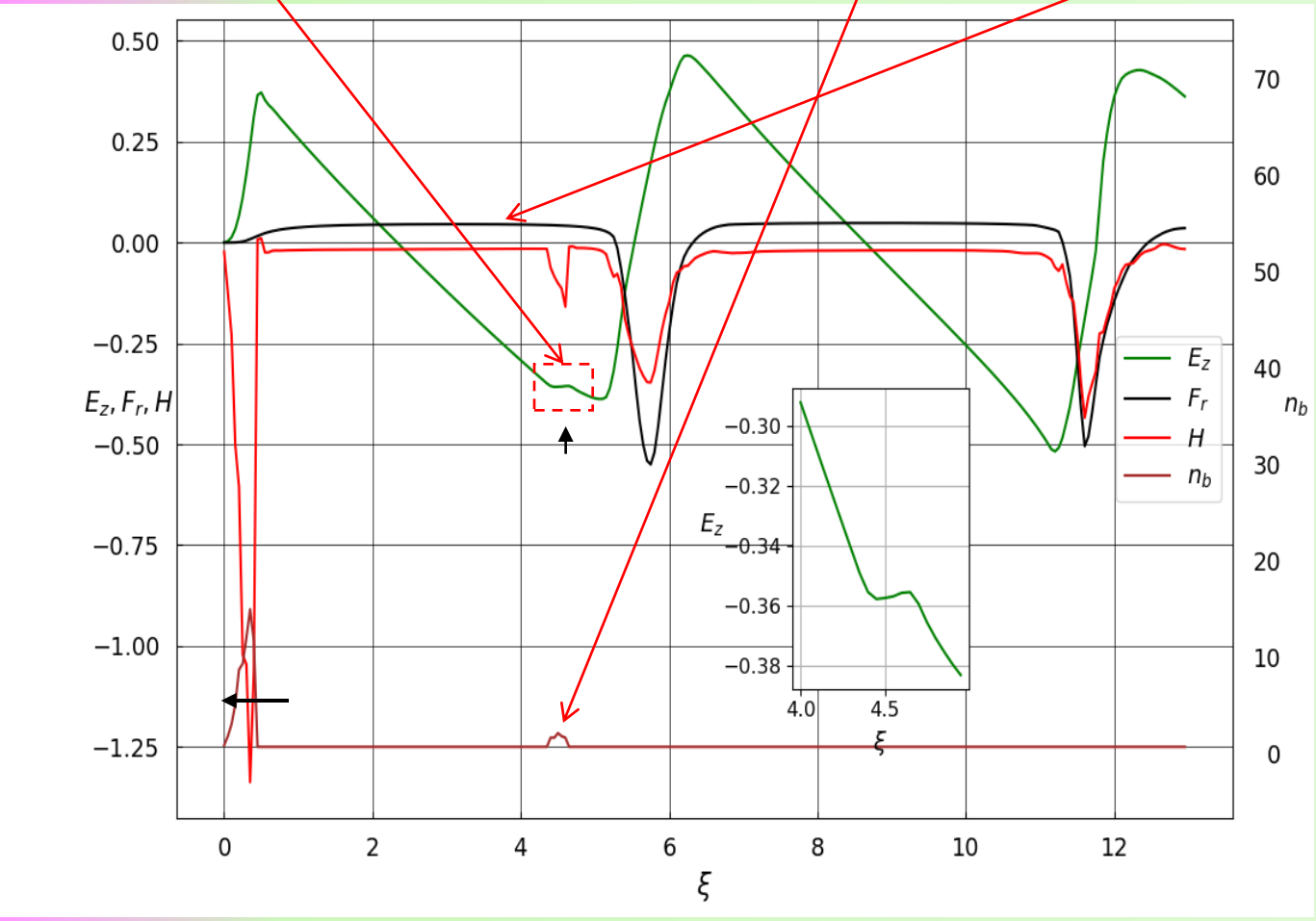
Plateau Formation on the Distribution of an Accelerating Wakefield in a Plasma by a Short Electron Witness-Bunch at Wakefield Excitation by Short Driver-Bunch



One can see that witness-bunch (homogeneous) of a certain charge leads to the formation of a plateau at $E_z(\xi)$ at the bubble periphery.

The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness, ξ=z-V_bt. Densities of bunches n_b on the axis. Plasma electron density n_e. The maximum current of bunch-witness is equal to I_b=1.0kA. The arrow shows the plateau

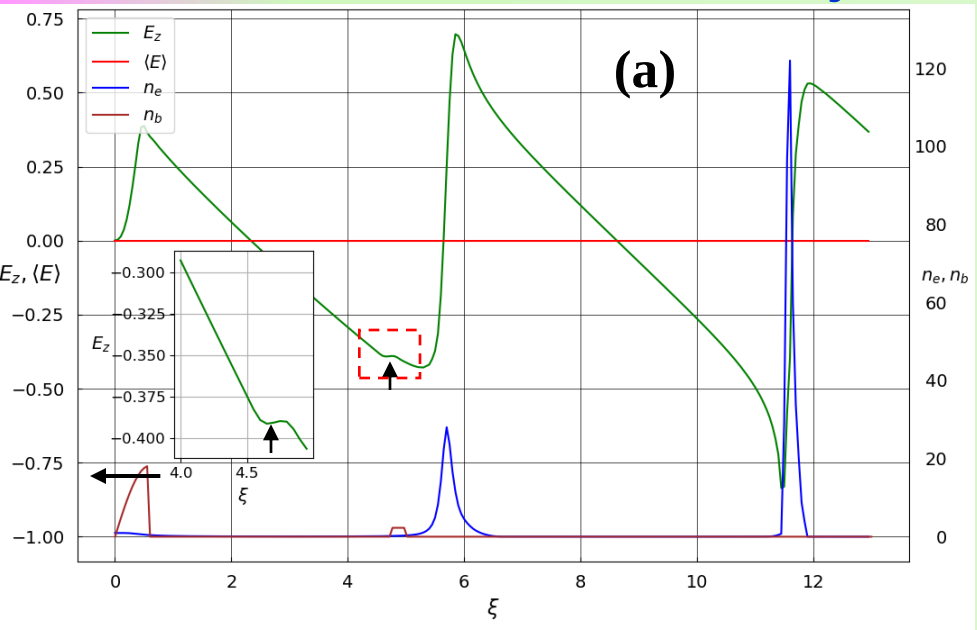
Plateau Formation on the Distribution of an Accelerating Wakefield for a Short Electron Witness-Bunch and Uniform Focusing Field

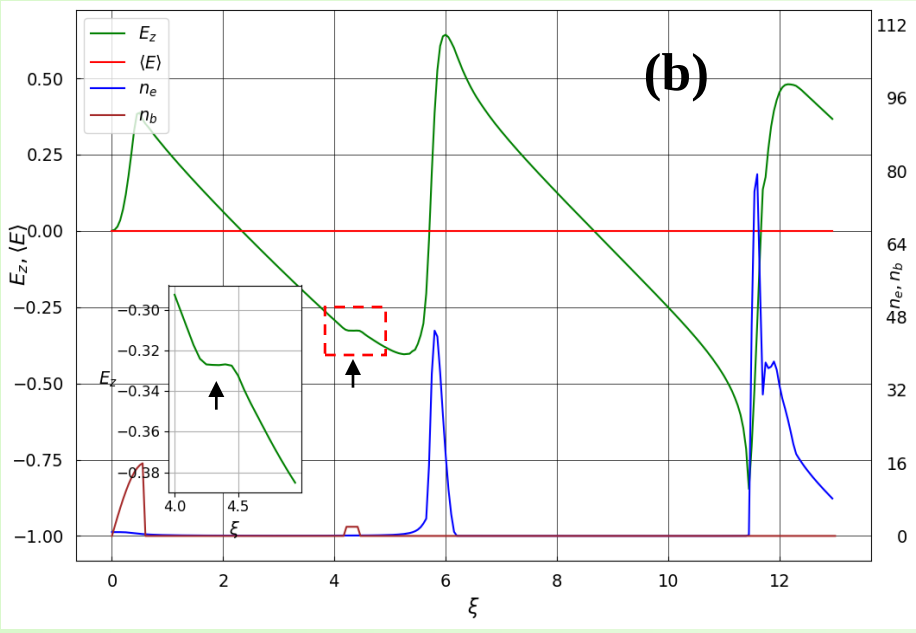


The plateau is formed and the witness-bunch is in a uniform focusing field.

The off-axis wakefield excitation E_z by short driver-bunch. The off-axis densities of bunches n_b are shown by brown. The off-axis wake focusing force F_r is shown to be black as a function of the coordinate ξ along the plasma. The arrow shows the plateau

Plateau Formation on the Distribution of an Accelerating Wakefield in a Plasma by a Short Electron Witness-Bunch at Wakefield Excitation by Short Driver-Bunch

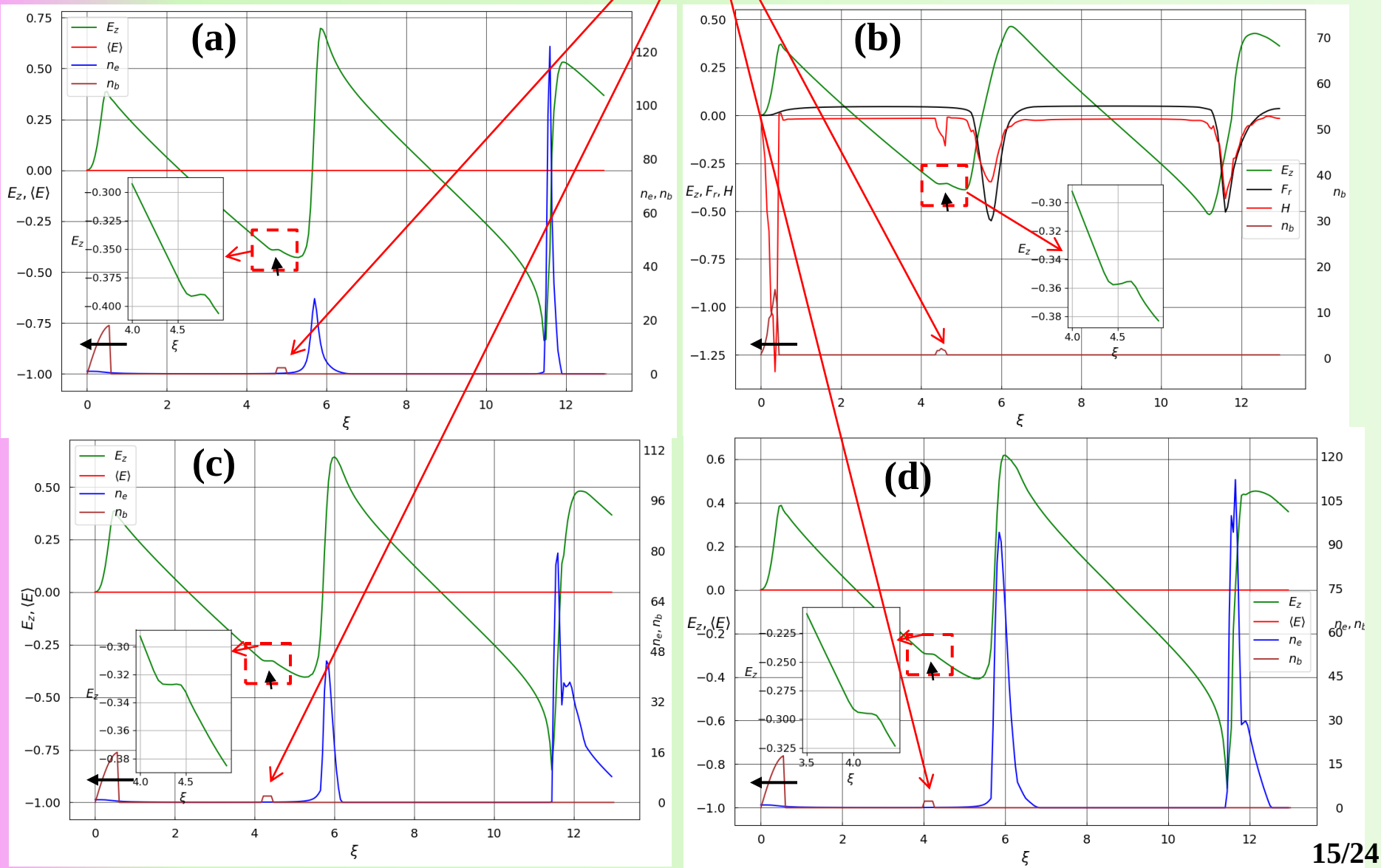


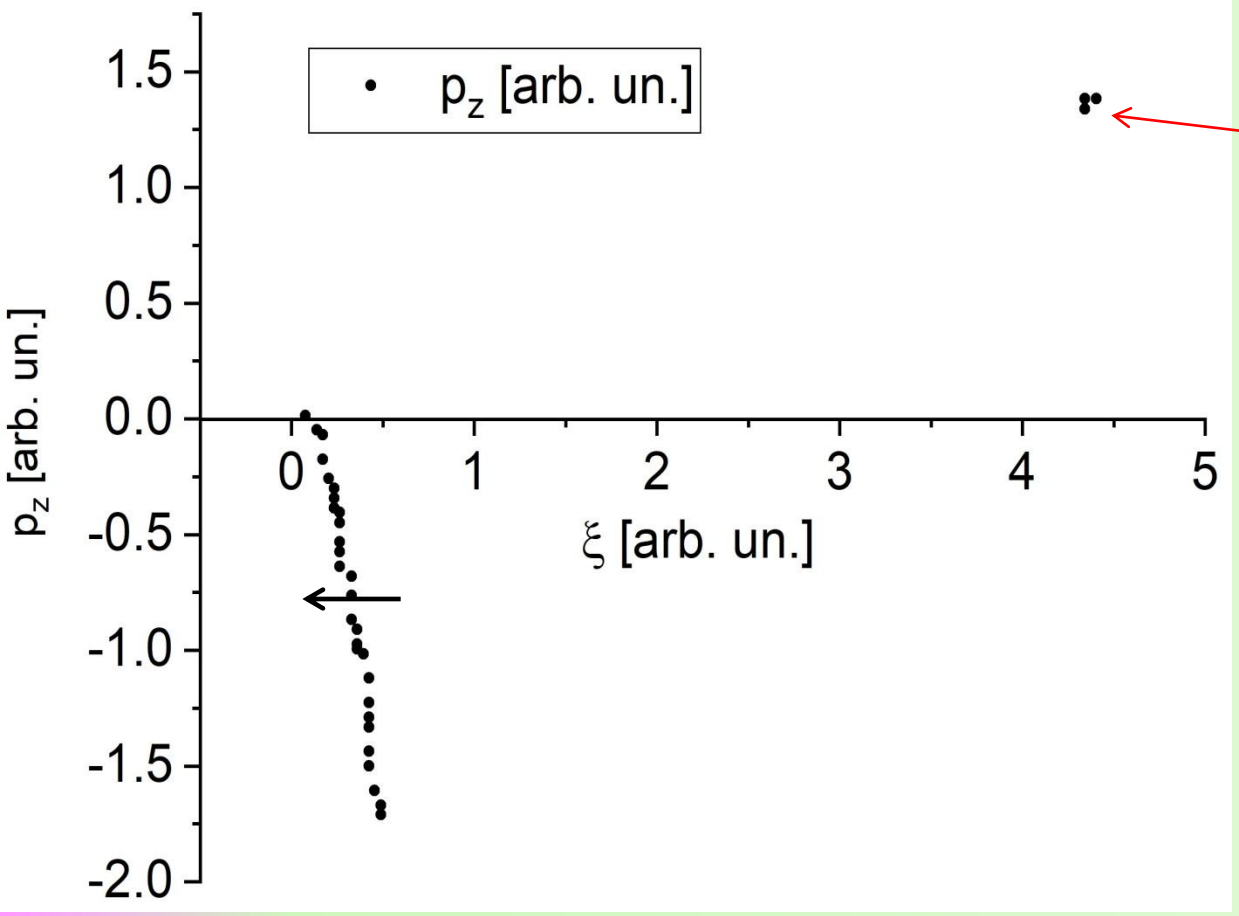


The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness. Densities of bunches n_b on the axis. Plasma electron density n_e. The arrow shows the plateau

At acceleration witness-bunch shifts into a bubble. We consider the dependence of plateau formation on the placement of witness in the bubble. Indeed, in (a) one can see that witness, with a certain charge and shape, forms a plateau in the distribution of the wakefield $E_z(\xi)$ on the periphery of the bubble. Also, a plateau is formed when the witness shifts inside the bubble (b).

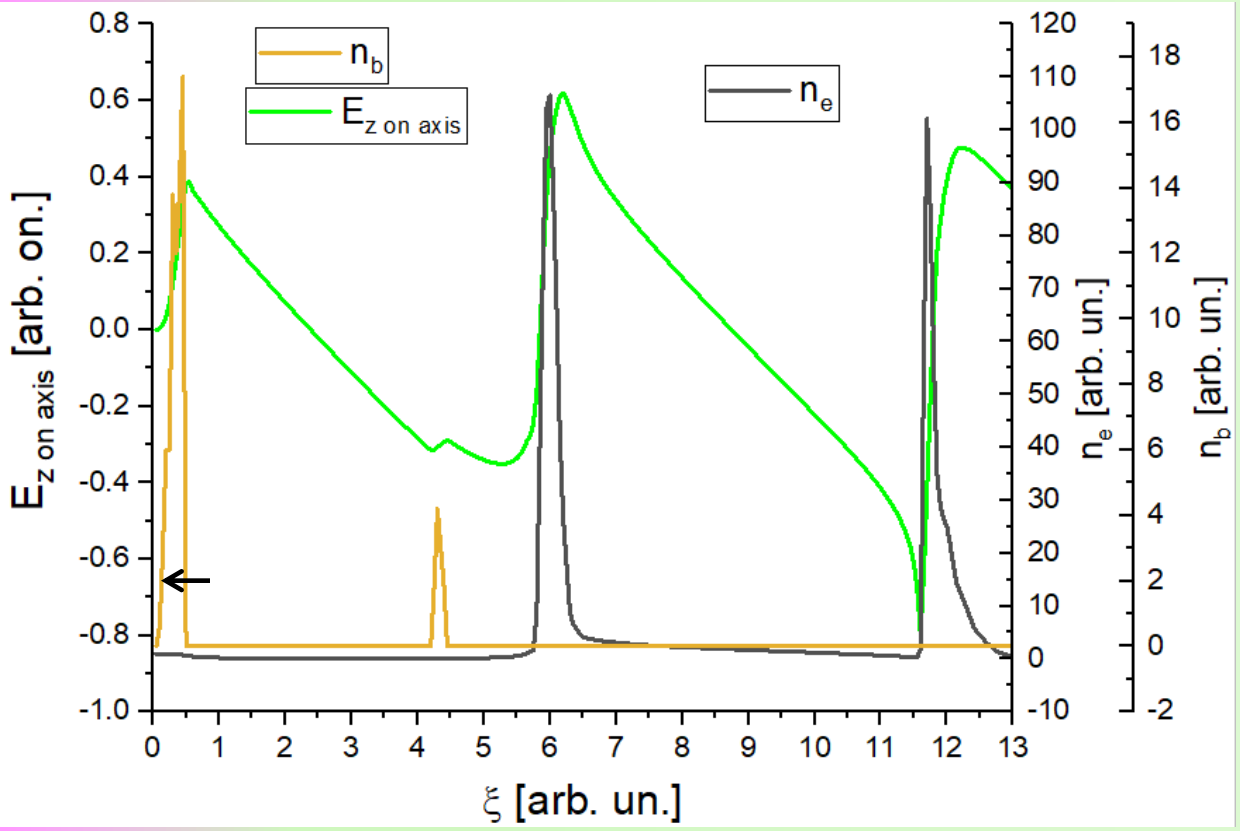
Shift of Supported Plateau into the Bubble at Acceleration of Witness-Bunch





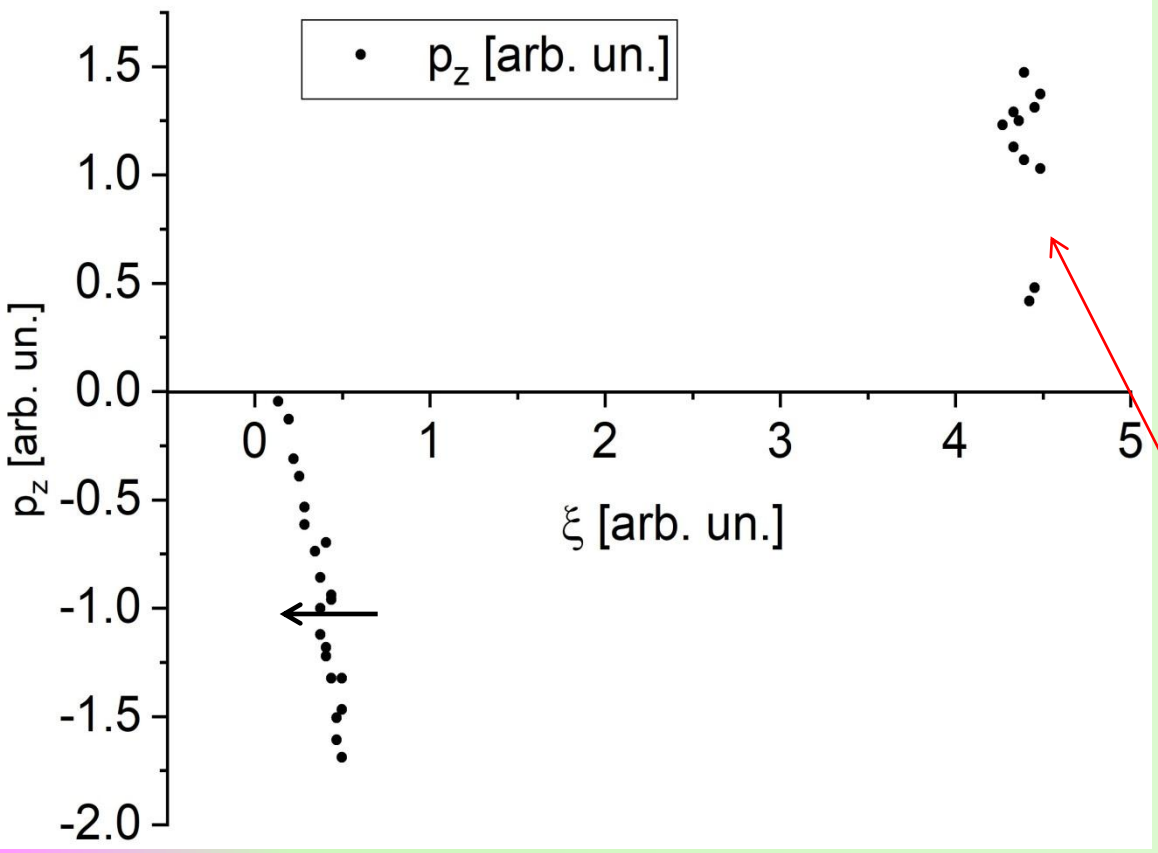
The plateau-like wakefield accelerates a monoenergetic electron bunch. Its energy spread in the case of a bunch energy ε_b=0.5GeV is 0.5%, and the longitudinal emittance is 21 μm GeV, and in the case of a bunch energy ε_b=42GeV it is 0.02%, and the longitudinal emittance is 0.84 μm GeV.

Decrease of the longitudinal momentum p_z of the electron bunch, which excites the wakefield, and the increase of the longitudinal momentum of the bunch, which is accelerated by the plateau-like wakefield



Excitation of the wakefield $E_z(\xi)$ by the driver-bunch and the formation of a nonmonotonic distribution $E_z(\xi)$ within the witness-bunch

Let us compare the longitudinal phase space of the electron witness-bunch with a plateau-like accelerating wakefield and with a non-monotonic distribution. We use the charge of the electron witness-bunch, twice as much as the plateau-like one. Then a non-monotonic inhomogeneous distribution of the accelerating wake field is formed within the witness-bunch.

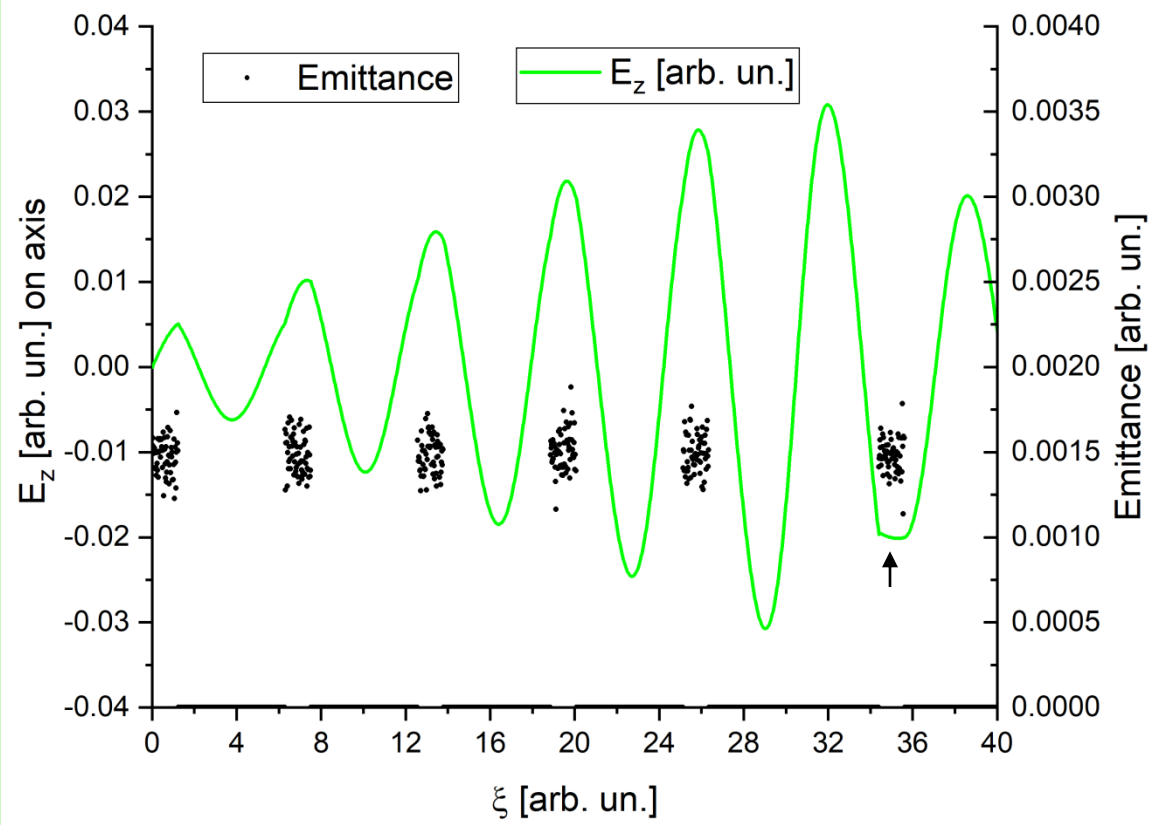


Decrease of the longitudinal momentum p_z of the electron bunch, which excites the wakefield, and the increase of the longitudinal momentum of the bunch, which is accelerated by the non-monotonic wakefield

How can this be done in the linear or weakly nonlinear case for a sequence of bunches? Let's consider this problem now.

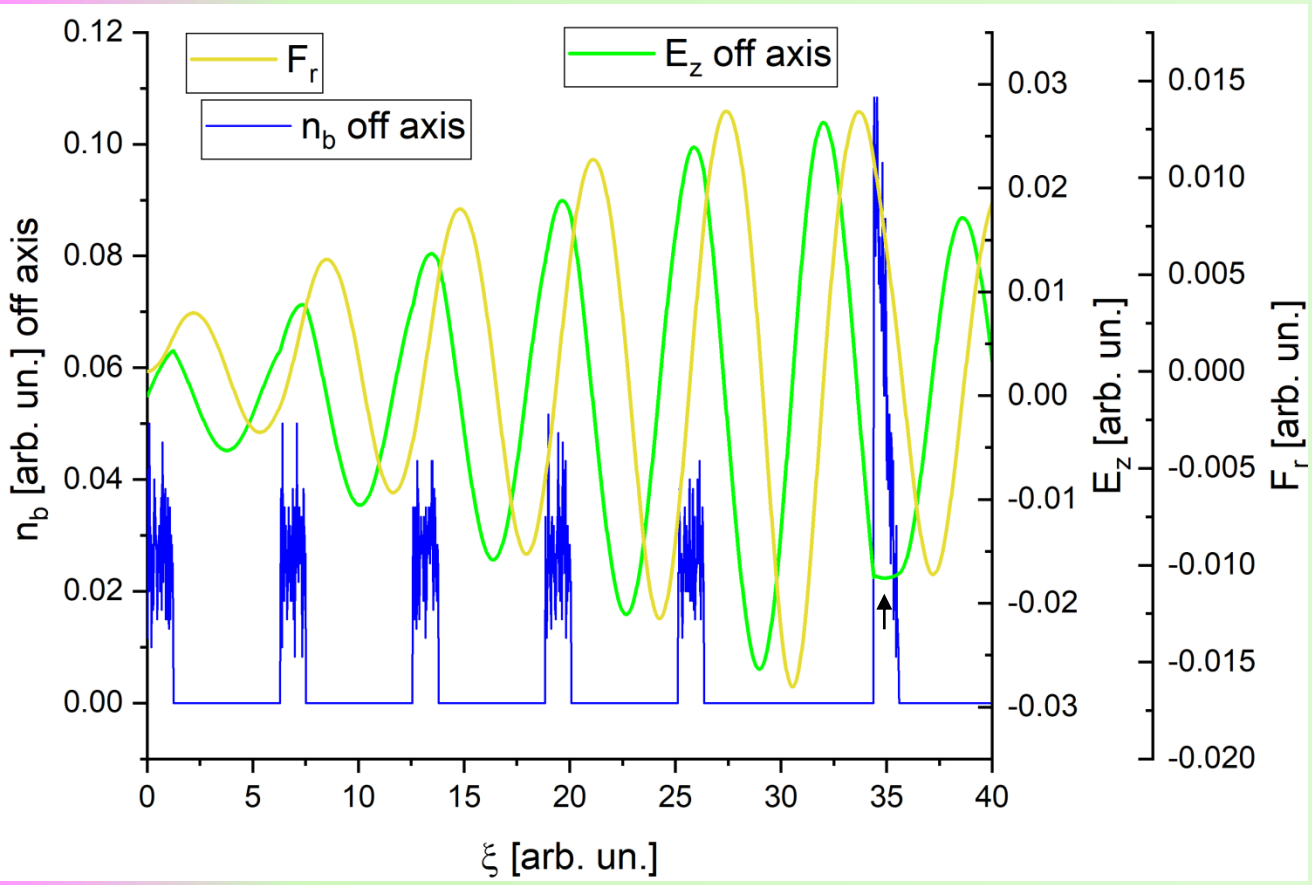
Katsouleas T., Wilks S., Chen P., Dawson T.J.M., Su J.J. Beam Loading in Plasma Accelerators. 1987

Plateau Formation by an Electron Witness-Bunch on the Distribution of an Accelerating Wakefield, Excited By Short Train of Resonant Driver-Bunches in a Plasma



The on-axis wakefield excitation E_z by short train of resonant electron driver-bunches and plateau formation on $E_z(\xi)$ by witness-bunch (decreasing triangle). Transversal emittance of bunches is shown below in dashes. The length of bunches is equal to 0.19 of bubble length. The radius of bunches is equal to 0.3. The maximum current of bunch-driver is equal to $I_b=2\times10^{-3}$. The maximum current of bunch-witness is equal to $I_b=8\times10^{-3}$. The arrow shows the plateau

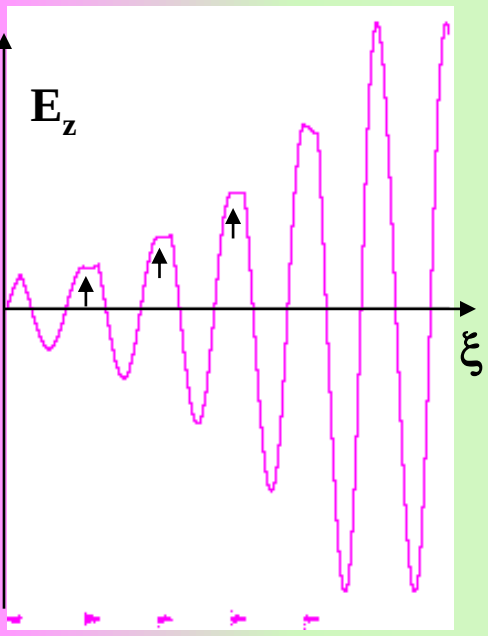
Plateau Formation by an Electron Witness-Bunch on the Distribution of an Accelerating Wakefield, Excited By Short Train of Resonant Driver-Bunches in a Plasma

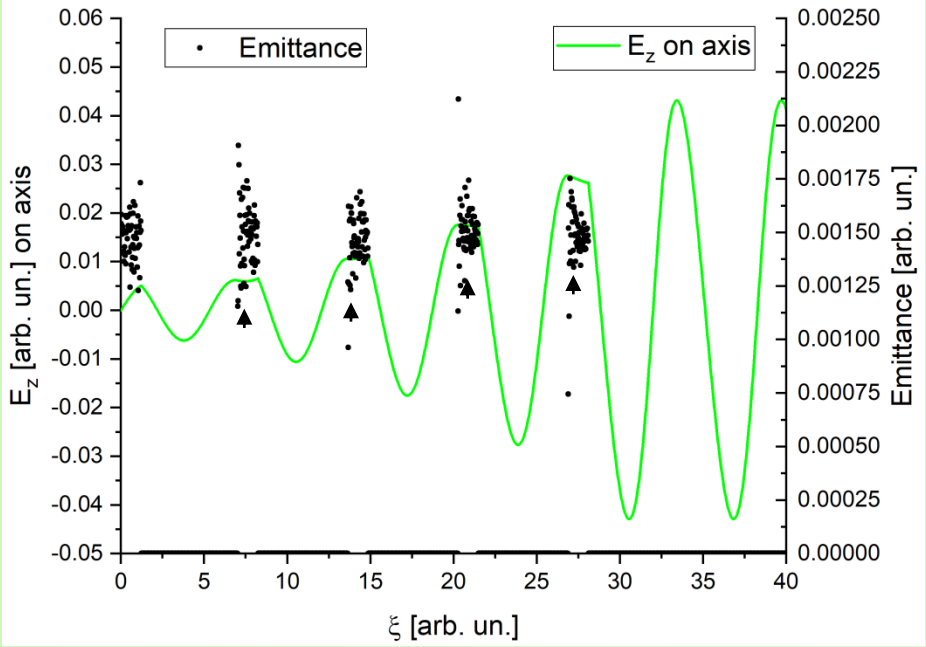


In this case, the whitness-bunch is entirely in the focusing field, in contrast to the Gaussian bunch, which would be partially focused and partially defocused.

The off-axis wakefield excitation E_z by short train of driver-bunches and plateau formation on $E_z(\xi)$ by witness-bunch. The off-axis densities of bunches n_b are shown by yellow. The off-axis wake focusing force F_r is shown to be blue as a function of the coordinate ξ along the plasma

Plateau Formation by an Electron Driver-Bunches on the Distribution of a Decelerating Wakefield, Excited By Short Train of Resonant Driver-Bunches in a Plasma

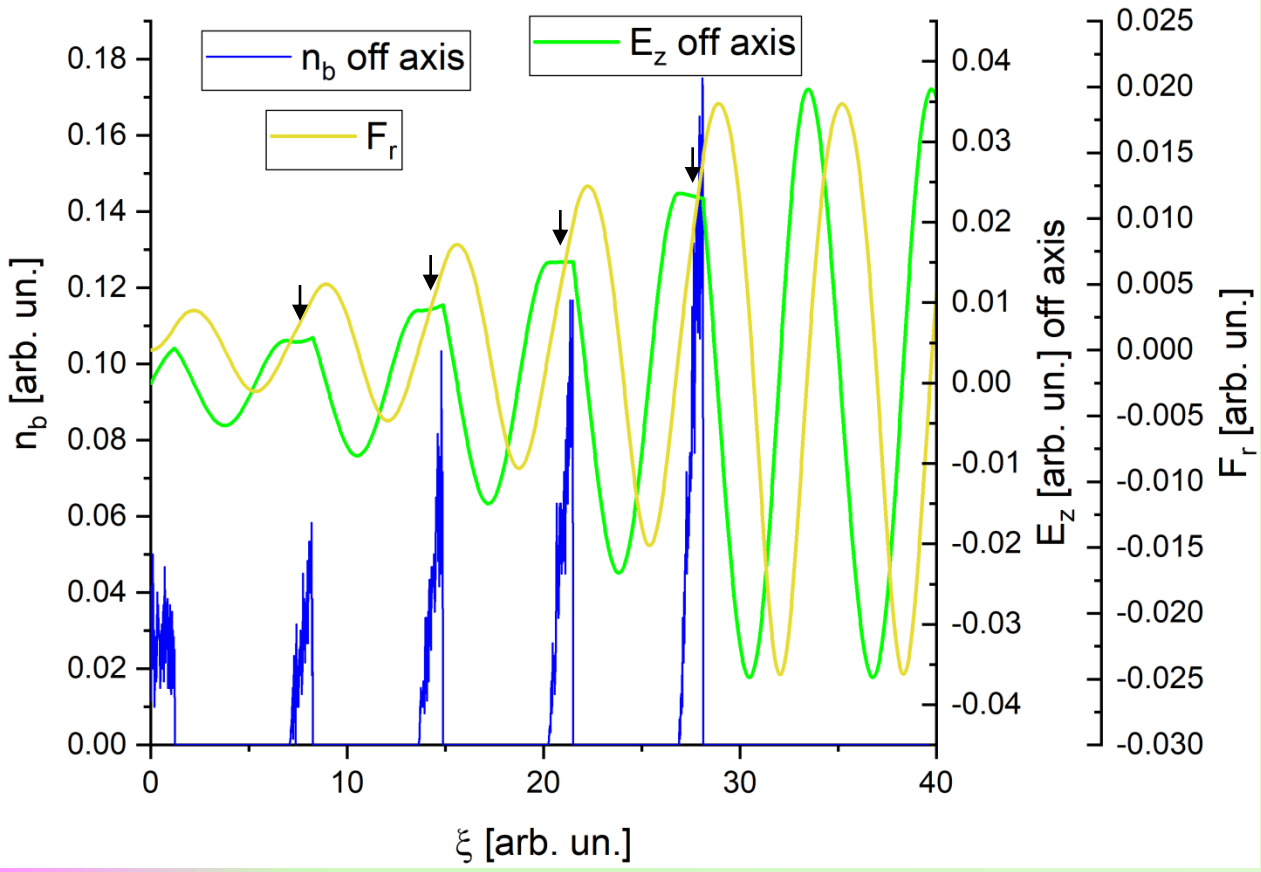




Now we simulate the plateau formation on the distribution of a decelerating wakefield, excited by short train of resonant electron driver-bunches in a plasma.

The on-axis wakefield excitation E_z by short train of resonant electron driver-bunches and plateau formation on $E_z(\xi)$ by driver-bunches (increasing triangles). Transversal emittance of bunches is shown below in dashes. The length of bunches is equal to 0.19 of bubble length. The radius of bunches is equal to 0.3. The maximum current of bunch-driver is equal to $I_b=2\times10^{-3}$. The maximum current of bunch-witness is equal to $I_b=8\times10^{-3}$. The arrow shows the plateau

Plateau Formation by an Electron Driver-Bunches on the Distribution of a Decelerating Wakefield, Excited By Short Train of Resonant Driver-Bunches in a Plasma



In this case, the driver-bunches are entirely in the focusing field, in contrast to the Gaussian bunches, which would be partially focused and partially defocused.

The off-axis wakefield excitation E_z by short train of driver-bunches and plateau formation on $E_z(\xi)$ by driver-bunches. The off-axis densities of bunches n_b are shown by yellow. The off-axis wake focusing force F_r is shown to be blue as a function of the coordinate ξ along the plasma

Conclusions

The formation of the distribution of accelerating and decelerating wakefields of plateau types has been investigated during wakefield excitation and electron acceleration by wakefield in linear and blowout regimes. The plasma wakefield is excited by an electron-bunch or by a short train of electron-bunches. The investigation has performed, using 2.5D PIC simulations by code LCODE. The final quality of the accelerated bunch strongly depends on the distribution of an accelerating wakefield. The part of energy, transferred to wakefield by driver-bunches, also strongly depends on the distribution of an decelerating wakefield. The investigations presented here show that the accelerated and decelerated bunch densities and their shapes can support plateau type distribution of accelerating and decelerating wakefields during acceleration in linear and blowout regimes. This can lead to energy spread of accelerated bunch decrease and to increase of part of energy, transferred to the wakefield by driver-bunches.

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Thank you!