Investigation of the Dependence of the Maximum Value of the Accelerated Witness Bunch Length on the Transformer Ratio*

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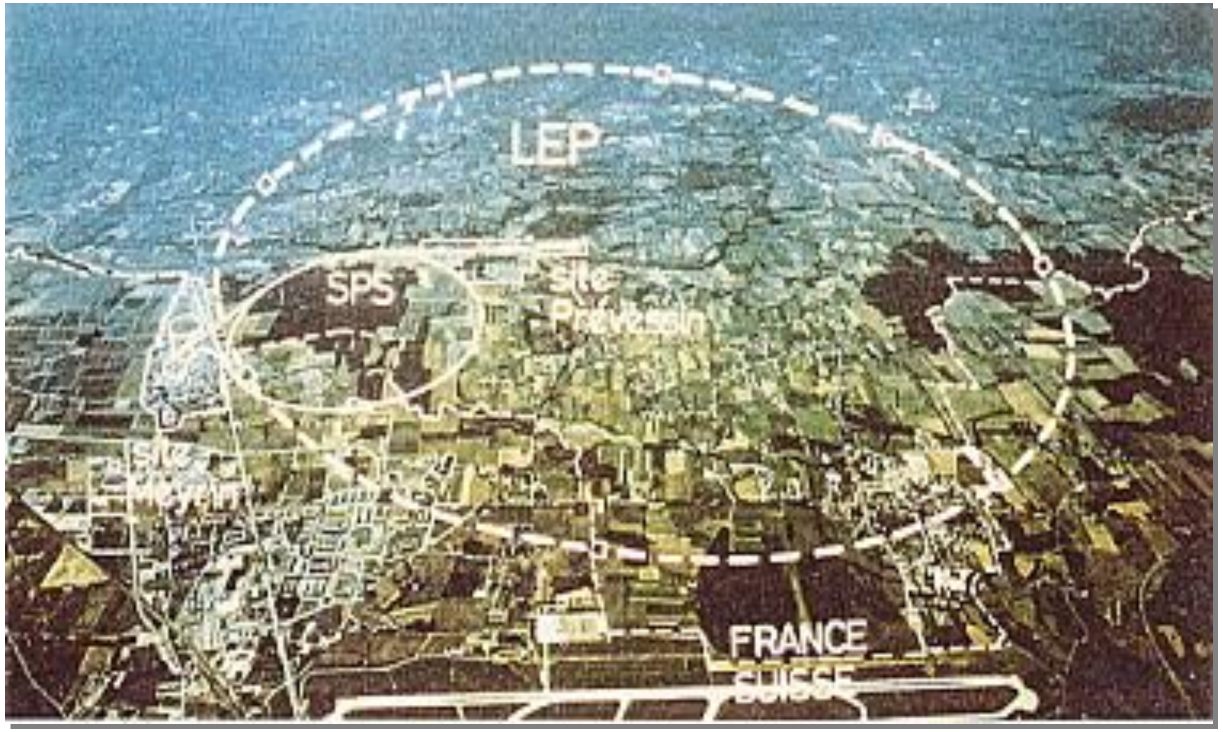
Roman Ovsiannikov[1], Vasyl I. Maslov[1,2], Iryna P. Levchuk[2], Ivan N. Onishchenko[2]

1) Karazin Kharkiv National University, Kharkiv, Ukraine

2) National Science Center Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

Problems of Modern Accelerators



Large Hadron Collider (LHC)
Circumference of the main accelerating ring - 27 km
Maximum energy - 6.5 TeV

Big sizes

↓

High cost

↓

Cause?

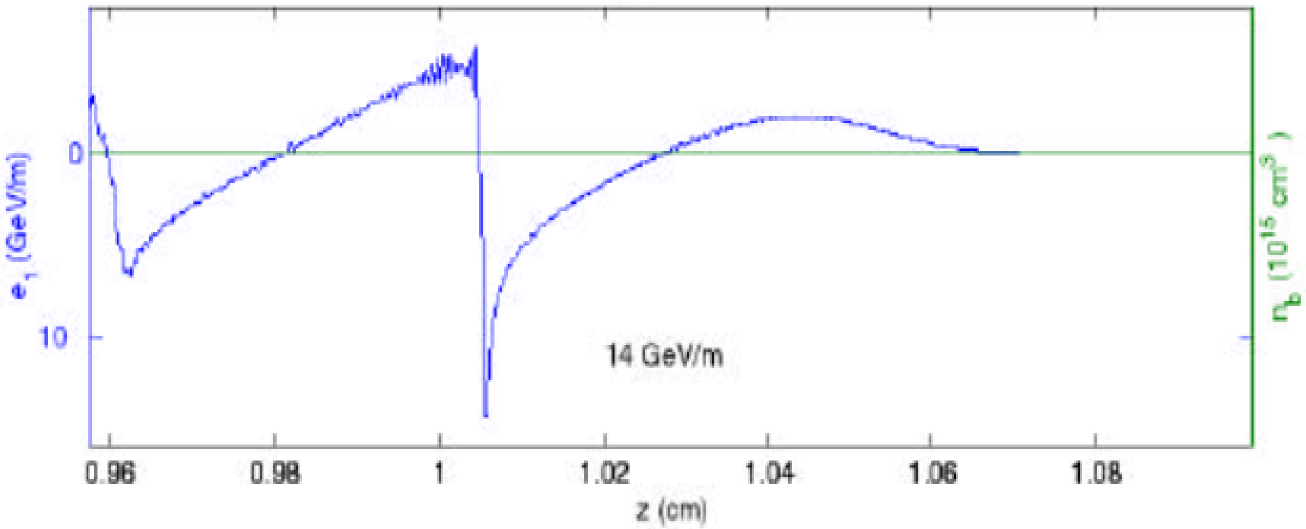
↓

Small acceleration gradients

Accelerating Gradient Problem

In conventional accelerators, due to breakdown on metal walls, accelerating gradients are currently limited to about 100 MV / m (in reality, 20-30 MV / m).

Esarey E. et al. 2009



Plasma wakefield accelerators are capable of withstanding accelerating gradients up to 100 GV / m.

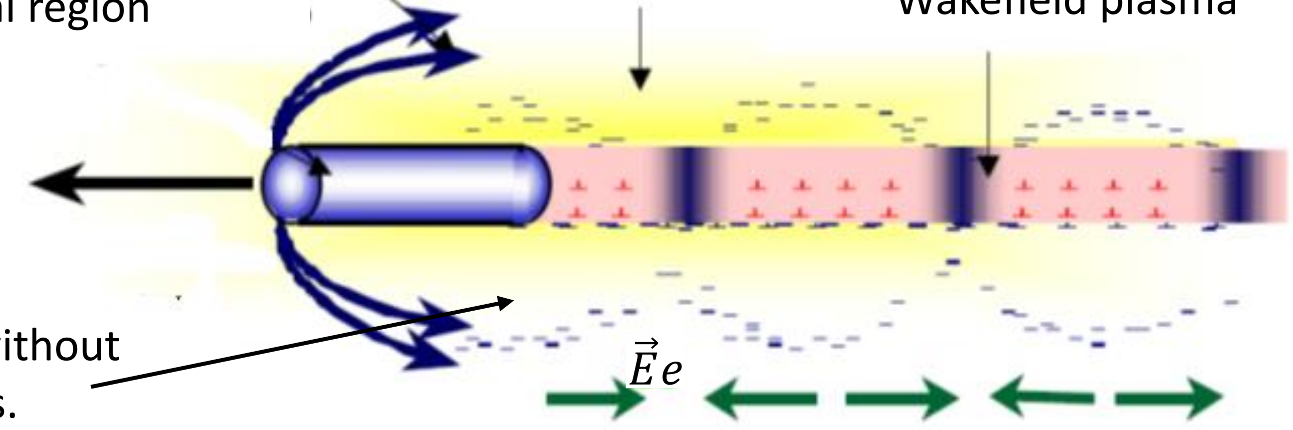
Leemans W.P. et al. 2014; Gonsalves A.J. et al. 2019; Blumenfeld I. et al. 2007.

The Operating Principle of Wakefield Accelerator

Electrons escaping from the central region

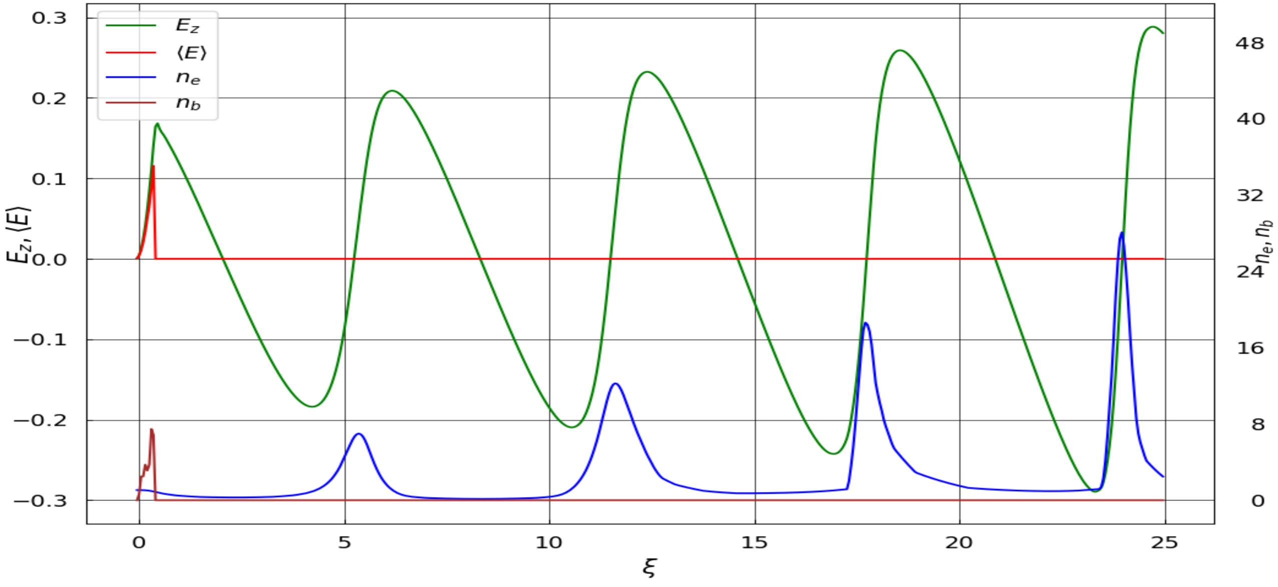
Plasma

Wakefield plasma



Excitation of the wakefield by an electron bunch.

Bubbles are formed without plasma electrons.

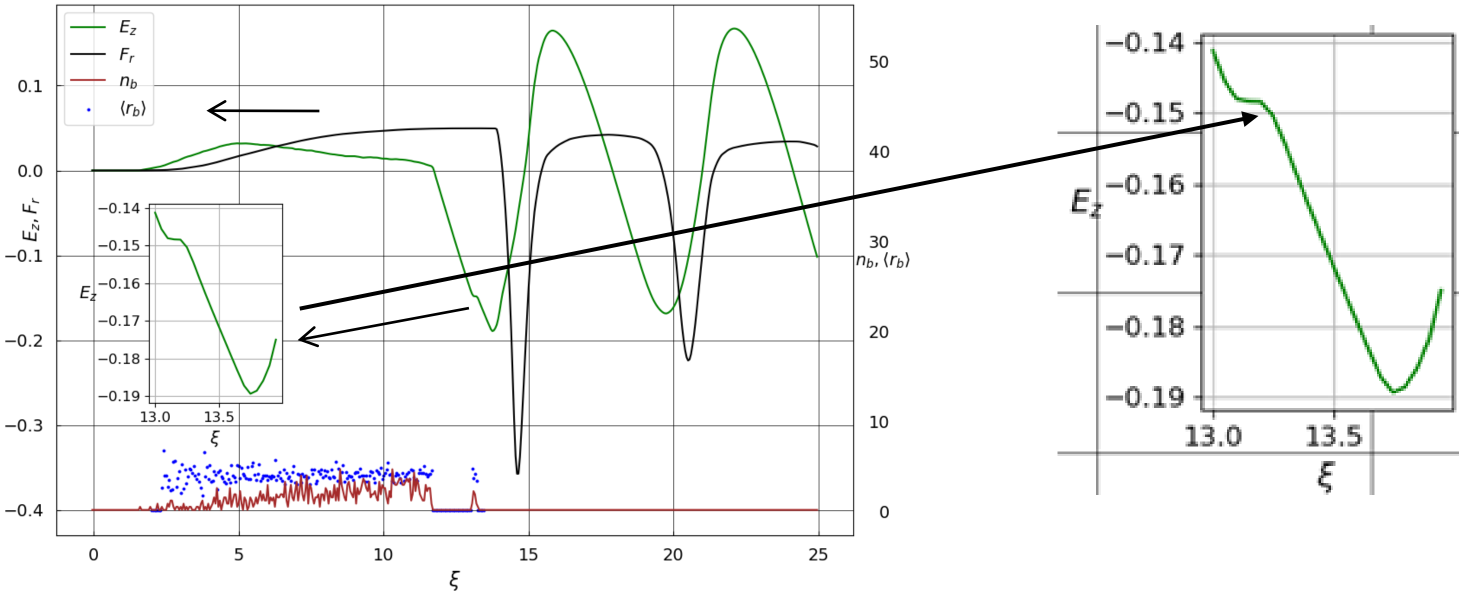


An example of the excitation of such a field by a short electron bunch, with a charge distributed along the cosine, from minimum to maximum values.

High-quality Accelerated Beams

Beam acceleration occurs in dense plasma → Dynamic electromagnetic fields appear in plasma → These fields tend to focus the beam.

Over the entire length of the accelerated beam, it is necessary to achieve : $E_z(z) = const$.

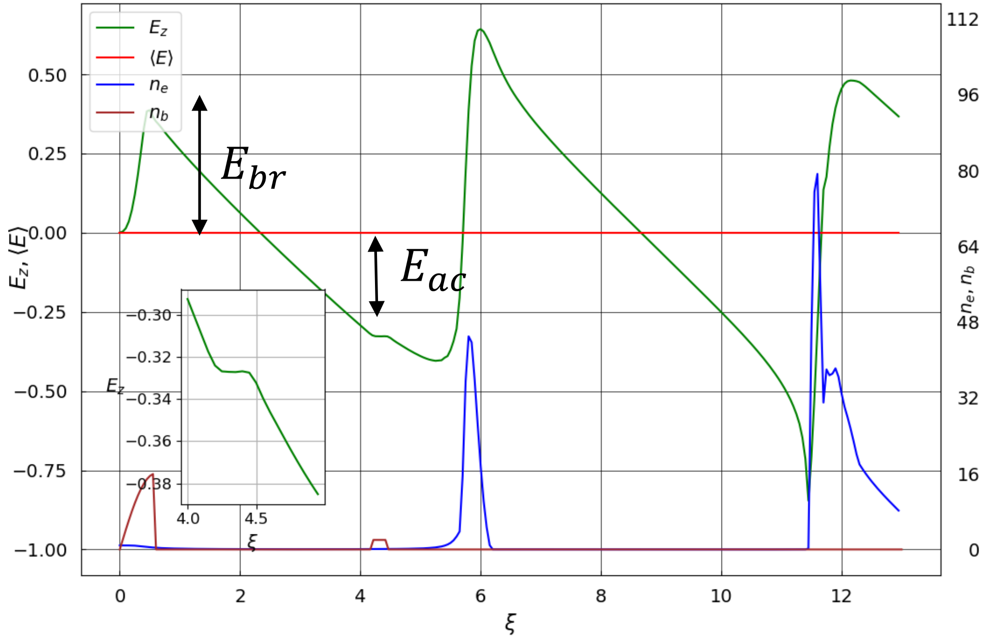


$E_z(z) = const$ – all electrons are accelerated by the same acceleration.

Formulation of the Problem

The E_z plateau can be obtained almost anywhere in the bubble.

Perhaps we can get quite large in length (about the size of the bubble) witness for which the accelerating field is constant.

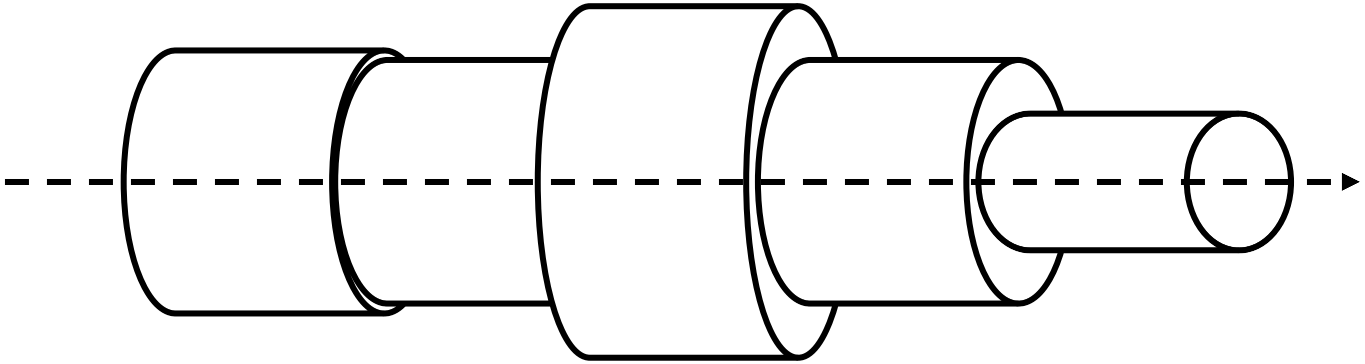


On the other hand, it is important for us that the so-called transformation ratio (E_{ac}/E_{br}) is also large.

The Principle of Building a Bunch-Witness

The assumption of long witnesses with a constant field along its entire length.

Each piece of long witness creates a shelf locally, in its area.



Schematic view of a witness bunch made of pieces of constant density.

The method for finding the required distribution for a witness bunch is to achieve a linear field distribution, for each piece of the bunch independently (the previous parts of the bunch should not significantly affect the next)

Obtaining a Small Witness-Bunch with a Large Transformer Ratio

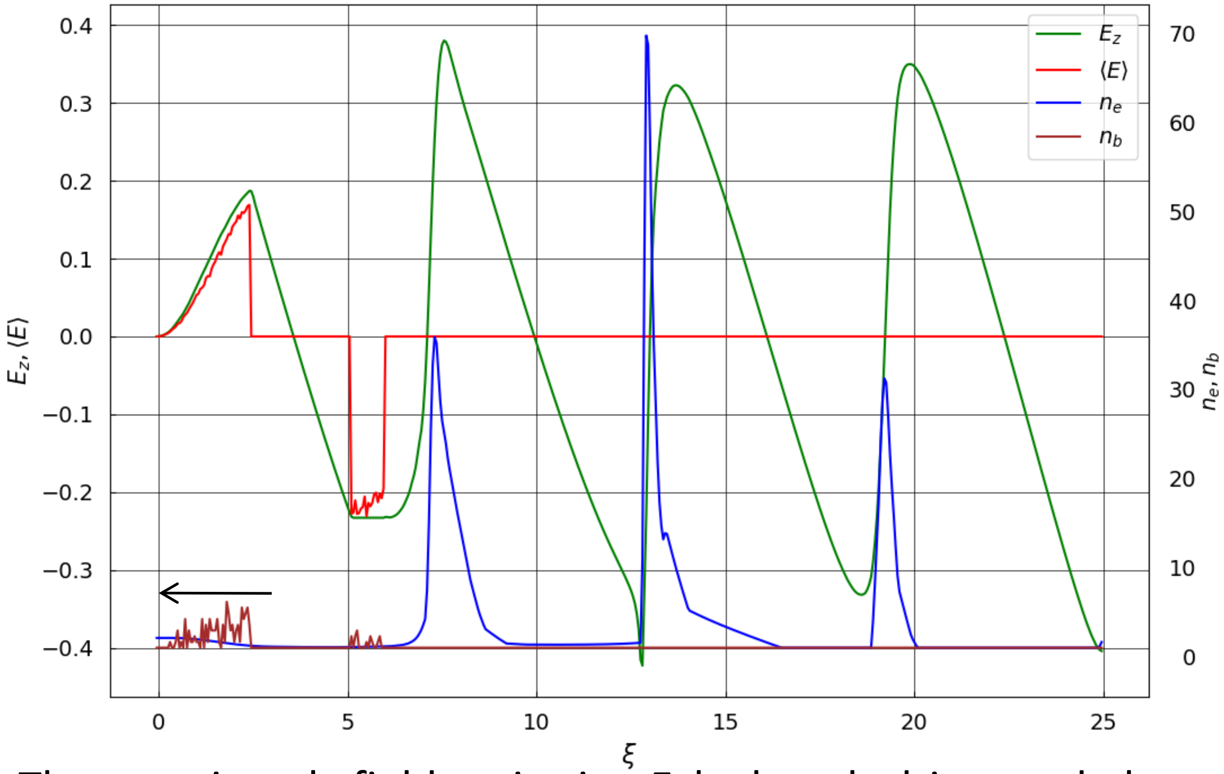


Figure 1: The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness, $\xi = z - V_b t$. Densities of bunches n_b on the axis are shown by brown. Average field <E> is shown by red. Plasma electron density is shown to be blue as a function of the coordinate ξ along the plasma. The length of uniform bunch-driver is equal to 0.33 of bubble length. 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.

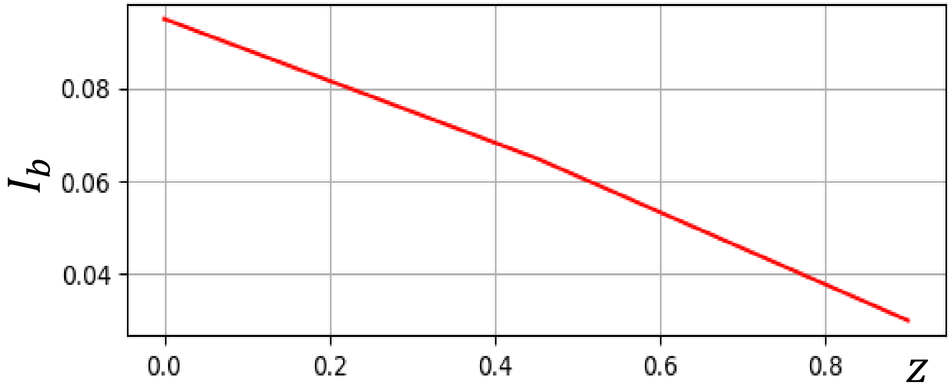
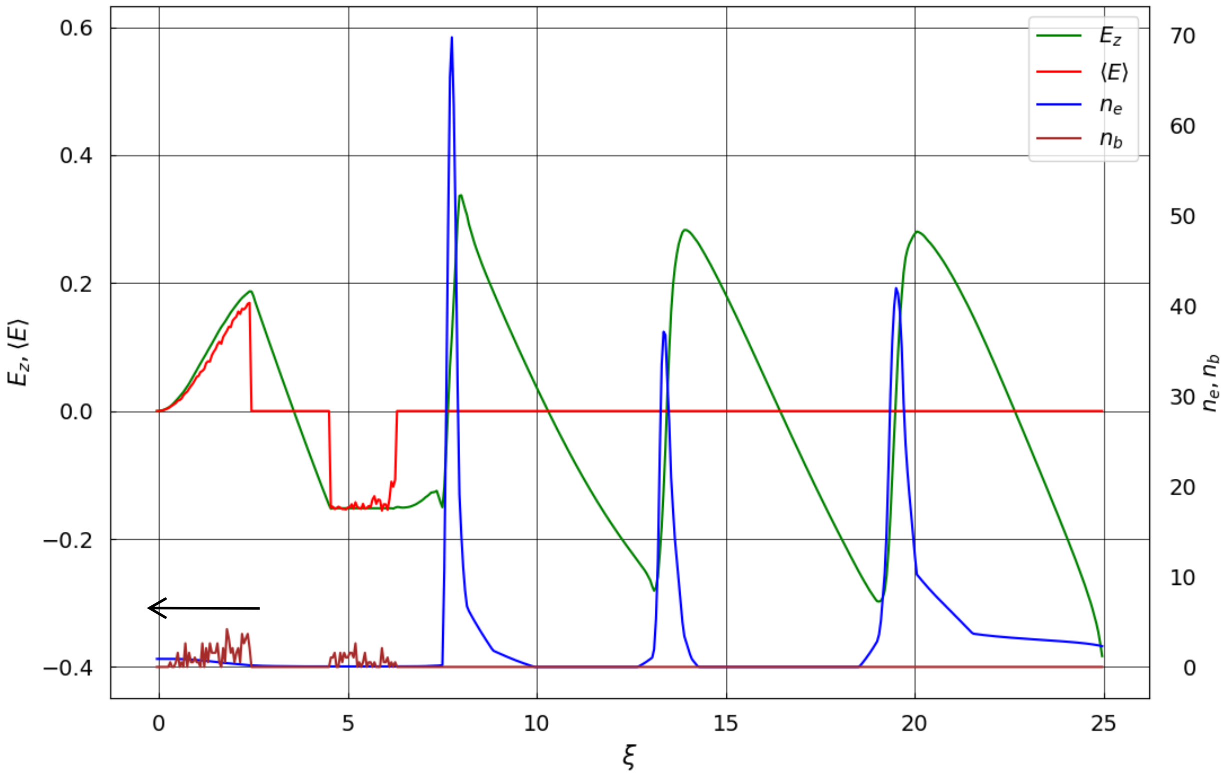


Figure 1a: Current distribution for a witness bunch. Dimensionless parameter, measured in 10 kA.

Obtaining the Average of the Parameters of the Witness-bunch



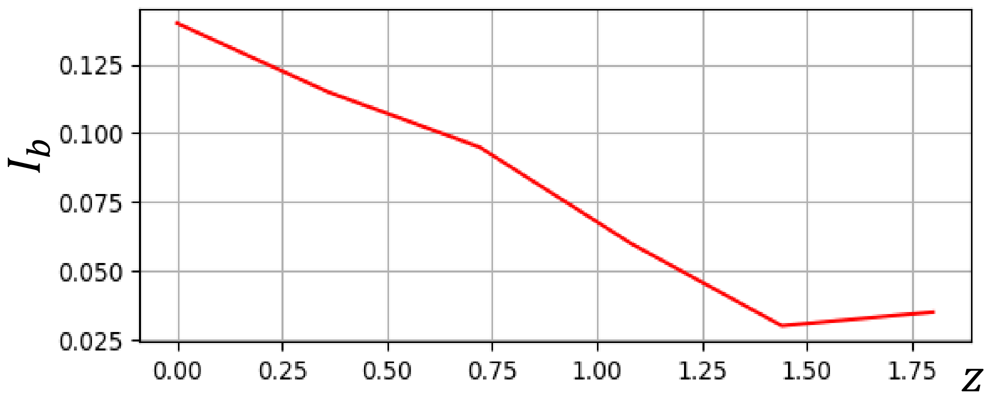


Figure 2a: Current distribution for a witness bunch. Dimensionless parameter, measured in 10 kA.

Figure 2: The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness, $\xi = z - V_b t$. The length of uniform bunch-driver is equal to 0.33 of bubble length. 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.

Obtaining a Long Bunch-Witness, with a Low Transformer Ratio

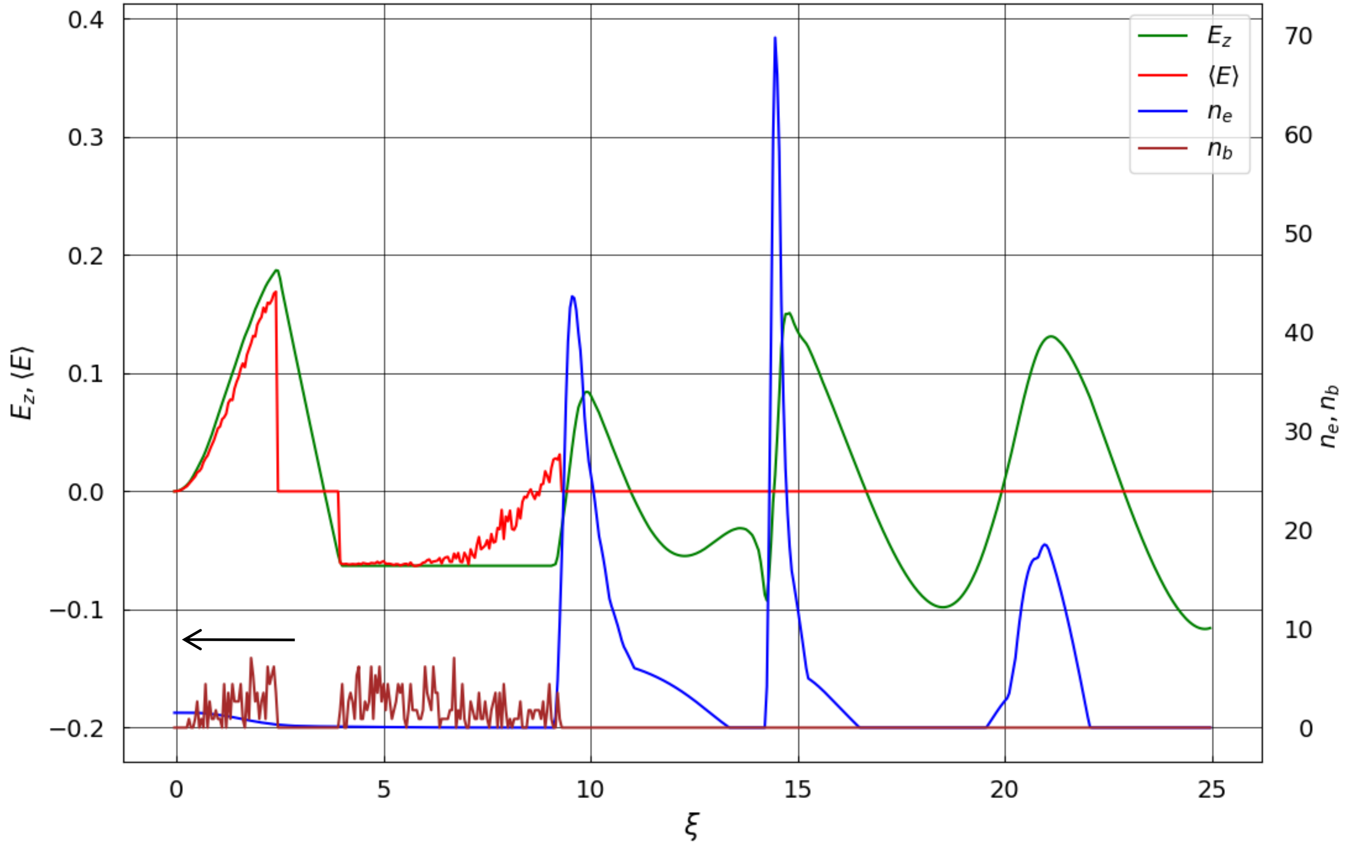


Figure 3: The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness, $\xi = z - V_b t$. The length of uniform bunch-driver is equal to 0.33 of bubble length. The parameters of driver-bunch are the same as in Fig. 1. The maximum current of bunch-witness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

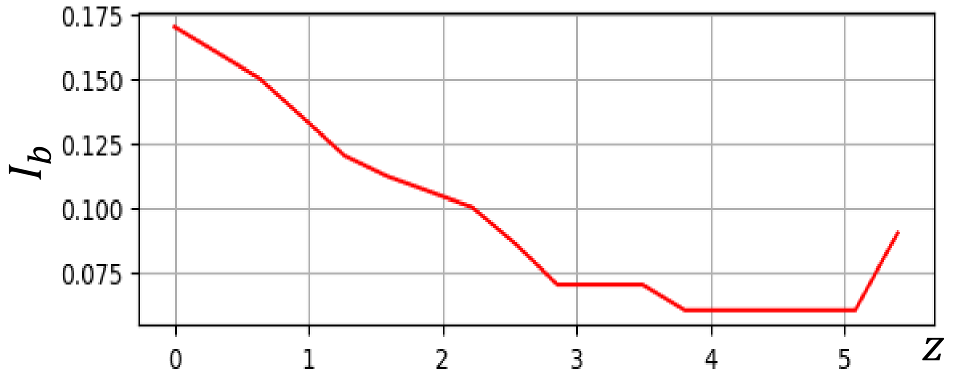


Figure 3a: Current distribution for a witness bunch. Dimensionless parameter, measured in 10 kA.

Obtaining a Very Short Bunch-Witness, with a Very High Transformer Ratio

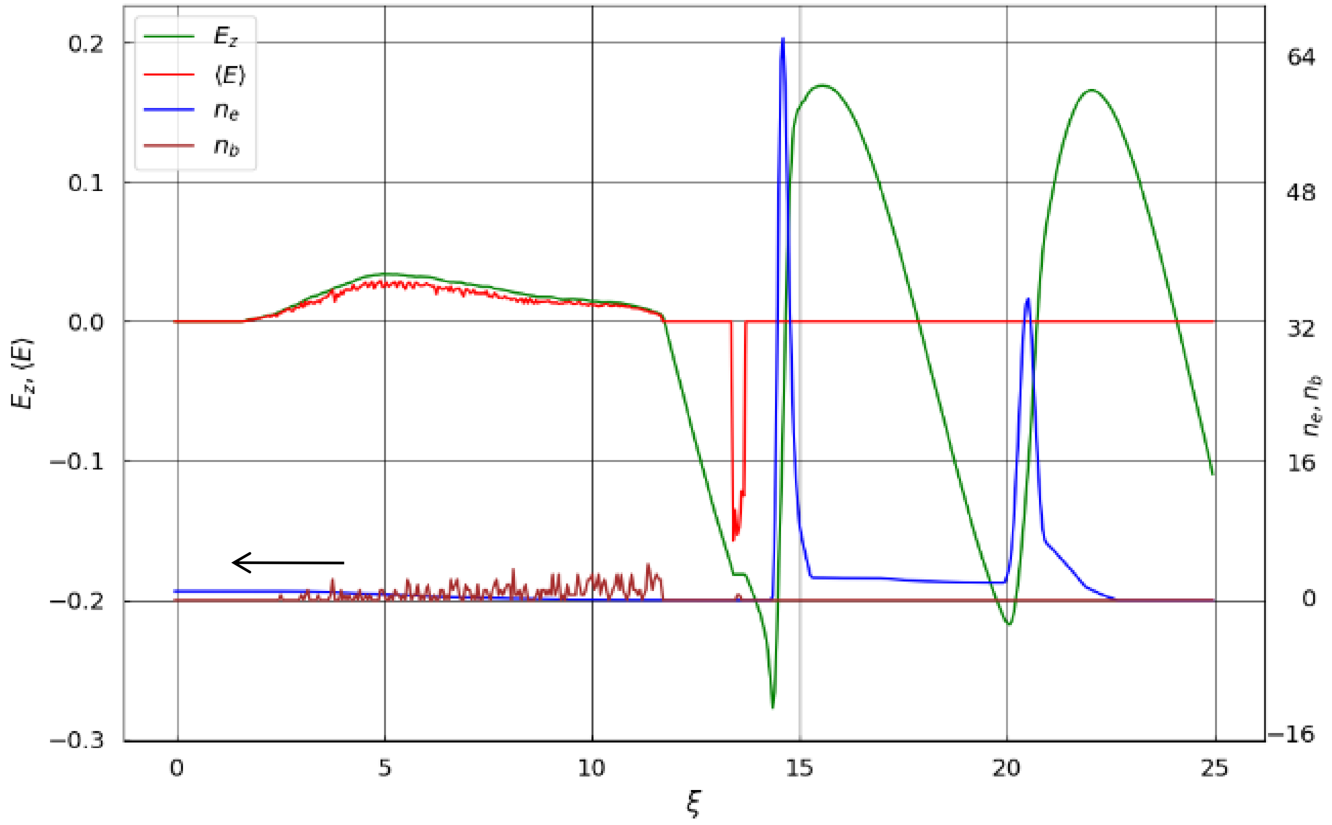


Figure 4: The on-axis wakefield excitation E_z by bunch-driver and plateau formation on $E_z(\xi)$ by bunch-witness, $\xi = z - V_b t$. Densities of bunches n_b on the axis are shown by brown. Average field <E> is shown by red. Plasma electron density is shown to be blue as a function of the coordinate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

Simulation results

Figs. 1 - 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.

Summarizing the results

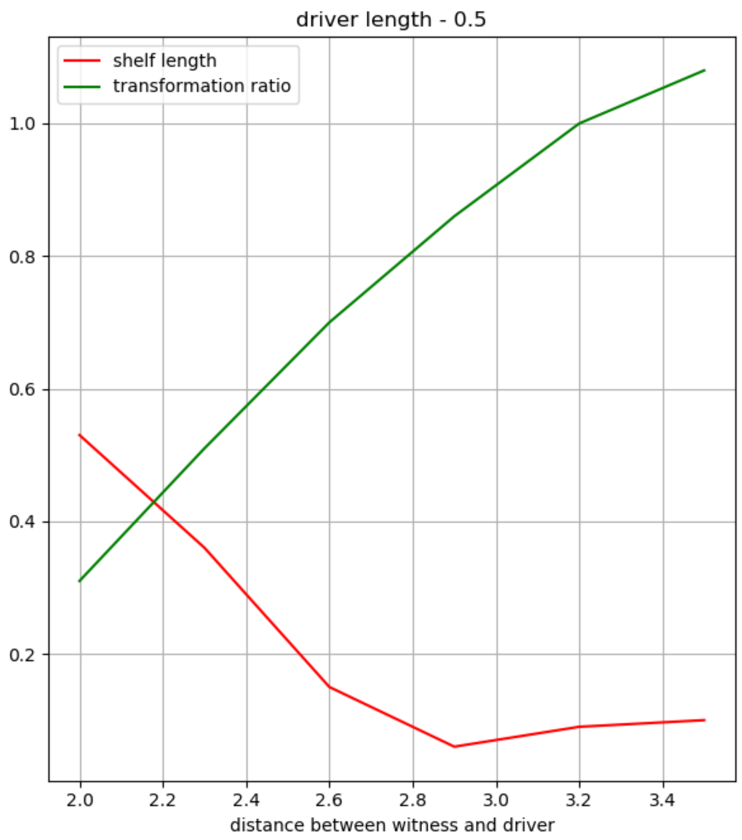


Figure 5: Dependence of the transformer ratio and the maximum length of the witness-bunch, depending on the distance between the witness-bunch and the driver-bunch. The driver length is 0.06 times the bubble length.

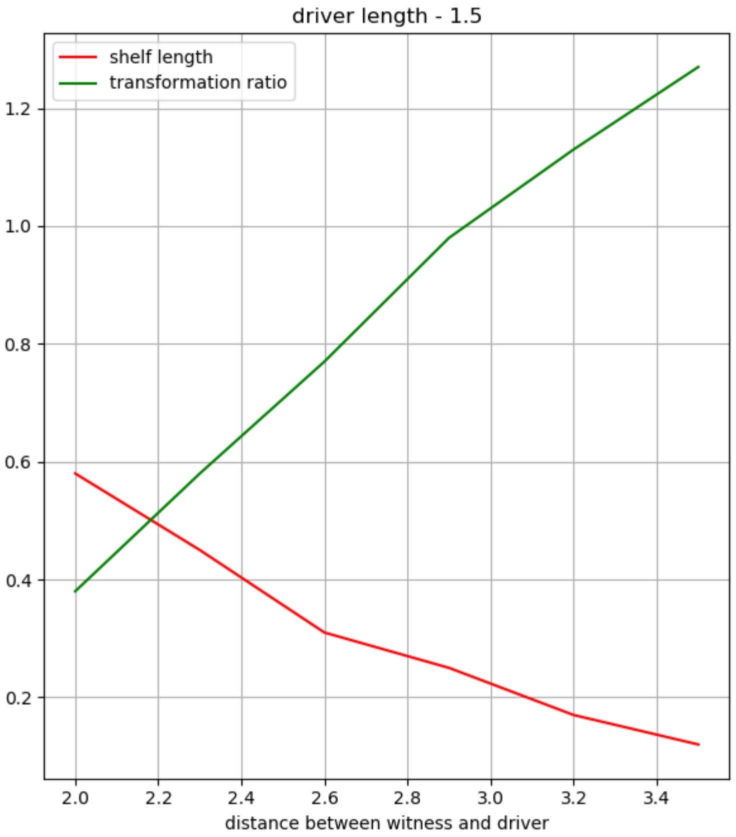


Figure 6: Dependence of the transformer ratio and the maximum length of the witness-bunch, depending on the distance between the witness-bunch and the driver-bunch. The driver length is 0.23 times the bubble length.

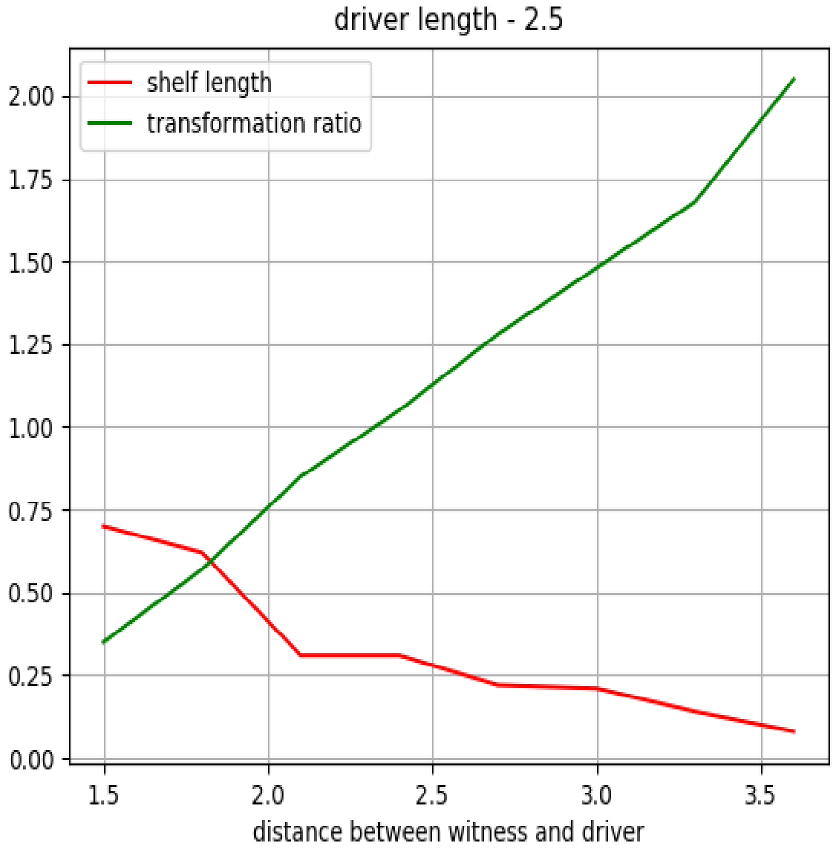


Figure 7: Dependence of the transformer ratio and the maximum length of the witness-bunch, depending on the distance between the witness-bunch and the driver-bunch. The driver length is 0.33 times the bubble length.

Simulation results

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

Conclusions

The formation of a longitudinal accelerating field for witness bunches of various lengths is investigated.

Very long witness bunches were obtained, which form a self-consistent accelerating field, such as a plateau.

For this system, the assumption about the local influence of small sections of the witness-bunch on the longitudinal accelerating field was confirmed.

References

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