Schemes for Simultaneous Large Transformer Ratio, High Efficiency, Low Energy Spread, High Charge of Accelerated Electron Beams by Tailored Wakefield Plateaus for Long Driver and Witness Bunches

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EUROPEAN NETWORK FOR NOVEL ACCELERATORS
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Plan

00 Problematic

01 Configurations for optimal parameters

- One driver and three witnesses bunch
- One driver and two witnesses bunch
- One driver and one witness bunch
- Two drivers and one witness bunch
- One driver and second bubble’s witness witness

02 Instabilities’ suppression approaches

03 Conclusions

Simulation info:

- 2.5D particle-in-cell numerical simulations via LCode;
- macro-particles;
- Gaussian electron distribution;

Units of measure

n_0- for all densities,
$\sqrt{4\pi n_0 mc^2}$- for all fields,
mc^2/e- for wakefield potential,
$c\omega_p$- for all distances and emittance,
mc- for beam and plasma momenta,
mc^2/ω_p- for beam angular momentum,
$n_0 mc^2$- for energy densities,
$n_0 mc^4/\omega_p^2$- for integral energies,
$n_0 mc^4/\omega_p$- for energy flux densities,
$n_0 mc^5/\omega_p^2$- for full energy flux

$n_0 = 10^{18}\text{cm}^{-3}$
$r_b = 1.7\mu\text{m}$

Problematic

- *Plasma accelerators are a centimeter-scale source of GeV beams.*

  → Leemans et al., Nature Physics 2, 696 (2006)

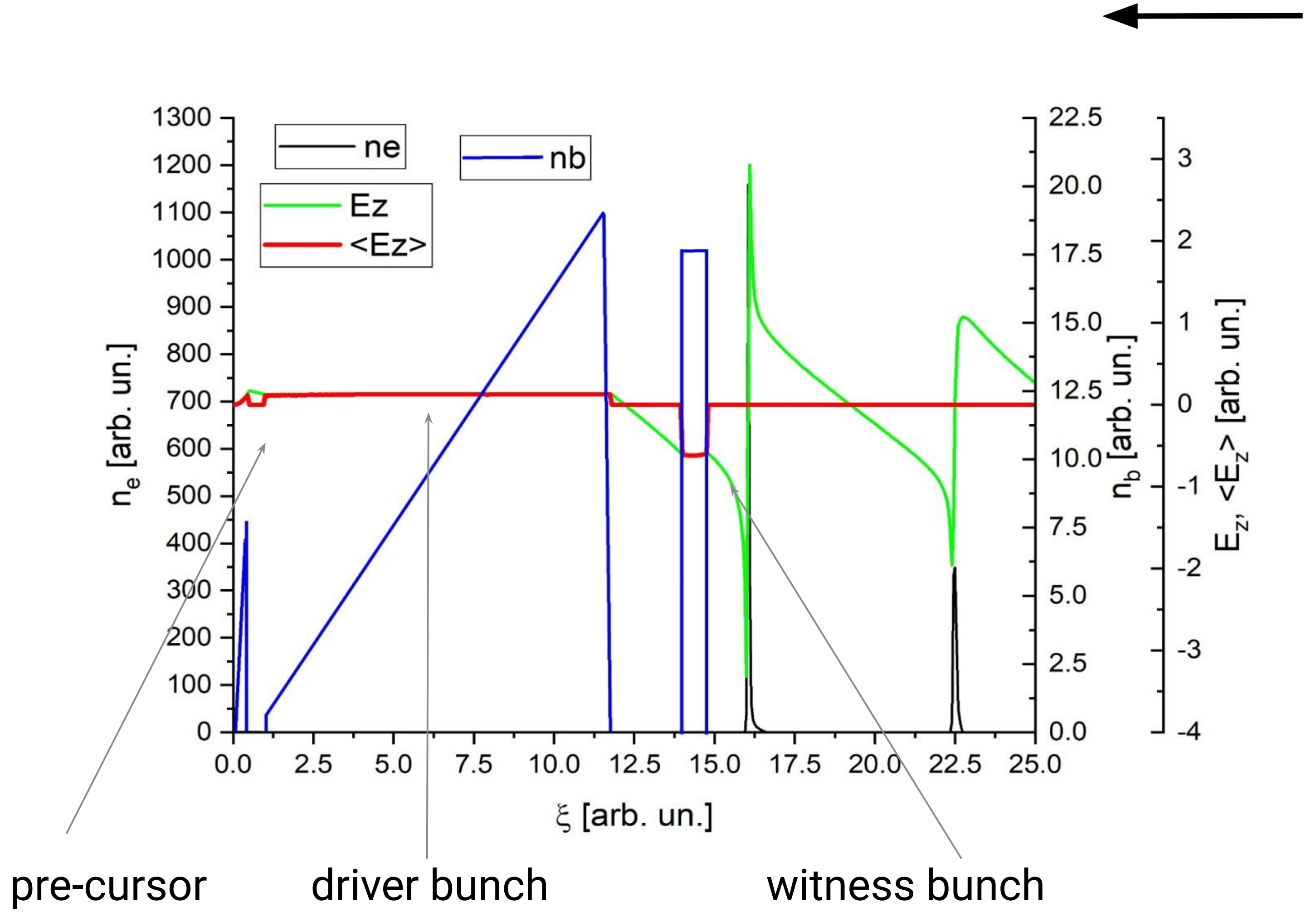
Conventional accelerators

- breakdown of the RF structure (100 MV/m)
- big sizes
- the energy loss by synchrotron radiation

Plasma wakefield accelerators

- gigavolt-per-metre (100 GV/m) electric fields
- compactness
- cheapness
- low repetition rate

Long Driver-bunch, **Large Transformer Ratio**, **Plateau** for Driver-bunch and Plateau for Witness-bunch but **Small Charge** of Accelerated Electrons and **Small Accelerator Efficiency**



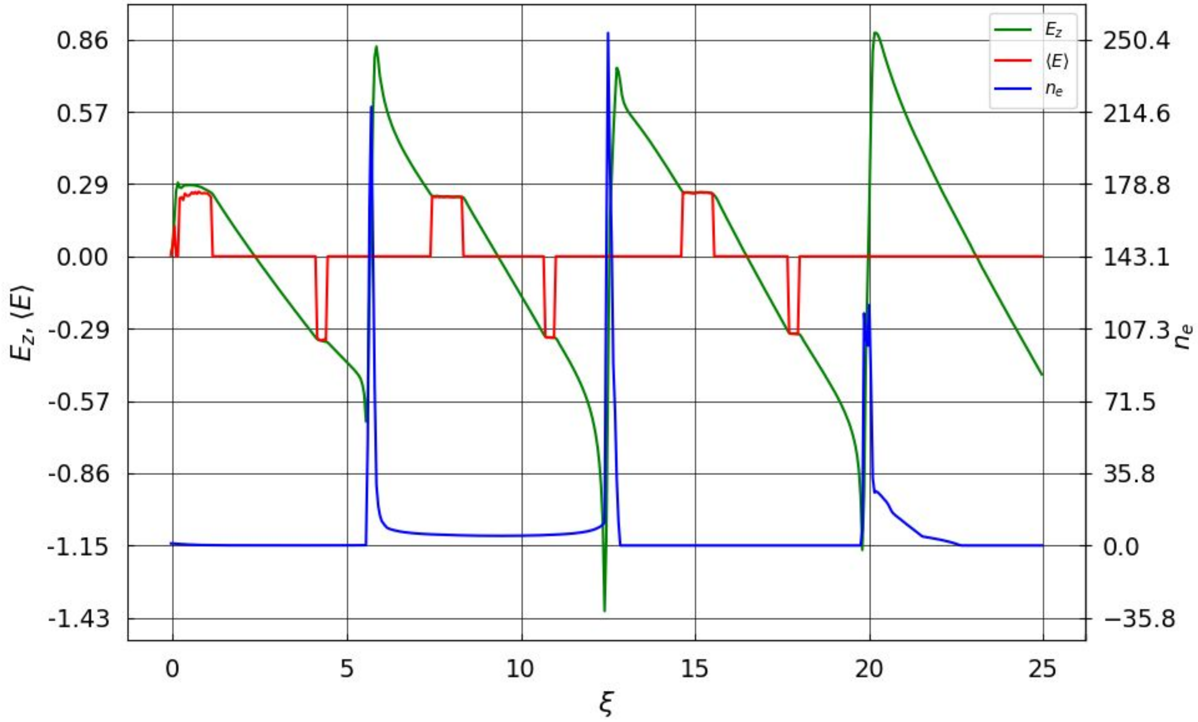
Simultaneous requirements:

- ❏ the long profiled driver-bunches;
- ❏ a large total charge of accelerated electrons;
- ❏ large transformer ratio;
- ❏ high efficiency.

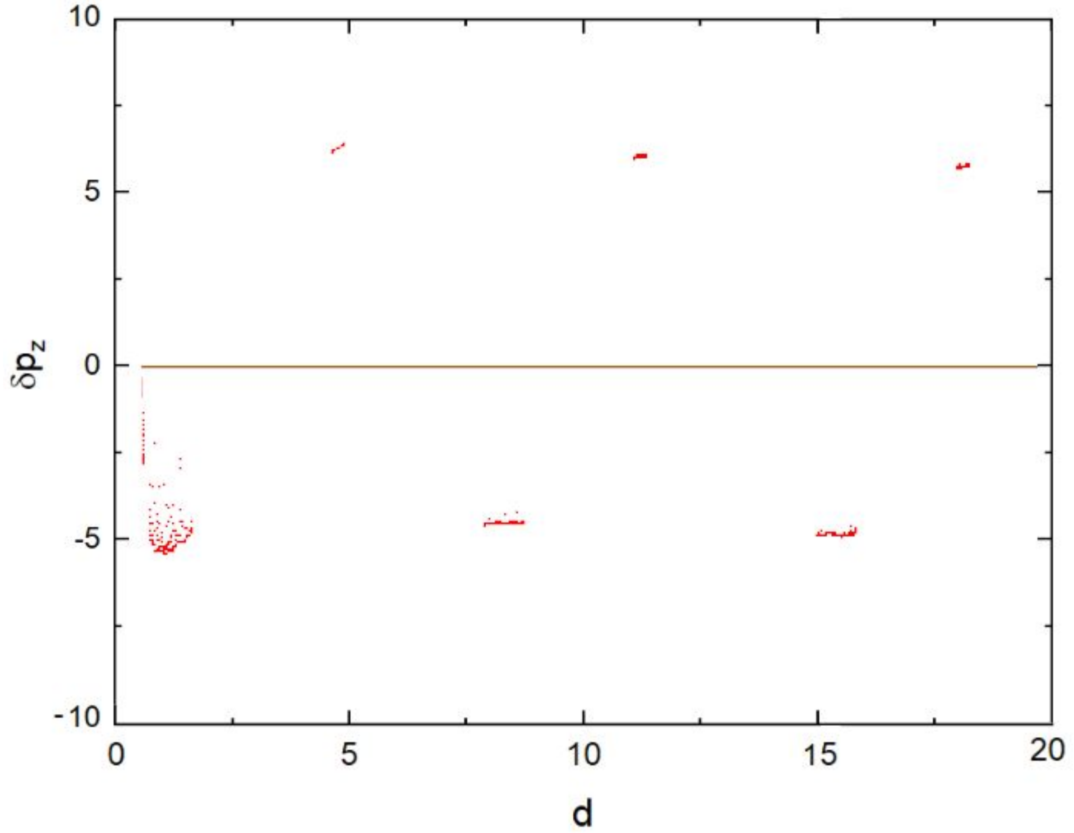
Three pairs driver-witness in three bubbles.

Identical plateaus on the decelerating and accelerating wakefields for the drivers and witnesses.

Large charge of accelerated electrons but **small accelerator efficiency**.



The dispersion of the witness z -momentum is 0.02%

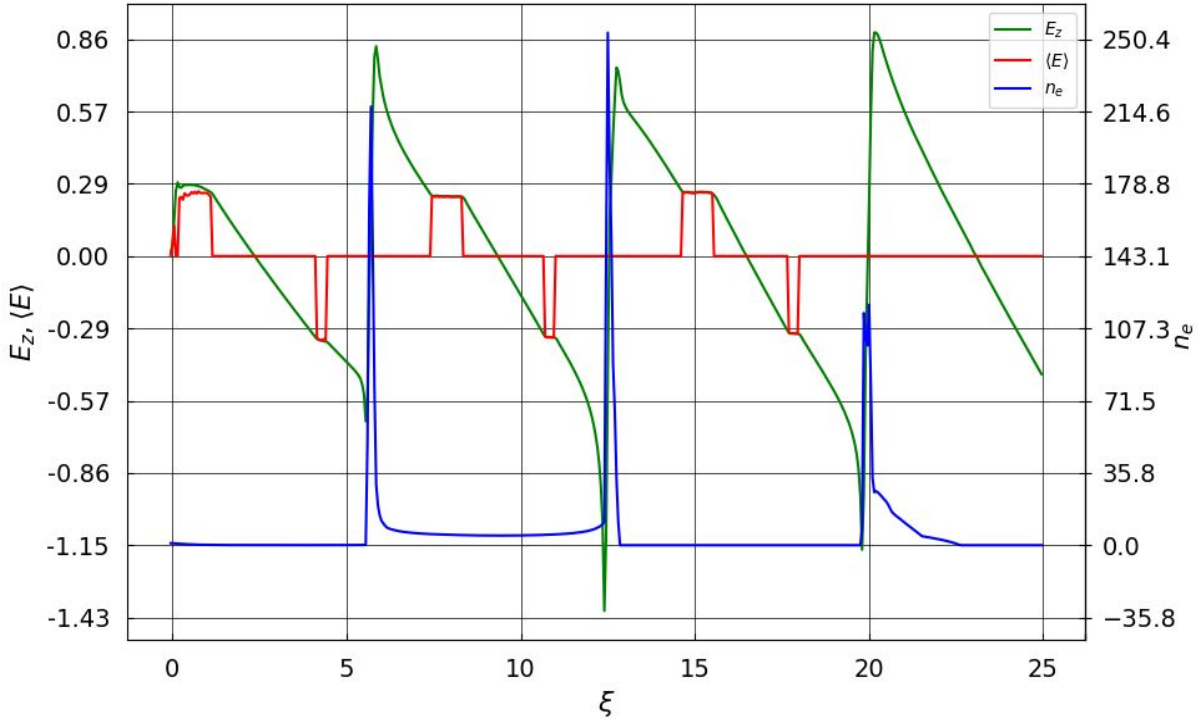


Phase space portrait of the bunches at the some instant. $\delta p = p_z - p_{z0}$

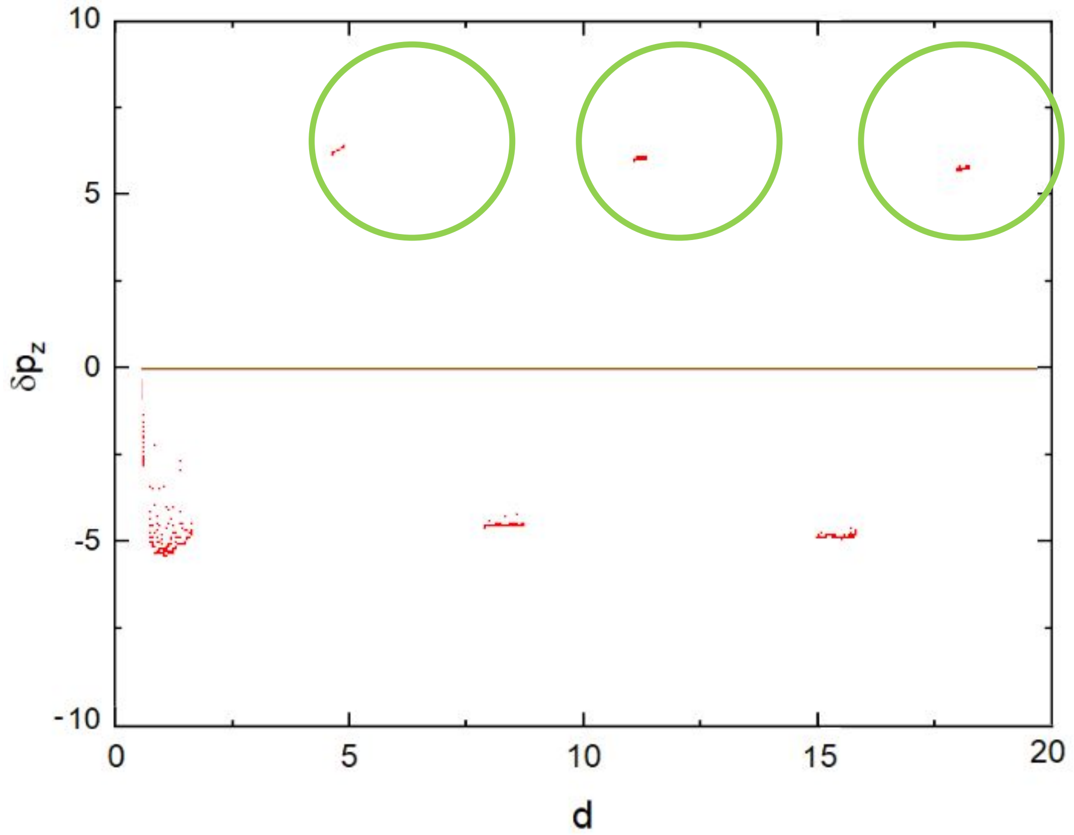
Three pairs driver-witness in three bubbles.

Identical plateaus on the decelerating and accelerating wakefields for the drivers and witnesses.

Large charge of accelerated electrons but **small accelerator efficiency**.



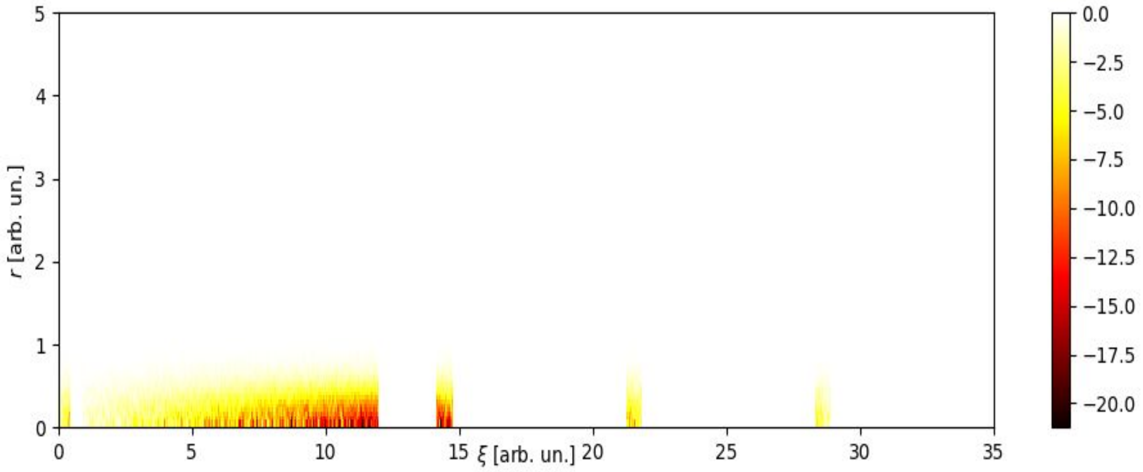
The dispersion of the witness z -momentum is 0.02%

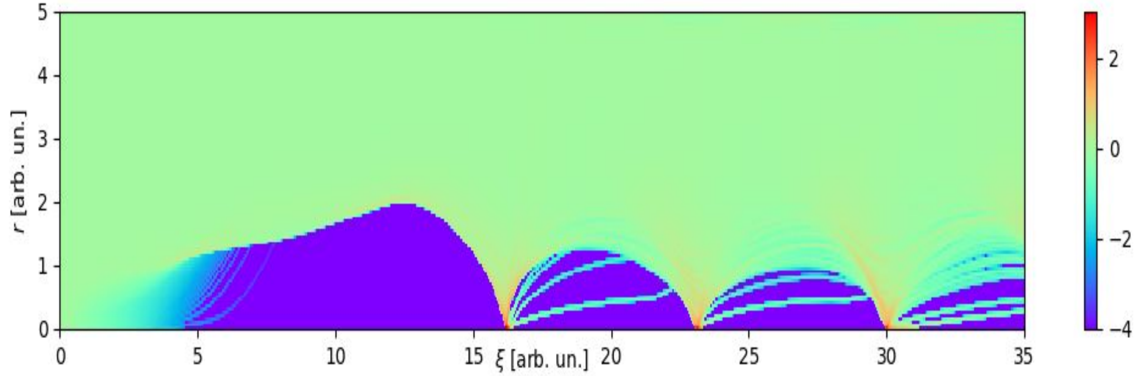


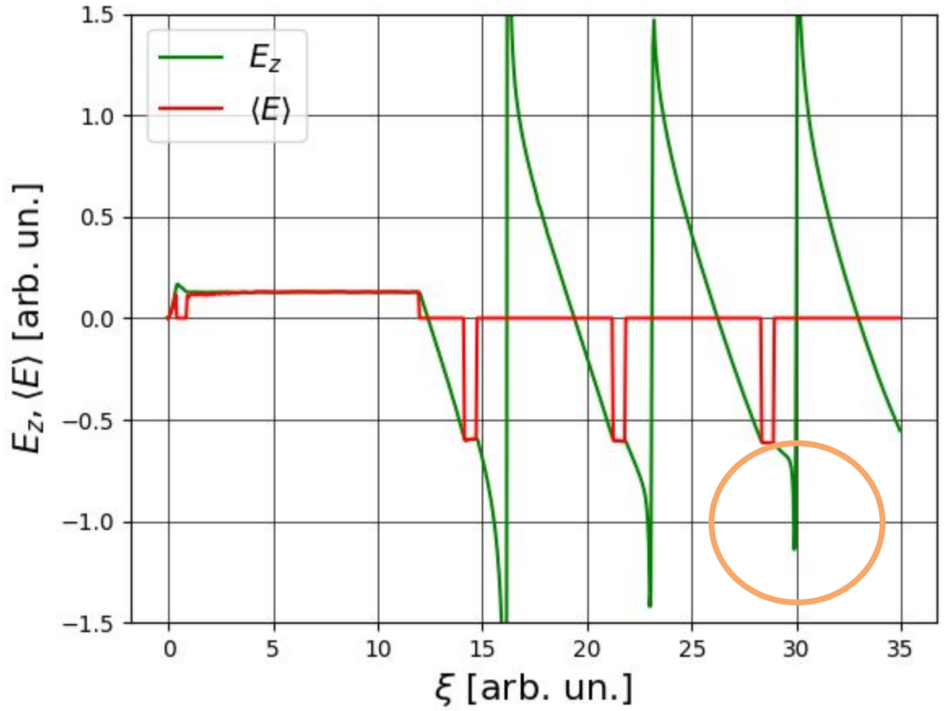
Phase space portrait of the bunches at the some instant. $\delta p = p_z - p_{z0}$

Large Charge of Accelerated Electrons, **Large Transformer Ratio**, and **High Efficiency** with Plateaus

for the **one Long Driver-bunch** and for t**he three Witness-bunches**

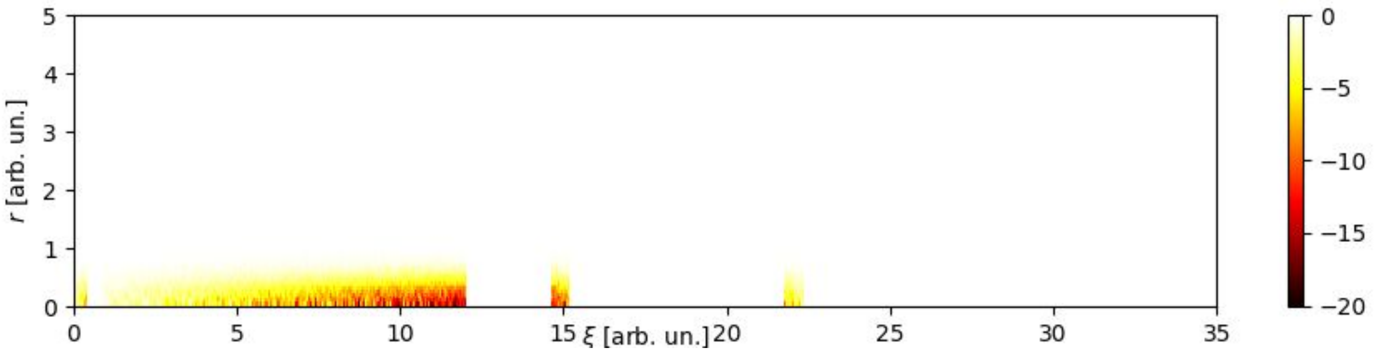




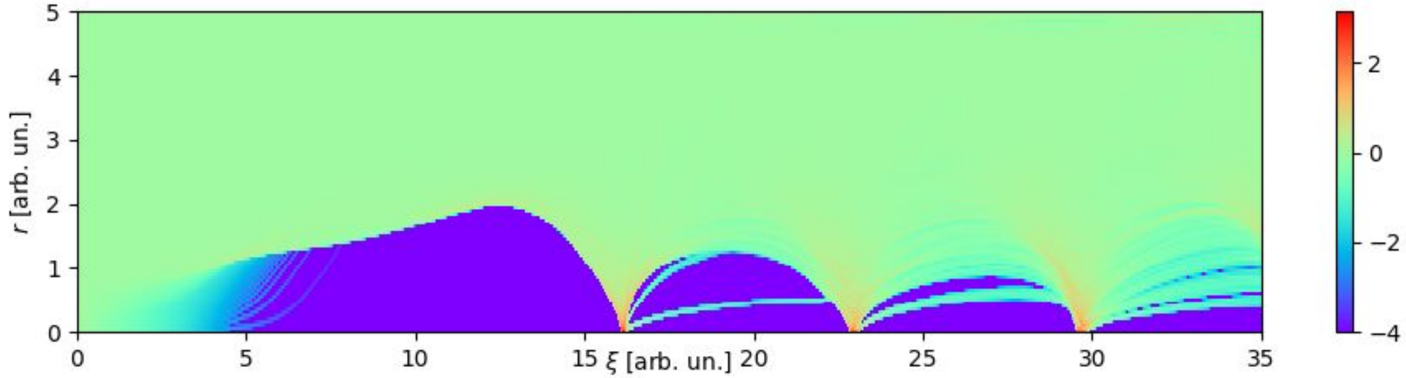


The maximum current of bunch-driver: Ib = 10.7 kA.
Transformer ratio: 4

Large Charge of Accelerated Electrons at **Large Transformer Ratio** and **High Efficiency** at Plateaus **for One Driver-bunch and Two Witness-bunches**

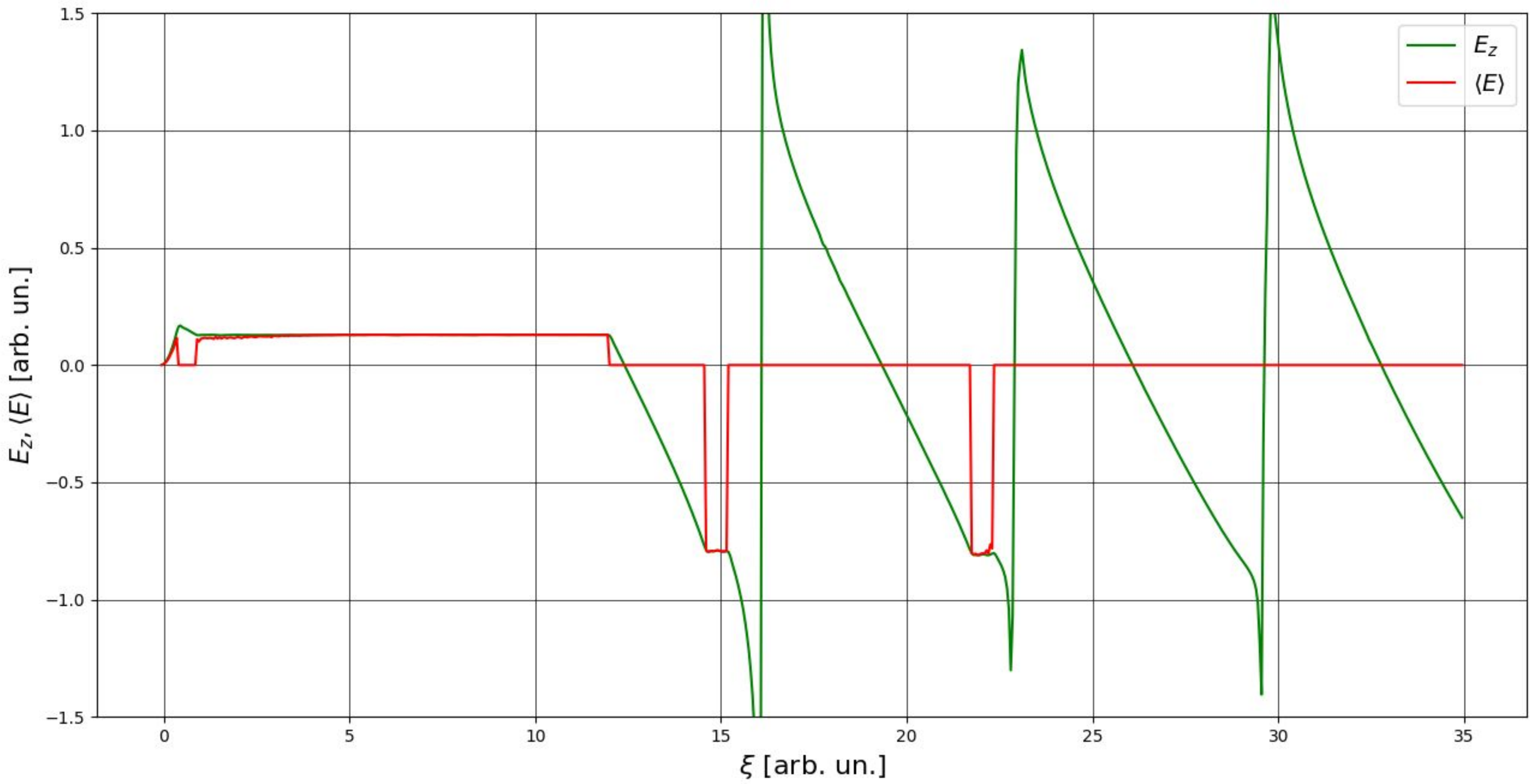


Spatial distribution of the density of two long profiled driver-bunches and of the profiled wintess-bunch



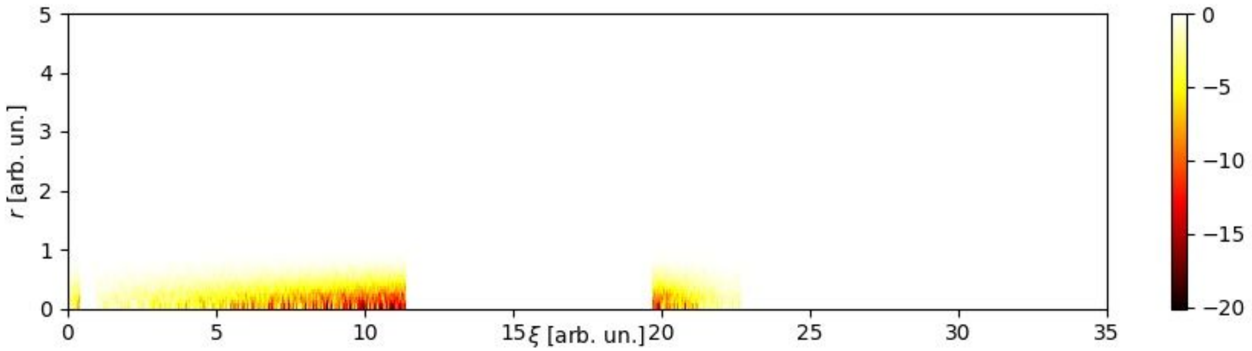
Spatial distribution of the plasma electron density, excited by two long profiled driver-bunches and reconstructed by the profiled wintess-bunch in blowout regime

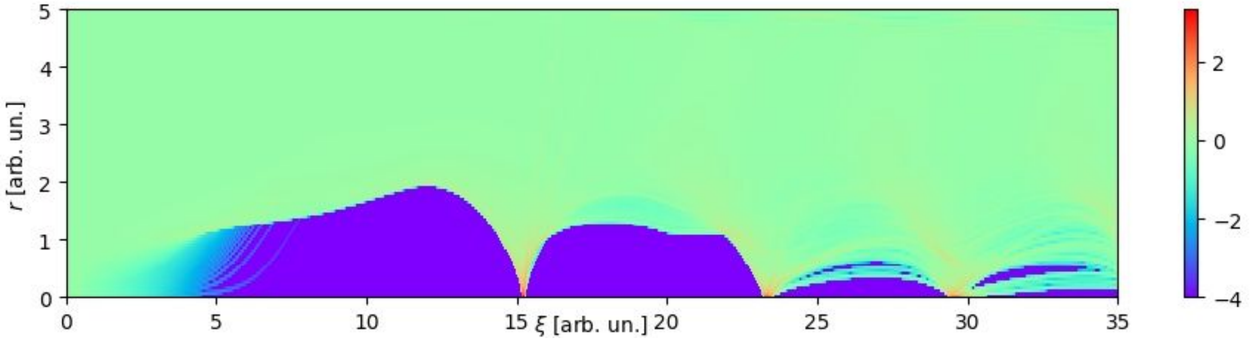
Large Charge of Accelerated Electrons at **Large Transformer Ratio** and **Low Efficiency** at Plateaus **for One Driver-bunch and Two Witness-bunches**

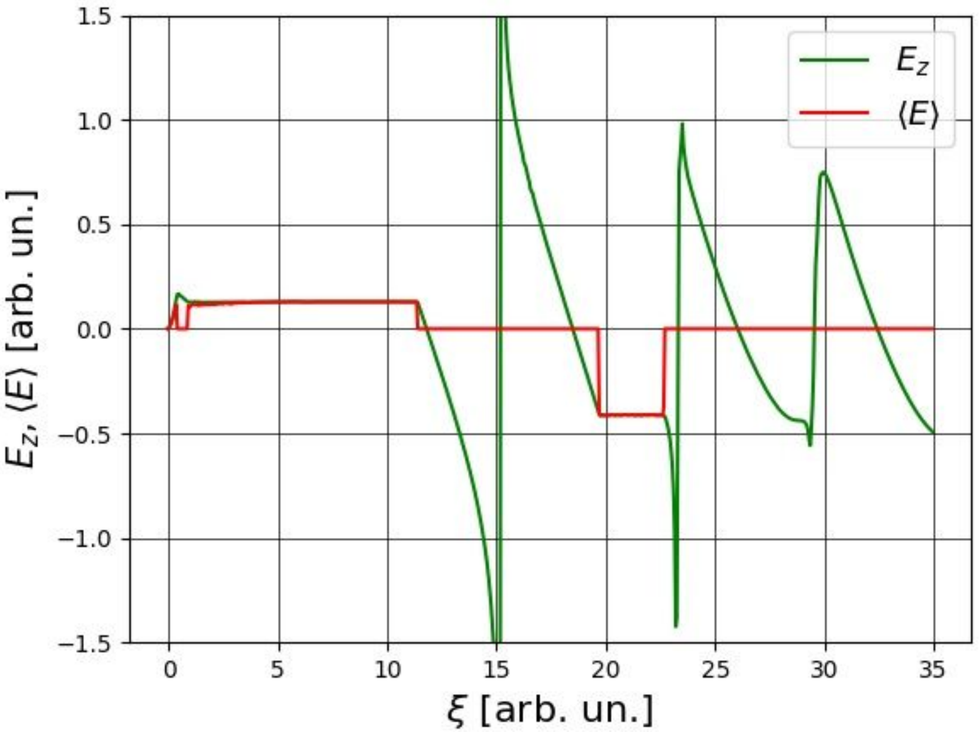


The maximum current of bunch- driver: Ib = 10.7 kA.
Transformer ratio: 6.1

Large Charge of Accelerated Electrons at **Large Transformer Ratio** and **High Efficiency** at Plateaus **for One Driver-bunch and One Witness-bunch**





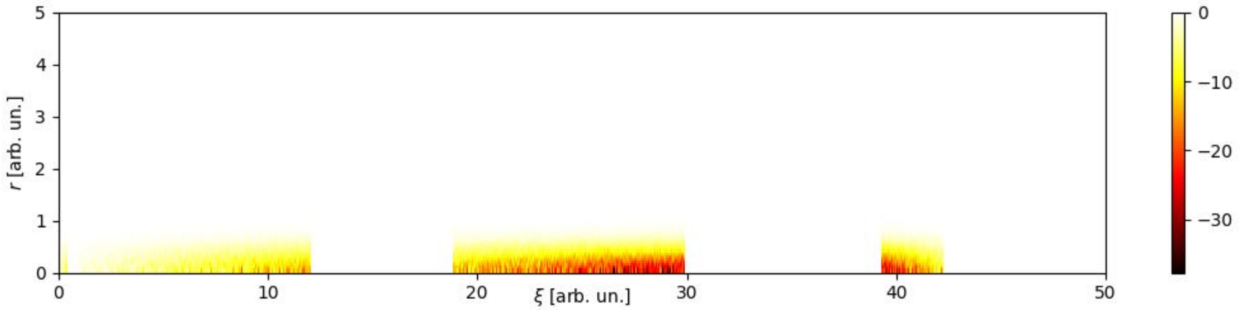


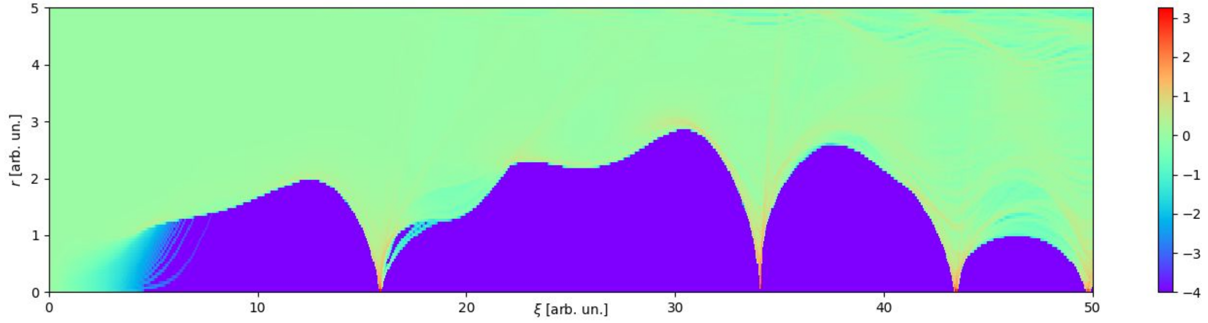
The maximum current of the bunch-driver: Ib = 10.1 kA.
Transformer ratio: 3.2

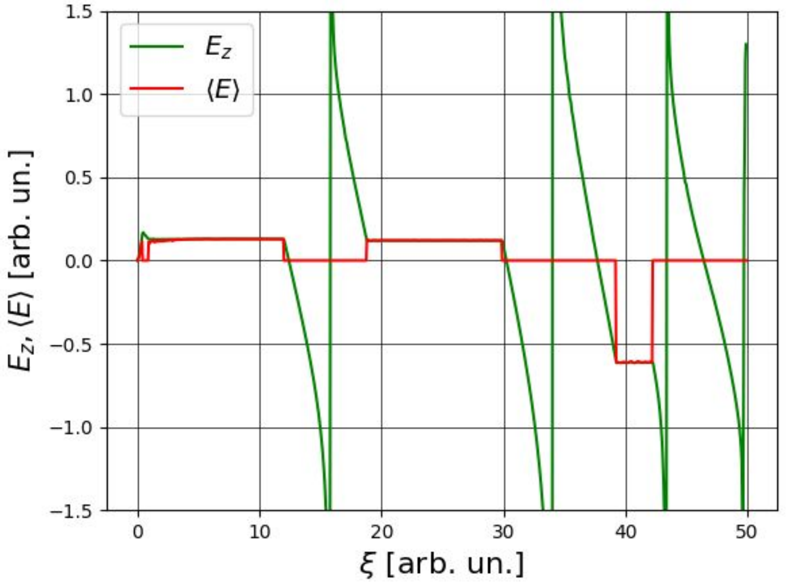
Modified and Developed Schemes

Large Charge of Accelerated Electrons at **Large Transformer Ratio** and **High Efficiency** at Plateaus

for Two Long Driver-bunches and for the Witness-bunch in the Accelerating Wakefield







The maximum current of the first bunch-driver is Ib = 10.7 kA and for second Ib = 19.7 kA. The transformer ratio is 4.5

Instabilities in plasma wakefield accelerators

- Betatron oscillations
- Moving ions
- Hosing instability
- Low radius bunches
- Heavy atoms
- Nonlinear or close to zero focusing force

S.Diederichs, C.Benedetti, E.Esarey, M.Thevenet, J.Osterhoff, C. B. Schroeder. Phys. Plasmas. 29, 043101 (2022)

Hosing Instability in the Blow-Out Regime for Plasma-Wakefield Acceleration

C. Huang,[1] W. Lu,[1] M. Zhou,[1] C. E. Clayton,[1] C. Joshi,[1] W. B. Mori,[1] P. Muggli,[2] S. Deng,[2] E. Oz,[2] T. Katsouleas,[2] M. J. Hogan,[3] I. Blumenfeld,[3] F. J. Decker,[3] R. Ischebeck,[3] R. H. Iverson,[3] N. A. Kirby,[3] and D. Walz[3]

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[3]*Stanford Linear Accelerator Center, Menlo Park, California 94025, USA*

The electron hosing instability in the blow-out regime of plasma-wakefield acceleration is investigated using a linear perturbation theory about the electron blow-out trajectory in Lu *et al.* [in Phys. Rev. Lett. **96**, 165002 (2006)]. The growth of the instability is found to be affected by the beam parameters unlike in the standard theory Whittum *et al.* [Phys. Rev. Lett. **67**, 991 (1991)] which is strictly valid for preformed channels. Particle-in-cell simulations agree with this new theory, which predicts less hosing growth than found by the hosing theory of Whittum *et al.*

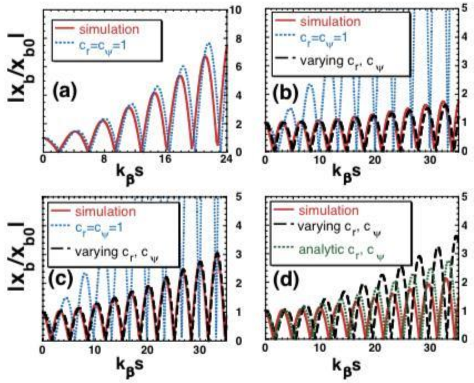
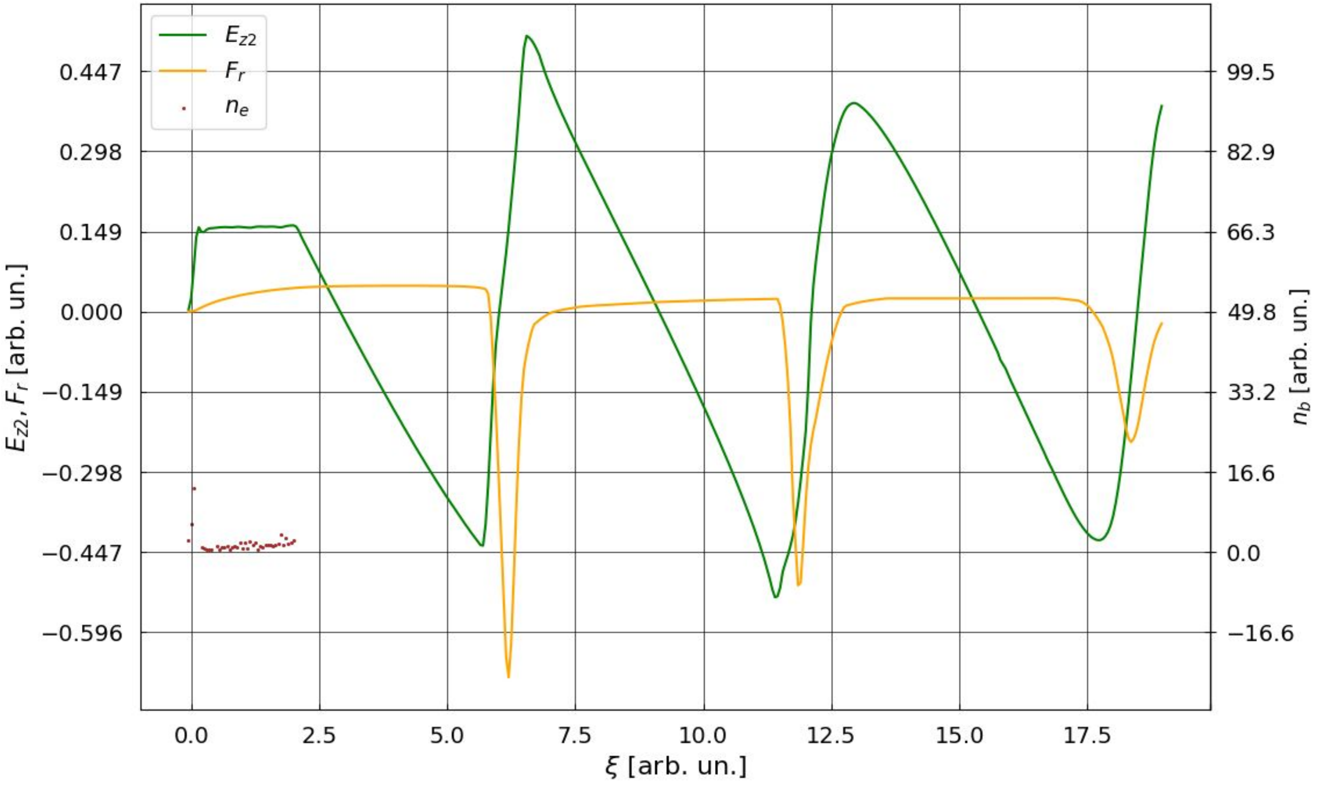
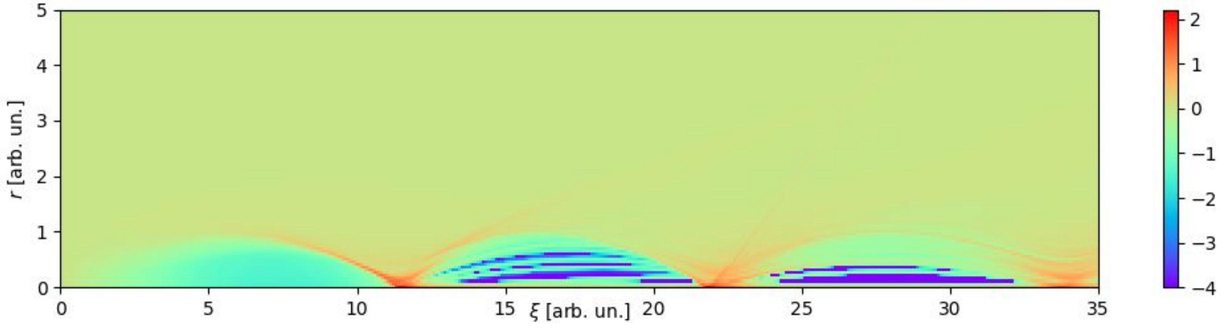


FIG. 3 (color). Hosing growth in four regimes. x_{b0} is the initial displacement of the beam centroid. We assume $\Delta_s = 0.1 r_0$, $\Delta_L = 1c/\omega_p$ for the analytic curve in case (d). The slightly slower hosing growth in simulation (d) is caused by nonlinearity in beam-channel centroid coupling.

Weakly Nonlinear Mode with Narrow Bunches



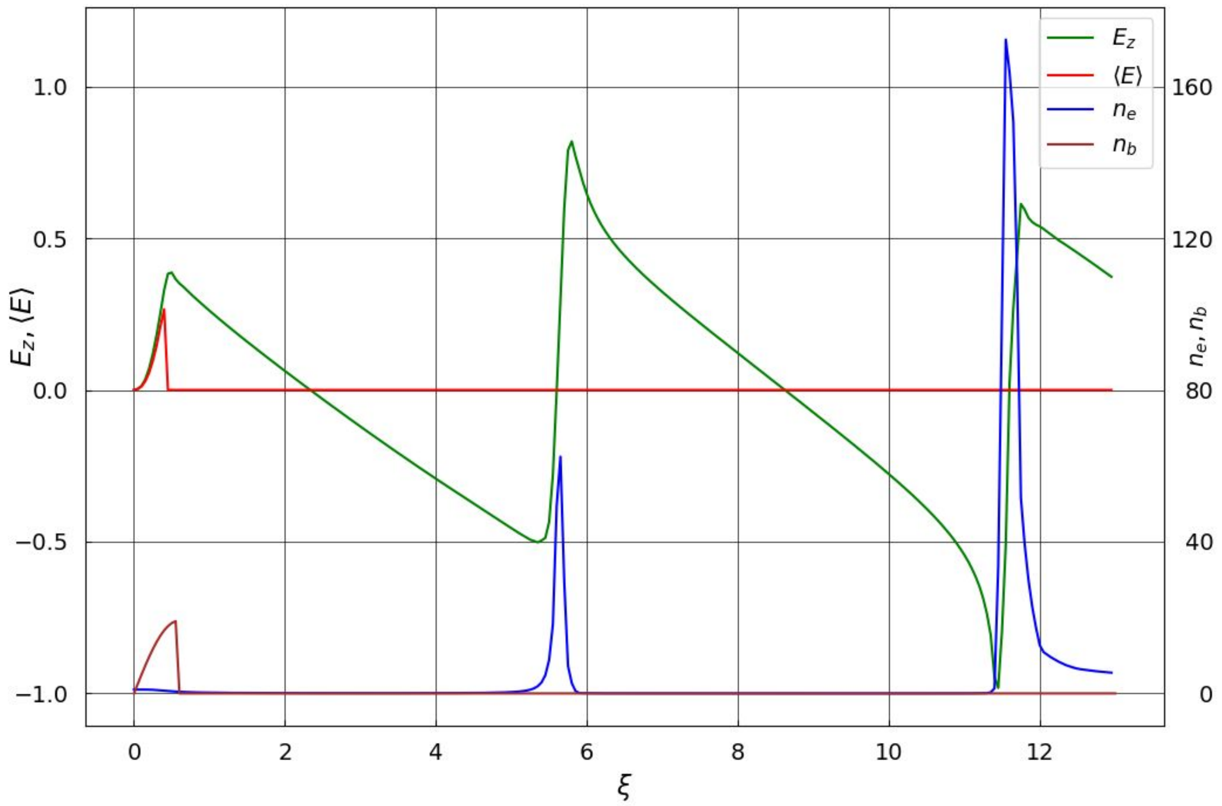


Analytical investigations

T.J.Mehrling, R.A.Fonseca, A.Martinez de la Ossa, J.Vieira. Phys. Rev. Lett. 118(2017)174801;

A.Knetsch, B.Sheeran, L.Boulton et al. Phys. Rev. Accel. Beams. 24, 101302 (2021);

Regularization and **Advantages** of Wakefield in a Weakly Nonlinear Regime with Narrow Bunches



from V. Maslov, R. Ovsiannikov, Numerical simulation of plateau formation by an electron bunch on the distribution of an accelerating wakefield in a plasma

1d $$\frac{dE_z}{dz} \approx 4\pi e n_b \;\rightarrow\; E_z \sim \xi - \xi_w(t),$$

3d $$4\pi r^2 E_r = \frac{4\pi}{3} e n_i r^3$$

$$E_r = E_z = \frac{e n_i}{3} r \sim r \sim z - z_{bub}.$$

$$E_r = E_z = -\frac{e n_b}{3} r \sim -r \sim z_b - z.$$

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V. Maslov, R. Ovsiannikov, N. Delerue et al Problems of Atomic Science and Technology, v. 6, p. 47, 2020.

Thank you

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