MAX-PLANCK-INSTITUT FÜR PHYSIK

Advanced Linear collider for Very high Energies — ALiVE

Energy transfer in a proton-driven wakefield accelerator

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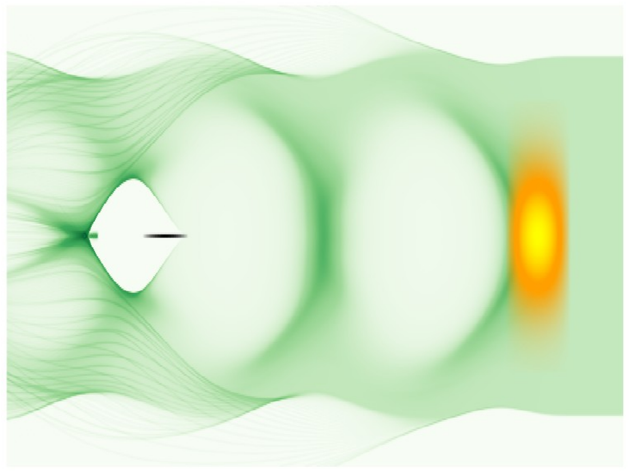
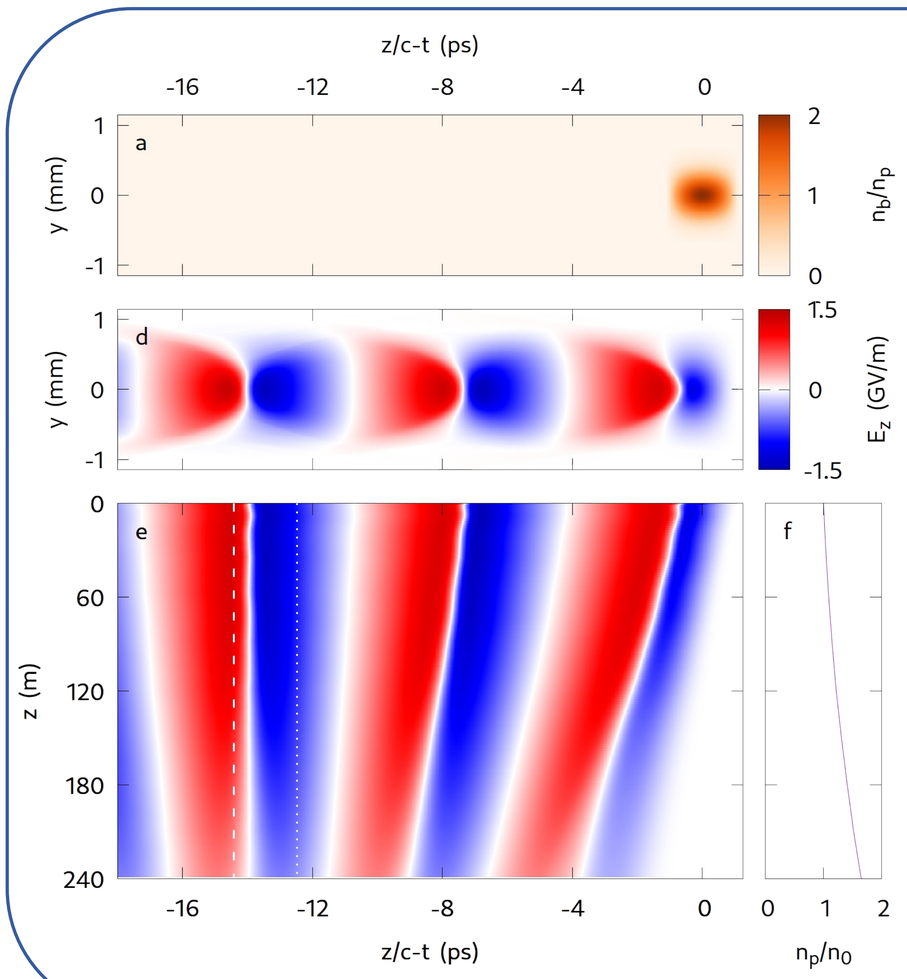
Plasma-based accelerators support large field gradients, but reaching high energies requires that these gradients be sustained over long distances. The high energy of currently available proton sources offers the potential to accelerate a witness bunch to the energy frontier, avoiding the need to couple sequential plasma stages [1,2].

However, a proton driver presents its own unique challenges. The large proton mass means that the limiting factor at low energies is longitudinal dispersion of the driver, while the asymmetric plasma response introduces additional constraints on the transformer ratio due to the positive driver charge. In this work, we investigate the efficiency with which energy can be transferred from a proton driver to a trailing witness, and the scaling with driver energy.



Left: A short proton driver (yellow/orange), propagating to the right, excites a density wave in the plasma electron density (green). The associated wakefields can be used to accelerate a trailing witness, in this case an electron bunch (black), to high energy.



Dispersion limit

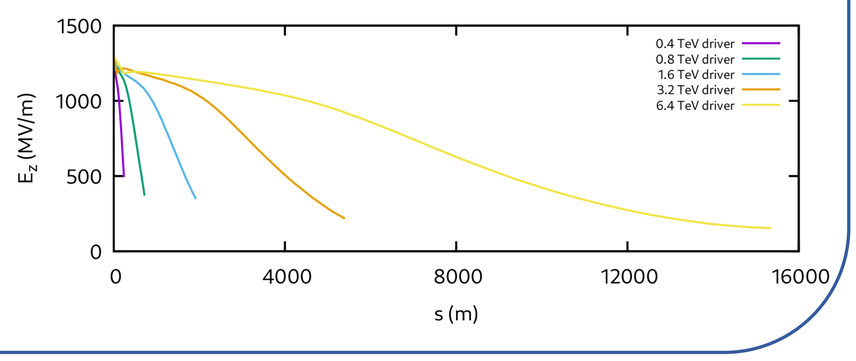
Currently available proton beams have per-particle energies well beyond that available in electron accelerator facilities. This makes them a promising candidate as wakefield drivers, as they can potentially accelerate a witness bunch to the energy frontier in a single plasma stage.

The large mass of the protons means that the gamma factor of the driver is is relatively modest. Dephasing between driver and witness can be overcome by using a plasma with a tailored density gradient. However, as the driver loses energy to the plasma, it develops a correlated energy spread, leading to dispersion. This stretching of the drive beam reduces the effectiveness with which it excited wakefields.

In this dispersion-limited regime, increasing the driver energy allows a better-than-linear increase in achievable witness energy, with $E_{witness} \sim E_{driver}^{3/2}$.

Left: A short proton drive bunch excites a plasma wakefield (d). The dephasing between the driver and the witness can be overcome by using a tailored density profile, seen in f. This allows the witness to remain in an accelerating field over long distances.

Right) Increasing the driver energy leads to a better-than-linear increase in the distance over which the wakefields can be maintained.



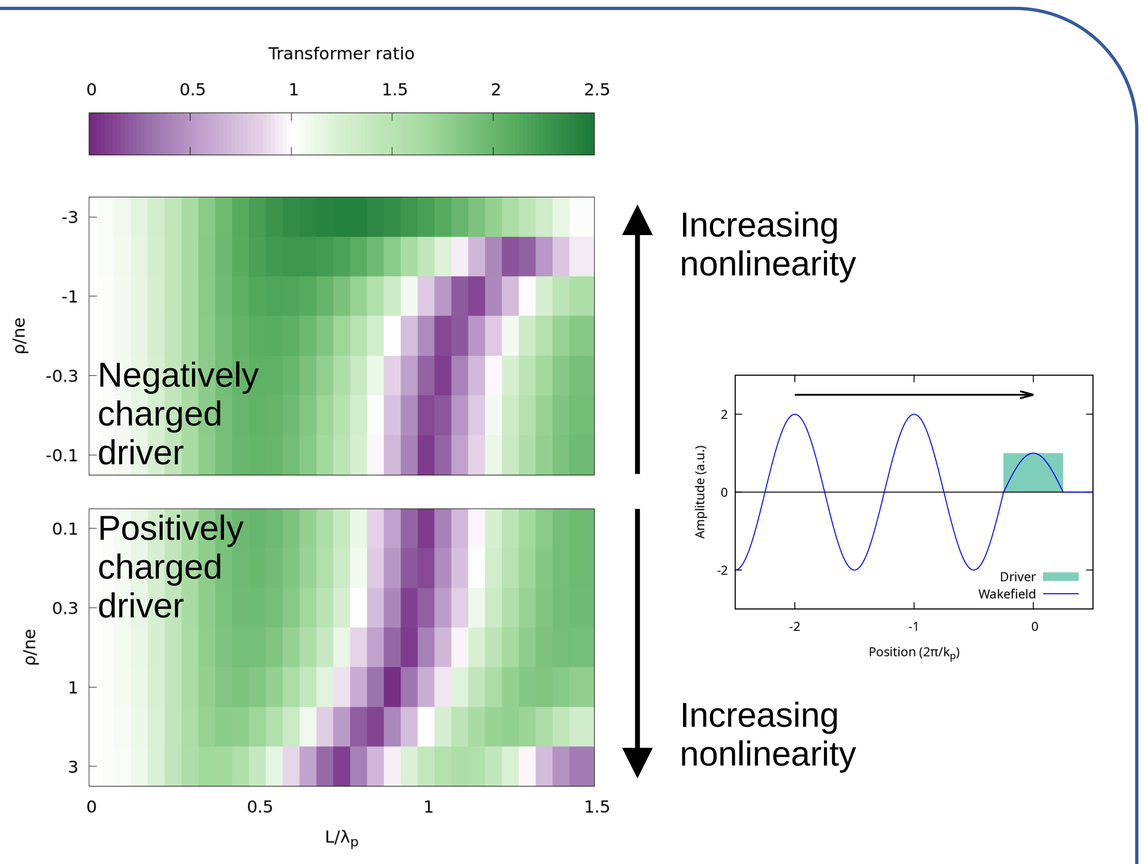
Transformer ratio

The transformer ratio represents the achievable per-particle witness energy gain in terms of the per-particle driver energy. In the linear regime, the maximum transformer ratio [3] for a symmetric driver is 2. However, plasma nonlinearities modify both the optimal driver length and the transformer ratio.

A negatively charged driver screens the plasma ion charge, reducing the local plasma frequency and allowing the use of a longer drive bunch. After the driver has passed, the plasma frequency increases, and the absence of screening increases the wakefield amplitude, increasing the transformer ratio. For a positively charged driver, the opposite is true.

This asymmetry in the plasma response reduces the driver-to-plasma energy transfer efficiency in a proton-driven wakefield accelerator. A detailed optimisation is required to weigh the relative merits of higher accelerating fields against reduced transformer ratio.

This limitation is balanced by the intrinsic benefits of proton wakefield drivers, with acceleration in a single stage offering less stringent constraints for alignment and potentially larger average accelerating gradients.



Left: unloaded transformer ratio for a flat-top driver as a function of driver length and density. At low density, the result converges with the $\lambda_p/2$ expected from linear theory. Right: model configuration. A driver radius of $1/k_p$ is used.

ALiVE: next steps

- Applications beyond the Higgs (offers improved efficiency)
- Optimization using shaped bunches [4], with simulations including ion motion [5] and ionization
- Development of demonstrator concepts
- Study of high-disruption IPs relevant for plasma-accelerated beams

Key challenges

- Further development of the proton accelerator concept, including collective effects
- New schemes for positron acceleration, one of the “grand challenges” of plasma physics [6]
- Development of suitable plasma sources for high-rep-rate

[1] J. P. Farmer, A. Caldwell and A. Pukhov, New J. Phys. **26**, 113011 (2024).
[2] “Proton-Driven Plasma Wakefield Acceleration for Future HEP Colliders”, Input to the EPPSU (2025).
[3] R. D. Ruth *et al.*, SLAC-PUB-3374 (1984).
[4] S. van der Meer, CERN Technical Report: CLIC Note No. 3 (1985).
[5] J. P. Farmer *et al.*, Proc. LCWS, EPJ Web Conf **315**, 02019 (2024).
[6] “Design Initiative for a 10 TeV pCM Wakefield Collider”, Input to the EPPSU (2025).