Beam Energy Deposition in Plasma Electrons during Wakefield Acceleration by Long Drivers

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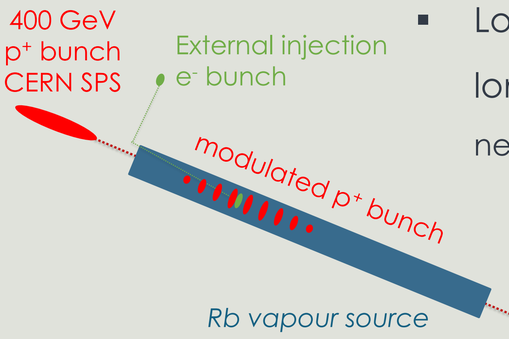
Abstract

In this work, we investigate the energy transfer from a long proton bunch driver to the plasma in the context of the AWAKE experiment, using particle-in-cell simulations with OSIRIS. As the driver propagates through the plasma, it excites wakefields by displacing plasma electrons, which gain kinetic energy. This energy can dissipate through several mechanisms, including electromagnetic radiation. We analyse the correlation between the kinetic energy of plasma electrons and the longitudinal accelerating field. Initially, a linear relationship is observed; however, as the wake evolves, phase slippage (dephasing) introduces curvature into the wake structure. Multiple wake phases then contribute to the energy of individual plasma electron slices, breaking the simple linear scaling. We characterise this transition and quantify how dephasing affects the distribution of deposited energy.

Introduction: AWAKE Proton Driven PWFA [1,2]

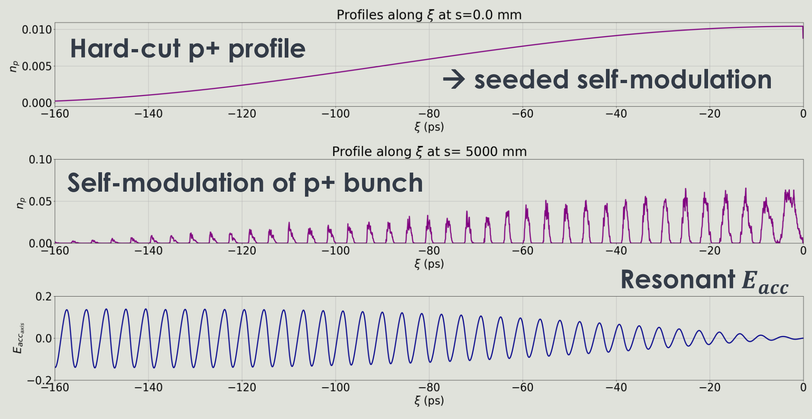


- Long proton driver (σ_z~ 160 ps ~ 5 cm, σ_r~ 200 μm) longer than λ_{pe} (λ_{pe}~ 1.2 mm for n_e ~ 7x10^{14} cm^{-3} necessary to drive GeV/m)
  - Self-modulation **[3]**
  - Wakefield grows resonantly along the bunch (ξ) and along the plasma (s), until saturation **[4]**

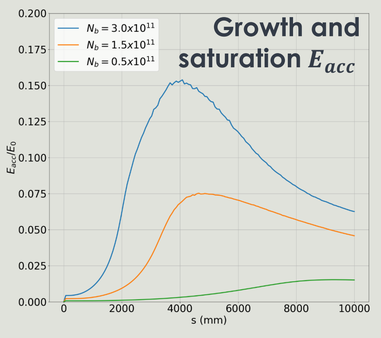
AWAKE demonstrated p+ bunch self-modulation and e- acceleration to 2 GeV **[1]**

Methods:

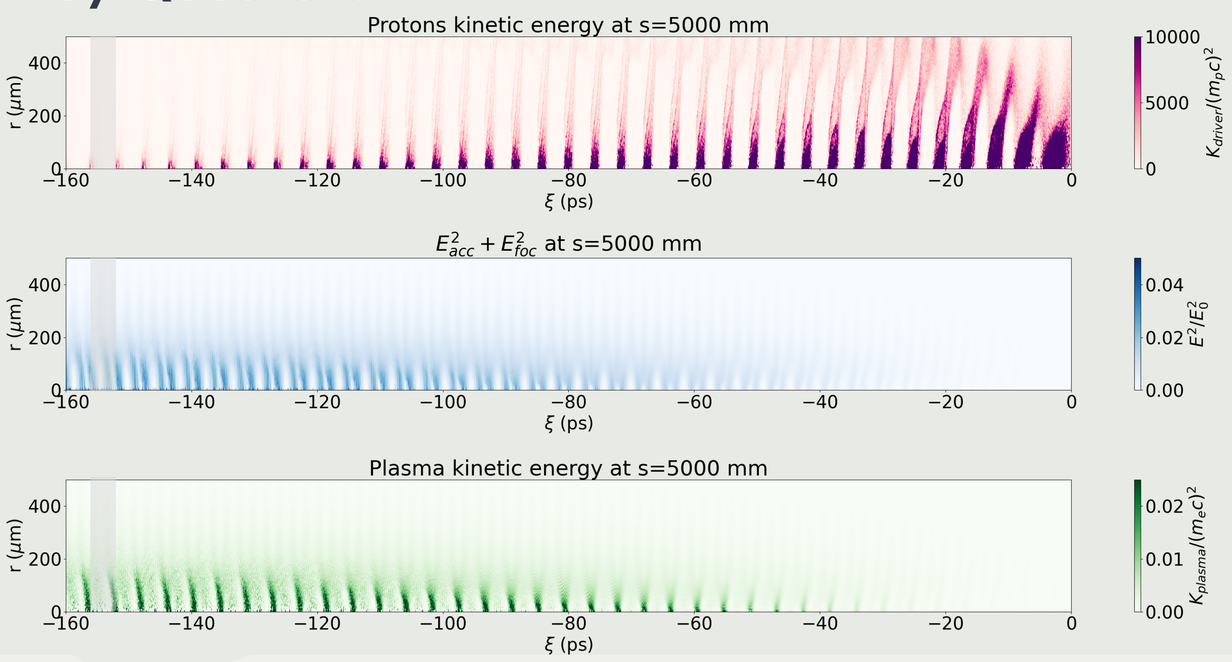
- PIC simulation OSIRIS **[5]** for long p+ bunch



Simulation details:
moving window, 2D cylindrical geometry
grid size: 4375x 450
window size: 350x9 $[k_p^{-1} \times k_p^{-1}] \cong$ 5x0.16 cm
Δt: 0.0175 $[\omega_p^{-1}]$



Key Question:



- Wakefield acceleration → Electrostatic field $\boldsymbol{E}$
  → longitudinal component → accelerating field $\mathbf{E_{acc}}$
  → transverse component → focusing field $\boldsymbol{E_{foc}}$
- Driver transfers its kinetic energy ($\boldsymbol{K_{driver}}$) to wake potential and to the **plasma electrons** that gain kinetic energy ($\boldsymbol{K_{plasma}}$):

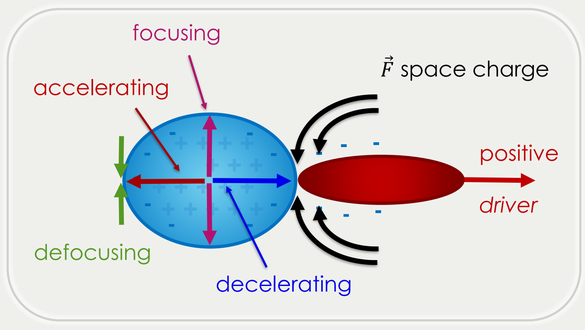
$$\boldsymbol{K_{driver} + K_{plasma} + \frac{1}{2}\left(E_{acc}^2 + E_{foc}^2\right) = conts.}$$

Is the $K_{plasma} \propto E_{acc}$ in the long driver case?

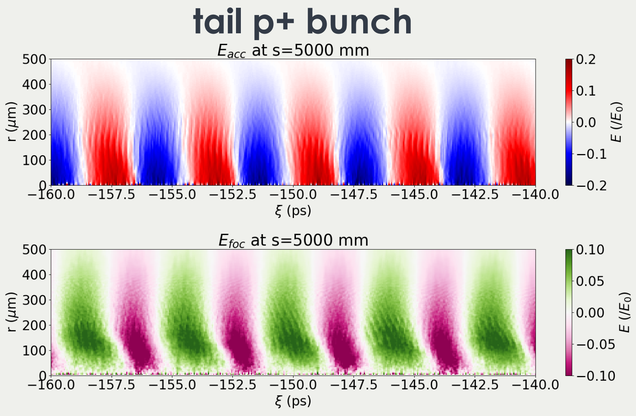
Motivation: spectral energy released by the plasma as optical diagnostic for plasma wakefield accelerators **[6]**

Results:

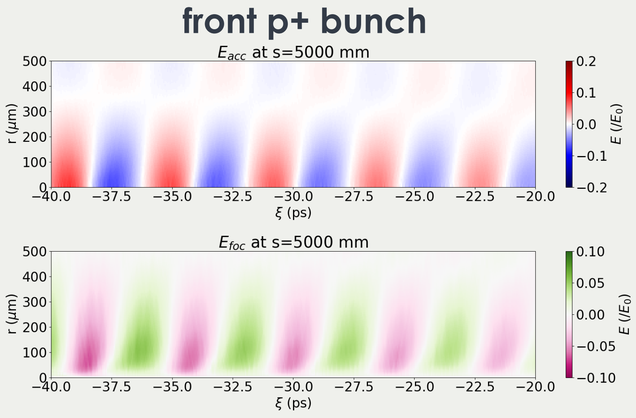
- After the beam passage, $K_{driver} \rightarrow 0$,
  → $\left[E_{acc}^2 + E_{foc}^2\right] \propto K_{plasma}$
  (integrated over 1 plasma periods)
- In the linear regime:
  → $\max(E_{acc}) \propto \max(E_{foc}) \propto K_{plasma}$



tail p+ bunch



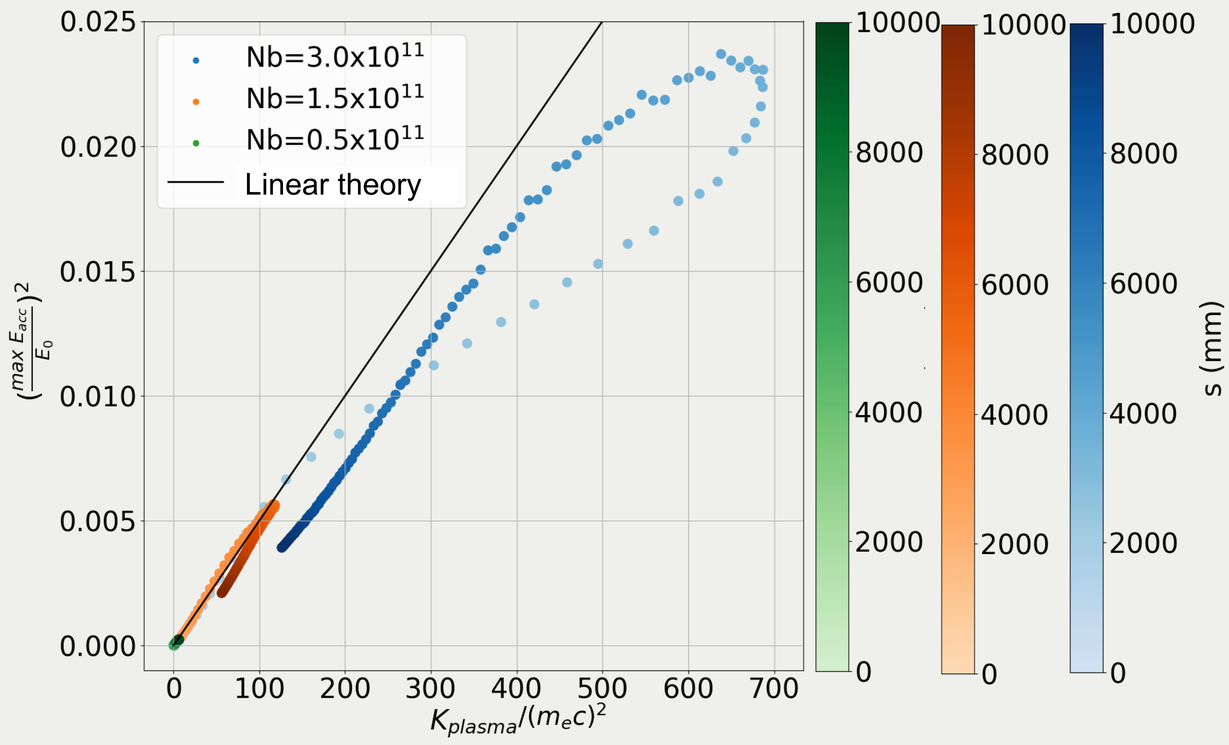
front p+ bunch



- Higher bunch population → larger wakefield
  Non-linearities break this relation
  → E_{foc} phase has radial dependence in tail p+ bunch
  Breaks correlation $\max(E_{acc}) \propto K_{plasma}$

Discussion:

Correlation accelerating field with plasma kinetic energy



At low bunch charge, early propagation: $\max E_{acc}^2 \propto 2 \times K_{plasma}$ **(linear theory)**

Conclusion

- Found a regime where the proportionality $\max(E_{acc}) \propto K_{plasma}$ is valid for the multi-bunch driver case;
- K_{plasma} is the energy deposited in the plasma instantaneously after the beam (timescale of the wakefield excitation ~ps);
- Energy dissipation by emission of light is a longer process (in the scale of ms) that would require collisional-radiative plasma models to simulate it. This study frames the boundaries where the linear regime is valid for diagnostics of the wakefield amplitude **[7,8]** based on the energy deposited in the plasma.

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References

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