Light Emission of Dissipating Wakefields

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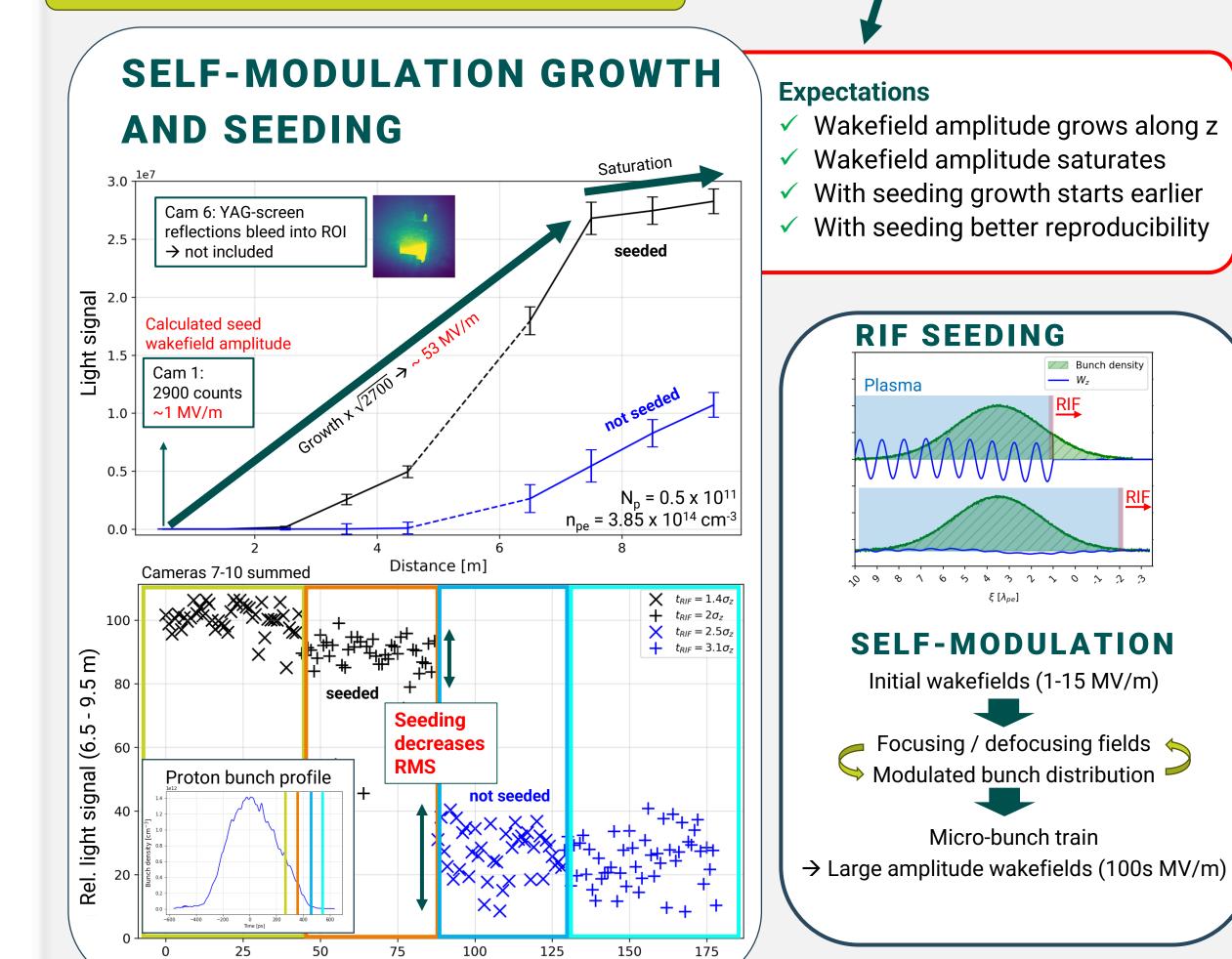
ABSTRACT

In plasma wakefield acceleration, energy is transferred from a driver to a witness bunch through the wakefields. Energy lost by the driver is stored in wakefields as kinetic energy of the oscillating electrons, and as potential energy of the electric and magnetic field. A witness bunch can be accelerated by the longitudinal electric field. Wakefield energy is eventually dissipated in the plasma. A part of this energy is emitted as light. We discuss the proportionality between emitted light, deposited energy and wakefield amplitude. We utilize this relation with the light diagnostics and showcase how it is used to investigate the longitudinal evolution of wakefields driven by a long relativistic proton bunch at AWAKE.

Setup **PROTON BUNCH IONIZING LASER** Plasma entrance Plasma exit Laser Dump → Drive bunch 780 nm Ti:Sa – laser pulse Laser pulse CERN SPS - 400 GeV Pulse duration ~ 100 fs Pulse energy: 0 – 120 mJ "Gaussian" distribution Peak intensity ~ 10 TW/cm² $\sigma_{7} \sim 180 \text{ ps } (5.4 \text{ cm})$ → Field ionization $\sigma_r \sim 200 \text{ um (at plasma entrance)}$ Pos. 10 (Rb vapor 100 % singly ionized) Pos. 1 Y ~ 427 Protons Plasma Cameras Interferometer View ports 9.5 m Ionization front moves near c $0.5 \, \mathrm{m}$ $N_p = (0.5 - 3) \times 10^{11} \text{ protons}$ → RIF (Relativistic Ionization Front) **Motivation** $N_p = 3 \times 10^{11}$ $N_p = 3 \times 10^{11}$ $N_p = 2 \times 10^{11}$ Laser only - 7000 **Light signal of the laser** 15.0 Colorscale micro-bunch train 6000 p+ bunch pulse along plasma source 5000 Light signal: $n_{pe} = 3.85 \times 10^{14} \text{ cm}^{-3}$ modulation sum of 1.75 80 mJ calibrated Laser envelope Deposited energy counts in ROI (field ionization) Wakefields evolve as the p+ bunch self-modulates 1.50 -(vacuum) $0.5 \, \mathrm{m}$ $0.5 \, \mathrm{m}$ $0.5 \, \mathrm{m}$ 9.5 m Light emission of plasma as measurement of 1.25 31 m) wakefield amplitude along plasma? is 0.75 **OBJECTIVE** s Light – drive bunch E_{loss} Light 9.20 **SLAC 2004** Diagnostic for the Wakefield Amplitude E_{out} =0.0 mJ 0.00 **Explore New** Oz et al. [2] Test with Established Verify Z, m ¹⁰ Distance [m] Wakefield Physics sum of all Wakefield Physics Assumptions cameras **Proportionality Studies** Total counts compared to total energy deposited **Assumption** $n_{pe} = 3.85 \cdot 10^{14} \text{ cm}^{-3}$ \star $t_{RIF} = 0ps$, dataset 1 Emitted light proportional to energy deposited $t_{RIF} = 0ps$, dataset 2 Camera data $t_{RIF} = -100ps$, dataset 2 How to verify? 3σ detection threshold Use laser pulse! Light measured at 0.5 m → Pulse enegy measured at entrance and exit **Energy loss** → No growth / seed wakefields Ê 24000 data [1] → Correlate measured light with energy loss $N_p = 3 \times 10^{11}$ signal (0.5 $n_{pe} = 1.05 \times 10^{14} \text{ cm}^{-3}$ Conclusion → Low density for Arbitrary fit to energy deposition data large ratio of Light emitted proportional to energy deposited $N_p = 1 \times 10^{11}$ wakefield signal to Light Verified for 0-12 mJ/m with laser pulse 100 laser signal Laser pulse energy (entrance) [mJ] $N_p = 2 \times 10^{11}$ Fit to data E_{loss} weighted Light emitted by plasma is proportional **Assumption** to energy locally deposited by ionizing Findings at SLAC: by individual Bunch density [cm⁻³] Light proportional to e Wakefields deposit energy proportional to W₇ r² cam counts bunch energy loss [2] **Longitudinal Bunch profiles** Wakefields of unmodulated bunch signal 1.25 → Near the plasma entrance How to verify? Not practical to $W_{\!\scriptscriptstyle Z,r}{\sim}\,n_b$, $u_{\scriptscriptstyle E}{\sim}\,n_b^2$ Tight 1.00-Use seed wakefields! measure energy loss $Z = 0.5 \, \text{m}$ of 400 GeV p+ bunch → Wakefields calculated from linear theory $Z = 1.5 \, \text{m}$ → Correlate with measured light |Z = 9.5 m→Here: Light proportional to laser **Conclusion** pulse energy loss Some proportionality (larger W_{z,r} -> more light) Bunch density [cm-No strong evidence for strictly squared relation Estimated energy deposited at cam pos. [mJ/m] Open questions: → Ongoing research topic How do wakefields dissipate their energy?

Self-Modulation Studies

Data for the laser pulse energy loss taken from reference [1]; curtesy of Dr. Gabor Demeter



Event#

[2] E. Oz et al. "Optical Diagnostics for Plasma Wakefield Accelerators", AIP Conference Proceedings 737, 708 (2004)

GROWTH SUPRESSION

Low charge / large density gradient along z:

- \rightarrow Increasing / decreasing ω_{pe} causes phase shift
- \rightarrow Micro-bunch frequency does not match ω_{pe}
- → Disrupts feedback loop 💢

High charge & small density gradient:

 $\rightarrow V_{\rm ph} < V_{group}$

What proportion of the wakefield energy ends up in the plasma?

- \rightarrow Phase shift compensates lower V_{ph}
- → More charge in micro-bunch train ✓

