Numerical simulation study of the propagation of a short electron bunch and a long proton bunch in a plasma ramp

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AWAKE AND ITS PLASMA RAMP

The Advanced Wakefield Experiment (AWAKE) [1] is a proof-of-principle experiment located in CERN for a plasma based particle accelerator using self-modulation (SM) [2].

The 10-m-long plasma has a density ramp at its entrance [3]. There, $n_b \gg n_e$ leading to a non-linear plasma response.

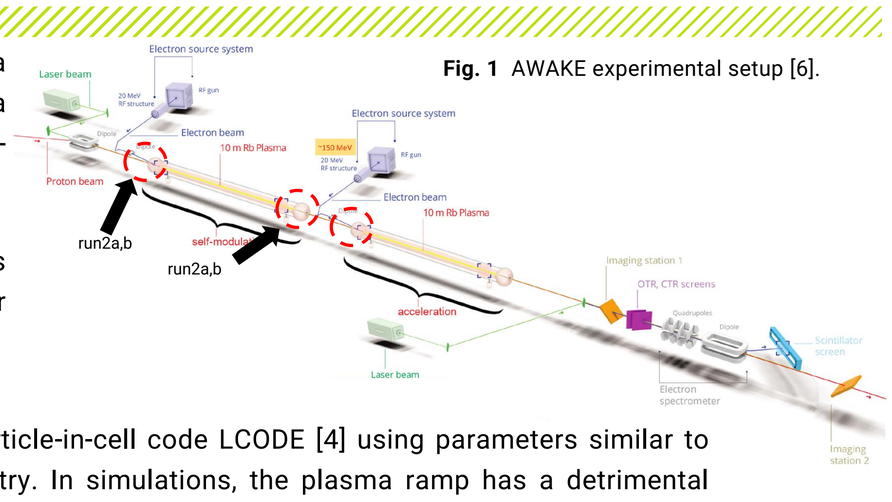
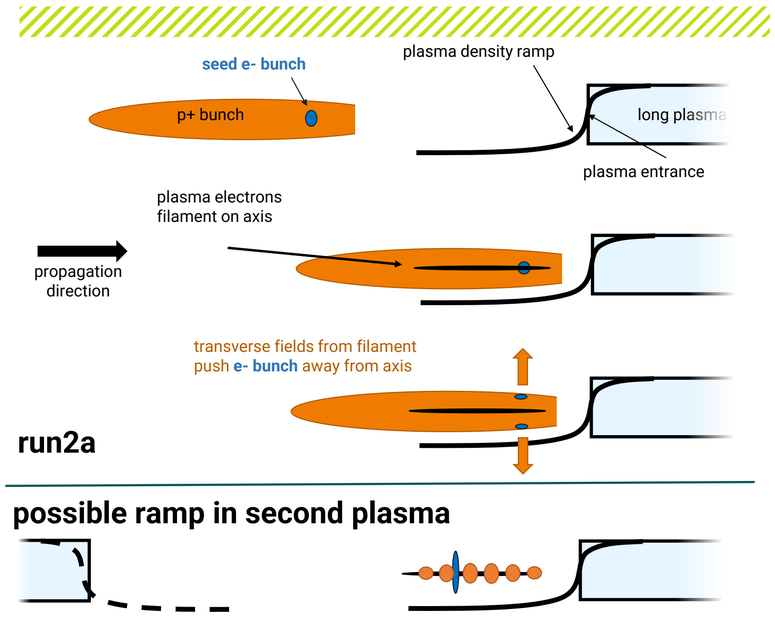


Fig. 1 AWAKE experimental setup [6].

We present a numerical study performed with the particle-in-cell code LCODE [4] using parameters similar to those of the experiments in 2D axisymmetric geometry. In simulations, the plasma ramp has a detrimental effect on both a seed electron bunch placed inside of the proton bunch and on an electron bunch injected in a second plasma for acceleration [5], if that plasma had a density.

PLASMA RAMP SCHEMATIC (NOT TO SCALE)



SEED ELECTRON BUNCH INSIDE PROTON BUNCH

Density in ramp changes from $n_e \approx 1 \times 10^9$ to 2×10^{14} cm^{-3}

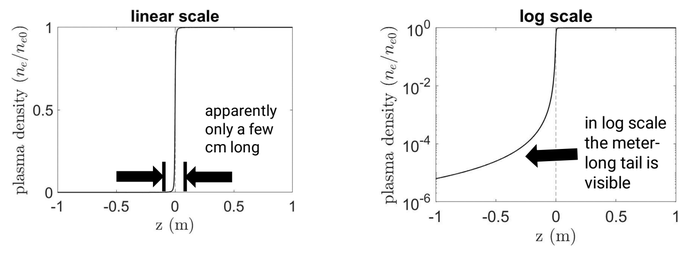


Fig. 2–3 Plasma ramp in linear and log scales.

AWAKE: long gaussian **p+ bunch** entering ramp
- rms length $\sigma_z = 7.5$ cm
- rms width $\sigma_r = 0.2$ mm
- density cut 2 σ_z ahead of bunch center to seed the SM
- 3×10^{11} protons

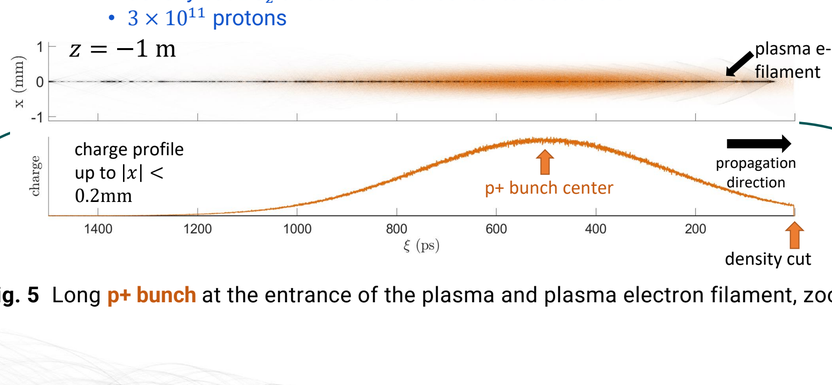


Fig. 5 Long **p+ bunch** at the entrance of the plasma and plasma electron filament, zoom below.

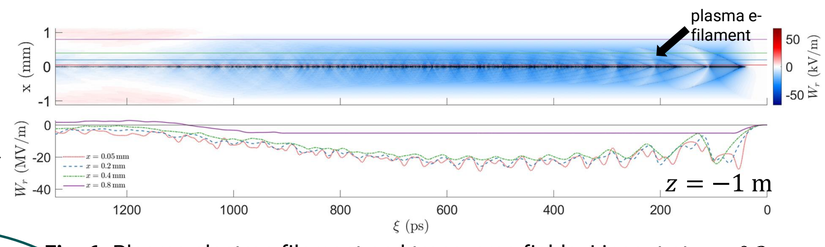
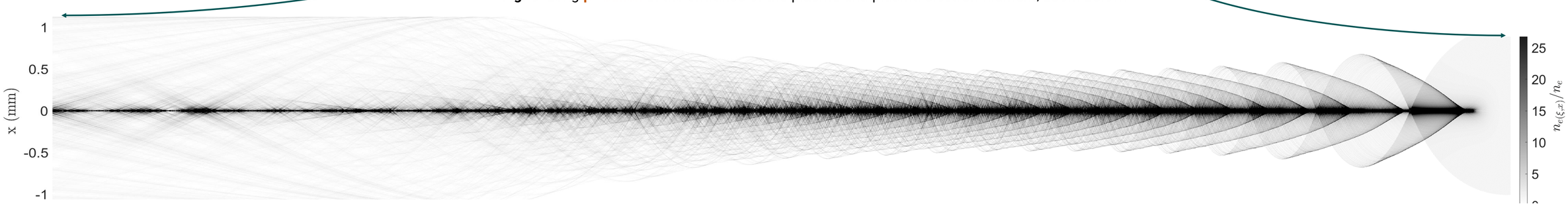


Fig. 6 Plasma electron filament and transverse fields. Lineout at $x = 0.2$ mm

- $W_r(50 \text{ ps} < \xi < 800 \text{ ps}) \sim 20$ kV/m

(seed) **19 MeV** e- moved from axis to $k_p^{-1} = 0.37$ mm in **60 cm**



ELECTRON BUNCH FOR ACCELERATION INSIDE MICROBUNCH TRAIN

seed e- bunch for SM

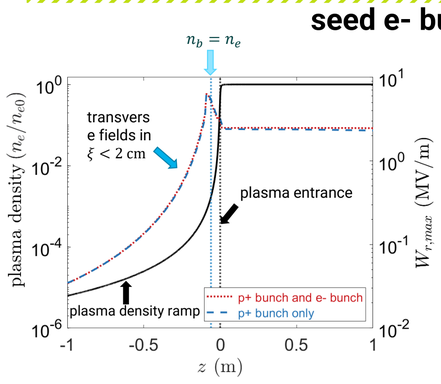


Fig. 7 Left axis: plasma density ramp. Right axis: transverse fields maximum amplitude.

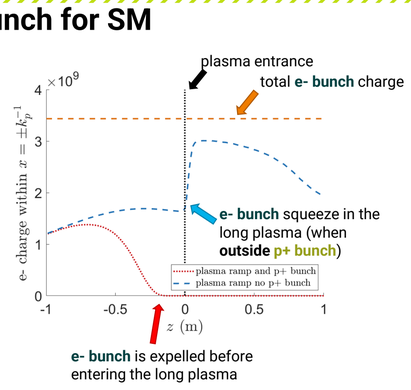


Fig. 8 **e- bunch** along z with and without plasma ramp.

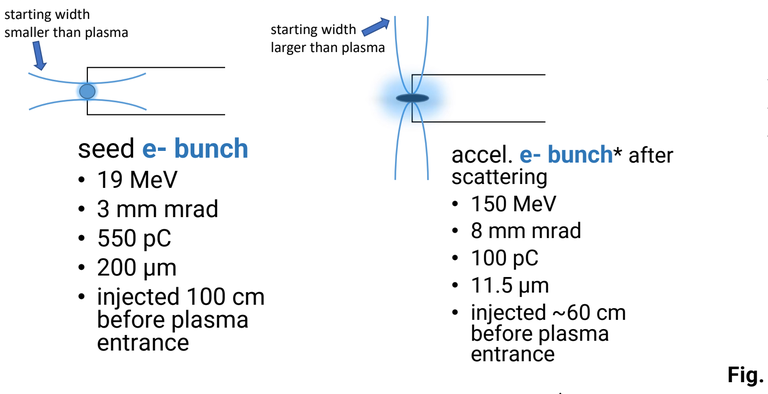


Fig. 9 AWAKE Run 2c schematic [6, and original material].

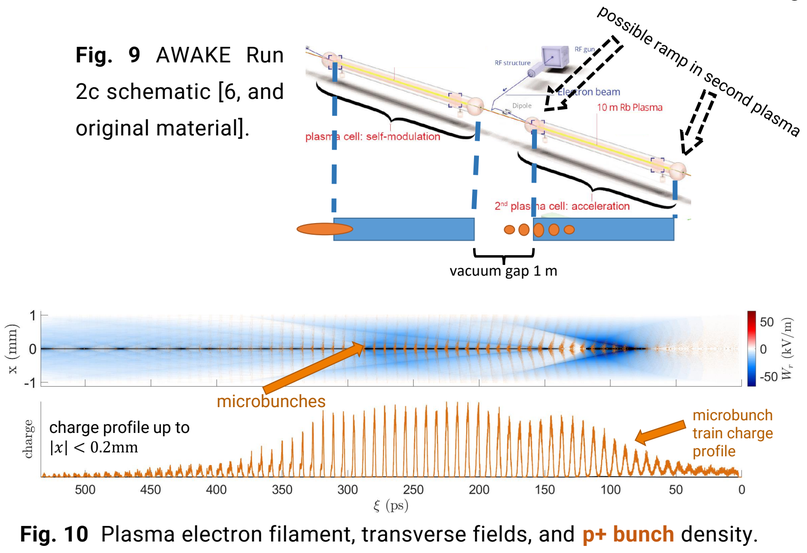


Fig. 10 Plasma electron filament, transverse fields, and **p+ bunch** density.

e- bunch for accel.

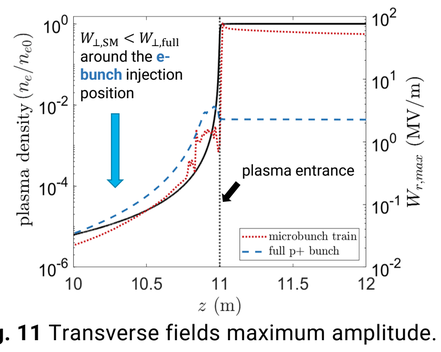


Fig. 11 Transverse fields maximum amplitude.

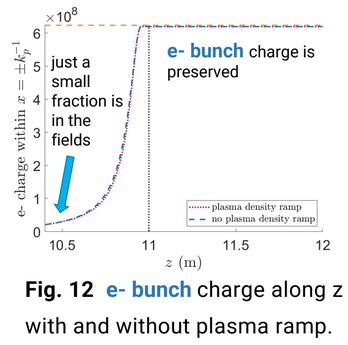


Fig. 12 **e- bunch** charge along z with and without plasma ramp.

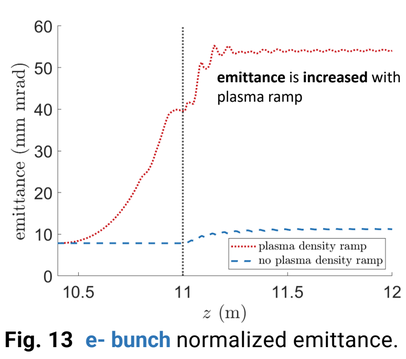


Fig. 13 **e- bunch** normalized emittance.

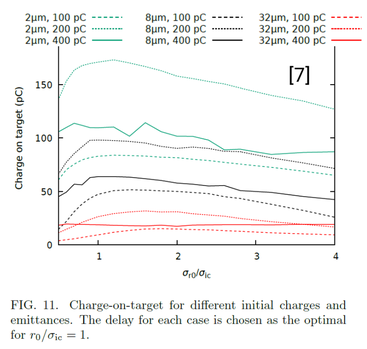


FIG. 11. Charge-on-target for different initial charges and emittances. The delay for each case is chosen as the optimal for $r_0/\sigma_{rc} = 1$.

e- bunch cannot be used for seeding **when inside the p+ bunch**
- Frequency of fields in plasma ramp < frequency of self-modulation
- Amplitude of fields is too low for the propagation distance

Agreement with **experiments**
- e- bunch not measured by plasma end when inside **p+ bunch** (see Jan's poster)
- no seeding

- (accel.) **150 MeV** e- moved from axis to $k_p^{-1} = 0.37$ mm in **160 cm** (20 kV/m fields)
  - microbunch train has less charge than full bunch → less dense filament → **lower amplitude of the fields**
  - most of the **e- charge** outside plasma

higher initial emittance → lower charge on target for applications

*final parameters subject to change.

CONCLUSIONS AND OUTLOOK

At the plasma start, the non-linear plasma response to the proton bunch or microbunch train leads to a filament on axis. This filament sustains fields that do not affect the protons, but may expel and/or increase the emittance of the electron bunch.

Plasma density ramps are detrimental for the acceleration of electron bunches in wakefields driven by a proton bunch.

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[6] AWAKE Collaboration, unpublished
[7] J. Farmer et al. arXiv:2203.11622 (2022)