# Seeding Proton Bunch Self-Modulation in AWAKE with a Long Electron Bunch

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on behalf of the AWAKE Collaboration
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Abstract: The Advanced Wakefield Experiment (AWAKE) at CERN uses CERN SPS bunches to develop proton-driven plasma wakefield acceleration. However, to excite ~GV/m wakefields, the long SPS bunches must undergo self-modulation (SM) in plasma. SM is a beam-plasma instability and can be seeded to ensure wakefield reproducibility. During Run 2a (2021–2022), AWAKE demonstrated SM seeding using wakefields driven by an electron bunch ahead of the proton bunch in plasma. In these experiments, the electron bunch length was shorter than the plasma wavelength. In this contribution seeding with an electron bunch longer than the plasma wavelength is experimentally explored. This is interesting as higher plasma electron densities yield higher acceleration gradients, however, have shorter plasma wavelengths and sub-picosecond electron bunches needed for the seeding at these high densities are not readily available.

## AWAKE:

**The Advanced WAkefield Experiment (AWAKE) at CERN is developing proton driven plasma based wakefield acceleration [1]. The driver is a 400GeV/c proton beam which can generate up to GV/m wakefields in a 10m long laser ionised rubidium plasma.**

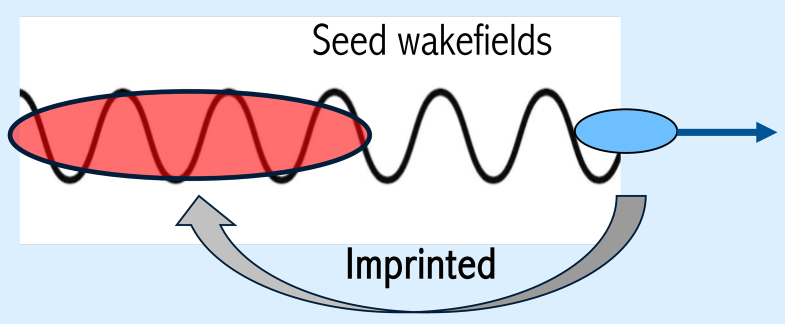
## Context:

Long (length $\sigma_z >>$ plasma wavelength, $\lambda_{pe}$) charged particle bunch in plasma (electron density $n_{pe}$) → subject to plasma instabilities e.g. Self Modulation instability (**SMI**).

Instability growing from noise → wakefields typically not reproducible.
Accelerator: **amplitude** + **phase** must be **reproducible**.

## Seeding:

Reproducibility achievable by setting same initial conditions (seed).
Seed wakefields must **exceed** noise (< a few MV/m **[2, 3]**).
E.g.: electron bunch (charge density $n_{b,e}$ $\sigma_e$ ~O($\lambda_{pe}$)) drives linear (**$n_{b,e}/n_{pe}$ << 1**) wakefields O($E_z$) ~ $n_b/n_{pe}$ $E_0$, $E_0$: cold plasma wavebreaking limit.
Optimal bunch length (rms) $\sigma_{z\_opt}$ to drive wakefields **$k_p\sigma_{z\_opt}$ ~√2.**




## Previous Results:

Seeding SM of long proton bunch in plasma demonstrated using :
1) Intense (~200 mJ), short (~120 fs) laser pulse which creates a relativistic ionisation front (**RIF**) **[3]**.
2) 20 MeV electron bunch at low (1e14 cm$^{-3}$ ) plasma density with $\sigma_e$ ~ $\sigma_{z\_opt}$ ~0.8mm **[4]**.

## Motivation & Challenges:

High accelerating gradients ←→ high wakefield amplitudes
←→ high plasma densities ($\lambda_{pe}$ =1.2mm, $\sigma_{z\_opt}$ ~0.3mm at AWAKE baseline density, 7e14 cm$^{-3}$ ).
**Challenges:**
1) Available electron bunch length at AWAKE $\sigma_e$ ~0.6mm > $\sigma_{z\_opt}$.
2) Phase reproducibility
If $\sigma_e \geq \lambda_{pe}$ → seed wakefields *susceptible to variations* in electron beam profile & timing. O(variations) ~ ps scale ~ O($\lambda_{pe}$).

## Suggested Solution:

Truncating the electron bunch with the ionising laser pulse
**Possible advantages:**
1) Higher electron beam seed wakefields due to optimal bunch length (see Fig 1. green curve) → higher initial seed wakefields (see Fig 1. green curve), faster growth and earlier saturation of SM.
2) Sharp onset of the electron beam density (~ fs scale < O($\lambda_{pe}$)) enables control over phase of seed wakefields (additionally ionising laser pulse and electron bunch timing intrinsically tied).

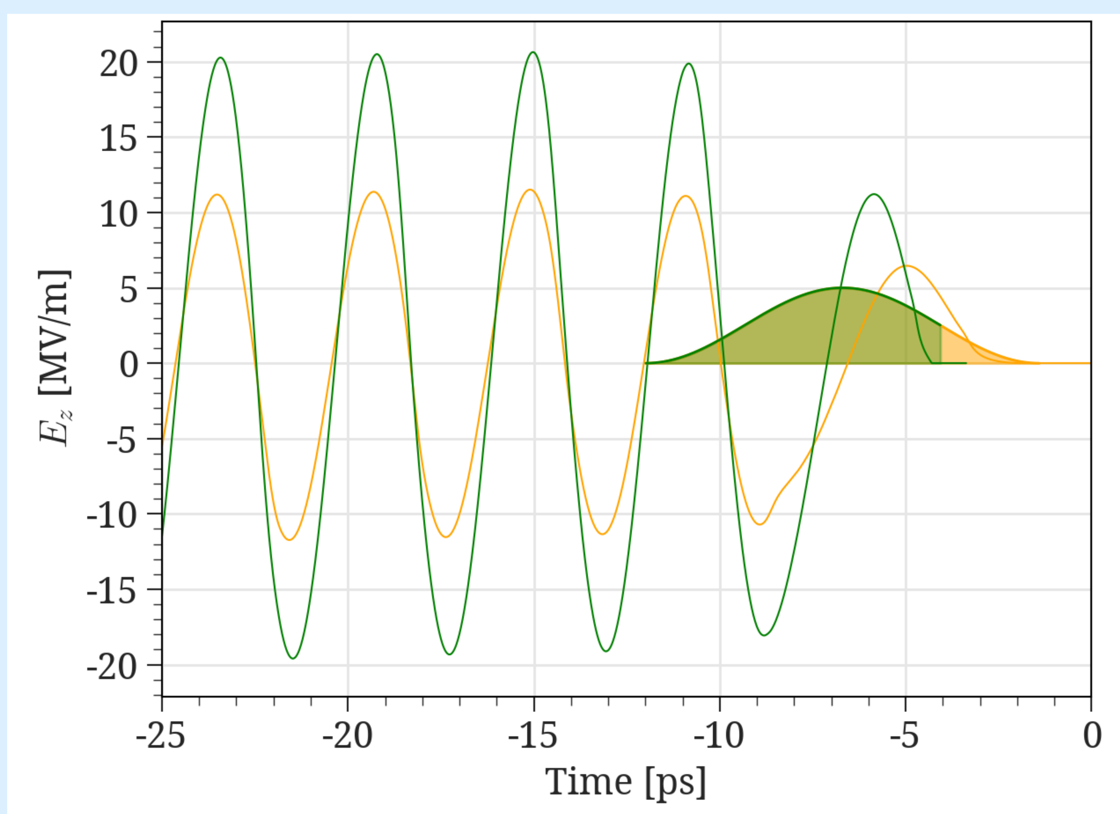



**Figure 1**: LCODE **[5]** simulation of longitudinal wakefield amplitude $E_z$ driven by a full (orange) and truncated (green) electron bunch 0.5m into plasma (7e14 cm$^{-3}$ ). Bunch profiles are illustrative sketches of the bunch at the entrance. Parameters chosen close to experimental ones.

## Experimental Setup:

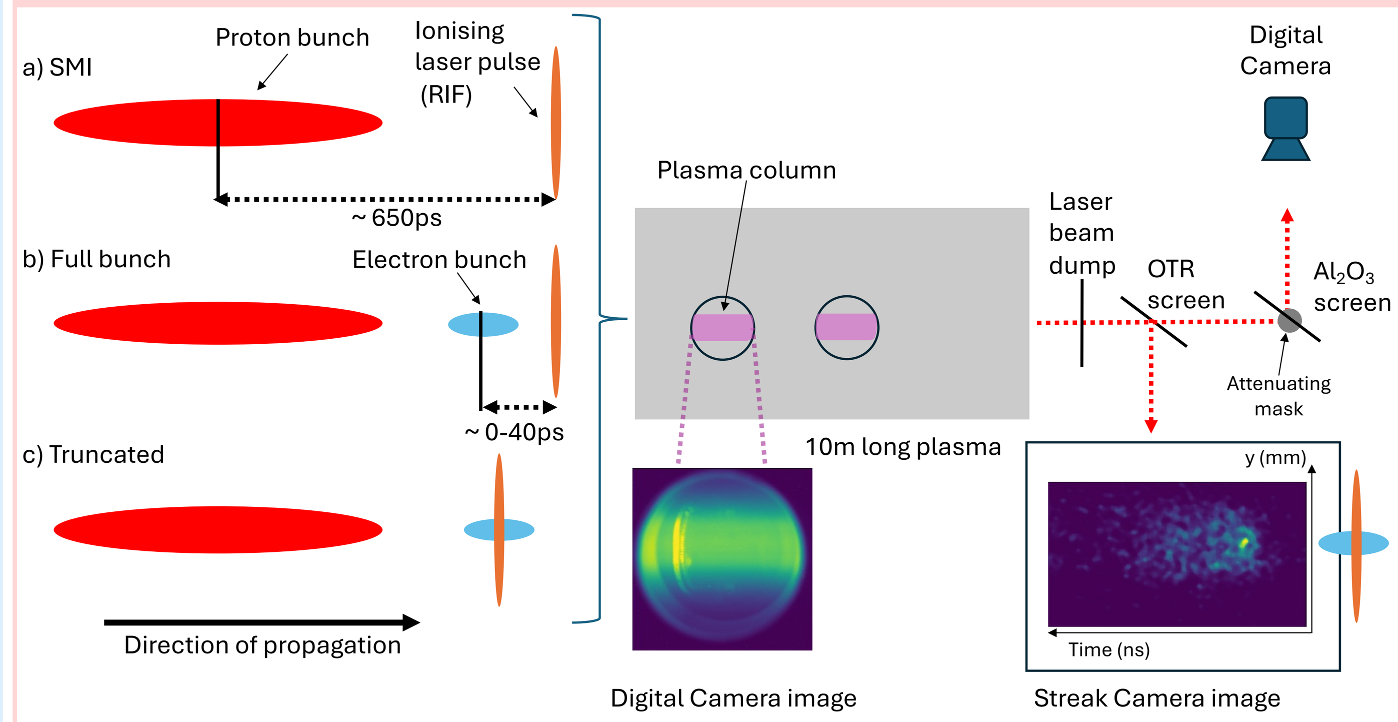



**Figure 2:** Schematic drawing of experimental setup, not to scale. Propagation from left to right. Proton bunch (red) travels through **10m** of plasma:
a) preceded by **RIF**; **SMI** seed: noise

b) preceded by **RIF** and electron bunch (fully in plasma). SM seed: wakefields of full electron bunch

c) preceded by **RIF** truncated electron bunch. SM seed: wakefields of truncated electron bunch

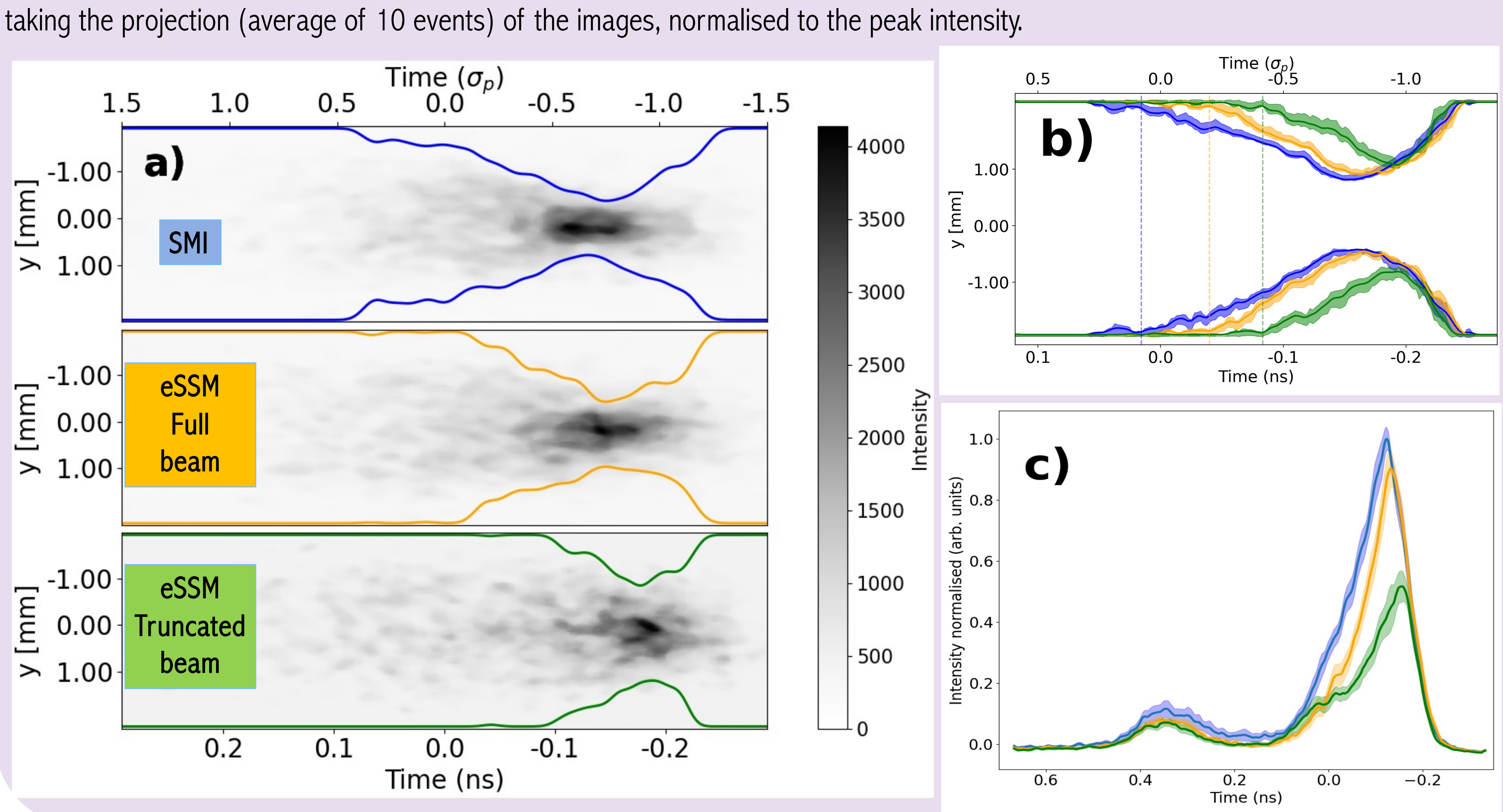
After the plasma:

- Laser pulse & electron bunch dumped (200 um aluminium foil).
- Proton beam traverses **OTR screen** → time resolved measurement of the proton bunch density using a **streak camera**.
- Proton beam traverses **$Al_2O_3$ screen** → measurement of transverse distribution. Attenuating mask (~20%) avoids camera saturation at core.

Additional diagnostic **digital camera** images **plasma light** emitted via a viewport (0.5m into the plasma).

## Experimental Results:

**Figure 3:** Streak camera images of the proton bunch at the OTR screen in 1 ns window same colour scale. Blue lines (SMI), orange lines (eSSM full beam) and green lines (eSSM truncated) indicate, for each time column of the image, where the transverse distribution reaches 20 % of its peak value. For single images in a) and average profiles of 10 single images in b). c) obtained by taking the projection (average of 10 events) of the images, normalised to the peak intensity.



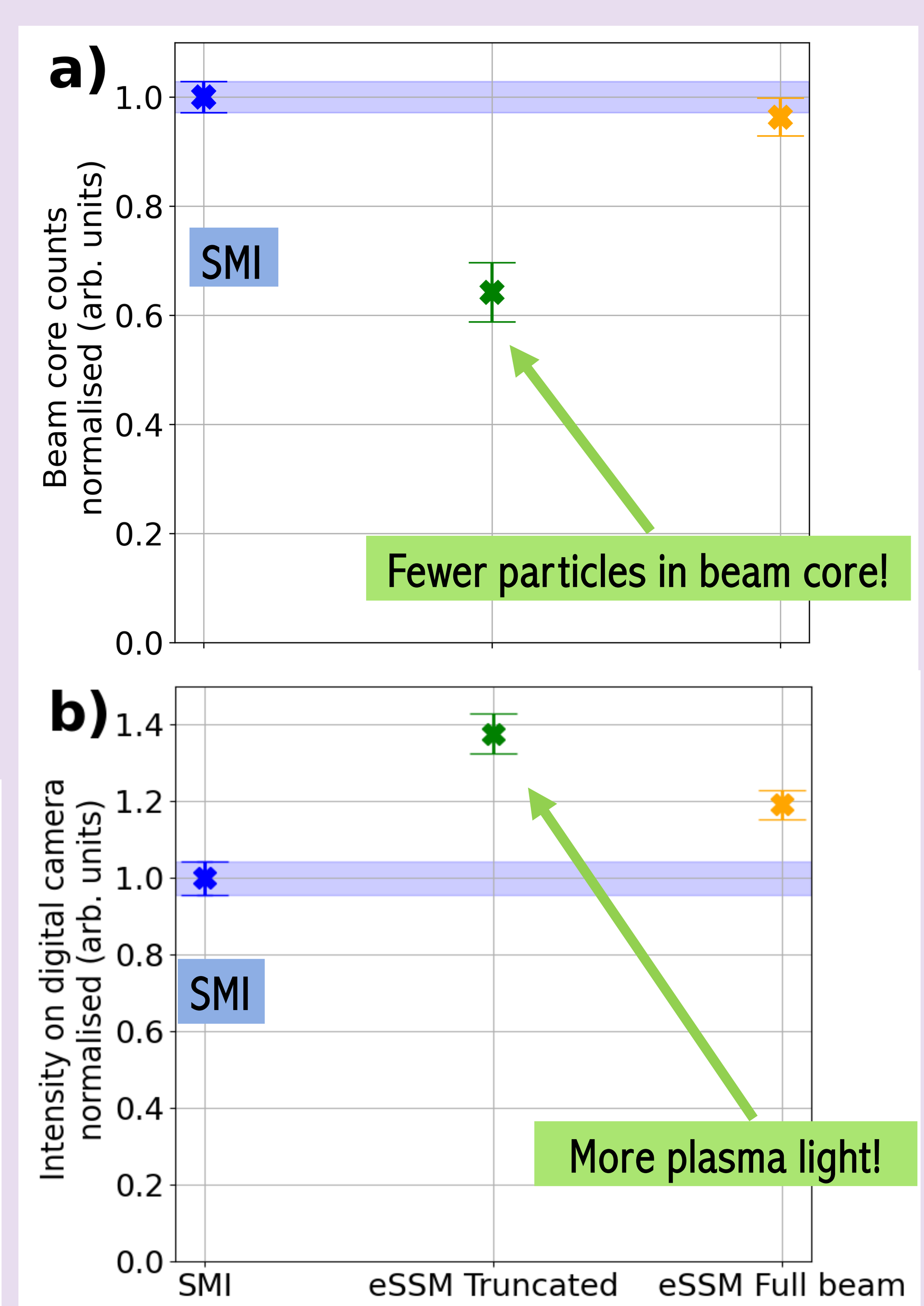




**Figure 4:** For SMI (blue), eSSM Truncated (green) and eSSM Full beam (orange)
a) Charge in proton bunch core after plasma.
b) Plasma light signal detected 0.5m into plasma. Normalised to the SMI case. Error bars are shot to shot variations.

Faster onset of SM
→ more protons defocused from core
→ lower intensity

Higher wakefields over first 0.5m consistent with more plasma light at 0.5m

T: Time (in units of $\sigma_p$ , $\sigma_p$ = 170 ps, incoming proton bunch length) at which lines on Fig 3a) and b) cross y = ±2 mm. Figure 3a) and b): SMI, $T_{SMI}$~ + 0.1 $\boldsymbol{\sigma_p}$. $T_{Full\ bunch}$ ~ - 0.2 $\boldsymbol{\sigma_p}$ ; SM defocusing effect starts earlier than in the SMI case.
$T_{Truncated\ bunch}$ ~ - 0.4 $\boldsymbol{\sigma_p}$ ; SM defocusing effect starts even **earlier** than in the eSSM Full beam case.
Faster onset of the SM defocusing effect → stronger seed wakefields → higher number of protons defocused earlier along the bunch → lower peak intensity

Figure 3c): peak intensity drop from 1 to 0.95 in the case of eSSM full beam, and down to 0.5 in the case of eSSM truncated.
→ Lower peak intensity (Fig 3c) & earlier crossing of y = ±2 mm (Fig 3a, b) consistent with truncated bunch driving higher initial seed wakefields

## Conclusions:

1) Measurements show: SM develops more rapidly along the bunch(Fig. 3 and Fig. 4a)) when seeding with a truncated electron bunch, compared to using the full bunch or relying on noise.
2) When using the truncated electron bunch, increased plasma light is observed near the plasma entrance (Fig. 4b), indicating the presence of stronger wakefields.

These results suggest cutting electron bunches that are longer than optimum using a RIF allows for stronger SM seeding. This could further imply a better wakefield phase accuracy, due to the sharp onset in electron beam density.

[1] The AWAKE Collaboration, "The AWAKE Run 2 programme and beyond." *Symmetry* 14.8 (2022): 1680.
[2] Lotov, K. V., et al. "Natural noise and external wakefield seeding in a proton-driven plasma accelerator." *Physical Review Special Topics—Accelerators and Beams* 16.4 (2013): 041301.
[3] F. Batsch, et al. (The AWAKE Collaboration), "Transition between instability and seeded self-modulation of a relativistic particle bunch in plasma." *Physical review letters* 126.16 (2021): 164802.
[4] Verra, L., et al. (The AWAKE Collaboration), "Controlled growth of the self-modulation of a relativistic proton bunch in plasma." *Physical review letters* 129.2 (2022): 024802.
[5] Lotov, K. V., A. P. Sosedkin, and P. V. Tuev. "LCODE user manual." *Budker Institute of Nuclear Physics of SB RAS* (2022).

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 101004730 'I.FAST'.

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