# Seeding of proton bunch self-modulation by an electron bunch in plasma

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## Introduction

The AWAKE experiment at CERN [1] relies on the self-modulation in plasma of the long 400 GeV/c proton bunch from the CERN SPS, to accelerate an externally injected electron bunch to GeV energies. The control of the acceleration requires that the self-modulation process and the electron beam injection are reproducible from event to event. Making the self-modulation instability (SMI) reproducible means that the phase and the amplitude of the plasma wakefields along the driver bunch are fixed, once the process has saturated. This is achieved by seeding the instability, and the process is therefore called seeded self-modulation (SSM). Proton bunch SSM using a relativistic ionization front method [2, 3, 4], and the acceleration of electrons [5] were demonstrated during AWAKE Run 1. The physics of seeding using a short electron bunch will be studied during Run 2a (starting in July 2021) [6, 7].

## Electron bunch seeding of the self-modulation

When an electron bunch travels in plasma, it drives wakefields that can impose a charge modulation on the trailing proton bunch (see Figure 1a). If this modulation is deep enough (i.e. the amplitude of the wakefields is above the seeding threshold), the self-modulation process is seeded and grows resonantly until the proton bunch is fully modulated (see Figure 1b). Thus, the final phase of the microbunch train (and of the wakefields) is uniquely related in phase to the short seed electron bunch.

AWAKE Run 2a is using the same experimental setup as Run 1 [1, 7]. The main elements are: a 10 meter-long Rb vapor source, a 120 fs, $<450$ mJ laser pulse ($\lambda = 780$ nm) ionizing the Rb atoms and creating the plasma column, the electron beam source and transfer line, a magnetic spectrometer system downstream of the plasma. The initial plasma electron density $n_{pe}$ can be varied in a range from 0.5 to $10 \cdot 10^{14}$ cm$^{-3}$, the energy of the electron bunch from 10 to 20 MeV

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with 0.5% relative energy spread, the charge from 100 to 600 pC (with normalized transverse emittance and bunch length $\sigma_z$ scaling accordingly from 1 to 6 mm·mrad and from 2 to 5 ps). The electron bunch transverse size at the plasma entrance can be adjusted using a quadrupole triplet final focusing system to a minimum size $\sigma_r \sim 200\,\mu$m.

As shown in [4], the phase of the train of proton microbunches is reproducible (therefore SSM has occurred) when the amplitude of the seed wakefield is larger than a threshold value. Using the relativistic ionization front seeding method, the threshold was determined to be between 4 and 6 MV/m (with $n_{pe} = 0.9 \cdot 10^{-14}$ cm$^{-3}$). Linear plasma wakefields theory [9] shows that with the initial parameters of the AWAKE electron bunch, it would not be possible to effectively seed the self-modulation. For $Q = 150$ pC, $\sigma_z = 2$ ps, $\sigma_r = 200\,\mu$m, $n_{pe} = 2 \cdot 10^{-14}$ cm$^{-3}$, the maximum amplitude of the transverse wakefields $W_\perp$ behind the bunch at $r = \sigma_r$ is 3 MV/m. The electron beam transverse size, though, evolves according to $\gamma m \frac{d^2\sigma_r}{dt^2} = qW_\perp$ (where $q$ and $m$ are the electron charge and mass and $\gamma$ the relativistic factor): using linear optics, one can estimate the initial bunch radius $\sigma_{r0}$ at the injection so that the amplitude of the wakefields within the bunch at $r = \sigma_{r0}$ balances the divergence of the bunch and therefore the size remains constant along the plasma. For the same parameters mentioned above, $\sigma_{r0} \sim 35\,\mu$m, much smaller than the minimum achievable size at the plasma entrance in the experiment. Therefore, the bunch undergoes severe non-linear pinching in the first centimeters of propagation in plasma [10], and numerical simulations are required to describe and compute its transverse size. Simulations [11, 12] show that, because of this transverse size evolution, the bunch charge density becomes high enough to drive transverse wakefields with amplitude above the seeding threshold.

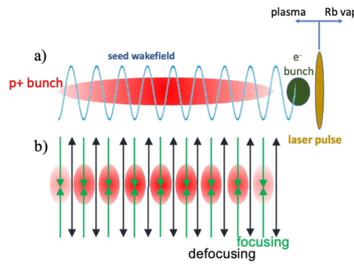


Figure 1: *Schematic of the electron bunch seeding process. a) Beams at the injection and initial wakefields; b) Fully modulated train of microbunches and transverse wakefields at saturation.*

The goal of Run 2a is not only to experimentally prove the seeding of the self-modulation of the long proton bunch using an electron bunch, but also to vary the initial parameters of the electron bunch (and therefore the amplitude of the initial wakefields) to observe the transition between SMI and SSM.

### Preparatory experimental studies

Before performing the electron bunch seeding experiment with the SPS proton bunch, we want to study the effect of the propagation through the 10 meter-long plasma column [13] on the electron bunch. As the low-energy bunch drives wakefields and loose a significant amount of its energy, we expect a fraction of the electrons to be dephased with respect to the wakefields, and to be defocused, and to detect the energy loss as a long low-energy tail in the energy spectrum of the bunch on the spectrometer screen. Figure 2a shows the 150 pC and $\sim 18.5$ MeV electron bunch, propagated through vacuum and imaged onto the spectrometer screen. Figure 2b shows the electron bunch with the same input parameters after propagation through 10 m of plasma ($n_{pe} = 2 \cdot 10^{14}\,\text{cm}^{-3}$). As the beam is dispersed in the horizontal plane, the horizontal axis of the screen is converted into energy. One notices the long low-energy tail, showing energy loss occurred in the plasma.

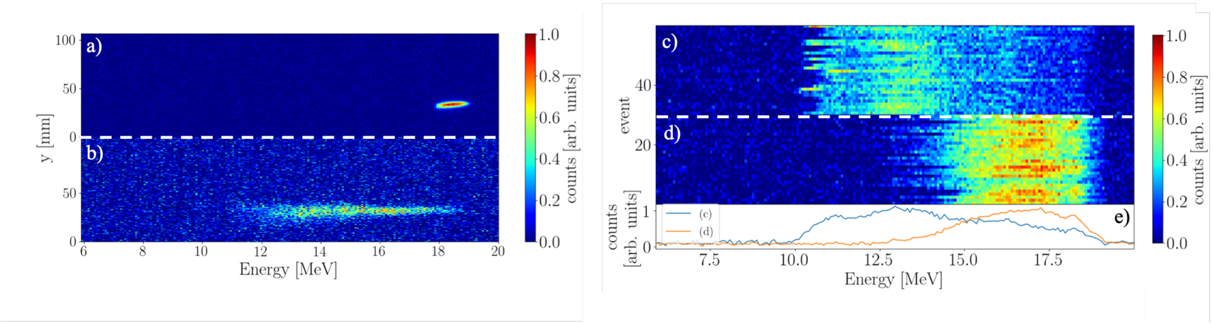


Figure 2: *a) Electron bunch imaged onto the spectrometer screen after propagation through vacuum. b) Electron bunch imaged onto the spectrometer screen after propagation through* 10 *meters of plasma. The horizontal axis is the dispersive plane. The counts of each image are normalized to the respective maximum. c) and d) show a waterfall plot of the energy projections of the electron beam imaged on the spectrometer screen. c) 30 events with the smallest beam size at the plasma entrance; d) 30 events with the largest beam size at the plasma entrance. e) sums of the energy distributions for the two cases: (c) in blue and (d) in orange. For all images, the electron bunch charge at the plasma entrance is* 150 *pC and the energy is* $\sim 18.5$ *MeV.*

During the first experimental campaign, we varied the size at the plasma entrance of the 150 pC, 18.5 MeV electron bunch (and $n_{pe} = 2 \cdot 10^{14}\,\text{cm}^{-3}$). Figure 2 (c and d) show a waterfall plot of the projections along the energy axis of images at the spectrometer screen. We collected 30 events with the smallest beam size at the injection (beam focused at the plasma entrance, $\sigma_r \sim 200\,\mu$m (c)) and 30 events with the largest beam size (beam focused 5 m downstream of the plasma entrance, $\sigma_r \sim 1$ mm (d)). We note here that the energy distributions reach lower values for the smaller beam size (the minimum energy is detected around 10 MeV) indicating that the smaller beam (with larger charge density) experiences more energy loss. We also show in Figure 2e the sum of the energy distributions for the two cases: the minimum energy and the mean of the distribution are clearly different in the two cases. The energy of one electron along the propagation length $L$ evolves according to: $\Delta W = q \int_0^L E_z(z)dz$, where $E_z$ is the longitudinal wakefield within the bunch. What we observe on the screen is the results of a complex dynamics, as $E_z$ varies along the bunch and along the plasma.

Simulations [12] show that the amplitude of the decelerating fields inside the bunch and of the transverse fields behind the bunch are maximum over the first 2 meters of plasma, where the transverse pinching occurs. Then, due to dephasing, some charge is expelled out of the plasma and the bunch length becomes comparable to the plasma wavelength, making the wakefields decrease and the bunch transverse size increase. To summarize, the energy spectrum, observed after the propagation in plasma, is mostly affected by the longitudinal and transverse evolution of the bunch and of the wakefields over the first meters of propagation, which in turn are directly related to the initial parameters of the electron bunch, in particular its charge density.

## Conclusions

We have discussed the electron bunch seeding process of the proton bunch self-modulation, that will be studied in the context of AWAKE Run 2a. We have shown that we are able to vary the energy loss of the seed electron bunch in plasma by changing its initial parameters. We will perform the same type of measurements in the presence of the proton bunch, including the variation of other parameters (e.g. electron bunch charge, for a fixed bunch size), to study the phase reproducibility of the self-modulation of the proton bunch and the transition from SMI to SSM, using the electron bunch seeding method.

## References


[1] P. Muggli et al. (AWAKE Collaboration), Plasma Phys. Control. Fusion, **60**(1) 014046 (2017).

[2] AWAKE Collaboration, Phys. Rev. Lett. **122**, 054802 (2019).

[3] M. Turner et al. (AWAKE Collaboration), Phys. Rev. Lett. **122**, 054801 (2019).

[4] F. Batsch et al. (AWAKE Collaboration), Phys. Rev. Lett. **126**, 164802 (2021).

[5] AWAKE Collaboration, Nature **561**, 363–367 (2018).

[6] P. Muggli, J. Phys.: Conf. Ser. **1596** 012008 (2020).

[7] E. Gschwendtner, for the AWAKE Coll., in 12th International Particle Accelerator Conference, ID: 1768 (2021).

[8] P. Muggli et al., J. Phys.: Conf. Ser. **1596** 012066 (2020).

[9] R. Keinigs and M. E. Jones, The Physics of Fluids **30**, 252 (1987).

[10] K. V. Lotov, Phys. Plasmas **24**, 023119 (2017).

[11] A.-M. Bachmann, Ph. D. Thesis, Technical University of Munich (2021).

[12] K.-J. Moon, these Proceedings, ID: 2301.

[13] G. Zevi Della Porta et al., in 12th International Particle Accelerator Conference, ID: 1764 (2021).