PREPARATION FOR ELECTRON-SEEDING OF PROTON BUNCH SELF-MODULATION IN AWAKE

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Abstract

The next milestone of the Advanced Wakefield Experiment (AWAKE) at CERN will be to demonstrate that the self-modulation of a long proton bunch can be seeded by a short electron bunch preceding it. This seeding method will lead to phase-reproducible self-modulation of the entire proton bunch, as required for the future AWAKE program. In the Spring of 2021, before receiving proton beams from the CERN SPS, AWAKE plans to hold a dry run of the electron seeding experiments, to commission the system and to determine the parameter scans that will be used in experiments with protons. Electron bunches of 10-20 MeV with varying charge, radius, emittance and energy will be sent in 10 m of low-density plasma. The effects of beam-plasma interactions on the amplitude of the wakefields driven by the different bunches will be studied by observing the energy spectra at the end of the plasma. This paper presents preliminary experimental results from the first two days of measurements as well as the beginning of a simulation-based study of electron propagation in plasma.

INTRODUCTION

The Advanced Wakefield Experiment (AWAKE) at CERN aims to accelerate an electron bunch to the GeV scale using plasma wakefields generated by a long, high-energy proton bunch. In its first data taking period, Run 1, AWAKE demonstrated control of the self-modulation of a long proton bunch in plasma, which results in microbunches forming at the characteristic frequency of the plasma [1–3]. It also demonstrated and studied electron acceleration [4, 5]. The next data taking period, Run 2, spans several years and its physics goals and milestones are described in Refs. [6–9].

During the first period, Run 2a, AWAKE plans to demonstrate that an electron bunch placed ahead of the proton bunch can be used as ‘seed’ for the self-modulation, so that the phase of the modulation can be controlled by the electron bunch position, as proposed in Ref. [10]. This strategy would ensure that the entire proton bunch undergoes self-modulation at a fixed phase, as opposed to the strategy used in Run 1 which leaves the first part of the bunch unmodulated.

In this work, we study the interaction of the AWAKE electron bunch with plasma, in preparation for self-modulation experiments with a proton bunch following the electron bunch in plasma. We present initial findings from Particle-In-Cell (PIC) simulations of the propagation of an electron bunch with realistic AWAKE parameters in a 10 m-long plasma, and preliminary results from an experimental dataset collected on March 23-24, 2021. The experiments aim to fully commission the electron beam and the plasma system, in order to have an immediate start of the seeding experiments as soon as AWAKE will receive proton beams from the CERN SPS. Specifically, they aim to address the event-to-event stability of the observed charge and energy distribution of the electron bunch at the end of the plasma, and to study how these two quantities vary as a function of experimental parameters. The simulations aim to link these two observables with the wakefields generated by the electron bunch in the first few meters of plasma, since these wakefields are expected to act as a seed for the self-modulation of the proton bunch. Further simulations and experiments are planned for the near future, along the lines of those presented here.

SIMULATION RESULTS

Simulations of the AWAKE electron bunch and plasma were performed using the FBPIC [11] software, which has features of intrinsic mitigation of Numerical Cherenkov Radiation (NCR), no Courant limit, and cylindrical representation with azimuthal decomposition. The electron bunch transverse and longitudinal parameters for the two incoming charge values are based on recent measurements of the AWAKE electron bunch: for −150 pC (−350 pC), the bunch length is $\sigma_\mathrm{z} = 2.1$ ps (2.45 ps), the transverse dimensions are $\sigma_\mathrm{x} = 0.17$ mm (0.36 mm) and $\sigma_\mathrm{y} = 0.22$ mm (0.29 mm), the energy is 18 MeV, with an energy spread of 0.4%, where the higher charge bunch parameters are in brackets. The plasma radius is 1 mm. The resolution of the simulation is set to be $\Delta z = 0.02k_p^{-1}$, $\Delta r = 0.01k_p^{-1}$, and $\Delta t = \Delta z/c$ in the laboratory frame with the plasma wave number $k_p = \sqrt{n_0 e^2/\epsilon_0 m_e c^2}$, where $n_0 = 2 \times 10^{14}$ cm^{-3} is the ambient plasma density, e the elementary charge, ϵ_0 the vacuum permittivity, m_e the electron mass, c the speed of light in vacuum.

Simulation results are shown in Fig. 1 as a function of the electron bunch position in the plasma, and in Fig. 2 at the end of the plasma. In Fig. 1 (top) the electron bunch is seen to pinch significantly in the first few centimeters, and holding this size for a few meters. This pinching results in much larger transverse wakefields than at the plasma entrance, which are sustained for the first two meters and then fall until they are negligible, as shown in Fig. 1 (bottom). The peak amplitude of the wakefields reaches values of 10 – 20 MV/m,

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which, based on the results in Ref. [3], is above the amplitude needed to observe seeded self-modulation with relativistic front seeding. In Fig. 2, the energy spectrum of electrons exiting the plasma shows significant evolution with respect to the initial 18.00 ± 0.07 MeV: a small fraction of the bunch gains energy, while the majority of electrons lose as much as half of their initial energy in the plasma.

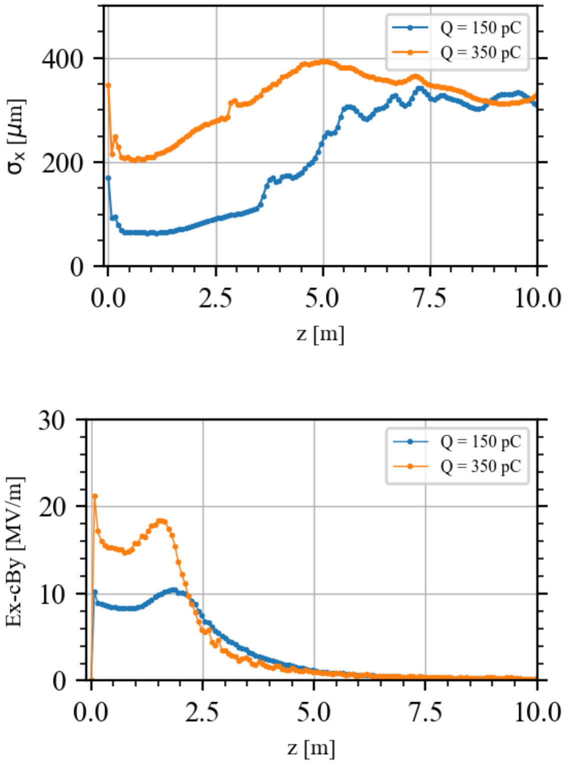

Figure 1: Evolution of the electron bunch size calculated within r < 1 mm (top) and of its maximum transverse wakefield observed at r = 200 m (bottom) as a function of its position along the 10 m plasma, for two different sets of beam parameters in FBPIC [11] simulation.

EXPERIMENTAL RESULTS

Experimental results are based on images of the electron spectrometer, described in Ref. [12], using a reconstruction procedure analogous to the one of Ref. [5], yielding an energy spectrum and a measurement of total charge for each event. Three individual measurements, taken in conditions analogous to those of the −350 pC simulation, are shown in Fig. 3. The signal corresponding to the charge collected is well above the noise level and, while the high-end of the energy spectrum remains very close to the initial energy of the electron bunch, the low-end of the spectrum varies between events. Similarly to the simulation, electrons lose as much as half of their initial energy in the plasma, although the overall distribution is not peaked at low-energy, as expected from simulation. Further experiments and simulations are planned to quantify and investigate these features.

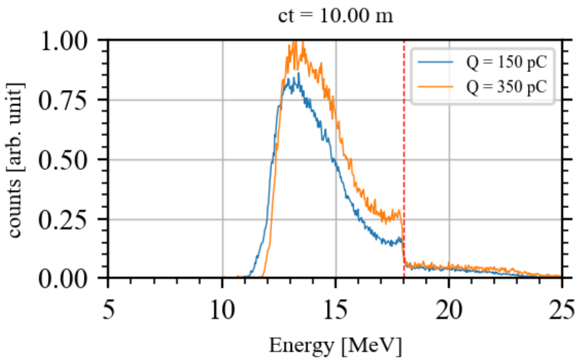

Figure 2: Energy distribution of the electron bunch after the 10 m plasma in FBPIC [11] simulation, for two different sets of beam parameters. The dashed red line marks the initial energy, 18 MeV.

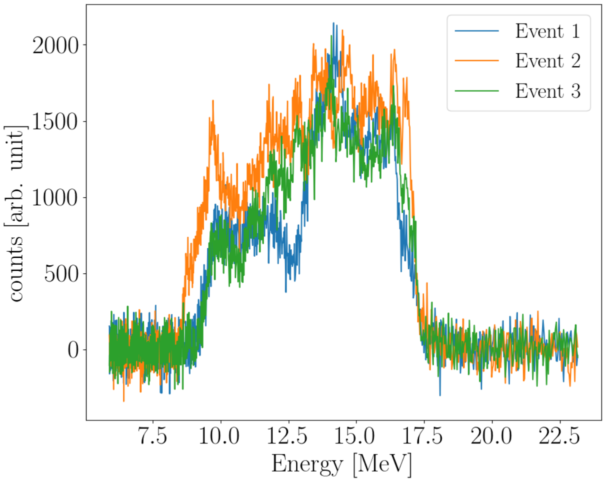

Figure 3: Measurement of bunch distribution after the spectrometer, showing the energy spectrum of the electron bunch after the 10 m plasma, for three representative events.

In Fig. 4, images of electrons on the spectrometer screen are displayed to form waterfall plots, with the bunch dispersed in energy along the horizontal direction. The events in Fig. 4 (top) are without plasma, so that electrons propagate entirely in vacuum, while those in Fig. 4 (bottom) are with plasma. An incoming electron bunch of charge −350 pC is used in all events and– except for σ_x and σ_y which are varied in Fig. 4 (bottom)–the other parameters correspond to those of the simulation.

In Fig. 4 (top), after propagation in vacuum, the energy spectrum is narrow, the energy variation from event to event is small (1%), while there is a non-negligible (9%) variation in the collected charge. In the bottom plot, with plasma, five datasets of 30 events each are shown. Each datasets is characterized by a different waist position with respect to the plasma entrance, as specified by the dashed white line and the upper axis. The electron bunch transverse size at the plasma entrance is smallest (corresponding to the simula-

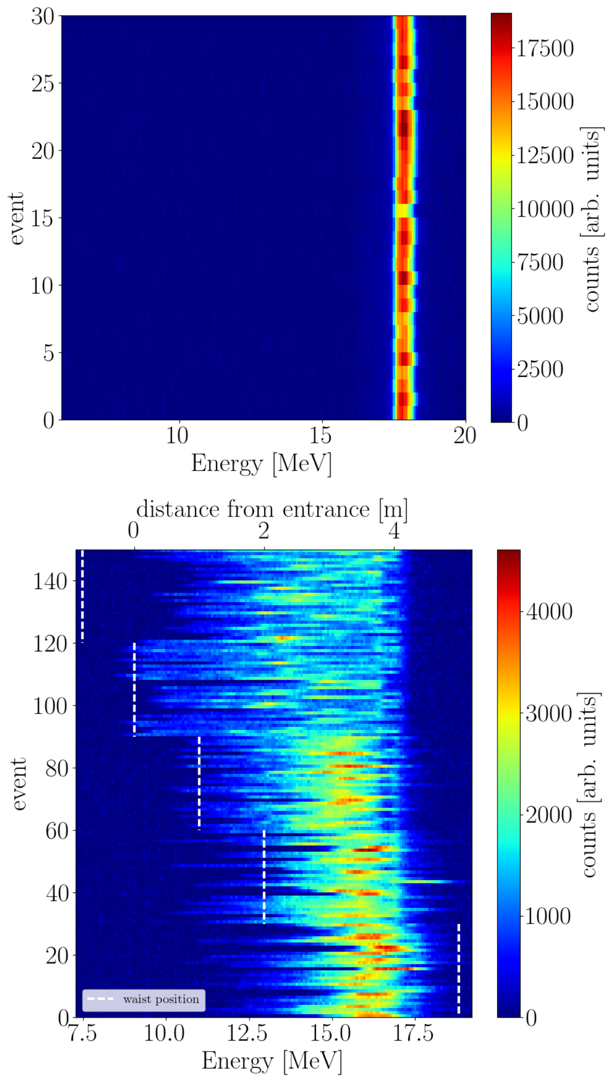

Figure 4: Images of electron bunches on the spectrometer screen, with the bunch dispersed along the horizontal axis, and with the vertical axis representing different events, after propagating through vacuum (top) and plasma (bottom). In the bottom plot, the white dashed lines and the upper axis represent the position of the electron bunch waist with respect to the plasma entrance.

tion σ_x and σ_y) when the waist is at 0 m, and it increases by more than 300% as the waist is moved away from the plasma entrance. As a result of the changes in transverse size, the charge density and the total charge entering the plasma channel are also affected. In the small preliminary datasets of Fig. 4 (bottom), the energy spectrum seems affected by the waist position, but there are also significant event to event variations, and more data will be needed in order to draw definite conclusions.

CONCLUSIONS

In preparation for the beginning of the next proton beam from the CERN SPS, scheduled for Summer 2021, AWAKE has begun studying in detail the interaction between its 18 MeV electron beam and the 10 m-long plasma. Several recent efforts, including those described in Refs. [13–15], have improved the control and reproducibility of the AWAKE electron beam delivery. The experimental work introduced in this paper aims to ensure the system is fully commissioned before the start of the proton beam, to evaluate event-to-event and day-to-day reproducibility of the electron-plasma system, and to determine which parameters of the incoming electron bunch affect its behavior in plasma, focusing in particular on the energy spectrum and the total charge measured downstream of the plasma. A parallel effort, based on simulations, aims to relate these observed quantities to the transverse wakefields generated by the electron bunch in the first few meters of plasma, since these wakefields are expected to provide the seed for the self-modulation of a proton bunch immediately following the electron bunch. Further experiments and simulations are continuing and will determine the electron beam parameter scans that will be used to study electron-seeding of proton bunch self-modulation in AWAKE.

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