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THE AWAKE EXPERIMENT IN 2021: PERFORMANCE AND PRELIMINARY RESULTS ON ELECTRON-SEEDING OF SELF-MODULATION

E. Gschwendtner†, L. Verra, G. Zevi Della Porta, CERN, Geneva, Switzerland
P. Muggli, Max-Planck Institute for Physics Munich, Munich, Germany
for the AWAKE Collaboration

Abstract

The future programme of the Advanced Wakefield (AWAKE) experiment at CERN relies on the seeded self-modulation of an entire proton bunch, resulting in phase-reproducible micro-bunches. This important milestone was achieved during the 2021 proton run by injecting a short electron bunch ahead of the proton bunch, demonstrating for the first time the electron-seeding of proton bunch self-modulation [1]. This paper describes the programme, performance and preliminary results of the AWAKE experiment in the 2021 proton run and introduces the programme of the 2022 proton run.

INTRODUCTION

AWAKE is an accelerator R&D experiment to demonstrate plasma wakefield acceleration of electrons in wakefields driven by a proton bunch and, in the future, take advantage of the large energy store in the proton bunch to reach very high energy gain in a single plasma for first particle physics applications using plasma wakefield acceleration. During its first run period (2016 – 2018) AWAKE observed the strong modulation of high-energy proton bunches in plasma, which demonstrated for the first time that strong wakefields are generated by proton beams [2-4]. In addition, the acceleration of externally injected electrons to multi-GeV energy levels in the proton driven plasma wakefields [5] was demonstrated.

The goal of the AWAKE Run 2 programme [6, 7] which started in 2021, is to produce high-charge bunches of electrons accelerated to high energies (~10 GeV) while maintaining beam quality as well as to demonstrate the scalability of this process.

In order to accelerate with low energy spread, an accelerated bunch charge of at least 100 pC and an emittance control at the 10 mm-mrad level, the scheme of AWAKE Run 2 includes two plasma sources, i.e. a self-modulator and an accelerator, and a new electron beam system. In the first plasma source the proton beam self-modulation (SM) is seeded by an electron bunch [6] and modulates along the entire bunch. The self-modulation process must reach saturation before electrons are injected for acceleration in the second plasma source.

The roadmap for AWAKE Run 2 is well-defined and is subdivided in four phases spanning over several years [7].

The programme of the first phase, Run 2a (2021-2022), focusses on the demonstration of the self-modulation of the entire proton bunch reproducibly seeded by an electron bunch.

† edda.gschwendtner@cern.ch

Seeded Self-Modulation

The self-modulation instability (SMI) is a self-consistent process, where the wakefields driven in plasma by a long, narrow, relativistic, charged particle bunch act back on the bunch itself, modulating its transverse distribution along the bunch. The modulated distribution drives enhanced wakefields, initiating a feed-back loop that converts the bunch into a train of micro-bunches. Hence, the timing of the micro-bunch train along the bunch is tied to that of the transverse wakefields: the micro-bunches develop in their focusing phase. When a long ($\sigma_t \sim 240$ ps) proton bunch enters a pre-ionized plasma with a much shorter plasma wavelength, it undergoes the self-modulation instability. SMI develops from the noise [8] or from the imperfections [4] in the proton bunch charge distribution. Thus, it is neither reproducible in amplitude nor in timing from event to event [4]. However, when a seed wakefield is applied, SM grows from the initial modulation of the radius along the bunch caused by the seed wakefields: the timing and initial amplitude of SM is then defined by the seed wakefields.

During AWAKE Run 1, seeding was obtained by placing the ionizing laser pulse (that generates the plasma) within the proton bunch. The fast onset of the beam-plasma interaction was therefore driving the seed wakefields. This method has the advantage of the inherent alignment between the proton bunch and the plasma, avoiding the hosing instability, but it has the disadvantage of leaving the front of the bunch unmodulated, because it travels as if in vacuum. Since the final stage of the AWAKE experiment (Run 2c and Run 2d) is composed by two plasmas (the first one being the modulator, the second the accelerator [7]), the unmodulated front of the bunch may self-modulate in the second (preformed) plasma and disrupt the structure of the self-modulated back of the bunch. Therefore, the entire proton bunch must be self-modulated with reproducible timing and amplitude, when entering the accelerator section. This can be obtained only if the seed wakefields act on the entire proton bunch.

In AWAKE Run 2, the SM process is achieved by seeding SM with an electron bunch preceding the proton bunch.

Experimental Layout

The experimental layout is shown in Fig. 1. For the experiments during 2021/22 the same infrastructure as that of AWAKE Run 1 can be used. In addition, the 18 MeV electron beam coming from the existing electron injector of Run 1 can be used for seeding. The experiment uses a 400 GeV/c proton bunch from the CERN SPS, with a rms bunch length of ~240 ps, to drive wakefields in a 10 m-long rubidium plasma section with a plasma electron

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density of $0.5\text{x}10^{14} - 10^{15}$ cm^{-3}, corresponding to plasma wavelengths λ_{pe} between 4.73 mm and 1.05 mm. A ~120 fs, ~100 mJ laser pulse (λ = 780 nm) produces a relativistic ionization front, RIF, that creates the plasma by ionizing the vapour. The electron energy spectrum is measured with a magnetic spectrometer downstream of the vapour source. The proton bunch passes through an optical transition radiation (OTR) screen installed downstream of the vapour source. The OTR light is imaged onto the entrance slit of a streak camera, which produces time-resolved images of the transverse charge density distribution of the proton bunch.

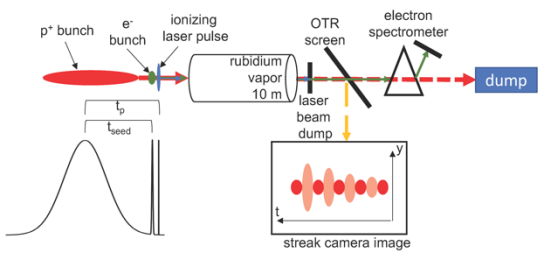

Figure 1: Layout of the AWAKE Run 2a experiment [1].

EXPERIMENTAL PERFORMANCE 2021

Improvements and Challenges

The Run in 2021 had a particularly smooth start, especially thanks to the many preparations done during CERN's Long Shutdown during 2019 and 2020. These included studies of electron energy loss in plasma necessary to estimate the electron-driven wakefields affecting the proton bunch and are summarized in [9, 10].

To improve the performance and reliability of AWAKE Run 2a, a Data Quality Monitoring (DQM) system was introduced. The DQM system constantly monitors the timestamps and errors for all data written to disk (50 MB per event, corresponding to ~250 properties and images), it displays a visual summary of the main diagnostics for each event, and monitors beam trajectories in real time using moving averages to overcome jitter and resolution.

The leading performance challenge connected to the Run 2a programme is the consistent transverse alignment of the three beams of AWAKE: protons, electrons and the ionizing laser forming the plasma. While the longitudinal (i.e. timing) alignment of these beams is controlled by a combination of electronics and optical translation stages, the transverse alignment of the beams is controlled by independent devices and monitored by separate detectors. Additionally, the transverse alignment of each beam is affected by significant event-to-event jitter, hour-to-hour drift, and requires averaging over many events to estimate its position. The laser beam, focused to a size of ~700 µm, jitters in position by ~200 µm, and its position is reconstructed by intercepting screens along the beamline, with a ~50 µm average precision. The electron and proton beams, focused to a transverse size of ~200 µm, jitter in position by ~40 µm [11], and their position is reconstructed with Beam Position Monitors (BPMs) with an average resolution of ~100 µm for protons and ~200 µm for electrons (all values given in rms). The DQM system, providing a rolling average position for events with protons, was used to spot significant drifts of the proton beam. To take advantage of the higher rate of the electron and laser beams (10 Hz, while protons arrive at 0.05 Hz), online systems were set up to monitor the electron and laser trajectories averaging over hundreds of events, providing additional information on trajectory drift. For the laser beam, this measurement was indirect, relying on an optical line parallel to the beamline since screens could not be inserted in the main beamline without interrupting the experiment.

2021 Programme

The 2021 proton run consisted of three run periods of at least two weeks, between July and October. During the first run period, electron-seeded self-modulation of the proton bunch was observed with an electron bunch charge of only 150 pC, leaving significant room to vary this parameter up to its maximum of ~ 800 pC during the second run period. In addition, in the second run period, the proton bunch intensity was varied between $1\text{x}10^{11}$ and $3\text{x}10^{11}$ protons per bunch, and the relative transverse position of the electron and proton bunches was varied to seed the hosing instability. In the third AWAKE run period, scans of the longitudinal position of electrons with respect to protons were performed, and a new technique was developed to combine multiple 2D (x, t) profiles of the proton beam to produce a 3D (x, y, t) measurement [12].

RESULTS OF THE ELECTRON BUNCH SEEDED SELF-MODULATION

The left part of Figure 1 shows the timing setup of the Run 2a experiment. The relativistic ionization front (RIF) is located t_p ~ 620 ps ahead of the center of the proton bunch. At this location, the charge density of the proton bunch is too small to drive wakefields with amplitude large enough to seed SM [12]. Thus, RIF ionizes the vapour but does not seed SM. SM is seeded using an electron bunch with Q_e = 249 pC, traveling t_{seed} = 580 ps ahead of the center of the proton bunch but behind the laser pulse. To prove that the electron bunch seeds the self-modulation of the proton bunch, the longitudinal charge density distribution of the proton bunch was measured with the time-resolved images obtained with the streak camera. Consecutive images are aligned in time with respect to each other with sub-ps precision using a timing reference signal [4].

Figure 2 shows the sum of ten consecutive 73 ps-scale time-resolved images of the Q_p = 40.8 nC proton bunch after propagation in plasma. The bunch is clearly modulated into a train of micro-bunches with modulation frequency close the plasma electron frequency.

The periodicity is clearly visible on the sum of consecutive images, which is due to the event-to-event reproducibility of the phase of the modulation. Consequently, the summed image shows the same characteristics as the original signals.

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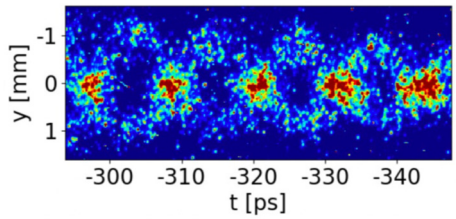

Figure 2: Sum of ten consecutive time-resolved images of the proton bunch after propagation in plasma.

To measure the modulation frequency and the phase φ on time-resolved images, the discrete Fourier transform (DFT, see Supplemental Material of [4]) of the on-axis distribution was calculated.

Figure 3(a) shows a histogram of the phase for 11 events, when the seed electron bunch is not present. The phase varies over the entire [-π,π] range, and the rms of the phase is rms(φ)/2π=0.27, in agreement with a uniform random variation. In this case, self-modulation occurs as an instability.

When the seed electron bunch is present, the phase of the ten consecutive event composing Figure 2 varies over a much smaller range, as shown in Figure 3(b) with rms(φ)/2π=0.08. The phase variation is much smaller than in the instability case and indicates that the electron bunch effectively seeds the SM of the proton bunch.

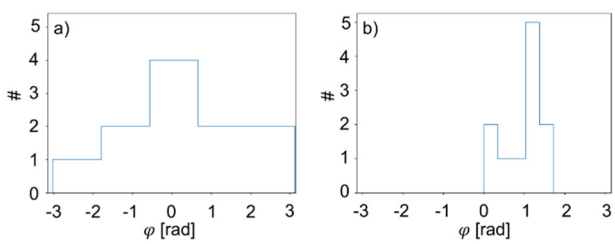

Figure 3: Histogram of the modulation phase φ for 11 events without (a) and with (b) seed electron bunch present.

The results are discussed in detail in [1], where it is also shown that the timing of the modulation is tied directly to the timing of the electron bunch: a delay of the seed causes a delay of the micro-bunch train. In addition, it is demonstrated that when seeding with an electron bunch, the amplitude of the seed wakefields and the growth rate of the self-modulation are independent from each other and can be varied by varying the parameters of the electron and proton bunches, respectively.

PROGRAMME FOR 2022

Several improvements were made to increase the performance of AWAKE in 2022, focusing on the transverse alignment of electrons, protons and laser. A new screen was installed less than 10 cm from the entrance of the plasma, to observe the position and shape of the three beams at their waist with high resolution, using a single diagnostic. In addition, the laser alignment algorithm was developed from a manual to an automated procedure, after characterizing the laser jitter and the correlations of the optical system. Finally, the characterization of the electron line corrector magnets was improved to provide a more precise steering algorithm.

The physics program of the 2022 proton run is primarily focused on completing the Run 2a objectives mentioned above. Additional data are needed to study the hosing instability, to fully quantify the effect of transverse and longitudinal misalignment of the electron beam and to study the effects of the longitudinal position of electrons with respect to protons. In addition, several measurements without electron beam are planned for 2022: proton bunch propagation in low-density plasma to study adiabatic focusing, propagation of a lower charge-density proton bunch to study the onset of self-modulation and dependence of laser-ionization-front seeding threshold as a function of proton bunch intensity.

CONCLUSION

After AWAKE Run 1 (2016 – 2018) achieved all its milestones, AWAKE Run 2 has successfully started in 2021. To improve the performance and reliability of the experiment during that run, several optimizations of the data quality, the alignment and online analysis were implemented. One of the main goals of the first phase of AWAKE Run 2 was achieved during the first run periods in 2021: it was demonstrated that the electron bunch effectively seeds the self-modulation of the proton bunch in plasma, and that the timing of the modulation is tied to the timing of the electron bunch. The physics program of 2022 focuses on completing the remaining AWAKE Run 2a objectives.

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