ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-WE1AA02

RUN 2 OF THE ADVANCED PLASMA WAKEFIELD EXPERIMENT (AWAKE) AT CERN

G. Zevi Della Porta† (CERN, Geneva, Switzerland)
for the AWAKE Collaboration

Abstract

After successful completion of Run 1 of the Advanced Plasma Wakefield Experiment (AWAKE) at CERN, the experiment started Run 2 in 2021. The goals of AWAKE Run 2 are to accelerate electrons in proton-beam-driven plasma wakefields to high energies with gradients of up to 1 GV/m while preserving the electron beam normalized emittance at the 10 µm level, and to demonstrate the acceleration of electrons in scalable plasma sources to 50-100 GeV. The first milestone towards these final goals is to demonstrate electron seeding of the self-modulation of the entire proton bunch. This was achieved in the 2021 run and some highlight results are shown. In the next phases of AWAKE Run 2, a new X-band electron source will provide a 150 MeV, 200 fs, 100 pC electron beam, to be accelerated in the plasma wakefields.

INTRODUCTION

The Advanced Plasma Wakefield Experiment (AWAKE) at CERN [1] has been developed as a proof-of-principle R&D experiment to study proton-driven plasma wakefield acceleration of electrons. AWAKE relies on 400 GeV proton bunches of the SPS accelerator at CERN, which could potentially accelerate electrons to energies as high as 200 GeV in a 400 m long plasma [2]. Approved in 2013, AWAKE observed Self-Modulation (SM) of a proton bunch travelling in a 10 m plasma in 2016-2017 [3-5], and plasma wakefield acceleration of electrons from 19 MeV to 2 GeV in 2018 [6], completing its Run 1 programme.

After the successful demonstrations obtained in Run 1, the AWAKE Run 2 programme [7-9] aims to demonstrate the possibility to use proton-driven wakefield acceleration for high-energy physics applications, starting with experiments where a high-energy bunch collides with a target. Such fixed-target experiments do not require colliding bunches and their physics performance is determined by the energy and number of electrons on target. Demonstrating the ability to deliver beams for such an experiment is the goal of Run 2 and is a prerequisite for designing more complex facilities such as laser-electron and electron-proton colliders.

Experimental Layout

In its current layout, the AWAKE experiment includes a 10 m long rubidium vapor source supporting vapor densities in the range 10^{14}-10^{15} cm^{-3} and a 120 fs laser, with central wavelength of 780 µm and energy of 120 mJ, used to singly ionize the rubidium vapor, creating plasma. The 18 MeV electron beam, with charge ranging from 100 to 800 pC, is provided by an S-band RF photo-injector with a UV-illuminated Cs_2Te cathode, followed by a 1 m long booster structure. Both the injector and the booster are powered at 3 GHz by a 30 MW klystron, with a repetition rate of 10 Hz. The beam is then delivered to the entrance of the plasma by a 15 m long beamline of dipole and quadrupole magnets, instrumented with beam screens and beam position monitors. The beamline downstream of the vapor source includes a magnetic spectrometer to measure accelerated electrons and several Optical Transition Radiation (OTR) screens whose light, when crossed by the proton bunch, is sent to transverse and longitudinal diagnostics, producing both time-integrated and time-resolved distributions of the proton bunch charge density.

Seeded Self-Modulation

The proton bunches of the SPS are longer (6-8 cm r.m.s.) than the wavelength of the plasma used by AWAKE (1 mm), and they are subjected to the Self-Modulation Instability (SMI) as soon as they enter a dense plasma. During SMI, the wakefields generated by a long proton bunch act back on the bunch itself, creating focusing and defocusing regions that modulate the long bunch into a train of micro-bunches at the scale of the plasma wavelength [10]. SMI can develop from noise or from controlled initial wakefields. When the SMI is 'seeded' by an initial modulation, its timing and amplitude become reproducible, creating the Seeded Self-Modulation (SSM) process which is necessary to achieve reproducible electron acceleration.

AWAKE has experimented with two types of SSM. In Run 1, it was observed that by timing the ionizing laser pulse to overlap the proton bunch, the subsequent sharp onset of the beam-plasma interaction could drive well-defined seed wakefields and produce SSM in the second half of the proton bunch [3]. In Run 2a, an electron bunch preceding the proton bunch provided the seed, modulating the entire proton bunch [11].

AWAKE RUN 2 PROGRAMME

The goal of the Run 2 programme is to demonstrate stable acceleration of electron bunches with high gradient (0.5-1 GV/m) over significant distances (10 m), while maintaining small electron bunch emittance (10 µm) and relative energy spread (few %), as well as to demonstrate a scalable plasma source technology to support O(100) m of plasma [9]. In order to achieve these goals, several challenges must be met, resulting in the research programme described below.

AWAKE Run 2a (2021-2022)

The first phase of the Run 2 programme relies on the Run 1 infrastructure and focuses on the SSM process. Run 2a aims to demonstrate that an electron bunch can

† gzevi@cern.ch

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provide sufficient transverse wakefields to seed the SSM of the entire following proton bunch. Electron-bunch-seeded SSM (eSSM) will be necessary starting from Run 2c, as the entire proton bunch will have to be modulated to prevent it from undergoing SMI when it enters a second plasma where electron acceleration takes place (see Fig. 1). In addition, to complement the eSSM studies, the Run 2a programme includes studies of electron-seeded transverse instability of the proton bunch. Understanding the growth and potential mitigation of the hose instability [12], which was not observed in Run 1, is one of the keys to extending the length of the AWAKE plasma.

AWAKE Run 2b (2023-2024)

The second phase of Run 2 is dedicated to the stabilization of the SM process. Simulation studies show that once the SM process has reached saturation, the velocity difference between the defocusing fields and the micro-bunches results in continuous charge loss which quickly diminishes the longitudinal wakefields [13, 14]. This undesired evolution can be prevented by introducing a short ramp in the otherwise constant plasma density, such as a ~2% density step over O(10) cm.

The objective of Run 2b is to experimentally verify these simulation-based predictions. A new Rb vapor source, already in advanced design state, is scheduled for installation in mid-2023. The new vapor source will include 9 independent electrical heaters in the first 5 meters, to test different density steps, and 13 viewports to measure Rb density and plasma light.

AWAKE Run 2c (2027-2028)

The third phase of Run 2 focuses on electron acceleration, upgrading both the geometry of the experiment and the properties of the injected electron beam.

In the Run 1 design, electrons are injected at the beginning of the plasma, while the proton bunch is not yet self-modulated: this configuration results in losing around 80% of the electron bunch [6]. The loss is due to the defocusing wakefields of the unmodulated proton bunch and by the variable phase velocity of wakefields during the SM process. To overcome these known challenges, in the Run 2 design the electrons are injected after the SM process has saturated, in a second 10 m long plasma cell.

Furthermore, the transverse and longitudinal parameters of the witness electron bunch are chosen to reach high energies while maintaining a low energy spread and preserving transverse emittance. Three main criteria are considered: (i) the transverse size of the electron bunch must match the linear plasma focusing to avoid size fluctuations; (ii) the bunch length must be smaller than a quarter of a plasma wavelength to fit into the accelerating-focusing region of the wakefields; (iii) the electron bunch density n_{b0} must exceed the plasma electron density n_{e0} ($n_{b0} >> n_{e0}$) to reach blow-out and provide the linear plasma focusing needed for emittance conservation and also to load the wakefields to minimize the final energy spread. As described below, a new electron source and beamline is needed to satisfy these criteria. A layout of the AWAKE Run 2c experiment is shown in Fig. 1.

The additional plasma cell and the new electron beamline require significant infrastructure changes, including the emptying of the ~100 m long target cavern of the CERN Neutrinos to Gran Sasso (CNGS) experiment downstream of AWAKE. The considerable size of the ex-CNGS area would also allow for further expansion of AWAKE.

AWAKE Run 2d (2028 and beyond)

The last phase of Run 2 focuses on demonstrating acceleration in scalable plasma sources capable to reach O(100) m lengths.

The plasma technology used in Run 1, based on Rb vapor ionized with a high-power laser pulse, does not scale beyond 10 m due to the focusing geometry and the depletion of laser energy. In order to reach O(100) m of plasma, two new scalable technologies using noble gases are in development: a direct-current electrical discharge plasma source [15], and a helicon source where RF-powered antennas produce a magnetized wave which generates the discharge [16]. The achievable density uniformity is being studied, having already demonstrated operation at the plasma densities relevant for AWAKE for both technologies.

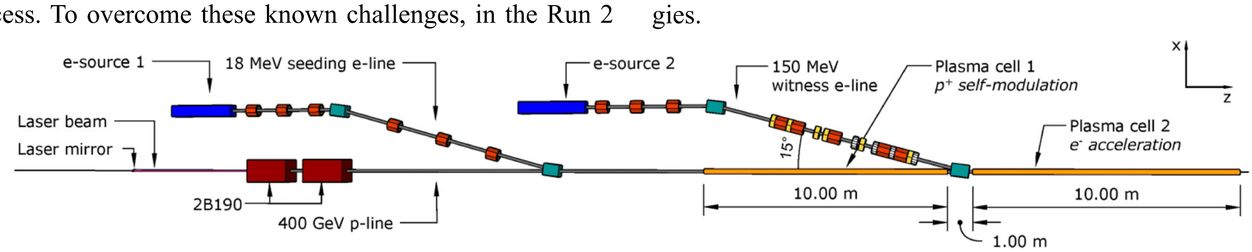

Figure 1: Schematic of the layout for Run 2c, showing the 18 MeV electron line used to provide a seed for eSSM in the first plasma (p^+ *self-modulation*) and the 150 MeV electron line generating the witness bunch for acceleration in the second plasma (e^- *acceleration*). The last section of the proton transfer line is also shown, with protons moving from left to right [17].

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RUN 2A: PERFORMANCE AND RESULTS

Preparation for Run 2a

The achievements of Run 2a, summarized below, are the result of comprehensive preparations which took place in 2019-2021, during CERN's Long Shutdown 2. This included the re-commissioning of the electron line, the addition of beam diagnostics, and the study of electron deceleration in plasma to determine the beam parameters to use in the proton experiments [18, 19]. During this period, numerical optimization and machine learning techniques were developed to improve the control of trajectory and optics [20-22].

Improving the reliability and shot-to-shot reproducibility of the experiment was a pre-requisite for studying eSSM, since the process can only be confirmed by comparing data taken in tens of consecutive events. A Data Quality Monitoring (DQM) framework was introduced to monitor and control the diagnostics of the three beams (electron, proton, laser). The DQM provides automatic checks of timestamp and errors for all ~250 properties and images, and it displays histograms and history plots of the most important ones, as well as a detailed view of the most recent event. To reduce the uncertainty on transverse alignment of the three beams, including trajectory jitter and drift, dedicated tools were developed taking advantage of the higher rate (10 Hz) of the electron and laser beams with respect to the protons (0.05 Hz), and making use of a parallel optical line to the laser beam [23].

2021 and 2022 Proton Runs

The CERN SPS provides proton beams for the LHC as well as for several stand-alone experiments. AWAKE received 7 weeks of proton beam in 2021, and is scheduled for 12 weeks in 2022, divided in run periods of two or three weeks. In the 2021 proton run, AWAKE achieved eSSM within the first two weeks, and dedicated most of the beam-time to study the growth of SM as a function of the charge of the proton and electron bunches. During the 2022 proton run, the focus has shifted to studying the hosing instability as a function of transverse misalignment of the electron beam.

Results

Run 2a is still underway, but the experiments have already yielded several new results.

The first major achievement is the demonstration of electron-bunch-seeded self-modulation of the proton bunch. The eSSM experiments require placing a significant distance (620 ps) between the ionizing laser pulse and the center of the proton bunch (240 ps r.m.s.), to avoid a sharp onset of the beam-plasma interaction which could seed the SM. Without an electron bunch, the SM timing is not reproducible from event to event, yielding discrete Fourier transforms (DFT) of time-resolved images showing significant phase variations (r.m.s. of 26% of the plasma period, consistent with a uniform distribution). When the electron bunch is placed immediately behind the laser pulse, stabilizing the SM process, the event-to-event phase variation is reduced to the 6% level, and clear micro-bunches become visible in the average of many consecutive images, as shown in Fig. 2(b). Finally, delaying the electron bunch by approximately half a plasma period results in a shift in the longitudinal distribution of the modulated proton bunch, Fig. 2(c), with the difference in phase matching the shift in electron bunch timing, Fig. 2(d), confirming the controlled reproducibility of eSSM. The demonstration described above, together with an analysis of the growth of SM along the proton bunch and along the plasma as a function of electron and proton charge density, forms the basis of Ref. [11].

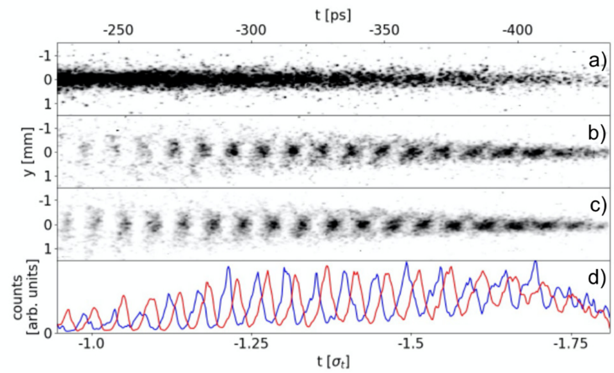

Figure 2: Proton bunch charge density distribution at the OTR screen, filtered by a 20 μm slit to select a narrow region in x, and imaged by a streak camera to display the longitudinal coordinate, t. The average of 10 events is shown for: (a) the proton bunch with no plasma, (b, c) the proton bunch undergoing eSSM with two different timing of the electron bunch. The time profiles of (b) and (c) are shown in (d) [11].

Having achieved eSSM early in Run 2a allowed for several additional studies, which are still ongoing. Introducing transverse misalignments in the electron bunch with respect to the proton bunch generates the hose instability, leading to the preliminary results of Ref. [24]. Dedicated studies of how the unmodulated head of the proton bunch evolves as it traverses plasma of varying densities, compensating for the Coulomb force, can provide insight into the adiabatic focusing of a long proton bunch in plasma, as discussed in Ref. [25]. The interaction of an unmodulated proton bunch head with the second plasma of Run 2c can be emulated in the current layout by adjusting the optics of the proton bunch, as discussed in Ref. [26].

ELECTRON INJECTOR FOR RUN 2C

Electron Beam Requirements for Run 2c

As discussed above, achieving energy gain for a significant charge, while maintaining small energy spread and emittance, is only possible with specific parameters for the electron beam. A set of parameters satisfying these requirements was tested in simulation and found to provide the energy and beam quality expected [27]. The latest version of the parameters, which have evolved during the design process, is: 150 MeV energy, 100 pC charge, 200 fs bunch

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length, 0.2% energy spread, 2 µm normalized emittance, 5.75 µm transverse size at the injection point [17].

Electron Source Design

The reference design for the electron source consists of a 1.5 cell S-band RF gun developed by INFN [28], which can produce bunches of ~2 ps length from a UV laser spot size of ~1 mm. A 25 cm long X-band bunching section with a 22 MV/m gradient is needed to shorten the bunch to ~200 fs, followed by two X-band accelerating structures, each 1 m long and with a gradient of ~ 80 MV/m. The RF gun and accelerator are embedded in a solenoidal magnetic field which maintains the beam transverse size at the 100 µm level, and the normalized emittance at the 1 µm level [29, 30].

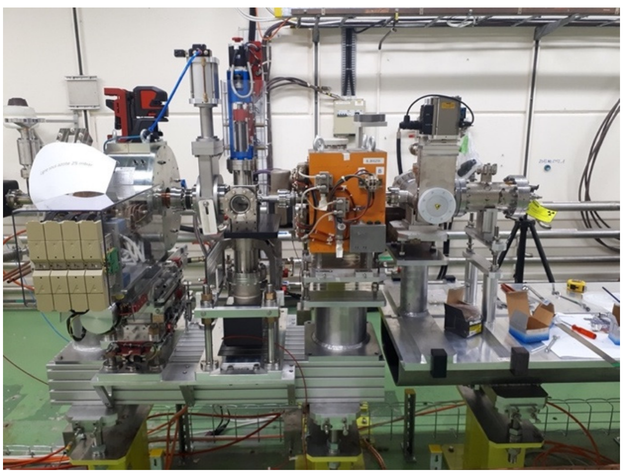

Figure 3: The Run 2 Test Injector in August 2022.

The electron source is scheduled to be installed in the AWAKE experimental area in 2027. A prototype system, the Run 2 Test Injector shown in Fig. 3, is under development in cooperation with the CLEAR team at CERN, based on the layout shown in Fig. 4. The RF gun has been installed and high-power conditioned, reaching 120 MV/m gradient, and beam tests are forthcoming. The status of the RF configuration and optimization are described in Ref. [30].

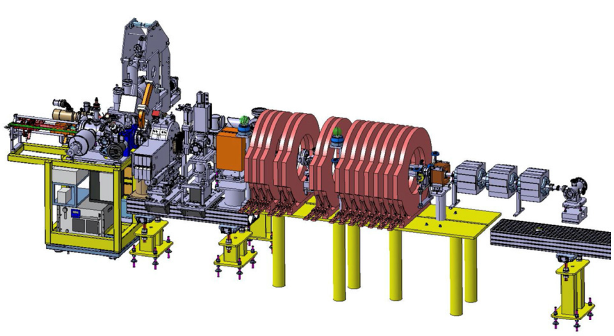

Figure 4: Design of the Run 2 Test Injector, developed in collaboration with the CLEAR team at CERN.

Electron Beamline Design

The beam line to transport the 150 MeV electron bunches from the electron source to the entrance of the plasma presents several challenges. Injection takes place between the two plasma cells, in a gap that should be as short as possible to avoid divergence of the proton microbunches and reduction of the accelerating fields (see Fig. 3 in Ref. [31]). The beam at injection must be at a waist ($\alpha_{x,y}$ = 0), with zero dispersion and well-defined size and emittance to match the plasma focusing strength. Additionally, simulation studies of injection tolerances show that the event-to-event jitter in beam size and trajectory must be kept at the micro-meter level in order to obtain the desired beam quality after acceleration [32].

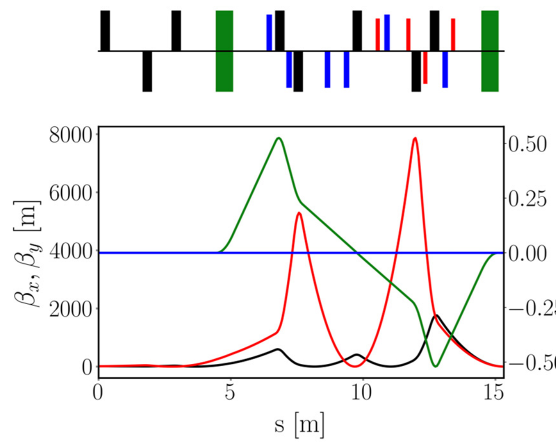

Figure 5. Top: Schematics of the optimized electron beamline, with dipole magnets (green), quadrupoles (black), sextupoles (blue) and octupoles (red). Bottom: Simulated optics of the electron beamline, with Twiss parameters $\beta_{x,y}$ (black, red) and dispersion $D_{x,y}$ (green, blue) [17].

To satisfy these challenging requirements, several techniques are employed in the design of the Run 2c beamline, as described in Ref. [17]. The beamline is modelled with MAD-X [33], including 6D particle tracking, starting from an input bunch based on simulations of the electron source. Genetic algorithms produce the initial dog-leg design, determining the position of dipoles and quadrupoles. Numerical optimizers are then used to build upon this design including sextupoles and octupoles to address the chromatic effects related to strong focusing, yielding the optics of Fig. 5 and the final beam distributions of Fig. 6. Numerical algorithms are also introduced to re-match the line considering the effect of thin foils which might be needed to separate the vacuum and Rb sections of the beamline. The effect of misalignments of each optical element on the measured beam size at injection is significant, and a beam-based alignment procedure is outlined, relying on movers with 1 µm step size for each magnet.

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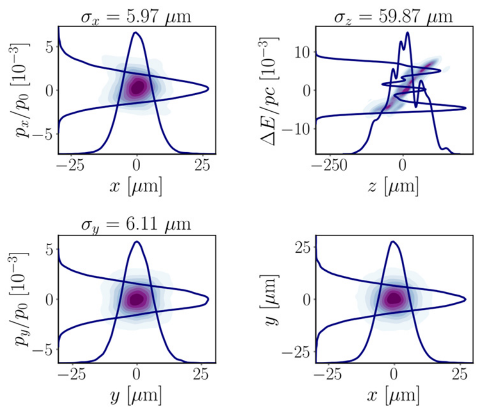

Figure 6: 2D projections of the beam distribution at the plasma injection point, based on tracking the output of the electron source through the transfer line optics of Fig. 5 [17].

CONCLUSIONS

The AWAKE Run 2 programme is designed to demonstrate stable acceleration at high gradient over significant distances, while maintaining good emittance and energy spread. The first two phases (Run 2a, b), until 2024, are focused on seeding and stabilizing the self-modulation of the proton bunch. The last two (Run 2c, d), starting in 2027, will focus on acceleration and will require significant modifications of the experimental layout, introducing a second plasma cell, a second electron injector, and new technologies for plasma formation.

The primary objective of Run 2a, seeding the proton bunch self-modulation with a preceding electron bunch, has been achieved, and additional studies are being pursued during the remaining weeks of SPS proton beam. The design of the electron injector for Run 2c is progressing using realistic simulations of the electron beamline, with a prototype of the electron source being built.

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