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AWAKE RUN 2 AT CERN

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Abstract

The AWAKE Run 2 experiment, starting in 2021 at CERN, aims to achieve high-charge bunches of electrons accelerated to high energy (~10 GeV) while maintaining beam quality. AWAKE Run 2 also aims to show that the process is scalable so that, by the end of the run, the AWAKE-scheme technology could be used for first particle physics applications. The first two phases of Run 2 include the investigation of the seeding of the proton bunch self-modulation with the current electron beam in the existing AWAKE facility and the test of a second new plasma source with a density step allowing to maintain strong accelerating fields. In the third phase of Run 2, electrons with an energy of 150 MeV, produced in a newly installed electron source, will be injected into a second plasma source and accelerated to high energies (several GeVs) while keeping good emittance. In the fourth phase it is planned to replace the second plasma source with a scalable one, which eventually could be used for long-distance acceleration and first applications. In this paper we present the program of the four phases of AWAKE Run 2, the technical challenges and the proposed schedule.

INTRODUCTION

The Advanced WAKEfield Experiment at CERN, AWAKE, is an accelerator R&D experiment to demonstrate for the first time ever plasma wakefield acceleration of electrons in wakefields driven by a proton bunch and, in the future, take advantage of the large energy stored in the proton bunch to reach very high energy gain in a single plasma. The AWAKE collaboration completed its Run 1 at the end of 2018 achieving all set milestones: the seeded self-modulation of a long SPS proton bunch and generating strong plasma wakes was demonstrated for the first time [1, 2]. Moreover, the microbunches that are formed in the modulation process can be phase controlled via seeding, allowing for synchronized injection of particle bunches to be accelerated [3]. In addition, in AWAKE Run 1, the acceleration of externally injected electrons to multi-GeV energy levels in the proton driven plasma wakefields were demonstrated [4].

AWAKE Run 2 starts in 2021 and aims to bring the technology to a point where particle physics applications based on the AWAKE scheme can be proposed and realized. For this purpose, the goals of Run 2 are to achieve high-charge bunches of electrons accelerated to high energy, about ~1 GeV/m, while maintaining beam quality through the plasma and showing that the concept is scalable to long acceleration distance scales.

By the successful end of AWAKE Run 2 the AWAKE scheme could be used for first high-energy physics applications already in the intermediate timescale; first high energy experiments are within reach, where proton driven plasma wakefield acceleration technology could be used for fixed target experiments for dark photon searches and also for future electron-proton or electron-ion colliders, where low luminosity is acceptable [5, 6].

GOALS AND TIMELINE OF RUN 2

In order to achieve acceleration 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 is seeded by an electron bunch [7] and the bunch modulates along the entire bunch length. The self-modulation (SM) process must reach saturation before electrons are injected for acceleration in the second plasma source. Simulations also show that by introducing a density step in the first plasma source the amplitude of the wakefields do not decay and allow for much higher final electron energies over long acceleration distances. In order to meet the beam quality goals of AWAKE Run 2, the electron bunch that is injected from a new electron source needs to have sufficient charge density that beam loading can occur, thereby flattening the field shape and limiting emittance growth. The second plasma source must be able to produce a plasma with uniform density for a distance of ten to several hundreds of meters. The detailed physics program is summarized in IPAC21 paper [8].

Following these goals, the AWAKE program of Run 2 is subdivided into four phases:

- Run 2a: Demonstration of the electron seeding of the proton bunch self-modulation in the first plasma source.
- Run 2b: Demonstration of the stabilization of micro-bunches with a density step in the first plasma source.
- Run 2c: Demonstration of electron acceleration and emittance control.
- Run 2d: Demonstration of electron acceleration in scalable plasma sources.

Figure 1 shows the proposed timeline for the different phases of AWAKE Run 2. Phases Run 2a and 2b are foreseen to take place before the Long Shutdown 3 (LS3) of the LHC, followed by the removal of the CNGS target area in order to house the additional equipment needed for Run 2c and 2d. These phases will take place after LS3.

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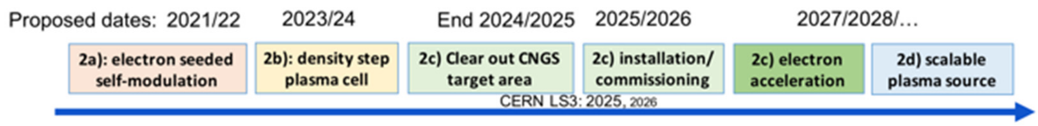

Figure 1: Proposed timeline for AWAKE Run 2.

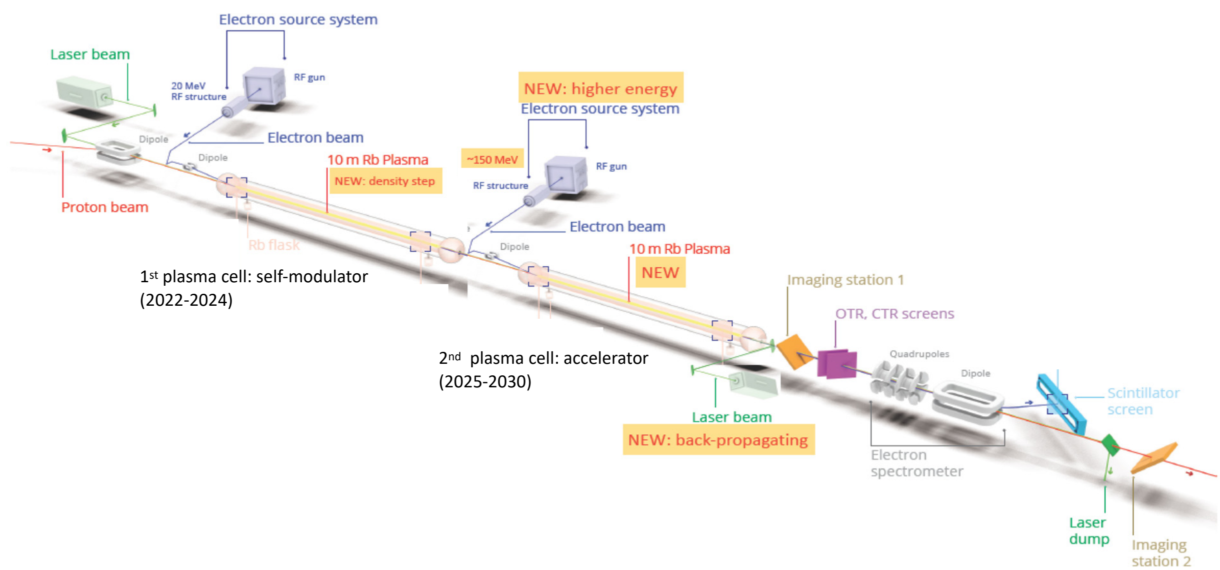

Figure 2: Schematic of the AWAKE Run 2c and 2d layout.

AWAKE RUN 2 PROGRAM

AWAKE Run 2a

During AWAKE Run 1, a 120 fs long, 100 mJ laser beam generated a pre-formed plasma in the Rb vapour source. The laser creates a relativistic ionization front (RIF) and when placed within the proton bunch this RIF seeds the SM process. In AWAKE Run 2 however, the SM process is seeded by the wakefields driven by a preceding electron bunch [7, 9], allowing to produce a self-modulated proton bunch over the entire length. For this experiment the same infrastructure as that of Run 1 can be used and the electron beam coming from the existing electron injector of AWAKE Run 1 can be employed. During CERN's Long Shutdown 2 the entire electron beam system has been re-commissioned, beam diagnostics has been added and modified and the electron beam parameters, which will be used in the experiments with protons, have been determined [10].

AWAKE Run 2b

In the experiments of Run 2b the effect of the plasma density step on the SM process will be measured. This requires a new vapour source and corresponding new diagnostics. The new vapour source is in its design phase and will be exchanged with the current one for Run 2b. It includes additional observation ports in order to diagnose the electron plasma density that sustains wakefields. The experimental program will focus on direct measurements of the plasma 'wave'. To this aim, different diagnostics are currently evaluated (e.g. THz shadowgraphy diagnostics, plasma light diagnostics) requiring possibly a new vacuum laser beam transport line.

AWAKE Run 2c

The AWAKE Run 1 experiment is installed upstream of the previous CERN Neutrinos to Gran Sasso, CNGS, facility. The ~100 m long CNGS target cavern, which currently houses the CNGS target and secondary beam line while its activation levels decay, is separated from the AWAKE experiment by a shielding wall.

The baseline of AWAKE Run 2c includes a second electron source, beam line and klystron system as well as a second vapour source in order to demonstrate the experimental goals of Run 2c. Figure 2 shows the setup of this experimental layout.

In order to be able to integrate the entire Run 2c experiment in the AWAKE facility, the first plasma cell will be shifted by around 40 m downstream its current location and consequently the new equipment will also be accordingly moved downstream. This change also needs some downstream shifting of the proton beam line final dipole magnets, however, although aperture constraints might be challenging, no extra magnets need to be added [11].

The second electron source needs to deliver electrons with 150 MeV energy, bunch charge of a few 100 pC, beam emittance of 2 mm-mrad and a short bunch length of 200 fs duration. The baseline proposal is a novel RF gun and two X-band structures for velocity bunching and acceleration.

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A prototype system is currently developed together with the CLEAR facility in order to demonstrate the required beam parameters for AWAKE and to study the mechanical and integration aspects in the AWAKE facility. Figure 3 shows a photo of this new electron source, installed at CERN and currently under commissioning.

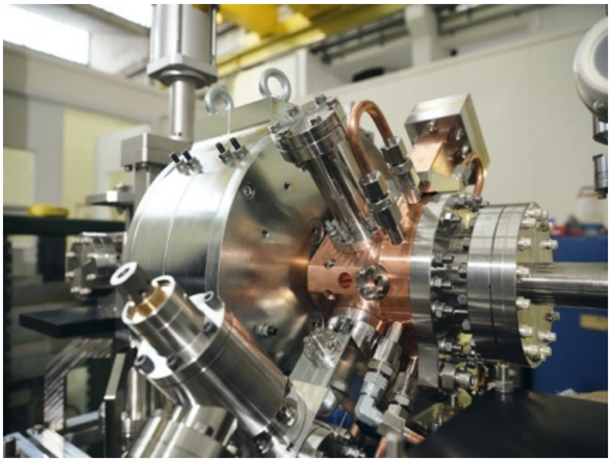

Figure 3: Electron source prototype for Run 2c.

The beam line design for the 150 MeV electron beam from the electron source to the plasma source is very challenging, given the tight beam specifications; the beam must be matched to the plasma at the plasma merging point, with a beam size σ satisfying $\sigma = (0.00487\varepsilon)^{1/2}$, zero dispersion and $\alpha_{x,y} = 0$ (with the emittance ε and the Twiss parameter $\alpha_{x,y}$). In addition, the gap between the two vapour sources must be as short as possible, <1 m. Considering also additional integration limits from the width of the tunnel, the baseline proposal of the electron transfer line is a dogleg design and is well advanced [11]. Studies on the injection tolerances of the proton and electron beam are currently ongoing and are key to controlled plasma wakefield acceleration [11-13].

In the second vapour source the witness electrons will be accelerated in the plasma wakefield driven by the fully self-modulated proton beam. In order to demonstrate electron acceleration to high energies (~10 GeV), the accelerator plasma source will have a length of about 10 m and will be based on the laser ionized Rb vapour source (as used in AWAKE Run 1 and in the first vapour source).

The laser beam for the ionization in the second vapour source will be injected from its downstream end counter-propagating to the proton beam. Although the same laser as for the first one can be used in Run 2c by splitting its output beam on two branches, additional laser transport lines and a compressor chamber needs to be integrated.

Major infrastructure changes are therefore required for AWAKE Run 2c in order to house this additional equipment foreseen for the experiment. The proposed Run 2 facility layout extends over 50 m more downstream than the current Run 1 facility, considering not only the position of the main elements, but also their installation procedure as well as the needed general services, the accessibility and safety during operation. Hence, prior to the installation of the AWAKE Run 2c facility, dismantling and decontaminating the entire CNGS target area is needed. Detailed Monte Carlo simulations were performed resulting in a very good understanding of the residual dose rate levels of the equipment and in the CNGS target area. Radionuclide inventories have been assessed to understand the requirements for radioactive waste disposal. Also, transport constraints have been studied in order to estimate the duration of the dismantling as well as the additional transport shielding needs.

The dismantling works will have a major impact on the schedule and the cost of AWAKE. First studies show that the dismantling will take 1 – 1.5 years and therefore the work is proposed to be done during LS3 in order to minimize the impact on the AWAKE experimental program with beam.

AWAKE Run 2d

Once Run 2c demonstrated electron acceleration to high energies while controlling beam quality, the second vapour source can be exchanged with a different plasma technology that will be scalable to long distance in order to accelerate electrons to energies to several 10s of GeV with the SPS beam. This technology would then allow for first particle physics applications.

The plasma technologies currently under study at CERN are helicon plasma sources [14] and discharge plasma sources [15]. A dedicated plasma laboratory is operational at CERN where studies on the density uniformity and scalability of ~1m long prototypes are performed. In addition, several plasma diagnostics [16] is developed to understand the features of the plasma. A design for scalable, several meter-long plasma sources are developed.

With the CNGS target cavern fully dismantled, there is enough space available to install a several 10s of meter long plasma source. First studies also show that space is available for a prototype fixed-target experimental setup in order to perform first particle physics experiments with electrons accelerated from AWAKE.

CONCLUSION

The AWAKE Run 2 program is well defined for the next years and has a clear roadmap; Run 2 is subdivided in four phases and starts in summer 2021. The first two major goals for Run 2 are to be realized before Long Shutdown 3 and do not require significant modifications of the AWAKE facility. The last two phases are proposed to take place during and after LS3 and need the extension of the experimental area into the CNGS target area and the installation of a new vapour source, a new X-band electron source and beamline.

Whereas AWAKE Run 1 was a proof-of-concept experiment achieving all its milestones, the next phase of AWAKE aims to bring the understanding of proton-driven plasma wakefield acceleration to a level where particle physics experiments based on this technology can be proposed. Many of the challenges that AWAKE addresses will benefit the whole plasma accelerator community.

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