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RESULTS AND PLANS FOR RUN 2 OF THE ADVANCED PROTON DRIVEN PLASMA WAKEFIELD ACCELERATION EXPERIMENT AWAKE

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Abstract

The Advanced Wakefield Experiment, AWAKE, at CERN is an accelerator R&D experiment, which moved from a proof-of-concept experiment (Run 1) to a facility that develops the proton-driven plasma wakefield acceleration technology (Run 2) to be ready for proposing first particle physics applications. In this paper the plans, challenges, and key components of the four phases in the AWAKE Run 2 roadmap are summarized. In addition, an overview of the rich measurement program of the second phase, AWAKE Run 2b, during 2023 and 2024 is given. Preliminary results from a unique 3-week measurement opportunity with a 10 m discharge plasma source prototype are shown. A new 10 m long rubidium vapor source was installed in summer 2023 with the possibility to generate a density step (0-10%) every 50 cm along the first 4 m. First measurements with this plasma source are also presented.

INTRODUCTION

AWAKE was initially developed to verify the concept of proton driven plasma wakefield acceleration; The possibility to use proton bunches as drive beams allows the electron acceleration to take place in one stage given the high stored energy available in the existing proton accelerators. This circumvents the need for multiple accelerating stages required when using laser or electron bunches, which carry much less energy [1]. However, to drive strong wakefields in plasma for efficient electron acceleration, the proton bunch length must be at the order of the plasma wavelength (λ_p =1 mm at AWAKE). The proton bunch length from SPS though is at the order of 6 cm. As the long proton bunch traverses the plasma, it splits into a train of shorter bunches, a process known as self-modulation (SM) [2]. These micro-bunches then resonantly excite the plasma wave resulting into strong wakefields and accelerating externally injected electrons to high energies.

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 ever that strong wakefields are generated by proton beams [3-5]. In addition, the acceleration of externally injected electrons to multi-GeV energy levels in the proton driven plasma wakefields [6] was demonstrated.

In 2021, the AWAKE collaboration has started with the Run 2 program. The goal of Run 2 is to achieve electron acceleration with GeV per meter energy gain, while controlling the beam quality. In addition, scalable plasma sources that can be extendable up to 100s of meters in length, are developed. Once these goals will be demonstrated, AWAKE could propose this acceleration concept for particle physics applications. The first application could be to produce electron beams with energies between 40 and 200 GeV impinging on a fixed target in order to search for new phenomena related to dark matter [7].

Current Experimental Setup: In the AWAKE experiment a 400 GeV, 6 cm long proton bunch is extracted from the SPS and sent into a 10 m long plasma source containing rubidium vapor. The source is at a temperature of around 200˚C to reach the required plasma electron density of $n_{p,e}$= 0.5×10^{14}-10^{15} cm^{-3}. A ~ 120 fs, ~ 100 mJ laser pulse (λ = 780 nm) is placed within the proton bunch and produces a relativistic ionization front (RIF) that creates the plasma by ionizing the vapour. The proton bunch passes through an optical transmission radiation screen installed downstream the vapor source. Time-resolved images of the charge density distribution are produced when imaging the OTR light onto the entrance slit of a streak camera. 18 MeV electrons from an RF photo-injector based on an S-band structure are externally injected into the plasma source. The energy spectrum of the accelerated electrons is measured with a magnetic spectrometer downstream the vapor source.

AWAKE RUN 2 PROGRAM

The AWAKE collaboration has developed a well-defined plan to reach the goals of Run 2; the program is staged in four phases (Run 2a – 2d), has started in 2021 and lasts over several years until CERN's Long Shutdown 4, LS4. The phases address the following milestones:

- Run 2a (2021 – 2022): *Control:* Demonstration of the seeding of the self-modulation of the entire proton bunch with an electron bunch.
- Run 2b (2023 – 2024): *Stabilization:* Maintaining large wakefield amplitudes over long plasma distances by introducing a step in the plasma density.
- Run 2c (2028 – 2031): *Quality:* Demonstration of electron acceleration and emittance control of externally injected electrons.
- Run 2d (2032 – LS4): *Scalability:* Development of scalable plasma sources with sub-% level plasma density uniformity.

For the experiments of AWAKE Run 2a and 2b the same infrastructure as that of Run 1 and described above, is exploited. Figure 1 shows the layout for Run 2c and 2d, where two plasma sources are used: the first one is the 'self-modulator', where the entire proton bunch undergoes seeded self-modulation and maintains high wakefield amplitudes (program of Run 2a and 2b).

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The self-modulation process must reach saturation before electrons are injected into the second plasma source, the ‘accelerator’ source. To achieve acceleration with low electron energy spread (5-8%), an accelerated bunch charge of ~100 pC and a normalized emittance control of (2-30) mm-mrad (Run 2c program), the injected electron bunch needs to have sufficient charge density that beam loading can occur, thereby flattening the field shape and limiting emittance growth. These requirements can be met with a new electron beam system based on a RF-photoinjector with two X-band structures and a sophisticated transfer-line design providing 150 MeV electrons with a beam size of 5.75 µm and normalized emittance of 2 mm-mrad at plasma injection. The design of the new electron line, the laser lines both for the two plasma sources and the two electron sources, the additional beam instrumentation (e.g. proton beam position monitors requiring 10 µm resolution) and the additional infrastructure are already well underway. A prototype of the new electron source is installed in CERN’s CTF2 area and has already been successfully commissioned [8].

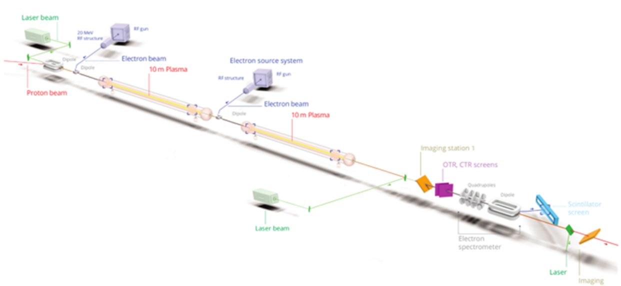

Figure 1: Layout of AWAKE Run 2c and 2d.

Once the process of electron acceleration to high energies with controlled beam quality will have been demonstrated, the second plasma source will be exchanged in Run 2d with a different plasma technology, scalable to several 10s of meters and reaching several 10s of GeV electrons. Successful demonstration could allow proposing first particle physics applications. Currently helicon plasma sources (HPS) and discharge plasma sources (DPS) are under study at CERN in a dedicated lab. Density uniformity and scalability of ~1m long HPS and 10m long DPS prototypes as well as several plasma diagnostics are investigated. By stacking units of RF antennas and magnetic field coils (HPS) or multiple sources with one cathode at high voltage in the middle and a grounded electrode at each end (DPS), scalability can be obtained.

The current AWAKE experiment is installed upstream of the 100 m long CERN Neutrinos to Gran Sasso (CNGS) target cavern, separated by a shielding wall. This target cavern needs to be dismantled to gain the additionally required space for the AWAKE Run 2c,d experimental setup. The CNGS dismantling and AWAKE experiment installation works are planned to start by end 2024 in order to be ready for first protons after the LS3 to start AWAKE Run 2c in 2028.

RECENT PRELIMINARY RESULTS

Run 2a completed successfully its measurement program in 2022. The results are summarized in [9-11].

Discharge Plasma Source Prototype

Before Run 2b started in July 2023, the collaboration profited from a unique opportunity during a three-week proton run in May 2023 to test a 10 m long discharge plasma source (DPS) prototype, developped by CERN and IST [12]. The goal of the run was to show that the DPS can be integrated into the AWAKE facility, the propagation of a proton bunch results in the self-modulation instability (SMI) signature as in the laser-ionized rubidium vapor source and it can be used for a variety of experiments. These goals were all met. The DPS was installed, commissioned and operated very successfully and performed reliably. The large plasma radius of ~10 mm strongly facilitated the experimental alignment procedures. In addition, no laser and electron beams were used as the DPS has metallic windows at both ends, and consequently seeded self-modulation of the proton bunch was not possible. Therefore only SMI was studied. Eventually, a huge variety of measurements could be performed due to the flexibility of operation of the DPS in terms of:

- Plasma density range: 0.1 to $10\mathrm{x}10^{14}$ cm^{-3}.
- Ion species: Argon, xenon, helium.
- Plasma length: 3.5m, 6.5m, 10m, 3.5+6.5m

Figure 2 shows the 10 m long discharge plasma source installed in the AWAKE experiment. The three photos show the discharge light of the discharge plasma source when filled with three different ion species, i.e. Argon, Xenon and Helium (first, second, third picture).

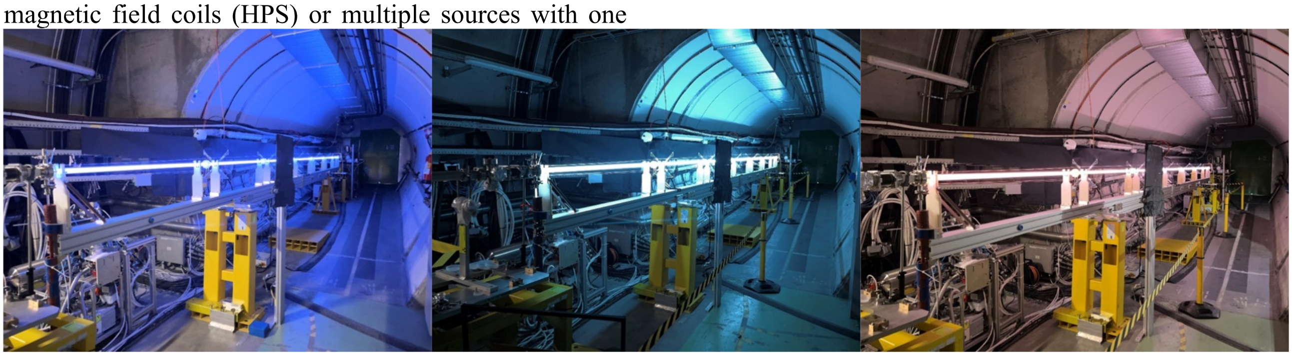

Figure 2: 10 m long discharge plasma source installed in the AWAKE facility. The discharge plasma light of the DPS filled with Argon/Xenon/Helium in the first/second/third picture is measured.

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Ion motion: The self-modulation relies on wakefields resonantly developing over many periods. However, ion motion may detune the resonance between bunch train and wakefields and affect the growth of the wakefields. By operating the DPS with heavy (Ar and Xe) and light (He) ions, the effect of ion motion on the growth of the plasma wakefields was studied. Preliminary results show clear effects when using heavy and light ions consistent with the simulations and theory [13]. The results will be submitted for publication in a high-impact journal.

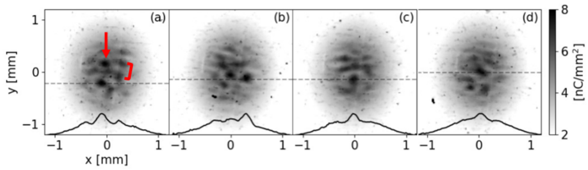

Figure 3: Transverse, time-integrated, single-event images of the proton bunch after propagation in plasma. Black lines: Lineouts along the corresponding dashed grey lines. Red arrow shows a filament ($\sigma \sim 0.12$mm) [14].

Current Filamentation Instability: When the proton bunch is wider than the cold plasma skin depth ($\sigma_{r0} \gg c/\omega_{pe}$, with ω_{pe} the plasma electron frequency and c the speed of light) current filamentation instability (CFI) can occur modulating the proton bunch transversely into finite-length, high-current-density filaments. This was studied by operating the DPS at the highest possible plasma electron densities in Ar (n_{pe}=9.38x10^{13}cm^{-3}), and widening the proton bunch radius resulting in σ_{r0} = 2.9 c/ω_{pe}. The experimental results show that this effect already happens when the transverse size of the proton bunch is larger than 1.5 plasma skin depth. CFI though does not occur, when the transverse size is smaller than the plasma skin depth. Instead the proton bunch undergoes SMI. Figure 3 shows clear evidence of filaments in four single-event, time-integrated images of the proton bunch at the exit of the plasma source. The results were published in [14].

Impact Ionization: Impact ionization could detune the resonant driving of wakefields by changing the plasma density. This was studied by recording time-resolved images of the proton bunch propagating in various gases and various pressures. Further analysis is ongoing, but preliminary results indicate that the effects can be neglected for acceleration experiments.

Plasma light: The discharge emits light (see Fig. 2). When the proton bunch propagates through the plasma, the dissipation of the energy of the plasma electrons supporting the wakefields results in additional light. This would give an indication of the plasma wakefield amplitude. First measurements with fast CCD cameras showed that when the proton bunch intensity or plasma density increased also the light signals increased. Further measurements will be done to directly link the light signal amplitude with the wakefield amplitude.

New Rubidium Vapor Source

Numerical simulations show that when introducing a density step at a certain position in the plasma, the wakefields maintain high amplitudes past their saturation for a long distance [15] and consequently reaching higher accelerating gradients. To demonstrate this, a new rubidium vapor source was developed by MPP, Munich and WDL, UK, which has the possibility to impose a density step (0-10%) every 50 cm along the first 4 m of the 10 m long plasma source (see Fig. 4). This new baseline source for AWAKE Run 2b was installed and commissioned in summer 2023. The source has 10 observation ports to measure the light emitted by wakefield dissipation along the plasma once the proton bunch passed. First measurements show an increase of the relative light signal towards the end of the plasma indicating the positive effect of the density step. Further measurements will be performed in the 2024 run to map the light along the plasma and to determine the local wakefield amplitudes. In addition, the achieved energy gain of side-injected 20 MeV electrons was measured. Preliminary tests with a density step are very encouraging and show an increase in the energy gain compared to a uniform-density plasma. Also these measurements need to continue in 2024 and will be used to conclude on the optimized density step parameters. The understanding of the electron injection process and the transverse beam size at the injection point, which was studied in the recent months, will also feed into the 2024 measurements [16]. Moreover, it is planned to install movable screens along the plasma source in summer 2024 in order to block the ionizing laser pulse and hence vary the plasma length. This allows to measure the energy gain per additional meter of plasma length and gives a clear indication of the accerating gradient.

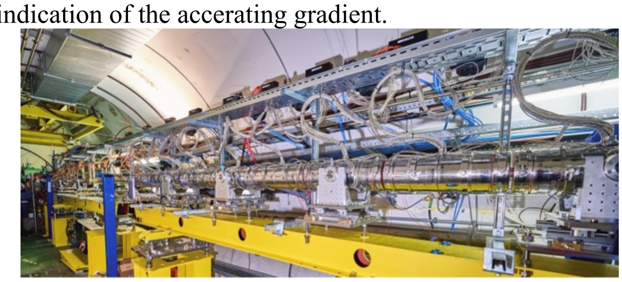

Figure 4: New 10m long rubidium vapor source with possibility to impose a density step.

CONCLUSION

The AWAKE Run 2 program is well-defined and addresses key challenges of accelerator concepts based on plasma wakefields. It is an integral part of the European Strategy for Particle Physics plasma roadmap. AWAKE has achieved all milestones to date. A candidate for scalable plasma sources was successfully tested in a 3-week measurement campaign in 2023, resulting in rich scientific results. AWAKE is now in the 2nd phase of its Run 2 program. Imposing a density step in the plasma allows to maintaining high wakefield amplitudes over longer distances. First measurements with a new plasma source to study the effect of the density step on the light dissipated along the plasma as well as on the energy of accelerated electrons are very encouraging. The measurements will conclude in 2024.

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