

# AWAKE: PREPARING FOR PHYSICS BEYOND LS3

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## Abstract

The AWAKE programme at CERN has evolved from its initial proof-of-principle phase to a comprehensive facility dedicated to advancing proton-driven plasma wakefield acceleration towards first particle-physics applications. In preparation for this next stage, AWAKE will undergo a major upgrade during CERN’s Long Shutdown 3 enabling the demonstration of electron acceleration to 4–10 GeV in a 10 m plasma source with controlled beam quality and validated scalability. Meeting the targets of 5-8% energy spread, 100 pC of accelerated charge and controlled emittance requires strong beam loading. This will be provided by a new RF photo-injector system equipped with two X-band structures and an optimized transfer line, delivering 150 MeV electrons with 5.75  $\mu\text{m}$  beam size at injection and 2 mm mrad normalized emittance. In parallel, the 400 GeV SPS proton bunch must reach full self-modulation in the first plasma source (‘self-modulator’) before the electrons are injected into the second plasma source (‘accelerator’). Extensive infrastructure modifications are already in progress, including the dismantling of the CNGS target area in order to create the space required for the upgraded AWAKE facility. We present the consolidated roadmap, the scientific goals, upgrade status and the key challenges associated with both the facility design and the experimental programme starting in 2029.

## INTRODUCTION

Proton-driven plasma wakefield acceleration was proposed as a route to very high particle energies by exploiting the large energy stored in the proton beams of existing high-energy accelerators such as the CERN SPS or LHC [1]. Using proton bunches as drivers allows electron acceleration in a single plasma stage, circumventing the need for multiple accelerating stages required when using laser or electron drivers. The AWAKE experiment at CERN is the world’s first realisation of this concept, using a 400 GeV SPS proton bunch to drive plasma wakefields in a rubidium vapour source. The driver bunch length must however be comparable to the plasma wavelength ( $\lambda_p \sim 1$  mm at AWAKE), whereas the SPS proton bunch is  $\sim 6$  cm long. As the long bunch traverses the plasma, it splits into a micro-bunch train through the self-modulation instability (SMI) [2] that then resonantly drives strong wakefields in which externally injected electrons can be accelerated to high energies. This unique approach leverages infrastructure already in place at CERN and offers a compelling path towards compact, high-energy particle accelerators for both fundamental physics research and future applications.

The AWAKE experiment has successfully achieved all objectives to date. AWAKE Run 1 (2016–2018)

demonstrated, for the first time, the proton-driven plasma wake-field acceleration concept: in particular, the controlled self-modulation of a long proton bunch in plasma [3–5] and the subsequent acceleration of externally injected electrons to 2 GeV in a 10 m plasma source [6]. Building on these results, AWAKE entered Run 2 in 2021 with a programme extending through Long Shutdown 3 (LS3) up to LS4, aiming at electron acceleration to 4–10 GeV in a 10 m plasma, control of beam quality (normalised emittance in the range 2–30 mm mrad), and demonstration of scalability of the acceleration process [7].

Run 2 consists of four phases: seeding of the proton bunch self-modulation with an electron bunch (Run 2a); use of a plasma density step to freeze the evolution of the modulation and sustain high wakefield amplitudes over the full plasma length (Run 2b). Both phases were successfully completed in 2025 with all milestones achieved [8].

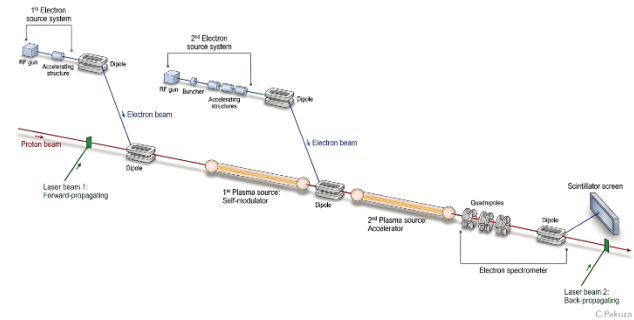


Figure 1: AWAKE Run 2c layout.

To address the goals of the remaining two phases substantial area extensions and facility upgrades are foreseen during LS3: Run 2c will demonstrate electron acceleration with controlled bunch emittance using two plasma sources: a first plasma dedicated to optimising the self-modulation of the proton bunch, and a second plasma for controlled electron acceleration in the resulting wakefields. A second photo-injector and electron beamline providing 150 MeV for injection into the accelerating plasma source, is a key element of this upgrade [9]. Figure 1 shows the AWAKE Run 2c layout. During Run 2d, scalable plasma source technologies extending plasma lengths to the tens-of-metres scale will be implemented. The timeline of the preparation programme for the AWAKE post-LS3 run is shown in Fig. 2. After completing the CNGS target area dismantling in end 2026, Run 2c service and equipment installation takes place in 2027–2028, with commissioning completing before LS3 ends in Q2 2029. Run 2c physics operation with protons begins thereafter.

## CNGS TARGET AREA DISMANTLING

Run 2b concluded its proton beam measurement program on 2 June 2025. Subsequently the AWAKE facility

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was fully dismantled in 2025 to enable nuclear clearing of the former CNGS (CERN Neutrinos to Gran Sasso) target area. This  $\sim 100$  m cavern, currently classified as a limited-stay controlled radiation, needs to be emptied to provide the space required for the upgraded two-plasma-source Run 2c layout. The dismantling commenced in autumn 2025, is proceeding on schedule, and is expected to be completed by October 2026, allowing Run 2c equipment installation to begin as planned.

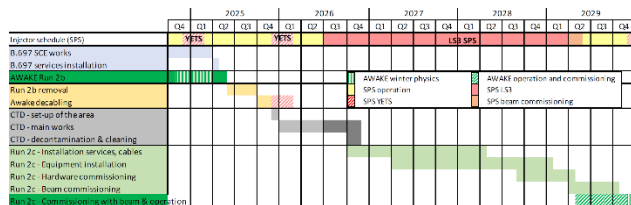


Figure 2: Global planning of CNGS dismantling and Run 2c installation, commissioning and operation [8].

## RUN 2C PREPARATION

The post-LS3 programme Run 2c targets electron acceleration from 150 MeV to 4–10 GeV in 10 m plasma while controlling the beam quality. Achieving this requires a high-quality injected electron bunch, a two-plasma-source layout, and comprehensive infrastructure upgrades. The plasma sources are rubidium vapour sources, as used in the previous runs, and are each about 11 m long and separated by a 30 cm gap, where the 150 MeV electron beam is injected on-axis. In parallel to the design studies, simulations with LCODE, OSIRIS, and HiPACE are performed in order support the experimental designs and to confirm the Run 2 specifications.

### Facility Layout and Integration

The integration studies of the Run 2c experiment (Fig. 3) are well advanced ensuring compatibility between the different subsystems. The beam line layouts are completed, the positions of the beam line elements are well defined, the design and integration of services including vacuum, cooling, access system, EL infrastructure have started.

### Proton and 18 MeV Electron Beam Lines

The 400 GeV proton beamline has been reconfigured to account for the plasma source position being shifted  $\sim 40$  m downstream, making use of existing magnets reorganised to fit the new layout. A key design challenge arises from the dipole magnet in the injection region, which deflects the 150 MeV electron beam and the 400 GeV proton beam in opposite directions. To compensate, a new configuration of the proton line is under study [9], allowing the proton beam to enter the second plasma source on-axis together with the electron and laser beams.

The existing 18 MeV electron beamline, which provides the seed bunch for proton self-modulation, has been redesigned using existing hardware adapted to the new tunnel geometry. Mu-metal shielding is being evaluated along the section approaching the first plasma source to mitigate the

influence of the Earth's magnetic field on the low-energy beam trajectory.

## New 150 MeV Electron Beam System

**150 MeV electron source:** A central hardware upgrade is the new 150 MeV RF photo-injector including a photocathode gun and high-gradient X-band travelling-wave structures at 11.994 GHz. The X-band choice enables compact, high-gradient acceleration to 150 MeV. The mechanical design and brazing concepts are finalised; a first short prototype of an X-band accelerating structure was built at CERN in 2025. The klystron and pulse-modulator turn-key contract was signed in 2025, with delivery scheduled for the 2027–2028 installation phase. A prototype of the new electron source is installed in CERN's CTF2 area and has already been successfully commissioned [10].

**150 MeV electron beamline:** The new 150 MeV beamline transports electrons from the photo-injector exit to the injection point at the entrance of the second plasma source. Beam-quality requirements at the injection waist are very challenging: transverse RMS beam size  $\sigma_r = 5.75 \mu\text{m}$ , normalised emittance  $\epsilon_n = 2 \text{ mm mrad}$ , bunch charge 100–200 pC, and RMS bunch length  $\sigma_z \sim 60 \mu\text{m}$ . These parameters are necessary for strong beam loading, which flattens the wakefield shape and limits emittance growth [7]. The electron beam waist position was shifted 25 cm upstream relative to the original design to maintain the  $\sim 30$  cm plasma gap; a full updated error analysis and active alignment procedure shows that the overall stability and robustness of the configuration can be achieved [9].

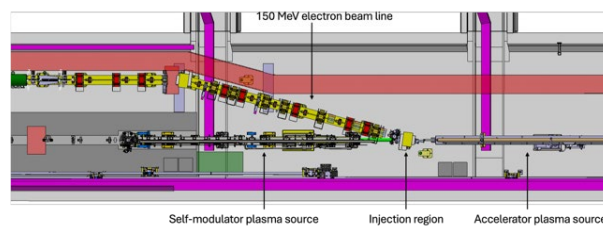


Figure 3: Integration of the new 150 MeV beam line and the two plasma sources in the tunnel area.

### Electron Injection Region

The 150 MeV electron beamline connects to the injection region via a compact expansion volume inserted into the last dipole magnet of the beamline, where the electron beam is made co-linear with the 400 GeV proton beam before both enter the second plasma source on-axis. The chamber is filled with rubidium vapour at  $\sim 220^\circ\text{C}$ , matching the conditions of the accelerating plasma source. This injection region is one of the most challenging areas of the Run 2c design. Keeping the gap between the two plasma sources as short as possible is crucial for achieving high wakefield amplitudes in the accelerating plasma source [11], and with the current design a gap of  $\sim 30$  cm is achieved. The limited available space and the need to merge two high-energy beams of very different energies require several custom-designed components and careful layout optimisation. The layout is being further optimised

to accommodate the diagnostics required to measure the electron beam size at the injection waist, which is essential for validating the injection conditions and ultimately for achieving the Run 2c beam quality goals.

### *LLRF and Synchronisation*

Run 2c requires femtosecond-level synchronisation between the two electron beams, the proton beam, and the ionizing laser pulses. To meet these demanding requirements, ultra-low jitter stabilised optical fibre links will be deployed as the timing distribution backbone. The main AWAKE Menlo laser oscillator is synchronised to the RF master oscillator and serves as the primary timing source for these distribution links. This laser has been relocated to a dedicated laboratory to improve environmental stability and locking reliability. A thorough characterisation of the laser's phase noise and locking performance will be carried out during LS3 to confirm its suitability for this role. The stabilised optical links will be connected to the cavity controllers to ensure stable control of the RF pulses and to key diagnostic equipment. One of these diagnostics is a high-bandwidth beam arrival monitor (BAM), designed around an existing beam position monitor (BPM) and to be validated at CLEAR/CTF2. The BAM provides real-time measurement of the arrival time of each electron beam relative to the other beam and the ionizing laser pulse. It is therefore a critical diagnostic for maintaining synchronisation throughout Run 2c operation.

### *Laser Beamlines*

The upgraded Run 2c facility requires precise spatio-temporal delivery of four laser beams. Two UV pulses drive electron production in the RF photo-injector guns; their relative timing jitter must be kept well below 20 fs. To minimise this jitter, a single UV source feeds both guns via a partial reflector, ensuring precise synchronization at the injection point. The UV system has demonstrated stable production of 700 pC electron bunches under continuous 24/7 conditions at CTF2; planned upgrades include image-relay systems, UV spatial shaping, and a pulse stretcher for bunch-duration optimization.

To produce the plasma columns, a TW-class Ti:sapphire laser is split into two arms, each delivering 120 fs, 150 mJ pulses for efficient Rb vapor ionization. A distinctive feature of Run 2c is that these IR pulses enter their respective vapour sources in a counter-propagating geometry. Since the vapour sources are located several tens of metres downstream of the laser room, a vacuum relay imaging system will transport the IR pulses over ~90 m using high-reflectivity mirrors and low-loss relay optics. To avoid optical non-linearities, the relay systems operate with stretched pulses; vacuum pulse compressors in the source area will recompress them to ~120 fs for rubidium ionization. Auto-aligned transport and delivery lines, vacuum sections, and diagnostic systems are under design, with attention to integration, vacuum compatibility, and long-term alignment stability.

### *Beam Instrumentation*

Run 2c requires a comprehensive new and upgraded diagnostics for the 150 MeV beamline, the existing electron and proton lines, and characterisation of the accelerated beam downstream of the plasma sources. Most diagnostic locations have been defined, and production is being launched. The 150 MeV electron line will be equipped with electro-optic spectral interferometry (EOSI) bunch-length monitors and the 18 MeV beam line with a coherent Cherenkov diffraction radiation (ChDR) monitor, both systems validated at CLEAR in 2025 and providing sub-picosecond longitudinal resolution. Transverse profile and emittance measurements will be performed using optical transition radiation (OTR) screens and optical synchrotron radiation (OSR) extraction ports. The existing proton button BPMs and electron stripline BPMs on both electron lines are being upgraded with RFSoc-based front-end electronics developed for the HL-LHC, offering position resolution at the 10s of  $\mu\text{m}$  level while reducing production and maintenance demands. A specialised Cherenkov-based pick-up is under development to measure the electron bunch position in the presence of the co-propagating proton bunch in the common 18 MeV – proton beamline upstream of the first plasma source, exploiting time discrimination between the two beam species. Downstream of the second plasma source a spectrometer consisting of a quadrupole triplet (24 T/m, magnetic length ~3 m per magnet) followed by a dipole (3.66 Tm) measures the accelerated electron energy up to at least 10 GeV. Emittance is determined via the butterfly method on the spectrometer screen, with an independent cross-check available through OSR extraction.

### *Scalable Plasma Sources*

In parallel, R&D continues on two scalable plasma source technologies for Run 2d, the Helicon Plasma Source (HPS) and the Discharge Plasma Source (DPS), both scalable to tens of meters. The central challenge is achieving the required 0.25% plasma density uniformity; current measurements yield  $\pm 11\%$  over 50 cm (HPS) and  $\pm 6\%$  over 3 m (DPS), presently limited by diagnostic precision. A 12 m DPS from four 3 m segments is under construction.

## CONCLUSION

The AWAKE programme is progressing well towards its next major milestone. Run 2b was completed successfully in 2025. Dismantling of the CNGS target area is under way and on schedule for completion in October 2026. The key hardware elements of Run 2c are all in advanced stages of design or procurement. AWAKE is on track to install and commission the new facility during LS3 and to begin Run 2c physics operation in 2029. Once the goals of Run 2c and Run 2d have been demonstrated, AWAKE will be ready to propose first particle physics applications.

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