BEAM INSTRUMENTATION FOR AWAKE FROM RUN 2B TO RUN 2C

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Abstract

The AWAKE experiment at CERN is a proof-of-principle facility that uses proton-driven plasma wakefields to accelerate externally injected electrons. Since initial operations in 2016, multiple experimental phases have been completed, with the most recent being Run 2b. Beam diagnostics played a crucial role during this phase, enabling reliable operation and characterisation of the particle beams. The next phase, Run 2c, planned to begin in 2029, will introduce a second electron beamline delivering 150 MeV, 200 fs (RMS)-long electron bunches together with a second plasma. The increased experimental scale and the new measurement requirements impose new demands on beam instrumentation, requiring upgrades to existing systems and the development of new, specialised diagnostics. This contribution presents a non-exhaustive overview of the diagnostic systems used during Run 2b, describes the planned upgrades and developments for Run 2c, and discusses the associated integration challenges.

INTRODUCTION

Following the successful completion of Run 2b in 2025 [1] [2] [3], the AWAKE facility at CERN is undergoing a major upgrade to enable the next stage of proton-driven plasma wakefield acceleration studies. The experiment was originally installed in the TCC4 experimental area in front of the former CERN Neutrinos to Gran Sasso (CNGS) target wall [4]. To accommodate the expanded beamline configuration required for the upcoming phase, the facility is being relocated downstream by ~40 m. This relocation necessitates dismantling of the former CNGS infrastructure, after which the upgraded experiment will be installed in stages, with commissioning planned for 2028 and first proton beam operations expected in 2029 [5].

The next operational phase, Run 2c, will involve a two-plasma configuration, as shown schematically in Fig. 1. A second electron beamline [6] will be added, delivering higher-energy and shorter electron bunches (150 MeV, 200 fs RMS) compared to the existing 18 MeV injector (1–4 ps RMS). In the Run 2c baseline configuration, self-modulation (SM) of the SPS proton bunch will continue to be seeded using the relativistic ionisation front (RIF) of the ionising laser pulse, as successfully demonstrated in previous runs [7]. The lower-energy electron beam will continue to support studies of electron-beam seeding [8] and alignment tolerances, while the higher-energy beam will serve as the witness beam for acceleration studies in the second plasma.

The expanded experimental layout, together with the introduction of additional beamlines and plasma sources, significantly increases the demands placed on beam instrumentation. During Run 2b, beam diagnostics played a central role in enabling reliable operation and detailed characterisation of beam parameters, including transverse beam profile measurements using screen-based diagnostics. For Run 2c, these systems must be extended, upgraded, and complemented with specialised diagnostics capable of, for example, resolving ultrashort electron bunches and supporting precise alignment of the laser and multiple particle beams, the parameters of which are detailed in Table 1, across a larger experimental footprint.

Table 1: Beam parameters at injection for AWAKE Run 2c.

Parameter	Nominal	Range
Proton Beam		
Energy	400 GeV	390–410 GeV
Bunch length (RMS)	85 ps	80–340 ps
Beam radius at waist (RMS)	200 µm	150–220 µm
Charge per bunch	48 nC	8–64 nC
18 MeV Electron Beam		
Energy	18 MeV	–
Energy spread (RMS)	0.2%	–
Bunch length (RMS)	2.1 ps	1–4 ps
Beam radius at waist (RMS)	200 µm	150–220 µm
Normalised emittance	2 mm mrad	–
Charge per bunch	–	100–600 pC
150 MeV Electron Beam		
Energy	150 MeV	–
Energy spread (RMS)	0.2%	–
Bunch length (RMS)	200 fs	200–300 fs
Beam radius at waist (RMS)	5.75 µm	5–10 µm
Normalised emittance	2 mm mrad	–
Charge per bunch	100 pC	100–400 pC

BEAM POSITION MEASUREMENTS

During Run 2b, proton beam position measurements were performed using 21 dual-plane button beam position monitors (BPMs) distributed along the ~800 m-long TT41 transfer line between SPS extraction and the AWAKE experimental area. These BPMs have a 60 mm aperture, matching

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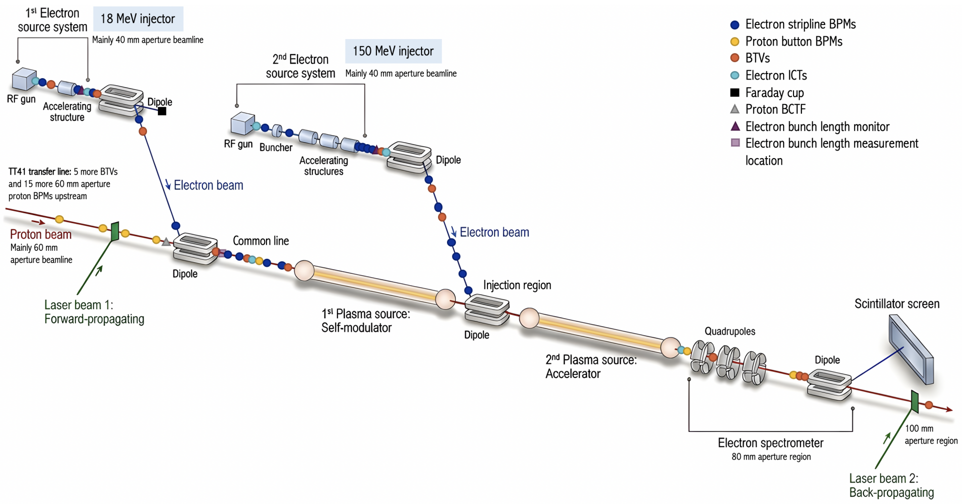

Figure 1: Schematic layout of the AWAKE Run 2c experimental configuration showing the proton beamline, electron injectors, plasma stages, and their associated beam diagnostics.

the majority of the beam pipe aperture along this line. The Run 2b proton BPM system is described in detail in [9]. For Run 2c, all 21 existing proton BPMs will be reused, with the final seven units relocated to accommodate the updated layout. One experimental requirement is to maximise the distance between the final two proton BPMs upstream of the first plasma source, where no magnetic elements for the proton beam are present, to improve pointing accuracy at injection. A similar requirement applies downstream of the second plasma source, where two proton BPMs will be installed with maximised spacing between them. The first of these two BPMs, which is also the last of the standard 60 mm aperture proton BPMs, will be installed immediately downstream of the second plasma source. The beam pipe aperture then increases to 80 mm at the entrance to the first spectrometer quadrupole and remains at this aperture along the line until the end of the spectrometer dipole where it then increases to 100 mm to accommodate the larger proton beam size expected at this location. The second BPM, placed just upstream of the spectrometer dipole, will therefore require a larger-aperture unit. An 80 mm aperture button BPM developed for the High-Luminosity LHC (HL-LHC) (BPTQX type) [10] will be used here.

For the 18 MeV electron beam, position measurements in Run 2b were performed using shorted stripline BPMs and electronics developed by TRIUMF for AWAKE, based on a design used in their electron linac [11]. The flange-to-flange length of the BPMs is 207 mm. The corrector magnets are installed around the BPM bodies, forming combined BPM–corrector assemblies with the BPM feedthroughs located outside the magnets. Seven 40 mm aperture BPMs were installed in the electron line and five 60 mm aperture BPMs in the common line [12]. For Run 2c, five of the existing 40 mm BPMs will be reused in the 18 MeV line and four of the 60 mm BPMs will be used in the common line.

The 150 MeV beamline requires new BPMs which are based on the TRIUMF stripline design, with an overall length of 307 mm chosen to accommodate the longer corrector lengths of the higher-energy electron line while retaining the same geometry of the active parts. Eleven 40 mm aperture BPMs will be installed along the beamline, of which three will incorporate integrated bellows and have an intermediate total length of ~260 mm to accommodate spatial constraints in the source and injection regions. One additional 60 mm, 307 mm-long BPM will be installed in the dogleg to accommodate the larger beam size at that location.

For Run 2c, all BPM systems described above will use the RF System-on-Chip (RFSoC)-based front-end electronics developed for the HL-LHC upgrade, discussed in detail in [13], allowing standardisation across CERN. Subcomponent tests of the prototype indicate position resolutions of approximately 20 µm for the proton BPMs, 30 µm for 100 pC electron bunches and 15 µm for charges above 200 pC for the 40 mm stripline BPMs, and 40 µm for 100 pC and 20 µm for charges above 200 pC for the 60 mm stripline BPMs. Full system testing is planned to refine these estimates.

BEAM TRANSVERSE PROFILE MEASUREMENTS

Transverse beam profile measurements in AWAKE are performed using Beam Television (BTV) systems. A BTV consists of a screen inserted into the beam path that produces visible light either through scintillation (e.g. YAG or Chromox) or optical transition radiation (OTR) from, for example, metal-coated wafers such as silver-coated silicon (SiAg) which is prompt providing also arrival time information. The emitted light is recorded using a camera, typically through a viewport and filter wheel, allowing direct imaging of the transverse beam profile at the measurement location.

During Run 2b, a total of six BTV systems provided transverse profile measurements for the proton, electron and laser beams [9]. These do not include the additional five BTVs located upstream the TT41 transfer line. Two BTVs were installed in the 18 MeV electron line and were inherited from CTF, equipped with both YAG and SiAg screens mounted on linear stages with horizontal insertion. These systems, which have a 40 mm aperture, also incorporate replacement chambers. The remaining four BTVs were installed in the common line, with two located upstream of the plasma source and two downstream. The upstream systems (LHC Maltese cross-type rotational BTVs with 60 mm aperture) were primarily used for beam alignment prior to plasma entrance, while the downstream systems (LHC and SPS Maltese cross-type) were additionally used for monitoring the proton beam halo [14], the observation of which indicates the occurrence of proton bunch SM in the plasma.

In Run 2c, the five BTVs located in the TT41 transfer line will remain largely unchanged, with only the last unit relocated downstream. At the experiment, the two linear BTVs from Run 2b will be redistributed between the 18 MeV and 150 MeV electron lines and installed upstream of the first dipole in each line, allowing both lines to be equipped with a multi-screen BTV and enabling optional bunch length measurements using a streak camera coupled to the OTR screen. These BTVs will also be used for emittance measurements with quadrupole scans.

New BTVs are being developed for the four additional BTVs required in the electron lines in Run 2c, where the locations are shown in Fig. 1. The BTV located just after the first dipole in each electron line is primarily for energy and energy spread measurements. The new BTVs, originally foreseen only for the electron lines, had an initial design with 40 mm aperture and a single YAG screen mounted on a magnetically-coupled linear actuator. The actuator inserts the screen vertically into the beam path from above, allowing the emitted light to be directed into the horizontally mounted imaging system. The screen is oriented such that its tilt axis is parallel to the 150 MeV beam's larger vertical dimension, mitigating depth-of-field limitations. Due to the limited space available in the 150 MeV line, these BTVs also allow the option of mounting a vacuum pump beneath the chamber. In the common line upstream of the first plasma source, three BTVs are required for multi-beam alignment and optics validation. Downstream of the second plasma source, four BTVs are required in the spectrometer region: one between the first two spectrometer quadrupoles for multi-beam alignment, two just upstream of the spectrometer dipole for alignment and halo monitoring (where the latter requires a central hole in the screen to allow transmission of the back-propagating laser), and a final BTV downstream of the laser merge point also for halo monitoring without the need for a hole in the screen. The rotational BTVs were initially considered to be reused in the common line upstream of the first plasma source. Following recent laboratory tests which demonstrated better performance of the linear system, it is now being investigated to adapt the 40 mm aperture design to 60 mm for this region, and 80 mm and 100 mm aperture for the BTVs downstream of the second plasma source. To meet the requirement for multi-beam measurements, a multi-screen design incorporating three-positions (two screens and a screen-out position) is under investigation to replace the initial single-screen design.

BUNCH CHARGE AND LENGTH MEASUREMENTS

In Run 2b, interceptive bunch charge measurements in the 18 MeV electron line were performed using a Faraday cup (FC) [15], while a commercial integrated current transformer (ICT) was installed before the spectrometer dipole to provide online electron bunch charge measurements and for charge calibration of the electron spectrometer [16]. For Run 2c, the FC will be reused and installed in a short straight section following the first dipole in the 18 MeV line. In addition, new ICTs are required at the source and downstream of the accelerating structures in both electron lines. In the common line, ICTs are required upstream of the first plasma source and downstream of the second plasma source. An additional ICT will be installed at the injection region, where space is limited, for use during commissioning only. For the proton bunches, the baseline is to reuse the fast beam current transformer (BCTF) from Run 2b.

Bunch length measurements in Run 2c will be performed using a Cherenkov diffraction radiation (ChDR)-based monitor and an electro-optic spectral interferometry (EOSI) system, both under development by teams at the University of Manchester [17, 18]. The ChDR monitor will be moved between two locations in the 18 MeV and common line, as shown in Fig. 1, with its final location to be determined based on bunch length stability measurements during commissioning. The EOSI system will be installed just before the first dipole in the 150 MeV line. Both systems provide single-shot, non-interceptive bunch length measurements. However, EOSI is selected for the 150 MeV line due to the more constrained layout and its more compact implementation. It is also preferred over conventional interceptive OTR screen and streak camera measurements, as it is expected to be capable of resolving bunch lengths of order 200 fs and distinguishing variations at the 10% level as required for Run 2c.

CONCLUSION

The transition from AWAKE Run 2b to Run 2c requires significant developments in beam instrumentation to support the expanded experimental layout and more demanding measurement requirements. Existing systems are being reused where possible, while new diagnostics are under development to enable measurements of ultrashort electron bunches and multi-beam alignment across the facility. These upgrades will be essential for the successful operation of the Run 2c configuration.

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