AWAKE status report

AWAKE Collaboration

CERN-SPSC-2021-029 / SPSC-SR-299
04/10/2021

October 2021

Contents

1 Executive summary

2021 has seen the start of Run 2 of AWAKE. After an intense two-year preparation for this second run of AWAKE, first data taking started in July this year. The initial program of Run 2 has as focus the study of the seeding of the self-modulation process with an electron bunch that precedes the proton bunch. Should this be successful, the full proton bunch will become available for generating plasma wakefields and a possible competition between phase-unstable modulation in the leading part of the proton bunch and the modulated section in downstream plasma cells can be avoided. Initial results from data acquired this summer look very promising in this regard, as phase stability has been demonstrated at low plasma density. Systematic investigations of the parameter dependence has now begun. This initial run uses essentially the unchanged configuration developed for Run 1.

The studies for the further running periods of Run 2 have been a major focus of a bulk of the collaboration. A prototype of the electrically heated section of the plasma cell foreseen for Run 2b was successfully tested and we are now proceeding with plans to procure the new plasma cell. The new plasma cell will allow for a step (or gradient) in the plasma density, which simulations indicate will allow to freeze the microbunch evolution. The new plasma cell is foreseen to be installed in the winter break 2022-2023. Run 2c and beyond will require the installation of a new electron injection system that will allow the injection, trapping and acceleration of a bunch of electrons with resulting emittance that will be sufficient for particle physics experiments. An extension of the available laboratory space will be required and a detailed initial planning for clearing the CNGS area for this purpose has been developed. Accelerating electron bunches in the future over long distances will require new plasma cell technologies. Two schemes are currently under study in AWAKE for this purpose (discharge cell and helicon cell) and new results are available on this front.

The requirements for Run 2c and beyond will require major modifications of the AWAKE experimental area as well as significant investments in new systems such as a new electron bunch injection system. CERN has scheduled a Cost-and-Schedule-Review (CSR) on November 18 2021 to review these aspects. The Collaboration is intensively preparing for this important review as the outcome will determine the future program of AWAKE.

We hereby request support from the SPSC for a 15 week running period next year to complete the experimental program planned for Run 2a. We understand that this should be feasible given the extended running period of the CERN accelerators planned for 2022.

2 Run 1 results

Since the last report to the SPSC, the AWAKE Collaboration has completed and published several additional studies on Run 1 data (see [1] for a full list of AWAKE publications). These are:

2.1 Plasma wakefield dynamics using injected electrons

Plasma wakefield dynamics over timescales up to 800 ps, approximately 100 plasma periods, were studied using Run 1 data. The development of the longitudinal wakefield amplitude driven by a self-modulated proton bunch was measured using the external injection of witness electrons that sample the fields. In simulation, resonant excitation of the wakefield causes plasma electron trajectory crossing, resulting in the development of a potential outside the plasma boundary as electrons are transversely ejected. Trends consistent with the presence of this potential were experimentally measured and their dependence on wakefield amplitude were studied via seed laser timing scans and electron injection delay scans. The results were published in PRAB [2] and preliminary results were discussed in the previous report to the SPSC committee.

2.2 Transition to phase-stable wakefields

Phase reproducibility is essential for deterministic external injection of particles to be accelerated. The timing of the laser ionization front relative to the center of the proton bunch was changed in Run 1 to provide various initial transverse wakefield amplitudes for the self-modulation. We showed experimentally that, with sufficient initial amplitude, the phase of the modulation along the bunch is reproducible from event to event, with < 7 % rms variations all along the bunch. The uncertainty in these measurements was dominated by measurement uncertainties. The main results are shown in Fig. 1, where the transition from phase stable modulation (SSM) to random phase behavior (SMI) is clearly seen. The analysis allowed to determine the seeding parameters of a relativistic ionization front that are necessary to realize the SSM regime. The results were published in PRL [3].

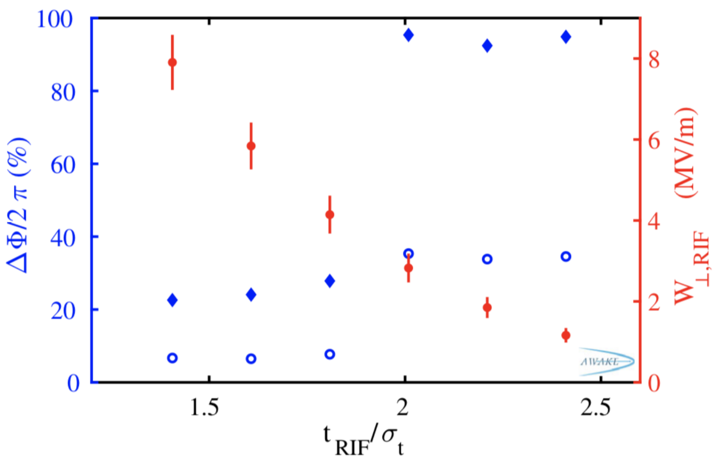

Fig. 1: Measured rms (blue circles) and full range (blue diamond), and initial linear transverse wakefield amplitude (filled red circles) as a function of the timing of the ionization front $t_{\rm RIF}$ normalized to one standard deviation of the proton bunch. The error bars indicate the statistical uncertainty of 10 %.

2.3 Comparison of Simulation and Experimental Data for Density Gradients

Numerical simulations were compared to experimental data with linear density gradients along the beam path. Simulation results agree with the experimental results reported previously with negative gradients, including charge loss for negative gradients and a modulation frequency that depends on the gradient. Simulation results show that dephasing of the wakefields with respect to the protons along the plasma is the main cause for the loss of charge. The study of the modulation frequency reveals details about the evolution of the self-modulation process along the plasma. In particular for negative gradients, the modulation frequency across time-resolved images of the bunch indicates the position along the plasma where protons leave the wakefields. Simulations and experimental results are in excellent agreement. As an example, a comparison of the observed modulation frequency as a function of the plasma density gradient is shown in Fig. 2. The results are accepted for publication in PRAB [4].

2.4 Incoming Proton Bunch Parameter Study

Previous studies have shown that a precise characterization of the incoming proton bunch parameters is required to accurately simulate the self-modulation process. A detailed analysis of the parameters of the incoming proton bunches used in the later stages of theAWAKE Run 1 data-taking period was therefore carried out. The transverse structure of the bunch was observed at multiple positions along the beamline using beam observing systems with scintillating or Optical Transition Radiation (OTR) radiation screens. The parameters of a model that describes the bunch transverse dimensions and divergence were fitted to

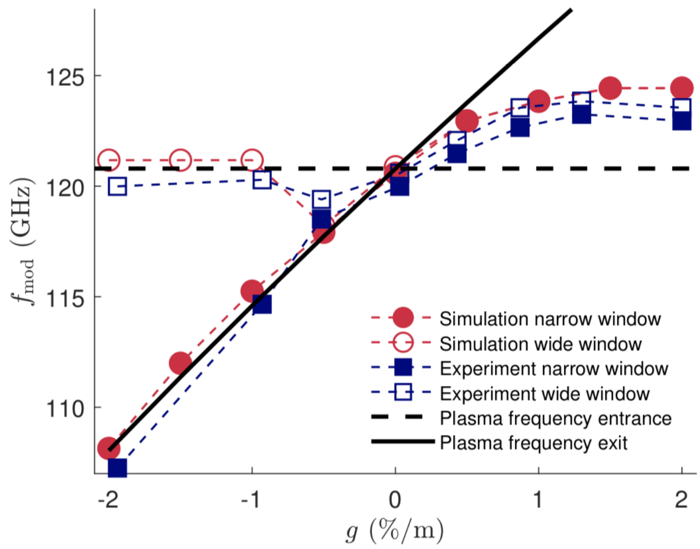

Fig. 2: The observed modulation frequency, f_{mod}, as a function of the plasma density gradient, g, after propagating 10 m in plasma and 3.5 m in vacuum using two different regions for the DFT analysis of time-resolved images, for both simulations (red symbols) and experiment (blue symbols). Black lines: plasma frequencies at plasma entrance f_{pe} (dashed) and exit f_{pe} (continuous).

represent the observed data using Bayesian inference. It was found that in this running period, the proton bunch was significantly more compact than previously assumed, and that it was not possible to describe the transverse bunch shape with a single Gauss function, and a sum of two Gauss functions was used to provide a good representation of the data. Figure 3 gives the extracted transverse bunch sizes and emittances extracted from the data. The results are nearing submission to PRAB [5].

2.5 Summary

We anticipate that, with these publications, the analysis of Run 1 data is largely complete.

3 Overall plans for AWAKE Run 2

The main goals of AWAKE Run 2 [6, 7] are:

- Accelerate an electron bunch to high energy with sustained accelerating gradients of $0.5-1$ GV/m.
- Preserve the electron bunch quality, preserving the emittance at the 10 mm mrad level.
- Demonstrate a scalable plasma source technology.

The layout of the final AWAKE Run 2 set-up in order to achieve these goals is shown in Fig. 4, with several new key features, such as two plasma cells and a new high-energy longitudinally compact electron witness bunch. The final set-up will be significantly longer than in AWAKE Run 1 and so will require the CNGS target area to be cleared and so AWAKE will extend into this area.

In order to achieve these, AWAKE Run 2 program is split into several parts which also take into account the development time of new systems, clearing of the CNGS target area and the schedule of the SPS.

- Demonstration of electron-seeded self-modulation (Run 2a, 2021–22).
- Demonstration of maintaining high and stable accelerating gradients in a plasma source with a controlled density profile (Run 2b, 2023–24).

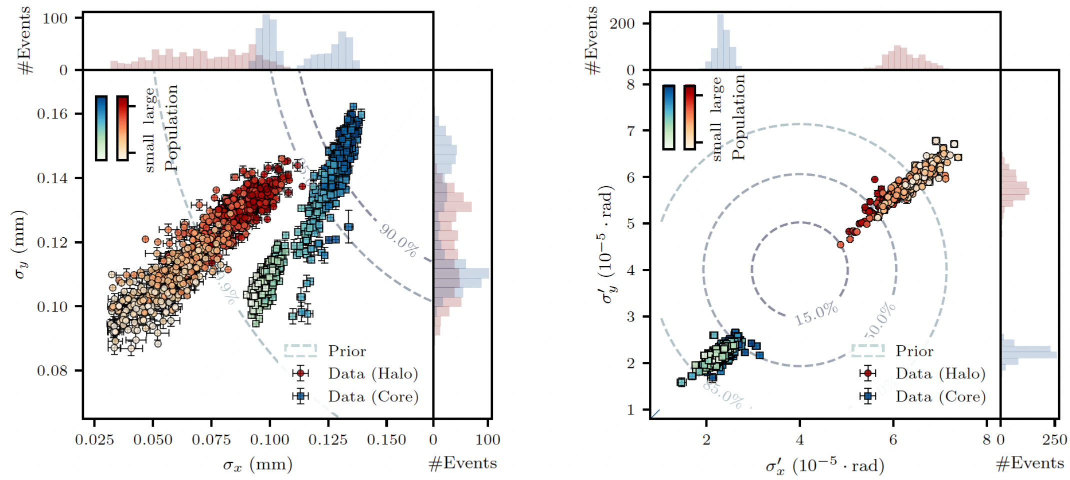

Fig. 3: Left panel: The transverse size of the proton bunch at the waist position is shown using a double Gaussian model. Each event is represented by two symbols that show the halo and core components. Darker colors correspond to a larger bunch population. Right panel: The x and y components of the angular spread of the proton bunch are shown for different bunch populations using a double Gaussian model. Each event is represented by two symbols that show the halo and core components. Darker colors correspond to a larger bunch population.

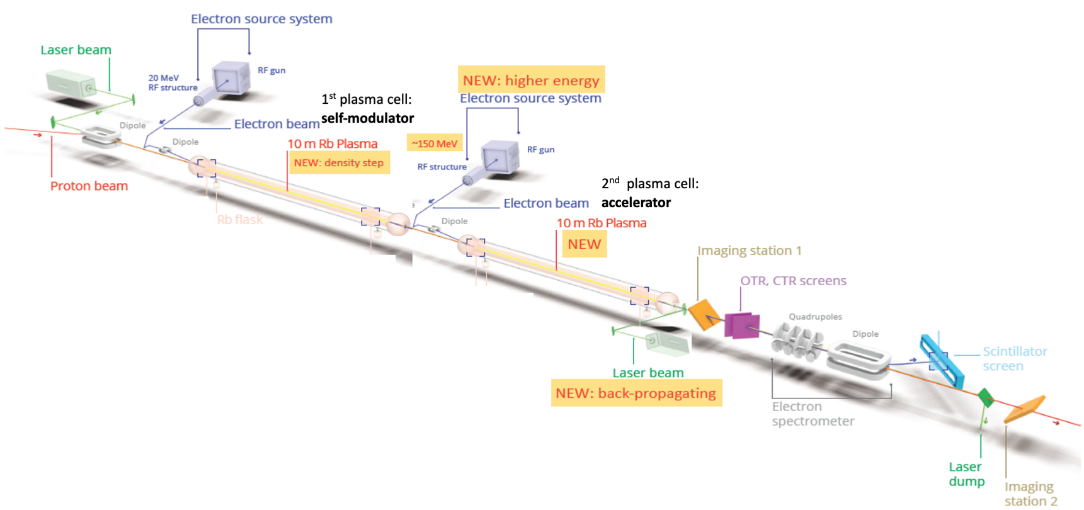

Fig. 4: Layout of the AWAKE Run 2 set-up.

– Acceleration of short electron bunch to high energies with sustained accelerating gradients of $0.5 - 1\,\text{GV/m}$ (Run 2c, 2027–).
– Demonstration of scalable plasma sources (Run 2d, 2028–).

Investigations of seeding the self-modulation with an electron bunch have already successfully started and will be discussed in more detail in Section 4. This will be followed by a discussion of planning for the subsequent parts of AWAKE Run 2.

By the end of Run 2, the AWAKE scheme should be sufficiently developed such that it can be considered for certain particle physics experiments requiring a high energy electron beam.

The AWAKE Run 2 programme and plans will be discussed in a Cost and Schedule review in November 2021.

4 Run 2a

The primary goal of Run 2a is to study the electron bunch seeding of the proton bunch. Additional important goals are the determination of whether the light intensity from the plasma can be used as a probe of the strength of the plasma wakefields and to test whether Cerenkov diffraction radiation can be used to simultaneously make beam position measurements of the electron and proton bunches. We are also studying whether ionization of the plasma can be achieved with off-resonance ionization as this could give us the ability to ionize the Rb over a large radius and over longer distances. The setup of Run 2a is largely identical to that of Run 1. Major modifications are foreseen for the later phases of Run 2.

4.1 Preliminaries

During CERN's Long Shutdown 2 a huge effort was carried out in advance of the start of Run 2 to recommission the experimental setup while also making significant improvements to a number of systems. In particular, detailed studies were performed on the electron system to better understand the electron guiding and bunch parameters. The diagnostic systems (beamline screens, optical light transport systems, new cameras for the light measurement, etc.) were overhauled and the DAQ systems were significantly improved. A significant number of new collaboration members are carrying Run 2, and they used this commissioning and upgrade period to become familiar with the AWAKE systems. These efforts paid off: the running period started very smoothly and very important new data has been collected.

4.2 Highlights to-date from Run 2a

Run 2a started on July 22, with the first running period extending to August 3rd. The second running period was from August 23rd to September 12th. A third run period in 2021 will take place from October 11th to October 25th.

The initial tasks consisted of synchronizing the different beams used in the experimental setup (proton, electron, ionizing laser, marker laser) and aligning the proton and electron beams to each other and to the ionizing laser channel. A number of technical issues needed to be addressed, including timing jitter of the proton bunch. After restoring the conditions seen in Run 1, the program of studying seeding of the modulations with electron bunches rather than the laser started.

The first results from seeding the proton bunch modulation process with the existing low-energy electron bunch look very encouraging! Figure 5 shows streak camera images taken with a 70 ps time range of the proton microbunches. The plasma density for this data was set to $1 \cdot 10^{14}$ cm^{-3}, the average proton bunch population was $1 \cdot 10^{11}$ protons, and the electron bunch had a charge of 150 pC. The electron bunch was positioned just in front of the proton bunch, and the result was the observation of well-spaced microbunches. It is seen that the microbunch positions line up very well from event to event for this series of events. The summed image from the events is shown in the right panel, and shows very little smearing of the bunch structure, indicating excellent phase stability. The analysis of these data has just started, but initial indications are that the phase stability is comparable to that seen with laser ionization front seeding.

These initial measurements were followed with the start of a systematic evaluation of the dependence of the stability of the seeding on the parameters of relevant quantities: the electron bunch charge, the proton bunch charge and the plasma density. This multiparameter study will be the main focus of the remaining running periods foreseen for 2021.

A further initial result from Run 2a is the observation of light variations from the plasma depending on various operational parameters. The results are still quite preliminary, but a dependence on parameters such as the location along the proton bunch where the seeding was performed indicate that the plasma light measurement could indeed be a useful diagnostic of field strengths.

Hosing studies have also started, and it was seen that the hosing could be seeded with the electron bunch by displacing the electron bunch transversely relative to the proton bunch. The ability to seed the hosing will allow us to study this effect in detail in further running periods.

While the run started as well as could be hoped, the alignment of the electron beam onto the proton beam clearly became the biggest issue to resolve for future running, as the current procedure is not fully reliable and is time consuming. This situation was foreseen, and the installation of a screen in the expansion volume has been planned for Run 2, which is planned to occur before the next running periods.

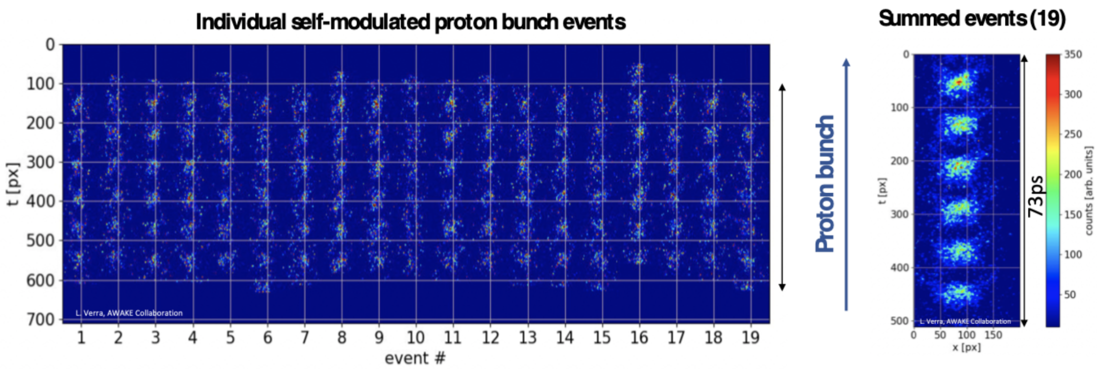

Fig. 5: Left: streak camera images from 19 consecutive events. Right: summed images from the 19 events.

5 Status of Runs 2b–2d

5.1 Run 2b plans

The major change to the AWAKE set-up for Run 2b is the delivery of a new rubidium vapour plasma source which can provide a step in the density profile and so freeze the accelerating gradients at a constant value in the region of $0.5 - 1$ GV/m. The new plasma source will replace the current source developed for Run 1. From an integration aspect, this new source will be located at the same place and have the same dimensions and require the same services.

Specifically, the plasma source for Run 2b has the following properties, with a schematic shown in Fig. 6. The source will be about 10 m in length with a 6 m section heated by galden and 50 cm independent electrical heaters from 0.5 to 4 m. This will permit a step height in the density of up to $\pm 10\%$. Three diagnostic viewports will be included along source.

A heatpipe prototype is installed at CERN in a test area in the North Hall and tests performed with temperature steps between 5°C and 50°C and density steps from 1% to 10%. The steps (ramps) have been shown to be reproducible and controllable.

As this new plasma source will effectively replace the plasma source from Run 1, the experimental set-up in Run 2b will be similar to that in Run 1. Further electron acceleration experiments can then be performed with this new source in order to sample the increased, stable gradients.

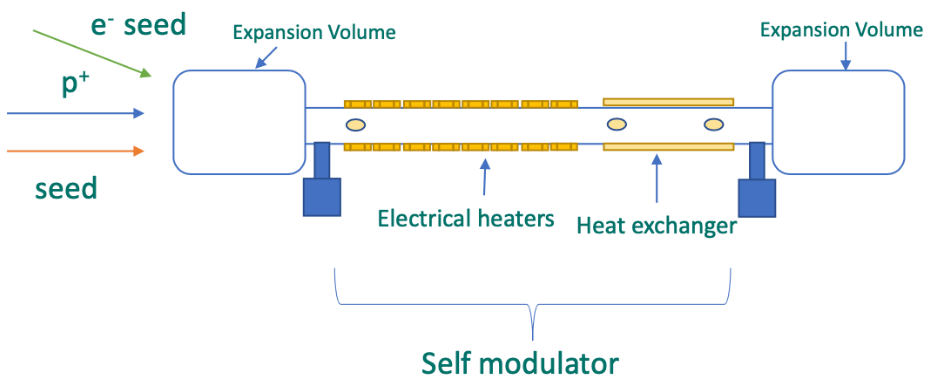

Fig. 6: Schematic of the rubidium vapour plasma source under development for Run 2b.

5.2 Clearing of CNGS target area

Given the extended length of AWAKE Run 2 compared to Run 1 and that during Run 1 the instrumentation extended up to the wall separating the experimental area from the CNGS target area, the wall needs to be removed and the old CNGS target, horns, and associated infrastructure needs to be cleared and cleaned. This needs to be done carefully as it is a highly radioactive area. A pre-study has been performed to assess the cost and schedule of clearing the CNGS target area. This has been presented to the Accelerator and Technology Sector Management Board (ATSMB) in June 2021.

The clearing of the CNGS target area has been estimated to take 18 months require about 15 FTE in personnel and cost about 10 MCHF. The dismantling and clearing will take place after Runs 2a and 2b, during LS3, and before Run 2c. The ATSMB recognise that this work is necessary for AWAKE to carry out Run 2c and beyond. They also believe the cost and schedule to be well estimated and that this should be treated as a separate project and not part of AWAKE Run 2. As such, it will be shown in the AWAKE Cost and Schedule Review for information, but not approval which will be handled separately.

5.3 Plans for Runs 2c

The layout for Run 2c is shown in Fig. 4 in which an accelerator plasma source is added in addition to the modulation source developed for Run 2b. For the rubidium plasma source a new back-propagating laser line will be installed. A high-energy (about 150 MeV) electron source with short pulses (about 200–300 fs) will be installed and the electrons injected into the second plasma source.

The design, integration and parameter optimisation for the electron injector are progressing as planned with a solid baseline. To complement the designs, a prototype electron injector has been installed in CTF2.

Diagnostic systems are under development to be able to fully characterise the beams in electron acceleration experiments. New electron beam position monitors are being developed which can measure the electron beam position in the common line, i.e., in the presence of the (more intense) proton bunch, before the plasma source. The beam position monitor is based on measuring Cherenkov radiation generated in a dielectric as the electron beam passes close to it. Extensive simulations and studies have been performed, with a prototype being built and to be tested in the CLEAR beamline. The prototype can then be installed in AWAKE during Run 2a or 2b for testing.

The position could also be measured by a screen placed at the start of the rubidium plasma cell. Such a screen could also be used to measure the transverse profile of the beam. Tests of screens in rubidium vapour are ongoing with measurements at CLEAR. To complement this, a digital micro-mirror device (DMD) could be used to distinguish the light from the proton bunch from the light from the electron bunch. This is proposed to be used for electron bunch emittance measurements. A prototype

DMD system has been installed in AWAKE for tests to be done this year.

Diagnostics to measure the electron bunch length are also under development based on coherent transition radiation, Cherenkov diffraction radiation and electro-optical sampling. Various tests at CLEAR and MAX IV have been undertaken and with the different methods, we are confident that this quantity will be well understood in Run 2c.

The magnetic electron spectrometer to measure the accelerated electron bunch is being upgraded from a single iCCD camera placed 17 m away from the scintillator screen to an array of mutliple CCD cameras 1.5 m away. A test system of 4 cameras is currently installed in AWAKE, along with the Run 1 system (for redundancy and cross calibration), for testing. The multi-camera system should give significantly improved resolution and so the possibility to measure the emittance of accelerated electron bunches, as well as the energy distribution, in Run 2.

5.4 Plans for Runs 2d

One of the primary goals of AWAKE Run 2 is the development of a plasma source that is scalable to long lengths, in principle kilometres in length. Although the rubidium vapour source has been a very successful technology for AWAKE, due to the use of a high-power laser to ionize the rubidium, its use is limited to 10s of metres. Therefore two other technologies are being considered to reach the longer distance scales, a helicon source and a discharge source.

A 1 m helicon prototype plasma source is available in the CERN plasma lab. Recent development has focused on a Thomson scattering diagnostic to measure the plasma density with the goal of performing measurements of sufficient precision at the nominal AWAKE plasma density of 7×10^{14} cm^{-3}. Preliminary and first measurements taken in July show a plasma density of $(1.7 \pm 0.5) \times 10^{14}$ cm^{-3}, where the uncertainty will be improved with more data and better calibration. Work continues on achieving the higher plasma density needed at AWAKE.

Prototype discharge sources of up to 5 m in length are in operation in test laboratories and their properties under study. The ignition and heating is being tested in a 1.6 m prototype at the CERN plasma lab and a 5 m prototype at IST. The discharge and heating is imaged using a fast camera at timescales of $O(10\,\mu\text{s})$. The operation of double plasma set-up of two sources (2 m and 5 m) with a common cathode has been demonstrated. This suggests that scalability is viable. A double plasma set-up with two 5 m sources is planned which could potentially be used in the AWAKE experiment later in Run 2.

6 Running Plan 2022

The overall running schedule for AWAKE is shown in Fig. 7. As seen in the figure, Run 2a is intended to be completed in 2022, after which the plasma cell will be exchanged with a new cell that will allow for a plasma density variation along the length of the cell. To realize the full program foreseen for Run 2a, we will need substantial running time with the SPS proton beam in 2022. Given the extended running time foreseen for the CERN accelerator complex next year, we would therefore request a total of 15 weeks of running (three weeks in addition to our nominal 12 week request).

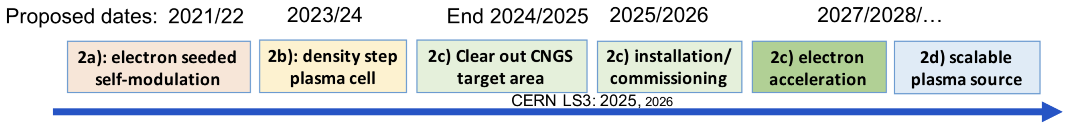

Fig. 7: The planned running periods for AWAKE Run 2.

References

[1] https://twiki.cern.ch/twiki/bin/view/AWAKE/AwakePublic

[2] J. Chappell et al. (AWAKE Coll.), Phys Rev. Accel. Beams **24** (2021) 011301.

[3] F. Batsch et al. (AWAKE Coll.), Phys Rev. Lett. **126** (2021) 164802.

[4] P.I. Morales Guzmán et al. (AWAKE Coll.), arXiv:2107.11369.

[5] V. Hafych et al. (AWAKE Coll.), arXiv:2109.12893.

[6] E. Adli, in IPAC 2016 Proceedings, WEPMY008 (2016).

[7] P. Muggli, J. Phys. Conf. Ser. **1596** (2020) 012008.