AWAKE status report

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1 Executive Summary

The AWAKE experimental setup has been further improved in 2022 with the introduction of a scintillating screen close to the entrance aperture to the plasma, offering better beam alignment possibilities. A second streak camera has been installed and commissioned downstream of the plasma, allowing the study of modulation and hosing effects along different axes. Additionally, a full set of digital cameras recording various screens were installed to replace analog cameras, allowing for higher data recording capabilities, a Cs_2Te cathode was installed for the electron source, as well as a number of other improvements as reported in this document. We have also started to commission the Cherenkov diffraction radiation beam position monitors. To-date, four running periods have taken place in 2022 and a wealth of interesting results from this year's data has already been presented in conferences.

A highlight in 2022 was the immediate approval by Phys. Rev. Lett. of our paper on the seeding of the proton bunch modulation by an electron bunch. We now obtain reliable electron-seeded self-modulation over a range of plasma densities. We have studied the adiabatic focusing of the proton beam in low density plasma and expect this to lead to an important publication. The hosing induced by an offset between the electron-bunch seed and the proton bunch has been studied in detail, and is also expected to lead to a high-level publication. Further studies include the development of the self-modulation of a proton bunch with significantly increased transverse size as this provides important information on the choice of the seeding scheme we intend to use in Run 2c and beyond. We are also intensely studying the variation in the light produced by the plasma under different conditions. The latter is expected to be one of the main diagnostics used to validate the effect of the plasma density step on the field strengths in Run 2b. An unexpected effect discovered in the 2022 running was the creation of a plasma-electron filament by the proton bunch in low density plasma present in the ramps at the plasma entrance and exit. This filament scatters low energy electrons and provides at least part of the explanation why on-axis electron injection in AWAKE Run 1 was not possible. The low density plasma upstream of the plasma source aperture prohibits this on-axis injection. This is not foreseen to be important for AWAKE Run 2c and beyond as we do not anticipate any section of the electron beamline to be populated with plasma.

We have designed and are now producing2222, in partnership with Wright Design Ltd, the company that produced our current Rb plasma source, a Rb plasma source for AWAKE Run 2b that will allow for a plasma density step. Our simulations show that the density step will allow the modulation of the proton bunch to be frozen. Determining the optimal parameters of the density step will be the main focus of Run 2b. The plasma light diagnostic mentioned above, as well as electron acceleration experiments, are intended as the diagnostics to determine the effectiveness of the density step. At this point, we are on track to start installation of this new Rb plasma source in June, in time for the later running periods in 2023.

A further significant activity in 2022 was the preparation of a discharge plasma source for use in the AWAKE beamline next spring. Our aim is to investigate the proton bunch modulation process in the discharge plasma in the first proton running periods in 2023, prior to the installation of the density-step Rb system. This planned test of the discharge source has stimulated intense developments and significant progress has been made on the reproducibility of the plasma. Furthermore, tests of plasma density diagnostics have taken place in the CERN plasma laboratory, including a test of the 'frequency cutoff' technique. Initial results of this technique were encouraging enough that further testing is planned.

Due to these important measurements during 2023 and the associated installation procedures, our beam requests for 2023 are very constrained: We request 11 weeks in total of proton run, adapting to the reduced beam-time in 2023. During the first 3-week run, requested to start in week 17, we will perform measurements with the discharge plasma source. We then need 10-11 weeks between the end of the first run and the start of the 2nd run for the discharge plasma source de-installation and the installation/commissioning of the Rb density step plasma source. In the following we request three 2-3 weeks blocks of proton run, separated by at least 2 weeks. It is important to note that the AWAKE run requires stable beam for at least 8 hours without interruptions from e.g. LHC filling periods or any other super-cycle modifications, where the duty cycle of AWAKE could be much reduced.

The design studies for AWAKE Run 2c are proceeding well. Significant development work has taken place in the CTF2 facility on the new electron gun that will form the start of the higher energy electron beamline. The X-band acceleration stage design is well advanced, as is the scheme for the power source and modulator system. Extensive simulation campaigns are accompanying these technical developments.

A CERN cost-and-schedule review took place on November 18, 2021. The review was very positive and the committee gave AWAKE support for the funding requests for Runs 2c,d. The committee agreed that CERN must make the strategic decision whether to support the full AWAKE Run 2 program by early 2022. This has taken place, and in CERN's MTP (mid-term-plan) the resources required to clear out the CNGS target area to make space available for AWAKE Run 2 have been added (11 MCHF). In addition CERN has prolonged the AWAKE support until 2030. We also requested a CERN staff position for a plasma-based acceleration scientist and this was approved. We have recently concluded this hiring process and now await the start of Dr. Marlene Turner at CERN on January 1, 2023. However, it should be pointed out that, while the resources needed for Run 2b are in place, a part of the resources that will be needed for Runs 2c,d were not yet granted and await further developments. Further non-CERN involvement and investments will also be necessary in the future, e.g. to develop the necessary plasma sources.

Concerning actions with respect to the Russian invasion of Ukraine, the AWAKE Collaboration Board has decided to suspend a colleague from a Russian institute from his coordinating duties. The Russian institutes remain members of AWAKE and remain as authors on AWAKE papers as they were instrumental in the design and planning of the experimental program.

2 Run 2a operational activities, issues, upgrades

2.1 Introduction

Activities in the AWAKE experimental area focused on achieving the objectives of the Run 2a physics program. From February to November, the 2022 program has included 11 weeks of proton beam, 16 weeks of standalone commissioning of electron and laser beams, while the remaining time has been dedicated to access for hardware maintenance and upgrades.

In addition to continuous maintenance activities, several systems were involved in significant hardware upgrades. The laser team is developing an interlock system to reduce the chances to damage sensitive equipment (screens, cameras, mirrors). A new $\mathrm{Cs_2Te}$ cathode has been produced and installed in the electron injector. The Rb vapor source expansion volume was opened to allow for the installation of a new beam screen to measure the transverse properties of the electron beam at the entrance of the plasma. A current transformer was installed to allow for in-situ calibration of the spectrometer charge and two prototype BPMs have been installed in the common electron-proton beamline and are being commissioned. The BI-developed FESA class for digital cameras has reached sufficient maturity to replace the NI PXI system supported by EN-SSM.

Several weeks of standalone laser beam time were dedicated to characterizing the long-term trajectory jitter of the laser and putting in place an automated alignment system based on the high-resolution cameras of the ‘virtual line’ which runs parallel to the beamline and can be used to monitor the laser during physics experiments.

Electron beamtime was dedicated to commissioning the newly installed BTV at the entrance of the plasma, and using this BTV to measure the electron beam optics and to commission new steering algorithms.

Training sessions were held to teach new members of the AWAKE team to operate the electron and laser beams. As the experimental requirements become more challenging, AWAKE is continuing to improve alignment procedures to obtain faster, more precise and more reproducible setup and alignment of all 3 beams.

Completing the physics program of Run 2a has been the priority during the proton beamtime. While the low-intensity (1×10^{11} protons/bunch) proton beam worked well throughout the run, the high-intensity (3×10^{11} protons/bunch) beam was unstable for the early runs, until a stable RF configuration was found in July. Proton beamtime was also negatively affected by the start of the LHC in July, while the LHC stop of late August provided several days of stable beam, which allowed for the multi-hour parameter scans that are the basis of the current physics program of AWAKE. The physics program started from the electron-seeded self-modulation studies which began in 2021, and focused mainly on two types of scans: a position scan of electron/proton alignment to induce electron-seeded hosing of the proton beam, and a longitudinal timing scan exploring the seeding capability of the electron bunch as it gets closer and eventually overlaps with the proton bunch. Additional goals were also achieved: commissioning a new plasma-light diagnostic, commissioning the new BPMs, studying the behavior of the proton beam in low density plasma (where it undergoes adiabatic focusing) and studying the behavior of a proton beam with larger transverse size (which creates weaker wakefields).

2.2 Laser beam lines

The UV laser line is used to produce the electron bunches and was improved during 2022 by replacing multiple optical elements in its chain (including mirrors and vacuum windows) with a view to enhancing the beam quality on cathode and subsequent electron beam. After this maintenance work was completed, UV saturation measurements were carried out for the newly commissioned photocathode installed during March 2022. This new cathode has shown quantum efficiencies (QE) exceeding 20% and a saturation fluence of about 5 μJ/cm^2, and currently is being evaluated for lifetime and homogeneity to ensure the continuation of high quality electron beams during 2023. Together with the regular measurements of the electron yield, a new diagnostic has been installed for measuring the UV pulse duration with a view to improving further the charge and emittance characteristics of the electron bunches. As a result, the UV pulse duration is of the order of σ = 1.2 ps. The resulting injector performance has been documented in several publications, comparing measurements and simulations [1] and capabilities for efficient charge capture in [2]. It is foreseen the testing of charge production with long UV pulse durations during 2023, to minimize its emittance and optimizing the electron yield.

Regarding the ionizing laser beamline, multiple improvements have been carried out. Firstly, the virtual lines for alignment have been debugged and automatized, and now the alignment is carried out systematically. This was improved thanks to the correlation studies performed between real and virtual lines. An auto-alignment tool is in use to reduce the beam alignment time. Second, the irradiated areas of the laser beam dumps have been precisely measured with contact profilometry, concluding that they can sustain up to 50% more shots than originally estimated. Third, a new interlock system for the ionizing laser is being commissioned. This interlock system is designed to protect the instrumentation and equipment in the laser beamline at different energy levels, allowing users to quickly change the laser configuration in a safe manner. This system has been deployed in the existing laser PLC and is currently controlling the laser output energy level by contact relays connected to the laser triggers. And lastly, laser maintenance work has been carried out in the pumping and cooling groups, shutter systems, as well as motorized actuator power supplies replacements.

2.3 Electron and proton beam line

The main modification to the 18 MeV electron injection line consisted of the installation of an expansion volume BTV at the entrance of the plasma cell. This new element provides a powerful tool for a more precise characterization of the beam parameters at the plasma cell entrance. The hosing studies performed during 2022 revealed the need of improving the performance of the electron beam line. A machine development campaign was carried out with mainly three purposes: systematically measure beam position and size jitter and minimize it, adjust the optics to produce a rounder beam at the plasma cell entrance, and increase the orthogonal steering accuracy. Measurements at low charge (200 pC) showed that after fine tuning of the RF gun and beam alignment a beam position jitter of 20–30 μm (r.m.s.) and a beam size jitter within 15% can be achieved. Lower values would require a hardware upgrade of the beam line. To provide a round beam during operations, a dedicated optimization tool was developed and was successfully tested on a beam of 200 pC charge. The tool is designed to compensate for the day-to-day changes in the beam produced by the RF gun, automatically re-matching it to the required parameters. The next step for the study will consist of commissioning the tool for different charges, and to include a functionality to compensate for orbit changes during optimization. Hosing studies also highlighted the limits of the orthogonal steering tool, needed to change beam central position and angle at the entrance of the plasma cell. The main limitation to the achievable pointing precision is given by the hysteresis in the corrector magnets. To address this issue, a new corrector, close to the plasma entrance, is being installed and a new operational tool is under development.

To match new experimental requirements, a new optics for the proton transfer line (TT41) was designed, commissioned, and successfully tested. The new optics, which provides a symmetric 500 μm beam at the plasma cell entrance, is now available during standard operations.

2.4 Beam instrumentation

Throughout the year 2022, several new beam instrumentation systems have been installed or commissioned in AWAKE:

- Two new beam positioning monitors (BPMs) based on diffracted Cherenkov radiation have been installed in the common proton–electron line for the measurement of the ps-long electron bunch in the presence of the more intense, hundreds-of-ps-long proton bunch. The instruments as well as the electronics were installed in June. One is already connected to the DAQ developed by TRIUMF. The commissioning of this system is ongoing and is expected to continue in 2023. Parallel studies are being performed in the CLEAR facility.

- A new digital camera acquisition system for beam and laser cameras has been deployed. All analog cameras that were present in AWAKE until summer 2022 have been replaced by digital cameras. The acquisition system is running since the beginning of summer, a number of issues (related to missing images, incorrect timestamping, etc.) caused by the high data rate have been identified and are being solved.
- A new imaging system for the electron spectrometer has been installed, as an alternative to the 17-m-long optical line. The new system is based on standard, non-intensified cameras with 75 mm camera lenses that achieve a better optical spatial resolution.
- To allow the absolute calibration of the spectrometer system in-situ, a beam current transformer has been installed just before the spectrometer dipole. The system is being commissioned and is expected to be operational for 2023.
- The beam instrumentation team provided support for the alignment of the electron streak camera line, as well as the installation and operation of a digital micromirror device for the proton halo measurement system.

3 Summary of Run 2a physics results

Run 2a spans over 2021 and 2022, with one more run to come (November 2022). Results obtained in 2021 were highlighted in the previous report.

We summarize here the measurements that were performed since the last report. They consist of programmatic experiments, possibly directly influencing parameters for future designs and experiments (e.g., e-bunch seeding, SM of large-size bunches, plasma light), and of experiments meant to better understand the system as whole and its physics (e.g., hosing, propagation in low density). Each of the topics should lead to publications in refereed journals.

3.1 Seeding of SM with a preceding electron bunch

Since the last report, experimental results on the seeding of SM with an electron bunch that were outlined were published in Phys. Rev. Lett. [3]. Published results show that indeed SM can be seeded by the short (few ps), 19 MeV electron bunch sent ahead of the long proton bunch. That means that SM is made reproducible, unlike in the instability regime (no seed) of SM (SMI). Moreover, measurements show that the growth of SM can be controlled using two independent parameters. The first one is the electron bunch charge Q_e that determines the amplitude of the initial wakefields: $W_{\perp,0} \propto Q_e$. The second one is the charge of the proton bunch Q_p that determines the growth rate of SM: $\Gamma \propto Q_p$. SM then grows as $W_{\perp,0} \cdot \exp(\Gamma \cdot z)$. Therefore, growth of SM, as observed from time-resolved images $\cong$3.5 m from the exit of the 10 m-long plasma increases when we increase either of the charges, as shown in Fig. 1.

3.2 Hosing studies

The electron bunch and its wakefields aligned with the proton bunch seed SM, as described above [3]. On time-resolved images, SM is symmetric about the bunch axis (position=0, see Fig. 2 a)) and contours on time integrated images are mostly circular (Fig. 2 b)). However, when misaligned, hosing is induced in the plane of misalignment and SM is in the perpendicular plane. We misaligned the two bunches and observed this fact both on longitudinal, time-resolved (Fig. 2 c)) and on transverse, time-integrated (Fig. 2 d) images of the bunch. In this case misalignment is along the slit.

Hosing manifests itself as a periodic, growing oscillation of the centroid position along the bunch,

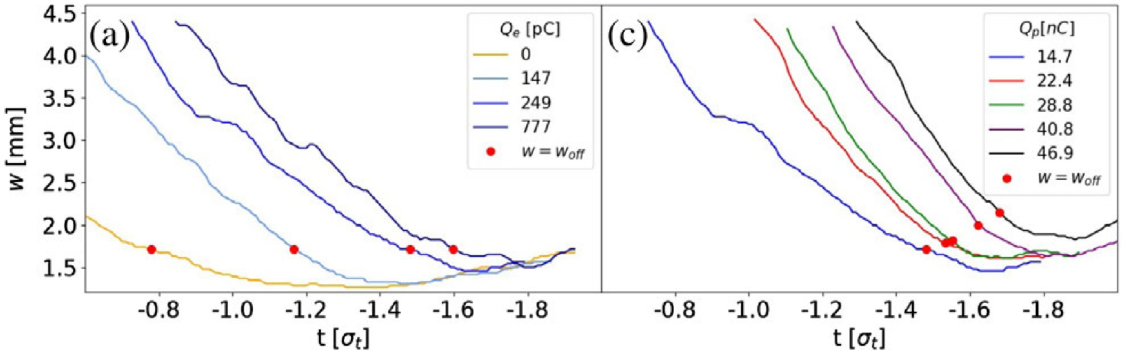

Fig. 1: Transverse extent w along the proton bunch as a function of time along the bunch, normalized to the incoming bunch duration σ_t. (a) Varying the e bunch charge (see legend), $Q_e = 0$ (SMI), $Q_e > 0$ (seeded SM), Q_p=14.7 nC. (c) Varying the proton bunch charge Q_p (see legend), Q_e=249 pC. Red points indicate the times along the bunch when w reaches its value without plasma (transverse size of the incoming bunch at the observation screen, w_{off}). Bunch front on the right hand side. From [3].

resulting in an correspondingly elongated transverse profile along the slit direction for this case of misalignment. The oscillation frequency is close to that of SM and to the plasma frequency.

Occurrence of hosing could limit the acceleration process and its efficiency [4]. Experimental characterizations of hosing are therefore important to validate analytical and simulation models and devise eventual mitigation strategies. Electron/proton bunch misalignment provides a unique opportunity to induce and study hosing of a charged particle bunch in plasma. Occurrence of hosing in any plasma-based accelerator would degrade the quality of the acceleration process.

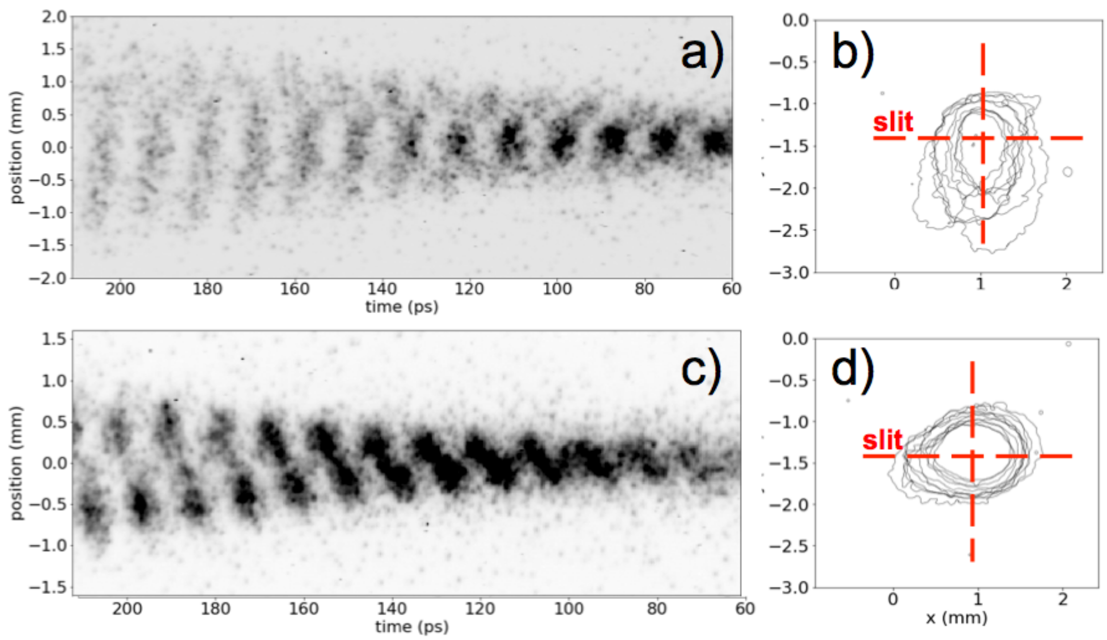

Fig. 2: Time resolved images of the proton bunch density in the case when the electron and the proton bunch trajectories are aligned (a) and SM occurs (train of microbunches separated by defocused proton distributions), and when misaligned (c) and hosing occurs (no microbunches visible, oscillation of the bunch centroid position). Corresponding time-integrated images in b) and d). The streak camera slit is shown as the horizontal, red dashed lines.

3.3 Plasma Light Measurements

Measuring the amplitude of wakefields driven in the plasma is a challenge. As the energy stored in wakefields dissipates in the plasma and its surroundings, a small fraction of this energy is emitted as atomic line radiation. Previous measurements [5] indicate that the time-integrated plasma light signal is proportional to the energy deposited in the plasma (as wakefields) by the drive bunch. We therefore measured the plasma light emitted near the entrance of the plasma, proportional to the amplitude of the seed wakefields, and near the exit of the plasma, proportional to the amplitude of grown, saturated wakefields. Preliminary results indicate that when SM is seeded, variations in plasma light signals are significantly less than when it is not seeded and occurs as an instability. The plasma light signal also depend on the position of the RIF along the bunch, i.e., on the amplitude of seed wakefields and on the amount of proton bunch charge contributing to SM.

A plasma-based accelerator using SM to drive wakefields requires both reproducibility of the phase of the wakefields, that we previously demonstrated [6], to enable external injection, but also reproducibility of their amplitude, to enable reproducible energy gain. Information provided by plasma light signals is essential in demonstrating full reproducibility of the process driving wakefields. Moreover, we will use this plasma light diagnostic to study the effect of a plasma density step on the amplitude of wakefields at ten locations along the plasma in Run 2b (see Section 4.2). The new vapor source is especially designed to allow for this key measurement. It will in principle allow for distinguishing between the development of seeded wakefields along a plasma with constant density, whose amplitude grows and decays after saturation (Fig. 3), and along a plasma with a density step, with amplitude of wakefields that maintains a large value after saturation. The combination of new vapor source with the ability to apply a vapor/plasma density step of various relative heights of 1–10% at various locations along the plasma (every 50 cm along the first 4 m of the plasma) will allow us to verify and optimize the predicted effect of the density step.

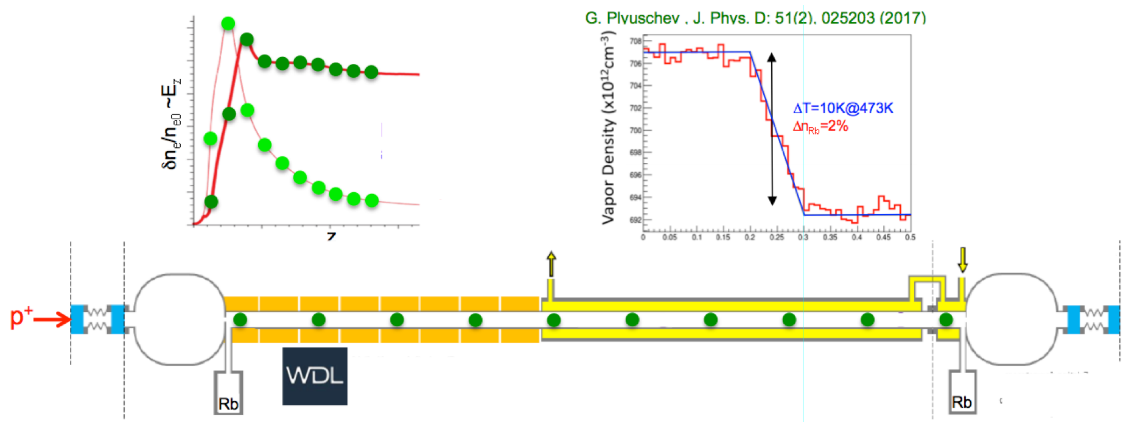

Fig. 3: Top left: Example of numerical simulation result for the development of the amplitude of longitudinal plasma wakefields or corresponding plasma electron density modulation along a plasma with constant density (thin line) and with a step in plasma density (thick line) (from [7]). Green dots show ten possible measurements locations for plasma light. Top right: numerical simulation result (from [8]) showing that imposing a linear temperature increase, from 473 K at 0.2 m to 483 K at 0.3 m (∼2%, mimicking a "real" temperature step) along the source wall, leads to a density decrease of a corresponding ∼2% (red line). Bottom: schematic of the vapor source with the measurement ports (green dots). Beams travel from left to right.

3.4 Plasma Density Ramp

The vapor source has very short (scale on the order of the 10 mm apertures [8]) at its entrance and exit. While the bunch density ($\sim 10^{12}\,\mathrm{cm}^{-3}$) is lower than the plasma density in the 10 m plasma (typically $> 10^{14}\,\mathrm{cm}^{-3}$), it is much larger in the ramps, whose density decreases by about five orders of magnitude in 1 m away from the apertures of the source. Simulation (see Fig. 11) and experimental results [9] show that in this very low density plasma the positively-charged proton bunch generates on the bunch axis a very narrow, very high density filament of plasma electron (see simulation Fig. 11). This filament has negligible effect on the bunch of relatively massive and high-energy protons, but a significant effect on the bunch of low-energy, relatively light electrons. Measurements and simulations confirm that when the electron bunch enters the plasma traveling within the proton bunch (as would be the case for external, on-axis injection), it does not reach or exit the long plasma because it is lost in the ramp by the strong defocusing fields of the plasma electron filament. We observe this effect in experiments where, when the electron bunch travels within the proton bunch it does not seed SM, whereas, all other parameters being equal, it does seed when traveling ahead of the proton bunch.

These results indicate that one must avoid having a density ramp at the entrance of the accelerator plasma (e.g., Run 2c). Indeed, current designs do not have an entrance ramp. However, one must study in numerical simulations the effect of the exit ramp on the much higher energy accelerated bunch.

3.5 Propagation in Very-Low-Density Plasma

The vapor source can also produce plasma densities comparable to those in the ramp, over $\sim$10 m, which allows for the study of the plasma electron filament on the bunch itself. We obtain low densities by operating the vapor source at low temperatures. Results (see Fig. 4) show that the proton bunch is indeed focused by this effect. They also show that focusing occurs all along the bunch, unlike in the SM case in which focusing has the periodicity of the wakefields (see middle images). However, when increasing plasma density there is a value above which SM is observed again (see right hand side images), possibly showing the transition between focusing by the filament, when the bunch density is larger than the plasma density, to SM in the other case. The finite plasma radius ($\sim$1 mm) may also play a role in the transition from one regime to the other.

3.6 SM of a Wide Proton Bunch

In order to avoid the current filamentation instability, the rms transverse size of the proton bunch, or width, at the plasma entrance must be smaller than the cold plasma skin depth (c/ω_{pe}). Relativistic ionization front (RIF) seeding leaves the fraction of the proton bunch ahead of the RIF not modulated. Runs 2c and beyond will use a first plasma for SM and a second plasma for acceleration. Therefore, that not-self-modulated-part of the bunch could experience SM instability in the second plasma. Development of the instability could yield wakefields that would perturb acceleration in wakefields driven by the RIF-seeded part of the bunch. However, when reaching the second plasma, the front of the bunch would have a lower density than at the entrance of the first plasma, because of divergence from that point on (over 10^{+} m). It would also be diverging. Its tendency to develop SM would thus be reduced when compared to what it is at the entrance of the first plasma, in which case measurements have shown that SM does develop as an instability [6]. We studied at low plasma density ($10^{14}\,\mathrm{cm}^{-3}$) the development of SM with a bunch with width at the plasma entrance of $\sim$500 μm, i.e., similar to what it would be at the entrance of the second plasma. Preliminary results show that without seeding (RIF head of the proton bunch), SM develops as an instability on some events, but then much later along the bunch than where the RIF would be for seeding in the first plasma. This indicates that SM of the front of the bunch in the second plasma of Runs 2c and beyond is most likely not an issue, and should even less of an issue with a diverging bunch.

Results also show that SM of the wide bunch can be seeded, as in the narrow bunch case ($<$200 μm)

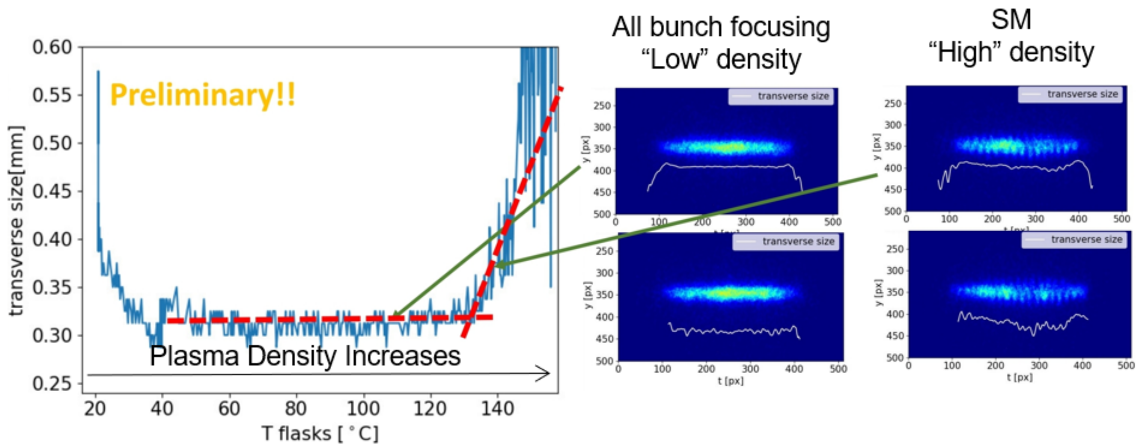

Fig. 4: Left: Measurement of the transverse size of the proton bunch as a function of the temperature of the rubidium reservoirs (flask). The vapor and plasma densities increase with temperature. The size we observe first decreases quickly with temperature/density ($T < 40^{\circ}$C), then remains essentially constant ($40 < T < 130^{\circ}$C), before increasing because of SM appearing. Middle images (labelled: All bunch focusing, "Low" density) in the ($40 < T < 130^{\circ}$C temperature range the whole bunch is focused as one, no signs of SM are visible. Right hand side images (labelled : SM, "High" density) for $T > 130^{\circ}$C, SM appears again as the formation of microbunches.

by placing the RIF within the proton bunch.

3.7 SMI/RIF-SSM Transition

Measurements of the transition form SM as an instability (SMI) to RIF-SSM were performed with various charges and widths of the proton bunch to extend the results published in [6]. Preliminary analysis results with narrow bunches indicate that, as expected, the transition point along the bunch is independent of bunch charge.

4 Run 2b

4.1 Streak Cameras

Streak cameras provide time-resolved images of the proton bunch charge density distribution. These images are the main diagnostic for SM and hosing development.

We installed a second streak camera with an image rotation so that the charge density distribution of the bunch in two, perpendicular planes can be acquired simultaneously. These two images are important in determining whether, or in which plane hosing develops.

A third camera is currently under repair and will be installed so that we will be able to acquire simultaneously two, perpendicular images at the picosecond timescale (timescale of SM) with the current cameras, and one image at the nanosecond timescale (the timescale of the proton bunch). The nanosecond timescale provides information about the growth of SM (see e.g. [3]) and on the possible development of long wavelength hosing (as opposed to that at the wavelength of the wakefields, as when induced by misalignment, see above), or about possible effects of ion motion.

4.2 Rubidium Plasma Source For Run 2b

We are developing together with the company WDL, a new rubidium vapor source that will allow for testing the predicted effect of a plasma density step on the development of SM [7]. Since the density of the rubidium vapor, that becomes that of the plasma upon ionization by the laser pulse, is determined in part by the temperature along the 10 m source tube (see Fig. 5 a)), imposing a temperature step is equivalent to imposing a plasma density step. We replaced fluid heating of the first 4 m of the source with eight, 50 cm-long, electrically heated sections. This allows for imposing a 0–10% relative density step at any location between electrical heaters.

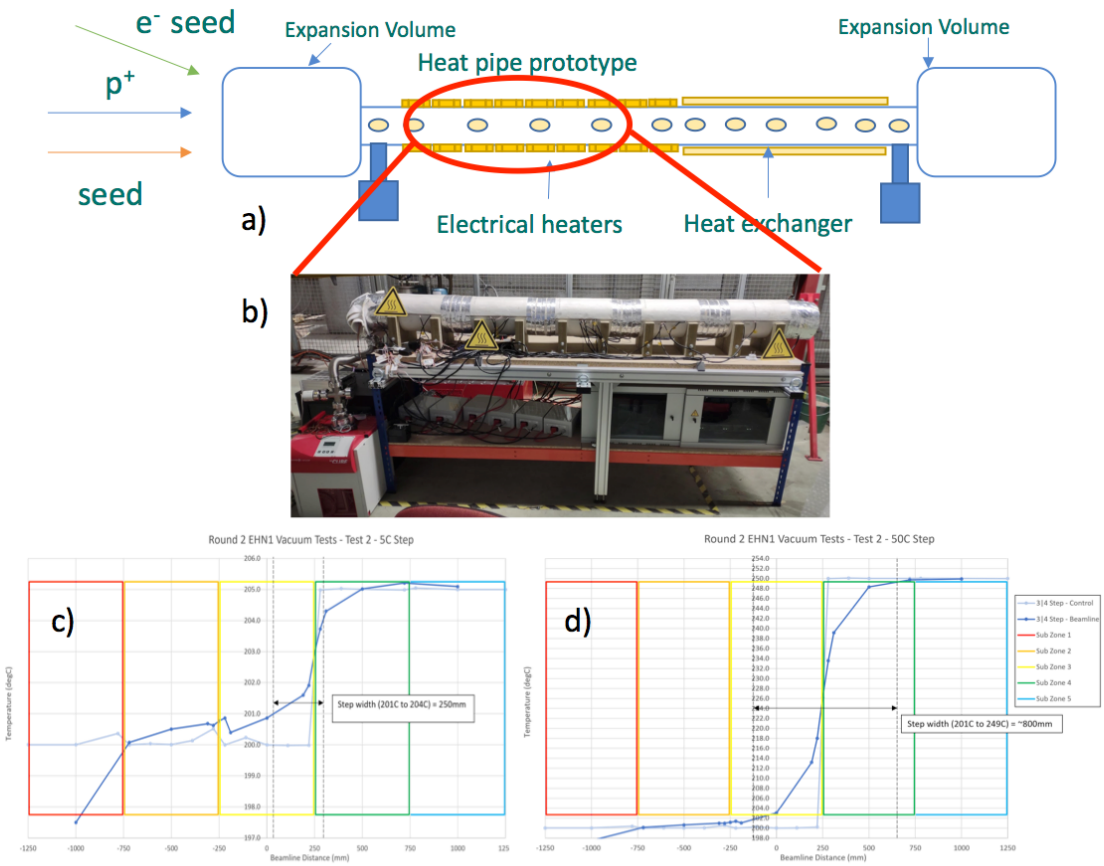

Fig. 5: a) Schematic of the vapor source with electrical heaters over the first 4 m and fluid heating over the last 6 m. b) Picture of a prototype with five electrical heaters we built to measure the characteristics of the temperature steps we can impose, here between heaters two and three and three and four. Temperature measurement along the source with c) $\Delta T \cong 5^{\circ}$C (or $\cong$1% around 500 K) showing an $\cong$25 cm-width of the step, and d) with $\Delta T \cong 50^{\circ}$C (or $\cong$10%) showing an $\cong$80 cm-width of the step.

We built a prototype of the electrically heated section with five heaters (see Fig. 5 b)). Temperature measurements show that indeed, these temperature steps can be imposed, with a "width" that increases with the height of the step, e.g., $\cong$25 cm for ΔT=5°C at T$\cong$200°C, to $\cong$80 cm for $\Delta T \cong 50^{\circ}$C. Numerical simulation results show that the effect of the step on SM is very weakly dependent on its width.

The design of the source is completed (see CAD drawing on Fig. 6) and fabrication has started.

The new source is fitted with three ports for measurement of the rubidium vapor density and ten ports for measurement of plasma light (see Section 3.3). It has an enhanced cooling for the expansion volumes. The control system is more complex than that of the previous source, since it has eight more sections with three heaters each, each with two temperature probes, and with corresponding overheating protection circuits. However, the insulation system has been improved. The reservoirs are now modular and connected through cable bundles. Temperature probes are encased in stainless steel sleeves to decrease their risk of failure. The rubidium recycling system is potentially considerably simplified. All of these are improvements when compared to the previous source.

The schedule calls for operation with proton beam in July 2023. Replacement of the source entails

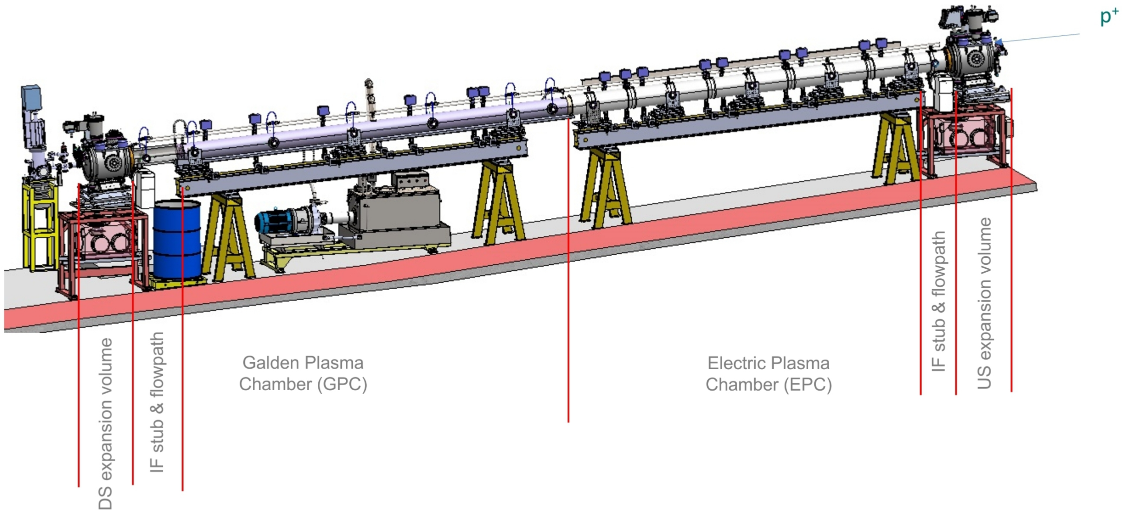

Fig. 6: CAD drawing of the new vapor/plasma source as it will be installed in the experimental area. In this case, beams travel from right to left. Electrically-heated section on the right hand side, fluid-heated section on the left hand side with circulation system below the source. Expansion volume at both ends.

decommissioning and disposal of the current source, which has been in operation for the entire AWAKE experiment so far (since 2016). We are developing procedures to safely remove rubidium from the source.

4.3 Preparation of the Rb vapor source exchange for Run 2b

The transition from the Run 2a program to the Run 2b program consists of two major activities: the dismantling of the current plasma source and the installation of a new rubidium vapor plasma source which has features for a density step implemented. This new plasma source will take the same location as the current one, as well as the same dimensions and services. Hence, the experimental set-up in Run 2b will be similar to that in Run 1 and Run 2a. Several aspects have been studied and coordinated for this installation:

The current vapor source will not be used again and needs to be disposed of properly. Studies are on-going regarding mostly the handling of the potential traces of rubidium that will remain in the system once the plasma source is dismantled.

The cabling campaign for the new step density vapor source has been anticipated to be in October 2022 to avoid the YETS period.The cables are now ready for use and they will be connected in March 2023 to the new equipment. The technical drawing of the inner tube of the step density vapor source have been produced. This drawing was then used by the mechanical workshop to manufacture this piece directly at CERN. The piece was completed mid October 2022 and is now with the vacuum service for vacuum firing and vacuum testing. Discussions have started to establish a procedure for the alignment of the new vapor source. The current 10-m-long plasma source needs to be taken out of the tunnel. Because of the many equipment present in that area, complex maneuvers are needed. To allow this, it will be necessary to dismantle some of the shielding blocks in TCC4 as well as the high-precision mirrors of the spectrometers located at the end of TCC4. For the new plasma source, the transport will be simpler as it is composed of two pieces of 5 m.

The decommissioning of the current plasma source is scheduled from mid-December until mid-February 2023. The installation of the new step-density plasma source includes two phases:

- The pre-building of the equipment on the surface is scheduled from mid-March until beginning of May.

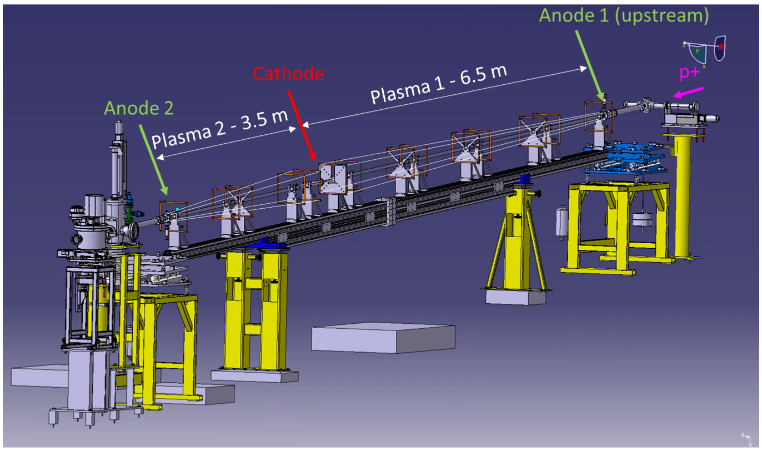

Fig. 7: CAD drawing of the 10 m long discharge plasma source in the AWAKE tunnel.

– The equipment will then be transported to the tunnel for installation and commissioning, which is scheduled from the end of May until the end of July.

4.4 Discharge plasma source tests in the beam line in 2023

With the Rb vapour source dismantled and the new density step Rb vapour source not yet installed, a window of opportunity has opened up to use the first proton run period in end April/beginning of May to test a 10 m long discharge plasma source (DPS) in the AWAKE beam line.

The main goals of such an experiment are (besides the proof of principle of such an alternative plasma source):

– Study the effect of the plasma length on the proton beam SMI using three different plasma lengths (3.5/6.5/10 m)
– Investigate the ion motion effect on the SMI by changing the gas (argon and helium)
– Investigate low/high plasma densities and their effect on the hosing instability

The test program is summarized in [10] and presents the detailed physics program, technical plan, resources, planning and decision points.

The new generation pulsed DC generators to power the DPS have been designed and fabricated by IST Lisbon. The cell has been designed at CERN and will be first assembled by the end of the year in a lab at the surface to conduct the necessary qualification tests and measure the plasma density for the different lengths with a Michelson interferometer. The vacuum, gas injection and control systems of the cell have been designed and built at CERN for a remote control operation from the AWAKE control room. The safety aspects (electrical, cables, materials, radiation, R2E) have been addressed and validated.

The experiment is planned to take place during the first proton run period of 2023 at the end of April 2023 lasting 2–3 weeks, however, the final planning and organisation are still under discussion.

5 Physics Plan, Runs 2a and b

5.1 Run 2a, November 2022

The physics program for the last experimental period of Run2 a focuses on determining what information about the amplitude of the wakefields can be extracted from the plasma light measurements. In addition, we will acquire the data missing to complete the measurements described in Section 3.

5.2 Run 2b, 2023–

5.2.1 Discharge Plasma Source

For the first part of Run 2b (April 2023) the current vapor source will be replaced by the DPS (see Section 4.4). The DPS will allow for variation of the plasma length: 3.5, 6.5, and 10 m. It consists of two discharges, 3.5 and 6.5 m, sharing a common cathode, that can be fired separately or together. We will observe the effect of plasma length on SMI only, since solid windows placed at each end to contain the gas of the discharge prevent use of the electron bunch for seeding.

The DPS also allows for operation with various noble gases: Xe(A=131), Ar(40) and He(4). Operation with ion masses lighter than that of Rb(85) may allow detection of the effects of ion motion on SM.

We will repeat the measurements of focusing at low plasma densities, this time with better-known plasma densities. Very low plasma density values can be obtained by delaying the travel of the proton bunch with respect to that of the start of the discharge. The density along the time of the discharge can be measured by longitudinal laser interferometry.

We will also revisit measurements that showed that hosing instability occurs at very low plasma densities ($< 0.5 \times 10^{14}\,\mathrm{cm}^{-3}$), probably induced by relative misalignment between the proton and the laser beams in the vapor source.

We will install a camera to measure plasma light along the entire plasma for each event, through the glass tube. This may provide direct information about the development of the SM process along the plasma.

The DPS allows for quick changes of plasma parameters (when compared to the vapor source) and requires no particular daily alignment since the plasma extends over the 24 mm inner diameter of the source. We therefore expect quick systematic measurements.

5.2.2 Vapor Source with Density Step

The DPS will then be replaced by the new vapor source allowing for an adjustable plasma density step (see Section 4.2). The effect of the step on the SM process, observed on time-resolved and time-integrated images, on plasma light signals (ten of them), and on the energy of side-injected electrons, will be the core of the Run 2b program (2023–24). In addition, confirming that seeding of SM with RIF and electron bunch is still effective at making the phase and amplitude of SM reproducible will be necessary. An important parameter will be the plasma density since measurements of SM phase (i.e., relative timing) are more challenging at the predicted optimum density for acceleration, $\sim 7 \times 10^{14}\,\mathrm{cm}^{-3}$. Most experiments are practised at lower densities $(1-4) \times 10^{14}\,\mathrm{cm}^{-3}$, corresponding to modulation frequencies in the 90 to 180 GHz range, where the frequency bandwidth of the streak camera is sufficient to produce meaningful images of SM. The streak camera optical system will be optimized for higher frequencies ($\sim$240 GHz).

As before, we will also study interesting effects that (such as hosing), that contribute to the general understanding of the experiment and of the effects we observe. We will also continue to improve and develop diagnostics, in particular towards challenging Run 2c parameters, such as measuring very small transverse electron beam sizes, beam vector, emittance, energy spread, etc.

The expectation is that at the end of Run 2b, we will have characterized the "self-modulator" plasma of Run 2c and beyond, and confirmed its suitability to be integrated into the two-plasma system. In parallel, operation with the DPS and further development of the two scalable sources will inform us on the choice of plasma for the accelerator section: a prudent, but more complex vapor source for Run 2c, or directly one of the scalable sources (sees Sections 4.4 and 7).

6 Run 2c

6.1 Run 2c integration/Installation

The 2020 AWAKE SPSC status report described the global integration layout of Run 2c. While the main integration layout remains as presented in 2020, the klystron area was updated with five instead of four klystrons.

6.2 Run 2c UV laser beam lines

AWAKE's Run 2c requires two synchronized electron beam sources: one for seeding the proton bunch modulation and another one for producing the witness electron bunches. The existing electron source used for Run 2a and 2b will be used until 2024 in its current configuration, but during Run 2c and afterwards it will be moved and utilized in the proton bunch modulator cell using a new UV laser system. As for the generation of the witness electron bunches, a new photoinjector has been developed at CTF2. This photoinjector operates with copper cathodes, and so the requirements of UV pulse energies are increased by 3 orders of magnitude compared to the existing AWAKE electron gun. Accordingly, a high energy UV laser system and beam line has been installed at CTF2 and the production of 500 pC electron bunches in the coming months is expected.

During Run 2c and onwards the synchronization between electron bunches becomes important for precise electron injection studies in the plasma wakefields. To synchronize the electron bunches, both electron guns will be driven by a single UV laser, by splitting its output into two identical beams with path lengths accurately matched to the experimental timing requirements. The relative timing fluctuations between the two UV laser beams illuminating the cathodes is expected to be well below 100 fs. The main laser beam is generated using a Light Conversion Pharos laser system, capable of producing up to 450 μJ of UV pulse energy with an energy r.m.s. stability of less than 0.11% and TEM00 beam profile. The development of the RF locking system for this laser has been completed, and currently the timing jitter fluctuations between laser and RF signals are of the order of <100 fs, when using the 1.5 GHz reference at CLEAR. The current locking scheme can be further improved to <25 fs timing fluctuations by use of additional electronic feedback loops and different RF reference signals. In addition, the triggering and timing systems for the laser have also been integrated into the CERN standard timing systems.

In terms of UV beam delivery and conditioning systems, the existing one at AWAKE will be adapted for the electron gun feeding the modulator plasma cell, whereas a new one has been constructed for the accelerator plasma cell and currently being developed at CTF2. The capabilities and performance of the UV beamline for the first electron source have been documented in [11].

As for the UV beam delivery and conditioning of the second photo-injector, due to the use of copper cathodes, the system has been designed significantly differently. The main difference here is in the focusing of the UV beam on the cathode, which employs a motorized Keplerian telescope rather than a motorized aperture. This scheme allows the use of high energy UV beams in small areas, maximizing charge production while minimizing emittance. In addition to the variable beam magnification, a set of diagnostics and control systems have already been implemented, including beam steering, virtual cathode imaging beam line (BTV), power control and variable pulse duration, which are already integrated in knobs in a WorkingSet.

6.3 New Electron Source development for Run 2c

AWAKE Run 2c will need a new electron accelerator to inject high quality electron bunches into the the second plasma cell to demonstrate plasma wakefield acceleration with emittance preservation and low energy spread of electron bunches suitable for high energy physics experiments. The baseline for this injector consists of a S-band photo injector and X-band cavities for bunching and acceleration. The injector has to deliver electron bunches with an energy of 150 MeV, a bunch charge of 100 pC, a bunch length of 200 fs and an energy spread of 0.1% with an emittance below 2 mm mrad. All this has to be achieved in

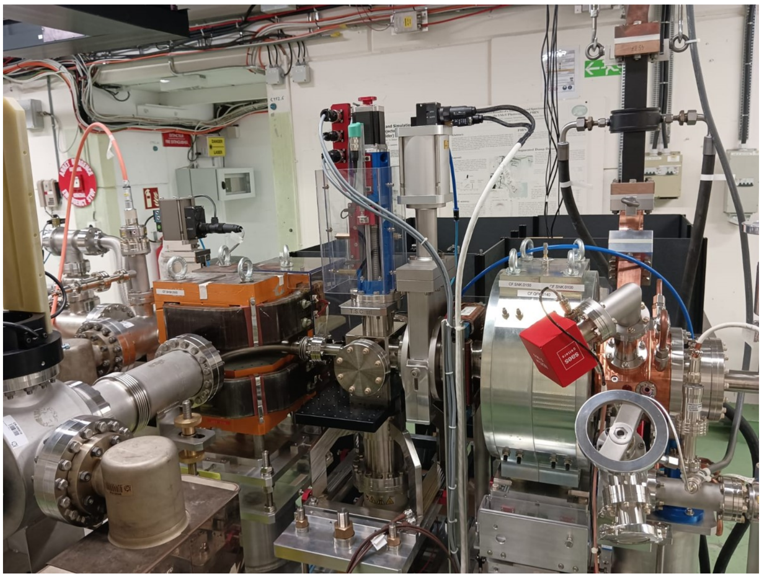

Fig. 8: Picture of the Photo Injector test stand for AWAKE in the CTF2 tunnel.

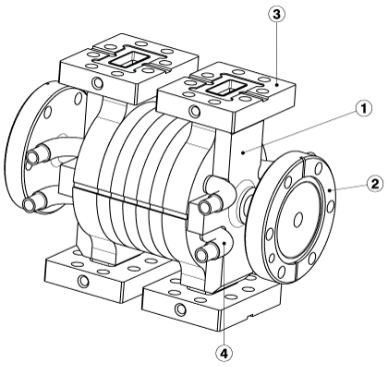

Fig. 9: Mechanical design of a prototype X-band accelerating structure under fabrication at CERN.

a very small space available in the existing CNGS tunnel therefore high gradient X-band technology and a challenging beam dynamics concept for bunching has been chosen. The AWAKE collaboration developed a detailed beam dynamics design in the last few years and started now prototyping key elements in order to build a reduced scale injector to demonstrate the required performance. In collaboration with the CLEAR project an RF-gun, built by INFN Frascati, has been installed in the former CTF2 tunnel. The RF-gun has been high power tested and conditioned up to a cathode voltage of 120 MV/m. The gun showed a low breakdown rate at this high voltage and reached an excellent vacuum. The next step will be to test the electron source with a laser and create electron bunches with the required parameters for AWAKE. A picture of the installation of the gun followed by a short beam diagnostic section is shown in Fig. 8. Another example of the prototyping work is the mechanical design of a short X-band accelerating structure as shown in Fig. 9. The RF and mechanical design takes advantage of the rich knowledge of the CLIC study and the CompactLight design study. This short prototype is now under construction at CERN.

During the past year a lot of work has been done in collaboration with Uppsala University on the detailed layout and optimisation of the RF systems needed for this injector. Uppsala University is focusing on the overall layout, the modulators and the low level RF system. A prototype LLRF system based on μTCA technology is under development. The high power RF distribution including pulse compressors and its optimisation in terms of power efficiency and cost has been studied at CERN [12].

6.4 Updates on beamline design for Run 2c

Run 2c foresees three main challenges in terms of beam transfer lines: the installation of a new 150 MeV witness electron line, the replacement of the present 18 MeV electron line with a new beamline and the upgrade of the proton beamline to account for the change of the plasma cell position.

The design of the new 150 MeV line was finalized at the end of 2021 [13]. In the same period, new details about the mechanical dimensions of the magnets to be installed on the line were provided. The new lengths are now included in the beamline model, slightly changing the original beamline design. The optics matching and the alignment procedure optimization were therefore performed again, confirming the capability of the new design of providing beam parameters within specifications.

For the new 18 MeV electron line, the constraints and main specifications were collected from the interested stakeholders and a first design of the line was proposed. The new layout only includes magnets and beam instrumentation devices that are installed on the present injection line. The matched optics for the new design provides a beam within the defined specifications. Further studies will be performed to assess the effects of magnet field, alignment, and input beam parameters errors on the output beam.

The updated design of TT41 proton line was not modified since 2021.

6.5 Beam instrumentation for Run 2c

Studies for the development of a sub-ps bunch length system for the future 150 MeV electron line are currently on-going. Test are being performed in the CLEAR facility.

7 Scalable plasma source R&D

7.1 Helicon plasma source

Several technical and physics campaigns took place in 2022. In March, a 3-weeks campaign with SPC Lausanne was conducted to harvest measurements with the Thomson Scattering setup installed in 2021. This campaign was dedicated to the comparison of two antenna designs (ring and half-turn helical), B-field variations and power variations. Further studies are needed as the obtained densities are still below those obtained in Greifswald and there is about 20-30% difference between the TS and the CO2 interferometer data.

A second campaign at the beginning of April was dedicated to the test of a microwave cut-off frequency measurement with support form MPP-Munich. The MPP setup has been installed and tested on both HPS and DPS cells at CERN. Due to the relatively low frequency (15–39 GHz) of the generator/horn antenna/oscilloscope system, it was challenging to find stable plasma conditions to operate. These frequencies correspond to a density range of $2.8x10^{18}$ to 1.9×10^{19} m^{-3} which is low with respect to the HPS/DPS setup design and usual working point (around 2×10^{20} m^{-3} at 3 kW/antenna). However, it was possible to observe transitions/cut-off on the measurements, which make this approach worth investigating at higher frequencies towards higher densities. The data processing relies also on the modelling of the wave diffraction across the tube and the plasma and additional effort is required to get quantitative values of the plasma cut-off frequency. IPP-Greifswald is working in parallel on a setup capable of working at higher frequencies ($\sim$100–250 GHz) to tackle densities relevant for AWAKE and propose a diagnostic/monitoring method compatible with operation in the AWAKE tunnel. Such a setup could be ready around spring 2023.

In the following campaigns some technical issues especially were tackled on the RF setup, the grounding scheme and the matchbox and the LIFF setup from University of Wisconsin was assembled and tested with plasma. Further improvements are required.

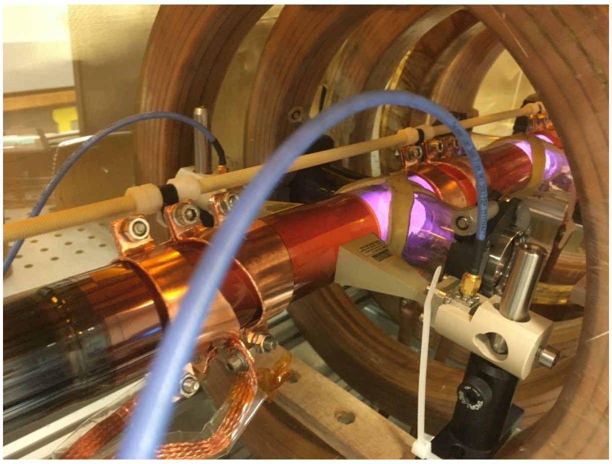

Fig. 10: MPP cut-off frequency setup on the helicon plasma source.

The last campaign took place in October for two weeks to investigate in a systematic way the effect of the RF phase shift between antennas on the matching and voltage/current on two antennas. This campaign highlighted that the antenna voltage is largely insensitive to the matching situation and magnetic field and that the RF noise on the interferometer detectors reach a minimum in the phase region ($\sim$250-350°) when the voltage on antenna three is lower than the voltage on antenna two. It is also the region where the plasma looks qualitatively brighter with an extended blue-core. With a focus around 320° phase difference between the two generators, the arcing threshold was around 5–5.3 kW/antenna.

7.2 Discharge plasma source

The DPS activities of 2022 were driven by the tunnel test proposal and its preparation (see dedicated section). However, lab activities at CERN on the 1.6 m source went on with optical emission spectroscopy coupled with residual gas analysis to monitor the time and space evolution of the species in the plasma. At IST, Lisbon a longitudinal interferometry diagnostic has been installed on the 5 m test bench to assess the length integrated plasma density.

8 Simulations

8.1 Simulations for Run 2b

Simulations play a vital role in the development of the AWAKE experimental program and the interpretation of experimental results. The difficulties inherent in making measurements inside the plasma mean that the behavior of the electron and proton beams inside the plasma must be uncovered by modeling the beam dynamics. The high-amplitude plasma wakefields that charged beams can excite provide the basis for the AWAKE acceleration scheme, but also mean that these beam dynamics are strongly nonlinear. Continuous work is carried out to develop and evaluate the specialized simulation tools necessary for these studies.

AWAKE Run 2b will see the installation of a new plasma source which permits the introduction of a step in the plasma density, which has been predicted by simulations to increase the average accelerating field [14, 15]. Experiments will be carried out to probe the wakefield amplitude using a witness electron bunch, which will allow the validation of these simulations. However, the dynamics of acceleration in Run 2b are extremely complex, as the phase and amplitude of the wakefields vary significantly during the development of SSM. Further simulations are now being carried out to predict when trapping of the witness bunch will occur, which will allow an estimate to be made for the achievable energy gain. In addition to this work, new analytical models have been developed to characterize how such density steps

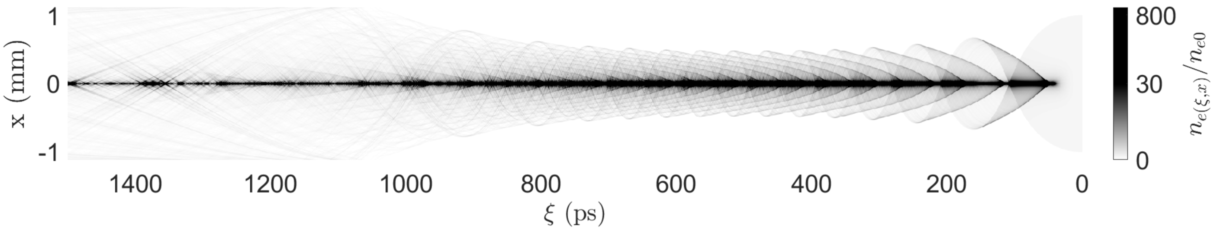

Fig. 11: In regimes where the proton charge density is much greater than that of the plasma, plasma electrons are pulled towards the beam axis, forming a filament.

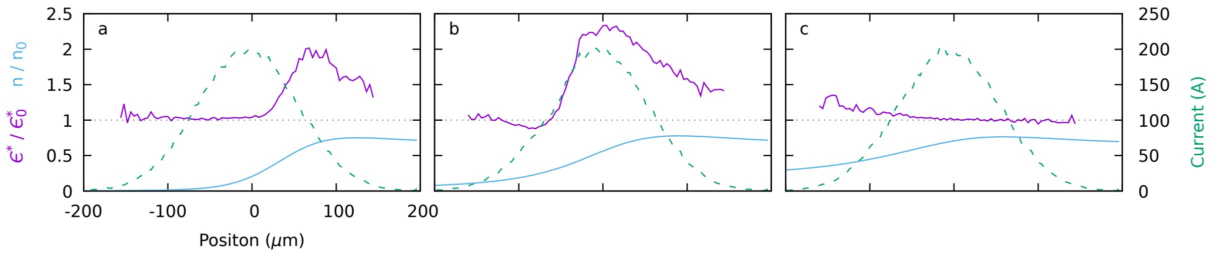

Fig. 12: Plots showing the current and slice emittance of witness bunch, as well as the on-axis plasma density, after 10 m acceleration. a) A bunch with a 2 μm initial emittance rapidly expels the plasma electrons (blue line), allowing emittance preservation (purple line) for most of the beam. b) For an initial emittance of 8 μm, the plasma electrons are expelled more slowly, resulting in an increase in emittance. c) This effect can be avoided by increasing the initial bunch radius.

can be used to control the growth of beam–plasma instabilities [16]. Simulation studies are also being carried out to determine the optimal parameters for the density step for Run 2b.

The ability to accurately model the highly nonlinear dynamics of the electron bunch inside the plasma is a vital step towards simulating the injection process in Run 2b. Investigations have been carried out to determine whether dispersion introduced by the electron beamline modifies the beam dynamics within the plasma. The results of this study show significant differences in the electron beam evolution for different distributions within the error of measurements. This work will now be built upon, and comparisons made to experimental measurements of the electron bunch spectrum after the plasma in the absence of the proton beam. Together, these studies will allow the initial electron bunch to be better characterized, and provide a sound basis for the simulation studies of acceleration.

The electron bunch dynamics will also be significantly altered by the presence of the proton beam. Key amongst these effects is the development of an on-axis plasma filament [17], shown in Fig. 11, in the low-density plasma in the rubidium expansion volumes [8, 18]. This process has previously been observed in the case of positron beams [9]. This filament is predicted by simulations to defocus the electron bunch at both the plasma entrance and exit, and its influence has already been observed experimentally in Run 2a. Simulation studies are ongoing to gauge the impact of this filament on AWAKE Run 2, which will allow mitigation strategies to be developed.

8.2 Simulations for Run 2c

An extensive simulation study has been carried out to characterize the tolerances for injection in Run 2c [19], which have allowed the further development of the engineering specification. One key finding was that scattering of the electron bunch prior to injection alters the optimal bunch parameters due to self-wakefields driven by the witness bunch in plasma, as shown in Fig. 12. Additional studies show that the acceleration process is only weakly sensitive to the specific shape of the phase space distribution, depending instead on the macroscopic bunch characteristics [20].

A new analytical model for the influence of the gap between the two plasma sources, supported by simulations, shows that varying the gap changes the field in the acceleration stage, but not the optimal parameters of the plasma density step. Further simulation studies on the use of a plasma density gradient in the acceleration stage show only modest gains, suggesting the baseline variant of a uniform plasma is close to optimal.

Simulations were also carried out to investigate the evolution of a proton beam with a larger initial radius, as part of the study to gauge whether laser seeding of the self-modulation instability would be applicable to Run 2c. This initial study showed evidence of filamentation instabilities in the plasma. This work will be continued by collaborators from the Max-Planck Institute for Plasma Physics, who are investigating whether regimes of astrophysical interest could be studied within the AWAKE experimental setup.

9 Publications and presentations

9.1 Publications by AWAKE and AWAKE collaboration members on AWAKE-related topics

- E. Gschwendtner et al. (AWAKE Collaboration), The AWAKE Run 2 programme and beyond, Symmetry 2022, 14(8), 1680
- L. Verra et al. (AWAKE Collaboration), Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma, Phys. Rev. Lett. 129, 024802 (2022)
- L. Liang et al., Acceleration of an electron bunch with a non-Gaussian transverse profile in a quasilinear plasma wakefield, arXiv:2208.04585
- M. Moreira et al., Mitigation of the onset of hosing in the linear regime through plasma frequency detuning, arXiv:2207.14763
- L. Liang et al., Simulation study of betatron radiation in AWAKE Run 2 experiment, arXiv:2204.13199
- J. P. Farmer et al., Injection tolerances and self-matching in a quasilinear wakefield accelerator, arXiv:2203.11622
- R. Ramjiawan et al., Design of the AWAKE Run 2c transfer lines using numerical optimizers, arXiv:2203.01605
- V. Khudiakov and A. Pukhov, Optimized laser-assisted electron injection into a quasi-inear plasma wakefield, Phys. Rev. E 105, 035201 (2022)
- M.A. Baistrukov and K.V. Lotov, Evolution of equilibrium particle beams under external wakefields, Plasma Phys. Control. Fusion 64 075003 (2022)
- A.A. Gorn and K.V. Lotov, Generation of plasma electron halo by a charged particle beam in a low density plasma, Phys. Plasmas 29, 023104 (2022)

9.2 Conference proceedings and presentations

- IPAC 2022 (https://accelconf.web.cern.ch/ipac2022/):
  - E. Gschwendtner et al., The AWAKE Experiment in 2021: Performance and Preliminary Results on Electron-Seeding of Self-Modulation
  - E. Granados et al., Mapping Charge Capture and Acceleration in a Plasma Wakefield of a Proton Bunch Using Variable Emittance Electron Beam Injection
  - T. Nechaeva et al., A Method for Obtaining 3D Charge Density Distribution of a Self-Modulated Proton Bunch
  - E. Senes et al., Recent AWAKE Diagnostics Development and Operational Results
  - C. Pakuza et al., A Beam Position Monitor for Electron Bunch Detection in the Presence of a More Intense Proton Bunch for the AWAKE Experiment

- LINAC 2022 (http://linac2022.vrws.de/html/author.htm)
  - J. M. Arnesano and S. Doebert, Design of an X-Band Bunching and Accelerating System for AWAKE Run 2
  - G. Zevi Della Porta, Run 2 of the Advanced Plasma Wakefield Experiment (AWAKE) at CERN
- EPS Plasma Physics 2022 (https://indico.fusenet.eu/event/28)
  - Talk by T. Nechaeva, Hosing of a long proton bunch induced by an electron bunch
  - Poster by L. Verra, Adiabatic Focusing of a Long Proton Bunch in Plasma
  - Poster by J.P. Farmer, Injection tolerances for a quasilinear wakefield accelerator
  - Poster by P. Morales, PIC Simulations of the Interaction between Self-Modulation in the Front and Rear of an ultra-relativistic Proton Bunch in Plasma
  - Poster by K. Moon, Analysis of electron bunch energy spectra after meter scale over-dense plasma
  - Poster by M. Moreira, Control of the self-modulation and long-bunch hosing instabilities through plasma frequency detuning
- NAPAC 2022 (https://attend.ieee.org/napac-2022/)
  - M. Bergamaschi, Results of AWAKE Run 1 and Plans for Run 2 Towards HEP Applications
- EuroNNAC 2022 (https://agenda.infn.it/event/28376/)
  - Talks by E. Gschwendtner, P. Muggli, M. Bergamaschi, L. Verra, T. Nechaeva, M. Moreira, S. Doebert, J. P. Farmer, D. Minenna, G. Zevi Della Porta
- Heraeus Seminar
  - Talks by L. Verra, T. Nechaeva, P. Morales, J. P. Farmer, J. Pucek, G. Zevi Della Porta

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