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THE PROTON DRIVEN ADVACED WAKE FIELD ACCELERATION EXPERIMENT (AWAKE) AT CERN*

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Abstract

The Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) aims at studying plasma wake field generation and electron acceleration driven by proton bunches. It is a proof-of-principle R&D experiment at CERN and the world's first proton driven plasma wake field acceleration experiment. The experiment uses the 400 GeV proton beam from the super proton synchrotron (SPS) which travels through a 10 m long Rb-vapour plasma cell where it gets self-modulated and generates the plasma wake fields. An electron witness beam is injected externally to probe the wake-fields. AWAKE has completed several experimental campaigns, starting in 2016. Results from the initial characterization of the plasma cell and measurements of the seeded self-modulation of the proton beam will be presented. First results on electron witness beam acceleration using the proton driven plasma wake field have been obtained recently and are presented in this paper.

INTRODUCTION

The AWAKE experiment at CERN aims to study and demonstrate for the first time proton driven wakefield acceleration. Laser driven plasma wake field acceleration (LPWA) has been proposed almost 40 years ago [1] and impressive experimental results have been achieved in recent years, demonstrating several GeV electrons from a short plasma cell [2,3]. LPWA provides very high gradients over short, centimetre scale length. To reach particle energies suitable for high-energy physics many acceleration stages have to be coupled and therefore dephasing and energy depletion issues need to be solved.

A second well known and already demonstrated option is electron driven plasma wakefield acceleration, here gradients of the order of 50 GV/m over meter scale plasmas have been demonstrated [4,5]. This scheme suffers from a limited energy transfer from the drive bunch to the witness bunch [6] and therefore requires as well a large number of stages to reach TeV scale energies.

Proton driven wakefield acceleration has in principle the potential to overcome these challenges since high energy proton bunches carry enough energy to accelerate electrons to TeV scale energies in a single stage [7]. Readily available proton beams come from large synchrotrons and have therefore a long, centimetre scale, bunch length, prohibiting high wakefields when used as a driver. The AWAKE experiment therefore uses a seeding laser pulse to trigger a self modulation resulting in a micro-bunching of the long proton bunches [8]. These micro-bunches can then drive the plasma wake fields resonantly up to GV/m gradients. This process will be described below in more detail.

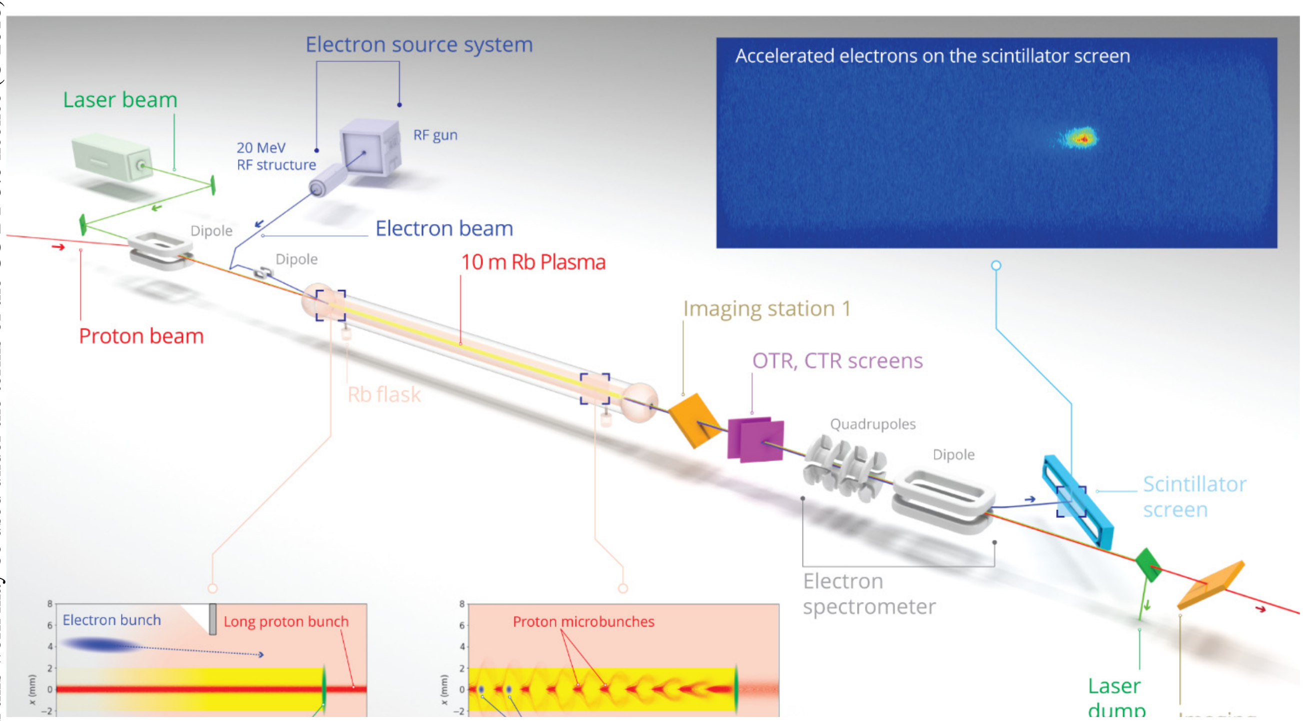

Figure 1: Schematic layout of the AWAKE experiment at CERN. A proton beam from the SPS (left) is focused into a plasma cell. A laser beam and an electron beam are injected synchronized to generate the plasma and probe the wakefileds. A diagnostic section (right) allows to observe the self-modulation process and the accelerated electrons.

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AWAKE EXPERIMENT

The AWAKE experiment is part of the CERN accelerator complex [9, 10]. It uses a 400 GeV proton beam with an intensity of up to $3{\cdot}10^{11}$ protons/bunch and a bunch length of 12 cm, coming from the SPS. The bunches are extracted from the SPS and focused into a 10 m long plasma cell. A schematic layout of the experiment can be seen in Figure 1. The plasma cell is consisting of a uniformly heated pipe, filled with rubidium vapour at a temperature around 200 ºC corresponding to a nominal plasma density of $7{\cdot}10^{14}$ cm^{-3} [11]. The plasma density can be changed by adjusting the temperature and has a measured uniformity of better than 0.2%. In addition a slight taper of the plasma density can be achieved by adjusting the flow of rubidium from both ends of the plasma cell. The critical parameter of the local plasma density can be measured with a white-light interferometer to a precision of better than 0.2 %. A picture of the installed plasma cell in the AWAKE experiment can be seen in Figure 2.

A high power laser system with a central wavelength of 780 nm delivers short pulses synchronised with the extracted proton beam. The laser ionizes the Rb vapour thus creating the plasma during the passage of the proton beam. The 120 fs long laser pulse with an energy of up to 450 mJ, creates a plasma channel with a radius of about 1 mm collinear with the proton beam trajectory. Secondly the laser pulse is seeding the self-modulation of the proton bunch, transforming it into micro-bunches, which drive the wakefield resonantly. This is indicated in the lower left part of Figure 1.

A fraction of the laser energy tapped off from the laser and frequency tripled, serves to generate the electron beam, using an rf photo injector. The laser and the rf source, used for the electron injector, are synchronised better than 1 ps enabling the witness beam acceleration, while the laser and the proton beam are synchronised to the level of 15 ps which is sufficient given the long bunch length of the proton beam. The electron injector for the witness beam consist of an S-band rf gun and an S-band booster structure powered by a single klystron. The rf gun uses a high quantum efficiency (QE) Cs_2Te cathode which provides a QE of a few percent. The nominal beam parameters are a bunch charge of 200 pC, an energy of 18 MeV and a bunch length of 4 ps (σ). A detailed description of the electron injector can be found in [12].

The entire experiment is equipped with a whole suite of beam diagnostics for all three beams. Cameras and virtual focus lines allow monitoring the alignment and profile of the laser beams in the relevant positions at the photo cathode of the injector and in the plasma cell. Beam position monitors and transverse profile monitors (screens) are installed in both particle beam lines to monitor the trajectory, measure the relevant beam parameters for matching and beam alignment. All three beam have to overlap temporally and spatially in the plasma. The timing can be measured with a streak camera using OTR light from a screen in front of the plasma cell and adjusted with delay lines in the laser setup. Behind the plasma cell, a set of transverse profile monitors allow to observe the transvers proton beam defocusing due to the self-modulation [13]. OTR and CTR radiators are used to characterize the micro bunching of the proton beam, indicating the wake field development. The optical emission is monitored on a second streak camera, delivering time resolved images of the self-modulated proton bunch and the coherent microwave emission can be characterised in the frequency domain with a heterodyne measurement system. The principle diagnostic for acceleration of the witness beam is the spectrometer at the end of the beam line, which deflects the electrons but hardly changes the trajectory of the 400 GeV proton beam. A large high-resolution scintillator screen is used to view the accelerated electron beam.

The AWAKE experiment was divided into two phases. In a first phase mainly in 2017 the seeded self-modulation of the proton beam and the development of the wakefields were studied. The second phase in 2018 is dedicated to demonstrate the proof of principle of proton driven plasma wake field acceleration with an electron witness beam. Finally in a second RUN after the long shutdown at CERN the AWAKE team wants to show acceleration of high quality electron beams [14].

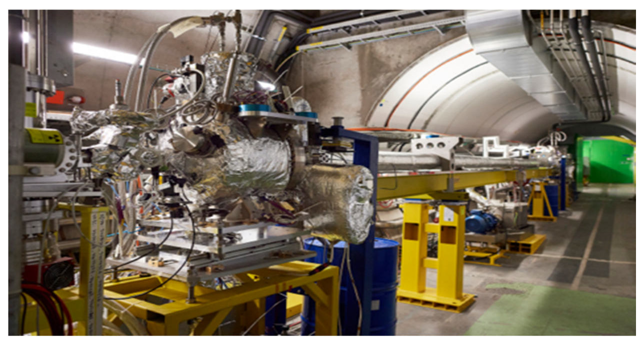

Figure 2: Picture of the 10 m long rubidium vapour plasma cell installed in the AWAKE experiment. One of the end-caps can be seen which includes the RB flask and the flow and temperature regulation.

SEEDED SELF MODULATION (SSM)

The process of self-modulation is essential for the AWAKE experiment because the existing long proton beam would not excite significant wake fields. The plasma frequency $\omega_p = (4\pi\, n_0\, e^2/m_e)^{-1/2}$ depends on the plasma density n_0 with m_e and e being the elementary electron mass and charge. In order to drive a wakefield efficiently the length of the drive bunch ideally needs to be shorter than the plasma wavelength $\lambda_p = 2\pi c/\omega_p$. In AWAKE this problem is solved by converting the long proton bunch into a series of micro bunches, each short enough to drive the wakefield, taking advantage of a self-modulation instability (SMI) [8] seeded by the short laser pulse. Simulations indicated that the instability grows exponentially both along the bunch and along the plasma, resulting in large wakefields suitable for acceleration. The self-modulation

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is actually a transverse proton density variation resulting in focused and defocused areas.

This structure of the beam propagates over very long distances in the plasma according to simulations [15]. Figure 3 shows an example of such a simulation of a self-modulated proton beam at different time steps to visualize the process [16]. The modulation starts slowly and consists of alternate transverse focusing and defocusing of the protons resulting in a periodical longitudinal density variation. Finally, a clear micro bunching can be seen which drives the plasma wakefield resonantly.

Phase 1 of the AWAKE experiment was dedicated to verify these predictions and to study the seeded self –modulation of the proton beam extracted from the SPS. The proton beam was aligned collinear with the high power laser in the 10 m long plasma cell. A streak camera could monitor the timing of the laser with respect to the proton bunch after the plasma cell. In the nominal scheme the laser is placed right in the middle of the proton bunch and therefore the modulation should start in the centre of the bunch.

Examples of the original data taken by the streak camera and its analysis can be found in [17] and resemble very much the lower right picture in Figure 3. The self-modulation can be clearly seen in particular that it is a transverse modulation of the proton beam. The plasma cell was set to a density of $2.1 \cdot 10^{14}$ cm^{-3} during the experiment and the distance of the micro-bunches was measured to be 7.6 ps accordingly.

It was found that the spine like structure of the modulated proton bunch is extremely reproducible and consequently produces phase stable wakefields suitable for acceleration. The modulated proton beam can be interpreted therefore as a standing wave accelerating structure with a resonance frequency of 131 GHz. The frequency has been varied in the experiment from 50 GHz to almost 300 GHz by changing the plasma density from $0.5 \cdot 10^{14}$ cm^{-3} to $11 \cdot 10^{14}$ cm^{-3}. The plasma frequency and therefore the frequency of our plasma wakefield accelerator scales with the square root of the plasma density. The modulation frequency has been measured with the streak camera in the time domain using the visible emission from the screen and as well in the frequency domain using microwave detectors at the coherent part of the emission spectrum. Both measurements show excellent agreement with each other and with the theoretical predictions. More in depth insights and analysis of the self-modulation studies can be found in [17, 18]. The transverse defocusing of the proton beam during the self-modulation can be observed indirectly by transverse profile monitoring after the plasma cell [19].

ACCELERATION RESULTS

The first goal of the AWAKE experiment was the study of the seeded self-modulation. It was demonstrated that one can expect a phase-stable wakefield, allowing to inject a probe beam and accelerate particles.

In the second phase the main goal was to demonstrate electron acceleration, using the proton driven wakefields. An electron injector has been added to the experimental facility in 2017, allowing the injection of low energy electron bunches into the wakefield. Ideally, one would use an electron bunch which is short with respect to the plasma wavelength and which can be focused to the transverse size of the useful wakefields. This would require a very sophisticated electron accelerator, which was not available for the first phases of AWAKE.

The injected electron bunches used for the present experiments have an energy of 19 MeV and a bunch charge of 600 pC, the bunch length is about 2-3 ps (σ). They are focused at the entrance of the plasma cell to a spot size with a radius of about 600 µm due to the larger beam emittance compared to the specifications. The electron beam is injected with a delay of approximately 200 ps with respect to the seeding laser. The beam spreads longitudinally over several plasma wavelength and the electron beam focus is larger transversely than the plasma radius defined by the size of the laser beam. The simulations suggest therefore

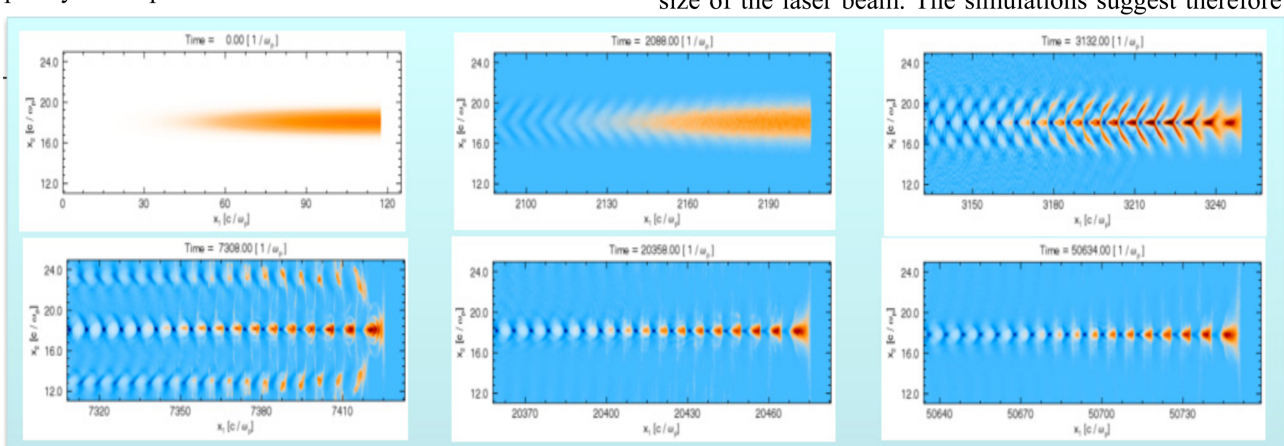

Figure 3: Simulation of the self-modulation process of the proton beam using a short seed-laser in the centre of the proton bunch. From upper left to lower right snapshots at different times during the self-modulation are shown. The first snapshot (upper left) shows no modulation yet, in the third and forth (upper right and lower left) one can clearly see the transverse nature of the modulation resulting in transversely focused and defocused protons. The last picture (lower right) depicts the fully developed modulation. Here the micro-bunches which will drive the wakefield resonantly are clearly visible.

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that some electrons are captured at the right phase and are accelerated in the wakefields up to high energies along the 10 m long plasma cell. Final energies up to 2 GeV with an energy spread of the order of 10-15% are expected [20]. Furthermore, the simulations indicate a better capturing of the electron beam if it is injected with a slight angle with respect to the proton beam. In the experiment a crossing angle between 1-2 mrad with respect to the proton beam was used.

In a first experiment in 2018, electrons have been injected into the plasma and acceleration of electron with energies of up to 2 GeV have been observed [21]. Figure 4 shows an example of such an acceleration event as seen by the spectrometer at the end of the proton beam line. In this example an electron beam with an energy of 800 MeV has been measured, the energy spread is about 17 % FWHM in this case. The captured charge in this first experiment was 0.25 pC.

In this series of measurements a plasma density of $1.8\cdot10^{14}\,\mathrm{cm}^{-3}$ has been used with a 5% density taper over the length of the plasma cell. Tapering the plasma density allows to preserve slightly higher wakefields over the length of the plasma cell. During the first acceleration experiments the plasma density and tapering was varied. A summary of the data points obtained can be seen in Figure 5. The acceleration gradient goes up with the plasma density as expected and a density ramp along the cell boosts the wakefields in addition. The uncertainty of the peak energy and energy spread measurements is estimated to 10% because it is dominated by the emittance of the accelerated electrons, which is not measured.

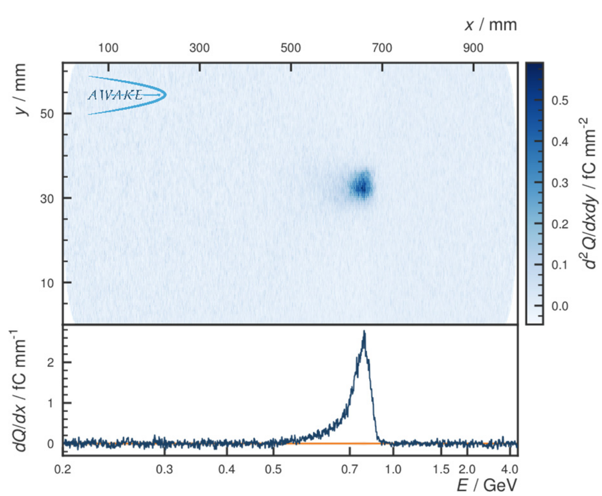

Figure 4: Witness beam acceleration measurement example. The image observed at the spectrometer after background subtraction and its vertical projection below. The charge of the beam is visualized in the colour coding of the image. The red line in the projection graph shows a 1 σ uncertainty band from the background subtraction

In the first proof of principle experiment, the electron beam parameters were not yet optimised. The emittance of the beam is still higher than originally specified and the control of the beam spot and location in the plasma cell not yet fully developed. There is no diagnostic in the plasma cell available were one wants to verify and guaranty the overlap of the three beams. Nevertheless, the acceleration events appeared very consistently and reliably.

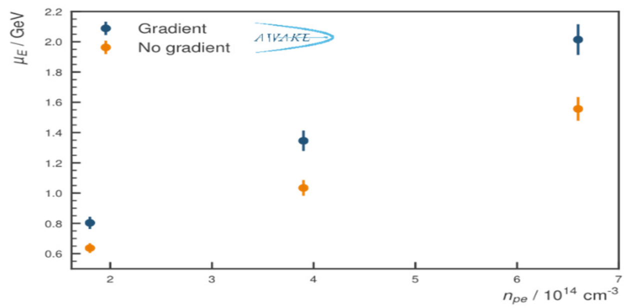

Figure 5: Summary of acceleration results as a function of plasma density. Shown are the highest acceleration results obtained with and without a gradient in the plasma density along the plasma cell.

The next steps are to be able to precisely change the focal point and crossing angle of the electron beam with the plasma, over a wide range of parameters, in order to optimise the acceleration results in terms of captured charge and energy spread. Since reliable 3D simulations of the capturing and acceleration process are very difficult, this is as well the way to systematically study the dependences of the results on these parameters.

CONCLUSION AND OUTLOOK

The AWAKE collaboration managed to observe and study, for the first time, the self-modulation of a proton beam. The seeded self-modulation process provides stable wakefields suitable for high gradient acceleration. This was demonstrated with the first acceleration of electron bunches in a proton driven plasma wakefield. Final energies up to 2 GeV, using a tapered plasma density have been observed. This results present a new milestone in plasma based particle acceleration.

The AWAKE team will continue in 2018 to study and optimise the acceleration process. Afterwards there is a two-year shutdown at CERN with no protons available from the SPS. The next phase of AWAKE called RUN2 will start in 2021 with the goal to accelerate high quality electron beams using the proton driven plasma wakefields. The aim is to demonstrate emittance preservation and low energy spread electron beams to pave the way towards possible high-energy physics application of this scheme. To achieve these goals a new electron injector is probably needed providing electron bunches with a bunch length of the order of 100 fs, a very small emittance and the right intensity to load the wakefields correctly [12]. In addition the electrons have to be injected once the growth of the wakefields during the self-modulation process is saturated and a high accelerating gradient can sustained over a longer distance. Two plasma cells are needed, separating the micro bunching and the pure acceleration, with electron injection in between [14].

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Possible applications of such an acceleration scheme are studied by the AWAKE collaboration and as well within the framework of Physics Beyond Collider at CERN [22]. Tens of GeV electron beams could be achievable using the SPS as a driver, for dark matter searches or e-p-collisions while using the LHC as a driver would in principle allow to accelerate electrons to the TeV scale for very high energy e-p collisions [23].

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