AWAKE - A PROTON DRIVEN PLASMA WAKEFIELD ACCELERATION EXPERIMENT AT CERN

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Abstract

It is the aim of the AWAKE project at CERN to demonstrate the acceleration of electrons in the wake created by a proton beam passing through plasma. The proton beam will be modulated as a result of the transverse two-stream instability into a series of micro bunches that will then drive strong wakefields. The wakefields will then be used to accelerate electrons with GV/m strength fields. The AWAKE experiment is currently being commissioned and first data taking is expected this year. The status of the experimental program is described as well as first thoughts on future steps.

PATH TO AWAKE

It has been known for some time that plasmas can support very large electric fields, and can therefore be used for accelerating particles to relativistic energies [1]. Initially, laser driven plasma wake field acceleration was considered in the literature [2], and experimental verification of the ideas followed [3]. Detailed simulations of the process are now available which have predicted the production of electron beams with interesting characteristics. In recent experiments, gradients in the range 10-100 GV/m have been achieved. These have so far been limited to distances of a few cm, but the progress has been very impressive [4]. In order to accelerate an electron bunch to 1 TeV, these gradients would have to be maintained over distances of tens of meters, or many acceleration stages would have to be combined. Both of these options are very challenging, both because of dephasing and energy conservation issues.

It was later recognized that plasmas could also be excited by a bunch of electrons [5]. Given an intense enough bunch of electrons, the plasma is both created [6] and excited by the passage of the bunch. Very large electric fields were predicted and later observed [7]. In the case of electron driven plasma wakefield acceleration (PWA), a gradient of 50 GV/m was achieved and sustained at SLAC for almost 1m [8]. However, the maximum energy that can be transferred to a particle in the witness bunch is limited by the transformer ratio and is at most 2 for longitudinally symmetric drive bunches [9]. This upper limit can in principle be overcome by asymmetric bunches [10], but this will be technically very difficult to realize. Energy issues also dictate that an electron-bunch driven PWA would require a large number of stages to reach the TeV scale, and therefore be quite complex.

The scheme proposed for study in the AWAKE experiment is based on proton-driven PWA [11]. The principle advantage of using protons to driving the wake is that proton

bunches are today accelerated to high energies, and so have enough energy to bring a bunch of electrons to the TeV scale in a single acceleration stage. However, the length of existing proton bunches requires the use of a bunching scheme to drive the plasma wakefield in such a way as to produce GV/m fields.

Self-Modulation Instability

The angular frequency ω_P of the plasma wave is fixed by the local plasma density n_0 via

$$\omega_P = \sqrt{\frac{4\pi n_0 e^2}{m_e}},$$

where m_e is the electron mass and e is the elementary charge. On the time scale of a few wave oscillations, the much heavier plasma ions can be considered immobile. The plasma wave or wake follows the drive bunch, and its phase velocity v_{ph} is close to that of the drive bunch [12]. Its wavelength is therefore approximately $\lambda_P = \frac{2\pi c}{\omega_P}$. The maximum amplitude of the longitudinal electric field in the wave is on the order of the wave-breaking field $E_0 = \frac{m_e c \omega_P}{e}$ [13].

The extremely short driver length required for efficient excitation of the plasma wave (a small fraction of λ_P generally is required) presents a serious obstacle to the realization of the concept. The CERN proton bunches available today are approximately 10 centimeters long (the root-mean-square length) and are therefore ineffective at driving large wakefield amplitudes. Various bunch compression schemes have been studied in the early stages of studying proton-driven plasma wakefield acceleration [14]. While technically feasible, the concepts developed will be costly and require extensive amounts of space.

An alternative to extreme bunch compression is multibunch wave excitation. In this scheme the plasma wave is resonantly driven by a train of short micro bunches spaced one wakefield period apart. It is exactly this scheme that was first proposed as the plasma wakefield accelerator in [5]. In our application, the long proton bunch is converted into a stream of micro bunches, each short on the scale of the plasma wavelength, by an instability. The instability of interest is the self-modulation instability (SMI), which can be viewed as the axisymmetric mode of the transverse two-stream (TTS) instability. The SMI is a convective instability that grows both along the bunch and along the plasma. Analytical calculations and three-dimensional simulations [15] predicted an exponentially fast growth of the SMI and confirmed that non-axisymmetric modes of the TTS instability are also suppressed if the seed perturbation is strong enough.

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The micro bunches propagate stably during very long distances, provided that the nonlinear regime is avoided [16]. The concept of the SMI is visualized in Fig. 1. This development has opened the path to experimental verification of proton driven plasma wakefield acceleration.
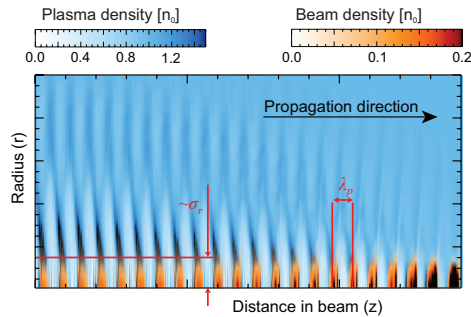

Figure 1: Example of a self-modulated proton bunch resonantly driving plasma wakefields sustained by the plasma density perturbation (OSIRIS simulations [17]). The plasma electrons are shown in blue, and the protons in orange. Darker shading represents higher density. The initially Gaussian bunch density profile with z=12cm has been converted into a series of micro bunches with spacing 1.4mm..

AWAKE

While a collider based on plasma wakefield acceleration is clearly still many years away, there is a path to wakefield acceleration with protons via modulation of the proton bunch as described above which allows for the use of existing infrastructure. This is the scheme that has been proposed by the AWAKE Collaboration, and an experimental program has been approved in 2013 making use of the SPS beam at CERN to demonstrate the concept. The first experimental results on proton beam modulation are expected late this year. The AWAKE Collaboration will demonstrate GV/m-scale gradients in the next 1-2 years.

AWAKE Overview

The AWAKE experiment [18] will use the SPS proton beam with $E_P = 400$ GeV and up to $3 \cdot 10^{11}$ protons/bunch to drive the plasma wakefields. The experiment is hosted in the previous CNGS beamlime just upstream of the target area. The area has been completely refurbished to host the AWAKE experiment, including the construction of two small tunnels to allow laser and electron beam passage. The layout of the AWAKE experiment is seen in Fig. 2. The different elements of the AWAKE setup are briefly described.

Proton Beam

The proton beam line is largely identical to that used for producing a neutrino beam for LNGS (the CNGS facility). However, a number of magnets needed to be relocated at the downstream end to allow sufficient space for the plasma cell and diagnostics, and also to allow a merging with the laser beam. Installation of the proton beam line was finished
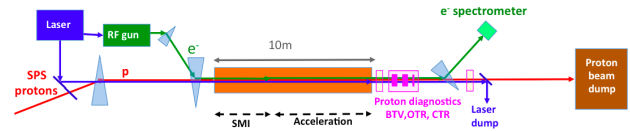

Figure 2: Schematic of the AWAKE experiment for Run I (not to scale). The proton beam (in red) is merged onto the path of a laser beam with a strong dipole 22 m upstream of the plasma cell. The electron beam (in green) is then merged with the proton and laser beams just upstream of the plasma cell. The 10 m plasma cell is shown in orange. An array of diagnostic elements are placed behind the plasma cell (optical transition radiation - OTR, coherent transition radiation - CTR, optical screens - BTV, and an electron spectrometer.

in May 2016 and first beam was extracted on 15 June 2016 from the SPS onto the beam dump at the end of the beam line. The proton beam commissioning took place in the second half of September and all design parameters were met. A picture of the beam line is shown in Fig. 3.

Figure 3: The elements of the proton beam line just upstream of the plasma cell.

Laser Beam

A schematic view of the laser beam lines can be seen in in Fig. 4. The beam line between the laser and plasma comprises five mirrors (MP1 - MP5) on motorized vacuum compatible mirror mounts, a precise linear translator holding the laser-proton merging mirror mount MP5, laser safety shutters LSSP1 and LSSP2 and three laser beam dumps LBDP1–LBDP3. Most of these elements have been manufactured, assembled and installed in the beginning of 2016. The laser beamlines have now been fully commissioned.

Electron Beam Line

Electron bunches will be generated using the PHIN photoinjector from the CLIC Test Facility [19] using a laser pulse derived from the ionization laser (see Fig. 2). They will be subsequently accelerated in a custom produced RF
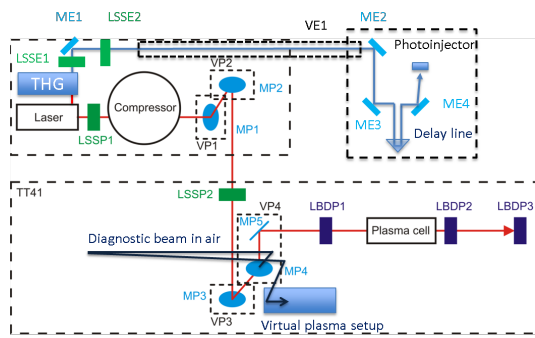
Figure 4: The elements of the laser beam lines.

structure to energies between 10-20 MeV. The layout of the electron beam line is fixed and construction of different elements has begun (see Fig. 5). The installation of the electron line is planned to start in spring 2017.
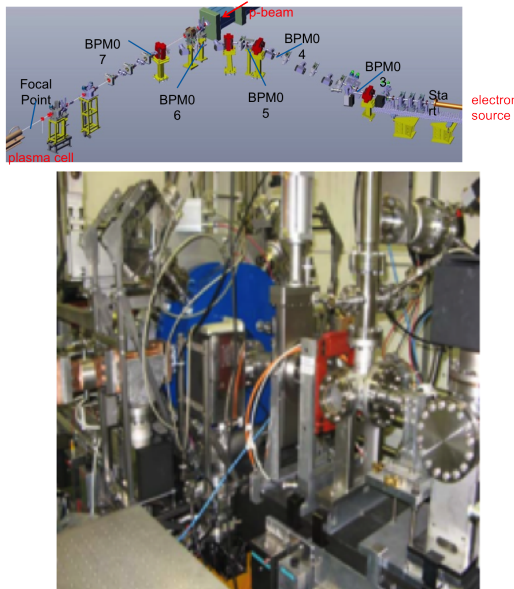

Figure 5: Top: Layout of the electron beam line. Bottom: picture of the PHIN photoinjector.

Plasma Cell

The plasma cell [20] for Run I of AWAKE consists of a 10 m long Rubidium heat exchanger with Rb sources at each end. The beam line has a 10 mm orifice at each end of the plasma cell through which Rb is constantly flowed and collected in expansion chambers. This solution provides the required density uniformity and density profiles needed. The Rb vapor is produced by heating the Rb vessels and heat pipe to ca. 200°C and is then ionized with the high power laser to produce the plasma. The laser pulse co-propagates with the proton beam and provides a sharp plasma turn-on, thus seeding the correct instability. The plasma cell design is complete and all components are at CERN and are currently being assembled and commissioned. Figure 6 shows different elements of the plasma cell.
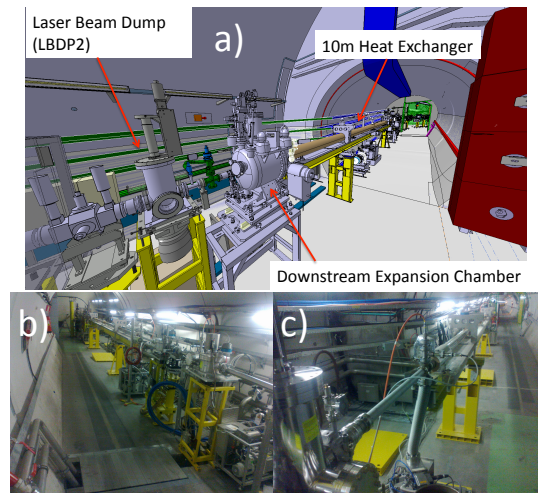

Figure 6: a) Schematic of the AWAKE beam line showing the heat exchanger and downstream expansion chamber. b,c) pictures of the setup as of end of September in the AWAKE tunnel.

Diagnostics

The SMI will defocus approximately one quarter of the proton bunch with a typical angle in AWAKE of 1 mrad. This defocusing will be observed on screens recording the (time integrated) transverse image of the bunch downstream of the plasma. This diagnostic uses standard CERN equipment and is installed and commissioned.

Additionally, a aluminum-coated, 150 μm-thick silicon screen was installed in a diagnostic station ~3 m downstream from the plasma exit and at a 45 ° angle to the beam axis to measure optical transition radiation in a time-resolved manner using a streak camera. Figure 7 shows a schematic of the OTR setup on the beam line. For the AWAKE density range the modulation period is between 11 and 3.5 ps. Test results with gated and modulated laser light mimicking the expected OTR light have shown that modulation frequencies up to 350 GHz (corresponding to a period of less than 3 ps) can be measured from the FFT of the streak images. A second diag-
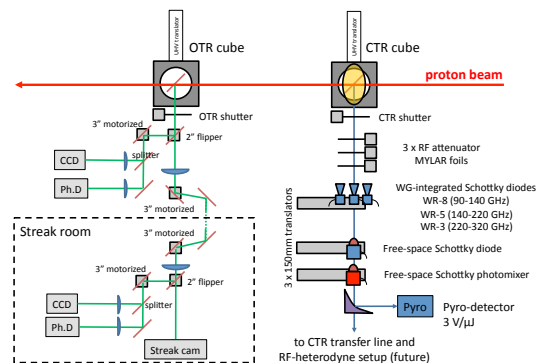

Figure 7: Schematic of the OTR and CTR setup installed on the proton beam line.

nostic section similar to the OTR has been installed upstream of the OTR diagnostic (see Figure 7). Instead of looking

at the time structure of incoherent OTR it will measure the frequency of the coherent transition radiation (CTR) emitted at the bunch modulation frequency. In this diagnostic, the frequency of the CTR, f_{RF}, will be determined by mixing the signal on a diode with the signal of a local oscillator at a known frequency f_{LO} to bring the f_{IF} frequency into reach of a $10 - 20$ GHz-bandwidth oscilloscope.

The second phase of AWAKE RUN I will focus on the acceleration of externally injected electrons. Numerical simulations indicate that electrons will reach an energy larger than 1 GeV with a finite energy spread of a few percent. A magnetic spectrometer based on a CERN HB4, C-shaped magnet and two quadrupoles will be used (see Fig. 8). The resolution of the energy measurement is expected to be at the % level,.
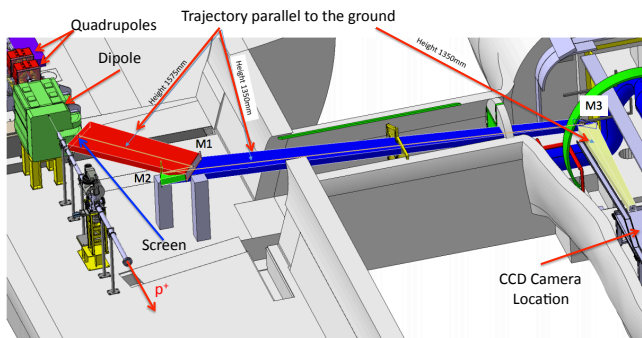

Figure 8: CAD drawing of the electron magnetic spectrometer integration in AWAKE, including the light transport line from the spectrometer screen to the CCD camera in the shielded area. Optical mirrors for the screen light are labeled M1 to M3. The optical line is enclosed in a light shield.

First Beam

The proton and laser beams have been commissioned and the synchronization is established. The parameters on beam pointing stability and spot sizes have been met or exceeded. The spatial overlap of the laser with the proton beam was determied by using profiles measured on screens (BTVs) immediately upstream and downstream of the Rb vapor source. Comparison images of proton beam and laser on these BTVs after alignment of the centroids of the profiles to within 300 μm is shown in Fig. 9.

A milestone was reached during the beam commissioning period at the end of September when the SPS proton beam was synchronized to better than 100 ps accuracy with respect to the laser beam. Figure 10 shows the streak camera measurement in the BTV upstream of the plasma cell.

RUN II

During Run I of the AWAKE experiment, ending with the start of the LHC LS2, the objectives are to demonstrate the proton beam self-modulation instability (AWAKE Phase 1) and to sample the strong wakefield with test electrons (AWAKE Phase 2). Run II of AWAKE is proposed to start right after the LHC LS2 with objectives to demonstrate
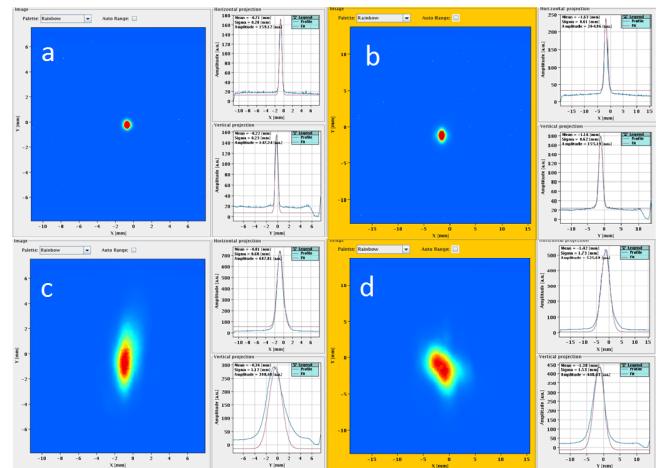

Figure 9: Laser Positioning after alignment on BTVs. a) and b): proton profiles for BTVs upstream and downstream of the vapor source. c) and d): laser profiles. The projected laser profile peaks were placed on the projected proton peaks to within 300μm.
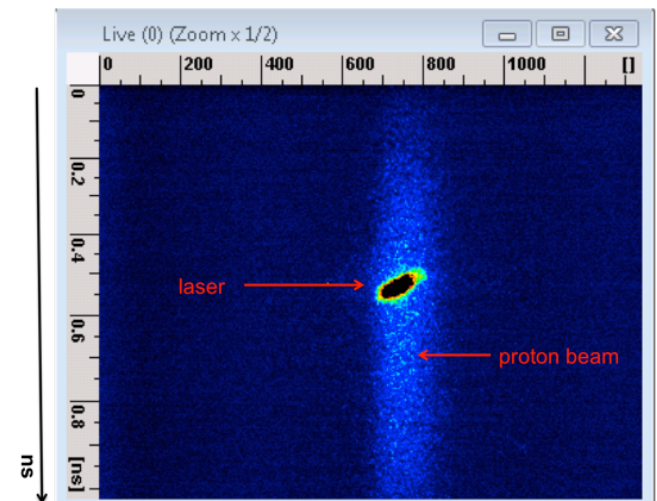

Figure 10: Synchronization of the AWAKE proton and laser beam. Streak camera measurement with the BTV upstream of the plasma cell.

high-gradient acceleration of bunches of electrons to many GeV preserving reasonable beam quality, and to demonstrate scalable plasma source technology. Successful demonstration of these two objectives will open up the path towards high energy physics applications for proton driven plasma wakefield acceleration. An option for Run II electron injection is on-axis injection between two plasma stages, as shown in Fig. 11. In order to prepare Run II, a significant research effort is required for a number of topics including scalable plasma sources, compact high peak current electron injectors, plasma staging, proton beam optimization and instrumentation development. Most research topics require numerical simulation studies. More information can be found in [21].
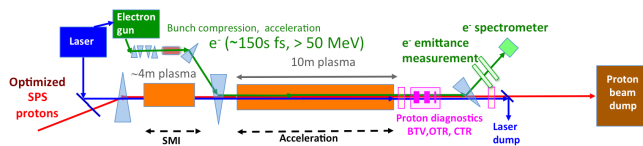
Figure 11: A possible layout for AWAKE Run II. A first plasma cell is used to self-modulate the proton beam. An electron beam is injected after the first cell and is accelerated by the modulated proton beam in a second plasma cell.

PERSPECTIVES

Plasma wakefield acceleration is a promising scheme to realize shorter or higher energy accelerators in particle physics. With the aim of demonstrating O(GV/m) accelerating gradients in a plasma, scalable over long distances, by the end of AWAKE Run II, experiments utilizing such beams could become reality from about 2025 onwards. Some ideas for future experiments based on the AWAKE scheme [22] and making strong use of the current CERN infrastructure and facilities were presented at the recent Physics Beyond Colliders Kick-off Workshop held in CERN in September. These include ideas for fixed-target experimentation with electron beams as well as ideas for very high energy electron-proton colliders.

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