AWAKE: ADVANCED PROTON DRIVEN PLASMA WAKEFIELD ACCELERATION EXPERIMENT AT CERN

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Abstract

Plasma wakefield acceleration is a promising alternative reaching accelerating fields a magnitude of up to 3 higher (GV/m) when compared to conventional RF acceleration. AWAKE, world's first proton-driven plasma wakefield experiment, was launched at CERN to verify this concept. In this experiment proton bunches at 400 GeV/c will be extracted from the CERN SPS and sent to the plasma cell, where the proton beam drives the plasma wakefields and creates a large accelerating field. This large gradient of ~GV/m can be achieved by relying on the self-modulation instability (SMI) of the proton beam; when seeded by ionization through a short laser pulse, a train of micro-bunches with a period on the order of the plasma wavelength (~mm) develops, which can drive such a large amplitude wake from a long proton bunch (~12 cm). An electron beam will be injected into the plasma to probe the accelerating wakefield.

The AWAKE experiment is being installed at CERN in the former CNGS facility, which must be modified to match the AWAKE requirements. First proton beam to the plasma cell is expected by end 2016.

INTRODUCTION

Motivation

In order to search for new physics, as well as to complement the results from the LHC at CERN, one option for a next energy-frontier accelerator could be a linear collider of electrons and positrons at the TeV energy scale. The accelerating field of today's RF cavities or microwave technology is limited to ~100 MV/m, therefore the length of future linear colliders would be several tens of kilometres. However, plasma can sustain much higher gradients [1], so plasma-based accelerators are of great interest. Three orders of magnitude higher acceleration gradient than in RF cavities have been demonstrated: with laser excitation, electrons have been accelerated to 1 GeV in 3 cm, with a gradient of 33 GV/m [2]. In [3] an electron bunch was used as driver, the energy of particles in the tail of a bunch was doubled from 42 GeV to 85 GeV in 85 cm-corresponding to a gradient of 52 GV/m.

However, the energy gain is limited by the energy carried by the laser or electron drive beam (<100 J) and the propagation length of the driver in the plasma (<1 m). Hence, staging of a large number of acceleration sections would be required to reach the interesting region of 1TeV. Proton beams, as those routinely produced at the CERN SPS, carry much higher energy (19 kJ with 3 10^{11} protons/bunch at 400 GeV/c), which makes it possible to drive wakefields over much longer plasma lengths and potentially take a witness beam to the TeV scale in a single plasma stage. Simulations have shown that an LHC-type proton bunch (1 TeV, 10^{11} protons) with an rms bunch length of 100 μm can accelerate an incoming 10 GeV electron bunch to more than 500 GeV in around 500 m of plasma with an average gradient ≥ 1 GV/m [4].

Self-Modulation Instability

To reach accelerating gradients at the GV/m level the plasma density must be on the order of $n_e = 10^{15}$ electrons/cm^3. With $\lambda_{pe} \approx (10^{15}/n_e)^{-1/2}$, the plasma wavelength is about 1 mm. In order to excite large amplitude wakefields, the proton bunch length σ_z has to be comparable with the plasma wavelength λ_{pe}. The nominal SPS bunch length at top energy (450 GeV) is $\sigma_z \sim 12$ cm. However, it was shown in [5] that a long proton beam propagating in plasma undergoes a transverse self-modulation instability (SMI) that modulates the bunch radius and density and drives the wakefields to large amplitudes – opening the path for an immediate experimental investigation of large gradient plasma wakefields with the existing proton bunches at CERN.

At saturation, the initially long and smooth beam is split into a train of micro-bunches naturally spaced at $\sim\lambda_{pe}$ and that resonantly excites the strong plasma wave. When seeded, the self-modulation instability saturates after 4 m of plasma with a density of (1-10) 10^{14} electrons/cm^3. In addition, the injection of the witness electron beam can be controlled with seeding.

THE AWAKE EXPERIMENT

AWAKE, under construction at CERN, will be the first proof-of-principle accelerator R&D experiment addressing the challenges of proton driven plasma wakefield acceleration and is under construction at CERN [6,7].

The measurement program of AWAKE includes benchmark experiments using proton bunches from the CERN SPS at 400 GeV/c to drive the wakefields and to understand the physics of the proton self-modulation instability process in the plasma. It will also probe the accelerating wakefields with externally injected electrons, study the injection dynamics and production of multi-Giga-electron-Volt electron bunches, and develop long, scalable and uniform plasma cells, and schemes for the production and acceleration of short proton bunches.

Baseline Design

For the AWAKE experiment at CERN, an LHC-type proton bunch of 400GeV/c (but with higher intensity of 3 10^{11} protons/bunch) will be extracted from the CERN SPS and sent towards a plasma cell. The proton beam will be focused to $\sigma_{x,y}$ = 200 µm near the entrance of a 10 m long plasma cell, which will have an adjustable density in the 10^{14} - 10^{15} electrons/cm^3 range.

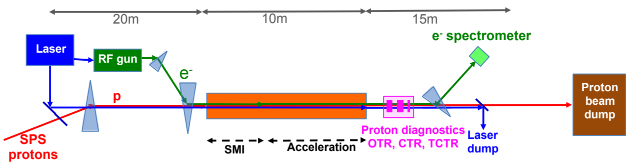

Figure 1: Baseline design of the AWAKE experiment.

When the proton bunch with an rms bunch length of σ_z = 12 cm (0.4 ns) enters the plasma cell, it undergoes the SMI [5]. The effective length and period of the modulated beam is set by the plasma wavelength (for AWAKE typically λ_{pe} = 1 mm).

A high power (< 2 TW) laser pulse, co-propagating and co-axial with the proton beam, will be used to ionize the neutral gas in the plasma cell and also generates the seed of the proton bunch self-modulation. An electron beam of 1.2 10^9 electrons, will be injected at 10 – 20 MeV/c, serves as witness beam and accelerated in the wake of the proton bunch. Several diagnostics tools will be installed downstream of the plasma cell to measure the proton bunch self-modulation effects and the electron bunch properties. Fig. 1 shows the baseline design of AWAKE.

Baseline Parameters

The baseline parameters of the AWAKE experiment are summarized in Table 1. Short high-intensity bunches have been studied at the SPS and the scaling of bunch length and transverse emittance as a function of beam intensity have been identified to help to guide the design parameters of AWAKE. At the design intensity of 3 10^{11} protons, a transverse emittance of about 1.7 µm, an r.m.s. bunch length of 9 cm (0.3 ns) and a peak current of 60 A were reproducibly achieved [8]. However, the proton baseline parameters in Table 1 reflect a conservative estimate used for integration issues and used for input in the wakefield simulation codes such as VLP [9], OSIRIS [10], LCODE [11].

Table 2: AWAKE baseline parameters

Parameter	Value
Plasma cell	
Plasma density	7 x 10^{14} cm^{-3}
Length	10 m
Plasma radius	> 1mm
Skin depth c/ω_{pe}	0.2 mm
Wavebreaking field, $E_0 = mc\omega_{pe}/e$	2.54 GV/m
Proton Beam	
Momentum	400 GeV/c
Protons/bunch	3 10^{11}
Bunch extraction frequency	0.5 Hz (ultimate: 0.14 Hz)
Bunch length	σ_z = 0.4 ns (12 cm)
Bunch size at plasma entrance	$\sigma^*_{x,y}$ = 200 µm
Normalized emittance (r.m.s.)	3.5 mm mrad
Relative energy spread	$\Delta p/p$ = 0.35%
Beta function	$\beta^*_x = \beta^*_y$ = 4.9m
Dispersion	$D^*_x = D^*_y = 0$
Electron Beam	
Momentum	16 MeV/c
Electrons/bunch (bunch charge)	1.2 E9 (0.2 nC)
Bunch length	σ_z =4ps (1.2mm)
Bunch size at focus	$\sigma^*_{x,y}$ = 250 µm
Normalized emittance (r.m.s.)	2 mm mrad
Relative energy spread	$\Delta p/p$ = 0.5%
Beta function	$\beta^*_x = \beta^*_y$ = 0.4 m
Dispersion	$D^*_x = D^*_y = 0$
Laser Beam to Plasma Cell	
Laser type	Fiber Ti:Sapphire
Pulse wavelength	λ_0 = 780 nm
Pulse length	100-120 fs
Pulse energy (after compr.)	450 mJ
Laser power	2 TW
Focused laser size	$\sigma_{x,y}$ = 1 mm
Energy stability	±1.5% r.m.s.
Repetition rate	10 Hz
Laser Beam for Electron Source	
Laser type	Ti:Sapphire Centaurus
Pulse wavelength	λ_0 = 260 nm
Pulse length	10 ps
Pulse energy (after compr.)	32 µJ
Electron source cathode	Copper
Quantum efficiency	3.00 E-5
Energy stability	±2.5% r.m.s.

The electron beam parameters show the requirements for the first proof-of-principle acceleration experiment. However, the facility must be designed in such a way that at a later stage, for split plasma cell experiments [6], higher intensities (1 nC) and shorter bunch-lengths (< 1 ps) can be provided.

The high-power laser pulse used to ionize the gas in the plasma cell and also generates a seed for the proton self-modulation instability and the laser pulse used to produce the electrons on the electron source photo-cathode are derived from the same laser oscillator, thereby insuring synchronization.

For the first experiments, the plasma cell will be a 10 m long rubidium vapour source with a low ionisation potential of 4.2 eV for the first electron [12]. Current filamentation instability, which breaks the bunch into transverse current filaments [6] and prevents the efficient excitation of plasma wakefields, should be avoided. Therefore, the plasma skin depth should be kept larger than the bunch transverse size ($c/\omega_{pe} > \sigma_{x,y}$), resulting in a limiting factor for the nominal plasma density (c/ω_{pe} prop. to $n_{p,e}^{-1/2}$) the plasma density is kept in the 10^{14} – 10^{15}cm^{-3} range. The necessary longitudinal density uniformity is around 0.2% [13].

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ELECTRON INJECTION SCHEME

On-axis injection is the baseline injection option for AWAKE; the electron beam is externally injected beam into the plasma on-axis and collinearly with the proton and laser. The on-axis injection point is upstream of the plasma cell, which allows measuring all beam injection parameters and at the same time simplifies the design of the scheme. This is contrary to the side-injection [14], where the electron beam would be injected at an angle and at a location inside the plasma cell where the SMI has fully developed.

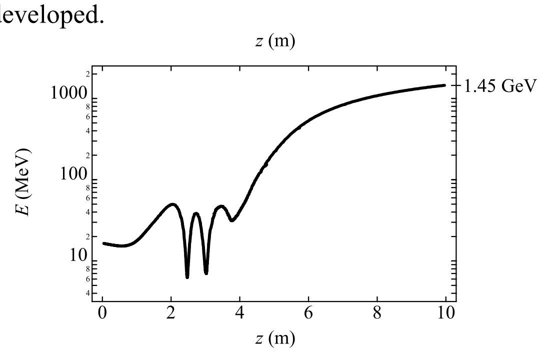

Figure 2: Energy of the electron beam gained along a 10 m long plasma cell [15].

In the on-axis scheme the electrons are trapped by the wakefield from the very beginning of seed perturbation and move with the wave while the beam self-modulates. Because of the superluminal behaviour of the phase velocity of the plasma wake after the SMI saturation, the trapped electron, which was previously oscillating near the minimum of accelerating/decelerating electric field E_z ends up in the accelerating phase. Fig. 2 shows the energy E of accelerated electrons along the plasma cell as simulated with LCODE.

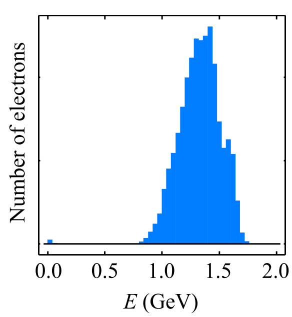

Figure 3: Energy distribution of the accelerated electron beam after 10 m plasma.

The short laser pulse propagates collinearly with the long proton beam bunch, ionizes the Rubidium vapour and creates the plasma. The leading half of the proton beam propagates in the neutral gas and only the rear half undergoes self-modulation. The electron beam is delayed with respect to the laser pulse by the distance ξ_e. Using the parameters in Table 1 simulation results show [16] that for electron acceleration to high energies the optimal distance between the electron bunch and the seed pulse is $\xi_e \approx 16$ cm. The electron capture efficiency for the beam parameters in Table 1 is at the order of 14 % and the electrons are on average accelerated up to 1.3 GeV in the 10 m long plasma cell (see Fig. 3). However, for electron beams, which are shorter than 0.5 mm, the trapping efficiency can be up to 100 %.

AWAKE AT CERN

The AWAKE experiment will be integrated in an existing area, which previously housed the CNGS (CERN Neutrinos to Gran Sasso) facility. This facility is a deep-underground area and is designed for running an experiment with high proton beam energy, such as AWAKE. The facility is fully operational, however, challenging modifications to the area are required [17].

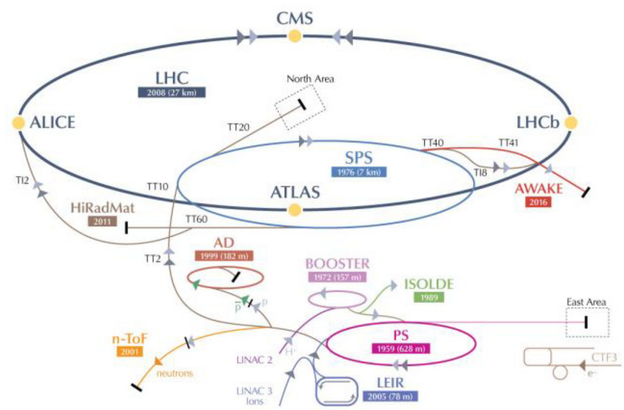

Figure 4: The AWAKE experiment in the CERN accelerator complex.

The 400 GeV/c proton beam is fast extracted from the SPS (see Fig. 4) and sent along a 750 m long proton beam line towards the plasma source, which is installed at the downstream end of the proton tunnel. Fig. 5 shows the integration of the AWAKE experiment in the facility. The beam diagnostics for the outgoing protons, as well as the electron spectrometer system, are installed in the area upstream of the CNGS target. The laser system will be installed in a dedicated clean-room and the laser beam for plasma ionization and SMI seeding is transported through a newly built tunnel (0.5 m diameter, 4 m length) connecting the laser area to the proton beam tunnel.

The PHIN injector [18], currently used in CTF2 and in a program that will stop end 2015, fulfils the electron beam requirements of AWAKE (see Table 1) and will be used as electron-source for the AWAKE experiment. In addition the klystron and modulator system will be recuperated from CTF3. However, although the hardware for the electron source exists, the performance of this complex system must be optimized and tested. The electrons are transported from the electron source system to the proton beam tunnel along the electron beam line through a new liaison tunnel (7 m long, 2.5 m wide). Downstream of the diagnostics instrumentation the proton beam vacuum tube passes the shielding separating the AWAKE area from the CNGS target area. The proton beam exits through a vacuum window and passes the 100 m long CNGS target chamber and the 1000 m long CNGS decay tunnel before being dumped in the existing CNGS beam dump, a 15 m long carbon–iron block equipped with a water cooling system.

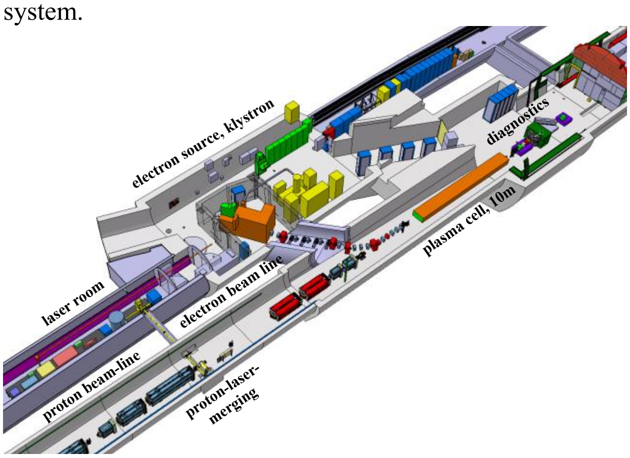

Figure 5: Integration of the AWAKE experiment in the experimental area at CERN.

Proton and Electron Beam Line

The existing CNGS proton beam line requires changes in the final part (~80 m) to comply with the AWAKE requirements [6]. Merging the proton beam with the laser beam is done by introducing a chicane in the proton beam-line; with this system an offset of 21 mm between the laser beam axis at the tuning mirror and the proton beam can be achieved ~20 m upstream of the plasma cell. The proton and laser beam have to be kept co-axial over the full length of the plasma cell and a pointing precision of 100 μm is required at the cell entrance resulting in a maximum angular error of 15 μrad for the proton beam line. The alignment of the two beams will be done with two identical OTR monitors installed around the plasma cell. Two high resolution (50 μm) BPMs will be placed downstream the plasma to check the position and angle of the proton beam [19].

The 12.2 m-long electron beam line will go from the electron source to the plasma cell. The first 1.5 m are dedicated to the acceleration system (booster linac) needed to reach a maximum energy of 20 MeV. The proton and electron beam will share a common line over the last 5 m, where the electron beam will be merged with the proton beam for on-axis injection into the plasma cell. Calculations are ongoing to study the impact of the wake-fields of the proton beam on the electron beam. These results will drive the final design of the common beam-line and the diagnostics.

Beam Synchronization

The AWAKE experiment relies critically on the relative timing of the proton, electron and laser beams. A scheme for the SPS synchronization with AWAKE has been developed.

Synchronization at the level of a few tens of femtoseconds (a fraction of the plasma period of ~4 ps) is required for the deterministic injection of the witness electron bunch into the plasma wakefields. This is achieved by driving the RF-gun of the electron source with a laser pulse, which is derived from the same laser system as used for plasma ionization and seeding. In the baseline layout the mode-locking frequency reference required by the laser generates a harmonic signal that is locked to the RF-gun.

The synchronization between the proton and the laser beam must be better than 100 ps, i.e. better than the r.m.s. proton bunch length of ~400 ps. The laser mode-locker cannot follow the changes in the SPS frequency through the acceleration cycle, and therefore the SPS beam must synchronize to the AWAKE reference just before extraction of the proton beam. The individual steps in the synchronization procedure have been well defined.

In the current baseline the mode-locking frequency (88.17 MHz) has been chosen to comply with the frequency constraints from the SPS RF frequency at extraction (200.394 ± 0.001 MHz) and the RF gun (2998.5 ± 1 MHz). In this way the relationship between the frequencies can be generated in hardware.

A system will be installed which allows to exchange the synchronization signals on ~3 km long fibres between the AWAKE facility and SPS RF Faraday Cage in BA3; these signals include the RF frequency reference as well as a pulse train at one fifth of the SPS revolution frequency (8.86 kHz) and at the laser system repetition rate (~10 Hz). The jitter of the signal transmission must be in the picosecond range; this level of synchronization has been verified with a similar system for LEP [20].

Plasma Source

The AWAKE plasma source [12] consists of rubidium vapour with a density adjustable from 10^{14} – 10^{15} cm^{-3} confined in a 10 m long 4 cm diameter stainless-steel tube.

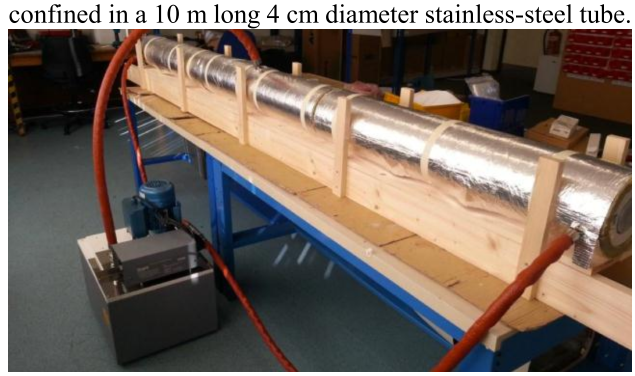

Figure 6: Prototype of a 3 m long Rubidium plasma source, courtesy of Grant Instruments Inc.

The plasma is formed using a laser pulse that has enough intensity (1.7 10^{12} W/cm^2) to field-ionize or over-the-barrier-ionize Rubidium. Since this is a threshold process, the vapour is fully ionized (first electron); therefore the plasma density and uniformity are equal to the vapour density and uniformity. By adjusting the temperature of the liquid Rb from 150 to 200°C, the required vapour densities can be reached. To provide a constant temperature within the requirement ($\Delta T < \pm 0.5$ K) and hence the required density uniformity (0.2 %) an oil bath with a heat exchanger is used. A 3 m-long prototype has been built (see Fig. 6) and the measured temperature profile showed a uniformity of $\Delta T < 0.2$ K over < 2 m. In addition the Rb

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density has been measured with an interferometry system (see [21]).

Passing the beams through the plasma is provided by custom built fast valves [22], that can open in ~ 10 ms, work in the required temperature range and Rb environment and perform at least 43000 times during a two week experiment run with beams going through every 30 seconds.

Diagnostics

The AWAKE experiment aims at measuring the proton bunch self-modulation in late 2016 and accelerating externally injected electrons a year later.

SMI Diagnostics

The SMI results in radial modulation of the proton bunch with a longitudinal period given by the plasma wave period λ_p. Different techniques will be used to measure the characteristics of the proton beam after propagating through the plasma source.

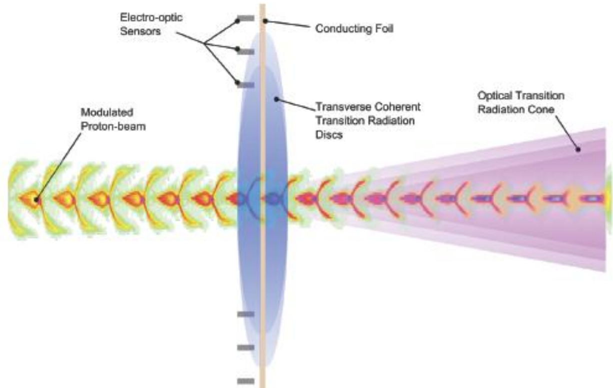

Figure 7: Schematic of the CTR and TCTR generation by a modulated particle bunch passing through a conduction foil.

The temporal intensity of the Optical Transition Radiation (OTR) from the proton bunch lasts 400 ps (see Table 1) and has a modulation period of ~4 ps. This bunch radius variation can be time-resolved with a streak camera. This diagnostics can also be used to measure the relative phasing of the laser pulse, the proton bunch and the electron bunch at the sub-picosecond level [23].

In addition detectors are under design that measure the effect of Coherent Transition Radiation (CTR) as well as the Transverse Coherent Transition Radiation (TCTR). CTR is used to determine the bunch envelope modulation period. In the TCTR the radially modulated density of the particle bunch should be imprinted to the TCTR amplitude variations. Modules with integrated waveguides and pickup antennas will collect the CTR/TCTR effectively [23].

Electron Spectrometer

The peak energy and the energy spread of the accelerated electrons will be measured with an electron spectrometer: a CERN MBPS dipole with 1 m length, 140 mm vertical and 300 mm horizontal aperture and a maximum field of 1.8 T separates the electron beam from the proton beam and allows measuring an electron energy in a range between 10 MeV and 5 GeV. The dispersed electron beam impacts on a scintillator screen and the resulting light is collected with an intensified CCD camera. The simulation code BDSIM [24] has been used to track the electron beam from the exit of the plasma cell through the quadrupoles and dipole down to the scintillator screen. The quadrupoles can be used to image the electron beam at the plasma exit (object plane) into the spectrometer image plane. Using the quadrupoles strongly improves the energy resolution and the particles density at the screen. Studies are ongoing to integrate in the simulations upstream sources of background such as particle scattering in the plasma cell in order to optimize the diagnostic components. However, first results show that the energy reconstructed with the spectrometer system agrees will with the input spectrum and demonstrate the suitability of the spectrometer system [25].

CONCLUSION

The AWAKE experiment at CERN will start in 2016 and will be the first proton-beam driven plasma wakefield acceleration experiment. The experiment will test the principle of proton beam self-modulation in plasma and electron acceleration in the excited wake. Preparations for the experiment are progressing well and the technological and experimental challenges for this new facility are under control.

The results of the AWAKE experiment will inform future larger scale R&D projects on proton driven plasma wakefield acceleration; key elements are scalable plasma sources such as metal vapour or helicon-wave plasma cells and shorter proton bunches.

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