STARTING UP THE AWAKE EXPERIMENT AT CERN

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Abstract

AWAKE, the Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN was approved in 2013. The facility was commissioned in 2016 to perform first experiments to demonstrate the self-modulation instability (SMI) of a 400 GeV/c SPS proton bunch in a 10 m long Rubidium plasma cell. The plasma is created in Rb vapor via field ionization by a TW laser pulse. In the second phase starting late 2017, the proton driven plasma wakefield will be probed with an externally injected 10 – 20 MeV/c electron beam.

This paper gives an overview of the AWAKE facility, describes the successful commissioning of the laser and proton beam line, the plasma cell and diagnostics and shows the successful synchronization of the proton beam with the laser at the few ps level so that the facility is ready for the SMI physics runs.

In addition the status of the electron acceleration experiment for late 2017 will be presented.

INTRODUCTION

The Advanced Proton Driven Plasma Wakefield Experiment, AWAKE [1, 2], is a proof-of-concept experiment at CERN and in an initial phase, aims to demonstrate 1) the self-modulation instability (SMI) [3] of the proton bunch in plasma and 2) the acceleration of externally injected electrons in the plasma wakefield, driven by the proton beam to the GeV level.

In the SMI the proton bunch is modulated due to transverse plasma wakefields into micro-bunches that are spaced at the plasma wavelength $\lambda_{pe} = 2\pi/k_{pe}$. The micro-bunches of the proton beam then resonantly drive the plasma wave.

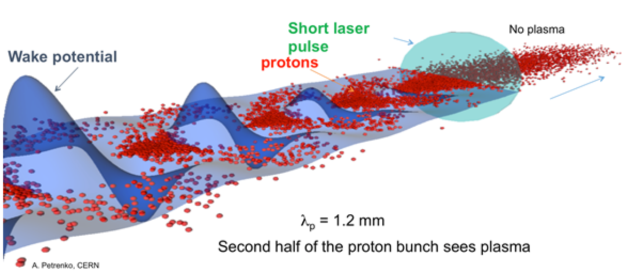

Figure 1: Simulation of the Self-Modulation Instability. The strong modulation is seen when comparing the proton distribution ahead of and behind the laser pulse.

In the AWAKE experiment, the SPS proton beam with $3x10^{11}$ protons/bunch has a momentum of 400 GeV/c and a length of σ_z = 12 cm. The plasma wavelength λ_{pe} is 1.2mm at the nominal plasma density of $7x10^{14}$ electrons/cm^3. In AWAKE the SMI effect is seeded by ionization of Rb vapour by a 4 TW laser that enters the plasma collinearly and longitudinally centred with the proton bunch. Figure 1 shows a simulation of the modulation process.

The facility for the experimental phase to demonstrate the SMI was successfully commissioned in 2016. The first physics run for SMI studies took place at the end of 2016.

In 2017 the electron source and electron beam line will be installed to be ready by the end of 2017 for first commissioning of the acceleration of electrons in the plasma wakefield driven by the SPS proton beam. Demonstration of GV/m scale accelerating gradients for electrons is planned until the CERN Long Shutdown 2 (LS2) at the end of 2018.

The AWAKE Facility

Figure 2 shows the layout of the AWAKE experiment. The proton beam extracted from the SPS is sent towards the 10 m long plasma cell. The laser is installed in a class 4 clean room and merged with the proton beam 22 m upstream the plasma cell. The SMI diagnostics are installed downstream the plasma cell.

In the following, the status and the commissioning results of the AWAKE systems are described. In addition the status of the electron source and electron beam line that are currently being installed, will be shown.

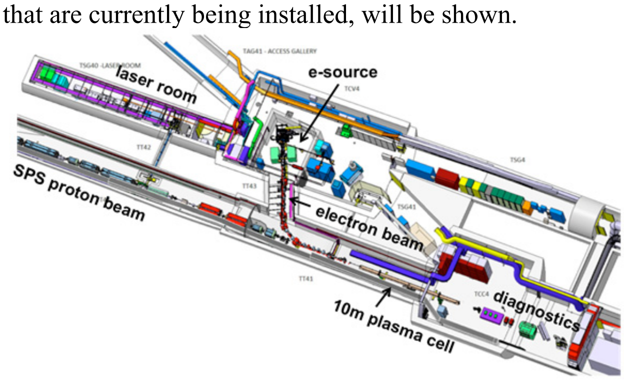

Figure 2: Layout of the AWAKE experiment.

COMMISSIONING

The commissioning of the proton, laser line, the plasma cell and experimental diagnostics has been performed during several periods in 2016 (i.e. June, September and November), interleaved by completing the installation of infrastructure, services and the SMI experiment, as well as hardware commissioning periods of the equipment.

Plasma Cell

The AWAKE plasma cell is a 10 m long laser-ionized Rb vapour cell. The required vapour density of 1 – $10x10^{14}$ cm^{-3} and its uniformity are achieved by evaporat-

ISBN 978-3-95450-182-3

ing the Rb in a heat exchanger that imposes a very uniform temperature (< 0.2%) along the 10 m. The Rb density is reached within a 180° – 230° C temperature range [4]. In order to meet the requirement of a sharp density ramp (order of ~10 cm) at the entrance and exit of the source, the vapour cell ends have a continuous Rb flow through a 10 mm diameter iris into the vacuum of a large (~170 l) expansion chamber whose walls are kept below the Rb condensation temperature of 39°C (see Figure 3). The Rb sources are installed at each end of the source close to the orifices and allow control of the vapour density gradient by the temperature difference of the Rb sources. The system consists of 15 independently controlled heating zones and of four cooling zones; 79 probes monitor the temperature.

The two Rb sources also allow the introduction of a density gradient along the source, possibly beneficial for compensating the dephasing between accelerated electrons and the plasmas wakefields. The Rb vapour density can be measured within 0.2% accuracy with white light interferometry and the anomalous dispersion around the D2 line of Rb at ~780 nm [5].

A replica of the heat exchanger and a simplified expansion chamber has been installed on the surface in the North Area experimental hall. The Rb density diagnostics as well as all control, operation and safety procedures have been developed and tested on this system both with and without Rb before Rb has been inserted into the plasma cell in the tunnel area.

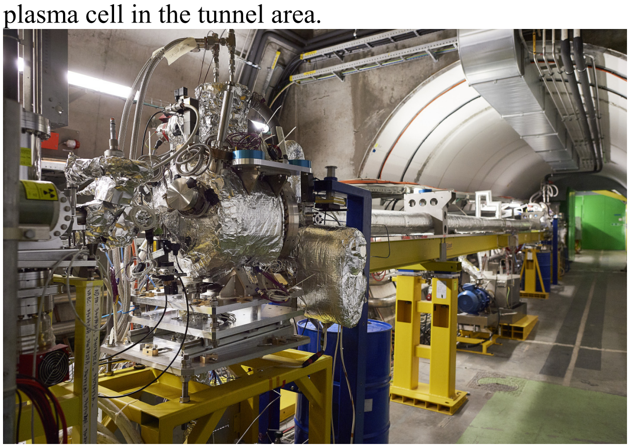

Figure 3: Looking upstream the proton beam line: Rb vapour cell with the 10 m heat exchanger and the downstream expansion chamber.

The heat exchanger was installed in the AWAKE facility in February 2016 and the plasma cell expansion chambers in October 2016. Rubidium was inserted in December 2016 after all safety procedures and the operation and control systems were approved and commissioned.

Proton Beam Line

The proton beam is extracted from the CERN SPS and sent ~810 m towards the AWAKE plasma cell. The main part of the beam line kept the configuration used for CNGS; in the last 80 m a chicane was introduced to create space for a mirror of the laser beam line, necessary to merge the laser pulse with the proton beam upstream the plasma cell. The beam instrumentation is described in detail in [6]. The detailed layout and specifications of the proton beam line have been presented in [7] and [8].

During the commissioning periods, the proton beam optics was verified and the reference trajectory established. Kick response, dispersion and optics measurements confirmed the nominal parameters. The proton beam was centred horizontally and vertically with respect to the 10mm irises of the plasma cell. The requirements on the proton size, positioning and shot-to-shot fluctuations at the plasma cell have been matched for the proton beam. Details of the proton beam line and diagnostics commissioning are presented at this conference in [6] and [9].

Laser System and Beams Synchronization

The 4 TW laser system is installed in a newly refurbished class 4 laser room. The laser system includes an erbium-doped fibre oscillator and a chirped pulse amplification system [10]. The frequency-doubled 780 nm out of the 88 MHz passively mode-locked oscillator is amplified in Ti:Sapphire crystals pumped by 543 nm beams provided by Nd:YAG lasers. The laser has a repetition rate of 10 Hz, a central wavelength of 780–875nm, pulse duration of 120 fs and an energy stability of 1.02%. The maximum output energy after compression is 450 mJ. The integration of the laser system is described in detail in [10].

The laser is connected from the optical compressor in the laser lab to the proton merging point through a vacuum tube at pressure of ~10^{-7} mbar. The deflection of the laser beam in the merging point is performed with dielectric mirrors held by motorized vacuum compatible mirror mounts [10]. A diagnostic beam line is installed in the proton beam line tunnel to measure the beam properties of a low-energy replica of the ionizing beam at exactly the distance that corresponds to the plasma cell location (i.e. 'virtual laser beam line'). The laser beam is imaged at positions corresponding to the beginning, centre and end of the plasma cell using CCD cameras.

The laser system also includes the laser safety shutters linked to the SPS access system. Thus laser experts can perform necessary work on setting up and commissioning the laser beam lines, while access of other personnel to respective zones is prohibited.

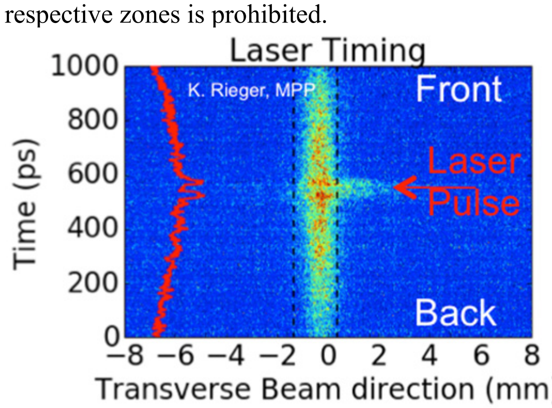

Figure 4: Measurement with the streak camera of the proton and laser beam synchronization in a 1ns window.

The alignment of the laser merging mirror with respect to the proton beam line and the virtual laser line alignment was successfully commissioned; the transverse alignment of the laser beam to the proton reference trajectory shows a laser position jitter of 130 (445) µm at the upstream (downstream) iris [9].

The longitudinal alignment, i.e. the synchronization between the laser and the proton beam has been achieved at the picosecond level (as seen in Fig. 4) and is now operational. Details of the complex synchronization system for the AWAKE beams can be found in [11].

Diagnostic Systems

The diagnostic systems aim at measuring the occurrence and characteristics of the SMI of the proton bunch. Several detectors have been installed:

1) A two-screen measurement system installed at two locations downstream the end of the plasma cell indirectly proves the successful development of the self-modulation of the proton beam by imaging protons that are defocused by the transverse plasma wakefields after passing through the plasma [12]. In order to measure the self-modulated proton beam edge next to the four orders of magnitudes more intense beam core, a combined screen consisting of an Aluminium screen surrounded by Chromox has been developed. The background signals are understood and were measured in the AWAKE experiment environment. Details of the diagnostics systems can be found in [12]. The indirect SMI system has been successfully tested and operated in 2016. Upgrades to include more flexibility in the alignment, screen changes and the readout-system for the SMI physics run in June 2017 are presented at this conference in [13].
2) The proton bunch produces incoherent, prompt optical transition radiation (OTR) when entering the aluminium coated 150 µm thick silicon screen installed 3 m downstream the plasma [14]. The OTR light is transported ~25 m by a mirror line to a streak camera with ps time resolution. The time-resolved image of the OTR light provides information on the seeding of the SMI as well as on the modulation period. The entire system has been successfully commissioned and has been operational for the first SMI studies in December 2016. Figure 4 shows the streak camera image of the proton beam and the laser synchronisation.
3) A coherent transition radiation (CTR) diagnostics has been installed upstream the OTR system and measures the frequency of the CTR emitted at the bunch modulation frequency. The CTR is in the microwave range, between 90 and 285 GHz, and can be detected when focused onto a pyro detector or when coupling part of a beam into a horn antenna and then detect it with the help of Schottky diodes. In addition, heterodyne systems will be used to measure the frequency of the CTR signal and thus of the proton bunch modulation [1]. The CTR system has been installed in 2016 and successfully tested. The integration of the experimental software into the CERN control system is described in [15].

First Physics Run for SMI Studies

During the last days of the CERN accelerator running in December 2016 first physics run for SMI studies were performed. Preliminary results show that the strong modulation of high-energy proton bunches has been observed. Further measurements in the Physics Run starting end of May 2017 will be performed to further investigate the SMI process.

ELECTRON ACCELERATION PREPARATION

The electron source for AWAKE consists of a 2.5 cell RF-gun and a 30 cell travelling wave structure (both at 3 GHz), which boosts the electron energy up to 20 MeV. They are powered by a single klystron delivering about 30MW. The operation mode is single bunch at 10 Hz [16].

The laser line to the electron gun is derived from the main driver laser for the plasma. Approximately ~3 mJ of laser light are compressed to ~10 ps using an in-air pulse compressor and a frequency converter to 260 nm via third harmonics.

The electron beam transfer line consists of an achromatic dog-leg to bring the electron beam up to the level of the proton line and a part that bends the electrons horizontally onto the proton beam axis [8]. The beam instrumentation is described in [6]. The required spot size at the focal point in the 0.5 m upstream the plasma cell is $1\ \sigma \leq 250\ \mu m$, the shot-to-shot stability is specified to ±10 µm. In the common beam line upstream the plasma cell the protons, electrons and the laser are travelling coaxially. Recent studies on proton beam – electron beam effects in the common beam line upstream the plasma cell are described in [17].

The electron spectrometer consists of a C-shaped dipole providing a 1.5T field to separate the electrons from the proton beam. The electrons are dispersed in energy onto a scintillating screen and a 17 m long optical line will transport the screen light to a CCD camera [18]. The installation of the electron source, the electron beam line and diagnostics is currently on-going. Commissioning of the electron acceleration is planned by end of 2017.

OUTLOOK

Whereas AWAKE Run 1 is a proof-of-concept experiment, AWAKE Run 2 is proposed to start after LS2, with the goal of accelerating electrons to high energies (~GeV) while preserving the beam quality and to show the scalability of this technique in order to be eventually used for first applications. In the first applications electrons of up to O (50 GeV/c) driven by an SPS proton beam could be used for fixed target experiments for deep inelastic scattering as well as dark photon searches. Other applications

ISBN 978-3-95450-182-3

include LHeC like colliders, where O (50 GeV/c) electrons could collide with LHC protons for QCD studies [19]. Finally new physics perspectives could be opened up in collisions of LHC 7 TeV protons with electrons at the TeV level, driven in the plasma wakefield by an LHC proton beam [20].

SUMMARY

The AWAKE facility has been successfully commissioned in 2016. The SMI studies, which started in 2016 will be continued in physics runs in 2017. The installation of the electron source, beam line and diagnostics is under way and commissioning of the electron acceleration experiment is planned starting end 2017. Studies on first applications of accelerators based on AWAKE-like technologies have started.

REFERENCES

[1] E. Gschwendtner et al., 'AWAKE, The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN', Nucl. Instr. Meth. Phys. Res. A 829, 76-82 (2016).

[2] A. Caldwell et al., 'Path to AWAKE: Evolution of the concept', Nucl. Instr. Meth. Phys. Res. A 829, 3-16 (2016).

[3] N. Kumar et al., 'Self-Modulation Instability of a Long Proton Bunch in Plasmas', Phys. Rev. Lett. 104, 255003 (2010).

[4] E. Oz et al., 'A novel Rb vapour plasma source for plasma wakefield accelerators', Nucl. Instr. Meth. Phys. Res. A 740(11), 197 (2014).

[5] E. Oz et al, 'An accurate Rb density measurement method for a plasma wakefield accelerator experiment using a novel Rb reservoir', Nucl. Instr. Meth. Phys. Res. A 829, 321 (2016).

[6] S. Mazzoni et al, 'Beam instrumentation developments for the Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN', these proceedings, IPAC2017, Copenhagen, Denmark, 2017.

[7] C. Bracco et al., 'The Challenge of Interfacing the Primary Beam Lines for the AWAKE Project at CERN', IPAC2014, Dresden, Germany, TUPME077, 2014.

[8] J. S. Schmidt et al., 'Status of the proton and electron transfer lines for the AWAKE Experiment at CERN', Nucl. Instrum. Meth. Phys. Res. A 829, 58-62 (2016).

[9] J. S. Schmidt et al., 'AWAKE Proton Beam Commissioning', these proceedings, IPAC2017, Copenhagen, Denmark, 2017.

[10] V. N. Fedosseev et al., 'Integration of a Terawatt Laser at the CERN SPS Beam for the AWAKE Experiment on Proton-Driven Plasma Wake Acceleration', IPAC2016, Busan, Korea, WEPMY020, 2016.

[11] H. Damerau et al., 'RF Synchronisation and Distribution for AWAKE at CERN', IPAC2016, Busan, Korea, THPMY039, 2016.

[12] M. Turner et al., 'The Two-Screen Measurement Setup to Indirectly Measure Proton Beam Self-Modulation in AWAKE', Nucl. Instr. Meth. Phys. Res. A 854, 100-106, (2017).

[13] M. Turner et al., 'Upgrade of the Two-Screen Measurement Setup in the AWAKE Experiment', these proceedings, IPAC2017, Copenhagen, Denmark, 2017.

[14] K. Rieger et al., 'GHz Modulation detection using a streak camera: suitability of streak cameras in the AWAKE experiment', Review of Scientific Instruments 88, 025110 (2017).

[15] V. Olsen et al., 'Data Acquisition and Controls Integration of the AWAKE Experiment at CERN', these proceedings, IPAC2017, Copenhagen, Denmark, 2017.

[16] K. Pepitone et al., 'The electron accelerator for the AWAKE experiment at CERN', Nucl. Instr. Meth. Phys. Res. A 829, 73-75 (2016).

[17] J. Schmidt, A. Latina, 'Simulations of Beam-Beam Interactions with RF-Track for the AWAKE Primary Beam Lines', these proceedings, IPAC2017, Copenhagen, Denmark, 2017.

[18] L. Deacon et al., 'A Spectrometer for Proton Driven Plasma Accelerated Electrons at AWAKE – Recent Developments', IPAC2016, Busan, Korea, WEPMY024, 2016.

[19] G. Xia et al., Nucl. Instr. Meth. Phys. Res. A 740, 173 (2014).

[20] A. Caldwell, M. Wing, Eur. Phys. J. C 76, 463 (2016).