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THE AWAKE EXPERIMENTAL FACILITY AT CERN

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Abstract

AWAKE, an Advanced Wakefield Experiment is launched at CERN to verify the proton driven plasma wakefield acceleration concept. Proton bunches at 400 GeV/c will be extracted from the CERN SPS and sent along a 750 m long proton line to a plasma cell, a Rubidium vapour source, where the proton beam drives wakefields reaching accelerating gradients of several gigavolts per meter. A high power laser pulse will co-propagate within the proton bunch creating the plasma by ionizing the (initially) neutral gas. An electron beam will be injected into the plasma cell to probe the accelerating wakefield.

The AWAKE experiment will be installed in the CNGS facility. First proton beam to the plasma cell is expected by end 2016. The installation planning and the baseline parameters of the experiment are shown. The design of the experimental area and the integration of the new beam-lines as well as the experimental equipment are presented. The needed modifications of the infrastructure in the facility and a few challenges are highlighted.

INTRODUCTION

An overview of the design, installation and physics program of the AWAKE experiment at CERN is shown in Figure 1; In order to house the AWAKE experiment in the CNGS facility several modifications are necessary. In 2014 part of the CNGS facility must be dismantled and two new tunnels must be dug for the electron and the laser beam. 2015 is dedicated to the installation and modification of the proton beam-line, the experimental area, the infrastructure and services.

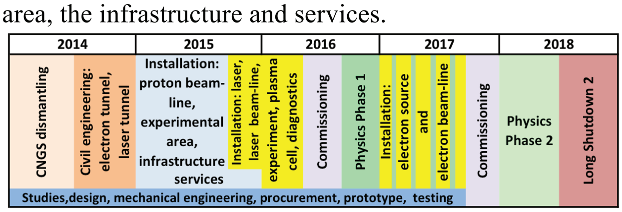

Figure 1: Overview of the AWAKE experiment program at CERN.

The experiment including the plasma cell, the laser system and the diagnostics will be installed by mid 2016. First proton beam to the plasma cell will be sent end 2016. During this period – Phase 1 – benchmark experiments using proton bunches to drive wakefields for the first time ever will be performed; the physics of the self-modulation-instability process [1] of the protons in the plasma will be studied and compared with detailed simulations. In 2017 the electron source and the electron beam line will be installed, interleaved with physics runs of 4 times two weeks. In Phase 2 (2017/2018) the accelerating wakefields are probed with externally injected electrons. In addition, the injection dynamics and production of multi-GeV electron bunches will be studied.

BASELINE PARAMETERS

The baseline beam parameters of the AWAKE experiment are summarized in Table 1. A short proton bunch length, small transverse emittance and high intensity are important requirements for AWAKE [2]. The electron beam parameters reflect the requirements for Phase 2. However, the facility must be designed in such a way that at a later stage, for split plasma cell experiments [3], higher intensities (1 nC) and shorter bunch-lengths (< 1 ps) can be provided. The high-power laser pulse, co-propagating and co-axial with the proton beam is used to ionize the gas in the plasma cell and also generates a seed for the proton self-modulation instability. The laser pulse used to produce the electrons on the electron source photo-cathode is derived from the low power level of the plasma source ionizing laser system.

Table 1: Baseline Parameters of the AWAKE Beams

Proton Beam	
Momentum	400 GeV/c
Protons/bunch	3 E11
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	$\beta^*_x = \beta^*_y$ = 4.9 m
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 = 4 ps (1.2 mm)
Bunch size at focus	$\sigma_{x,y}$ = 250 μm
Normalized emittance (r.m.s.)	2 mm mrad

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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	$\lambda_0 = 780$ 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	$\lambda_0 = 260$ 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.

AWAKE AT CERN

The AWAKE experiment will be integrated into an existing facility, imposing challenging modifications on the facility. Some highlights are shown in this chapter.

Experimental Facility

Figure 2 shows the integration of the AWAKE experiment in the CNGS facility. The existing CNGS proton beam line requires changes in the final part (~80 m) to comply with the AWAKE requirements [4]. The 10 m long Rubidium vapour plasma source [5] is installed at the downstream end of the proton tunnel. The beam diagnostics for the outgoing protons as well as the electron spectrometer system are installed in the area upstream of the CNGS target. Details of these detectors and their expected performance can be found in [6] and [7]. The design of the proton, electron and laser beam-line [8] allows the civil engineering for the laser and electron tunnel to start on time in July 2014 and to be completed by end 2014.

The laser system will be tested together with a plasma cell prototype at the Max Planck Institute in Munich, Germany, before it will be shipped to CERN and installed in the dedicated laser room in 2015. Merging the proton beam with the laser beam is done by introducing a chicane for 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 [8].

The PHIN injector [9], currently used in CTF2 and in a program that will stop end 2015, fulfils the electron beam requirements of AWAKE for Phase 2 (see Table 1). Therefore this injector 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. Studies on the integration of the electron-source in the AWAKE area are ongoing.

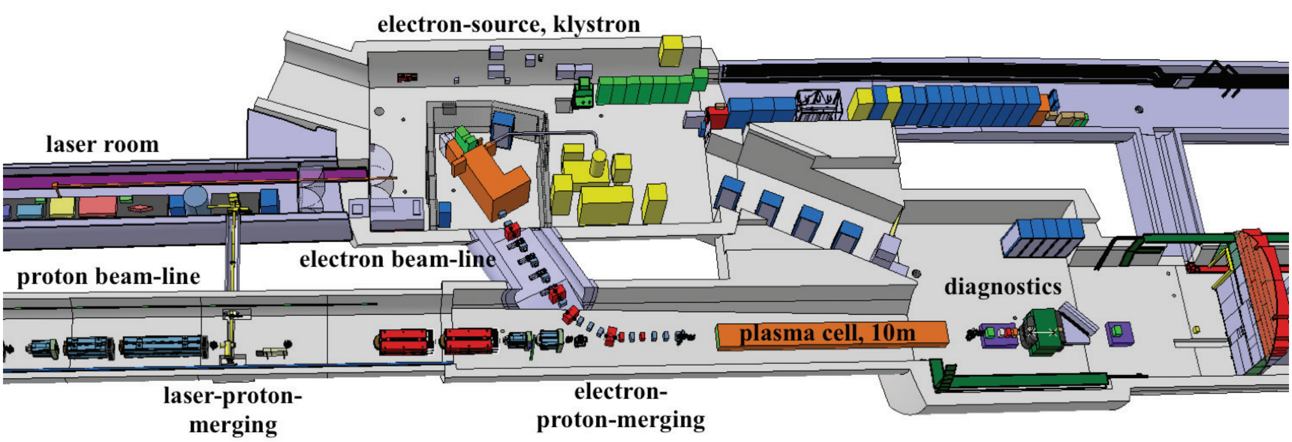

Figure 2: Integration of the AWAKE experiment in the experimental area. The 10 m long plasma cell (orange) is installed at the downstream part of the proton beam-line.

Radiation Protection

Radiation protection calculations have been performed using FLUKA Monte Carlo code [10,11] to study the radiation environment in the AWAKE facility. The preliminary results show that access to the AWAKE experimental area has to be prohibited during the proton beam operation as the dose equivalent rate is exceeding

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100 mSv/h (see Figure 3). Furthermore, the high-energy hadron fluence is estimated at the order of 10^8 cm^{-2} per month, which creates a harsh environment for electronics in the vicinity of the plasma cell. This has to be taken into account when defining the positions of electronic racks.

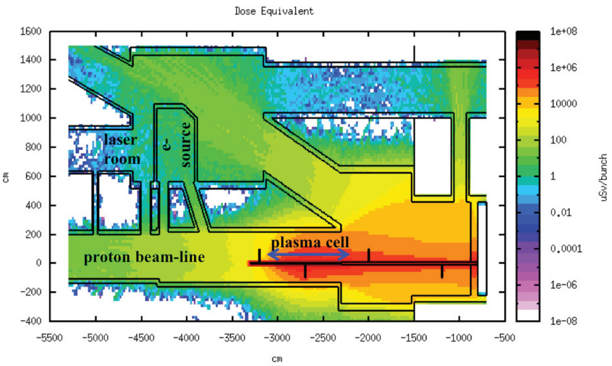

Figure 3: Dose equivalent rate during proton beam operation.

The AWAKE proton beam will hit the former CNGS target, causing airborne radioactivity downstream of the AWAKE experimental area. Therefore, an airtight separation wall is required between the two areas and a dedicated ventilation system will be installed. In addition, the separation wall will shield the activated material in the CNGS target area. To allow partial access to the ventilation chamber and the laser room during the operation of the electron beam, an appropriate shielding wall around the electron gun has to be designed.

Electron Injection

The electron injection into the plasma cell has a strong impact on the complexity of the design of the common beam part of the electron and the proton beam line [8] as well as on the plasma cell and the electron spectrometer. Therefore the injection of the electron beam into the plasma cell has been recently reviewed [12] and as a consequence the on-axis injection was selected as baseline injection option for the AWAKE experiment. Contrary to the side-injection, where the electron beam would be injected at an angle and at a location inside the plasma cell where the SMI has fully developed, the on-axis injection is done upstream of the plasma cell which allows to measure all beam injection parameters and at the same time simplifies the design of the injection scheme. Simulation results show [13] that the performance of the experiment is hardly affected by this simplified scheme; the electron capture efficiency for the beam parameters in Table 1 is at the order of 14% and the electrons are accelerated up to 1.3 GeV in the 10 m long plasma cell.

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 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. 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 at the order of 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.

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 has been verified with a similar system for LEP [14].

CONCLUSION

The AWAKE experiment will have first proton beam to the plasma cell by end 2016. The preparation of the facility is progressing well. The baseline parameters are defined. The integration of the facility is well advanced. Radiation protection issues are well under control. The on-axis injection scheme has been defined as baseline injection, simplifying the design of the area interfacing the proton, laser, electron beam as well as the plasma cell. A scheme for the three-beam synchronization has been developed.

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