FEASIBILITY STUDY OF THE AWAKE FACILITY AT CERN

E. Gschwendtner, C. Bracco, B. Goddard, M. Meddahi, A. Pardons, E. Shaposhnikova, H. Timko, F. Velotti, H. Vincke, CERN, Geneva, Switzerland

Abstract

Plasma Wakefield acceleration is a rapidly developing field which appears to be a promising candidate technology for future high-energy accelerators. The Proton Driven Plasma Wakefield Acceleration Experiment has been proposed as an approach to eventually accelerate an electron beam to the TeV energy range in a single plasma section. To verify this novel technique, a proof-of-principle demonstration experiment, AWAKE, is proposed using 400 GeV proton bunches from the SPS.

Detailed studies on the identification of the best site for the installation of the AWAKE facility resulted in proposing the CNGS facility as best location. Design and integration layouts covering the beam line, the experimental area and all interfaces and services are shown. Among other issues, radiation protection, safety and civil engineering constraints are raised.

INTRODUCTION

It has been recently proposed to use a high-energy proton bunch to drive a plasma wakefield for electron beam acceleration [1]. Numerical simulations have shown [2] that a 1 TeV bunch, with 10^{11} protons and an rms bunch length of 100 μm as driver could indeed excite a large amplitude plasma wave. Surfing the appropriate phase of the wave, an electron bunch reaches energies over 600 GeV in a single passage through a 450 m long plasma. Recent studies [3, 4] have shown that similar gradients can be reached with a modulated long proton bunch, opening the path for an immediate experimental investigation with the existing proton bunches at CERN. The modulation of the proton density on axis results from the transverse focusing and defocusing field along the bunch. For coherent wakefield excitation, this is equivalent to having a series of ultra-short proton bunches with an effective length and period set by the plasma wavelength.

The AWAKE experiment will use proton bunches for the first time ever to drive plasma wakefields. The main physics is explained in [5] and the goals of the experiment are:

- Perform benchmark experiments using proton bunches to drive wakefields.
- Understand the physics of the self-modulation instability process (SMI) in the plasma. Compare the experimental data with detailed simulations.
- Probe the accelerating wakefields with externally injected electrons, including energy spectrum measurements for different injection and plasma parameters.
- Study the injection dynamics and production of multi-GeV electron bunches. This will include using a plasma density step to maintain the wakefields at the GV/m level over meter distances.
- Develop long, scalable and uniform plasma cells.
- Develop schemes for the production and acceleration of short proton bunches for future experiments and accelerators.

BASELINE DESIGN

For the AWAKE experiment an LHC type proton bunch beam of nominally 400 GeV is extracted from the SPS and sent towards a plasma cell to drive plasma wakefields. An electron beam injected at 10 – 20 MeV serves as witness beam and is accelerated in the wake of the proton bunches. Table 1 characterizes the proton and electron baseline parameters. Figure 1 gives an overview of the baseline design of the AWAKE experiment. A laser pulse coincident with the proton bunch ionizes the (initially neutral) gas in the plasma cell, forms a plasma and also generates a seed of the proton bunch self-modulation.

Table 1: Baseline Parameters of the AWAKE Experiment

Parameter & notation	**Value**
Plasma density, n_e	$7\cdot10^{14}$ cm^{-3}
Plasma ion-to-electron mass ratio (Rb), M_i	157 000
Proton bunch population, N_b	$3\cdot10^{11}$
Proton bunch length, σ_z	12 cm
Proton bunch radius, σ_r	0.02 cm
Proton energy, W_b	400 GeV
Proton bunch relative energy spread, $\delta W_b/ W_b$	0.35%
Proton bunch normalized emittance, ε_{bn}	3.5 mm mrad
Electron bunch population, N_e	$1.25\cdot10^9$
Electron bunch length, σ_{ze}	0.25 cm
Electron bunch radius at injection point, σ_{re}	0.02 cm
Electron energy, W_e	16 MeV
Electron bunch normalized emittance, ε_{en}	2 mm mrad
Injection angle for electron beam, ϕ	9 mrad
Injection delay relative to the laser pulse, ξ_0	13.6 cm
Intersection of beam trajectories, z_0	3.9 m

The plasma length is determined by the distance it takes for the self-modulation instability to saturate (~4 m at a plasma density of n_e=7x10^{14} cm^{-3}) and from the desired energy gain by the injected electrons. Simulations show

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that the energy gain of 20 MeV electrons injected at the SMI saturation point can reach several GeV in a 5 m plasma. Therefore the total plasma length initially chosen is ~10 m. The longitudinal density uniformity must be of the order of 0.2%. For the first experiments, the plasma cell for the proton bunch modulation measurements is a metal vapour source (rubidium). In addition studies on long scalable uniform plasma cells such as discharge and helicon sources continue.

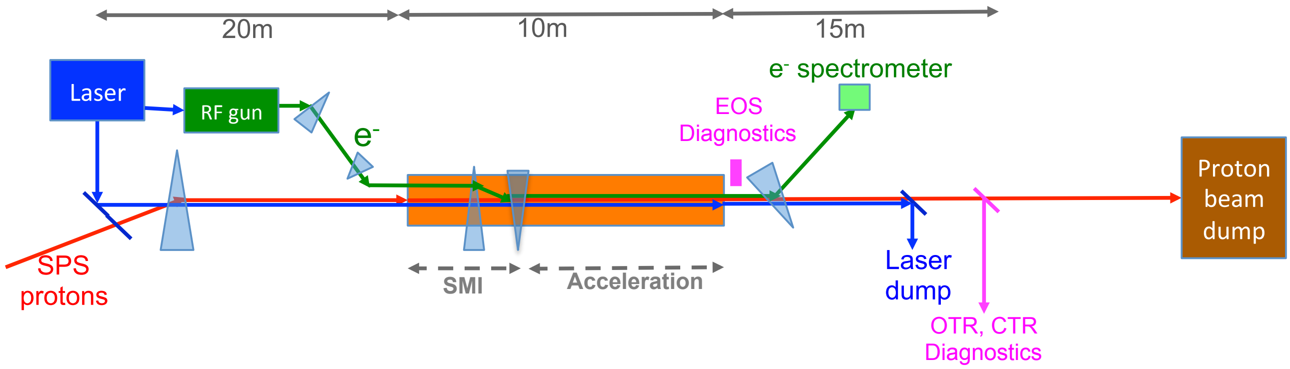

Figure 1: Baseline design of the AWAKE experiment.

The electrons are injected into the front-face of the plasma cell, accelerated in the wake of the proton bunches and analysed with a spectrometer system downstream the plasma cell.
The laser pulse that is used to produce the electrons on the source photo-cathode is derived from the low power level of the plasma source ionizing laser system ensuring synchronization between the different beam types. Currently a fibre/Ti:Sapphire laser system is under consideration.
Several diagnostic tools are installed in the experimental area in order to measure the proton bunch self-modulation effects. A state of the art magnetic spectrometer with a very large momentum acceptance (10 – 5000 MeV) and a good momentum resolution is installed downstream the plasma cell to measure the electron bunch properties; the electrons are separated from the protons by a dipole spectrometer magnet. Scintillating crystals connected to a CCD camera are used to image the electrons exiting the spectrometer.
A few measurement sessions were conducted to determine the achievable bunch properties and their reproducibility in order to obtain the shortest possible bunch length in combination with the smallest transverse emittances and highest bunch intensity. Details of these studies are presented in [6].

THE AWAKE FACILITY AT CNGS

Overview

The CNGS facility [7] is a deep-underground area and is designed for running an experiment with high proton beam energy, such as AWAKE, without any significant radiation issue. The facility is fully operational, with a 750 m long proton beam line designed for a fast extracted beam at 400 GeV as needed by AWAKE. Installing the AWAKE experiment upstream of the CNGS target (see Fig. 2) is possible with only minor modifications to the end of the proton beam line; these include changes to the final focusing system and the integration of the laser and electron beam with the proton beam. Details of the proton beam line can be found in [8]. General services such as cooling, ventilation, electricity, radiation monitoring and access system exist, are operational and need only some minor modifications to be adapted to the AWAKE experimental setup. Civil engineering modifications are necessary to be able to combine the electron beam and the laser pulse with the protons in the plasma cell. The AWAKE facility will be separated from the radioactive area located downstream the CNGS target area by a shielding wall.

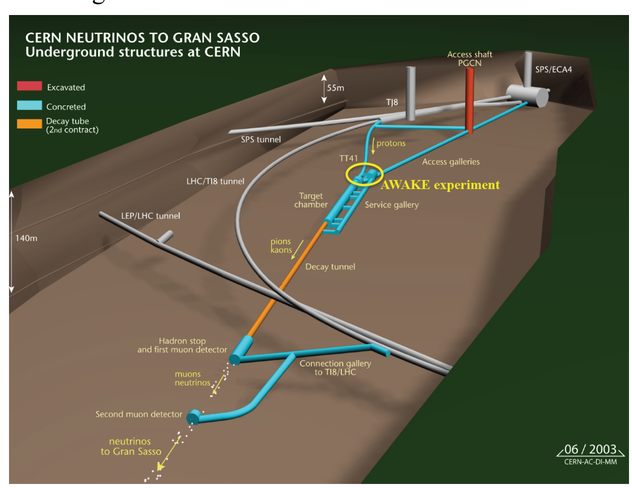

Figure 2: The AWAKE experiment in the CNGS facility.

Experimental Area

The AWAKE experiment will be installed in the CNGS facility as shown in Fig. 3. The plasma cell is housed in the downstream end of the CNGS proton beam tunnel. The beam diagnostics for the outgoing protons as well as the electron spectrometer system are installed in the area upstream the CNGS target. The CNGS storage gallery will be modified to become a dust-free (consequently over-pressurized) and temperature regulated area to house the laser system. The electron source is installed in the ventilation chamber. A major part of the electronic racks is installed in the service gallery parallel to the target area. The high power laser beam used for plasma ionization and bunch-modulation seeding is transported through a new dedicated tunnel (0.5 m diameter, 4 m length) connecting the laser area to the proton beam tunnel. The compression of the pulses will be performed in a vacuum chamber coupled to the proton beam line, located at the laser/proton beam junction. The laser beam for the electron injector (red line in Fig. 3) is taken from the uncompressed part of the pulse for the plasma production.

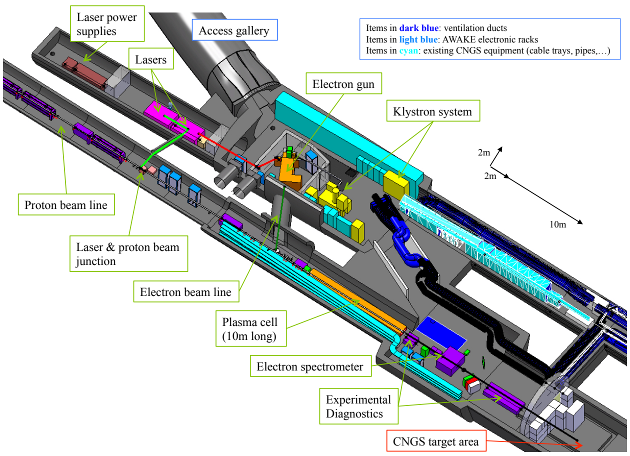

Figure 3: Integration of the AWAKE experimental components in the experimental area.

The klystrons powering the electron source are housed in the ventilation chamber, which is a low-radiation area and free of electromagnetic interference (necessary for the klystron). 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, 1 m wide and 2.5 m high). In the early stage of the experiment a 10 m long plasma cell is installed in the downstream end of the proton tunnel. This area can be modified to house a shorter vapor cell and a helicon and/or discharge source. In order to avoid accidental venting and possible contamination from the plasma vapor to the proton beam line vacuum, a double window system for the proton beam is integrated in the new design, 46 m upstream of the plasma cell. The electron beam dump is located immediately after the electron spectrometer. Energy deposition estimates lead to a beam dump design with a 30 cm thick block of iron surrounded by 30 cm thick concrete shielding. Downstream of the diagnostics instrumentation the proton beam vacuum tube goes through the shielding separating the AWAKE area from the CNGS target area. The proton beam exits through a vacuum window and passes the 100m long target chamber and the 1000 m long decay tunnel before being dumped in the existing CNGS beam dump, a 15m long carbon–iron block equipped with a cooling system.

Radiation and Safety Issues

For the AWAKE facility radiation protection studies on material, cooling and soil activation, prompt radiation and airborne activity were performed and showed no or acceptable radiological constraints. In addition, the general safety requirements of the experimental set-up are considered in the design of the facility. The AWAKE area is separated from the downstream part of the CNGS target area by an 80 cm thick concrete chicane shielding and dust-proof separation doors. This keeps radiation dose in the AWAKE experimental area minimal. The CNGS target area is also separately ventilated in order to avoid corrosion of the CNGS equipment inside (target, horns). Additional local access doors for the laser room, the electron source and the upper floor above the electron source as well as a 30 cm thick shielding wall around the electron source are required to allow stand-alone operation for the different systems. Special conditions are required for the doors to the laser area: access to this area must be allowed, but for laser specialists only when the laser beam is ON. The access system to the AWAKE area during proton beam mode is used in the same way as for CNGS: when the proton beam is switched on, access to the experimental area is prohibited and the corresponding access door is 900 m upstream in ECA4.

SUMMARY

The AWAKE experiment will use proton bunches for the first time ever to drive plasma wakefields. The CERN SPS beam is an ideal tool to perform this accelerator R&D proof-of-principle experiment. The feasibility of the baseline experiment has been shown. The infrastructure and beams can be made available at CERN with the first beam sent to the plasma cell by the end of 2015.

ACKNOWLEDGMENT

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