

PROGRESS TOWARD AN EXPERIMENT AT AWAKE

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Abstract

We briefly report on the progress towards an AWAKE experiment at CERN. First experiments are scheduled for the end of 2016 and will focus on the study of the self-modulation instability. Later experiments, scheduled for 2017-18, will study acceleration by externally injecting electrons into the wakefields.

INTRODUCTION

The AWAKE experiment at CERN aims at studying the use of proton (p^+) bunches to drive wakefields in plasmas to accelerate electrons (e^-) [1]. The first phase of the experiment, scheduled for the end of 2016, will study the physics of the self-modulation instability (SMI) [2] of a long ($\sigma_z = 12$ cm) CERN-SPS p^+ bunch in a dense plasma, i.e., such that $\sigma_z \gg \lambda_{pe} \sim n_e^{1/2}$. Here $\lambda_{pe} = 2\pi c/\omega_{pe}$ is the wavelength of the relativistic plasma wave or wakefields in an electron plasma of density n_e and plasma electron angular frequency $\omega_{pe} = (n_e e^2 / \epsilon_0 m_e)^{-1/2}$. In a second phase, scheduled for 2017-18, a low energy e^- witness bunch (10-20 MeV) with length $\approx \lambda_{pe}$ will be injected in the plasma to sample the wakefields and potentially reach an energy > 1 GeV, with a finite energy spread. We describe here the state of readiness of the major components of AWAKE for the first experiments.

FACILITY

A major component of the experiment is the facility that has been built in place of the CNGS facility. The commissioning of the facility will be completed in 2017.

PROTON BEAM LINE

The p^+ beam line consists mainly of: a final focus system; a horizontal magnetic chicane to allow for the p^+ bunch to become co-linear with a laser beam used for plasma formation and SMI seeding; three screens to measure the p^+ bunch transverse size; a number of magnetic correctors, beam position monitors, current transformers and beam loss monitors that form the standard beam line instrumentation. The first pilot p^+ bunch ($\approx 10^9 p^+$) was brought to the beam dump. The beam line was successfully commissioned and produced the expected p^+ bunch parameters: energy of ≈ 400 GeV (SPS beam), $1-3 \times 10^{11} p^+/\text{bunch}$, focused beam size $\sigma_r^* \approx 200 \mu\text{m}$ and $\beta^* \approx 5$ m.

The plasma source consists of a rubidium (Rb) vapor source and of a laser for ionization of the vapor [3].

Vapor Source

The vapor source is designed to produce an ≈ 10 m-long column of Rb vapor with density n_{Rb} in the $1-10 \times 10^{14} \text{ cm}^{-3}$ range ($7 \times 10^{14} \text{ cm}^{-3}$ nominal), with a very uniform density profile ($\delta n_{Rb}/n_{Rb} < 0.2\%$) and with a sharp density edge at each end, with a drop in density by approximately two orders of magnitude in a few centimeters. The source is based on a long heat exchanger (see Fig. 1) ensuring the density uniformity by imposing a very uniform temperature along the vapor column ($\delta n_{Rb}/n_{Rb} \propto \delta T/T$ in absence of flow). The sharp density edge at each end is created by expansion of the Rb vapor into a vacuum volume through a 1 cm diameter aperture [4]. The source uses two Rb evaporation reservoirs and the vapor density is measured at each end with a relative accuracy of better than 0.5% using the anomalous optical dispersion around the D2 line of Rb at 780 nm [5]. Note that



Figure 1: Picture of the vapor source 10 m-long heat exchanger under installation in the AWAKE facility. The picture is looking towards the SPS.

since the source has two Rb reservoirs it can also generate essentially linear density gradients along the source.

Rubidium was chosen because of its low ionization potential ($\phi=4.177$ eV for the first e^-) and its relatively large vapor pressure. Temperatures between 150 and 230 °C are sufficient to reach the desired density range. The heat exchanger satisfied the required temperature uniformity specifications and is installed in the AWAKE facility. The source ends are currently under installation and commissioning.

Laser

The laser for vapor ionization is an Erbium-doped fiber oscillator followed by a CPA Ti:Sapphire amplification chain.

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It delivers with a 10 Hz repetition rate a $\approx 120\text{ fs}$ pulse, with up to 450 mJ after the optical compressor. The laser is located in a radiation-free zone and the pulse sent under vacuum to the vapor source through a $\approx 50\text{ m}$ transport line. The beam is focused by a telescope located before the compressor, to a transverse radius of $\approx 1\text{ mm}$ near the entrance of the vapor column. The system is equipped with a "virtual plasma" with three cameras located at the virtual entrance, middle and end of the vapor column for online monitoring of the beam transverse size. The laser and transport lines have been installed (see Fig. 2) and commissioned, and delivered the expected laser parameters at the vapor source entrance.

Laser ionization serves two purposes in AWAKE. First, with a pulse intensity exceeding the ionization appearance value for the first Rb e^- ($\approx 1.7 \times 10^{12}\text{ W/cm}^2$) field-ionization converts the Rb density profile into an identical plasma density profile. Second, by propagating the laser pulse co-linearly with and within the p^+ bunch, the abrupt start of the beam/plasma interaction (time scale $\ll 1/\omega_{pe}$) seeds the SMI. This is necessary since numerical simulation results show that without seeding the SMI does not grow significantly over the 10 m plasma length. This is also necessary to produce a phase reference for the start of the wakefields, in order to be able to deterministically inject a witness e^- bunch into the accelerating and focusing phase of the wakefields in future experiments with a witness bunch shorter than λ_{pe} [6].



Figure 2: Picture of the laser room in the AWAKE facility. The optical compressor is in the foreground and the laser behind it. The optical transport line to the vapor source is on the left hand side, towards the ceiling.

Synchronization

For SMI experiments the laser pulse and p^+ bunch must only be synchronized at the 10 ps time scale. For the later experiments mentioned in the previous section, synchronization at the fraction of a plasma period ($< \pi/4\omega_{pe}$, i.e., sub- 100 fs) will be required. This is accomplished by using phase-locked-loops to ensure the laser oscillator (at $\approx 88\text{ MHz}$), the e^- RF-gun source (at $\approx 2.997\text{ GHz}$), the SPS RF frequency (at $\approx 204\text{ MHz}$) and the laser amplifier 10 Hz repetition rate are all synchronized to a master oscillator (at $\approx 6\text{ GHz}$), so that the laser pulse and the p^+ and e^- bunches enter the plasma with the desired delays. This is possible because the same laser oscillator will be used to drive the amplifi-

cation chain of the ionizing laser and that for the RF-gun photo-cathode.

Locking of the SPS RF to the AWAKE master clock is achieved using a $\approx 3\text{ km}$ -long phase-compensated optical fiber system [7].

Note that injection of a witness bunch generated by a laser wakefield accelerator is also envisaged [8]. In this case excellent synchronization may be achieved between the ionizing laser pulse (i.e., the wakefields) and the witness bunch. Synchronization with the p^+ bunch is limited by synchrotron oscillations of the bunch in the SPS RF bucket to an rms value of $\approx 15\text{ ps}$.

Synchronization between the laser pulse and the p^+ bunch was achieved during the September commissioning.

PROTON BUNCH SMI DIAGNOSTICS

The main diagnostics for the initial experiments are designed to detect the occurrence of the SMI.

Bunch Transverse Profile

The SMI creates a core of particles that originate from the focusing regions of the wakefields and a halo of particles that originate from the defocusing regions. These can in principle be distinguished on time integrated transverse profiles of the bunch. Three screens have been installed, one upstream of the plasma, one $\approx 2\text{ m}$ and one $\approx 10\text{ m}$ downstream from the plasma exit. Numerical simulations suggest that information about the SMI development can be retrieved from these profiles. In order to adjust to the various particle densities expected at these locations and acquire useful images in a single event, the screens use optical transition radiation (OTR) with a low light yield for the core, high-density of the bunch and high-light yield chromox screen for the low-density bunch halo [9].

OTR Time Resolved Diagnostic

The occurrence of SMI creates a modulation of the bunch charge density along its axis. This occurs because with the AWAKE parameters the SMI reaches the non-linear regime of the wakefields (i.e., $E_{z,max}/E_{WB}=0.1\text{--}0.5$ according to simulations, E_{WB} , the wave breaking field). Transition radiation in the visible spectrum range, i.e., OTR, emitted backwards when the bunch enters an thin aluminum-coated silicon wafer, is incoherent and has the same time structure as p^+ bunch charge density. It is imaged onto CCD cameras to obtain time integrated transverse bunch profiles and onto the entrance slit of a streak camera to time-resolve the signal at the ps -time scale. We have shown in test measurements that the modulation of a light signal with nanosecond duration can be detected up to modulation frequencies $>350\text{ GHz}$ in a single event [10]. The maximum modulation expected in AWAKE is on the order of $\approx 285\text{ GHz}$ with $n_e = 10^{15}\text{ cm}^{-3}$. The modulation frequency is detected in the power spectrum of the FFT of the streak camera image profile.

The OTR diagnostic set-up, including screen, light transport line, CCDs and streak camera have been installed (see

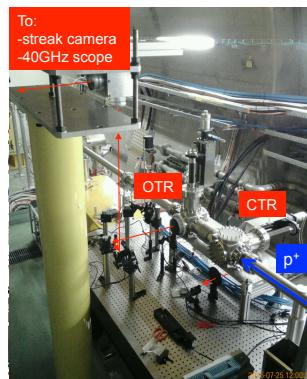


Figure 3: Picture of the laser room in the AWAKE facility. The optical compressor is in the foreground and the laser behind it. The optical transport line to the vapor source is on the left hand side.

Fig. 3) and commissioned. The OTR light yield is sufficient to observe the p^+ bunch on the streak camera even at the fastest streaking time scale.

CTR Heterodyne Measurements

The modulated bunch emits coherent transition radiation (CTR) at the modulation frequency, that is at $\cong 2\pi/\omega_{pe}$, in the microwave range, between 85 and 285 GHz in AWAKE. In this diagnostic, the frequency of the CTR, f_{RF} , will be determined by mixing the signal in a Schottky diode with the signal of a local oscillator at a known frequency f_{LO} . The diode will generate an intermediate frequency signal difference at $f_{IF} = |f_{RF} - f_{LO}| \ll f_{RF}, f_{LO}$. The f_{LO} value will be chosen from the value “guessed” from $f_{RF} \cong \omega_{pe}/2\pi \propto n_e^{1/2}$ to bring the f_{IF} frequency within reach of a 10-20 GHz-bandwidth oscilloscope. Note that because of the absolute value in the f_{IF} expression, two measurements with slightly different values of f_{LO} are necessary to determine f_{IF} unambiguously. The f_{IF} frequency must be kept large enough to be able to record multiple oscillations of the signal within the CTR emission time, i.e., within $\cong \sigma_z/c$.

Calculations of the CTR characteristics (emission angle, frequency, power, etc.) with the actual p^+ bunch distribution obtained from simulations show that the the modulation signal with frequency near $\omega_{pe}/2\pi$ has significant power (watts) and is emitted at an angle that varies with modulation frequency.

In one case the local oscillator signal will be generated directly on the Schottky diode itself from the rectification of the signal of two laser pulses with beating frequency f_{LO} [11]. In this case, the laser beams with wavelength around $1.5 \mu m$ will be brought to the diode by an optical fiber and the 10-20 GHz signal will be brought to the oscilloscope using a high-frequency coaxial cable and an amplifier.

In the other case the signal at f_{RF} will be transported to the waveguide-based heterodyne mixer using an over-moded rectangular waveguide.

The first system offers the advantage of the very broad spectrum application, possibly over entire desired range (85-285 GHz), at the expense of signal sensitivity. The second

system offer high-sensitivity at the expense or working only within microwave bands and therefore requiring three heterodyne systems to cover the desired frequency range.

The CTR diagnostics have been installed (see Fig. 3) and commissioned.

SUMMARY AND CONCLUSIONS

The commissioning of the AWAKE experiment is proceeding according to schedule. In particular, the full intensity p^+ bunch was brought to the dump, the ionizing laser pulse was aligned to the p^+ beam and the diagnostics were aligned. OTR light was detected on the streak camera even at the fastest time scale. The DAQ system performed well. The current schedule calls for a short experimental run in December 2016. The most challenging pieces of equipment are the Rb vapor source ends. They have been developed since their “invention” around New Year 2015. The challenges with the new source include the maintaining of the temperature uniformity all the way to the expansion apertures, the precise control of the Rb reservoirs temperatures, mainly for a precise control of the density gradient, and the handling of the (relatively) large amount of Rb required for operation. Safety, handling, recycling and disposal procedures are still actively being developed. We note here that the development of the SMI is very weakly sensitive to plasma density non-uniformities [12].

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3: Advanced Acceleration Techniques and Alternative Particle Sources