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Commissioning of beam instrumentation at the CERN AWAKE facility after integration of the electron beam line

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Abstract. The Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) is a project at CERN aiming to accelerate an electron bunch in a plasma wakefield driven by a proton bunch. The plasma is induced in a 10 m long rubidium vapor cell using a pulsed Ti:Sapphire laser, with the wakefield formed by a proton bunch from the CERN Super Proton Synchrotron (SPS). A 16 MeV electron bunch is simultaneously injected into the plasma cell to be accelerated by the wakefield to energies in the GeV range over this short distance. After successful runs with the proton and laser beams, the electron beam line was installed and commissioned at the end of 2017 to produce and inject a suitable electron bunch into the plasma cell. To achieve the goals of the experiment, it is important to have reliable beam instrumentation measuring the various parameters of the proton, electron and laser beams. This contribution presents the status of the beam instrumentation in AWAKE and reports on the performance achieved during the AWAKE runs in 2017.

1. Introduction

AWAKE is an experiment that operates at CERN to demonstrate the acceleration of electrons in a plasma driven by high-energy proton bunches[1, 2, 3]. A high-power infrared pulsed laser is used to ionize the rubidium vapor inside a 10 m long cell creating a plasma channel along the propagation path of the laser. The co-propagating 400 GeV proton bunch from the SPS interacts with this plasma resulting in a density modulation along the bunch and further enhancement of plasma oscillations through the creation of proton micro-bunches. The described process is called seeded self-modulation (SSM). The frequency of the proton density modulation (the duration of micro-bunches) is between 90 - 300 GHz and is defined by the plasma density which is in the range of 10^{14} - 10^{15} electrons/cm^3. Along with the laser and the proton beams, a 16 MeV electron bunch is simultaneously injected in the plasma cell, where it should be accelerated up to the GeV energy range in a very short distance by the plasma wakefields.

The layout of the AWAKE experiment is shown in Fig. 1. The high-energy proton bunch has an intensity of $\sim 3 \times 10^{11}$ protons, while 780 nm laser pulse has a duration of 100 fs and a typical energy of 450 mJ. The electron bunch with an intensity of about 10^{9} electrons is created by an RF photoinjector located in the electron hall and transported via a transfer line before being injected into the common proton/laser line.

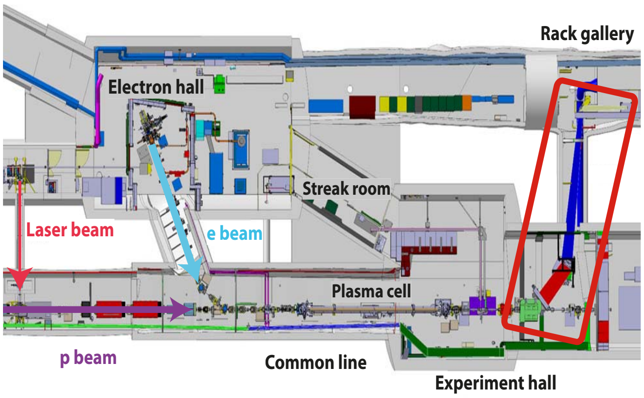

Figure 1. Layout of the AWAKE experiment. The part highlighted in red shows the spectrometer system.

Once the correct temporal synchronization and the spatial overlap between the three beams is achieved, SSM in the proton bunch should be observed and the electrons should be captured and accelerated by the plasma wakefield.
During 2017, various measurements were performed at AWAKE with the high-power laser beam and SPS proton bunches and SSM was carefully studied. In addition, the electron injector and transport line were finalized and commissioned to allow the generation of electron bunches and their insertion into the common line containing the plasma cell.

2. Beam instrumentation systems in AWAKE

During the AWAKE runs in 2017 various instruments were used for measuring the profile and transverse position of the proton bunch as well as its temporal synchronization with the laser pulse. Furthermore, different diagnostics systems were commissioned in the electron line enabling the measurement of electron bunch properties. The spectrometer system, to be used for electron energy measurements after their acceleration in the plasma cell, was also installed and aligned. A general description of the beam instrumentation systems installed in AWAKE is reported in [4].

2.1. Transverse profile measurement

The transverse profile and the position of the proton, electron or laser beam is measured by so-called Beam TV Observation (BTV) stations. The basic concept of the BTV system is to insert a screen into the beam path and register the light emitted from the screen with a camera. In this case the spatial distribution of the measured light intensity represents the transverse profile of the beam. Two different screens are normally used for these measurements: Chromox (Al_2O_3:CrO_2) scintillating screens sand silver coated silicon (SiAg) screens that produce optical transition radiation (OTR) when a charged particle beam passes through them. Chromox screens emit diffused light with a long decay time (∼300 ms), they produce more light compared to SiAg screens. Meanwhile, the OTR is emitted almost instantaneously and is very directional with an emission angle proportional to the inverse of the Lorentz factor ($\sim 1/\gamma$) of the particles. Chromox is used when more emitted light is required, while the OTR contains also information about the arrival time and the length of the bunch. The two screens exhibit comparable spatial resolutions.

There are in total six BTV systems positioned at various locations in AWAKE, serving different purposes. Two BTVs are installed along the electron line to measure the transverse profile of the electron bunch. As the energy of the electrons is relatively low (16 MeV), the emitted OTR is divergent: $\theta = 1/\gamma \approx 32$ mrad. For this reason, the cameras are positioned as close to the screen (vacuum viewport) as possible to collect more light. During the AWAKE run in December 2017 the two electron BTVs were successfully commissioned and were used for the electron beam alignment and profile measurement. The measurements were performed with a resolution of 120 μm for the upstream and 95 μm for the downstream BTVs for an electron bunch with a transverse size of a few millimeters.
The remaining four BTVs are positioned in the common beamline: two of them upstream of the plasma cell and the other two downstream of it. All four of these BTVs are used for aligning the laser and the proton beams with respect to each other along the beamline. Once the electron beam was transported and injected into the common line, the two BTVs upstream of the plasma cell were also used to optimize the electron beam and to align it to the entrance of the plasma cell. The two BTVs downstream of plasma cell are in addition used for observing the halo of the proton beam, which, if observed, gives an indication that SSM is occurring in the plasma cell. The details about the halo measurement setup and the operation of the so-called two-screen system is described in [5]. Masks of various sizes can be inserted in the intermediate image plane to block the central part of the light emitted by the core of the proton bunch. This enables the measurement of the bunch halo with intensities about 3 orders of magnitude lower than the core intensity, which otherwise would be impossible to see due to the limited dynamic range of the cameras.
As already reported in [4], the transverse profiles were measured with a resolution of 50 μm for all four BTVs in the common line.

2.2. Beam position measurement

The transverse position of both electron and proton bunches is measured by beam position monitors (BPMs) located at different parts of the AWAKE experiment. A detailed description of the proton BPMs is given in [4].
A total of 12 stripline type BPMs are used to measure the electron beam position. They were developed by TRIUMF (Canada) based on a design used in the TRIUMF electron linac [6]. Seven of these BPMs with 40 mm inner diameter are installed in the electron line and were commissioned during the AWAKE run in December 2017. The electron bunches were measured by these BPMs with a resolution better than 10 μm in both horizontal and vertical planes.
The remaining five BPMs with an inner diameter of 60 mm are installed in the common line and are meant to measure the position of the electron bunches in the presence of the proton bunches. This is particularly challenging as the proton bunch with a much higher charge produces a significantly larger signal on the BPMs compared to that produced by the electron bunch when using the standard proton or electron BPM acquisition electronics. Acquisition at much higher frequency (2 GHz) has therefore been attempted. This choice comes from the fact that the electron bunch is only a few picoseconds long while the rms length of the proton bunch is 400 ps. This means that at such high frequencies the signal from the proton bunch should be attenuated by four orders of magnitude and allow the electron bunch to be measured. Such measurements are foreseen to be tested in 2018.

2.3. Temporal synchronization of the beams

In order to drive the SSM process and accelerate the electrons in the plasma, it is of great importance to inject all three beams into the plasma cell with a correct temporal synchronization. To monitor the relative timing between the three beams, a streak camera from Hamamatsu (Fesca200) with a resolution of 200 fs is used. It is located in a separate dark room adjacent

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to the common line (Fig. 1). The OTR light produced at the first BTV in the common line is transported to the streak camera via an optical line approximately 9.6 m long. The transmission line was initially built using off-axis parabolic mirrors (as reported in [4]) in order to avoid any chromatic effects. Later, however, the mirrors were replaced by achromatic lenses to improve the imaging quality of the optical system, while the signal broadening due to the chromatic effects was mitigated by using a bandpass filter at 450 nm (where the camera is most sensitive) with a FWHM bandwidth of 40 nm. The two lenses with focal lengths of f_1 = 400 mm and f_2 = 200 mm transport the light while demagnifying the image 10 times (M=0.1) as apposed to the previous design with M=0.3. This results in a smaller spot size at the entrance slit and increases the amount of light collected by the camera. Using lenses instead of the mirrors does not affect the temporal resolution of the system, while improving its imaging properties. This enables obtaining additional information about the transverse profile from the measured images. The new optical line was aligned and used to synchronize all three beams during the AWAKE runs in 2017 (Fig. 2). One can see from the left image of Fig. 2 that the laser pulse is positioned at the center of the proton bunch as expected. It is worth noting that the signal from the electron bunch is much lower than that from the other two beams due to the large divergence of the OTR emitted by the low-energy electrons. This makes the electron bunch measurement more challenging. For this reason, some mirrors in the optical line are being replaced with larger ones (from 3 inch to 4 inch) to increase the amount of transmitted OTR light and to improve the signal on the streak camera. The upgraded optical line is planned to be tested during the AWAKE runs in 2018.

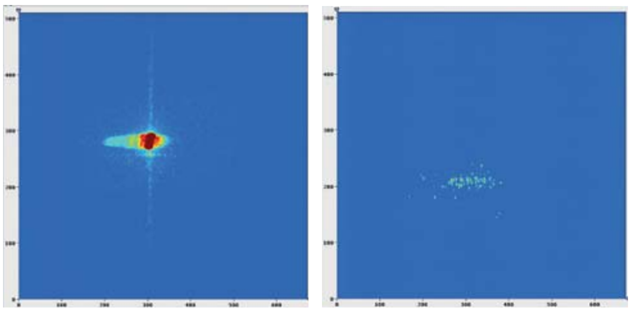

Figure 2. Screenshots from the streak camera measurements. The vertical scale corresponds to 1 ns time window. The image on the left shows the temporal overlap of the laser pulse (short bright spot) and the proton bunch (long narrow line), while that on the right side shows the electron bunch when no laser or proton bunch were present.

2.4. Electron bunch charge measurement

The electron bunch charge is measured by a Faraday Cup based on a design from TRIUMF. The signal created in the Faraday Cup is sent to a CAEN V965 charge-to-digital converter (QDC) card, where it is digitized and further processed. The card can operate in two modes: low-range and high-range. The former can measure charges up to 100 pC with a resolution of 25 fC, while the latter can measure up to 900 pC with a resolution of 200 fC. Before installation in the tunnel, the electronics of the system was tested in the laboratory by providing an input signal of the expected charge and measuring the readout. The tests revealed an accuracy of about 20 pC for an input charge of 200 pC.
The electron bunch charge was varied between 200 pC and 400 pC during the electron line commissioning and was monitored with the Faraday Cup throughout the run.

2.5. Optical Line of the electron spectrometer

The electron spectrometer is situated downstream of the plasma cell (Fig. 1, the part highlighted in red) and is designed to measure the energy distribution of the electrons accelerated inside the plasma. The spectrometer system consists of a dipole magnet, scintillating screen, optical transfer line and an intensified camera. The electrons exiting the plasma cell are bent in the spectrometer dipole magnet. At the exit of the magnet they hit a 1 m long gadox (Gd_2O_2S:Tb) scintillating screen producing light in the visible range. This material was chosen based on its light yield and radiation hardness. The created light is collected and transported by an optical line from the experiment tunnel to the adjacent rack gallery where an Andor iStar 340T intensified CCD camera is located. It is installed in a special dark room to be protected from any ambient light. The optical transfer line is about 16 m long and consists of three mirrors. The first two have dimensions of 926 × 150 mm, while the third one has a size of 524 × 160 mm. A calibration lamp with an optical target was also installed immediately after the scintillating screen and its position was scanned along the screen length while acquiring images by the camera. This allowed the light transmission through the optical line from different parts of the screen to be characterized and the vignetting effect to be studied, as well as gave an estimation for the resolution of the system. Figure 3 shows an image of the calibration mask taken by the Andor camera and the calculated modulation transfer function (MTF) of the system. The latter shows

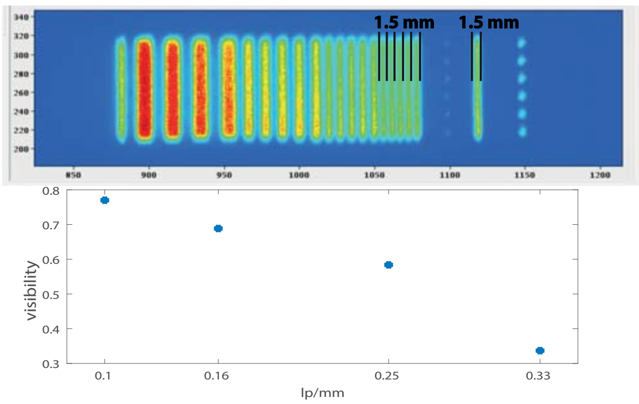

Figure 3. The image of the calibration mask measured by the camera (top) and the modulation transfer function (bottom). The highlighted lines have a spacing of 1.5 mm corresponding to 0.33 lp/mm.

the visibility of the line pairs depending on their sizes or number of line pairs per mm (lp/mm). One can see from the image that the target resolution of 1.5 mm was achieved for the system with a visibility of 0.34. This is consistent with the visibility worst case estimate of 0.2 for 1.5 mm obtained from the simulations with Zemax OpticStudio.

3. Conclusion

During 2017 the electron BTVs, BPMs and Faraday Cup were installed and successfully commissioned in the electron line. Halo measurement system was built and commissioned at the last two BTVs, streak camera optical line was upgraded. Furthermore, the electron spectrometer system was installed and calibrated. During the AWAKE runs in 2018, the electron BPMs in the common line will be operated in presence of the proton bunch. The spectrometer system will be used to measure the energy distribution of the electrons exiting the plasma cell.

References

[1] AWAKE Coll, Muggli P *et al.* 2015 *Proc. IPAC'15* **MOAC1** 34–36
[2] AWAKE Coll, Caldwell A *et al.* 2016 *Nucl. Instr. Meth.* A **829** 3–16
[3] AWAKE Coll, Gschwendtner E *et al.* 2016 *Nucl. Instr. Meth.* A **829** 76–82
[4] Mazzoni S *et al.* 2017 *Proc. IPAC'17* **MOPAB119** 404–407
[5] Turner M *et al.* 2017 *J. Phys.: Conf. Series* **874** 012031
[6] Verzilov V *et al.* 2103 *Proc. IBIC'13* **TUPC06** 361–364