BEAM INSTRUMENTATION DEVELOPMENTS FOR THE ADVANCED PROTON DRIVEN PLASMA WAKEFIELD ACCELERATION EXPERIMENT AT CERN

S. Mazzoni*, M. Barros Marin, B. Biskup[1], A. Boccardi, T. Bogey, S. Burger, E. Effinger, J. Emery, A. Goldblatt, I. Gorgisyan, E. Gschwendtner, A. Guerrero, L. Jensen, T. Lefevre, D. Medina, B. Moser, G. Schneider, L. Soby, S. Sousa, M. Turner[2], M. Vicente, M. Wendt
CERN, Geneva, Switzerland
V. Verzilov, TRIUMF, Vancouver, Canada
[1] presently at Czech Technical University, Prague, Czech Republic
[2] also at Graz University of Technology, Graz, Austria

Abstract

The Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) at CERN aims to develop a proof-of-principle electron accelerator based on proton driven plasma wake-field acceleration. The core of AWAKE is a 10 metre long plasma cell filled with Rubidium vapour in which single, 400 GeV, proton bunches extracted from the CERN Super Proton Synchrotron (SPS) generate a strong plasma wakefield. The plasma is seeded using a femtosecond pulsed Ti:Sapphire laser. The aim of the experiment is to inject low energy electrons onto the plasma wake and accelerate them over this short distance to an energy of several GeV. To achieve its commissioning goals, AWAKE requires the precise measurement of the position and transverse profile of the laser, proton and electron beams as well as their temporal synchronisation. This contribution will present the beam instrumentation systems designed for AWAKE and their performance during the 2016 proton beam commissioning period.

INTRODUCTION

The AWAKE project at CERN aims at demonstrating the acceleration of electrons using the wakefield generated by a self-modulated proton bunch propagating in a plasma. This technology can produce very high electric fields of the order of GVm^{-1}, and is therefore a potential candidate for a new generation of compact accelerators. See [1] and references therein for an up-to-date description of the project. A general layout is shown in Fig. 1. A single proton bunch with nominal energy of 400 GeV and population of 3×10^{11} is extracted from the SPS and sent via a 700m transfer line to a 10 metre long rubidium plasma cell. A 100 fs, 450 mJ pulsed Ti:Sapphire laser is merged collinearly with the proton beam to ionise the rubidium vapour creating a plasma with a density between 10^{14} and 10^{15} electrons / cm^3. In the future a single bunch of 10^9 electrons will be produced in a neighbouring alcove and accelerated to a nominal energy of 32 MeV before also being injected upstream of the plasma cell. All three beams, proton, electron and laser will transit the plasma cell and the pass through various diagnostic stations. These will initially measure the self-modulation of the proton bunch and then later the energy and energy spread of the single witness electron bunch once accelerated in the plasma wake.

* email address: stefano.mazzoni@cern.ch

BEAM INSTRUMENTATION SYSTEMS

Instrumentation for the measurement of the position, transverse profile and temporal synchronisation of the proton beam as well as its temporal synchronisation with the pulsed laser source have been developed and were installed for the 2016 SPS proton physics run. At present, instrumentation for the electron transfer line is being installed in view of the first electron acceleration commissioning runs foreseen for the second half of 2017.

Transverse Profile Measurement

The transverse beam profile of the proton and electron bunch must be measured to an accuracy of the order of 10%, corresponding to a spatial resolution varying from 50 μm to 200 μm depending on the location. A total of six so-called Beam Observation TV (BTV) systems, comprised of scintillation or OTR screens coupled to a camera readout system, are installed in AWAKE. The size (sigma) of the proton beam at BTV locations ranges from 240 to 900 μm, and that of the electron beam from 650 to 1900 μm. The electron beam, due to its lower bunch population and lower energy as compared to the proton beam, is the beam that poses the most challenges in term of optical acceptance. One of the BTVs is used as a light source for a streak camera for measuring the temporal synchronisation of the beams. The need for fast timing ruled out the use of a scintillator screen due to the presence of long (ns to ms) emission tails. An Optical Transition Radiation screen was used instead, with the drawback of lower light yield and, in the case of the electron beam, a lower acceptance due to the larger OTR emission angle $\theta = 1/\gamma = 16$ mrad. The OTR BTVs were therefore designed with the aim of maximising the light collection from the OTR screen. This light collection efficiency was simulated with the ray tracing code Zemax for both the electron and proton beam with a 45º screen geometry (Fig 2). The BTV vacuum tank was also designed to have the first optical element as close as possible to the screen, resulting in an acceptance of 23% for a 2-inch diameter lens. After the plasma cell a standard CERN BTV conceived for SPS and LHC beams is used, installed

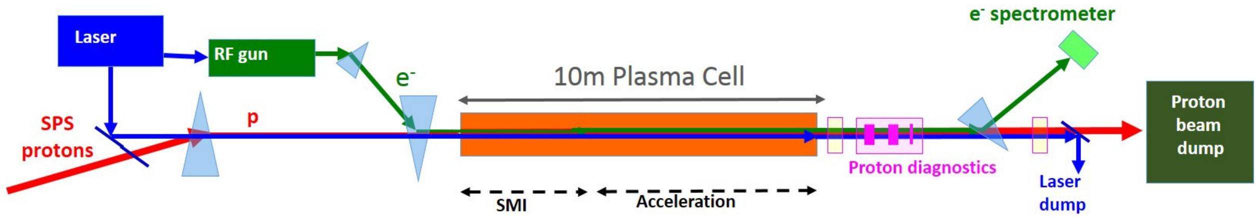

Figure 1: Schematic of the AWAKE underground installations.

with both an OTR and scintillator screens. The optical line has, however, been modified to add a proton halo measurement in addition to the standard transverse profile system [2,3]. All BTVs systems were successfully commissioned in the 2016 June and October commissioning runs. Transverse profiles of the proton beam were acquired with the target spatial resolution down to 50 µm. In the course of the commissioning runs, the acquisition software of the BTV was modified to allow the acquisition of images at 1 Hz synchronised with the fs pulsed laser to facilitate laser alignment and pointing stability analysis.

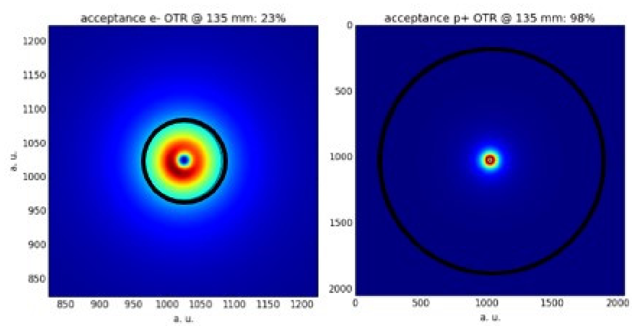

Figure 2: Simulation of OTR light collection from the electron beam (left) and the proton beam (right). Signal falling outside the black circle is not collected by the optical system (the images have a different spatial scale).

Temporal Synchronisation

Key to the generation of the self-modulated instability in the proton bunch is the control of its temporal synchronisation with the laser pulse and, eventually, with the witness electron bunch with picosecond accuracy. For this purpose, the OTR signal from the BTV system upstream of the plasma cell is recorded with a Streak Camera (Hamamatsu Fesca200) with 200 fs temporal resolution. The optical transport line for this system is approximately 10 metres long, and has been designed without any refractive optical elements to minimise dispersion. It consists of two off-axis parabolic (OAP) mirrors of f_1 = 545 and f_2 = 152.4 mm. The OTR source and streak camera are positioned at the back focal distance of the respective mirrors, so that the OTR beam is collimated along the line. As a consequence, this design is prone to very pronounced vignetting, as off-axis illumination is only partially collected by the second mirror. This is visible in the right inset of Fig. 3, where a 1.5 mm off-axis point source (green trace) is only partially reflected by the f_2 mirror. Laboratory tests and simulations confirmed a field of view of 2mm, considered an acceptable trade-off given the extremely simple and relatively inexpensive optical design. The line is installed with a set of ancillary systems for remote operation: motorised wheel hosting neutral density optical filters and a 535 nm notch filter to attenuate the pulsed laser; a beam splitter at the f_2 mirror position to monitor the light pulse with a photo diode connected to an oscilloscope; the motorisation of the most critical optical elements. Dedicated software following the CERN Front-End Software Architecture (FESA) for the remote control and logging of the streak camera has also been developed.

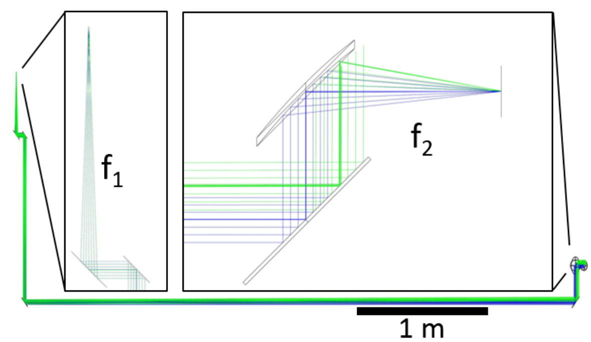

Figure 3: Simulated layout of the streak camera line. The insets show the off-axis parabolic mirrors at the source (f_1) and image (f_2) side. On axis illumination (Blue) and off-axis illumination (Green).

The complete streak system was fully commissioned in November 2016 and is now operational for the proton-laser synchronisation. Figure 4 shows the proton bunch displayed on a 1 ns (vertical) window, along with the shorter, more intense laser pulse It can be seen that the streak system is not able to correctly measure the temporal width of the 100 fs laser pulse, as it is convoluted with the much larger entrance slit of the system. Such convolution, however, does not affect the temporal position of the signal, therefore still allowing accurate synchronisation. The full temporal synchronisation scheme with electrons is expected to be commissioned during 2017.

Proton Beam Position Measurement

The Beam Position Measurement (BPM) system of the AWAKE proton beam line is composed of 21 dual plane button pickups distributed along the transfer line from the SPS extraction point to beyond the plasma cell. The readout electronics is divided in two parts: the front-end electronics located close to the pick-ups in the tunnel and the back-end electronic that concentrates the communication

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with the different front-ends into a single point, close to the control room.

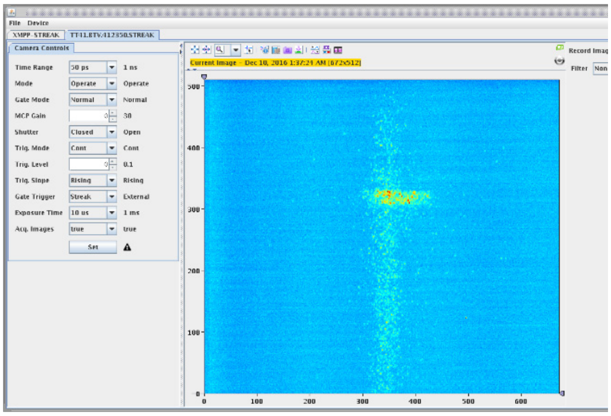

Figure 4: Streak camera image of the proton bunch and laser pulse taken during the December 2016 physics run.

The communication between the front-end and the back-end is performed through a custom protocol running at 10Mbps over 1 km of copper cables. The front-end electronics is composed an analogue circuitry based on a resonant filter followed by logarithmic amplifiers and finally 40MSa/s ADCs. It is important to mention that due to the low radiation levels expected in the AWAKE beam line, radiation tolerant components are not required. The back-end electronics is based on two custom VME boards and their respective auxiliary cards for interfacing with the electrical serial link.

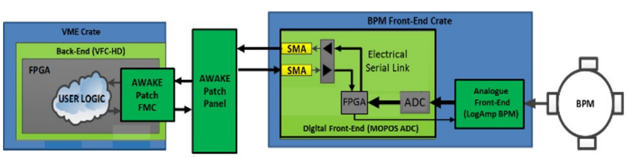

Figure 5: Button BPMs signal acquisition and processing scheme.

For every BPM, the Front-end electronics provides both horizontal and vertical beam position signals as well as a summation of all electrodes proportional to the beam intensity. The acquisition system is auto-triggered (Fig. 5). All signals are processed by the front-end FPGA, that checks if the summation signal reaches amplitudes higher than a preset threshold value. This allows the presence of beam to be detected, starting the sending of data to the back-end acquisition electronic through the electrical serial link. In the back-end, the two VME boards concentrate the data from the 21 front-end channels and store them in memory until read-out by the operational software. This software calculates the beam position in millimetres using calibration and pick-up non-linearity compensation factors.

Tests performed in our laboratory have shown that the BPM resolution is better than 40µm for high intensity bunches (>10^{11} protons) and of the order of 300 µm for pilot bunch intensity (5 x 10^9 protons). These numbers have been confirmed by beam measurements in 2016. One should note that the button pick-ups sitting in the close vicinity of the plasma cell were affected by interference when the laser was powered at high intensity. Recent observations indicate that secondary electrons from ionized rubidium vapour could be the cause of these signals, but investigations are still on going to confirm this.

Electron Beam Position Measurement

Shorted stripline BPMs have been developed by TRIUMF (Canada) for the AWAKE electron beam lines, based on a design used for the TRIUMF electron linac [4]. A total of seven BPMs with 40 mm inner diameter have been produced for the electron transfer line, and five of 60 mm diameter for the common electron/proton line. The BPM electronics is based on a modified version of the existing TRIUMF e-linac design, with the front-end modified for single bunch operation. The system operates at 404 MHz for all BPMs, with the exception of the last two BPMs in the common line that use 2 GHz front end electronics to be able to measure the picosecond electron bunch in the presence of a 400 ps long proton bunch. At this frequency the proton bunch spectrum should be attenuated by four orders of magnitude compared to that of the electron bunch.

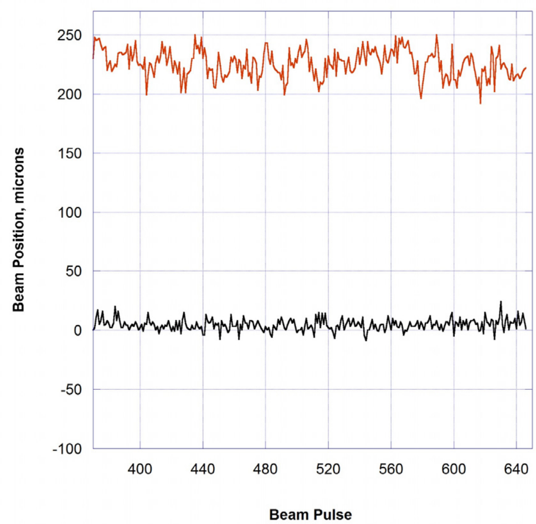

Figure 6: Horizontal (black) and vertical (red) beam position evolution of a 150 pC electron bunch as measured in CTF3.

A 40 mm BPM has been tested at the CERN Compact Linear Collider Test Facility (CTF3) using the 404 MHz acquisition electronics. Figure 6 shows the measured beam position over a few hundreds of beam pulses for a 150 pC bunch. Data show that the vertical position (red) is noisier than the horizontal one (black), while still being within 50 µm p-p. Since laboratory tests showed similar resolution and stability between the two channels, this was attributed to a worst vertical beam stability. In the end, when corrected for this effect, horizontal and vertical resolution of 4.3 and 7.8 µm respectively were measured. The performance of the 60 mm BPM using 2 GHz electronics in the presence of the proton beam is yet to be measured. The electron BPMs are currently being installed and are foreseen to be operational for the electron line commissioning in October 2017.

ACKNOWLEDGEMENTS

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