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RECENT AWAKE DIAGNOSTICS DEVELOPMENT AND OPERATIONAL RESULTS

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Abstract

The Advanced Wakefield Experiment (AWAKE) at CERN investigates the plasma-wakefield acceleration of electrons driven by a relativistic proton bunch. After successfully demonstrating the acceleration process in Run 1, the experiment has now started Run 2. AWAKE Run 2 consists of several experimental periods that aim to demonstrate the feasibility of the AWAKE concept beyond the acceleration experiment, showing its feasibility as accelerator for particle physics applications. As part of these developments, a dramatic effort in improving the AWAKE instrumentation is sustained. This contribution reports on the current developments of the instrumentation pool upgrade, including the digital camera system for transverse beam profile measurement, the beam halo measurement and the spectrometer upgrade studies. Studies on the development of high-frequency beam position monitors are also described.

INTRODUCTION

The Advanced Wakefield Experiment (AWAKE) at CERN successfully demonstrated plasma-wakefield acceleration (PWFA) of an electron bunch driven by a proton bunch [1] during AWAKE Run 1. The success of the acceleration, and the considerable experience developed [2], paved the way for the current experimental program, known as AWAKE Run 2 [3]. AWAKE Run 2 is formed of four operational periods, that plan to investigate different aspects of proton-driven PWFA between 2021 and 2028. The current period is known as Run 2a (2021-2022), investigates electron bunch seeding of plasma wakefields.

During AWAKE Run 1, an intense laser pulse was used to form the plasma by means of the relativistic ionization front and seed the proton bunch self-modulation of the cm-scale proton bunch into mm-scale micro-bunches. The anticipation of the laser pulse position in the proton bunch head, resulted in unseeded self-modulation, not reproducible event-to-event [4]. During Run 2a, the possibility to send the electron beam ahead of the proton bunch is explored. The role of the preceeding electron bunch is to seed the wakefields, allowing the self-modulation of the whole proton bunch [5]. The core experimental setup of AWAKE Run 1 is maintained for Run 2a, with the addition of a number of operational and R&D instruments.

This contribution describes a number of instrumentation projects that are currently taking place at AWAKE, for both upgrade and R&D purposes. A schematic layout of the AWAKE beamline is shown in Fig. 1. Numerous systems benefit from the upgrade of the camera system to digital cameras in terms of increase of resolution and dynamic range. This concerns the laser delivery and alignment, electron and proton transverse beam profile and halo measurement, and the spectrometer readout (items 1-6 in Fig. 1). Additionally, considerable effort has been put into the development of high frequency BPMs for the common beamline upstream of the plasma cell (items 7-8 in Fig. 1).

DIGITAL CAMERA SYSTEM

AWAKE is a demanding environment for a digital camera acquisition system, that must read out several devices with a fast repetition rate of 10 Hz and large image sensors, resulting in a large data throughput. Two independent camera acquisition systems are currently under commissioning in the experiment: one for the laser, with 8 cameras, and one for the beamline, with 18 cameras.

Each system is designed to handle up to 23 cameras. A 10 Hz physical trigger is distributed to the cameras. The large data volume is handled in two steps: all the cameras are connected via ethernet to a 24 port PoE switch; The switch forwards the data to a 64 core server for processing, via a 10 Gb fibre link roughly 2 km-long. Example features of some supported cameras are listed in Table 1.

The laser beam camera system is mainly devised to monitor the UV and IR laser beams delivery. The UV beam is observed on the electron injector virtual cathode [7], while a fraction of the IR beam is sent to the so-called "virtual beamline" (item 1 in Fig. 1). The virtual beamline relays the

Table 1: Cameras in use in the AWAKE camera system. All the cameras are manufactured by Basler AG [6].

Camera model	Format	Pixel size (μm^2)
acA1920-40gm	1920 × 1200	5.86 × 5.86
acA1600-60gm	1600 × 1200	5.3 × 5.3
acA1300-60gm	1280 × 1024	4.5 × 4.5

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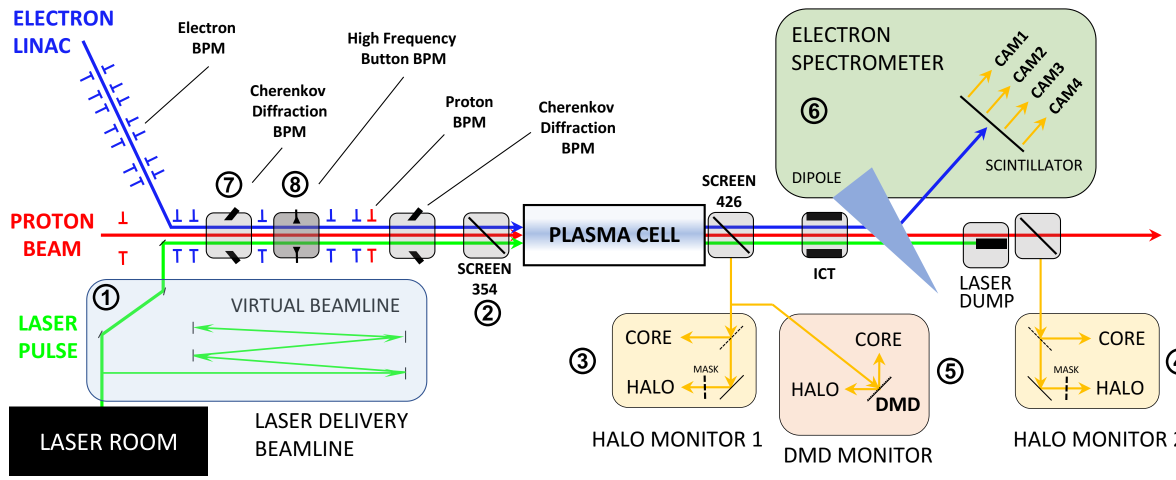

Figure 1: The present layout of the AWAKE experiment. The instrumentation systems described in this paper are highlighted with the numbers 1-8.

laser shape and relative position at interesting locations of the experimental beamline, such as the plasma cell entrance, centre and exit. The observation of the virtual line is crucial to provide online monitoring of the laser beam parameters, and perform the laser beam alignment to the electron and proton beams.

The beamline camera system is used to monitor all the screens that can interact with the particle beams (items 2-6 in Fig. 1). The eight screens in the beamline are used to monitor the transverse beam profile. Additionally, the different beams are aligned by separately measuring their positions of the screens up- and down-stream of the plasma cell. The beam screens are equipped with an OTR [8] and either a Chromox (Al_2O_3:CrO_2) or YAG:Ce [9] scintillation screen. Two screens are equipped with halo monitors [10], that measure the proton beam defocusing in plasma by means of fixed masks. Additionally, the screen light for the upstream halo monitor is split to serve also the Digital Micro-mirror Device monitor (DMD) [11]. In the DMD halo monitor, the beam image is relayed onto a digitally controlled micro-mirror matrix that splits the light in two distinct paths towards two cameras, that image the core and halo of the beam separately. The main advantage of this system compared to mask-based halo monitors is to provide a complete control of the mask shape with a minor light loss. The electron spectrometer located after the plasma cell consists of a 1 m-long scintillator tile and four cameras This system is further detailed later in the paper. Additionally, a number of cameras are used to monitor the optical alignments.

ELECTRON SPECTROMETER

The electron spectrometer is composed of a quadrupole doublet downstream of the plasma cell, a dipole magnet and a 1 m-long scintillator tile. Two different camera systems look simultaneously at the scintillator emission: the original acquisition system used during Run 1 [12] consists of a long optical line, terminating with an intensified camera outside the radiation area; the current upgrade consists of an array of four digital cameras placed at 1.5 m from the scintillator. The camera array images the scintillator with a 30 degrees angle. This arrangement does not obstruct the existing optical line and distances the cameras from the beam plane, where radiation is most intense. Therefore, the two spectrometer systems can be used at the same time.

Each camera, equipped with 75 mm lenses and bandpass filters at 525(46) nm, images one quarter of the scintillator. The resolution is improved by a factor ten with respect to the original system, being in the order of 250 µm. The resulting images are stitched together after lens distortion and vignetting compensation. As the camera array is placed at an angle with respect to the scintillator tile, the light collection is also corrected for the observation angle, according to a calibration that was performed at the CERN Linear Accelerator for Research (CLEAR) [13]. To provide the possibility for a calibration in-situ, a commercial Integrating Current Transformer (ICT) [14] was installed upstream of the spectrometer dipole during the past winter shutdown.

HIGH FREQUENCY BPM STUDIES

In AWAKE, a peculiar beam structure is used, involving an intense, long proton bunch and a weak, short electron bunch. The electron beam is produced at 10 Hz in the local 18 MeV injector [15], while the proton beam is extracted from the CERN SPS every 15-60 s. The beam parameters are reported in Table 2.

The large intensity and bunch length difference translates in a very diverse beam spectrum, shown in Fig. 2. Due to the different beam parameters, and assuming that the beam longitudinal shape is Gaussian, it is possible to distinguish between the different beams by frequency discrimination. In fact, the proton beam dominates the spectrum at low frequency, and rapidly drops when entering the GHz regime. Conversely, the electron beam presents a modest spectral power, which is constant over a longer frequency span. If

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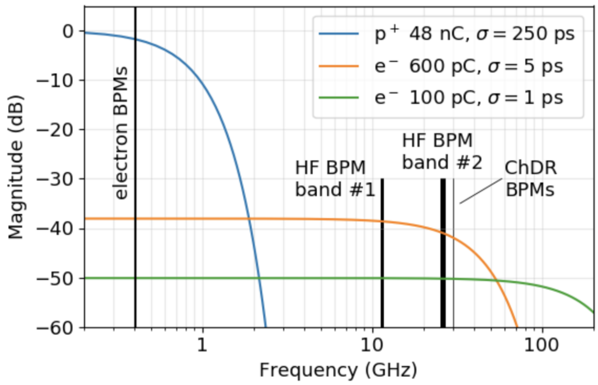

Figure 2: The beam spectrum for the electron and proton beam parameters in Table 2, assuming Gaussian beam shape. The detection frequency of the current and R&D electron BPM systems in indicated.

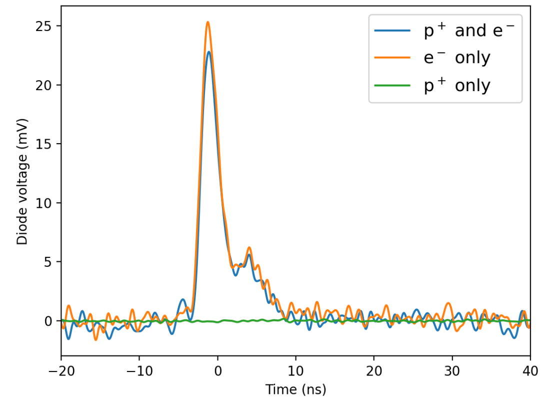

Figure 3: Signal in one channel of the ChDR BPM with electron and proton beam, and both.

Table 2: AWAKE beam parameters.

Beam	Charge [nC]	Length (1σ) [ps]	E [MeV]
Proton	16 – 48	250	4×10^5
Electron	0.1 – 0.6	1 – 5	16 – 20

Table 3: Detection bands used for in the tests at AWAKE.

Device	Plane	Detection band
HF-BPM	x	11.375 ± 0.250 GHz
HF-BPM	y	26.25 ± 0.900 GHz
ChDR-BPM	x	30.0 ± 0.300 GHz

the Gaussian shape assumption is met, the electron signal becomes dominant above few GHz. As the shape might not always be ideal, a safety margin is adopted by carrying out the measurements on the electrons above 10 GHz.

As producing a BPM capable of transducing the beam field to the acquisition electronics in the tens of GHz range is technically challenging, two separate projects were started: the use of conical button feedthroughs (HF-BPM) and the development of Cherenkov Diffraction radiation BPMs (ChDR-BPM).

The HF-BPM consists of four conical feedthroughs featuring a bandwidth of up to 40 GHz, originally designed for time of arrival monitoring in FELs [16]. One BPM body was installed in AWAKE, equipped with four buttons.

The ChDR-BPM is a CERN design that couples the beam electric field through a ceramic insert in the beampipe [17]. A number of prototypes were simulated and tested [17, 18]. A vacuum compatible device was realised, featuring ∅6 mm ceramic inserts brazed to a DN40 flange. A custom transition piece was numerically optimised to transmit the radiated power from the ceramic insert to a standard WR28 waveguide, at the detection frequency of 30 GHz. Further details are presented at this conference [19].

For both devices, the detection of each channel is carried out by means of a bandpass filter, followed by a zero-bias Schottky diode detector. In the HF-BPM, different frequency bands were tested in the horizontal and vertical plane.
In the ChDR-BPM, only the horizontal plane was tested, due to the available equipment. The detection bands in use are summarised in Table 3. This device was tested during the first AWAKE run in 2022, with electron, proton and both beams simultaneously to assess the rejection of the proton bunch signal of the device. Under the assumption of a Gaussian longitudinal distribution, a strong suppression of the proton beam signal is expected. Figure 3 presents the signal of the diode detector for a proton beam of 16 nC and an electron beam of 230 pC. As the diode detector is driven in the linear regime, the signal is proportional to the coupled power in the dielectric radiator. It is evident that for this proton beam intensity, the proton signal lies below the detectable threshold. The amplitude difference in signal between the electron beam and both beams present can be assigned to the electron beam charge jitter.

These very promising initial results are the basis for an in-depth study that will be performed to assess the proton signal rejection in different configurations of protons intensities and time overlap between the two beams..

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