ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPML118

THE AWAKE ELECTRON SPECTROMETER*

F. Keeble†, M. Cascella, J. Chappell, L. Deacon, S. Jolly, M. Wing, UCL, London, United Kingdom
I. Gorgisyan, S. Mazzoni, CERN, Geneva, Switzerland
P. La Penna, M. Quattri, ESO, Munich, Germany

Abstract

The AWAKE experiment at CERN aims to use a proton driven plasma wakefield to accelerate electrons from 10–20 MeV up to GeV energies in a 10 m plasma cell. We present the design of the magnetic spectrometer which will measure the electron energy distribution. Results from the calibration of the spectrometer's scintillator and optical system are presented, along with a study of the backgrounds generated by the 400 GeV SPS proton beam.

INTRODUCTION

In order to accelerate electrons at AWAKE, a plasma wakefield is driven by a high energy proton bunch [1, 2]. A high power infrared laser pulse co-propagates with this proton bunch, creating a uniform plasma, the electrons of which begin to oscillate upon interaction with the bunch. This oscillation results in the longitudinal density modulation (micro-bunching) of the proton bunch, which then further enhances the plasma oscillation. This process is called seeded self-modulation (SSM) and results in the generation of a strong wakefield in the plasma, with a frequency defined by the plasma density. Electrons injected into this wakefield experience large electric fields and can be accelerated to GeV energies over a few metres.

In order to measure these electrons, a magnetic spectrometer has been installed downstream of the plasma cell. The evolution of the spectrometer design has been covered in Refs. [3–5]. Here, a summary of the final design is presented.

SPECTROMETER DESIGN

Beam line components

The spectrometer, shown in Fig. 1, begins approximately 5 m downstream of the plasma cell. The beam line components include a quadrupole doublet (red) and a large dipole magnet (green) with a maximum field of approximately 1.5 T. This field bends accelerated electrons away from the beam line such that they are incident on a 1 m wide scintillating screen, which sits at 45° to the beam line. A large, triangular vacuum chamber sits in the cavity of the magnet, allowing the accelerated electrons to remain under vacuum for as long as possible. Electrons in the relevant energy range exit the vacuum chamber through a 2 mm thick aluminium window, designed to maintain the AWAKE vacuum pressure while minimally disturbing the beam. The scintillator is attached to the exterior of this vacuum window, minimising the distance through air that the electrons must propagate before measurement. The scintillator currently installed is DRZ-High, a 0.5 mm thick Gadolinium Oxysulfide (Gd_2O_2S:Tb) screen made by Mitsubishi Chemical, which predominantly produces light at 545 nm.

The relationship between the horizontal position on the scintillator ξ, and electron energy E, at the maximum dipole field, is shown in Fig. 2. The curve was generated with a BDSIM [6] simulation using the magnetic field map of the dipole and the relevant dimensions of the spectrometer components, as measured by a dedicated survey.

Optical line

The scintillator light is recorded by an intensified CCD camera (Andor iStar 340T). This camera is located 16 m away from the scintillator, in an adjacent tunnel, to protect it from the large amount of radiation produced by the SPS proton bunch passing along the main beam line. To collect as much light as possible while maintaining spatial resolution, a large diameter, 400 mm focal lengths lens (Nikon AF-S NIKKOR 400 mm f/2.8E FL ED VR) is attached to the camera. The lens has a 550 ± 25 nm filter on the front to reduce the background light. Scintillator light is brought to the lens via three highly reflective mirrors, two in the same tunnel as the scintillator and a third in the adjacent tunnel. The mirror dimensions are shown in Table 1 along with the clear surface area necessary to avoid clipping of the image. All three mirrors are optical-grade, with $\lambda/2$ flatness over any 100 mm, thus ensuring that the system resolution remains high. Between the second and third mirrors, a 3 mm thick BK7 window with an antireflective coating is installed in a fire wall. On the other side of this fire wall, a light-tight darkroom houses the camera, lens and third mirror.

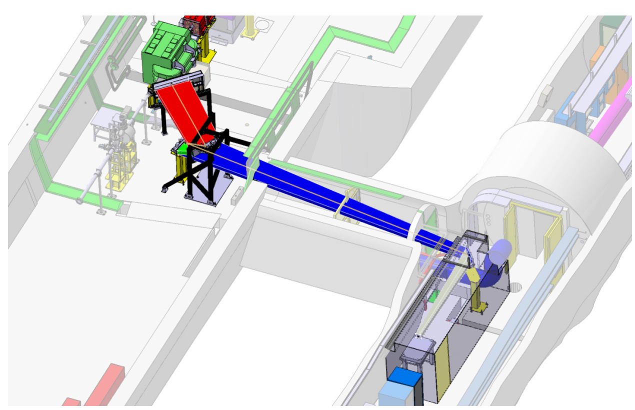

Figure 1: The electron spectrometer components, highlighted, within the AWAKE experimental area. The light path to the camera is shown in red, green, blue and gold.

* This work was supported in parts by a Leverhulme Trust Research Project Grant RPG-2017-143 and STFC, United Kingdom. M. Wing acknowledges the support of DESY, Hamburg.
† f.k@cern.ch

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPML118

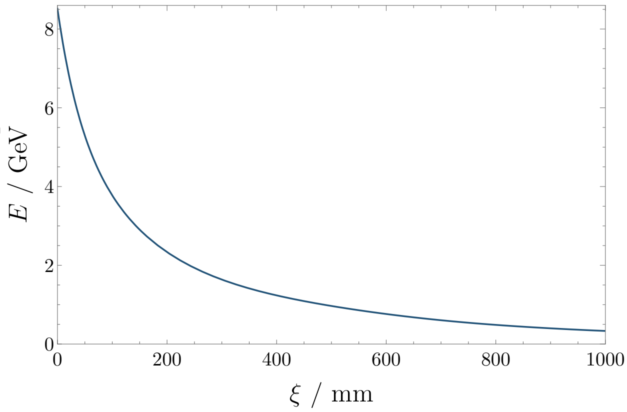

Figure 2: Electron position-energy relationship at the surface of the scintillator with the dipole set to its maximum field strength.

Table 1: Mirror dimensions and clear apertures. M1 is the mirror closest to the scintillator.

Mirror	Width / mm	Height / mm
M1 full	926.0	150.0
M1 clear aperture	898.2	121.5
M2 full	926.0	150.0
M2 clear aperture	819.5	126.4
M3 full	524.0	160.0
M3 clear aperture	504.6	140.5

Camera and DAQ

Readout and control of the camera are both handled by a rack computer situated just outside the darkroom. This is done through a purpose-built FESA class [7] using the Andor software development kit. A 500 MHz oscilloscope (Teledyne LeCroy WaveJet 354T) is also mounted in the rack, to diagnose timing and acquisition signals.

CALIBRATION

Scintillator

After radiation passes through the scintillator, its rate of photon emission rises quickly and then decays approximately exponentially. Before the installation of the spectrometer's optical line, a measurement of the scintillator's half life was made using a small CCD camera (Basler ace acA2000-50gm) situated close to the beam line. Scintillation was initiated by background radiation generated by the interaction of the proton beam with various diagnostic screens along the AWAKE beam line. The camera was triggered, with negligible jitter, by a timing signal derived from the proton extraction to AWAKE. The proton beam is estimated to have arrived approximately 700 µs after this trigger. From this point, a delay scan at a fixed exposure was performed. Exposures with delays less than 750 µs produced poor quality images, due to the large amount of radiation incident directly on the CCD during the passage of the protons. The

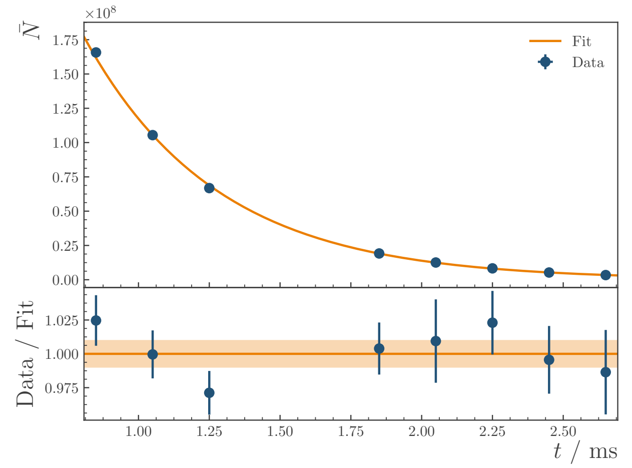

Figure 3: Temporal evolution of light emission by the scintillator. The proton bunch passes through AWAKE at approximately 700 µs.

exposure was set to 200 µs and the delay increased up to 2550 µs. Cuts were applied to the data to ensure a consistent beam charge as this affects the amount of radiation produced and, hence, the signal. The results are shown in Fig. 3. An exponential fit over the region returns a scintillator half-life of 324 ± 5 µs, in agreement with literature values for similar scintillators [8].

A calibration of the charge response of the scintillator has also been performed. The injection electron beam at AWAKE cannot be propagated all the way to the spectrometer due, in part, to the difficulty in correcting its trajectory as it traverses the 10 m plasma cell. Consequently, the scintillator was calibrated using the electron beam at the CLEAR facility [9]. In order to fully capture the conditions at AWAKE, the scintillator was installed attached to the 2 mm aluminium window from the spectrometer vacuum chamber. Analysis of this calibration is ongoing but early results suggest a response of $\mathcal{O}(10^6)$ counts per incident pC of charge is expected for typical camera settings at AWAKE.

Optics

Not all scintillation light is captured due to the finite size of the optics and the angular emission profile of the scintillator. This leads to a position-dependent correction to the light captured by the camera, known as vignetting. This effect is measured by a calibration lamp mounted on a rail in front of the scintillator. The lamp is a diffuse emitter of green light, mimicking the scintillator. The vignetting curve is constructed by scanning the lamp in steps across the surface of the scintillator, taking images at each point. These points are then normalised relative to the centre of the image. The vignetting curve for the current alignment is shown in Fig. 4. The non-smooth shape of the curve comes from the varying amount of reflection from the mirror's mounts.

In order to determine the resolution of the optical system a modulation transfer function (MTF) analysis has been carried out. This is done by placing a calibration mask over the

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPML118

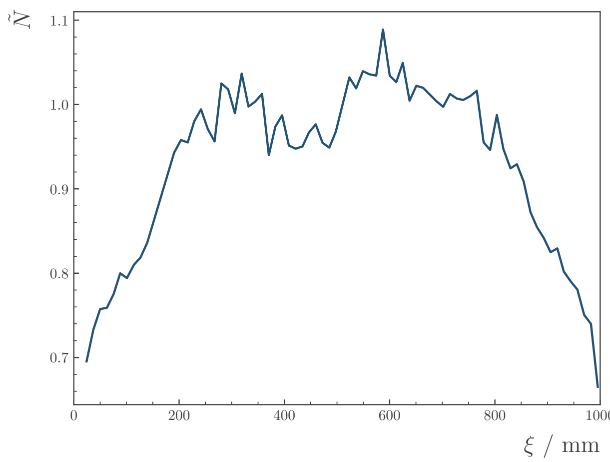

Figure 4: Normalised measured light output of an optical target as it is scanned across the surface of the scintillator.

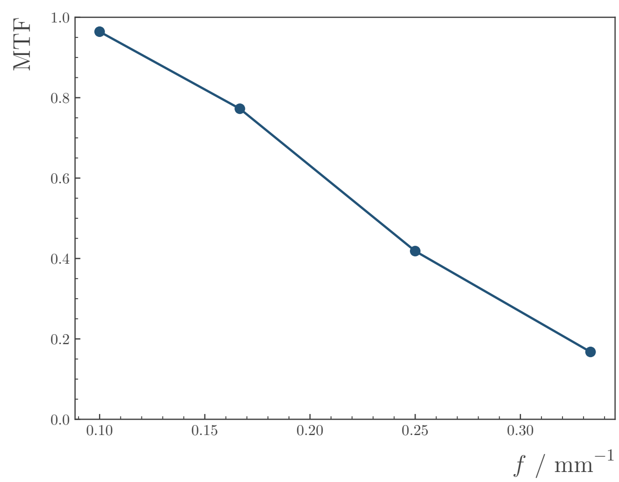

Figure 5: Modulation transfer function for four different line pair frequencies. The poor resolution at 1.5 mm line spacing indicates that the system is improperly aligned.

front of the lamp mentioned above. This mask has line pair spacings of 5, 3, 2 and 1.5 mm. Spacings smaller than this are expected to be unresolvable due to blurring effect of the camera's intensifier. The MTF results for an early alignment of the spectrometer's mirrors are displayed in Fig. 5. For this configuration the system is clearly not at the desired resolution, with 2 mm spacings barely resolvable. The system has recently been realigned and new MTF analysis results are expected to show a considerable improvement.

Proton backgrounds

The spectrometer was operational during the final AWAKE run of 2017 and took data to characterise the background generated by the radiation from the proton beam passing through the scintillator. When looking for accelerated electrons, all diagnostic screens upstream of the spectrometer are removed from the beam line. Two sources of radiation remain, however, a thin window between AWAKE and the SPS transfer line and a 0.6 mm thick copper iris downstream of the plasma cell. The inner radius of this iris is 5 mm, leading to negligible interaction with a standard SPS proton bunch with $\sigma_r \sim 200\,\mu$m. During the self modulation process, however, some protons become defocused, creating a halo around the core of the beam [10]. Simulations using the AWAKE baseline parameters indicate that this blowout leads to approximately 1% of the protons interacting with the iris.

Figure 6 shows the per-pixel standard deviation of the background σ_b across the screen, measured at a plasma density of 2×10^{14} cm^{-3}. The contribution from ambient light in the tunnel combined with readout, electronic and dark noise in the camera amounts to 15–20 counts while the proton background contribution varies with proximity to the beam line. The background noise at the baseline density (7×10^{14} cm^{-3}) is expected to be significantly higher and, as such, electron acceleration experiments are likely to begin at the lower density. Given this background noise and the results from the scintillator calibration at CLEAR, beam charges of $O(10^{-2}$ pC) or greater (electron capture rate $\gtrsim 0.01\%$) are expected to be clearly visible on the spectrometer.

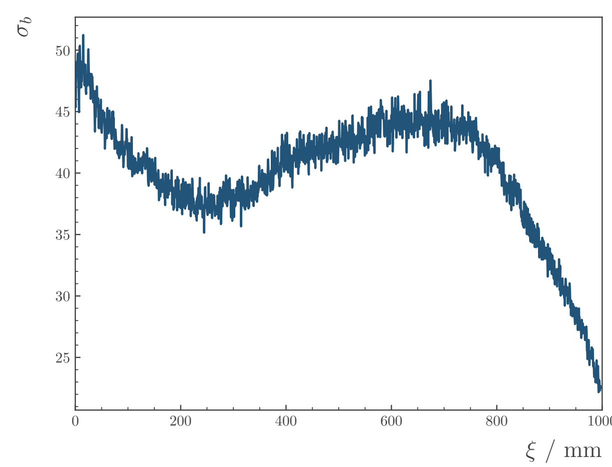

Figure 6: Background noise per-pixel across the scintillator as a result of proton bunch radiation.

REFERENCES

[1] R. Assmann *et al.*, "Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics", *PPCF*, vol. 56, 084013, 2014

[2] E. Gschwendtner *et al.*, "AWAKE, the advanced proton driven plasma wakefield acceleration experiment at CERN", *NIM A*, vol. 829, p. 76–82, 2016

[3] S. Jolly *et al.*, "A Spectrometer for Proton Driven Plasma Wakefield Accelerated Electrons at AWAKE", IPAC'14, Dresden, Germany, TUPME079, p. 1540–1543

[4] L. Deacon *et al.*, "Development of a Spectrometer for Proton Driven Plasma Wakefield Accelerated Electrons at AWAKE", IPAC'15, Richmond, USA, WEPWA045, p. 2601–2604

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPML118

[5] L. Deacon *et al.*, "A Spectrometer for Proton Driven Plasma Accelerated Electrons at AWAKE - Recent Developments", IPAC'16, Busan, Korea, WEPMY024, p. 2605–2608

[6] L. J. Nevay *et al.*, "Beam Delivery Simulation: BDSIM Automatic Geant4 Models of Accelerators", IPAC'16, Busan, Korea, WEPOY046, p. 3098–3100

[7] M. Arruat *et al*, "Front-end software architecture", ICALEPCS07, Knoxville, USA, WOPA04, p. 310–312

[8] I. Fujieda *et al*, "X-ray and charged particle detection with CsI(Tl) layer coupled to a-Si:H photodiode layers", IEEE symposium on nuclear science, Washington DC, USA, 1990

[9] D. Gamba *et al*, "The CLEAR user facility at CERN", *NIM A*, 2017, https://doi.org/10.1016/j.nima.2017.11.080

[10] M. Turner *et al*, "Proton Beam Defocusing as a Result of Self-Modulation in Plasma", NAPAC2016, Chicago, USA, WEPOA09, p. 707–709