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Verification of electron beam alignment and optics for external off-axis injection in AWAKE Run 2b

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ABSTRACT

The Advanced Wakefield Experiment (AWAKE) has the long term goal to accelerate electrons to particle physics relevant energies using self-modulated proton bunches as drivers in plasma. AWAKE is currently in its Run 2b (2023–2025), where the goal is to stabilise the wakefield amplitude after the saturation of the self-modulation process by introducing a plasma density step. To optimise witness electron injection, retractable YAG screens have been installed inside the vapour source. These screens enable, for the first time, direct measurements of electron bunch sizes at the injection location and estimates of the spatial overlap with the wakefields. This manuscript presents an overview of the upgraded experimental setup and measurements of the transverse distribution of the electron bunches, crucial for improved control over the injection process. Additionally, results show agreement between simulated and measured transverse bunch sizes and positions, and the influence of various factors (e.g., plasma density, electron bunch charge, and witness bunch timing) on the electron charge overlapping with the wakefields. Furthermore, alignment challenges as well as potential solutions are discussed.

1. Introduction

AWAKE is a CERN based R&D experiment aiming to develop proton-driven plasma wakefield acceleration. The wakefields are driven by a highly-relativistic (400 GeV, relativistic factor $\gamma_{p+} \sim 427$) and energetic (>19 kJ) proton bunch, supplied by the CERN Super Proton Synchrotron (SPS). The SPS proton bunch is longer than the plasma wavelength $\lambda_{pe} = 2\pi c/\omega_{pe}$, where $\omega_{pe} = \sqrt{\frac{n_{pe}e^2}{\epsilon_0 m_e}}$ is the plasma electron frequency, c the speed of light, m_e the electron mass, e the electron charge, ϵ_0 the vacuum permittivity and n_{pe} the plasma electron density. Due to this and the fact that the proton bunch is less dense than the plasma ($n_b < 10^{-3} n_{pe}$, where n_b is the bunch density), the proton bunch must undergo self-modulation to excite wakefields with GV/m amplitudes [1,2], this requires $n_{pe} > 10^{14}$ cm^{-3} (corresponding to $\lambda_{pe} < 3$ mm). The plasma is created by laser ionisation of a rubidium vapour (laser pulse length: ~100 fs, energy per pulse: ~100 mJ, central wavelength: 780 nm) [3,4]. The plasma column is 10 m long, with a radius >1 mm.

AWAKE demonstrated seeded self-modulation of proton bunches and subsequent wakefield growth, as well as the acceleration of externally injected witness electrons, during Run 1 (2016–2018) [5–7].

Numerical simulations suggest that introducing a plasma density step during the self-modulation process can stabilise wakefield amplitudes once self-modulation reaches saturation [8,9]. The current experimental campaign, Run 2b (2023–2024), aims to experimentally demonstrate this stabilisation using a density step [8]. The most direct method to verify the stabilised wakefield amplitude is through measuring the energy gain of externally injected witness particles.

Since the wakefields driven by the proton bunch in AWAKE are of relatively low amplitude (~0.5 GV/m) and have a high phase velocity (relativistic factor $\gamma \sim \gamma_{p+} \sim 427$) [10,11], external electron injection is necessary. Furthermore, the witness electron bunch must be injected off-axis and several metres into the vapour source at a position z_e ($z_e \sim 1-6$ m), to avoid the loss of witness particles due to wakefield phase shifts occurring during self-modulation or from the density step [8].

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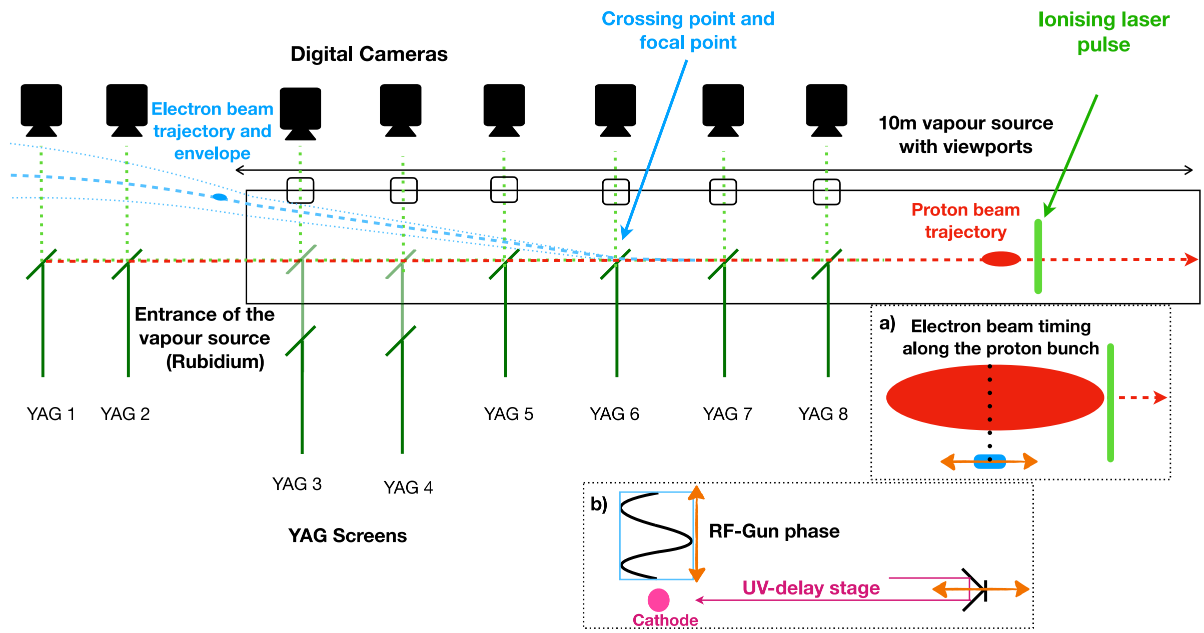

Fig. 1. Schematic drawing of experimental setup indicating the YAG screen positions along the 10m long vapour source. The trajectories of the proton bunch (red), the laser pulse (green) and the electron bunch (blue) are also shown. Inset (a) illustrates the adjustable electron bunch (blue) timing within the proton bunch (red) and with respect to the laser pulse (green). Inset (b) illustrates how the electron bunch timing is adjusted by adjusting the arrival time of the UV laser pulse on the photo cathode and a subsequent adjustment of the RF phase in the gun.

Achieving good spatial overlap between the injected electron bunch and the wakefields, along with a high witness electron bunch density at the site of injection, is critical to observe clear signals on the electron spectrometer (>1 pC required). The injection efficiency is expected to be <25 %, as only one-quarter of the plasma wavelength provides both acceleration and focusing for the electrons.

For Run 2b, a new vapour source was developed and installed [12]. Recent upgrades to the source (installation of retractable YAG screens inside the vapour source) enable, for the first time, beam diagnostic within the source. The transverse bunch size and shape at injection, previously predicted through optics simulations, can now be directly measured prior to the plasma experiments. The new screens also facilitate the spatial alignment of the three beams: the proton bunch driver, the laser pulse and the witness electron bunch. The alignment of the electron beam is done only in vacuum or vapour and if necessary in the presence of the proton beam. Once the electron beam alignment has been completed, the YAG screens are removed from the propagation axis of the beams. Only then the ionising laser pulse (which creates the plasma from rubidium vapour) can be sent. In this manuscript, the upgraded setup of the vapour source is presented together with a characterisation of the electron bunch. The previously demonstrated agreement between measured and simulated bunch sizes upstream of the vapour source entrance, shown in [13], is now extended to the location where electrons are injected into the wakefields, allowing for greatly improved control and understanding of the electron injection into the wakefields.

2. Experimental setup

2.1. Electron source and transport line

Electrons are extracted from a Cs_2Te cathode by a UV laser pulse (typical spot size: ∼1 mm, average energy: 200 nJ, top hat intensity profile [14,15]). These are then bunched and accelerated to an energy of ∼5 MeV inside an S-band RF-photo-injector [16,17]. Next, they are further accelerated to ∼19 MeV in a 1 m-long booster structure [17,18].

The bunch length ranges between ∼ 2 and 5 ps, depending on the bunch charge. This is comparable to the plasma wavelength for the nominal AWAKE plasma density of $n_{pe}=7\times10^{14}$ cm^{-3}, where $\lambda_{pe}/c=$ 4 ps.

Typical bunch charges range from 100 to 800 pC, as measured using a Faraday cup located on the electron transport line. Typical rms normalised emittance values range from 1 to 10 mm · mrad (depending on the bunch charge), measured using quadrupole scans. Witness bunches are transported to the vapour source entrance using a 15 m-long transport line. Further details regarding the optical setup and beamline can be found in [19].

2.2. Beam screens

Previously, the overlap of the electron beam trajectory with the plasma column could only be validated through observation of plasma light [13]. This method is experimentally challenging, because the signal yields are small, and no information on the spatial alignment of the electron beam with respect to the proton beam and thus the wakefields ($r\sim c/\omega_{pe}$) could be provided. Additionally, no information on the transverse bunch distribution and therefore charge overlapping with the wakefields could be extracted. Following recent upgrades to the vapour source, YAG:Ce beam screens (material: yttrium aluminium garnet activated by cerilium, thickness: 0.2 mm) can now be inserted at six positions downstream of the vapour source entrance, ranging from 0.5 to 5.5 m in 1 m intervals (labelled YAG3 to YAG8 in Fig. 1). The screens are oriented at approximately 45 degrees relative to the beam propagation axis. When the beams deposit energy into the screens, the screens emit light with an angular distribution of approximately 4π, part of which is imaged onto the CMOS of a digital camera, positioned at 90 degrees to the beam propagation axis, outside of the vapour source. The light exits through a UV-saphire view-port. This diagnostic system can now be used to determine:

1. The proton and electron beam positions and trajectories inside of the vapour source, to ensure spatial overlap of the beams at

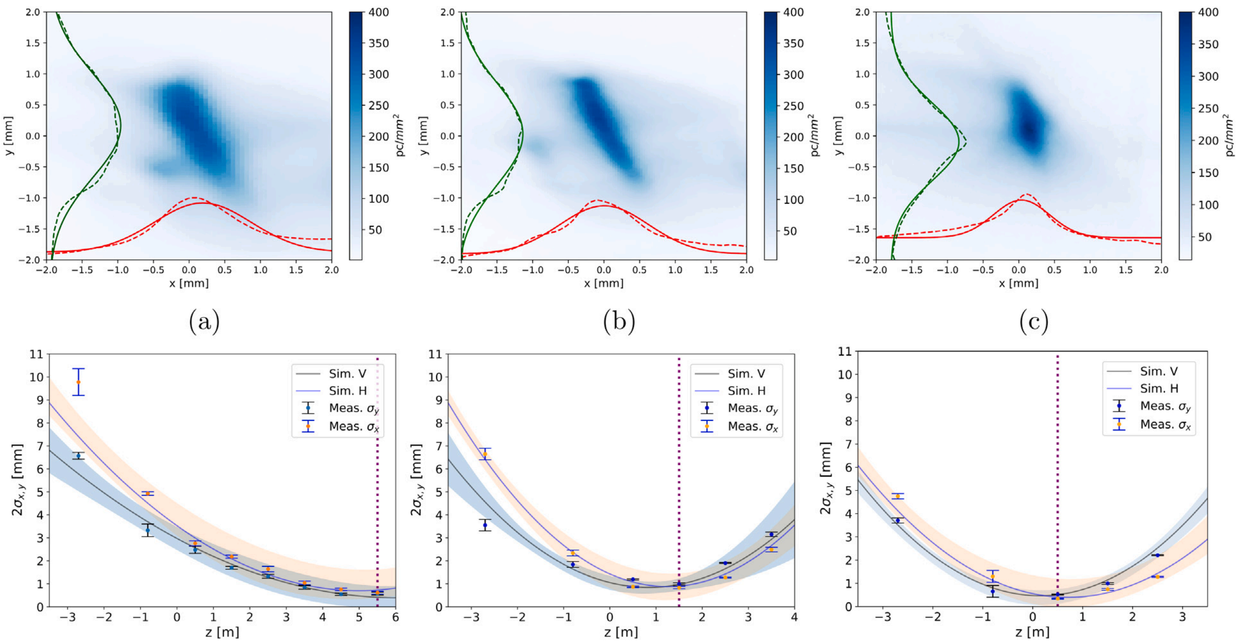

Fig. 2. Top: measurements of the transverse electron bunch distributions at waist positions for (a) 5.5 m, (b) 1.5 m and (c) 0.5 m. Horizontal (red) and vertical (green) projections (dashed lines) are shown together with the corresponding Gaussian fits (solid lines). Bottom: measured transverse 2σ bunch envelopes along the beamline for waist positions at (a) 5.5 m, (b) 1.5 m and (c) 0.5 m for the horizontal (orange dots) and vertical (blue dots) planes. Error bars include event to event variations as well as the uncertainty of the Gaussian fit. Simulation results are shown by the blue (horizontal) and black (vertical) solid lines and are envelope equation fits to the simulated beam sizes. The coloured bands indicate the uncertainty of the fit result. The entrance of vapour source is located at $z = 0$. The vertical purple dotted lines show the beam waist position.

the desired crossing location and diagnose potential variations in charge capture.

2. The beam envelopes and transverse beam sizes, to maximise the electron bunch density at the injection location, estimate the charge overlapping with the wakefields and maximise capture efficiency.

3. Measurement results

3.1. Beam envelope

The AWAKE Run 2b experiments require the flexibility to focus the electron beam at different locations z_e inside of the vapour source to inject into wakefields [13,19] (z_e = 1.5 – 5.5 m), maximise charge capture [13,19] (z_e = 1.5 – 5.5 m), or perform electron beam seeding [20] for the self-modulation process (z_e = 0.5 m). The electron beamline offers the flexibility for varying the focal point location from several metres upstream of the vapour source entrance all the way to the vapour source exit [19]. Three examples of measurements, corresponding to the three most commonly needed configurations for AWAKE Run 2b, are presented in Fig. 2. Figs. 2 a–c (top) show the transverse electron bunch distribution and the vertical and horizontal transverse electron bunch profiles as well as their Gaussian fits at focus, z_e = 5.5 m (a), 1.5 m (b) and 0.5 m (c) into the vapour source, for a bunch with 400 pC of charge. The rms normalised emittance was measured to be ∼4 mm · mrad after acceleration in the booster structure and before beam transport to the vapour source. The Figs. 2 a–c (bottom) show the transverse 2σ electron bunch size (from corresponding Gaussian fit to the horizontal and vertical profiles) measured at the focal point location as well as on multiple screens upstream and downstream, until the transverse bunch size becomes comparable to the YAG screen size (1×0.7 cm²), at which point the transverse size can no longer be evaluated correctly. Error bars include event-to-event bunch size variations as well as the error on the Gaussian fit. These measurements are compared to the expected bunch sizes from optics simulations performed in MADX [21], which are shown in Figs. 2 a–c (bottom). To guide the comparison these lines were obtained from fits of the envelope equation to the simulated bunch sizes at z =−2.7 m, −0.7 m as well as for each consecutive metre up to the focal point (Fig. 2 a) or two metres past the focal point (Figs. 2 b,c).

There is generally good agreement between the measurements and expectations from simulations, demonstrating a good understanding of the beam optics and the focal spot size.

3.2. Charge overlap with wakefields

To maximise electron charge density at injection into wakefields, the optics are designed such that a waist (focal point) of the electron beam occurs at the point where electron and proton beam trajectories cross (z_e).

From the measurements of the transverse electron bunch distributions at focus, similar to Fig. 2 b (top), the charge overlap with the wakefields can be estimated. Assuming no charge losses up to the site of injection, the intensity of the imaged beams can be calibrated for their charge (200 pC, 400 pC or 800 pC respectively). This allows for a direct estimate of the electron bunch charge within a radius of one plasma skin depth c/ω_{pe} around the proton beam centroid position, to which the electron beam is aligned. This is repeated for different plasma densities and injection angles.

Fig. 3 shows a summary of the fraction of the charge overlapping with the wakefields for electron bunches of charges Q = 200 pC, 400 pC and 800 pC, and injection angles of 1 and 7 mrad for different plasma densities. To estimate the total charge overlapping with the wakefields one can multiply the fraction of charge (Q_{oi}) with the total amount of charge in the bunch (Q). The errorbars result from bunch centroid and size variations and decrease with increasing bunch charge. A higher electron bunch charge does not necessarily lead to a higher percentage of the bunch being injected into the wakefields. Bunches

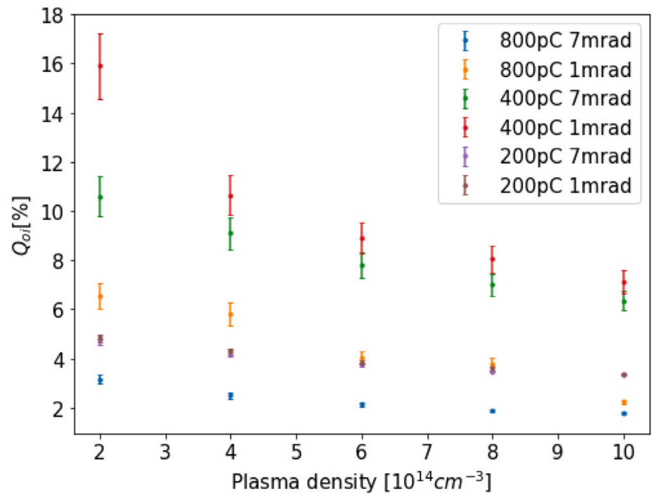

Fig. 3. Fraction (Q_{oi}) of the total electron bunch charge overlapping with the wakefields at injection as a function of plasma electron density for different incoming total electron bunch charges (Q) and injection angles (indicated in the labels). The error bars represent charge overlap variations resulting from bunch centroid jitter and size variations. The beam is focused 1.5 m downstream of the vapour source entrance.

with a higher amount of charge also have a higher rms normalised emittance: ε_N =2 mm · mrad for 200 pC, ε_N =4 mm · mrad for 400 pC and ε_N =10 mm · mrad for 800 pC, as well as more intense tails. Therefore, as the charge increases, the bunch size also increases and the charge density is not necessarily higher. The estimate shows that the maximum charge overlap occurs around 400 pC for 1 and 7 mrad injection angle.

3.3. Bunch centroid position for different arrival times

A key experimental requirement is the ability to finely adjust the timing of the electron bunch arrival within the proton bunch with picosecond precision ($\ll \lambda_{pe}/c$), without altering the spatial position of the bunch centroid. The electron bunch is generated by a UV pulse derived from the same laser pulse used to ionise the rubidium vapour and create the plasma column. This laser pulse also provides the timing for the radio frequency (RF) waves in both the electron gun and the acceleration structure as well as for the arrival of the proton bunch (illustrated in Fig. 1a, b) [4]. The arrival time of the UV laser pulse on the photocathode (at the repetition rate of 10 Hz) can be finely adjusted by a delay stage in the UV-beam path (Fig. 1 b). After each delay stage adjustment, the RF system also requires a phase adjustment of the electron gun and acceleration structure. For example, when the delay stage is moved by 1 mm, the UV light path increases by 2 mm (or 6.67 ps), requiring a phase adjustment of 7.2 degrees.

The measurements in Fig. 4 show that the UV laser delay stage alignment, as well as the RF timing adjustments, are sufficiently precise to avoid significant shifts in the mean bunch centroid position, $\Delta \mathrm{Cen}_{x,y}$. For the presented measurements, the electron bunch was focused at z_e = 5.5 m, on screen YAG8. Images of the transverse bunch distribution were recorded for different electron bunch charges (200 pC, 400 pC and 800 pC), and times with respect to the laser pulse. Delays of up to 800 ps behind the laser pulse were measured, corresponding to the maximum range used for injection into wakefields.

The measurements presented in Fig. 4 show that the mean bunch centroid positions, $\Delta \mathrm{Cen}_{x,y}$, shift by less than 20 μm for 200 pC, 50 μm for 400 pC and 80 μm 800 pC. Bunch centroid jitter (in x and y, illustrated as error bars) are on the order of (40,50) μm for 200 pC, (80, 60) μm for 400 pC and (100, 80) μm for 800 pC. In addition, transverse bunch size variations, not shown here, are smaller than (20,30) μm with 200 pC, (60,50) μm with 400 pC and (90, 60) μm with 800 pC.

Most importantly, the largest mean centroid shifts $\Delta \mathrm{Cen}_{x,y}$ and bunch size variation are on the order of the bunch centroid jitter, for all three bunch charges, and far below the transverse bunch sizes ($2\sigma_{x,y}$ ~400, 500 μm, ~700, 600 μm and ~700, 600 μm for charges of 200, 400 and 800 pC, respectively).

This enables adjustment of the electron bunch arrival time without impacting its alignment or transverse distribution, thereby preserving the charge overlap with the wakefields.

4. Deleterious effects

4.1. Magnet power cables

4.1.1. Proton beamline magnets

Some of the power cables for the 400 GeV proton beam magnets are routed in close proximity to those of the 19 MeV electron beamline, as well as to the signal cables for the electron beam position monitors (BPMs). This leads to undesirable effects, including erroneous BPM readings and electron bunch alignment changes (see Fig. 5).

The proton beamline magnets are pulsed. They ramp-up (current increases from zero to the desired value over ~1s) approximately ~6s before a proton bunch is extracted from the SPS to AWAKE. After extraction, the current decreases again to zero. This cycle is repeated approximately every 20s. It was observed that changes in the magnet current change the electron bunch position.

For example, when measured by a BPM near the vapour source entrance, (shown in Fig. 5) the maximum horizontal position change is ~600μm, and up to 200μm at the time when the proton bunch is extracted. Without any current changes in the magnets, the BPM reads position variations up to 200μm. The BPM is located after the final horizontal bend on the electron beamline [19]. Since the entrance aperture is horizontally elongated [19], horizontal variations may affect the maximum injection angle possible without beam losses. Vertical variations (not shown) were found to be within centroid jitter.

On a YAG screen after the first dispersive element of the electron beamline (YAG_{disp}), the vertical bunch centroid (recorded at 1 Hz) changes by ~200 μm, the corresponding bunch centroid position jitter on this screen is around 100 μm (see layout of the beamline in [19]). However, the vertical bunch centroid at a possible injection location, e.g. YAG8, varies only up to 80 μm at extraction of the proton bunch. This is on the order of the centroid jitter of the electron bunch on YAG8 without any ramping of the magnets.

It is noted here that vertical displacements of the electron bunch centroid at the site of injection reduce the charge overlap with the wakefields, since the two beams cross in the horizontal plane. Horizontal displacements (not shown) on the beam screens were observed to be on the order of the bunch centroid jitter (100 μm and 80 μm at YAG_{disp} and YAG8 correspondingly) and lead to a change of injection location (z_e) [13].

To mitigate any issues during the experiment, the final electron bunch alignment is verified and adjusted for the extraction events. Although this procedure is slow, with only one measurement every 20 s, it only needs to be performed once, each time the electron beam is being aligned.

4.1.2. Electron spectrometer magnets

Current changes in the magnets of the electron beamline downstream the vapour source, i.e. the quadrupoles and dipole of the electron spectrometer, also alter the electron beam alignment upstream the vapour source entrance. Unfortunately, these magnets require frequent current adjustments (e.g. to measure different electron bunch energies and emittances after acceleration in plasma) during experiments. Measurements of the horizontal and vertical bunch position, at the most downstream site of injection, YAG8, as a function of the magnet currents are shown in Fig. 6 for the spectrometer dipole (0–650 A) and quadrupoles (0–360 A). The centroid bunch position changes are on the

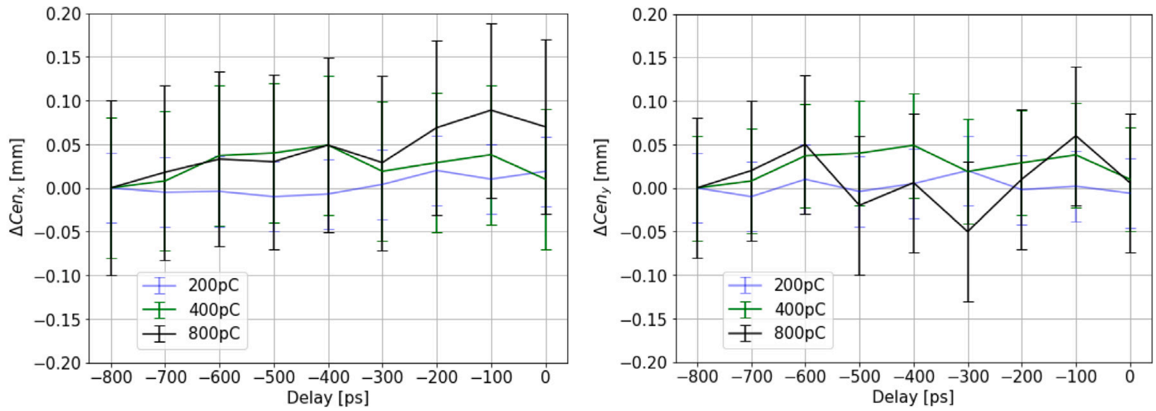

Fig. 4. Horizontal ΔCen_x (left) and vertical ΔCen_y (right) bunch position centroid changes as a function of the electron bunch delay for different electron bunch charges (indicated in the labels). The beam is focused and measured on YAG8, 5.5 m into the vapour source. Error bars show bunch centroid position jitter.

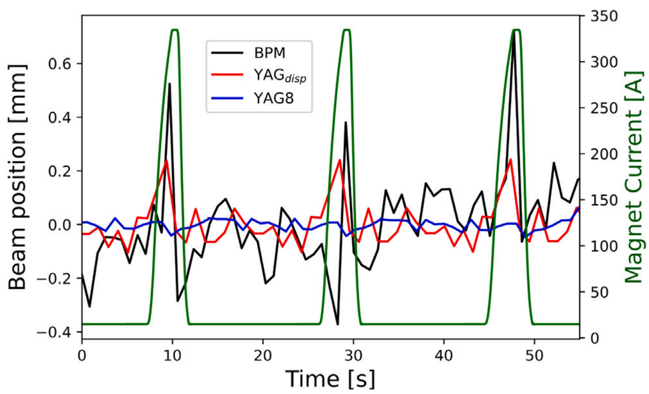

Fig. 5. Electron bunch centroid positions during an SPS cycle. Shown is the current in the magnets of the SPS as well as the SPS to AWAKE transfer line (green line) during three extraction cycles. The corresponding horizontal BPM signals close to the entrance of the vapour source are depicted with the black line (BPM). The red line shows the vertical centroid displacement of the electron bunch on YAG_{disp}. Finally, displayed in blue, is the measured vertical displacement of the electron bunch at focus on YAG8.

millimetre scale, much larger than the electron bunch transverse size and the size of the wakefields. Consequently, these magnets are kept continuously powered, at a fixed current, during measurements. The electron bunch alignment is checked and, when required, adjusted with every current change.

4.2. Vapour source heaters

The electric heaters of the vapour source (DC current) were identified as having a significant impact on the electron beam, causing centroid displacements of up to 2 mm at the site of injection. These heaters operate with a duty cycle, i.e. turning on and off as needed to maintain uniform temperature in the vapour source. To mitigate this effect, the vapour source was equipped with a blanking trigger that turns off all heaters from 130 ms to 60 ms before the bunches arrive, maintaining this state for a time interval of 250 ms and reducing any displacements down to the order of bunch position jitter.

5. Towards AWAKE Run 2c

For AWAKE Run 2c (2028-), the current photo-injector and booster structure will be reinstalled and reused as the seeding line for the self-modulator plasma. The following design changes will be advantageous:

1. **Building the electron beamline in the plane of the proton beamline:** In its current configuration, the electron beamline is designed to follow the tunnel layout, which includes two major bends. The first is a vertical dipole that bends the beam upward, followed by a skew dipole that redirects the beam to the left and downward. Due to the limited availability of other magnetic elements, this configuration results in zero dispersion occurring at only one specific point (typically at the focal point). Consequently, there is dispersion both upstream and downstream of this focal point, rendering the beamline highly sensitive to electron bunch energy variations. Further details on the current beamline can be found in [19]. The Run 2c design is forseen to include only one horizontal dogleg and chromaticity correcting magnets (sextupoles and octupoles). A preliminary design was developed in [22].
2. **Independent timing for the electron gun:** To simplify changes in the arrival time of the electron bunch, the timing for the gun and acceleration structure will be provided by an independent timing signal (from the main laser).
3. **Separation of cables:** It is essential to maintain adequate separation between the power cables for the magnets of the proton beamline and those for the electron beamlines, as well as the signal cables for diagnostics in order to avoid the effects described in Section 4.

6. Conclusion and outlook

In conclusion, the installation of YAG screens within the vapour source significantly improves the precision on the beam alignment for the upcoming AWAKE experiments. The screens not only enable accurate setting of the crossing location between the electron witness bunch and the proton bunch, but also provide a tool for measurements of the beam centroid jitter and allows to estimate the electron bunch charge overlap with the wakefields. Furthermore, since measurements can be performed at multiple locations along the vapour source, the electron beam envelope measured for different focal point positions shows to be in good agreement with results from simulations.

Additionally, measurements show that the electron timing can be adjusted without causing significant changes in the bunch centroid position. This allows probing the wakefields at various delays without the need for realignment. These findings are important for the upcoming Run 2b AWAKE experiments, which aims to show stabilisation of the wakefield amplitude through the use of a plasma density steps during self-modulation. Demonstrating stabilised wakefields amplitudes relies on the successful injection of a sufficient amount of electrons into the wakefields, making this enhanced beam alignment capability vital for achieving the experimental objectives.

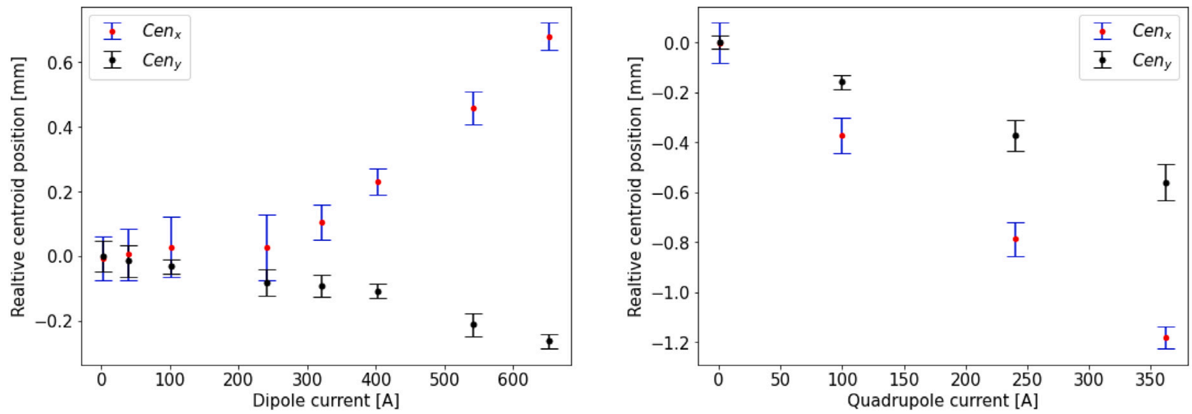

Fig. 6. Horizontal (blue) and vertical (black) electron bunch centroid positions measured at the most downstream site of injection, YAG8, as a function of the current in the spectrometer dipole magnet (left) and quadrupole magnets (right). Error bars include bunch position jitter and errors on the fit.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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