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STATUS OF THE COMMISSIONING OF THE X-BAND INJECTOR PROTOTYPE FOR AWAKE RUN 2C

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Abstract

The status of commissioning of the electron injector intended for the next phase of the proton driven wakefield experiment, Advanced Wakefield Experiment (AWAKE), is presented, showing first results from operating the brazing-free electron gun. To provide a high-quality electron beam, the UV laser was centered on the copper cathode, and a novel beam-based alignment of the focusing solenoid was performed. Measurements of the beam parameters and working points are addressed. The electron gun is shown to provide a high quality, stable and reproducible beam.

INTRODUCTION

Run 1 of the AWAKE at CERN, which concluded in 2018, achieved all milestones. It demonstrated phase-stable and reproducible self-modulation of the proton bunch in the plasma, consequently achieving high gradients, and accelerated externally injected electrons to GeV beam energies using these proton- driven plasma wakefields for the first time [1]. Run 2, which began in 2021, aims to demonstrate the acceleration of electrons with high gradients (1 GV/m) while controlling the beam quality and showing the scalability of this process. Once this is demonstrated, the AWAKE technology will be ready for use for first particle physics experiments.

Run 2 is staged in four phases (2a-d) and lasts for several years. While Run 2a (2021-2022) demonstrated that the electron bunch seeds the proton bunch self-modulation in the plasma, the goal of Run 2b (2023-2024) is to demonstrate that high-amplitude wakefields can be maintained over long distances. Run 2c, foreseen to start in 2028, aims for acceleration of a witness electron bunch while maintaining a sustained beam quality. In Run 2d the accelerating plasma source will be replaced with a longer one to achieve even higher electron energies.

For Run 2c and 2d, which will start after CERN's Long Shutdown 3, a new electron injector will be required, able to provide high quality electron bunches to the plasma cell with a low emittance and energy spread.

Given these requirements, a new injection scheme has been proposed, consisting of an S-band photoelectron gun, followed by two X-band accelerating structures. This design would allow for bunch lengths smaller than 200 fs, and a beam energy of around 150 MeV [2].

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ACCELERATOR BASELINE

A photo of the operating gun set-up is shown in Fig. 1. The S-band electron gun was fabricated with brazing-free technology [3]. It achieves a maximum RF gradient of 120 MV/m, providing an electron beam energy up to 6 MeV. The photogun is equipped with a copper cathode emitting small emittance electron bunches under a moderate vacuum level. To generate the electron bunches, a PHAROS laser is used, emitting infrared 2 mJ pulses, with a repetition rate of 1 kHz. The RF limits the electron bunch repetition rate to a maximum of 10 Hz. The infrared laser is frequency quadrupled to the ultraviolet to match the copper work function and minimise the thermal emittance. The nominal extracted bunch charge is 400 pC, however up to 800 pC bunches have been measured for the smallest laser pulse length of 112 fs RMS with a 270 µm RMS spot size. The nominal accelerating gradient is 106.7 MV/m, which achieves an electron beam energy of 6 MeV, and a relative energy spread of 2 %.

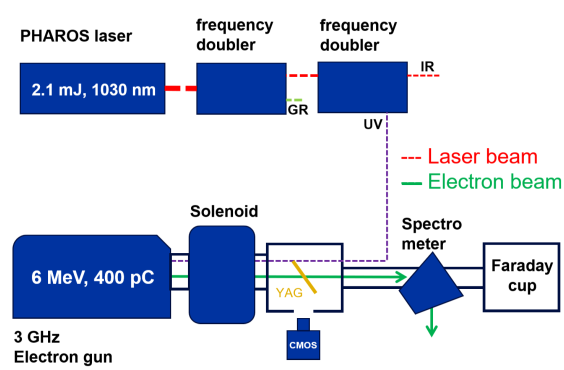

Figure 1: Schematic diagram of the AWAKE Run2 Test Injector.

The accelerated electron bunch is focused to a small spot by a double-coil solenoid in the plus-plus configuration. At 0.57 m from the cathode, the beam can be visualised with a YAG screen. The imaging system provides sufficient precision for measuring the variation of both the beam size and drift against the tuning parameters, namely the RF phase, the laser spot size and position on the cathode, along with the solenoid strength and transverse position. Beam energy measurements are made with a dipole spectrometer. Further downstream, a Faraday cup is installed for bunch charge readings. The stability in terms of bunch charge was found to be better than 5 %.

The AWAKE Run2 Test Injector (ARTI) presents sufficient diagnostic tools for a comprehensive analysis of the electron beam for commissioning. Following the initial calibration of the diagnostics equipment, the cathode laser and

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solenoid were aligned in order to minimise the extracted emittance using a novel offset inference method based on the simplex optimisation algorithm.

OFFSET INFERENCE METHOD

A solenoid scan was performed, and the beam drift and beam size sigma were recorded against the solenoid field strength. A simulation of the solenoid scan was then performed in RF-Track [4], with the same input beam parameters, while keeping the offsets as free parameters. For the laser input, an RMS laser pulse length of 327 fs and RMS spot of 160 by 230 µm was measured and used in the simulations. A bunch charge of 53 pC was set to minimise space charge effects. An RF gradient of 106.7 MV/m, and a relative RF phase of −20° were used.

The offsets considered were the position of the laser on the cathode, along with the angular and transverse offsets of the solenoid. Simulations showed that the laser position offset had the largest impact on the emittance. The simplex optimisation tuned the laser position until a corresponding match was achieved for the beam size measurement. Afterwards, the solenoid transverse and angle offsets were tuned to match the trajectory formed by the beam drift in X and Y.

The matching of the measured solenoid scan and RF-Track simulation is shown in Fig. 2, and the resulting offsets in Table 1. The calculated offsets could explain the discrepancy between the predicted 25 µm spot size from the simulations with no offsets applied, and the obtained 100 µm.

To check the results from the simulations, the beam profiles obtained from the offset inference script at the focus were compared with measured profiles. The result, shown in Fig. 3, indicated a strong correlation, where the simulation was able to predict an asymmetry in the tail distribution. Both the measured and simulated beam profile contained a significant beam halo, accounting for 80 % of the bunch population. The transverse shaping of the electron beam is best represented by a heavy-tailed Q-Gaussian.

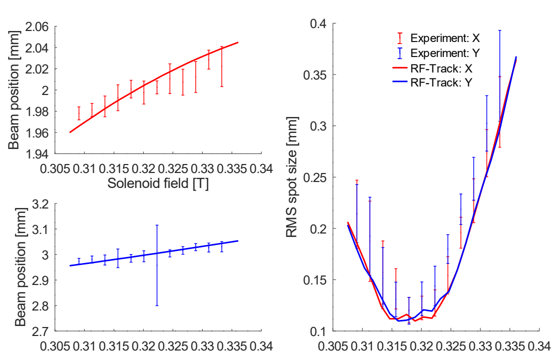

Figure 2: Comparison of the measured beam drift and size in a solenoid scan with simulations following the simplex-based offset inference.

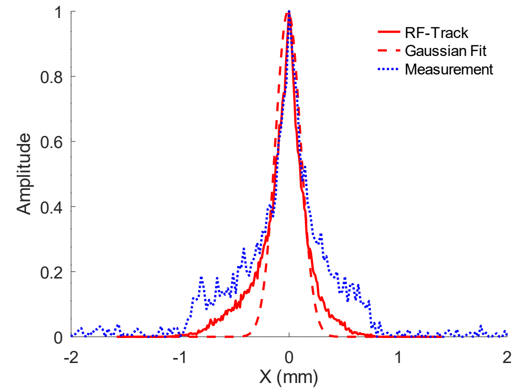

Figure 3: Comparison between the measured and simulated beam profiles.

Table 1: Offsets measured and inferred from RF-Track using the Simplex-based method

Offset	Inferred	Measured	Unit
Cathode X/Y	2.30 / 1.33	1.27 / 0.85	mm
Solenoid X/Y	2.66 / 3.19	0.82 / 1.63	mm

SMALL SPOT SIZE WORKING POINTS

To confirm the results obtained from the offset inference script, heatmaps of the electron beam size as a function of the solenoid field strength and RF phase or laser spot size on the cathode were reproduced in RF-Track simulations. The scans were done for a 400 pC bunch charge in order to determine the preferred RF phase and laser spot size for the minimum electron spot under space charge effects.

As shown in Fig. 4, a good agreement was found between simulation and experiment. The results showed that to obtain the minimum electron beam spot size the solenoid strength had to be adjusted for each phase, which can be explained by the change in beam energy with the RF phase.

The simulated heatmap of the electron beam size as a function of the RMS laser spot and solenoid strength showed no impact of the laser spot size on the beam energy. This was not fully reproduced in the measurements, which can be explained by a small drift of the laser position on the cathode during the change in focus, that shifted the beam energy.

By selecting the smallest electron spot obtained for each RF phase and laser spot size, as shown in Fig. 5, it was found that a −20° phase and 0.2 mm RMS laser spot are preferred for obtaining the smallest electron spot.

EXPERIMENTAL RESULTS FROM THE GUN ALIGNMENT

To check the results from the offset inference script, an alignment based on experimental methods was performed, and the resulting offsets were compared to the predicted ones.

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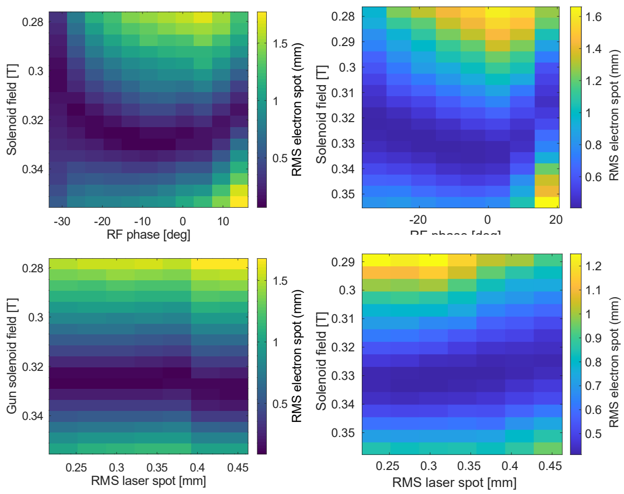

Figure 4: Comparisons between simulations (left) and measured data (right) of electron beam size as a function of the solenoid strength with respect to the RF phase (top) and laser spot size (bottom).

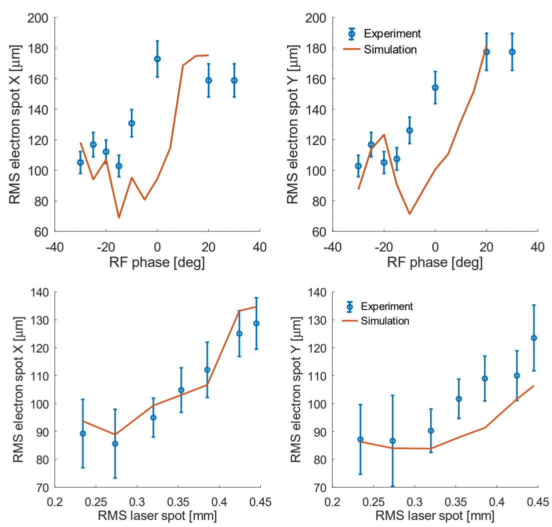

Figure 5: Comparisons between simulations (line, red) and measured data (marker, blue) of the minimum electron spot size sigma in X and Y, against the RF phase (top) and laser spot size (bottom).

Laser-Cathode Alignment

To align the laser on the cathode, RF focusing was used to contain the beam on the imaging screen with the solenoid, dipole, and corrector turned off, in order to avoid their contribution to the beam trajectory. To achieve this, a 1 MeV beam of 5 pC was used. The RF phase was then scanned for a given laser position on the cathode.

By scanning the RF phase, the electron beam drifts due to transverse RF fields in the gun, as seen in Fig. 6. The closer the beam is to the gun centre, the smaller the drift. The data was linearly fitted, and the process was repeated for a different laser position on the cathode. The point of intersection of the two linear fits corresponds to the laser position at the center of the cathode. This method is similar to the one described in [5]. The laser-cathode offset correction corresponded to 1.27 mm in X and 0.85 mm in Y.

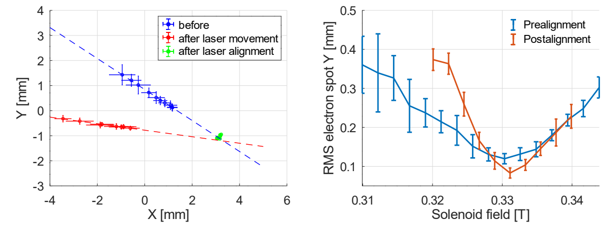

Figure 6: The laser cathode alignment process (left) and the comparison of a solenoid scan pre- and post-alignment (right).

Solenoid Alignment

To align the solenoid after finding the gun centre, a small solenoid strength was applied, and the beam drift tracked. It was found that the curve of the beam drift corresponded to a strong Y offset, which could be corrected using the solenoid movers. The edge of the scanning range was reached in Y, corresponding to an offset correction of 1.63 mm. The offset in X was also corrected by 0.82 mm. An even larger offset correction will be required to align the solenoid, however the limit switch of the solenoid mover motors was reached during the present study. The results, in Fig. 6, show that a 40 % decrease in the RMS electron spot at the focus was obtained by the preliminary alignment of the laser position on the cathode and the solenoid. Further reduction will be possible after the realignment of the solenoid.

Effects such as the non-uniformity of the cathode, or the set-up of the imaging system, could have also led to the mismatch between simulations and experiment. These potential contributions will be further investigated.

CONCLUSION

The commissioning of ARTI showed that the electron gun is able to deliver a stable and high-quality electron beam. In efforts to minimize the beam emittance, a novel offset inference method was developed, utilizing RF-Track and a simplex minimization technique to determine the deviation of the solenoid and laser-cathode based on solenoid scan measurements. Experimental methods, including tracking beam drift with RF phase scans and solenoid position adjustments, were employed in order to check the inferred offsets. Partial correction of these deviations resulted in a notable 40 % reduction in beam size during the preliminary alignment phase. The offset inference method showed good agreement with the measurements in terms of beam offset and size at the screen, but only approximate in terms of absolute offsets. Further studies will be performed in order to improve on the matching between simulations and experiment.

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