OPTIMISING THE PROTON AND ELECTRON TRANSFER LINES DESIGN FOR HIGH-QUALITY ELECTRON ACCELERATION IN AWAKE RUN 2C

E. Belli*[1,2], P.N. Burrows[1], Y. Dutheil[2], F.M. Velotti[2]
[1]John Adams Institute for Accelerator Science, Oxford, United Kingdom
[2]CERN, Geneva, Switzerland

Abstract

The Advanced Wakefield Experiment (AWAKE) is developing a novel plasma-based accelerator concept in which self-modulated proton bunches generate wakefields capable of accelerating electrons to energies relevant for particle physics. Completed in 2025, the Run 2b experimental phase aimed to demonstrate wakefield-amplitude stabilisation after saturation of the self-modulation process via a plasma density step while establishing the experimental configuration needed for high-quality electron acceleration in Run 2c. In Run 2c, the goal is to demonstrate acceleration up to about 10 GeV while preserving the quality of the accelerated electron beam. To achieve this, a new configuration of the proton transfer line is under investigation to compensate for the bending introduced by the 150 MeV electron line dipole in the interaction region between the two plasma cells. In parallel, the experimental requirements for the 150 MeV electron line have evolved to minimise the physical gap between the two plasma cells, demanding an optimised focusing scheme to deliver a beam with a transverse size of a few microns into the second plasma section. A new design of the 150 MeV electron transfer line is therefore proposed, including detailed error studies to assess its robustness under realistic operational conditions.

INTRODUCTION

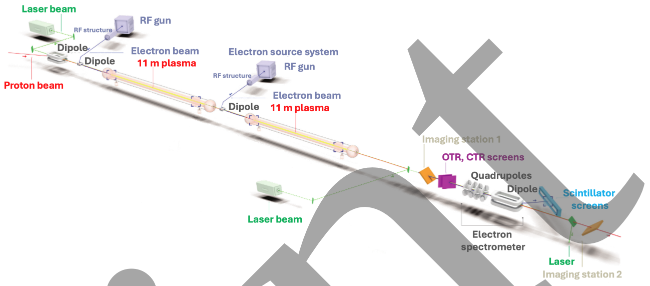

Figure 1: Schematic of the configuration of the seeding and witness electron beamlines and plasma cells in Run2c.

The goal of the upcoming Run 2c phase of the AWAKE experiment [1, 2] is to achieve electron energies up to 10 GeV while preserving the quality of the accelerated electron beam in terms of emittance and energy spread. To achieve this, the proton bunch self-modulation [3, 4] and the electron bunch acceleration will be separated into two plasma cells, in order to prevent the emittance growth of the electron bunch which would occur if exposed to the defocusing fields of the unmodulated proton bunch. A schematic of the proposed Run 2c beamline configuration is shown in Fig. 1. An 18 MeV seeding electron beamline [5] will be used to inject electron bunches into the first plasma cell to seed the proton bunch self-modulation. To include a second plasma cell in the new configuration, the first plasma cell will be shifted 40 m downstream, requiring a reconfiguration of the proton beamline [6]. In addition, a new 150 MeV beamline will be installed to inject a witness electron bunch, produced with a 10 Hz frequency, into the second plasma cell, thus probing the proton driven wakefield acceleration. This document focuses on the latest optics design of the 150 MeV electron line and the newly proposed configuration of the proton line.

ELECTRON LINE OPTICS DESIGN

A preliminary design of the witness electron transfer line was presented in [7]. To satisfy the spatial constraints imposed by the tunnel geometry, the design of this line was particularly challenging. A dog-leg configuration, consisting of two 15° bending dipoles, was therefore adopted to transport the electron beam from the source to the entrance of the second plasma cell, where it is then injected on the same axis as the proton and laser beams (on-axis injection). Additional complexity arises from the very tight experimental requirements: electrons must be injected into the second plasma stage with micron-level precision in both position and beam size, in order to ensure proper matching to the accelerating and focusing regions of the wakefields. The main beam parameters are summarized in Table 1.

Table 1: Beam parameters for the AWAKE Run 2c electron transfer line.

Parameter	**Value**
Momentum p	150 MeV/c
Relative energy spread $\Delta p/p$	0.2 %
Normalised emittance $\varepsilon_{x,y}$	2 mm mrad
Beam size $\sigma_{x,y}$ at waist	$\leq 1.5\sigma^*$, $\sigma^* = 5.75$ µm
Bunch length σ_z at waist	60 µm
Dispersion $D_{x,y}$ at waist	0 m

Compared to the initial design presented in [7], the new design described in this paper includes several modifications. The first is the use of existing magnets available from other facilities, which are compatible with a new family of power converters [8], providing the accuracy class required for this line. In addition, from the experimental physics requirements, the gap between the two plasma stages must be

---

[*] eleonora.belli@cern.ch

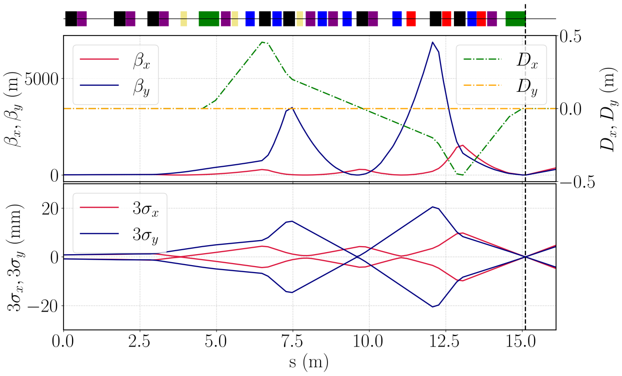

Figure 2: Horizontal (red) and vertical (blue) β- functions (top) and 3σ beam envelopes (bottom) along the transfer line. Horizontal dispersion is shown in green. The magnetic lattice is shown on top, where dipoles, quadrupoles, sextupoles, octupoles, BPM-corrector assemblies and BTVs are reported as green, black, blue, red, purple and yellow boxes, respectively. The black dashed line represents the updated waist location.

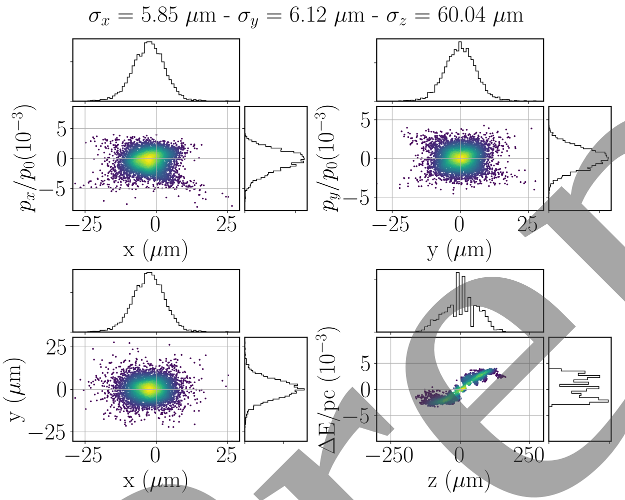

Figure 3: Top: horizontal (left) and vertical (right) phase spaces; bottom: transverse (left) and longitudinal (right) distributions of the tracked beam at injection point.

minimized as much as possible in order to avoid a significant reduction of the wakefield amplitude in the second stage [9]. To achieve a gap of about 30 cm between the two plasma cells, the design of the injection region required the beam waist to be located as close as possible to exit of the last dipole magnet and its fringe fields, with an optimal position at approximately 10–15 cm downstream of the end of the pole pieces (for a dipole aperture of 10 cm, with fringe fields extending over 10 cm). From an optics point of view, this is equivalent to shifting the focal point position upstream by 21 cm with respect to the initial design, while leaving the central positions of the magnets unchanged along the transfer line. The optics model has been migrated from MADX/PTC [10] to XSuite [11] and the existing genetic algorithms and numerical optimisation tools used for the previous design [7] have been revised and adapted to ensure full compatibility with XSuite multi-particle tracking simulations. Within this updated simulation environment, an optics rematching has been performed in the ideal case, i.e. assuming no errors or imperfections in the lattice, leading to the results shown in Figs. 2 and 3. The resulting optics functions show zero dispersion both at the waist and downstream, as requested by the experiment for vector alignment purposes, and the corresponding beam sizes at injection point are well within specifications in both transverse and longitudinal planes.

Error studies

The aim of this section is to evaluate the impact of static and dynamic errors on the beam parameters at injection point. While static errors remain constant over time or vary slowly, typically on timescales of several days, and can therefore be effectively mitigated, dynamic errors fluctuate from pulse to pulse and cannot be corrected. Both contributions can significantly affect the performance of the transfer line, therefore a correction scheme based on an active alignment procedure is needed to reach the required beam size and pointing specifications at injection into the second plasma cell. As described in [6], this procedure consists of a quadrupole shunting technique, dispersion-free steering, and the alignment of sextupoles and octupoles through numerical optimisation, and involves installing the high-order magnets (i.e. quadrupoles, sextupoles, and octupoles) on movers, allowing their vertical and radial positions to be adjusted at the micrometre level. For these studies, several sources of errors have been considered, including transverse alignment errors and magnetic field imperfections of the high-order magnets, position and angle offsets of the input beam, power converter ripple, and errors in the readings of diagnostic devices. Each error is assumed to be gaussian with the standard deviation summarised in Table 2. A set of 300 random configurations of errors (seeds) was simulated and corrected and the beam distribution was dumped at the injection point to evaluate the corresponding performance metrics.

The RMS horizontal and vertical beam sizes at injection point after correction are shown in Fig. 4 (left): the alignment procedure allows ≈ 97% of the shots to meet the experimental beam size tolerances. Fig. 4 (right) shows the beam centroid position in both planes, computed as the mean of the horizontal and vertical coordinates: considering a point-

Table 2: RMS values of the error distributions and measurement resolutions used in simulations.

Parameter	**Error**
BTV resolution	1 µm
BPM resolution	10 µm
Alignment	100 µm
Magnetic field	100 ppm
Power converter	7 ppm
Input beam position jitter	10 µm
Input beam angle jitter	1 µrad

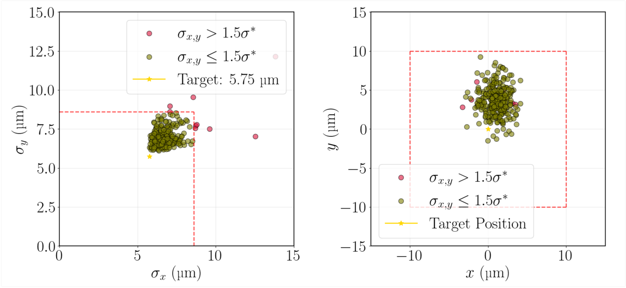

Figure 4: Horizontal and vertical RMS beam size (left) and beam position (right) at injection point for all seeds, considering the full set of errors after the alignment procedure. The red dashed line represents the tolerance, while the yellow star marks the target value. Green and red dots indicate seeds within and outside specifications, respectively.

ing tolerance of ± 10 µm required by the experiment, 97% of the shots are within both position and beam size specifications after alignment. As the relative proton-electron offset at injection point is relevant for the experiment, a proton beam jitter with $\sigma_{p,x}$ = 34.2 µm and $\sigma_{p,y}$ = 5.4 µm is considered [12]. The electron beam jitter is significantly smaller ($\sigma_{e,x}$ ≈1.3 µm, $\sigma_{e,y}$ ≈1.8 µm), such that the relative offset is dominated by the proton contribution, in particular in the horizontal plane. In these conditions, about 21% of shots are expected to be aligned within ±10 µm, which is above the baseline of 15% agreed in [13] for demonstration experiment. For 1000 shots, the estimated probability is 21% ± 2.5% (95% confidence interval).

PROTON LINE RECONFIGURATION

The dipole magnet located in the injection region between the two plasma sections bends the witness electron beam and the proton beam in two opposite directions. For the 400 GeV proton beam, the corresponding bending angle is about 0.1 mrad. In simulations, this effect has been modelled as a transverse kick applied at the dipole location, resulting in a horizontal trajectory offset of about −28 µm at the focal point and −1.1 mm at the exit of the second plasma cell. To compensate for this effect, two horizontal correctors have been used to inject the proton beam off-axis into the first plasma cell. This configuration ensures that the beam is on-axis at the focal point and remains centered up to the exit of the second plasma section, as shown in Fig. 5. The beam envelope ($6\sigma_{x,y}$) shown in Fig. 6 accounts for conservative assumptions on possible deviations from the nominal optics, namely an orbit error of 2 mm $\sqrt{\frac{\beta_{local}}{\beta_{max}}}$, a 2 mm alignment error and +20% error in $\beta_{x,y}$. Under these conditions, the beam envelope remains well within the available pipe aperture along the entire line, and the configuration provides a clearance of about 3 mm between the beam envelope and the laser mirror. For comparison, the previous design allowed for a clearance of about 2 mm [6], indicating an improvement in operational margin. Operationally, this configuration will not rely on correctors as implemented in simulations, but rather on the definition of a new golden trajectory through the dipole magnets, which set the nominal beam orbit.

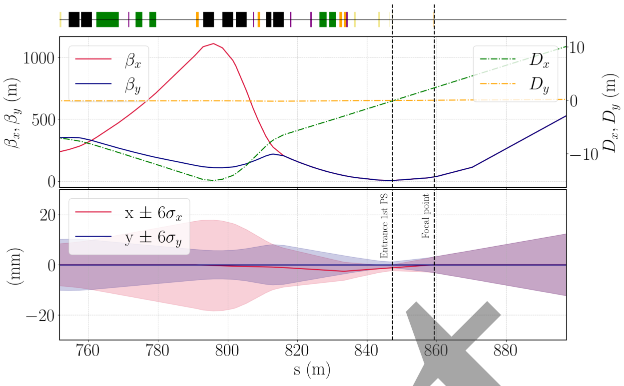

Figure 5: Horizontal (red) and vertical (blue) β- functions (top) and 6σ beam envelopes (bottom) along the transfer line in the new proposed configuration. Horizontal dispersion is shown in green. The magnetic lattice is shown on top, where dipoles, quadrupoles, correctors, BPMs and BTVs are reported as green, black, yellow, orange and purple boxes, respectively. The black dashed lines represent the entrance of the first plasma cell and the updated waist location.

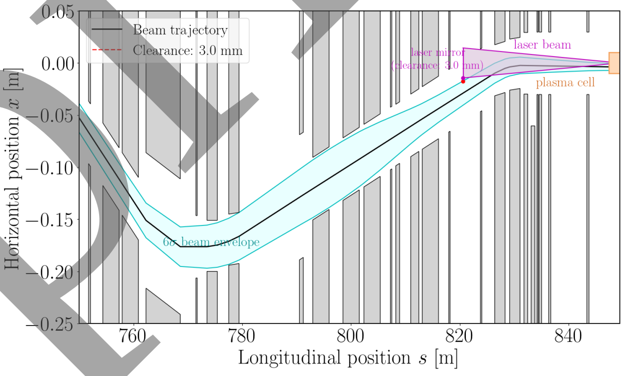

Figure 6: Horizontal 6σ beam envelope (in blue) with horizontal magnet apertures (in grey). The laser beam and the laser mirror location are shown in purple.

CONCLUSION

A new configuration of the proton and electron lines for AWAKE Run 2c has been presented, addressing the updated experimental requirements associated with the design of the injection region between the two plasma stages. For the 150 MeV electron line, a revised optics design has been developed to address the repositioning of the beam waist. Error studies show that the proposed correction scheme is effective in mitigating the impact of realistic imperfections, allowing the required beam size to be met for the majority of cases. In agreement with the baseline performance, 21% of shots satisfy the relative alignment and size tolerances, primarily limited by the proton beam jitter. For the proton line, the effect of the injection region dipole has been analysed and compensated through an adjusted injection strategy into the first plasma cell, ensuring proper on-axis injection into the second plasma stage while respecting aperture constraints.

REFERENCES

[1] `https://awake.web.cern.ch/`

[2] E. Gschwendtner *et al.*, "AWAKE: Preparing for physics beyond LS3", in *Proc.* 17th International Particle Accelerator Conf. (IPAC'26), Deauville, France, May 2026 paper TUP3049, this conference.

[3] M. Turner *et al.*, "Experimental observation of plasma wakefield growth driven by the seeded self-modulation of a proton bunch", in *Phys. Rev. Lett.*, vol. 122, no. 5, p.054801, 2019. `doi:10.1103/PhysRevLett.122.054801`

[4] E. Adli *et al.*, "Experimental Observation of Proton Bunch Modulation in a Plasma at Varying Plasma Densities", in *Phys. Rev. Lett.*, vol. 122, no. 5, p.054802, 2019. `doi:10.1103/PhysRevLett.122.054802`

[5] V. Bencini and F. M. Velotti, "Design of the new 18 MeV electron injection line for AWAKE Run2c", in *Proc.*, 14th Int. Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, pp. 287-290. `doi:10.18429/JACoW-IPAC2023-MOPA102`

[6] R. Ramjiawan *et al.*, "Design of the proton and electron transfer lines for AWAKE Run 2c", in *Nuclear Inst. and Methods in Physics Research, A*, vol. 1049, p.168094, 2023. `doi:10.1016/j.nima.2023.168094`

[7] R. Ramjiawan *et al.*, "Design and operation of transfer lines for plasma wakefield accelerators using numerical optimizers", in *Phys. Rev. Accel. Beams* , vol. 25, no. 5, p.101602, 2022. `doi:10.1103/PhysRevAccelBeams.25.101602`

[8] `https://sy-dep-epc-lpc.web.cern.ch/converters/mexico/general.stm`

[9] E. Adli, "Towards Awake Applications: Electron Beam Acceleration in a Proton Driven Plasma Wake", in *Proc.*, 7th Int. Particle Accelerator Conf. (IPAC'16), Busan, Korea, May 2016, pp. 2557-2560. `doi:10.18429/JACoW-IPAC2016-WEPMY008`

[10] `https://madx.web.cern.ch/`

[11] G. Iadarola *et al.*, "Xsuite: An Integrated Beam Physics Simulation Framework", in *68th ICFA Advanced Beam Dynamics workshop on high-Intensity and High-Brightness Hadron Beams (HB2023)*. `doi:10.18429/JACoW-HB2023-TUA2I1`

[12] V. Bencini, F.M. Velotti, "Proton beam jitter estimate for AWAKE Run2c", 2024. `https://cds.cern.ch/record/2910947`

[13] "AWAKE cost and schedule review", 2021. `https://indico.cern.ch/event/1080001/`