DESIGN OF THE PROTON AND ELECTRON TRANSFER LINES FOR AWAKE RUN 2C

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Abstract

The AWAKE Run 1 experiment achieved electron acceleration to 2 GeV using plasma wakefield acceleration driven by 400 GeV, self-modulated proton bunches from the CERN SPS. The Run 2c phase of the experiment aims to build on these results by demonstrating acceleration to ~10 GeV while preserving the quality of the accelerated electron beam. To realize this, there will be an additional plasma cell, to separate the proton bunch self-modulation and the electron acceleration. A new 150 MeV beamline is required to transport and focus the witness electron beam to a beam size of several microns at the injection point. This specification is designed to preserve the beam emittance during acceleration, also requiring micron-level stability between the driver and witness beams. To facilitate these changes, the Run 1 proton transfer line will be reconfigured to shift the first plasma cell 40 m downstream. The Run 1 electron beamline will be adapted and used to inject electron bunches into the first plasma cell to seed the proton bunch self-modulation. Proposed adjustments to the proton transfer line and studies for the designs of the two electron transfer lines are detailed in this contribution.

INTRODUCTION

AWAKE Run 1 was a proof-of-principle experiment which demonstrated that electron beams could be accelerated to GeV energies using proton-driven plasma wakefield acceleration [1,2]. The wakefield driver, a 400 GeV, 12-cm-long proton beam, was injected into a 10 m plasma cell where it underwent Seeded Self-Modulation to produce a train of microbunches with lengths approximately equal to the $O(1\text{ mm})$ plasma wavelength [3,4]. These trains of microbunches resonantly drove large-amplitude wakefields which were sampled by 18.84 MeV witness electron bunches [5].

The goal of AWAKE Run 2 is to achieve acceleration to higher energies while maintaining a smaller emittance and energy spread so as to be useful for high-energy physics applications [6]. Run 2 will be split into four intermediary stages [7]. Run 2a will study the seeding of the proton bunch self-modulation with a ~18 MeV electron bunch to ensure the self-modulation is phase-stable and reproducible. During Run 2b, a density step will be introduced in the plasma to stabilise the self-modulation process. For Run 2c, the proton bunch self-modulation and the electron bunch acceleration will be separated into two plasma cells to mitigate the emittance growth of the electron bunch from the defocusing fields of the unmodulated proton bunch. A schematic of the Run 2c beamline configuration is shown in Fig. 1. To minimise the defocusing of the proton beam between the plasma cells, the gap should be < 1 m [8]. The aim of Run 2d will be to demonstrate the scalability of the experiment to longer plasma cells and higher energies.

The design studies for the Run 2c transfer lines are ongoing. Simulations of the transfer lines were performed using MAD-X [9]. Here we present the current proposals for the designs of the witness electron line and the reconfiguration of the proton line; beam parameters for these lines are given in Table 1. The parameters for the seeding electron line will be determined as a result of the Run 2a studies. This line is foreseen to be adapted from the ~18 MeV Run 1 electron beamline.

Table 1: Beam Parameters for the AWAKE Run 2c Proton and Witness Electron Transfer Lines [6]

Parameter	**Proton line**	**Electron line**
Beam energy	400 GeV	150 MeV
Charge	48 nC	100-200 pC
Bunch length	6-12 cm	60 µm
Energy spread	0.03%	0.2%
Norm. emittance	3.5 mm mrad	2 mm mrad

PROTON TRANSFER LINE

To enable the Run 2c layout changes, the plasma cell will need to be moved approximately 40 m downstream. The transfer line should be reconfigured and rematched, without any additional magnets, to achieve the same beam parameters at the injection-point as for Run 1 (Table 2).

The Run 1 proton transfer line was adapted from the previous CNGS line. For the AWAKE experiment, the plasma is produced by ionising Rubidium gas using a short laser pulse. To incorporate the mirror needed to merge the laser beam onto the axis of the proton beam, a half-chicane was added to avoid the intersection of the high-energy proton beam with the mirror. The half-chicane was constructed by moving the dipole MBG.412115 (Fig. 2) downstream and adding two pairs of B190 dipoles to bend the beam onto the axis of the plasma cell. For Run 2c, to conserve the laser beam stability of Run 1, the merging-mirror should be moved downstream along with the plasma cell, requiring the half-chicane to be widened and lengthened. By moving MBG.412115 an additional 12.5 m downstream, the chicane would be widened

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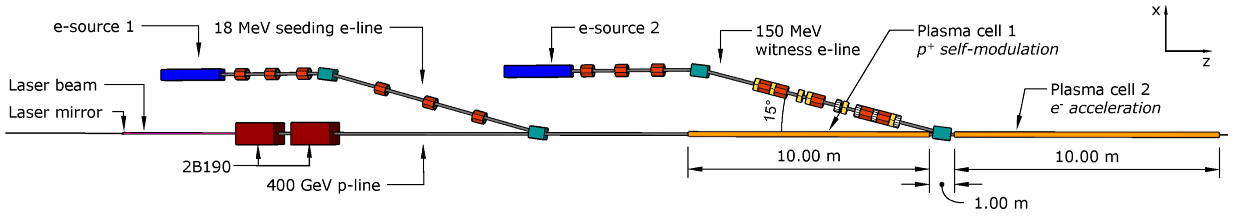

Figure 1: Schematic of the configuration of the two electron beamlines, plasma cells and a section of the proton transfer line. Dipoles are shown in cyan, the quadrupoles in red, the sextupoles in yellow and the octupoles in white.

from 8 cm to 18 cm. If the start and end of the half-chicane were shifted +20 m and +40 m, respectively, it would allow the laser mirror to be moved to within 26 m of the plasma injection-point which is expected to provide sufficient laser stability.

A design to reconfigure the proton line has been developed and the optics are shown in Fig. 2. The injection-point parameters are given in Table 2 alongside the specifications. This design would provide a 2 mm clearance between the beam envelope and the laser-merging mirror. The beam envelope ($6\sigma_{x,y}$) includes orbit error 2 mm $\times\sqrt{\frac{\beta_{local}}{\beta_{max.}}}$, 2 mm alignment error and 20% $\beta_{x,y}$ error. By extending the line without additional magnets, the apertures would be tight, particularly within the half-chicane (Fig. 3).

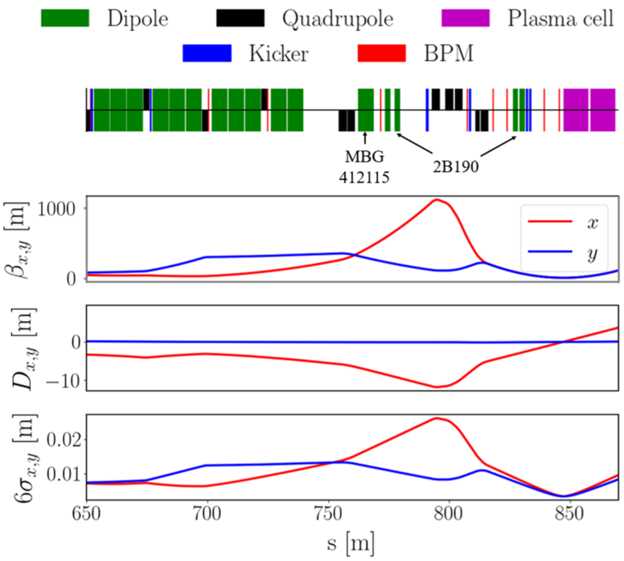

Figure 2: MAD-X simulation of the proposed Run 2c proton transfer line.

Table 2: Run 2c Proton Transfer Line Beam Parameters at the Injection-Point Into the First Plasma Cell

Parameter	**Specification**	**Design** (*x*/*y*)
$\beta_{x,y}$ [m]	4.9	4.9/4.9
$\alpha_{x,y}$ [rad]	0.0	0.0/0.0
$D_{x,y}$ [m]	0.0	0.0/0.04
$\sigma_{x,y}$ [µm]	200 ± 20	200.6/200.1

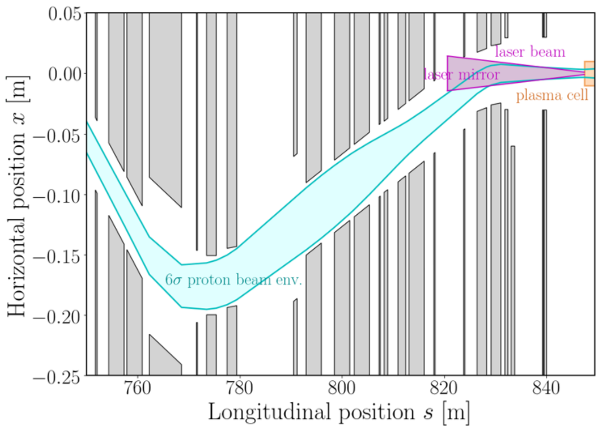

Figure 3: Simulated $6\sigma_x$ beam envelope with horizontal magnet apertures shown in grey. The location of the laser-merging mirror is indicated.

ELECTRON 150 MEV WITNESS TRANSFER LINE

Transfer Line Specification

For Run 2c, a new transfer line will be required to inject 150 MeV witness electron bunches into the second plasma cell. The beam energy was selected to be high enough to avoid space-charge effects but low enough to use only a single klystron. A dog-leg design, with 15° bends, was chosen to satisfy the spatial constraints from the positioning of the plasma cells and the width of the tunnel. The electron source is expected to be on the same horizontal plane and vertical inclination as the proton line.

The injected witness bunch should have a length of 60 µm, a specification deriving from the need to be within a regime of optimal beam loading to maintain a small energy spread during acceleration [10, 11]. To preserve a small emittance throughout acceleration, there should be sufficient charge density in the witness bunch to be able to drive a full blow-out of the electrons remaining in the accelerating plasma wakefield bubble [11].

To prevent oscillations of the witness beam within the plasma, the beam should be matched to the plasma, requiring [11]

$$\sigma^* = \sqrt[4]{\frac{2\varepsilon_0 m_e c^2 \gamma}{n_{pe} e^2}\epsilon^2} = 5.75\,\mu\text{m}, \quad (1)$$

where $\gamma = 293.5$, the plasma density $n_{pe} = 7 \times 10^{14}\ \mathrm{cm}^{-3}$, and normalised emittance $\epsilon = 2$ mm mrad. The beam profile should be Gaussian in six dimensions (x, px, y, py, z, pt).

Transfer Line Design

A transfer line design is proposed which satisfies the beam parameter specifications and spatial constraints; the simulated injection-point parameters are given in Table 3 alongside the experimental specifications. Meeting these requirements proved challenging and the use of numerical optimisers in the design process was crucial.

Table 3: Run 2c Witness Electron Transfer Line Beam Parameters at the Injection-Point of the Second Plasma Cell

Parameter	**Specification**	**Design (x/y)**
$\beta_{x,y}$ [mm]	4.87	4.80/5.34
$\alpha_{x,y}$ [rad]	0.0	-0.11/0.00
$D_{x,y}$ [m]	0.0	0.0/0.0
$\sigma_{x,y}$ [µm]	5.75 ± 2.88	5.72/6.03

A triplet of quadrupoles before the first dipole are the primary control for the focusing of the line. Five quadrupoles between the dipoles were used to make the dog-leg achromatic and provide additional focusing (Fig. 4). For a dog-leg with only two dipoles, it is difficult to construct a line which is both achromatic and isochronous. To meet the specification of a bunch length of 60 µm at the injection-point, the line was designed to have a shortening effect on the bunch which could be counteracted by injecting a bunch which is 40% longer into the line.

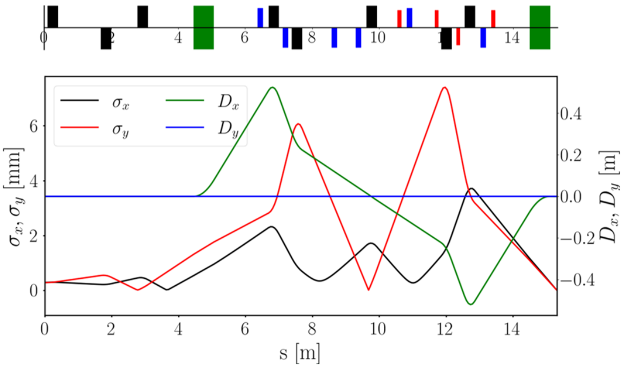

Figure 4: MAD-X simulation of the beam size $\sigma_{x,y}$ and dispersion for a beam of 2 mm mrad normalised emittance.

The strong focusing required to provide a beam size of several microns led to the rise of significant non-linearities, such as betatronic chromatic effects and detuning with amplitude. In order to keep these unwanted terms under control, sextupoles and octupoles were used. The footprint of the design is presented in Fig. 5, showing the locations of the sextupoles and octupoles. The apertures were modelled as ±25 mm and the two high-beta regions within the dog-leg mean that the beam envelope is close to the aperture limits so that the transfer line would not be suitable for a higher emittance beam.

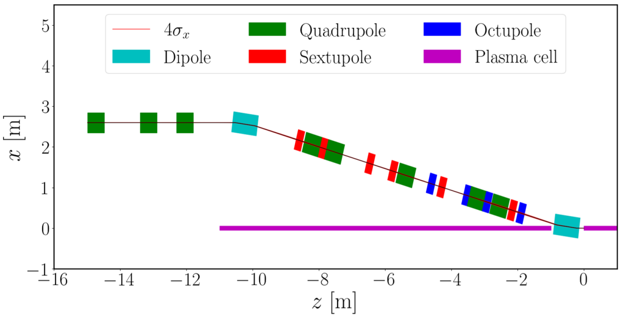

Figure 5: Footprint of the proposed witness electron transfer line with estimated element sizes; σ_x is the beam size.

To study the higher order effects, beam tracking studies were performed using a MAD-X implementation of PTC [12]. A beam distribution produced from simulations of the electron gun was adjusted to have Gaussian x, y, px, py profiles and tracked through the transfer line. Distributions of the tracked beam at the injection-point are presented in Fig. 6, showing that, even when including higher order effects, the proposed design meets the specifications.

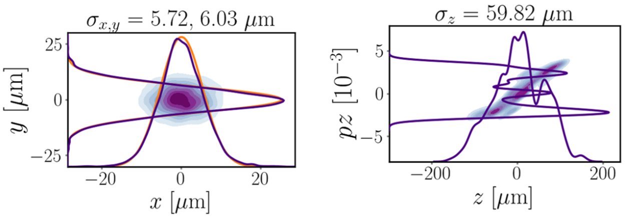

Figure 6: Beam distributions and profiles for a beam with normalised emittance 2 mm mrad and length $\sigma_z = 84$ µm tracked to the injection-point. The x-y plot has Gaussian distributions overlaid in orange. The structure in the z-pz distribution originates from the input distribution.

CONCLUSION

Design proposals for the AWAKE Run 2c transfer lines were presented. A 150 MeV electron line suitable to inject a witness beam with micron-level beam size was summarised. The design would use a dog-leg shape to satisfy spatial constraints of the experiment. The Run 1 electron beamline is planned to be modified so that it could be used to inject electron bunches into the first plasma cell to seed the proton bunch self-modulation. Adjustments to the Run 1 proton transfer line were suggested to extend it by 40 m to be suitable for Run 2c. Further studies are ongoing, focusing on optimising the stability and alignment of the lines to satisfy the challenging requirements on the driver-witness beam alignment.

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