THE AWAKE ELECTRON PRIMARY BEAM LINE

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Abstract

The AWAKE project at CERN is planned to study proton driven plasma wakefield acceleration. The proton beam from the SPS will be used in order to drive wakefields in a 10 m long Rubidium plasma cell. In the first phase of this experiment, scheduled in 2016, the self-modulation of the proton beam in the plasma will be studied in detail, while in the second phase an external electron beam will be injected into the plasma wakefield to probe the acceleration process. The installation of AWAKE in the former CNGS experimental area and the required optics flexibility define the tight boundary conditions to be fulfilled by the electron beam line design. The transport of low energy (10-20 MeV) bunches of $1.25{\cdot}10^9$ electrons and the synchronous copropagation with much higher intensity proton bunches ($3{\cdot}10^{11}$) determines several technological and operational challenges for the magnets and the beam diagnostics. The current status of the electron line layout and the associated equipment are presented in this paper.

INTRODUCTION

The AWAKE project at CERN will be the first experiment world wide to test plasma wakefield acceleration using a high energy (400 GeV) proton drive beam [1]. The first phase in 2016 will be focused on the study of the self-modulation instability of the drive bunch as described in [2]. In the second phase of the AWAKE project in 2017 the plasma wakefields will be probed with an externally injected electron beam.

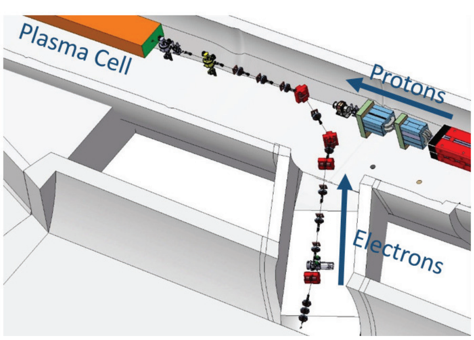

Figure 1: View of the AWAKE electron transfer line.

First studies on the electron transfer line have been presented in [3]. The bunch of $1.2{\cdot}10^9$ electrons will be produced by the PHIN electron gun, which will be recuperated from the CTF3 facility [4] with an output momentum of 5 MeV/c and accelerated to 10-20 MeV/c by a linac booster. The source will be located in a room adjacent to the proton gallery. From there the electron beam will be raised to the height of the proton line, where the two beams will be merged in a common beam line and injected into the plasma following the "on-axis" concept [3]. The general layout of the transfer line is shown in Fig. 1. The baseline parameters of the injected electron beam are summarized in Table 1. With these parameters, the capture efficiency of the electrons in the wakefields has been studied in [5].

Table 1: Electron Beam Parameters

Parameter	Value
Momentum [MeV/c]	10 - 20
Electrons/bunch	$1.2{\cdot}10^9$
Rep. rate [Hz]	10
Bunch length (z) [ps (mm)]	4 (1.2)
Relative momentum spread $\Delta p/p$ [%]	0.5
Emittance (r.m.s. norm.) [mm mrad]	2

ELECTRON BEAM LINE LAYOUT

Following the accelerator of the electron gun, a quadrupole triplet will match the beam into the transfer line. This 15 m long line will consist of three parts. After the matching triplet, two dipoles with a deflection angle of $\pm 18°$ form an achromatic dog-leg to raise the beam by 1.16 m up to the level of the proton line with a slope of 20%. At this level two horizontal dipoles of $\sim 32°$ bend the beam towards the proton line. The merging dipole is tilted by 3.2° to match the electron beam axis with the proton one, which has a slope 5.66% in the CNGS tunnel. The final part is the common beam line where the electrons and the protons share the same vacuum chamber and the electrons are focused by an independently powered quadrupole triplet to be captured in the plasma wakefield.

In total eleven quadrupoles will be distributed along the line to control the beta function and the dispersion of the beam. Their evolution along the transfer line is shown in Fig. 2 for the horizontal (x) and vertical (y) plane. The dispersion in y cannot be closed due to the general slope of the proton line and the plasma cell, but still crosses zero at the focal point. With this optics the experimental requirements are fulfilled with a 1σ bunch size at the nominal focal point of 228.1 μm in x and 226.04 μm in y as shown in Table 2.

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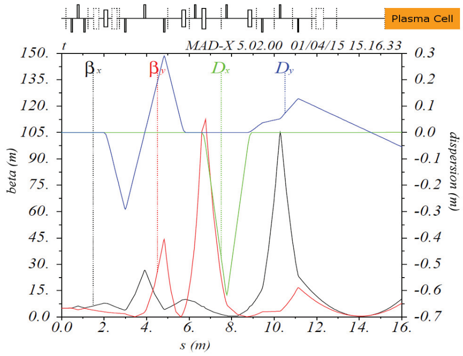

Figure 2: MadX simulation of the β-function and the dispersion along the electron beam line.

Table 2: Results of the Transfer Line Optics

Parameter	Value (x / y)
1σ bunch size at focal point [μm]	228.11 / 226.04
β-function at focal point [m]	1 / 1
Dispersion at focal point [m]	$4{\cdot}10^{-4}$ / 0
3σ envelope at focal point [mm]	1.768 / 1.77
Max. envelope [mm]	9.1 / 9.18

Flexibility of the Focal Point

For the experiment it was requested to allow to vary the longitudinal position of the focal point of the electron beam by about 1 m. The nominal focal point is positioned in the fast valve of the plasma cell system which is located 0.64 m upstream of the vapor source. The change of the spot size at the focal point according to a change of its position is shown in Fig. 3. The spot size shows only a minor growth with a shift of the focal point up to 80 cm and then starts increasing strongly. With a shift of 1 m (corresponding to 40 cm in the vapor source) the optics still fulfill the requirement of a spot size ≦250 μm at the focal point.

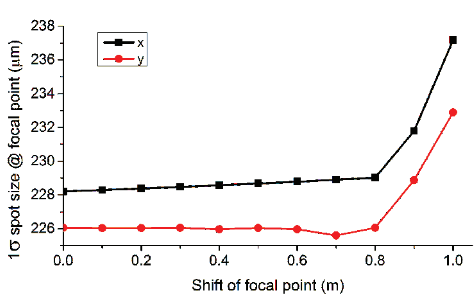

Figure 3: Effect of the shift of the focal point on the 1σ bunch size.

Magnet Specifications

According to the layout as it is described above, the technical specifications of the magnets for the electron line have been defined. Designs have been developed for the dipoles, quadrupoles and correctors that provide solutions for all requirements, including the operability at very low fields while keeping the field quality over the full operation range of 10-20 MeV/c. The results of these studies are presented in Table 3.

Table 3: Magnet Specifications

Parameter	Dipole	Quad	Corr
Units to install	4	11	11
Min. field [Tm]	0.0096		0
Max. field [Tm]	0.0456		$4.34{\cdot}10^{-4}$
Min. gradient [T]		0.01	
Max. gradient [T]		0.18	
Magn. length [mm]	177.5	70.8	110
Total length [mm]	290	114	34
Free aperture [mm]	≧ 70	≧ 70	≧ 70
Field quality [$\cdot 10^{-4}$] in	50	< 40	< 150
radius (x/y) [mm]	±30/20	20	13

BEAM INSTRUMENTATION

In order to set up the beam line and control the beam during operation in total four beam profile monitors (BTVs) and eleven beam position monitors (BPMs) are planned. The first BTV will be installed between the matching triplet and the first bending dipole. With this set-up an emittance measurement using a quadrupole scan will be performed. This measurement is described in [4]. The first bending dipole will be used as an energy spectrometer in combination with the second BTV which will be located ~65 cm downstream (center-to-center). At this BTV, the beam mean momentum will be measured together with the momentum spread Δp/p. For the measurement the matching triplet will be used to focus the beam onto the BTV and according to its energy the dipole current will be adjusted to center the beam on the screen. The Δp/p can be determined by measuring the spot size. The corresponding simulation for a momentum of 15 MeV/c is presented in Fig. 4. The beam current can be measured in a straight pipe at a Faraday cup, when the dipole is switched off.

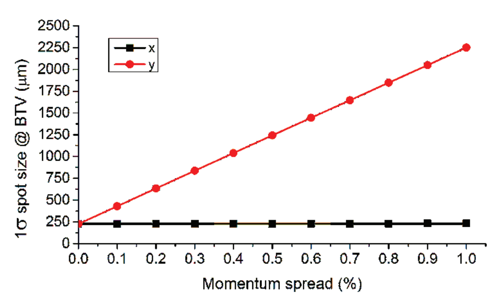

Figure 4: Change of the 1σ bunch size at the BTV for measurement of the momentum spread.

In the common beam line two BTVs, with a distance of ~1.5 m (center-to-center), will be used to align the electron beam with respect to the proton beam. The second one will have screens to measure the positions of the proton, laser

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and electron beam in reference to each other with a 50 μm resolution. It will be located ~1.4 m upstream of the vapor source and will be the last possibility to measure the electron beam position before the plasma. At the first of these BTVs the electron beam position will be measured as well as its synchronization with respect to the proton bunch at a ps level. BPMs, which are provided by TRIUMF, will be used to control the beam position in operation with a peak-to-peak resolution of 50 μm at 0.1 C bunch charge.

ERROR STUDIES

Error studies have been performed for the transfer line, including static errors as well as dynamic fluctuations. The static errors include field errors of the magnets, read out errors of beam position monitors as well as alignment errors of all the elements. To compensate these static errors eleven corrector coils will be used. Studies are ongoing to combine them with the BPMs. These sets will be located up- and downstream of the matching triplet after the source and the dog-leg, and in front of each quadrupole in the horizontal bending part and the common beam line. Two final correctors will be used to steer the beam precisely onto the target. As a baseline for these studies, an alignment accuracy of ± 0.1 mm is assumed for all the magnetic elements. This configuration and the field quality of the magnets, as given in Table 3, was used to simulate the pointing accuracy at the focal point. They show that the beam can be steered to the nominal transverse position with a standard deviation of 300 μm in x and 100 μm in y. The dynamic errors define the shot-to-shot variation of the electron beam on the target. They are caused mainly by current fluctuations in the power converters, which need to be $\leqq 1 \cdot 10^{-4}$ to fulfill the experiments requirements of a ±100 μm stability of the beam at the focal point (see Fig. 5).

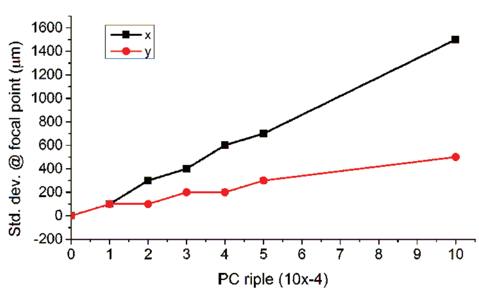

Figure 5: Standard deviation of the beam position at the focal point due to fluctuations in the power converters.

COMMON BEAM LINE

The common beam line of the electrons and protons is challenging due to the copropagating beams of different relativistic gammas (31.3 for electrons and 426.3 for protons). Dedicated studies are ongoing concerning the effects on the electrons of the wakefields induced by the protons on the vacuum chamber walls and direct beam-beam effects. The details about these simulations presented in [6].

In the baseline design, the two beams are copropagating coaxially with one reference trajectory. Still, flexibility is required to react to possible beam-beam effects, leading to a filamentation of the electron beam phase space. Therefore, an alternative scenario has been studied, where the electron beam is injected into the common beam line with an offset and merged with the proton beam only close to the plasma cell, using the final set of correctors. An offset of 2 mm would corresponds to an angle of ~2 mrad, which is the optimum value for the correctors. At the maximum current an offset of ~4.5 mm is possible. The alternative trajectory for the 2 mm offset is shown in Fig. 6 for two cases. In "case 1" the electron magnets are aligned with respect to the shifted electron trajectory, while they are centered with respect to the proton beam in "case 2". Due to the free aperture of the electron magnets of 70 mm (in comparison to 60 mm vacuum pipe), "case 2" is the baseline for following studies.

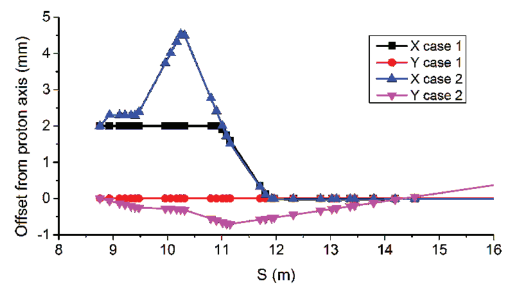

Figure 6: Beam trajectory of the electron beam injected into the common beam line with an offset for case 1 and 2.

CONCLUSION

A transfer line layout for the AWAKE electron beam has been developed which serves the needs of the experiment for high pointing accuracy and flexibility, matching also the space constrains defined by the installation in the former CNGS experimental area. Detailed beam dynamic studies are ongoing as well as the technical development of the beam line elements. First beam is planned in autumn 2017.

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