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Status of the proton and electron transfer lines for the AWAKE Experiment at CERN

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ABSTRACT

The AWAKE project at CERN is planned to study proton driven plasma wakefield acceleration with an externally injected electron beam. Therefore two transfer lines are being designed in order to provide the proton beam from the SPS and the electron beam from an RF gun to the plasma cell. The commissioning of the proton line will take place in 2016 for the first phase of the experiment, which is focused on the self-modulation of a 12 cm long proton bunch in the plasma. The electron line will be added for the second phase of AWAKE in 2017, when the wakefield will be probed with an electron beam of 10–20 MeV/c. The challenge for these transfer lines lies in the parallel operation of the proton, electron and laser beam used to ionize the plasma and seed the self-modulation. These beams, of different characteristics, need to be synchronized and positioned for optimized injection conditions into the wakefield. This task requires great flexibility in the transfer line optics. The status of these designs will be presented in this paper.

1. Introduction

Experiments with particle beam driven plasma wakefields are ongoing in several laboratories worldwide. The Advanced Proton-Driven Plasma Wakefield Acceleration Experiment (AWAKE) [1] is currently under development at CERN. It will be installed in the former CNGS (CERN Neutrinos to Gran Sasso) area, where a proton beam from the SPS (Super Proton Synchrotron) will serve as a drive beam for wakefields in a 10 m long plasma cell. These wakefields will be probed with an externally injected electron beam. Fig. 1 presents the general layout of the AWAKE primary beam lines.

The experimental program will be split into two phases. The first phase is dedicated to study the self-modulation of the proton beam in the plasma [2]. A 400 GeV/c proton bunch of $3 \cdot 10^{11}$ particles with an rms length of 12 cm is extracted from the SPS. When the proton bunch enters the plasma, which is ionized by a 4 TW laser pulse, it is expected to experience a self-modulation instability (SMI), creating micro-bunches with the plasma wavelength of 1 mm. Several complementary diagnostics are installed in the secondary beam line downstream of the plasma cell, including direct and indirect measurements of the self-modulated beam.

In the second phase, PHIN (the PHotoINjector from CTF3) [3], in combination with a 1 m long traveling wave linac, will be used to produce an electron beam with a momentum of 10–20 MeV/c. This electron beam will be injected into the wakefield and its output energy is measured by a spectrometer dipole in the secondary beam line. In this way, the amplitude of the electric fields in the wakefield can be probed.

The design of the proton transfer line for this project has been finished and is currently under development for the electron line. The dynamics of the processes in the plasma are strongly dependent on the characteristics of the injected beams. This requires a careful beam line design to meet the beam specifications at the plasma cell, while providing great flexibility and matching the conditions for the installation in the former CNGS target area. The main beam parameter are summarized in Table 1. The status of these transfer lines, optics simulations and specifications will be presented in the following sections.

2. The proton beam line

The general design of the proton beam line and the integration of the experiment in the CNGS target area are presented in [4]. For the main part of the beam line, the CNGS transfer line can be

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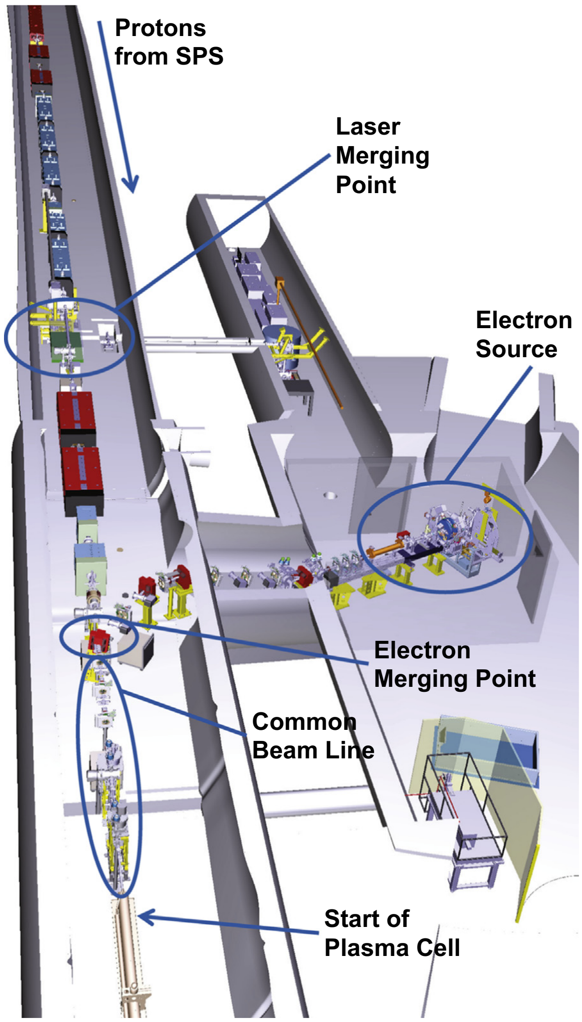

Fig. 1. View of the AWAKE primary beam lines. A proton bunch creates wakefields in a plasma, into which external electrons are injected. A laser pulse ionizes the plasma.

Table 1
The main parameter for the AWAKE primary proton (p+) and electron (e-) beam.

Parameter	p+	e−
Momentum (MeV/c)	400 000	10–20
Momentum spread (1σ) (%)	± 0.035	± 0.5
Relativistic gamma	426.3	19.6–39.15
Particles per bunch	$3 \cdot 10^{11}$	$1.25 \cdot 10^{9}$
Charge per bunch (nC)	48	0.2
Bunch length (1σ) (mm)	120 (0.4 ns)	1.2 (4 ps)
Norm. emittance (mm · mrad)	3.5	2
Repetition rate (Hz)	0.033	10
1σ spot size at focal point (μm)	200 ± 20	< 250
β-function at focal point (m)	5	0.4
Dispersion at focal point (m)	0	0

reused without major changes. In the last section of about 80 m, a chicane has been integrated in order to create space for a mirror of the laser beam line. This is necessary to merge the ionizing laser pulse with the proton beam about 22 m upstream of the plasma cell so that they propagate coaxially. The axis of the proton beam is shifted horizontally by 20 mm at the position of the laser mirror in the present layout [5]. The 6σ proton beam envelope and the laser beam are shown in Fig. 2. It can be seen that there is a very little margin between the proton beam and the mirror. This is why two beam position monitors (BPM) and a beam loss monitor (BLM) are

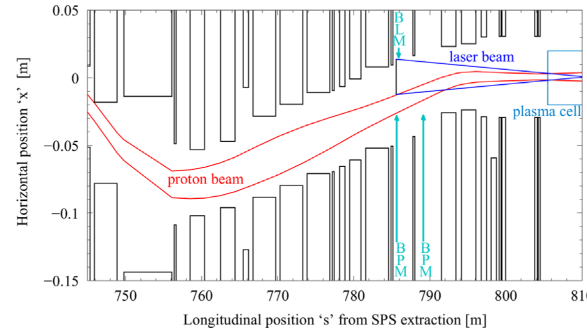

Fig. 2. Chicane of the proton optics to create space for the laser mirror with the 6σ envelope of the proton beam [5].

placed around the merging mirror in order to steer the beam and to interlock the SPS extraction in case the mirror is hit by the proton beam.

The synchronization of the two co-propagating beams has to be stable by ≤ 100 ps and the transverse pointing accuracy of the proton beam at its focal point is required to be ≤ 100 μm and ≤ 15 μ rad, so that the proton trajectory is coaxial with the laser over the full length of the plasma cell. Beam position monitors and screens (BTV) in combination with a streak camera close to the plasma cell allow us to measure the overlap and synchronization of the beams. Optics simulations predict a 1σ spot size of 210 μm at the focal point 0.5 m upstream of the plasma cell in agreement with the experiment requirements (see Table 1). The spot size is defined by $\sigma = \sqrt{\beta \cdot \epsilon + (D \cdot \Delta p/p)^2}$, taking into account the beta function β, the emittance ϵ, the dispersion D and the momentum spread $\Delta p/p$.

3. The electron beam line

The PHIN photo injector will be installed in an adjacent room 1.16 m below the level of the proton beam line. This means that the electron transfer line consists of an achromatic dog-leg to raise the electron beam up to the level of the proton line and a part which bends the electron beam horizontally onto the proton beam axis. This structure is built with two vertical dipoles of $\pm 18°$ and two horizontal dipoles of 32°. In order to follow the 5.66° vertical slope of the existing proton beam line and the plasma cell, the second horizontal dipole, which merges the electron beam onto the proton beam axis, is tilted by 3.2°. Fig. 3 shows the set up of the transfer line from the end of the linac to the plasma cell. Directly after the linac, a quadrupole triplet matches the electron beam into the transfer line; after the last bending dipole, another quadrupole triplet is used to focus the beam into the plasma. Beside these two triplets, five more quadrupoles are used to control the dispersion and beta function of the electron beam along the line. The principle layout and the magnet specifications have been published in [6].

The layout has been optimized and studied with Mad-X [7] simulations and PTC tracking. While the dispersion in the horizontal plane is almost zero along the part of the beam line downstream of the merging dipole (common beam line), the dispersion in the vertical plane is not closed due to the vertical kick given by the tilted merging dipole [6]. This is visible in the tracking simulations of 10,000 particles in a 3σ Gaussian distribution, represented in Fig. 4. The plots show the effect of 0.5 % momentum spread ($\Delta p/p$) on the horizontal and vertical phase space at the focal point. With this nominal $\Delta p/p$ some chromatic effects occur in the vertical plane downstream of the merging dipole.

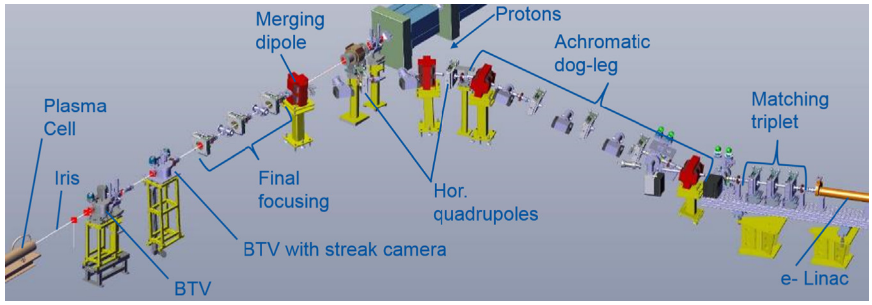

Fig. 3. View of the AWAKE electron transfer line. Following the linac (right), the electrons are matched into the transfer line and raised up to the height of the proton beam line, where they are bend onto the proton beam axis and focused into the plasma cell (left).

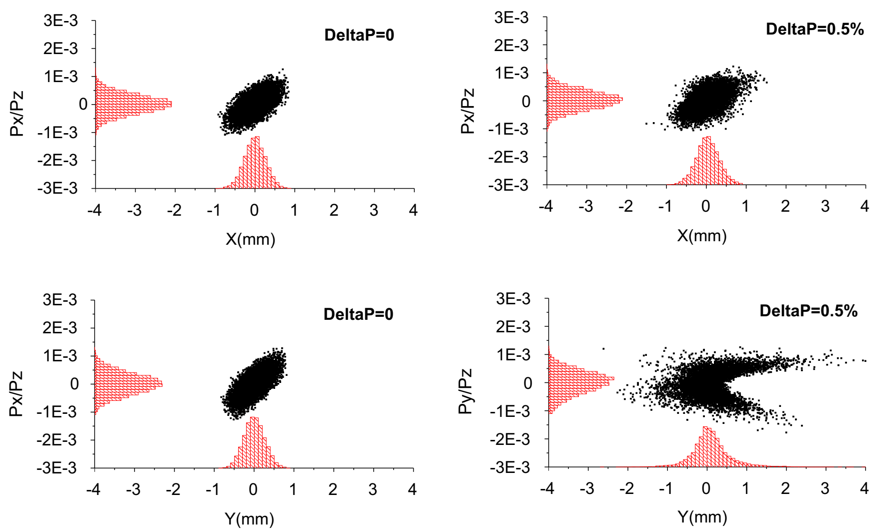

Fig. 4. Transverse phase space at the focal point from tracking simulations of an electron beam with and without momentum spread.

Still, the final focusing system matches the beta functions and dispersion to the required 1σ spot size of <250 μm at the focal point in both planes. Longitudinally, the focal point is set at an iris about 0.5 m upstream of the plasma cell. This iris has a free aperture of 10 mm and was introduced in order to control the plasma density distribution at the plasma edges (point “iris” in Fig. 5). The present optics provides the possibility to shift the focal point up to 0.8 m into the plasma cell without significant change of the beam spot size. Error studies have shown that systematic alignment and field errors of the magnetic elements can be compensated with ten kickers distributed along the beam line and a shot-to-shot stability of ± 100 μm is predicted for a current fluctuation of 0.01% in the power converters.

4. Proton–electron interactions in the common beam line and electron injection studies

Special studies are ongoing for the common beam line of the electron and the proton beam downstream of the merging dipole. In this part of the beam line the proton, the laser and the electron beam are traveling coaxially. These beams have very different characteristics (see range in Table 1). It is important to understand, how the beams influence each other for the reliable operation of the experiment. Simulations of the proton induced wakefields on the beam pipe walls and their effect on the electrons as well as direct beam–beam effects have been studied. An overview of these studies is presented in [8]. In summary they show that the influence of the proton beam wakefields on the electrons is negligible, but that beam–beam interactions lead to a blow up of the electron beam emittance [9].

Investigations on alternative injection schemes to mitigate the beam–beam effect have been performed and it was shown that this interaction can be reduced significantly by introducing an offset between the proton and electron beam axis. Two main scenarios have been defined:

1. The electron beam axis in the common beam line coincides with the one of the protons and the focal point of both beams is located in the center of the iris.
2. An offset between the proton and the electron beam is introduced in the common beam line. Before the focal point, the offset is closed and the electrons are injected on-axis and parallel into the plasma wakefield.

The offset in scheme 2 can be introduced either after or just before the merging dipole. It is controlled by the kickers, which are available in the common beam line and optionally one kicker just upstream of the merging point. A representation of the 3σ beam envelope for the on-axis trajectory and an offset trajectory is given in Fig. 5 in comparison to the proton beam.

In order to validate these simulations of beam–beam interactions, different possibilities to measure the electron beam profile and position in the presence of the proton beam are being explored in a collaboration between CERN and TRIUMF. Screens could be used for the set up, while beam position monitors are an option in operation.

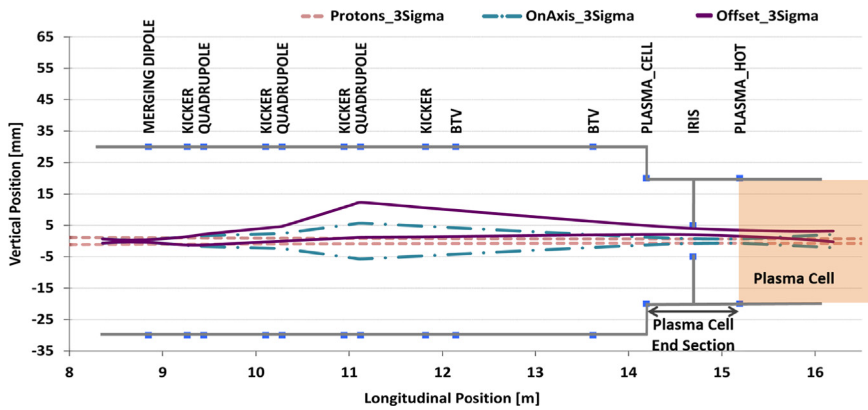

Fig. 5. The 3σ envelope of the electron beam in the common beam line, in case the electron beam is coaxial with the proton beam (OnAxis) or with an offset to the proton beam axis (Offset). The position and free aperture of the main beam line elements are represented by blue squares.

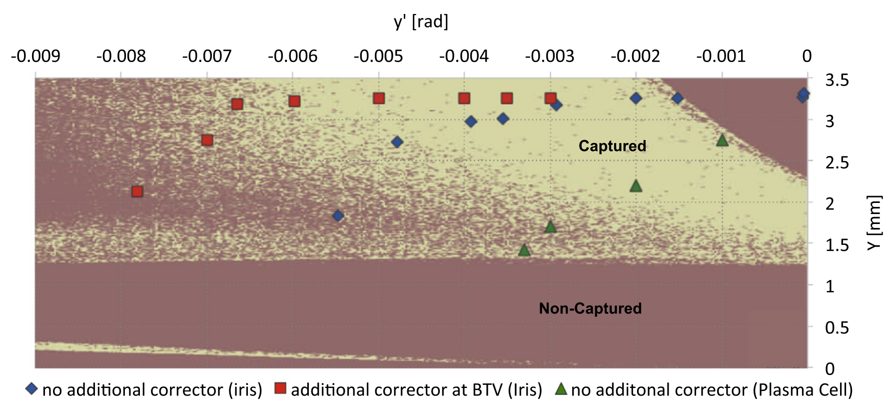

Fig. 6. The transverse phase space at the focal point of the electron beam. In the background, a simulation [10] shows the areas in the phase space in which a reference electron lies within the acceptance of the plasma wakefield "Captured" or outside "Non-Captured". Markers of the same color and symbol define the maximum possible offset-angle combination for different focal points (iris or start of the plasma cell) and corrector setups.

4.1. *Optimized electron injection into the wakefield*

In addition to beam–beam effects, the trapping of the electrons in the plasma wakefield was analyzed with respect to the transverse vertical position y and angle y' at injection [10]. The area in the transverse phase space, which defines the plasma wakefield acceptance, has been mapped and is shown in the background of Fig. 6. These simulations motivated the study of a third injection scheme

3. An offset is introduced in the common beam line, like in scheme 2, but is kept also at the injection point. In this scheme both the offset and the angle between the proton beam axis and the electron beam can be varied.

The markers in Fig. 6 show the maximum vertical offset, which can be obtained with a certain injection angle for different setups. The main limitation for the applicable offset comes from the aperture of the iris in the plasma cell end section, as it can be seen in Fig. 5. The full area in the transverse phase space, which is below each set of markers, can be covered at injection. This area depends on the longitudinal position of the focal point: it is about doubled, when the beam is focused into the iris (blue diamonds), compared to the focal point at the start of the plasma cell (green triangles). To gain larger flexibility, an additional kicker has been included in the design and is placed close to the plasma cell (directly following the last BTV in Fig. 5). Taking this kicker into account and focusing the beam into the iris allow to inject the electrons into the plasma wakefield with an offset of up to 3.25 mm and an angle between 0 and 8 mrad.

With this scheme the transfer line provides the required flexibility to optimize the injection of the electrons into the plasma wakefield.

5. Status and outlook

The modifications of the CNGS beam line magnets have been implemented. The installation of the proton beam instrumentation and vacuum equipment will be finished in March of 2016. Hardware and beam commissioning for phase 1 of the AWAKE experiment are planned for Summer 2016. The electron source and transfer line will be installed in parallel to the experimental program in 2017 in order to perform measurement for phase 2 before the long shutdown at CERN in 2019–2020.

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