THE CHALLENGE OF INTERFACING THE PRIMARY BEAM LINES FOR THE AWAKE PROJECT AT CERN

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Abstract

The Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) at CERN foresees the simultaneous operation of a proton, a laser and an electron beam. The first stage of the experiment will consist in proving the self-modulation, in the plasma, of a long proton bunch into micro-bunches. The success of this experiment requires an almost perfect concentricity of the proton and laser beam, over the full length of the plasma cell. The complexity of integrating the laser into the proton beam line and fulfilling the strict requirements in terms of pointing precision of the proton beam at the plasma cell are described. The second stage of the experiment foresees also the injection of electron bunches to probe the accelerating wakefields driven by the proton beam. Studies were performed to evaluate the possibility of injecting the electron beam parallel and with an offset to the beam axis. This option would imply that protons and electrons will have to share the last few meters of a common beam line. Issues and possible solutions for this case are presented.

INTRODUCTION

The construction of the first proof-of-principle experiment, using high energy (400 GeV) and high intensity ($3{\cdot}10^{11}$) proton bunches to generate plasma wakefield acceleration (AWAKE), is under construction at CERN. The proton beam will be produced in the CERN Super Proton Synchrotron (SPS) and extracted towards the TT41 beam line which hosted the CERN Neutrinos to Gran Sasso (CNGS) experiment until 2012. The new experimental apparatus will consist of a 10 m long Rb vapour plasma cell and will be installed at the end of the line [1].

In order to excite large amplitude wakefields, the proton bunch length (σ_z) has to be comparable with the plasma wavelength $\lambda_p \approx 1$ mm. The nominal SPS bunch length at top energy (450 GeV) is ~12 cm and, with the present RF system, can be only reduced by a factor of two (bunch rotation in the longitudinal phase space). However, the theory states that, when a long and narrow bunch of particles travels in a dense plasma, it experiences the so called Self-Modulation Instability (SMI) and is split in many ultra-short ($\sim\lambda_p$) bunches [2]. A 2 TW laser, co-propagating with the proton bunch, will be used to ionise the Rb gas into plasma and seed the SMI in a controlled way [3]. In 2016, the first proton and laser beams will be sent towards the plasma cell to demonstrate that SMI can indeed be achieved and measured (Phase 1).

The next step will consist in injecting a witness bunch of $1.2{\cdot}10^9$ electrons at 16 MeV to probe the proton driven wakefield acceleration in the plasma (Phase 2).

PROTON BEAM AND LASER INTEGRATION

The final part of the TT41 beam line (last ~80 m) has to be modified to cope with the new experiment requirements. The optics constraints (transverse beam size $\sigma_{x,y} = 200{\pm}20\ \mu$m at the entrance of the plasma cell) could be fulfilled just re-distributing and shifting the existing magnets in the line [4].

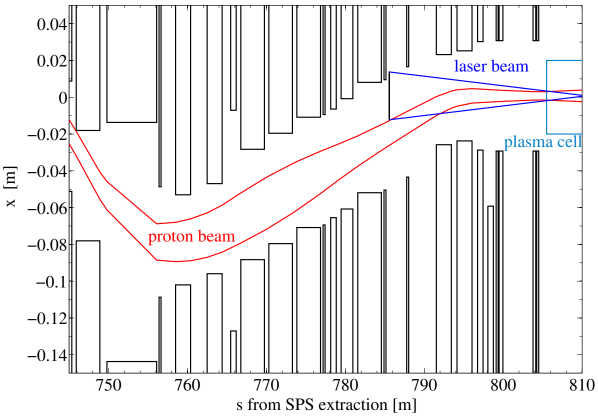

Figure 1: Horizontal chicane used to merge the laser and the proton beam. The beam envelopes and the aperture of the different elements (magnets and diagnostics) are shown.

A horizontal chicane was created to displace the proton beam from its ideal trajectory (x = 0 in Fig. 1) and insert the tuning mirror which bends the laser towards the plasma cell. The last main dipole (MBG), of the existing TT41 line, is moved 10 m forward to offset the beam axis by up to 80 mm. Two pairs of short dipoles (B190 type) are added into the lattice, 8 m and 41 m downstream of the MBG, to merge the proton beam with the laser. Each B190 provides a kick of 1.23 mrad. The tuning mirror is located 8 m before the last two B190; the proton beam axis is then shifted by about 20 mm from the laser axis. Almost no margin exists between the mirror edge (x =-13 mm) and the proton beam envelope ($\pm 6\ \sigma_x = \pm 6$ mm, assuming: 3.5 mm mrad normalised emittance, 10%beta-beating, 0.2‰ momentum spread, ±1 mm mechanical misalignment and ±1 mm trajectory instability), as shown in Fig. 1. Once defined the reference trajectory of the proton beam, an accurate beam

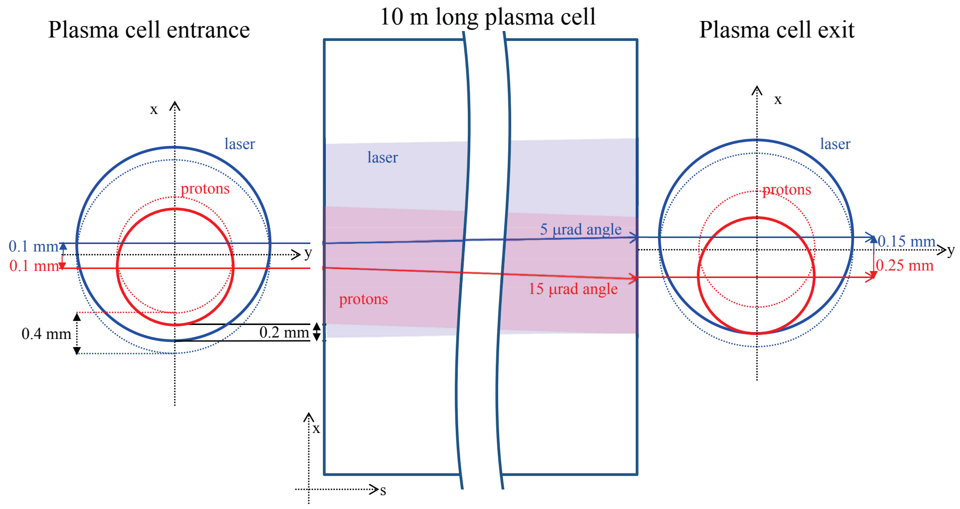

Figure 2: Schematic view of the required concentricity of the proton (red) and laser (blue) beam at the entrance and exit of the plasma cell. The dashed lines refer to the ideal case while the solid lines to the maximum allowed deviation. For simplicity, only drifts in the chicane plane (horizontal) are shown; analogous considerations hold also in the vertical plane.

based alignment of the mirror will have to be performed. A similar method as the one used for the LHC transfer line collimators [5] can be applied; on this purpose, a Beam Loss Monitor (BLM) will be installed just downstream of the mirror. The BLM and two Beam Position Monitors (BPMs) will be used to detect dangerous drifts of the beam towards the mirror and stop the SPS extraction before damaging it.

Required Pointing Accuracy

The successful establishment of the SMI in the plasma strongly depends on the fact that the proton beam and the laser are synchronised within 100 ps (see [1]) and kept coaxial over the full length of the cell. In particular, the $\pm 3\,\sigma_{x,y}$ proton beam envelope ($\pm 600\ \mu$m) has to fall inside the $\pm 1\,\sigma_{x,y}$ (± 1 mm) laser spot size, both at the entrance and the exit of the cell (Fig. 2). The laser tuning mirror is located ~20 m upstream of the plasma cell and a pointing precision of 100 μm is required at the cell entrance (i.e. 5 μrad angle at the mirror). The same pointing precision is also needed for the proton beam. In case of a 100 μm drift of the two beams in opposite directions, the margin between the two envelopes is reduced from 400 μm down to 200 μm already at the beginning of the cell. A maximum angle of 15 μrad can thus be tolerated for the proton beam as shown in Fig. 2. The precise alignment of the two beams will be performed using the same reference on two Optical Transition Radiation (OTR) monitors installed around the plasma cell (one upstream and one downstream). These monitors can be used only during the setup, with a reduced laser power, and have to be moved away from the beam during the physics measurements. Two high resolution (50 μm) BPMs will be placed right before the plasma cell, at a mutual distance of ~5.5 m, and will permanently check position and angle of the beam. An interlock inhibiting the SPS extraction, in case of drifts from the reference trajectory beyond acceptable limits, will be implemented.

Measurements were performed at the CNGS target and showed a beam position stability of 50 μm (r.m.s. averaged over several days) [6], that is well within AWAKE specifications.

ELECTRON BEAM INTEGRATION

The electron beam line will go from the RF gun, located in an adjacent room, up to the proton gallery, through a newly built tunnel (Fig. 3). The proton and the electron beam will share a common line over the last 5 m. No magnet of the proton beam line will be installed in this common part while one OTR and one BPM will be placed ~ 1.5 m before the plasma cell. The last part of the electron beam line contains: one quadrupole for dispersion matching, a vertical dipole to follow the 7% slope of the proton beam, the triplet for the final focusing, diagnostics and correctors. Initially,

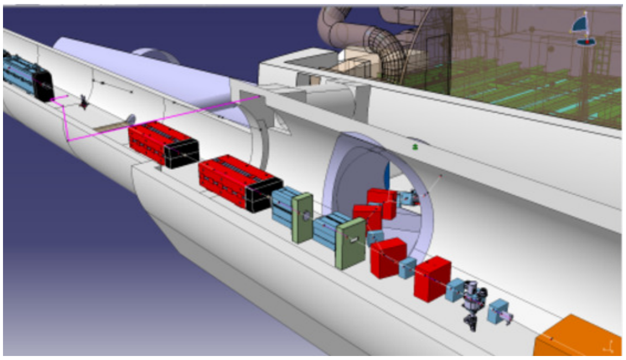

Figure 3: Layout of the merging between the proton and the electron beam lines.

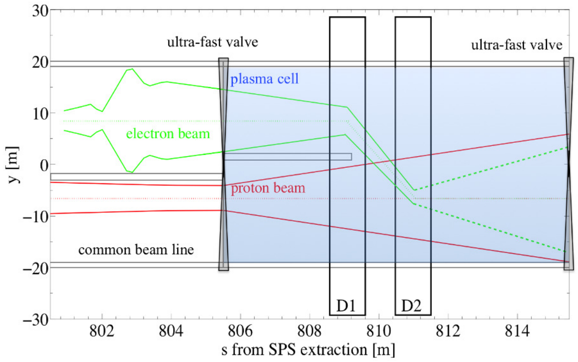

Figure 4: Common beam line for the side-injection of the electron beam into the plasma cell. The beam envelope at ±6 $\sigma_{x,y}$ and ±3 $\sigma_{x,y}$ is considered for protons and electrons respectively. The plasma induces a 1 mrad divergence on the proton beam. An arbitrary divergence is considered for the electrons after the merging point in the ~1 mm diameter plasma channel around the beam axis.

the option of injecting the electron beam parallel and with a vertical offset with respect to the proton beam axis was considered (side-injection). This would allow to bend the electrons, by means of two dipoles surrounding the plasma cell (D1 and D2 in Fig. 4), on to the proton beam axis only after the SMI accomplishment (3-4 m from the plasma cell entrance). Several limitations make this option challenging. The two beams have to fit in a diameter of 38 mm, along a 1 m drift space before the cell and over its full length. This diameter insures a 0.2% density uniformity inside the plasma, a reasonably fast opening of the valves (15 μs) at the cell extremities and the condensation of the escaping Rb in the drift space (details can be found in [3]). The maximum vertical offsets between the two beams is limited to 15 mm by the available diameter and the 1 mrad divergence induced by the plasma onto the proton (Fig. 4). The proton bunch induces a wakefield, at the metallic walls of the beam pipe, that affects the electrons. A metallic shielding has then to separate the two beams, both in the line and in the plasma. All these constraints translate in several integration issues and require custom-built and expensive designs for vacuum and diagnostics. In particular, the presence of the metallic shielding clashes with the conventional design of the OTR and BPM used to measure and insure the required pointing accuracy of the proton beam at the cell entrance (see above). The tight margin between the protons and the shielding increases the chance of beam losses and the related effects on background and electronics. Finally, in case of side-injection, direct measurements of the merging position and angle of the electrons with respect to the proton beam axis will not be possible. However, this information can be inferred from the applied magnetic fields of D1 and D2 and measuring the electron beam position and angle downstream of the plasma cell with extremely high resolution (10-20 μm) BPMs.

As a consequence of these considerations, new studies were performed considering the injection of the electron and proton bunches on the same axis from the beginning of the plasma cell (on-axis-injection). Promising results were found in terms of electron capture efficiency and energy gain [7]. This option remains challenging in terms of common diagnostics for the two beams but eliminates the main integration issues of the side-injection. Also the effect of W on the electrons is expected to be mitigated when the two beams are on the beam pipe axis all along their common path (detailed studies are ongoing).

On-axis injection is nowadays the baseline for the first AWAKE run. Nevertheless, depending on the physics results, the possibility of a future adaptation of the experimental setup for side-injection operation could still be envisaged.

CONCLUSIONS

In the AWAKE experiment, for the first time, three extremely different beams will have to coexist and comply with very strict requirements. The success of the experiment relies on an almost perfect control and reproducibility of the proton beam position, with respect to the laser beam, over the full plasma cell length. High resolution diagnostics and a system of interlocks will be used for this purpose. The technological and experimental challenges, involved in the integration of electrons and protons in a common beam line, have been described emphasising the complexity of side-injection. The design of the proton-laser interface for Phase 1 is almost completed. Dedicated studies are ongoing to finalise the proton-laser-electron interface for Phase 2.

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