BEAM TRANSFER LINE DESIGN FOR A PLASMA WAKEFIELD ACCELERATION EXPERIMENT (AWAKE) AT THE CERN SPS

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Abstract

The world's first proton driven plasma wakefield acceleration experiment (AWAKE) is presently being studied at CERN. The experiment will use a high energy proton beam extracted from the SPS as driver. Two possible locations for installing the AWAKE facility were considered: the West Area and the CNGS beam line. The previous transfer line from the SPS to the West Area was completely dismantled in 2005 and would need to be fully re-designed and re-built. For this option, geometric constraints for radiation protection reasons would limit the maximum proton beam energy to 300 GeV. The existing CNGS line could be used by applying only minor changes to the lattice for the final focusing and the interface between the proton beam and the laser, required for plasma ionisation and bunch-modulation seeding. The beam line design studies performed for the two options are presented.

INTRODUCTION

The construction of the first proof-of-principle experiment which uses p bunches to generate plasma wakefield acceleration (AWAKE) is proposed at CERN [1, 2]. AWAKE will use high intensity (up to $3{\cdot}10^{11}$ p per bunch) and high energy (up to 400 GeV) p bunches produced by the CERN Super Proton Synchrotron (SPS). When the 12 cm long p bunch enters the plasma cell it undergoes a self-modulation instability (SMI) which produces micro-bunches spaced at the plasma wavelength ($\lambda_p \simeq 1$ mm) [3]. A 2 TW laser pulse, co-propagating and co-axial with the p beam, is used to ionise the plasma and seed the bunch modulation in a controlled way.

A witness bunch of $1.25{\cdot}10^9$ e can be injected downstream of the SMI saturation to probe the longitudinal wakefield. Simulations predict that up to 40% of the injected e can be trapped and accelerated from 20 MeV up to 2.1 GeV over a 10 m plasma cell in the AWAKE experiment.

Two locations were considered for the installation of the plasma cell (stars in Fig. 1):

- The SPS West Area: a surface experimental facility located at the end of a dismantled secondary beam line named TT61.
- The CNGS beam line: an underground area designated for operation with high intensity and energy proton beams for neutrino physics (physics program terminated in 2012).

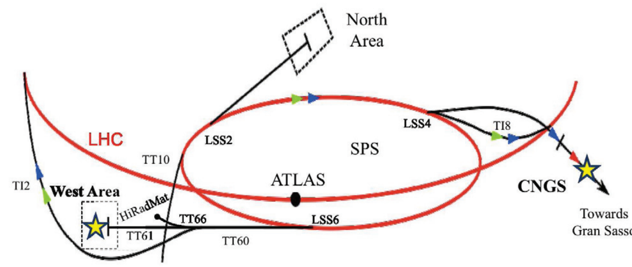

Figure 1: Possible locations for the AWAKE experiment (West Area and CNGS) in the SPS complex.

WEST AREA OPTION

A new primary beam line (TT61) has to be completely designed and built to fulfil the AWAKE requirements. The p beam is extracted from the SPS in the Long Straight Section 6 (LSS6), sent along the TT60 line (Fig. 1) and then presently directed either to the LHC transfer line (TI 2) or towards the HiRadMat facility (TT66 line). Switching magnets (MBS type) can be installed in TT66 to divert the AWAKE beam into TT61.

A movable passive absorber is installed right downstream of the MBS; this element has to be put into the beam to allow LHC and HiRadMat operation while accessing the AWAKE experimental area.

The TT61 beam line is ~650 m long and has a slope of 8.7% over 325 m. The last 150 m of the line, where the experimental area is installed, are on the surface (TT4 and TT5 halls). In total 13 vertical and 1 horizontal bending magnets of type MBN are used to bring the beam to the West Area along the existing TT61 tunnel (magnet parameters are summarised in Table 1).

The installation of the plasma cell at the surface represents a concern in terms of radiation protection due to the production of high energy muons coming from the interaction of the p with the material of the dump, located 20 m downstream of the plasma cell. To overcome this problem the p beam is bent towards the ground, by means of 6 strong MBE type vertical dipoles, and impact the beam dump at a depth of -2 m and under 2.6° angle. Excavation works are needed to dig a trench to the underground dump. The mentioned constraints and the need of fitting the new beam line into the existing TT61 tunnel, without further civil engineering works, limit the maximum beam energy to 300 GeV (magnetic rigidity of 1003 T m).

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Table 1: Main parameters and number of magnets installed in the new TT61 beam line. The maximum field for the quadrupoles is expressed in T/m. All magnets are available spares [4].

Magnet type	Max. Applied Field [T - T/m]	Length [m]	No.
MBS	0.76	3	8
MBNV	1.8	5	13
MBNH	1.2	5	1
MBE	2.0	6.2	6
QNLD	23	3	13
QNLF	23	3	13
MDXH	0.25	0.65	11
MDXV	0.25	0.65	12

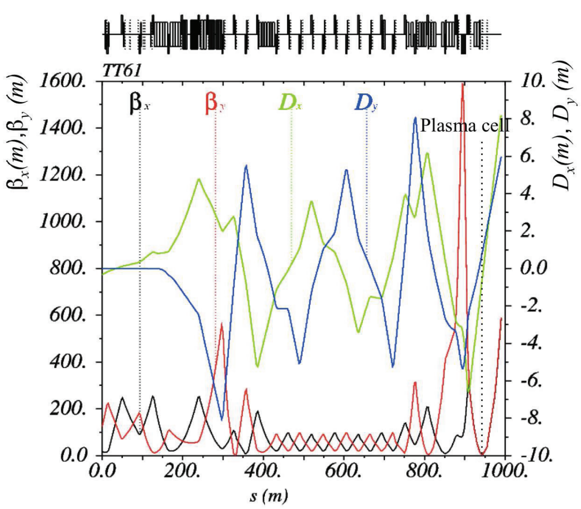

Figure 2: Horizontal (x) and vertical (y) optics functions for the TT61 primary beam line.

In total 26 main quadrupoles (QNLD and QNLF in Table 1) are installed in the line. A first matching section is followed by 5 FODO cells (phase advance ∼90°), a second matching insertion and the final focusing system.

The AWAKE experiment requires, at the entrance of the plasma cell, a round beam with a transverse beam size $\sigma_{x,y}$ = 200 μm (10% accuracy). This corresponds to a $\beta_{x,y}$* = 3.7 m at 300 GeV, for a normalised emittance $\varepsilon_{x,y}$ = 3.5 mm mrad and a dispersion $D_{x,y} \simeq 0$. The final focusing comprises 7 quadrupoles arranged in a triplet; the present lattice allows reaching the required $\beta_{x,y}$* (optics functions in Fig. 2). Further optimisation studies, in particular dispersion matching, are needed to meet the requirements on the beam size (now D_x = 0.4 m and D_y = 0.9 m corresponding to σ_x = 450 μm and σ_y = 900 μm, respectively).

Horizontal and vertical correctors (MDXH and MDXV) are used to steer the trajectory along the line and provide the required pointing accuracy and angular precision (±100 μm and ±20μrad, respectively) .

Laser Integration

The laser for plasma ionisation and SMI seeding is injected from the top and merged to the p beam at a distance of 14.6 m from the plasma cell, in between the two last MBE magnets (Fig.3). Each MBE applies a tilt of 12.5 mrad. The laser tuning mirror is at 3.3 m from the centre of the last dipole; this corresponds to an offset between the laser and the p beam axis of 41.3 mm.

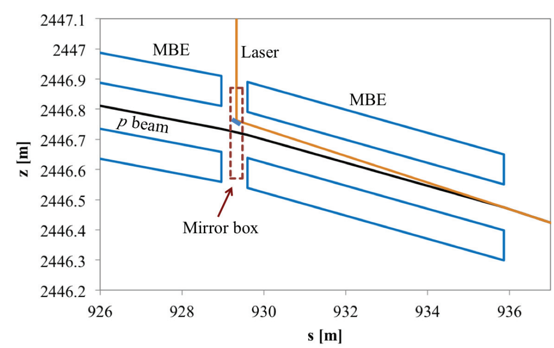

Figure 3: Integration scheme of the laser with the p beam (MAD-x survey coordinate system).

The minimum separation needed between the primary beam and the laser axis, to prevent intercepting p and inducing losses, is defined as the sum of the p beam size (10 mm for the 6 σ_y envelope, taking into account mechanical tolerances, orbit variations and β-beat) and the mirror occupancy (11.3 mm for a 45° angle, 6 mm thickness and a radius = 3 × laser radius).

Beam Instrumentation

The TT61 line has to be fully equipped with new diagnostics. One Beam Position Monitor (BPM) per corrector (in total 23) is installed for trajectory steering. Five screens (BTV) are used for emittance and profile measurements (in a dispersion free region) and for p beam setup (one upstream and one downstream of the plasma cell; they have to be out from the beam line when the high power laser is pulsing). One Beam Current Transformer (BCT) is placed at the end of the TT61 underground area and one at the beginning of the trench to the dump to measure changes in the beam current indicating potentially dangerous losses in the surface area. Finally one Beam Loss Monitor (BLM) of SPS type is installed per quadrupole.

CNGS OPTION

The AWAKE experiment can be installed in the underground CNGS facility in the downstream part of the p beam tunnel and the upstream part of the target area. The p beam will be sent to the existing CNGS hadron dump. The muons created at the dump will be fully absorbed in the dump or in the downstream molasse.

The existing CNGS beam line has been designed for a 400 GeV p beam. The same energy is used for AWAKE and only minor changes are needed in the matching section and in the final focusing part of the present line. Two main quadrupoles (QTG and QTS type) have to be removed and the remaining 7 magnets of the triplet (6 QTL type and 1 QTLS type) will be reshuffled and shifted by few m upstream (Fig. 4) to fit the plasma cell at the end of the CNGS tunnel.

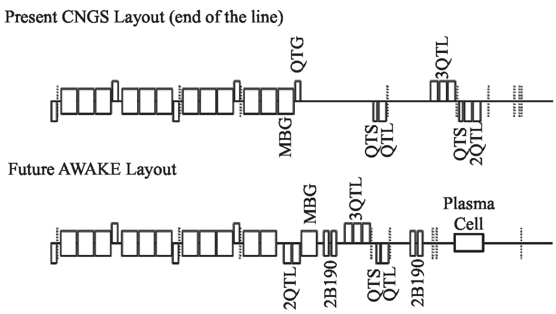

Figure 4: Comparison between present (top) and new (bottom) layout for the end of CNGS beam line.

A chicane is designed to integrate the laser by displacing the last main dipole (MBG) towards the experimental area and by installing four additional 1.9 m long dipoles of type B190, giving a kick of 1 mrad (0.7 T) each. In this design the laser tuning mirror is located 19.5 m upstream of the plasma cell and at 12 m from the centre of the last B190. The offset between p and laser beam axis corresponds to 24 mm, where the minimum needed clearance is 18.4 mm.

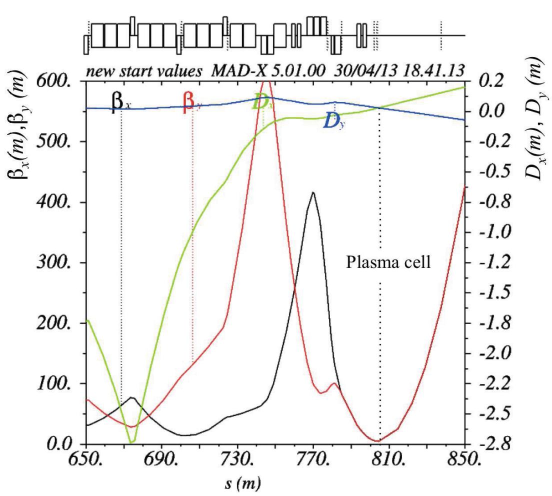

Figure 5: Horizontal (x) and vertical (y) optics functions for the modified part of the CNGS primary beam line.

Seven quadrupoles, organised in a triplet, compose the final focusing system. The proposed design allows fulfilling the AWAKE requirements at the entrance of the plasma cell: $\sigma_{x,y}$ = 224 μm ($\beta_{x,y}$ = 4.9 m and $D_{x,y}$ = 0.029 m as shown in Fig. 5).

Beam Instrumentation

The existing CNGS beam instrumentation [5] can be used for the diagnostic of the AWAKE beam with suitable modifications due to the different beam intensity (CNGS: 2100 bunches of $1.05{\cdot}10^{10}$ p, AWAKE: one bunch of $3{\cdot}10^{11}$ p). In particular the electronics of the BPM has to be exchanged with a system similar to the LHC transfer lines. Two additional high precision BPM (50 μm accuracy) have to be installed, up- and downstream of the plasma cell, to check the pointing precision of the p beam with respect to the laser during operation. An interlock can be implemented to stop extraction from the SPS in case of a drift of the p trajectory beyond the experiment tolerances. The present BTV can be used for profile and emittance measurements; additional Optical Transition Radiation (OTR) screens will be put around the plasma cell for p beam setup. The CNGS BLM and BCT can satisfy the AWAKE requirements provided the cable length and signal filtering for the BCT are optimised.

CONCLUSIONS

Studies were performed on the design of the primary p beam line for two possible locations of the AWAKE experimental area: West Area and CNGS. A new beam line has to be designed and built to bring the beam to the West Area. The proposed solution satisfies the AWAKE requirements and the geometric constraints needed to respect radiation protection restrictions. Only existing magnets are included in the lattice but new beam instrumentation, powering system and important civil engineering works are needed. Moreover the energy is limited to 300 GeV. On the other hand, minimal modifications have to be applied at the end of the CNGS line to fit the experiment, integrate the laser beam and adapt the optics. The present diagnostic can be reused with suitable modifications and the implementation of additional instrumentation around the plasma cell. On the basis of these studies and other considerations presented in [2], the CNGS option is the baseline for the AWAKE project.

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