AWAKE PROTON BEAM COMMISSIONING

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Abstract

AWAKE is the first proton driven plasma wakefield acceleration experiment worldwide. The facility is located in the former CNGS area at CERN and includes a proton, laser and electron beam line merging in a 10 m long plasma cell, which is followed by the experimental diagnostics. In the first phase of the AWAKE physics program, which started at the end of 2016, the effect of the plasma on a high energy proton beam is being studied. A proton bunch is expected to experience the so called self-modulation instability, which leads to the creation of micro-bunches within the long proton bunch. The plasma channel is created in a rubidium vapor via field ionization by a TW laser pulse. This laser beam has to overlap with the proton beam over the full length of the plasma cell, resulting in tight requirements for the stability of the proton beam at the plasma cell in the order of 0.1 mm. In this paper the beam commissioning results of the 810 m long transfer line for proton bunches with $3{\cdot}10^{11}$ protons/bunch and a momentum of 400 GeV/c will be presented with a focus on the challenges of the parallel operation of the laser and proton beam.

INTRODUCTION

The experimental program for the first run of AWAKE (the Advanced Proton-Driven Plasma Wakefield Acceleration Experiment at CERN) [1] consists of two phases. The first phase is focused on the study of the self-modulation instability (SMI) [2], which the proton beam experiences when passing through the plasma. This instability leads to a break-up of the long (12 cm) proton bunch from the SPS (Super Proton Synchrotron) into micro-bunches formed with the plasma wavelength of 1 mm. These micro-bunches are needed to efficiently drive the plasma wakefield. In a second phase the amplitude of the wakefield will be probed by a low momentum (10-20 MeV/c) electron beam. The beam will be injected into the plasma wakefield to be accelerated. The energy gain of the electrons in the plasma stage is a direct indicator of the accelerating field amplitudes in the plasma.

Figure 1 shows the experimental set-up of AWAKE, as mentioned the facility hosts in total three different beam lines; one for a laser beam [3], one for the proton beam from the SPS and one for the electron beam from a local source. The nominal parameter of the proton beam are given in Table 1. All three beams are merged into a common beam line upstream of the plasma cell and the proton and laser beam need to be overlapped on the full 10 m length of the plasma cell. This is crutial, since the proton beam would be

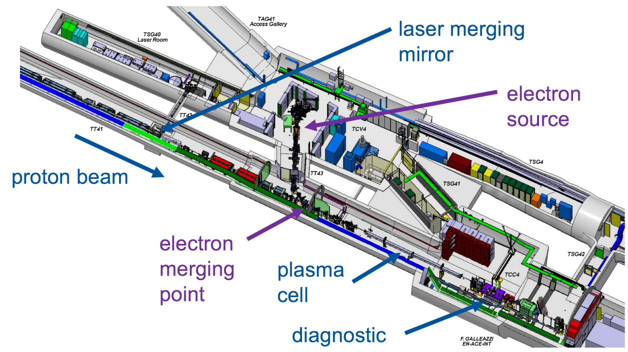

Figure 1: View of the AWAKE facility. The proton and laser beam are installed together with the plasma cell and SMI diagnostic for phase1, which has started in 2016. One year later, the electron beam line and additional diagnostics will be added for phase2.

located outside of the plasma channel, which is created by the laser pulse via field ionisation of the rubidium vapor in the plasma cell. The experiment diagnostics for SMI studies and the energy spectrometer for the accelerated electron beam are located downstream of the plasma cell.

Table 1: Proton Beam Parameters

Parameter	Unit	Value
Momentum	GeV/c	400
Momentum spread (1σ)	%	±0.035
Relativistic gamma		426.3
Particles per bunch		$3{\cdot}10^{11}$
Charge per bunch	nC	48
Bunch length (1σ)	mm	120 (0.4 ns)
Norm. emittance	mm·mrad	3.5
Repetition period	sec	30
1σ spot size at focal point	μm	200±20
β-function at focal point	m	5
Dispersion at focal point	m	0

The first physics run for SMI studies took place in December 2016, the electron beam line for phase two of AWAKE will be installed in summer 2017. This paper presents the main results of the proton beam commissioning with respect to the common operation with the laser beam. The preparations and plans for the commissioning of the TT41, AWAKE proton beam line were presented in [4] and [5].

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PROTON BEAM COMMISSIONING

The layout and specifications of the proton beam line have been presented in earlier publications [6], [7] . The former TT41, CNGS beam line has been modified to match the proton beam into the plasma cell and a chicane has been established to create space to install a mirror for the merging of the laser beam onto the proton beam axis.

The first beam (pilot beam, $1 \cdot 10^9$ protons/bunch) was sent down the full beam line in June'16. Figure 2 shows the beam profiles just after the extraction from the SPS and at a screen at the very end of the line. The profiles have been measured during the beam time in June, which was used mainly for hardware checks of magnets, beam diagnostic, trigger systems and the SPS extraction into TT41.

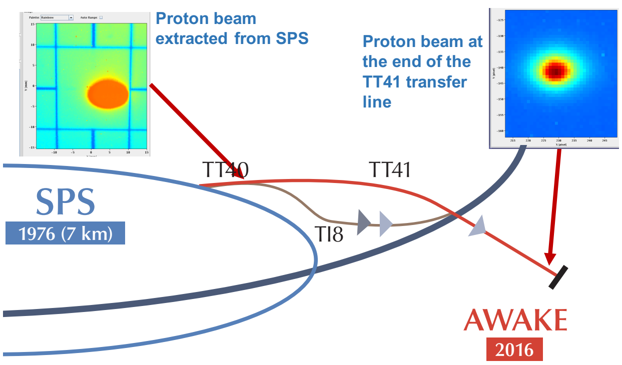

Figure 2: Proton beam profiles taken during the first beam time for AWAKE in June 2016. The beam is imaged on two BTV screens, one just following the SPS extraction channel and one at the end of the TT41 beam line.

Alignment of the Proton Beam at the Plasma Cell

In the following periods allocated to beam commissioning in September and November'16 the proton beam optics was verified and the reference trajectory established. Kick response measurements [8] [9] were performed together with dispersion and other optics measurements. All measurements confirmed the nominal beam parameters.

The beam optics of TT41 has been designed such that the beam waist is located at the entrance of the plasma cell, which is located approximately 9 m downstream of the last pair of vertical and horizontal correctors.

The main elements constraining the transverse alignment of the proton beam are two irises with a free aperture of 10 mm diameter at the start and the end of the plasma cell. These elements are necessary to guarantee the required density uniformity of the filling vapor (rubidium) in the plasma cell (see [10] for more details). Dedicated beam diagnostic was integrated in the beam line around the plasma cell. It includes two beam position monitors (BPMs) upstream and one downstream of the plasma cell with a resolution of 50 μm as well as one beam loss monitor (BLM) located downstream of each iris, in order to detect particle showers in case of proton beam hits. Figure 3 illustrates the arrangement of the different elements around the cell (BLMs in orange, BPMs in green).

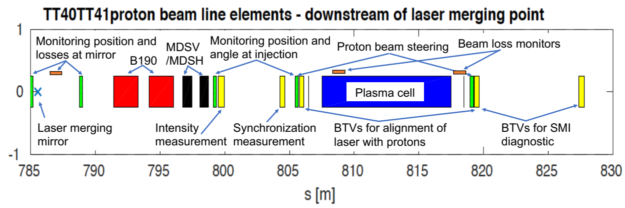

Figure 3: Set up of the last magnetic elements (B190 dipoles and MDSV, MDSH corrector magnets) and beam instrumentation downstream of the laser merging mirror.

In order to align the proton beam in the centre of these irises, the aperture was measured by displacing the beam transversely at the plasma cell, while recording the normalised losses at the iris BLMs. Figure 4 shows, as an example, the losses recorded at the downstream BLM for such a scan in the horizontal plane. In the analysis of this data, it is important to disentangle particle showers from the upstream and the downstream iris. Therefore the iris scan was performed changing the angles of the proton beam (parallel beam, negative and positive angle at the plasma cell). This angle is shown in the colour scale of Fig. 4. Including this information, the "shadow" of the first iris can be distinguished from the scan of the second iris. For example losses with a negative beam position can be related to losses on the upstream iris for angles ≥ 0 and to losses at downstream iris for angles < 0. Losses at beam position = 0 mm are related to the scan of the other plane.

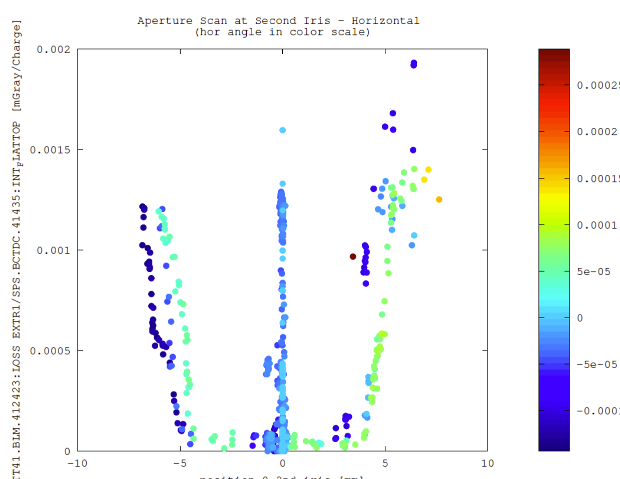

Figure 4: Example for a position scan of the plasma cell irises. The plot shows the normalised beam loss with respect to the beam position. The beam angle (in the colour scale) allows to distinguish losses at the first or second iris.

Following this method, the centre positions for both irises were determined. The proton beam was steered to be centred in both irises for the horizontal and vertical plane. Checks were repeated increasing the intensity in steps from pilot

($1 \cdot 10^9$ protons/bunch) to the nominal intensity $3 \cdot 10^{11}$ protons/bunch. This situation defines the reference trajectory for experimental operation, as shown in Fig. 5 from the laser merging point downstream. As a final step, stability measurements for several hours were performed in this configuration.

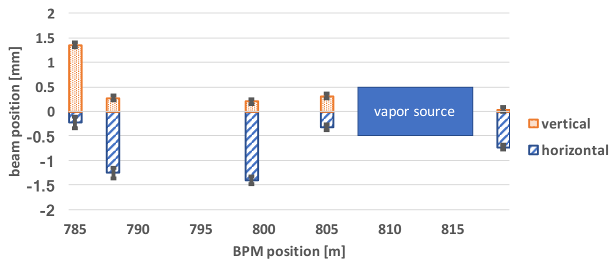

Figure 5: Measured reference beam positions for the proton beam downstream of the laser merging point. The trajectory has been optimised to be centred in the plasma cell irises.

ALIGNMENT OF THE PROTON AND LASER BEAM

The second main requirement for the set-up of the proton bunch is the longitudinal and transversel alignment with the laser pulse. Special modifications of the beam screens (BTVs) were prepared, in order to enable laser measurements with its repetition rate of 10 Hz and one BTV upstream of the plasma cell was equipped with a streak camera system, in order to measure the synchronisation of both beams [11]. The laser beam power was limited to 10 mJ for the alignment measurements and included in an interlock system for the BTVs, in order to avoid high power shots on the screens. In operation 10 mJ shots will be running continuously at 10 Hz and will be amplified up to ≈ 450 mJ for the pulses synchronised with the extraction of proton bunches at 0.033 Hz.

Positioning of the Laser Merging Mirror

The diagnostic at the laser merging mirror is sketched in Fig. 3. It is possible to move the laser merging mirror remotely, so that its optimum position can be set to be as close to the proton beam axis as possible, while avoiding proton beam losses at the mirror (including the margin for shot-to-shot fluctuations of the proton bunches).

Transverse Alignment of the Laser Beam to the Proton Reference Trajectory and Synchronization

It is essential for the experiment that the proton and laser beam overlap with each other over the full length (10 m) of the plasma cell.

Following the alignment of the proton bunch in the plasma cell irises, reference shots were taken on two BTVs, one just upstream and one downstream of the plasma cell. Table 2 summarises the results of this alignment (meas) in comparison with the specifications (spec) as presented in [6]. Even though the laser fluctuations are higher than originally expected, the overlap with the proton beam could still be achieved over the 10 m plasma cell length. The reason is the bigger spot size, in which the laser power is sufficient to ionise the rubidium vapor, or in other words, the bigger diameter of the plasma channel.

Table 2: Parameter, Which Play a Role in the Transverse Alignment of the Proton and Laser Beam — the Signs Correspond to a Worst Case Situation

Value	Unit	Iris 1 spec / meas	Iris 2 spec / meas
laser spot size	mm	1 / 1.2	1 / 2.3
proton 1sigma	μm	200 / 200	600 / 560
laser angle jitter	μrad	5 / 30	
proton angle jitter	μrad	-15 / -17	
laser position jitter	μm	100 / 130	150 / 445
proton position jitter	μm	-100 / -75	-250 / -245

After the transverse alignment of both beams, also the synchronisation of the high power laser pulse with the proton extraction was achieved on the required level of a few picoseconds by adjusting the trigger delay for the SPS extraction [12]. A measurement of the laser and proton pulse on the streak camera is shown in Figure 6. During further tests, an induced signal from the high power laser shots on two BPMs in the common beam line was discovered and is currently under investigation.

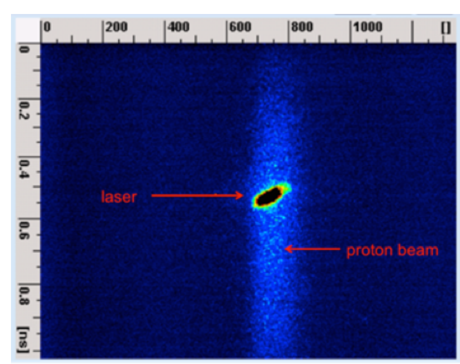

Figure 6: Streak camera measurement in a 1 ns time window for the laser and proton synchronisation. The short laser pulse is centred longitudinally on the long proton bunch.

CONCLUSION

The proton beam line TT41 for AWAKE was commissioned successfully in 2016. The requirements for the proton beam size, positioning and shot-to-shot fluctuation at the plasma cell have been matched and the proton and laser beam have been synchronised in time and overlapped in radial position. The first physics run took place in Dec. 2016 [13], [14].

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