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# Beam studies and experimental facility for the AWAKE experiment at CERN

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ABSTRACT

A Proton Driven Plasma Wakefield Acceleration Experiment has been proposed as an approach to eventually accelerate an electron beam to the TeV energy range in a single plasma section. To verify this novel technique, a proof of principle R&D experiment, AWAKE, is planned at CERN using 400 GeV proton bunches from the SPS. An electron beam will be injected into the plasma cell to probe the accelerating wakefield. The AWAKE experiment will be installed in the CNGS facility profiting from existing infrastructure where only minor modifications need to be foreseen. The design of the experimental area and the proton and electron beam lines are shown. The achievable SPS proton bunch properties and their reproducibility have been measured and are presented.



## 1. Introduction

The AWAKE experiment is the world's first proton driven plasma wakefield acceleration experiment, which will use a high-energy proton bunch to drive a plasma wakefield for electron beam acceleration. Simulations have shown [1] that an LHC type proton bunch (1 TeV, $10^{11}$ protons) with an rms bunch length of 100 μm can accelerate an incoming 10 GeV electron bunch to more than 500 GeV in ~500 m of plasma with an average gradient ≥1 GeV/m. Recent studies [2,3] have demonstrated that similar gradients can be reached with a modulated long proton bunch, opening the path for an immediate experimental investigation with the existing proton bunches at CERN.

### 1.1. Baseline design

For the AWAKE experiment at CERN, an LHC-type proton bunch of 400 GeV but higher intensity ($\approx 3\times 10^{11}$ protons/bunch) is extracted from the CERN SPS and sent towards a plasma cell to drive the plasma wakefields. The proton beam will be focused to $\sigma_{x,y} \approx 200$ μm near the entrance of a 10 m long plasma cell with a density adjustable in the $10^{14}$–$10^{15}$ cm$^{-3}$ range. When the proton beam with an rms bunch length of $\sigma_z = 12$ cm (0.4 ns) enters the plasma cell, it undergoes a self-modulation instability (SMI) which produces a series of ultra-short proton bunches that can resonantly drive wakefields to large amplitude [2]. The effective length and period of the modulated beam is set by the plasma wavelength (for AWAKE typically $\lambda_p = 1$ mm).

A high power ($\approx 2$ TW) laser pulse, co-propagating and co-axial with the proton beam, is used to ionize the (initially neutral) gas in the plasma cell and also generates a seed of the proton bunch self-modulation. An electron beam of $\approx 1.25\times 10^9$ electrons injected at 10–20 MeV serves as witness beam and is accelerated in the wake of the proton bunches. Several diagnostics tools are installed downstream the plasma cell to measure the proton bunch self-modulation effects and the electron bunch properties. Fig. 1 shows the baseline design of AWAKE.

### 1.2. The AWAKE facility at CNGS

The AWAKE experiment will be installed in the CNGS facility [4], a deep-underground area and designed for running an experiment with high proton beam energy without any significant radiation issues. The facility is fully operational, with a 750 m long proton beam line designed for a fast extracted beam at 400 GeV as

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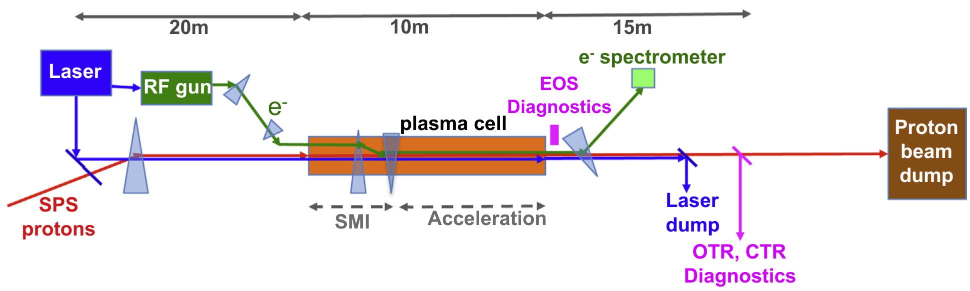


**Fig. 1.** Baseline design of the AWAKE experiment.

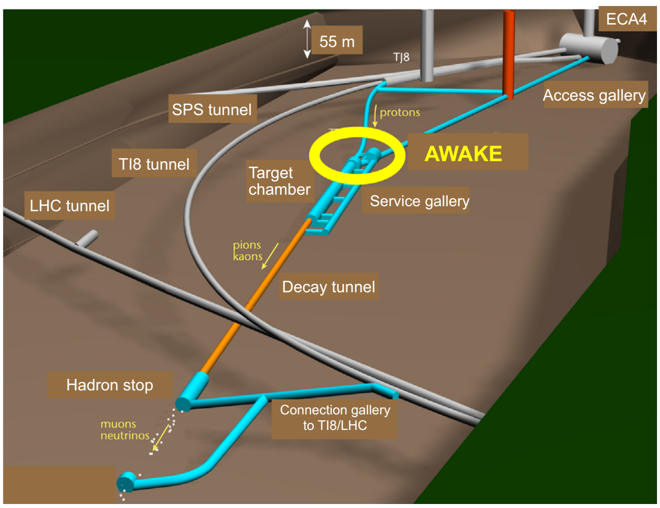


**Fig. 2.** The AWAKE experiment in the CNGS facility.

needed by AWAKE. The experiment will be installed upstream the CNGS target area (see Fig. 2); only minor modifications are necessary to the end of the proton beam line including changes to the final focusing system and the integration of the laser and electron beam with the proton beam. General services, such as cooling, ventilation, electricity, radiation monitoring and access system exist, are operational and need only minor changes to be adapted to the AWAKE experimental setup. Civil engineering modifications are required to be able to combine the electron beam and the laser pulse with the protons in the plasma cell. The AWAKE facility will be separated from the radioactive area located downstream the CNGS target area by a shielding wall.

## 2. Experimental area

The integration of the AWAKE experiment in the experimental area is shown in Fig. 3. The plasma cell is housed in the downstream end of the CNGS proton beam tunnel. For the first experiments the 10 m long plasma is a metal vapor source (Rubidium) [5] combining the self-modulation and the acceleration effect in one plasma cell. To this end the required longitudinal density uniformity is of the order of 0.2%. The area can be modified in order to house a shorter vapor cell (used for the self-modulation of the proton beam) followed by a helicon and/or discharge source (used for wakefield acceleration). In order to avoid accidental venting and possible contamination from the plasma vapor to the proton beam line vacuum, a double window system for the proton beam is integrated in the new design, 46 m upstream of the plasma cell.

The CNGS storage gallery will be modified to become a dust-free (consequently over-pressurized) and temperature regulated area to house the laser system. Currently a fibre/Ti:Sapphire laser system is under consideration, providing a 1–2 TW laser pulse in 30–100 fs and operating at 10 Hz. The high power laser beam used for plasma ionization and bunch-modulation seeding is transported through a new dedicated tunnel (0.5 m diameter, 4 m length) connecting the laser area to the proton beam tunnel. The compression of the pulses will be performed in a vacuum chamber coupled to the proton beam line, located at the laser/proton beam junction 20 m upstream the plasma cell entrance window. The laser pulse that is used to produce the electrons on the electron source photo-cathode is derived from the low power level of the plasma source ionizing laser system, ensuring synchronization between the different beam types.

The electron source as well as the klystrons powering the source is housed in an area adjacent to the experimental area (between the access gallery and the proton beam line), which is a low-radiation area and free of electromagnetic interference (necessary for the klystrons). The electrons are transported from the electron source system to the proton beam tunnel along the electron beam line through a new liaison tunnel (7 m long, 1 m wide and 2.5 m high) before being injected to the front-face of the plasma cell. Around the electron source area also a major part of the electronic racks is installed.

A state-of-the-art magnetic spectrometer with a very large momentum acceptance (10–5000 MeV) and a good momentum resolution is installed downstream the plasma cell to measure the properties of the accelerated electrons; the electrons are separated from the protons by a dipole spectrometer magnet. A scintillating screen connected to a CCD camera is used to image the electrons exiting the spectrometer. Before the dipole two additional quadrupoles are installed providing focusing in both planes to improve the energy resolution and reduction in the vertical beam size at the scintillator screen. The electron beam dump is located immediately after the electron spectrometer. Energy deposition estimates lead to a beam dump design with a 30 cm thick block of iron surrounded by 30 cm thick concrete shielding.

Optical Transition Radiation Diagnostics (OTR), Coherent Transition Radiation Diagnostics (CTR) and Diagnostics using Electro-Optical Sampling Methods will be installed downstream the plasma cell to measure the proton bunch self-modulation effects [5].

Downstream the diagnostic instrumentation the proton beam vacuum tube goes through the shielding separating the AWAKE area from the CNGS target area. The proton beam exits through a vacuum window and passes the 100 m long target chamber and the 1000 m CNGS long decay tunnel before being dumped in the existing CNGS beam dump, a 15 m long carbon–iron block equipped with a cooling system.

Additional safety measures are applied to allow for stand-alone operation of the different beams (laser, electron and proton beam). The AWAKE area is separated from the downstream part of the CNGS target area by an 80 cm thick concrete chicane shielding and dust-proof separation doors.

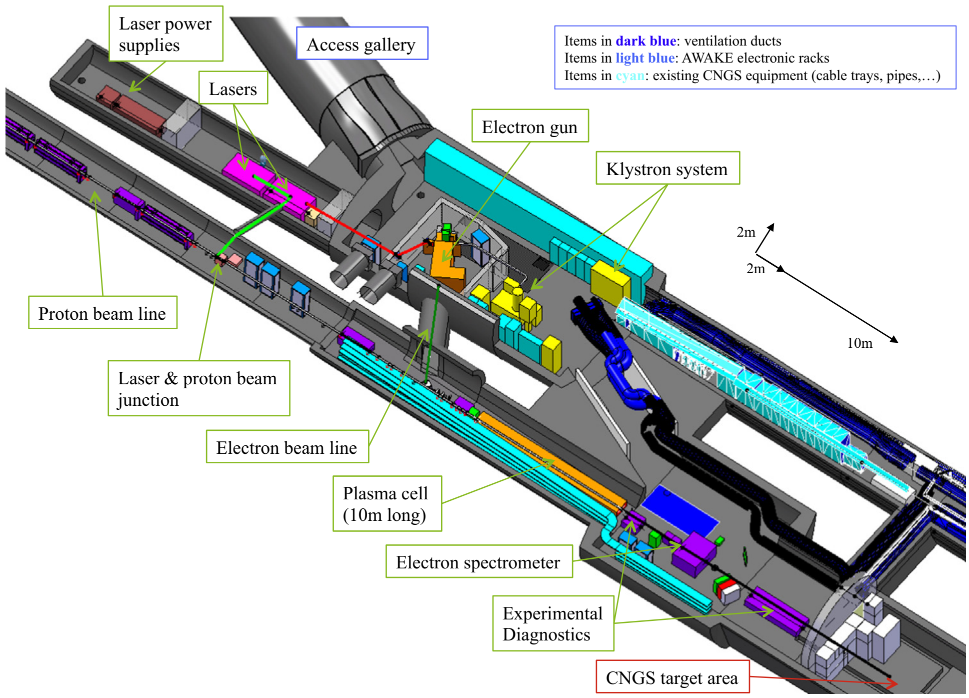


**Fig. 3.** Integration of AWAKE in the experimental area.

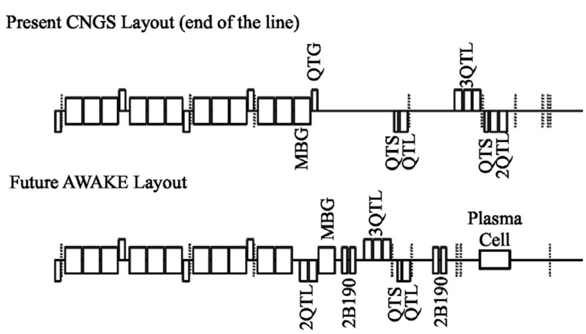


**Fig. 4.** Comparison between present (top) and new (bottom) layout for the end of CNGS beam line.

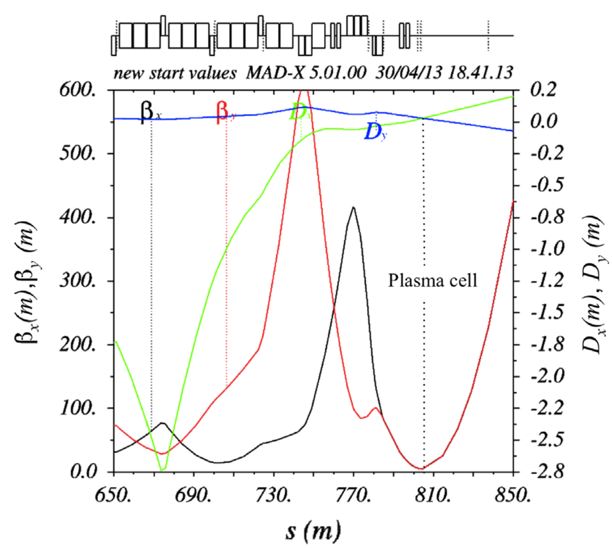


**Fig. 5.** Horizontal ($x$) and vertical ($y$) optics functions for the modified part of the CNGS primary beam line.

## 3. Proton beam line

The existing CNGS proton beam line requires only minor changes in the final part (about 80 m) to fulfil the requirements of the AWAKE experiment (see Fig. 4).

Two main quadrupoles of the present line will be removed and seven magnets of the final focusing will be redistributed and shifted by few meters upstream to fit the plasma cell at the end of the CNGS tunnel.

The AWAKE experiment requires a transverse beam size at the entrance of the plasma cell:

$$\sigma_{x,y} = \sqrt{\beta_{x,y} \cdot \varepsilon_{x,y} + (D_{x,y} \cdot \Delta p/p)^2} = (200 \pm 20)\ \mu\text{m} \qquad (1)$$

where $\beta_{x,y}$ is the beta optical function in the horizontal ($x$) and vertical ($y$) plane, $D_{x,y}$ is the dispersion, $\varepsilon_{x,y}$ is the geometric emittance and $\Delta p/p$ is the momentum spread. Considering a normalized emittance $\varepsilon_N = 3.5$ mm mrad ($\varepsilon_{x,y} = \varepsilon_n/\beta\gamma$, with the $\beta\gamma$ relativistic factor) and a momentum spread of 1‰, the newly designed final focusing allows reaching, at the entrance of the plasma cell, a transverse beam size of $\sigma_{x,y} = 224\ \mu$m ($\beta_{x,y} = 4.9$ m, $D_{x,y} = 0.029$ m as shown in Fig. 5) in agreement with the experiment specifications.

The proton beam has to be merged with the laser, which is used to ionize the plasma and seed the self-modulation, about 20 m upstream of the plasma cell, where the laser spot size is big enough to avoid damaging the tuning mirror. For this purpose, a chicane is introduced in the proton beam line by displacing the last main dipole (MBG) towards the experimental area and 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 center of the last B190 (Fig. 6). The chicane produces an offset of 24 mm between the proton and laser beam axis at the tuning mirror, where the minimum clearance needed to fit the mirror without intercepting the proton beam and inducing losses is 18.4 mm.

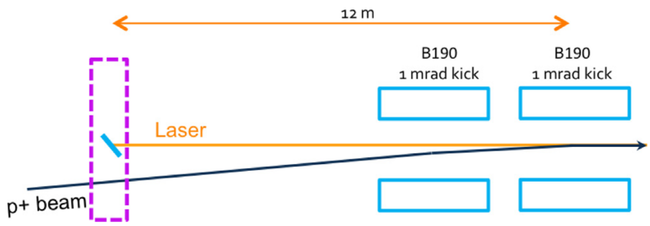


**Fig. 6.** Schematic view of the integration of the laser with the proton beam.

The proton and the laser beam have to be coaxial over the full length of the plasma cell; in particular, the $3\sigma_{x,y}$ proton beam envelope ( $\sim 600$ µm) must be contained in the $1\sigma_{x,y}$ laser spot size ($\sim 1$ mm). The pointing precision of the laser at the entrance of the plasma cell corresponds to 100 µm; a pointing accuracy of 100 µm and 15 µrad has to be guaranteed for the proton beam. Assuming that any systematic error (i.e. magnets misalignment) could be compensated by the trajectory correctors, the ripples in the main dipole power convertor current have to be kept below $\sim 5 \times 10^{-4}$. A maximum ripple of the order of $1 \times 10^{-4}$, in agreement with the AWAKE requirements, was measured for the CNGS main dipoles, quadrupoles and correctors.

### 3.1. Beam instrumentation

The existing CNGS beam instrumentation [6] can be used for the diagnostic of the AWAKE beam with suitable modifications due to the different beam intensity (CNGS: 2100 bunches of $1.05 \times 10^{10}$ protons during 10.5 µs, AWAKE: one bunch of $3\times 10^{11}$ protons). The Beam Position Monitors (BPM) accuracy along the line must be of the order of 200 µm with a resolution of 100 µm within a radius of 20 mm. Two more precise BPMs (50 µm accuracy) have to be installed, one upstream and one downstream of the plasma cell, to check the pointing precision of the proton beam with respect to the laser during operation. An interlock will be implemented to stop extraction from the SPS in case of a drift of the proton trajectory out of the experiment tolerances. The existing OTR screens (called BTV) along the proton beam line will be used for profile and emittance measurements. Two additional OTRs will be put around the plasma cell, one upstream and one downstream, for proton beam setup and to measure shot-to-shot variations of the transverse parameters. An interlock preventing the high power laser from pulsing when the OTR screens are in the beam has to be put into operation. Special attention has to be given to maintain the integrated radiation dose below 400 Gy to avoid damaging the CCD cameras of the OTRs. The CNGS Beam Current Transformers BCT could satisfy the AWAKE requirements (0.5–1% for the nominal beam and 10–20% for pilot bunch) for beam intensity measurements, provided some optimization on cable length and signal filtering is performed. Existing Beam Loss Monitors (BLMs) should fulfil the requirements in terms of resolution and interlocking needs.

## 4. Electron beam

### 4.1. Introduction

The longitudinal wakefields can be probed by injecting low energy witness electrons into the plasma cell. These electrons can be trapped and accelerated. Since the wakefield phase velocity during the development of the self-modulation instability (SMI) is slower than that of the drive bunch, the injection has to occur at a point along the plasma after the SMI has saturated (at around 4–6 m). Otherwise the electrons would de-phase with respect to the wakefields and be defocused by their transverse component and consequently they would be lost.

In the case of a single plasma cell, the electrons can be injected from the side of the plasma cell. In this side injection scheme, electrons of a 10 ps (bunch length longer than the plasma wavelength), low energy (10–40 MeV) bunch are injected with a small angle (a few mrad) with respect to the drive beam axis and can be trapped and accelerated. A fraction of the electrons reach the beam axis, de-phase, accumulate at the peak accelerating wakefield and form short bunches in a few accelerating buckets. They are then accelerated to high energies with a narrow energy spread (on the percent level). This side injection scheme relaxes the timing tolerances for injection and has a particle trapping efficiency between 5% and 40%.

The proposed injection scheme assumes that the electron beam enters the plasma section parallel to the proton beam with an offset of 1–2 cm. Later inside the plasma section (after the SMI is saturated) the electron beam is directed towards the developed plasma wave by a transverse magnetic field. The required magnetic field can be superimposed on the plasma section with an external dipole corrector at any desired location. Additional diagnostics might be considered for electrons that are scattered during the injection process.

### 4.2. Electron beam line design

A 12.2 m long beam line was designed to drive the electrons from the electron source to the plasma cell (see Fig. 7). The first 1.5 m are dedicated to the acceleration system (booster linac) needed to reach a maximum energy of 20 MeV. The lattice is formed by five dipoles and nine quadrupoles; the magnetic elements used in this beam line are based on an existing design in use at FERMI@Elettra facility [7]. The first two vertical bends bring the electron beam through the new liaison tunnel towards the proton beam line and form an achromatic dog-leg. A horizontal achromat is then used to bend the electron beam by about 60°, and a last vertical bend brings it parallel to the proton beam at the plasma cell entrance.

The electron beam will reach the plasma cell with an offset of 2 cm with respect to the proton beam. Two bending magnets have to be installed around the plasma cell: one to provide the transverse magnetic field in order to merge the two beams and the second to bend the non-captured electrons for diagnostic purposes and also the electron beam when the plasma is not present (see Fig. 8). The deflection angle needed to merge the two beams can

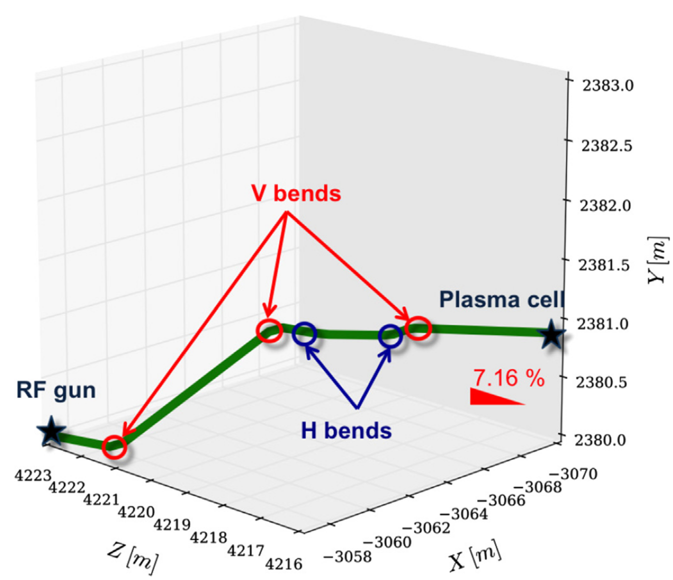


**Fig. 7.** Geometry of the electron beam line in the CERN Coordinate System (CCS).

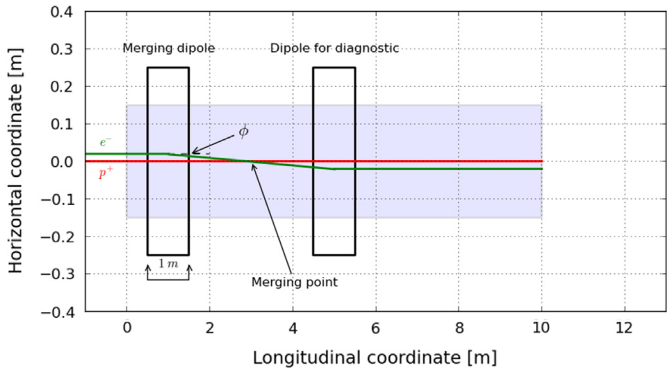


**Fig. 8.** Proposed configuration for the two dipoles needed around the plasma cell.

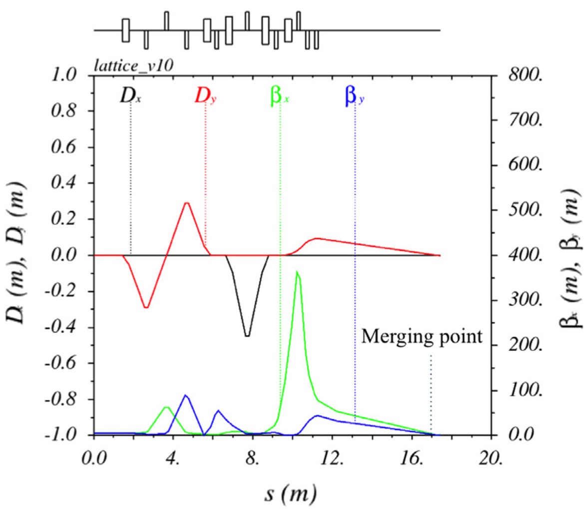


**Fig. 9.** Lattice functions along the electron beamline.

be up to $\phi=20$ mrad (as requested from the experiments) with a merging point between 2 m and 5 m along the plasma cell. The required magnetic and powering configuration has to be investigated in more detail when the specifications and the required flexibility of the system will be more precisely defined.

The AWAKE experiment requires for the electron beam a transverse beam size of $\sigma_{x,y}<250$ μm at the plasma cell. Due to the geometry of the line, only the horizontal dispersion could be exactly close to zero. Assuming a $\Delta p/p=1‰$ and a normalized emittance $\varepsilon_N=0.5$ mm mrad, $\sigma_{x,y}\approx 126$ μm can be obtained at the merging point (see Fig. 9), for a 16 MeV electron bunch with $\approx 1.25\times 10^9$ electrons and a bunch length of 10 ps. The electron beam will enter and exit the plasma cell through ultrafast valves that will be opened for a short time (ms scale); no window can be crossed by such a low intensity beam without experiencing a significant emittance blowup. Nevertheless, the plasma will act on the electron beam inducing an emittance blow-up corresponding to $\varepsilon_N=2$ mm mrad; the achievable beam size becomes $\sigma_{x,y}\approx 252$ μm, still in agreement with the experiment requirements. The final beam size is completely tuneable using the last three quadrupoles, so as to guarantee enough freedom to the experiment without affecting the whole line.

## 5. Short high-intensity proton bunches for AWAKE

Concerning the SPS proton bunches, achieving a short bunch length $\tau$ and small transverse emittances $\varepsilon_{x,y}$ at a relatively high intensity $N$ are both important requirements for AWAKE. Therefore the achievable SPS proton bunch properties and their reproducibility have been studied. The shortest achievable bunch length is determined by the maximum available RF voltage and the smallest possible longitudinal emittance. To avoid longitudinal instabilities, the longitudinal emittance $\varepsilon_L$ cannot be too low. The maximum voltage in the two RF systems of the SPS is currently limited to 8 MV at 200 MHz and 600 kV at 800 MHz, and will be increased to 12 MV at 200 MHz (around 2019) and to 1.2 MV at 800 MHz (in 2015).

The presently achievable SPS bunch parameters were measured at a flat top momentum of 450 GeV/$c$. Two different operational optics are available in the SPS, and below we present results obtained with the optics that has a lower gamma at transition ($\gamma_T=18$), where a similar bunch length but better transverse stability can be expected [8].

In this optics, the transverse emittances (obtained from wire scans at flat top with an accuracy of about $\pm 20\%$) scale roughly linearly with intensity, see Fig. 10, due to the space charge effect in the injectors; the slope is increased by injection losses that are $\propto N$. Within the calibration error of the wire scanners in different planes, the beam is round.

The highest flat top single bunch intensities achieved were in the range of $(2.7–3.7)\times 10^{11}$ protons, far beyond the typical operational range of $(1.2–1.8)\times 10^{11}$ protons/bunch for LHC beams. For longitudinal stability, the voltage programme was adjusted for a constant bucket area throughout the cycle. In addition to the 200 MHz RF, the 800 MHz RF system, longitudinal dampers, feedback and feedforward systems had to be used as well.

To obtain short bunch lengths, just before extraction the bunches were rotated in longitudinal phase space using a voltage step from 2 MV to 7–7.7 MV at 200 MHz with a fast 1 ms rise time. With the intensity variations of about 10–15% from the injectors, the achieved bunch lengths are the following:

- $\tau=1.1-1.3$ ns at $N=(2.19-2.56)\times 10^{11}$ protons,
- $\tau=1.25-1.6$ ns at $N=(2.68-3.73)\times 10^{11}$ protons,

where the bunch length was calculated as a $4\sigma$ Gaussian fit to the bunch profile.

The flat top bunch lengths measured before, at 2 MV, and after rotation, at 7–7.7 MV, are shown in Fig. 11. For comparison, we show also results that were obtained with adiabatic $V$ increase [9] at 7 MV for different intensities (FWHM bunch length, scaled to $\tau_{4\sigma}=\sqrt{2/\ln 2}\,\tau_{FWHM}$).

Above $\sim 3.1\times 10^{11}$ protons, some uncontrolled longitudinal emittance blow-up was observed towards the end of the cycle, indicating longitudinal instabilities, which not only increase the bunch length, but also deteriorate the reproducibility of bunch parameters. These instabilities could potentially be suppressed by using controlled emittance blow-up during the acceleration ramp, as already done for LHC beams.

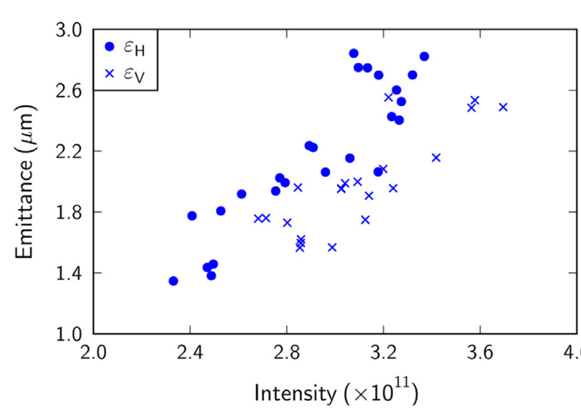


**Fig. 10.** Transverse emittances at SPS flat top.

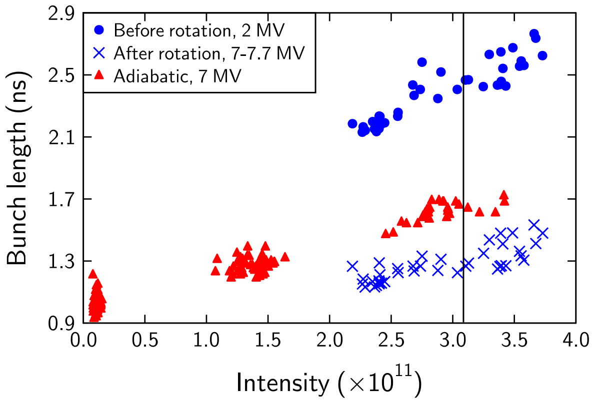


**Fig. 11.** Flat top bunch length ($4\sigma$ Gaussian fit) before and after rotation as a function of intensity. The vertical line marks roughly the threshold of stability.

Over the investigated intensity range, bunches were injected with a relatively constant bunch length and longitudinal emittance. Nevertheless, the bunch lengthening during the cycle due to intensity effects is significant (see Fig. 11). According to our present impedance model [10], the effect of potential-well distortion — which leads to a smaller effective voltage, and hence, longer bunches for higher intensities — alone cannot explain the observed bunch lengthening. Studies are ongoing to explain the observations.

The effect of instabilities is best seen on the rotated bunch. Higher-intensity, stable bunches will have a longer $\tau$ for the same $\varepsilon_L$, and hence a smaller momentum spread to begin with. After the rotation with less effective voltage, these bunches will have a $\tau$ similar to lower-intensity bunches; thus, $\tau$ is more or less constant between $(2.2\text{–}3.1) \times 10^{11}$ protons. Once the beam is unstable, also $\varepsilon_L$ will increase, and hence $\tau$ after rotation increases above $\sim 3.1 \times 10^{11}$ protons. On average, the bunch rotation reduces the bunch length by about 20%. The highest peak current $2\sqrt{2/\pi}Ne/\tau$ (assuming a Gaussian profile) achieved after rotation was $(59 \pm 4)$ A for stable and $(67 \pm 7)$ A for unstable bunches.

## 6. Summary

AWAKE, an accelerator R&D proof-of-principle experiment, will use the 400 GeV CERN SPS proton beam to drive plasma wakefields. The experiment will be installed in the fully operational CNGS facility, where only minor modifications on the existing infrastructure must be done. These modifications concern the end of the CNGS proton beam line to fit the experiment, integrate the laser and electron beam, and adapt the proton beam optics to achieve the required transversally round beams ($\sim 200$ µm) and a pointing precision of $\sim 100$ µm and $\sim 15$ µrad. In addition the area and corresponding services will be adapted to house the laser and electron source system. The studies have shown that these modifications are feasible. A new electron beam line has been designed to drive the electrons from the RF gun to the plasma cell. Furthermore short, high-intensity bunches have been studied at the SPS and the scaling of bunch length and transverse emittance as a function of beam intensity has been identified to help to guide the design parameters of the AWAKE project. At the design intensity of $3 \times 10^{11}$ protons, a transverse emittance of about 1.7 µm, an rms bunch length of 9 cm (0.3 ns), and a peak current of 60 A were reproducibly achieved.

## Acknowledgment

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