SHORT HIGH-INTENSITY BUNCHES FOR THE AWAKE EXPERIMENT

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Abstract

The AWAKE facility utilises high-intensity single bunches to drive resonant wakes in plasma for the acceleration of electrons. Twice shorter bunches are required from the CERN Super Proton Synchrotron (SPS) for the next phase of the experimental programme. In addition, the reproducibility of the bunch distribution and intensity is essential. This contribution summarises the key improvements to approach the new target parameters. An enhanced bunch production scheme was developed in the Proton Synchrotron Booster (PSB). It allows the preservation of the small longitudinal emittance during acceleration in the Proton Synchrotron (PS) without triggering an instability during the transition crossing. In addition, a double-voltage jump bunch rotation scheme has been implemented in the SPS, with radio-frequency (RF) voltage functions synchronised to the variable extraction time. The measurement results confirm the feasibility of achieving the target beam parameters.

INTRODUCTION

The Advanced WAKefield Experiment (AWAKE) [1], aims at demonstrating plasma wakefield acceleration of an electron beam for future high-energy physics applications. It requires as short as possible proton bunches to be extracted from the Super Proton Synchrotron (SPS) with a target intensity of 3×10^{11}. The initial longitudinal emittance is typically determined by the radio-frequency (RF) manipulations in the Proton Synchrotron Booster (PSB) and, then, limited by instabilities during the Proton Synchrotron (PS) transition crossing [2, 3]. The longitudinal beam stability during the SPS energy ramp is maintained by deploying a double-harmonic RF system operating at 200 MHz and 800 MHz. As soon as the synchronisation process is completed at a momentum of 400 GeV/c [4], a two-step bunch compression scheme is applied (Fig. 1): (i) the RF voltage is adiabatically decreased, resulting in bunch lengthening; (ii) a non-adiabatic RF voltage jump is triggered, resulting in a bunch rotation in phase space. After approximately one quarter of a synchrotron oscillation period, the bunch is extracted with about 170 ps rms length. Note that the extraction time, t_{extr}, with respect to the start of the SPS cycle can vary up to 100 ms. In the present system implementation, the voltage jump is initiated by the beam control (BC) module of the SPS low-level RF system [5] once an extraction timing event arrives in the synchronisation module. Since the 800 MHz cavity controller does not directly communicate with the BC module, the 800 MHz RF voltage stay constant during the 200 MHz RF voltage jump. This conventional scheme was in use until the end of 2023.

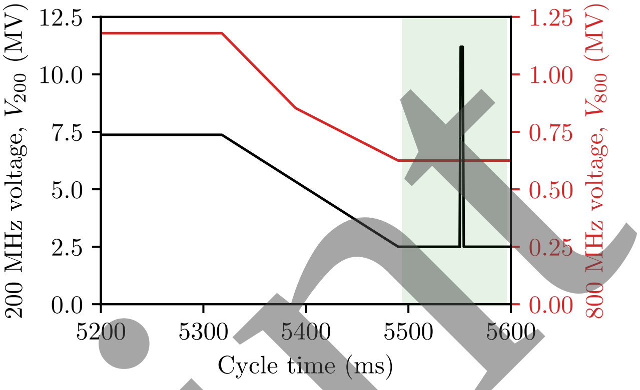

Figure 1: Example of 200 MHz and 800 MHz RF voltage programmes at 400 GeV/c in October 2023. The green area indicates the range of the extraction time variation.

For the next phase, Run 2c [6, 7], bunches twice as short are required based on the latest simulations [8, 9]. Moreover, reproducibility and stability of the proton beam parameters are essential. The following sections describe the necessary advancements to meet the target parameters and prepare for the next data-taking period in 2029.

DOUBLE BUNCH ROTATION IN SPS

The compression factor after a non-adiabatic RF voltage jump depends on the final, V_f, and initial, V_i, RF voltages. In linear approximation, it is equal to $\sqrt{V_f / V_i}$. The RF voltage, V_i, is limited by the initial longitudinal emittance and beam intensity, which define the longitudinal mode-coupling instability threshold. It was studied by comparing the dedicated measurements with macroparticle simulations [10], and more recently also applying the linearised Vlasov equation [11, 12]. Until the end of 2023, achieving the target bunch length at extraction required reducing the RF voltage to a level at which the instability was triggered. In that scenario, the bunch shape changed from cycle to cycle as the beam was extracted at different stages of the instability (Fig. 2).

To avoid this instability, an alternative approach was implemented. The first stage of adiabatic voltage reduction was replaced by an adiabatic voltage increase to guarantee beam stability. Then, the RF voltage is non-adiabatically reduced to a small value, leading to a fast bunch lengthening without instability (see Fig. 3). Finally, the RF voltage is restored non-adiabatically to the initial value, leading to a bunch rotation. A similar, double-bunch rotation scheme was originally proposed in [13] and tested to mitigate an

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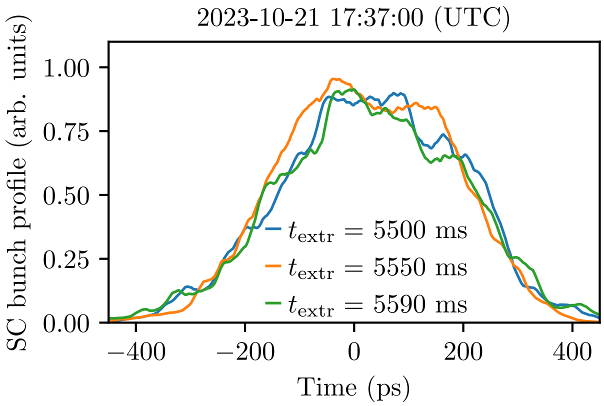

Figure 2: Bunch profile measurements with a streak camera (SC) in AWAKE for standard bunch rotation settings (Fig. 1).

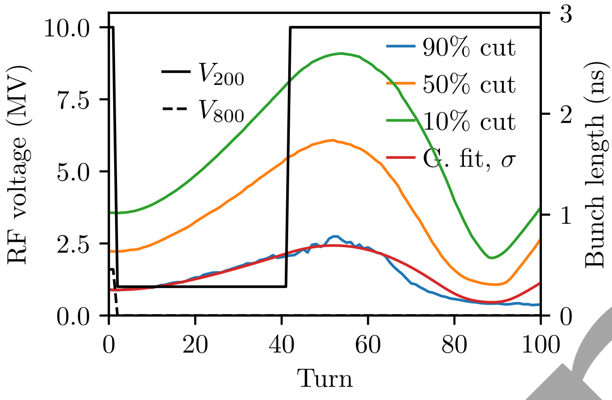

Figure 3: Example of the evolution of RF voltages and bunch length computed at different levels during the macroparticle simulation of the double voltage jump. The curve indicates the rms bunch length computed via a Gaussian fit.

electron-cloud instability of the multi-bunch beam at the PS extraction energy. The double bunch rotation was done in macroparticle simulations for the SPS parameters in 2020. However, it was not implemented after Long shutdown 2, as the 800 MHz RF voltage must be switched off synchronously with the first RF voltage drop. It was implemented in 2024, after initial tests at the end of 2023 with asynchronous bunch rotation with the double-voltage jump. Suppression of the uncontrolled longitudinal emittance blow-up at 400 GeV/c (see Fig. 4) opened the possibility of further decreasing the extracted bunch length by reducing the initial longitudinal emittance and optimising bunch rotation settings.

BEAM TESTS IN 2024

Production Scheme in PSB

In 2024, a production scheme was optimised, which allowed bunch acceleration at smaller emittance without triggering an instability after the PS transition crossing. Injection into the PSB was done over 41 turns compared to 6 turns for the standard production scheme with one third of the pulse duration (100 ns vs 330 ns) per turn. The RF voltage programmes of the main harmonic (h = 1) together with the higher harmonic (h = 10), used for the controlled emittance blow-up and longitudinal shaving, were also modified (Fig. 5). The large number of short injected beam pulses and increased longitudinal shaving resulted in a longitudinal distribution with a denser core, less tails, and smaller longitudinal emittance in comparison to the standard scheme. In addition, the working point, (Q_x, Q_y), at injection was changed from (4.17, 4.23) to (4.23, 4.33) to avoid transverse emittance blow-up in both planes.

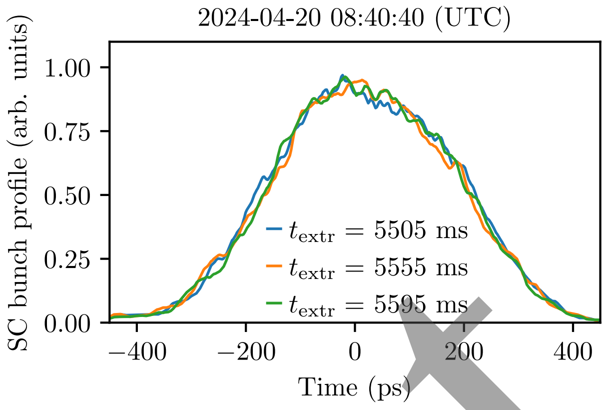

Figure 4: Bunch profile measurements with SC for double voltage jump bunch rotation settings similar to those shown in Fig. 3.

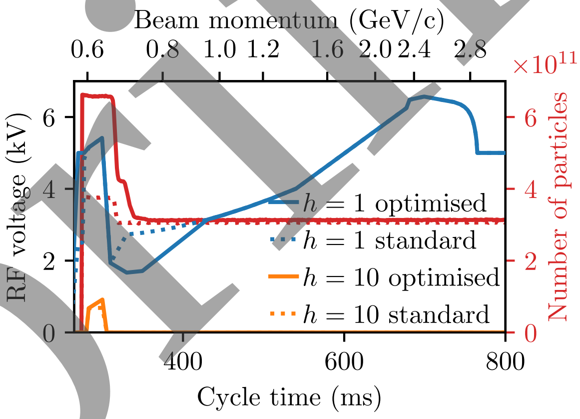

Figure 5: PSB voltage programmes and beam intensity evolution in 2024 for optimised (solid) and standard (dotted) settings.

Modified Rotation Settings in SPS

The time delay between the two voltage jumps, as well as the minimum and maximum RF voltages during rotation, directly impact the compression efficiency. The operational values of RF voltages were kept during the beam test: V_{200} = 10 MV and V_{800} = 1.6 MV. Since the initial emittance was decreased, a longer delay could be introduced, resulting in a shorter extraction bunch length (Fig. 6). Due to the finite bandwidth of the SPS wall current monitor [14] and the signal transmission chain, the measured bunch profiles are systematically longer compared to those measured with the streak camera (SC) in AWAKE. It turned out that,

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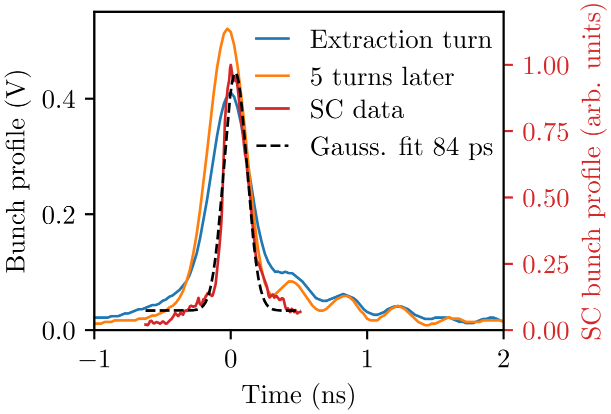

Figure 6: Comparison of the bunch profile measured in the SPS prior to extraction using the MD acquisition system and the AWAKE streak camera. The orange trace represents the bunch profile measured five turns after the nominal extraction time.

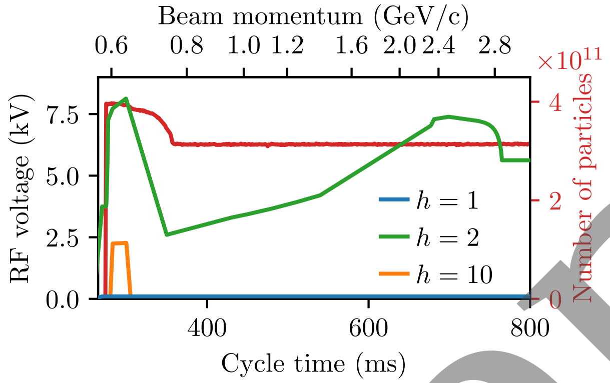

Figure 7: PSB voltage programmes and beam intensity evolution in 2026 for re-optimised settings.

during this test, the bunch rotation was not completed. The orange trace in Fig. 6 indicates the bunch becomes even shorter five turns after the expected beam extraction.

BEAM REPRODUCIBILITY IN 2026

Updated Scheme in PSB

To avoid significant losses (see Fig. 5) and improve reproducibility, the PSB production scheme was modified in 2026. Applying a similar strategy of injecting many short pulses, the beam was captured and accelerated mainly at the second harmonic ($h = 2$). A small RF voltage at the main harmonic ($h = 1$) had to be applied to ensure the operation of the beam-based feedback loops. The corresponding voltage programmes and the bunch intensity during the cycle are shown in Fig. 7. A similar working point was chosen, resulting in small transverse emittances of 1.7 mm mrad in both planes. For these extreme beam parameters, a vertical instability was triggered shortly after the PS transition crossing. It was cured by adjusting the working point and increasing chromaticity around the transition energy.

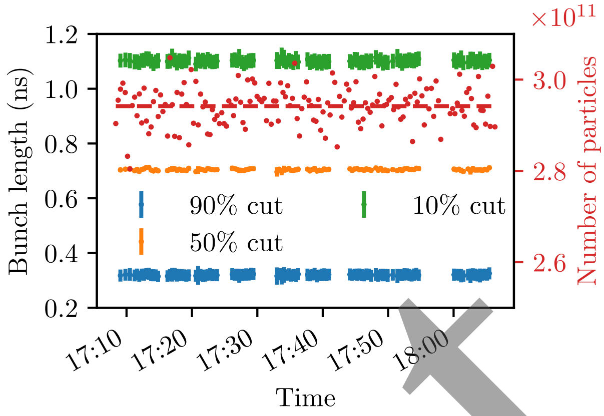

Figure 8: Cycle-to-cycle variation of beam parameters at 400 GeV/c, with error bars showing three times the standard deviation over 1300 turns. Data was taken on the 30th of March 2026. Bunch profiles were acquired over about 100 cycles.

Bunch Shape Stability in SPS

Since AWAKE entered the Long Shutdown 3 (LS3) phase in May 2025, the streak camera is not available for the bunch profile measurements. Nonetheless, beam tests were performed in March 2026 to monitor the reproducibility of beam parameters at the SPS flat-top energy. The beam intensity and different cuts of longitudinal profiles were acquired for about 100 cycles, demonstrating stability of the bunch parameters before the double-bunch rotation (Fig. 8). Further bunch length reduction can be explored after LS3 by further increasing the 200 MHz RF voltage up to its theoretical limit of 13.5 MV.

CONCLUSION

Shorter, high-intensity proton bunches are required for the next phase of the AWAKE experiment. A new bunch production scheme in the PSB has enabled a reduction of the longitudinal emittance while maintaining beam stability through the PS transition crossing, thanks to an improved longitudinal distribution. In the SPS, the implementation of a double-voltage jump bunch rotation scheme has successfully mitigated longitudinal instabilities and improved control over the bunch compression process.

Beam tests performed in 2024 demonstrated the feasibility of these approaches, while further optimisation in 2026 resulted in improved beam reproducibility and stability at flat-top energy. The measured cycle-to-cycle variations confirm reliable operation with reduced emittance and consistent bunch parameters. Although limitations in the bunch-profile observation system currently restrict precise bunch length measurements, the results indicate that further compression is achievable.

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