SHORT HIGH-INTENSITY BUNCHES FOR PLASMA WAKEFIELD EXPERIMENT AWAKE IN THE CERN SPS

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Abstract

Obtaining the shortest possible bunch length in combination with the smallest transverse emittances and highest bunch intensity — this is the wish list of the proton-bunch driven, plasma wakefield acceleration experiment AWAKE currently under feasibility study at CERN. A few measurement sessions were conducted to determine the achievable bunch properties and their reproducibility. To obtain a short bunch length, the bunches were rotated in longitudinal phase space using the maximum available RF voltage prior to extraction. Measurements were carried out in two optics with different transition energies. The main performance limitation is longitudinal beam instability that develops during the acceleration ramp. With lower transition energy, beam stability is improved, but the bucket area is smaller for the same voltage. Based on the results obtained, we shall discuss the choice of optics, the impact of longitudinal instabilities, the importance of reproducibility, as well as options for improving the bunch parameters.

INTRODUCTION

The proposed AWAKE project shall accelerate electrons in a plasma wakefield driven by SPS proton bunches with a momentum of 400 GeV/c or lower (down to 300 GeV/c) [1]. As part of the feasibility study, we investigated the bunch parameters of short, high-intensity single proton bunches that were created using bunch rotation in longitudinal phase-space at the SPS flat top momentum of 450 GeV/c. Achieving a short bunch length τ and small transverse emittances $\varepsilon_{\mathrm{H,V}}$ at a relatively high intensity N are equally important for this experiment.

The shortest achievable bunch length is determined by the maximum available RF voltage and the smallest possible longitudinal emittance. At high intensities, the longitudinal emittance cannot be too low, otherwise longitudinal instabilities develop that lead to uncontrolled emittance blow-up. The maximum voltage in the two RF systems of the SPS is currently limited to 8 MV and 600 kV at 200 MHz and 800 MHz, respectively. With future upgrades, this will be increased to 12 MV at 200 MHz (around 2019) and to 1.2 MV at 800 MHz (in 2015).

Since the longitudinal emittance is determined by the intensity, shorter bunches can be obtained either by adiabatic voltage increase, or by bunch rotation, for instance.

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MEASUREMENTS

Two measurement sessions were carried out using the two different optics available in the SPS. The so-called "Q20" and the "Q26" optics use betatron tunes $Q_{\mathrm{H,V}}$ close to 20 and 26, respectively, with a corresponding gamma at transition γ_T of 18 and 22.8 (for FODO cell lattices $\gamma_T \approx Q_H$ [2]). The slip factor $\eta = \gamma_T^{-2} - \gamma^{-2}$ and the longitudinal emittance ε_L increase the instability thresholds proportionally to $\eta\varepsilon_L$ for the transverse-mode coupling instability [3] and $\propto \eta\varepsilon_L^{5/2}$ for the loss of Landau damping [4]. Hence, in the Q20 optics, the transverse and longitudinal beam stability is increased [5]. On the other hand, to keep the same τ and ε_L, more RF voltage V is required, since also $V \propto |\eta|$. Also, the optics is less critical for longitudinal stability if ε_L can be increased. Altogether, we can expect a similar bunch length in both optics but better transverse stability in Q20.

The flat top single bunch intensities achieved were in the range of (2.7–3.8)$\times 10^{11}$ p, far beyond the typical operational range of (1.2–1.8)$\times 10^{11}$ p/b for LHC beams. In one measurement session with Q26, the voltage programme of the acceleration cycle was not optimized for these high intensities. Due to hardware restrictions at that time, the maximum voltage step achievable with a fast 1 ms rise time was from 2 MV to only 5.8 MV, which limited the bunch compression rate.

Better stability and better bunch compression were achieved in Q20 that used a voltage programme with constant bucket area throughout the cycle and a voltage step from 2 MV to (7–7.7) MV at 200 MHz for the bunch rotation, see Fig. 1.

For both optics, using the 800 MHz RF in addition to the 200 MHz RF system was required for beam stability during the cycle. Longitudinal dampers, feedback and feedforward systems were used, too.

At such high intensities, intensity variations from the injectors, around (10–15) %, are larger than for operational beams. As a consequence, bunch length and transverse emittance varied significantly as well.

RESULTS AND DISCUSSION

The achieved beam parameters important for AWAKE — intensity, shortest bunch length after rotation, and transverse emittances — are shown in Table 1. Each column represents the values at a given intensity, in a given optics; the spread in the values is due to the intensity variation of the injected beam.

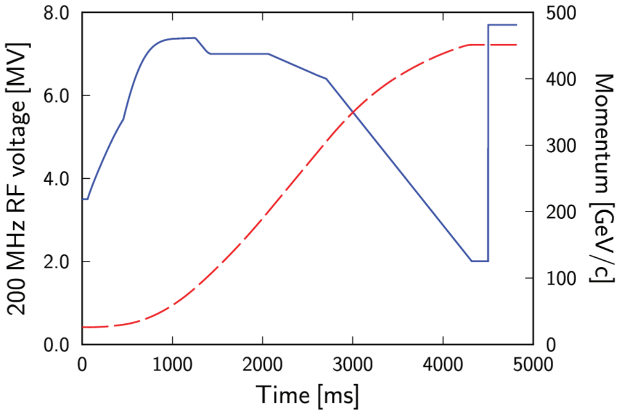

Figure 1: Beam momentum (dashed line) and 200 MHz RF voltage programme (solid line) used during Q20 measurements. Flat top and bunch rotation (with 1 ms voltage rise) start at cycle times 4320 ms and 4500 ms, respectively.

Table 1: Beam parameters at different intensities, in the Q26 and Q20 optics.

	Q26	Q20, set 1	Q20, set 2
N ($\times 10^{11}$ p)	2.66–3.61	2.19–2.56	2.68–3.73
τ (ns)	1.3–1.7	1.1–1.3	1.25–1.6
$\varepsilon_{\mathrm{H,V}}$ (µm)	1.6–2.4 [6]	1.3–1.7	1.8–2.8

The intensity was measured with a DC current transformer. The transverse emittances were obtained from wire scans at flat top with an accuracy of about ± 20 %. The bunch length was calculated as a 4σ Gaussian fit to the bunch profile. Bunch profiles were acquired throughout the cycle, at a higher rate (one profile every two turns) during the bunch rotation.

Longitudinal instabilities not only lead to an increased bunch length, but also deteriorate the reproducibility of bunch parameters, and hence, should be cured. Below $\sim 3.1 \times 10^{11}$ p, the beam was perfectly stable in the Q20 optics. At higher intensities, some uncontrolled longitudinal emittance blow-up was observed towards the end of the cycle, see Fig. 2, which could be potentially suppressed in the future by using controlled emittance blow-up during the acceleration ramp, as already done for LHC beams. As expected, in the Q26 optics, the beam was more unstable, also due to the unoptimized voltage programme.

The flat top bunch lengths measured in the Q20 optics before, at 2 MV, and after rotation, at (7–7.7) MV, are shown in Fig. 3. For comparison, we show also results that were obtained with adiabatic V increase, with Q20 [7] and Q26 [8] at 7 MV for different intensities (FWHM bunch length, scaled to $\tau_{4\sigma} = \sqrt{2/\ln 2}\,\tau_{\mathrm{FWHM}}$).

Over the investigated intensity range, bunches were injected with a relatively constant bunch length and longitudinal emittance of (0.35–0.4) eVs. Due to the effect of beam-induced voltage (potential-well distortion), the effective voltage is smaller for higher-intensity bunches, and

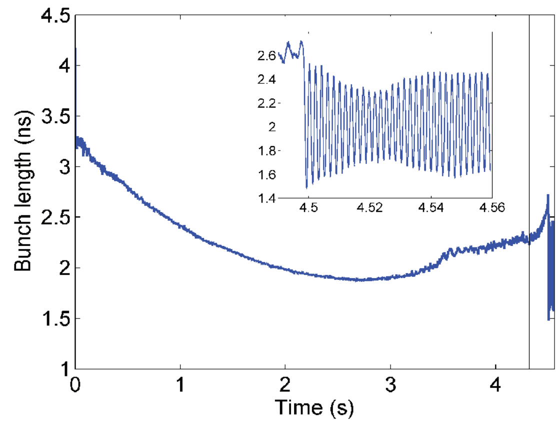

Figure 2: Typical bunch length (4σ Gaussian fit) evolution during the cycle in the Q20 optics, at 3.73×10^{11} p flat top intensity. The vertical line marks the beginning of the flat top. The inset shows the arrival to flat top and subsequent rotation in more detail. The bunch should be extracted after 1/4 of the synchrotron period.

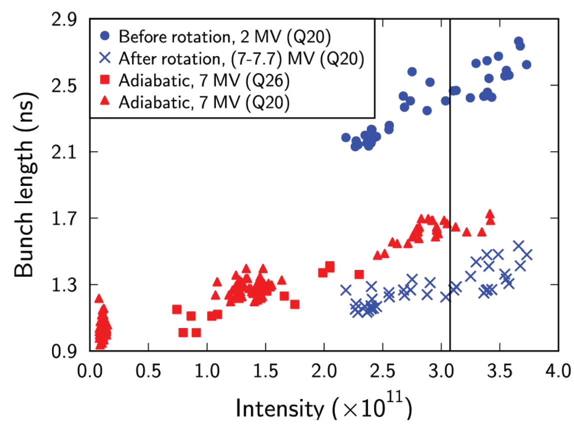

Figure 3: Flat top bunch length (4σ Gaussian fit) before and after rotation as a function of intensity. The vertical line marks roughly the threshold of stability in Q20.

hence, their bunch length is increased.

The adiabatically achieved bunch lengths in Fig. 3 follow the scaling of potential-well distortion, as long as the beam is stable. Assuming a parabolic line density bunch interacting with a constant inductive impedance $Z^{||}/n$, the impedance can be determined [9]. For the data sets in Fig. 3 we get $Z^{||}/n \approx 15\,\Omega$, which, according to our present impedance model [10], is probably overestimated by about a factor of 2 (in reality, bunches are closer to Gaussian and the impedance is not constant either). Ongoing simulation studies shall clarify this difference.

The effect of instabilities is best seen on the rotated bunch. Higher-intensity, stable bunches will have a longer τ for the same longitudinal emittance ε_L, and hence a smaller momentum spread to begin with. After the rotation with less effective voltage, these bunches will have a τ similar to lower-intensity bunches; thus, τ is more or less constant between (2.2–3.1) $\times 10^{11}$ p. Once the beam is

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unstable, also ε_L will increase, and hence τ after rotation increases above $\sim 3.1 \times 10^{11}$ p. On average, the bunch rotation reduces the bunch length by about 20 % for the same voltage with the Q20 optics.

For longitudinal beam stability, the 800 MHz RF has to be used in bunch-shortening mode in the SPS [11]. To see whether this influences the rotation, we tried different 800 MHz RF voltages between (0–0.7) MV in Q20, but no significant effect on the rotated τ was seen.

The peak current $2\sqrt{2/\pi}Ne/\tau$ (assuming a Gaussian profile) in the proton bunch is another important parameter for the plasma experiment. With the rotation applied to stable bunches, the maximum peak current achieved was (59 ± 4) A. For unstable bunches, (67 ± 7) A were achieved.

The transverse emittances measured in Q20 scale roughly linearly with intensity, see Fig. 4, due to the space charge effect in the injectors; the slope is increased by injection losses that are $\propto N$. The difference seen in the

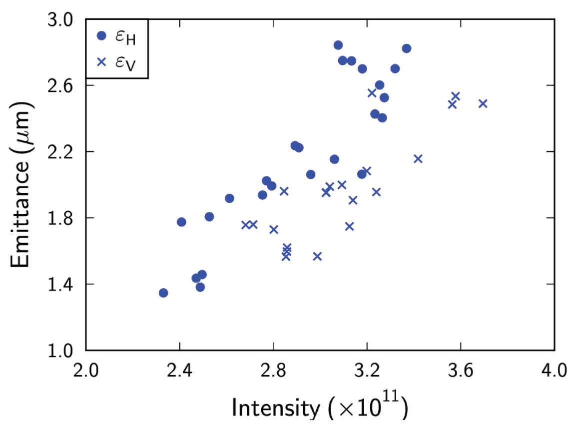

Figure 4: Transverse emittances in the Q20 optics.

horizontal and vertical components is most likely due to the calibration of the wire scanners used for the measurements; the beam is in principle expected to be round. In measurements with Q26 [12], it was seen that the emittance starts to deviate from the linear trend at around 2.5×10^{11} p, due to transverse instabilities.

In the case of a beam extraction at lower energy (as 300 GeV [1]), the bunches will be more stable, since the intensity threshold of longitudinal stability is roughly scaling with beam energy E as $\propto 1/E$ [4]. On the other hand, for the same RF voltage, the bucket area $A_b \propto \sqrt{E}$ [2] will be smaller as well. Therefore, the bunch length at extraction is expected to be similar. Stability is also important for obtaining reproducible bunch parameters and for finding an optimal working point. The large variation in injected intensities might become an issue then.

Further experimental and simulation studies are underway. The bunch compression could be optimized by adding a jump to the unstable phase as an intermediate step. Testing such a scheme will become possible in 2014 after hardware modifications of the SPS. Meanwhile, simulation studies shall help to explore different options and find the optimal bunch parameter space for the experiment. The SPS impedance model is currently being improved [10] in order to allow for such studies.

CONCLUSIONS

Short, high-intensity bunches have been studied at SPS flat top for the future AWAKE plasma wakefield acceleration experiment. The scaling of bunch length and transverse emittance as a function of intensity has been identified to help to guide the design parameters of the project. With the currently available maximum RF voltage and using bunch rotation, peak bunch currents of up to 67 A have been achieved at intensities of up to 3.8×10^{11} p.

The performance with the two optics available in the machine has been compared and, at least in the transverse plane, the lower-transition-energy optics is preferable for stability and small emittances. Longitudinal stability can be achieved with the aid of a higher-harmonic RF system and controlled emittance blow-up. Instabilities and fluctuations in injected intensity can deteriorate the reproducibility of bunch parameters.

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