ELECTRON CLOUD MITIGATION BY FAST BUNCH COMPRESSION IN THE CERN PS

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Abstract

A fast transverse instability has been observed with nominal LHC beams in the CERN Proton Synchrotron (PS) in 2006. The instability develops within less than 1 ms, starting when the bunch length decreases below a threshold of 11.5 ns during the RF procedure to shorten the bunches immediately prior to extraction. An alternative longitudinal beam manipulation, double bunch rotation, has been proposed to compress the bunches from 14 ns to the 4 ns required at extraction within 0.9 ms, saving some 4.5 ms with respect to the present compression scheme. The resultant bunch length is found to be equivalent for both schemes. In addition, electron cloud and vacuum measurements confirm that the development of an electron cloud and the onset of an associated fast pressure rise are delayed with the new compression scheme. Beam dynamics simulations and measurements of the double bunch rotation are presented as well as evidence for its beneficial effect from the electron cloud standpoint.

INTRODUCTION

Short bunches for the LHC are required from the PS to allow for a bunch-to-bucket transfer to the SPS, which captures the beam with its 200 MHz radio frequency (RF) system. To achieve a bunch length of 4 ns during operation with proton LHC beams, the bunches are first shortened from about 14 ns to 11 ns length by iso-adiabatically raising the voltage of the 40 MHz (harmonic number, $h = 84$) RF system [1] from 40 kV to 100 kV within 5 ms (Fig. 1). Then, some 280 μs before extraction, the RF voltage is rapidly increased to 300 kV [2]. The longitudinal mismatch of the bunches with respect to their buckets causes a rotation in longitudinal phase space, exchanging bunch length and momentum spread. Finally, 110 μs before extraction, an additional 80 MHz ($h = 168$) RF system [3] kicks-in to further reduce the bunch length. The beam is extracted when the bunches are at their shortest.

Using this operational scheme, a fast transverse beam instability growing within less than 1 ms has been observed when the bunch length gets below 11.5 ns [4]. Though the instability has not been seen anymore in 2007, measurements with a dedicated electrode set-up have demonstrated the development of an electron cloud (EC) prior to extraction [5]. Replacing the adiabatic compression by a much faster rotation has been successfully tested in 2007 and significantly delays the electron cloud instability in the PS.

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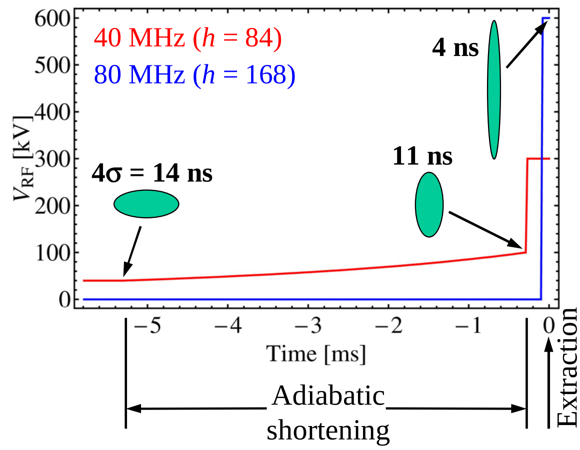

Figure 1: RF voltages during the nominal manipulation with LHC beams in the PS to compress the bunch length from 14 ns to 4 ns at extraction. The time is given with respect to extraction and the different bunch shapes in the longitudinal phase space are sketched.

DOUBLE BUNCH ROTATION

Slowly increasing the RF voltage with respect to the period of the synchrotron frequency and with a bunch in the linear region of the bucket, the bunch length decreases according to

$$\frac{\sigma_f}{\sigma_i} = \sqrt[4]{\frac{V_i}{V_f}}\,, \tag{1}$$

where σ_i, σ_f are the initial and final bunch length and V_i, V_f are the corresponding voltages. In the nominal scheme for the production of LHC beams in the PS, the voltage ratio of the pre-compression is $100\,\mathrm{kV}/40\,\mathrm{kV} = 2.5$, resulting in a bunch shortening ratio of 1.3 before the final bunch rotation starts.

To avoid a slow pre-compression, the same compression ratio is achieved much faster by a bunch rotation, similar to the bunch rotation before ejection. The RF voltage is rapidly increased to

$$V_{\mathrm{rot}} = \sqrt{V_i V_f} \tag{2}$$

and the bunch rotates in longitudinal phase space due to the longitudinal mismatch. To a linear approximation, with all particles close to the centre of the bucket, the rotation takes one quarter of a synchrotron period

$$t_{\mathrm{rot}} = \frac{T_{\mathrm{s}}}{4} = \sqrt{\frac{\pi^3 pR}{2h|\eta|\omega_0 e V_{\mathrm{rot}}}} \tag{3}$$

of the stationary bucket, where p is the beam momentum, R is the mean radius, $\eta = 1/\gamma_{\mathrm{tr}}^2 - 1/\gamma^2$ is the momentum compaction factor and $\omega_0 = 2\pi f_0$ is the revolution frequency.

The iso-adiabatic pre-compression (Fig. 1) can thus be replaced by a first bunch rotation with an RF voltage of $V_{\mathrm{rot}} = 63\,\mathrm{kV}$. The corresponding RF voltages of the 40 MHz and 80 MHz cavities are illustrated in Fig. 2.

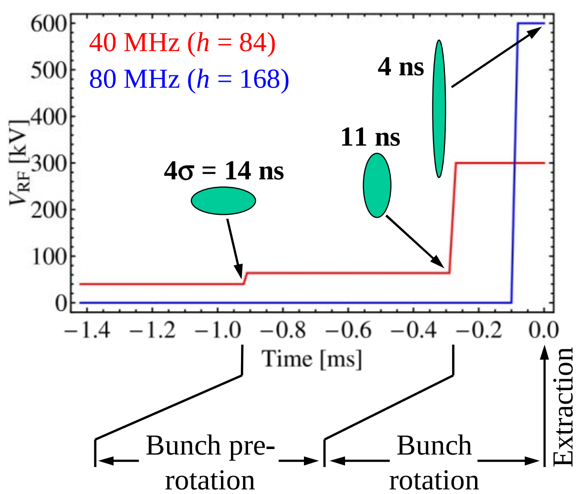

Figure 2: RF voltages during the new bunch compression scheme, consisting of a sequence of two bunch rotations. Note the different time scale compared to Fig. 1.

The rotation time becomes about $584\,\mu\mathrm{s}$ in the linear bucket approximation, saving almost 4.5 ms. After the pre-compression by bunch rotation, the length-to-momentum-spread aspect ratio of the rotated bunches is identical to a stationary bunch in a bucket with $V_{\mathrm{RF}} = 100\,\mathrm{kV}$ at $h = 84$.

BEAM MEASUREMENTS

The experimental verification of the longitudinal beam parameters during and after the double bunch rotation has been performed using the LHC beam with 25 ns bunch spacing. Since only four bunches were injected from the PS Booster, a batch of 48 bunches was produced at extraction. The intensity was about $6.3 \cdot 10^{12}$ ppp, corresponding to $1.3 \cdot 10^{11}$ ppb (nominal bunch intensity).

The rotation voltage and duration calculated above were used as the starting point for an optimization leading to the rotation parameters $t_{\mathrm{rot}} = 625\,\mu\mathrm{s}$ and $V_{\mathrm{rot}} = 64\,\mathrm{kV}$. The rotation is slightly longer since the synchrotron frequency decreases towards the outer regions of the bunch.

The peak detected beam signals (as a measure of the inverse bunch length) during the last 1.5 ms before extraction are compared for both compression schemes in Fig. 3. Applying the sequence of two bunch rotations (red trace), the peak amplitude of the bunches remains below the peak amplitude during the nominal compression manipulation (blue trace). During the first bunch rotation, the peak amplitude rises to the same value at the start of the

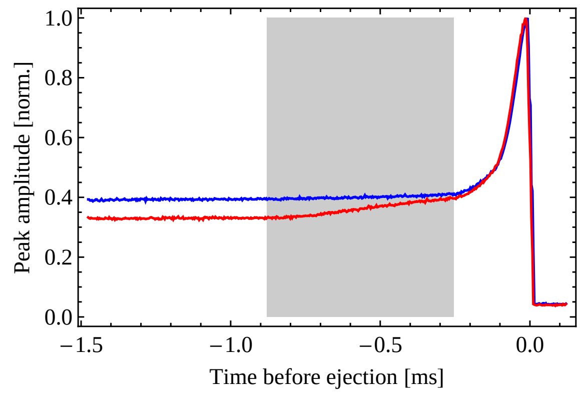

Figure 3: Measured normalized peak detected beam signals for the nominal compression scheme (blue) and the double bunch rotation (red), averaged over ten cycles. The gray shaded area indicates the time slot for the first bunch rotation.

final rotation for both schemes. The final bunch rotation is then the same in both cases.

The bunch length along the batch at extraction confirms that the double bunch rotation does not compromise the longitudinal beam quality at extraction (Fig. 4).

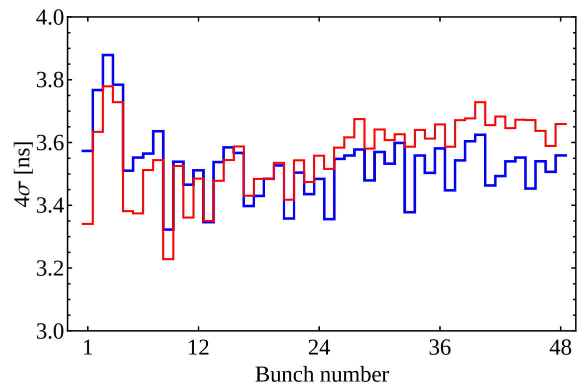

Figure 4: Measured bunch length along the batch of 48 bunches at extraction averaged over ten cycles. The standard bunch compression (blue trace) is compared with the new double bunch rotation scheme (red trace).

No significant difference between the nominal compression scheme and the double bunch rotation can be observed at extraction.

ELECTRON CLOUD MEASUREMENTS

The potential influence of the double bunch rotation scheme on the EC effect was evaluated using dedicated diagnostics [5]. For the nominal LHC beam in the PS, EC was observed starting already during the last bunch splitting on the flat-top, about 40 ms to 50 ms before ejection. An EC is therefore already present when the bunch compression starts. The EC performance of the double bunch rotation was compared to the standard bunch compression scheme for nominal LHC beams with 72 and 48 bunches at extraction. Fig. 5 shows the signals on shielded pickup 1 of the EC diagnostics for 72 bunches.

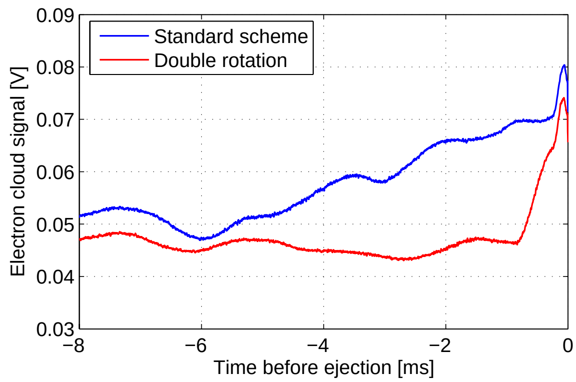

Figure 5: EC pickup signals for the nominal LHC beam with 72 bunches spaced by 25 ns. The standard scheme (blue) is compared to the double bunch rotation (red).

With the standard scheme, the EC signal increases during the iso-adiabatic bunch compression about 5 ms before ejection, while it remains at a lower level for the double rotation. Immediately before ejection, when the bunches reach their nominal length of 4 ns, the EC signals converge again for both schemes. For 48 LHC bunches, a still larger EC reduction was found (Fig. 6).

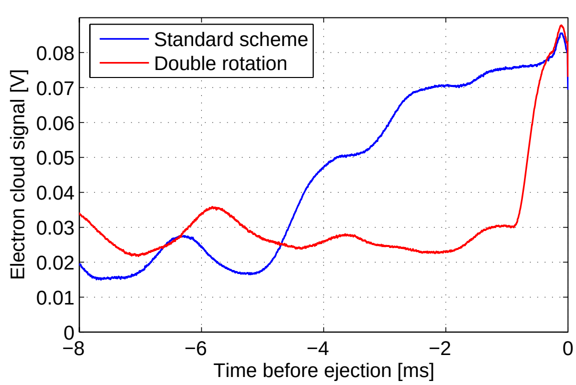

Figure 6: EC pickup signals for the nominal LHC beam with 48 bunches spaced by 25 ns (color coding according to Fig. 5). As in the 72 bunch case, there is a significant reduction during the last 5 ms.

In addition to the absolute signal strength, which is proportional to the EC density, the build-up time is a second characteristic parameter. It is evaluated for each turn from the growth rate of the EC pickup signal along the batch of 72 bunches (Fig. 7). With the double bunch rotation the EC build-up remains slow until about 900 μs before ejection. During the final bunch rotation, the build-up times of both schemes are very similar. This is consistent with the evolution of the EC signal strength mentioned above.

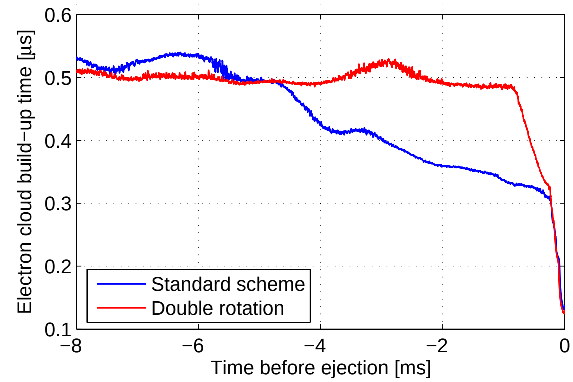

Figure 7: Comparison of the EC build-up time for the nominal LHC beam with 72 bunches. With the double rotation, the build-up time starts dropping only about 900 μs before ejection.

CONCLUSION

A cascade of two rotations allows bunches to be compressed from 14 ns to 4 ns significantly faster compared to the standard scheme, where an iso-adiabatic compression precedes the final bunch rotation. The new scheme reduces the time during which bunches are short by about 4 ms. The optimum duration and voltage for the first bunch rotation agree with expectations. No adverse effects on the longitudinal beam quality at extraction have been observed.

A substantial electron cloud reduction during the last 5 ms before the final bunch rotation was measured with dedicated pickups. The electron cloud build-up time remains larger for the LHC beam with 72 bunches using the new fast bunch compression scheme in the PS.

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