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BATCH COMPRESSION TO 50 NS SPACING AT PS FLAT-TOP

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Abstract

The bunch spacing in the injector chain has a direct impact on the total number of bunches in the LHC and hence on its integrated luminosity. The baseline scheme for lead ion beams within the LHC Injector Upgrade (LIU) project foresees the transfer of multiple batches of four bunches spaced by 100 ns from the PS to the SPS. The bunch spacing will then be reduced by momentum slip-stacking from 100 ns to 50 ns. Studies have been performed in view of alternatively producing 50 ns spacing directly at extraction from the PS, with the aim of demonstrating a batch compression-like RF manipulation to approach two bunches. Additionally, the proof-of principle tests allow to define the requirements for an additional RF system in the PS for the batch compression of four bunches to 50 ns spacing. Together with slip stacking in the SPS, this scheme would yield 25 ns bunch spacing with ions in the LHC.

INTRODUCTION

Reducing the bunch spacing of ion bunches in the injector chain has a direct impact on the total number of bunches which fit into the circumference of the LHC and hence on integrated luminosity. While the PS should deliver four bunches spaced by 100 ns for the LIU ion baseline scheme [1], the possibility to reduce the bunch spacing to 50 ns, beyond the LIU baseline, has been studied. In combination with the slip-stacking [2] in the SPS a bunch spacing of 25 ns would then become available to the LHC, significantly increasing the number of ion bunches per ring. Alternatively, generating the 50 ns bunch spacing directly in the PS could furthermore be considered as a back-up scenario for the momentum slip stacking in the SPS.

With proton beams a bunch spacing of 50 ns, as well as 25 ns is produced by bunch pair splitting at the flat-top in the PS [3] using dedicated RF systems at 20 MHz and 40 MHz. For lead ($^{208}Pb^{54+}$) ion beams such schemes are not feasible due to vicinity of the flat-top energy, $\gamma = 7.4$, to the energy of transition, $\gamma_{tr} = 6.1$. Even for low RF voltages in the range of 10 kV, the bucket filling factor remains small, which would require extremely precise relative phase control. In combination with the low synchrotron frequency the conditions for splitting are unfavourable. A test of bunch splitting from harmonic, $h = 21$, to $h = 42$ with lead ions in 2012 has illustrated the difficulties. In the middle of the process some particles were actually stuck at the unstable fixed-point during the separation of the two bunches [4]. The splitting scheme has therefore been abandoned.

Batch compression [5] at the flat-top has been studied as an alternative path to 50 ns bunch spacing at PS extraction. It does not suffer from the adiabaticity issues and excessive phase control precision as bunch splitting. During the RF manipulation all bunches stay within well defined sub-buckets without the need for separation at an unstable fixed point. The process is also tolerant to phase errors as the bunches are just handed over from bucket centres at the initial harmonic to bucket centres at the final one. However, the main drawback of batch-compression RF manipulations is the large number of intermediate RF harmonics which is required. In the case of batch compression of four bunches from 100 ns to 50 ns spacing, RF voltage on at least four intermediate harmonics (e.g., $h = 25$, 30, 36 and 42) is needed in addition to $h = 21$. Following the batch compression, the four bunches spaced by 50 ns can then be rebucketed to $h = 85$, generated by a slightly detuned 40 MHz RF system, and finally to $h = 169$ for the bunch shortening prior to extraction. The simulated mountain range plot of the complete RF manipulation at the PS flat-top is shown in Fig. 1.

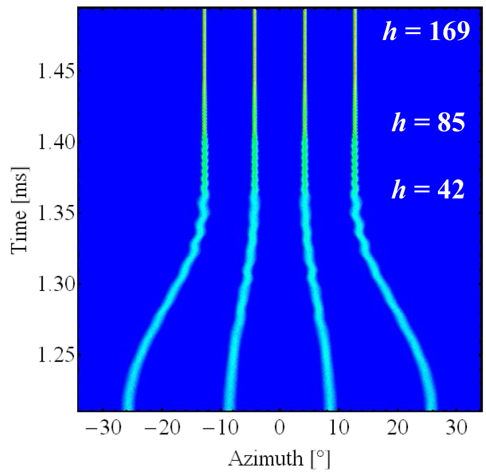

Figure 1: Simulated (ESME [6] without intensity effects) mountain range plot of the complete RF manipulation from $h = 21$ to $h = 169$ aiming at generating four short bunches with 50 ns spacing.

Since no RF system presently installed in the PS can deliver voltage at $h = 25$, 30 or 36 for a standard batch compression, a much simplified scheme has been tested with beam 2016. It allows to batch compress two bunches to 50 ns spacing, by starting from the first part of a bunch pair merging to approach the bunches combined with a hand-over to $h = 42$. The scheme is inherently limited to two bunches. The proof-of-principle tests permit nonetheless to evaluate voltage requirements and address the adiabaticity issues in case of moving bunches in azimuth at the flat-top in the PS.

In the following section the simulation results and measurements with beam for this simplified batch compression-like RF manipulations are presented. Special care has been taken to optimize the voltage programs such that, e.g., discontinuities of the synchronous phase are avoided when accelerating one bunch while decelerating the other during

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the approach. Based on these experimental results the requirements for additional RF systems needed for the full production scheme, yielding four bunches spaced by 50 ns, are discussed.

TWO-BUNCH MERGING COMPRESSION

Two bunches in adjacent buckets at an initial harmonic can be brought closer together in time by increasing the harmonic number of the RF system or, assuming sufficiently large bucket area, by adding RF voltage at a lower harmonic. The latter method is actually the first part of a bunch pair merging [7, 8].

Figure 2 shows a tracking simulation of two lead bunches spaced by 100 ns approaching each other. Initially the bunches are held by a single harmonic RF voltage of 10 kV in $h = 21$. An additional RF voltage at $h = 7$ is then brought up linearly with time until the same voltage is reached for both RF harmonics. Both bunches are then close enough to be handed over to an RF system at $h = 42$, corresponding to 50 ns spacing. At the PS flat-top energy of 5.9 GeV/n this manipulation takes about 100 ms. However, due to the linear voltage functions the initially stationary bucket instantly becomes accelerating, respectively decelerating, at the start of the process and vice versa at its end. The corresponding stable phase jumps excite dipole oscillations as observed in Fig. 2.

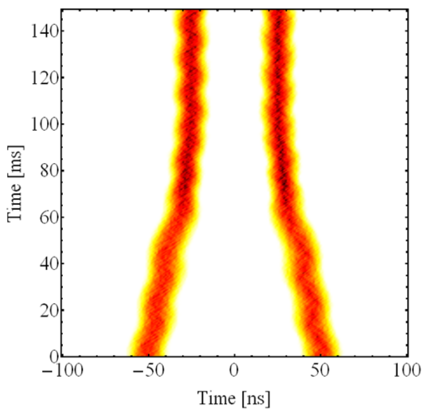

Figure 2: Simulated merging compression $h = 21 \rightarrow 21 + 7 \rightarrow 42$ using linear functions for the RF voltage programs.

These oscillations can be largely avoided by introducing non-linear voltage functions (with time) such that the bucket centres start to approach without jump in stable phase (Fig. 3). The reduction of the bunch spacing from 100 ns to 50 ns is again performed in 100 ms and the bunches follow the bucket centres smoothly.

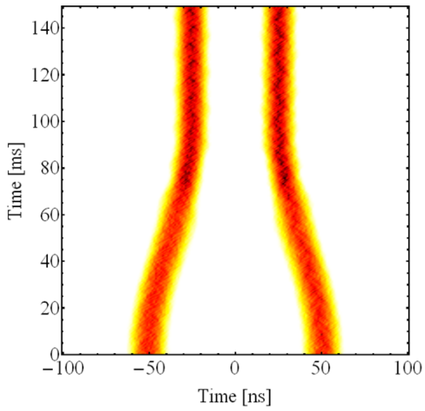

Figure 3: Simulated merging compression as in Fig. 2 using optimized voltage programs.

DOUBLE HARMONIC H=21+7

Similar conditions have been studied with a lead ion beam at the flat-top in the PS. Two ion bunches are injected from LEIR, accelerated to an intermediate flat-top at a kinetic energy of approximately 0.38 GeV/u and split according to the nominal four-bunch scheme described in [1]. Two of the four bunches held at $h = 21$ are then removed by the extraction kicker and the remaining two bunches are accelerated on $h = 21$ to the flat-top. This is the initial condition for the approach from 100 ns to 50 ns. Although the manipulations also works at lower RF voltages, sufficient margin has been chosen to keep beam phase and radial loops closed properly. Therefore the first series of measurements was taken with an initial RF voltage of 60 kV at $h = 21$.

Figure 4 shows a mountain range plot of the approach of two bunches when linearly increasing the RF voltage at $h = 7$ from zero to 120 kV. The beam phase loop is kept at $h = 21$ and towards the end of the process, when both bunches already get too close to deliver a meaningful phase information, the phase loop locks out.

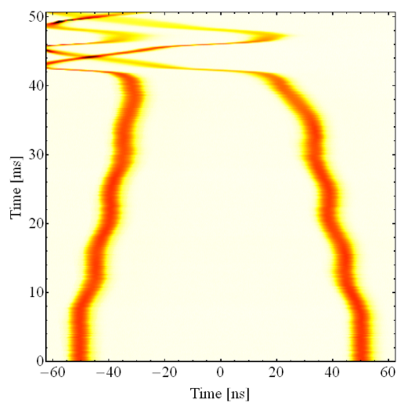

Figure 4: Measured merging compression $h = 21 \rightarrow 21 + 7$ in 40 ms using linear voltage programs.

The dipole oscillations due to the abrupt start of the approach are clearly visible. They are caused by the sudden change from a stationary to a moving bucket (Fig. 5, blue trace) and back to a stationary bucket. As the oscillations are triggered directly at the start of the process, they persist even for a twice longer linear rise of the RF voltage on $h = 7$. However, a non-linear voltage rise can be computed such that the bucket centres move adiabatically (Fig. 5, red trace).

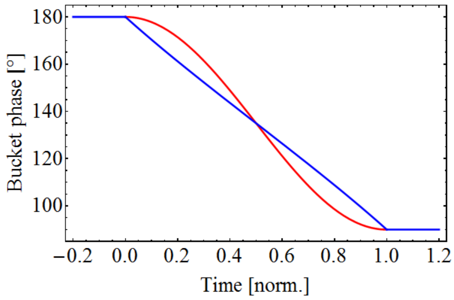

Figure 5: Bucket phase (in degrees of $h = 21$) for a linear (blue) and non-linear rise (red) of the RF voltage at $h = 7$, in combination with a constant RF voltage at $h = 21$. The non-linear voltage rise is evaluated numerically to achieve a sinusoidal approach of the buckets.

In this case they follow a sinusoidal function starting and ending with zero gradient. The corresponding non-linear voltage rise is plotted in Fig. 6, showing the detected voltages of the RF systems at $h = 21$ (constant) and $h = 7$.

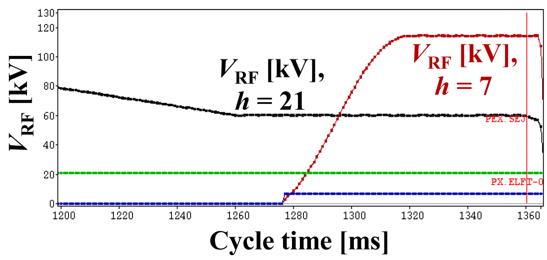

Figure 6: Detected RF voltages at $h = 21$ (black) and $h = 7$ (brown) together with the corresponding harmonic numbers (grren and blue) yielding the evolution of the buckets centres according to Fig. 5 (red).

As expected, the dipole oscillations at the start of process (Fig. 4) disappear when the RF voltage on $h = 7$ is not raised linearly but according to the curve shown in Fig. 6. The same effect is observed for various durations of the RF

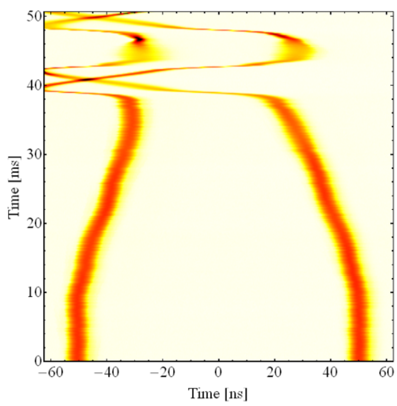

Figure 7: Measured merging compression $h = 21 \rightarrow 21 + 7$ in 40 ms using optimized voltage programs.

manipulations showing that the dipole oscillations are almost entirely due to the discontinuity at the beginning of the process. Two bunches can thus be adiabatically approached without significant impact on longitudinal beam quality.

REBUCKETING TO H=42

Approaching the two bunches from 100 ns to 50 ns spacing using only RF systems at $h = 21$ and $h = 7$ would require a twice larger RF voltage as at the lower harmonic as described in the previous section. However, for a rebucketing to $h = 42$ it is sufficient to approach the bunches close enough to hand them over into two adjacent buckets at $h = 42$. In a first step the RF voltage on $h = 7$ is therefore increased non-linearly to the same voltage at $h = 21$ (about 40 kV), which results in a bunch spacing of approximately 75 ns. Using a 20 MHz cavity tuned to 19.85 MHz, about 175 kHz below its frequency for protons, the RF voltage on $h = 42$ is then linearly increased to 20 kV. Finally, the voltages at both RF harmonics, $h = 7$ and $h = 21$ are simultaneously brought to zero, leaving two bunches spaced by 50 ns in a single-harmonic bucket at $h = 42$. Due to the limited beam time available for optimization, no attempt with non-linear voltage function during the re-bucketing part has been made.

The evolution of the detected RF voltages for the three harmonics during complete process is summarized in Fig. 8. The relative phases are adjusted such that the unstable fixed

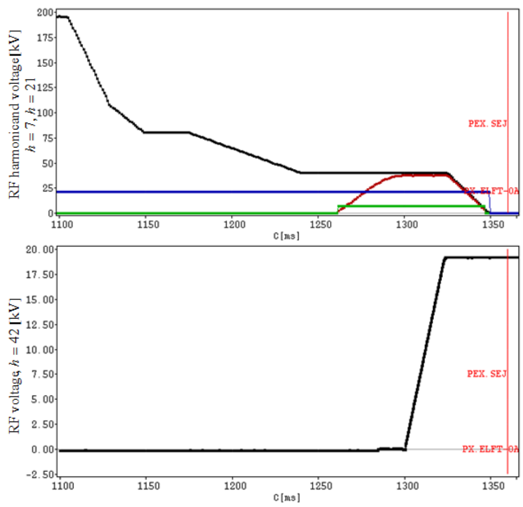

Figure 8: RF voltages at $h = 7$ (top, brown), 21 (top, black) and 42 (bottom) during the complete merging compression. The green and blue traces of the top plot are the measured harmonic numbers, $h = 7$ and $h = 21$.

point of initial ($h = 21$) and final ($h = 42$) buckets are aligned. The RF phase at $h = 7$ is programmed in counter-phase.

The resulting evolution of the bunch profiles during the RF manipulation is illustrated in Fig. 9. For a total duration of 100 ms the bunch distance is smoothly reduced and the longitudinal emittance blow-up remains below the measure-

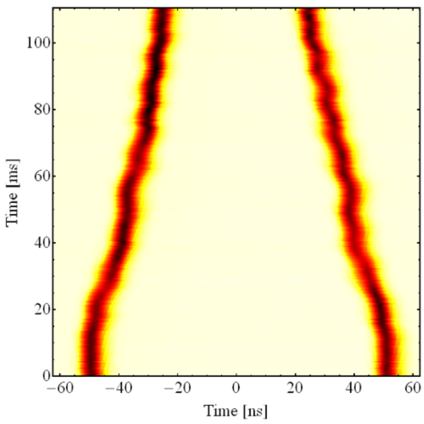

Figure 9: Measured mountain range plot of the complete RF manipulation from pure $h = 21$ to pure $h = 42$ in 100 ms.

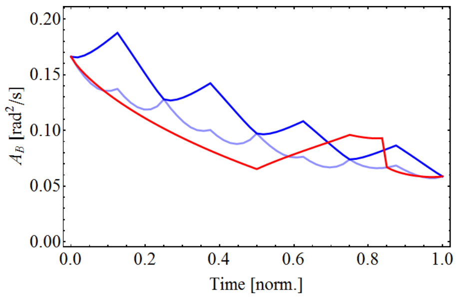

Figure 10: Comparison of normalized bucket area of the merging compression (red, $h = 21 \rightarrow 21+7 \rightarrow 42$) with the standard batch compression (inner bucket in dark blue, outer bucket in light blue, $h = 21 \rightarrow 25 \rightarrow 30 \rightarrow 36 \rightarrow 42$).

ment precision of few percent. Executing the RF manipulation twice faster results in strong dipole oscillations of both bunches though.

Ideally the harmonic for the beam phase loop should also follow from $h = 21$ to $h = 42$ to avoid losing the phase information of the beam on $h = 21$. For technical reasons, a beam phase loop at $h = 42$ could not be provided easily and the phase loop harmonic was only switched to $h = 24$ instead. This is sufficiently high to keep the loop locked although the bunches are already held by a single-harmonic RF voltage at $h = 42$. It is worth noting that the cavity return to the beam phase loop was emulated by a beam synchronous RF source programmed at $h = 24$.

SCALING TO STANDARD BATCH COMPRESSION

The beam measurements of the merging compression demonstrate that the spacing of lead ion bunches can be reduced on the flat-top by means of batch compression despite the vicinity to transition energy.

The normalized bucket areas for the merging and standard batch compression are compared in Fig. 10, showing that very similar RF voltages are required for both schemes to achieve comparable conditions. For the full implementation of the standard batch compression of four ion bunches from 100 ns to 50 ns spacing, the PS would thus need to be equipped with wide-band RF systems, delivering about 20 kV in the frequency range of about 12 MHz to 20 MHz ($h = 25$ to $h = 42$). Since two harmonics are required simultaneously the total RF voltage of the installation would amount to 40 kV.

For the batch compression with four bunches the outer bunches must move three times the azimuth of the two inner ones. Additionally, the motion of the bucket centres can not be optimized for inner and outer bunches at the same time. Hence the duration of the adiabatic batch compression scheme with four bunches is expected to be three times longer compared to proof-of-principle scheme with only two bunches, resulting in a duration of about 200 ms to 300 ms in total. This is slightly longer than expected from the tracking simulations. A detailed study must confirm if the duration is compatible with the maximum length of the flat-top in the PS. Additionally, the intermediate step of RF voltage at $h = 85$ from a detuned 40 MHz cavity to shorten the bunches for the re-bucketing to $h = 169$ has to be investigated.

CONCLUSIONS

Proof-of-principle beam tests have been performed with lead ion beams at the flat-top in the PS with the objective of producing 50 ns bunch spacing by batch compression. In the absence of RF systems at the necessary frequencies, a merging compression scheme has been set-up. It demonstrates that, despite the unfavourable conditions for RF manipulations at the flat-top, batch-compression is feasible. Furthermore, the beam measurements of the merging compression allow to specify the requirements of additional RF systems to produce four-bunch batches with 50 ns spacing: two RF systems covering the frequency range 12 MHz to 20 MHz with a voltage of about 20 kV. Based on the beam tests the total duration of the batch compression RF manipulation is estimated to be 200 ms to 300 ms.

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