RF MANIPULATIONS FOR HIGHER BRIGHTNESS LHC-TYPE BEAMS

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Abstract

In order to increase the transverse brightness of beams for the LHC, ever more complicated RF manipulations have been proposed in the PS machine to reduce the intensity demands per PS batch on the upstream PS Booster. Several schemes based on cascades of batch compression, bunch merging, as well as the more routine bunch splitting have been successfully commissioned and higher brightness beams have been delivered to the downstream accelerators for measurement. Despite all this complexity, longitudinal and transverse beam quality are well preserved. In addition, to profit fully from the brightness of all four PS Booster rings, the injection of twice 4 bunches into harmonic 9 buckets in the PS has been made operational as an alternative to the usual double-batch transfer of $4 + 2$ bunches into harmonic 7. This paper summarizes the new beam production schemes, their implementation in the PS low-level RF system and the experimental results.

INTRODUCTION

The proton beam with 50 ns bunch spacing for luminosity production in the LHC throughout the 2012 run was based on triple splitting at low energy in the PS [1] and binary splitting at top energy. To generate 25 ns or 50 ns bunch spacing, each bunch from the PS Booster (PSB) is longitudinally split into $3 \cdot 2 \cdot 2 = 12$ or $3 \cdot 2 = 6$ parts in the PS. In parallel an extensive study programme has been pursued in the injector chain to explore the possibility of delivering higher brightness beams to the LHC. The transverse emittance sum, $\varepsilon_H + \varepsilon_V$, of the beam at extraction from the PSB grows linearly with intensity [2], hence beam brightness is essentially constant at PS injection. Reducing the splitting factor in the PS demands less intensity from the PSB for a given intensity per bunch to the LHC. The lower intensity from the PSB translates into smaller transverse emittance and higher brightness at PS extraction.

However, reducing the splitting factor in the PS also shortens the batch length at PS extraction. This effect can be partially compensated by injecting two more bunches ($4 + 4$ instead of the usual $4 + 2$) into the PS by raising (from $h = 7$ to $h = 9$) the receiving harmonic for the double-batch transfer from the PSB. In addition, the SPS may accumulate 5 instead of 4 of these shorter, higher brightness batches from the PS. The new RF manipulations are based on batch compression (BC), the stepwise increase of the harmonic number to shorten the distance between bunches [3]. The new PS injection harmonic and RF manipulations with lower splitting factors required the commissioning of various hardware improvements and modifications to cope with the significantly increased complexity. Following first beam tests with $h = 9$ single-batch injection in the PS during the 2011 run [2], double-batch injection into $h = 9$ has been fully commissioned in 2012. Additionally, the generation of local oscillator signals, and the beam phase and radial loops have been upgraded to cope with arbitrary harmonic number sequences during the RF manipulations. Full phase control of the RF signals driving the 10 accelerating cavities had already been implemented earlier [4].

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H9 DOUBLE BATCH INJECTION

The transfer of $4 + 2$ bunches from the PSB into $h = 7$ buckets in the PS for the production of nominal LHC-type beams (50 ns and 25 ns spacing) is illustrated in Fig. 1, left. Two rings remain empty during the second PSB cycle for

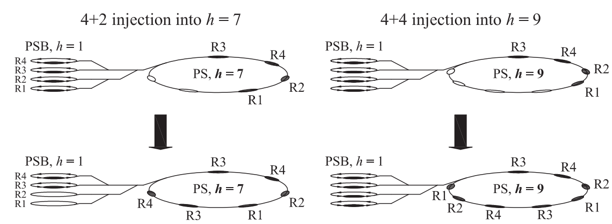

Figure 1: Double-batch transfer of $4 + 2$ ($h = 7$, left) or $4 + 4$ ($h = 9$, right) bunches from PSB to PS.

the transfer of the last two bunches. To profit fully from the beam brightness available from all four PSB rings during both injections, the injection of $4 + 4$ bunches into $h = 9$ buckets in the PS had been suggested [5]. New injection bucket selection and signal distribution hardware has been developed and commissioned to allow this. However, there is a penalty to pay due to the risetime of the recombination kickers in the transfer lines between PSB rings and their common entry point in the PS. The bunch length at transfer must be reduced from 180 ns ($h = 7$, corresponding to a matched 1.3 eVs) to a maximum of 150 ns ($h = 9$, corresponding to a matched 0.9 eVs).

Whereas the nominal production scheme based on triple splitting works with an arbitrary filling pattern in the $h = 7$ buckets, the correct bucket numbering at injection becomes important for the RF manipulations based on BC. As the difference between two consecutive harmonic numbers is only one unit (e.g., the first BC step from $h = 9$ to $h = 10$), the 8 bunches must be injected such that the additional empty bucket is subsequently introduced at the azimuth of the existing empty bucket(s). This constraint is illustrated in Fig. 2, which shows longitudinal phase space in the middle of the first harmonic number change.

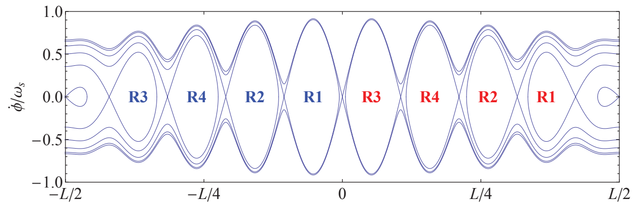

Figure 2: Normalized longitudinal phase space when the RF voltages at $h = 9$ and $h = 10$ are equal during the first BC step. The injection sequence from the PSB is also indicated (blue: first injection, red: second injection).

It is worth noting that in case shorter batches are needed at PS extraction, an even number of bunches must be injected symmetrically around the mirror plane in azimuth to avoid an asymmetry during the RF manipulation. For example if only 2 instead of 8 bunches (Fig. 2) should be injected, they must occupy the two central buckets normally taken by the bunches from ring 1 (first injection) and ring 3 (second injection).

TRIPLE SPLITTING

For the nominal production scheme, each of the 6 injected bunches is divided into three equal parts on the PS flat-bottom by triple splitting [1]. This single manipulation step directly yields 18 bunches at the pivotal harmonic $h = 21$ (Fig. 3). This is not only the highest harmonic on which acceleration can take place in the PS, it also corresponds to a bunch spacing of 100 ns from which binary splitting using dedicated, fixed-frequency cavities on the PS flat-top yields the 50 or 25 ns bunch spacing required by the LHC [6]. The evolution of longitudinal acceptance during triple splitting is plotted in Fig. 4. In practice the longitudinal emittance of the initial bunches should not exceed 1.3 eVs to avoid the leakage of large amplitude particles into the kicker gap.

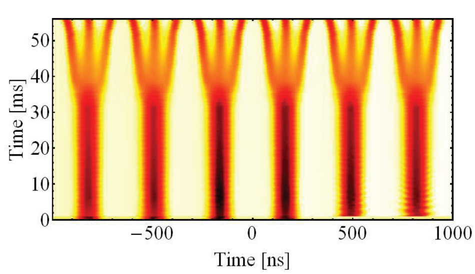

Figure 3: Second injection (2 bunches) and triple splitting of 6 bunches in the PS at 1.4 GeV (kinetic).

During triple splitting the harmonic number of the beam phase and radial loops must be switched once, from $h_{\mathrm{PL}} =$ 7 to 21.

BATCH COMPRESSION AND SPLITTING

The RF manipulations on the PS flat-bottom become more complicated for 8 injected bunches as $h = 21$ is no longer an integer multiple of the initial $h = 9$. In the simplest scheme [5], the 8 bunches are passed to $h = 10$ in a first BC step (Fig. 2 and Fig. 5, middle part). A binary splitting from $h = 10$ to $h = 20$ then produces 16 bunches and a final BC step to $h = 21$ brings the batch to the pivotal harmonic that must be established prior to the manipulations on the flat-top. The measured evolution of the bunch profiles is illustrated in Fig. 5.

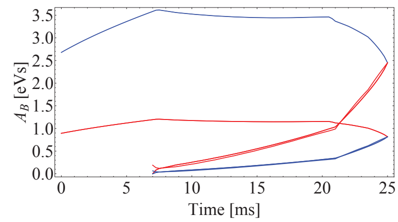

Figure 4: Bucket area during the triple splitting process of Fig. 3. Blue: total area of the outer bucket (upper trace); area of the inner three sub-buckets (lower traces). Red: one third of total bucket area (upper trace); total area within the three inner buckets (lower, rising traces).

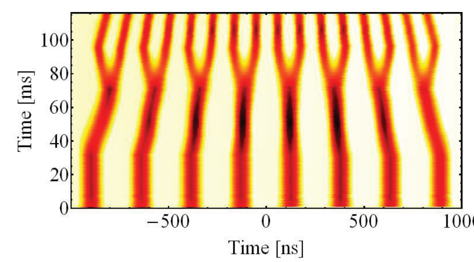

Figure 5: $4 + 4$ bunches injected into $h = 9$ and following the sequence $h = 9 \rightarrow 10 \rightarrow 20 \rightarrow 21$.

Compared to triple splitting these manipulations take twice as long and two harmonic number steps ($h_{\mathrm{PL}} = 9 \rightarrow 20 \rightarrow 21$) of the phase and radial loops. Omitting the intermediate $h_{\mathrm{PL}} = 10$ step is possible because the phase loop locks the beam to a simulated cavity return, which remains present even when the cavities produce no voltage on $h = 9$ anymore. Binary splitting instead of triple splitting reduces the overall splitting factor. Hence each bunch from the PSB is split into $2 \cdot 2 \cdot 2 = 8$ parts for 25 ns bunch spacing and into $2 \cdot 2 = 4$ parts for 50 ns. However, in the middle of the BC steps, the effective RF voltage around the circumference is amplitude modulated due to the beating of the two simultaneous RF voltages (one harmonic number unit apart). The modulation of the bucket area along the batch as illustrated in Fig. 2 causes a severe acceptance limitation of 0.9 eVs for the outer buckets during the $h = 20 \rightarrow 21$ step (cf., $\simeq 1.3$ eVs for triple splitting).

This batch compression and splitting scheme was used to produce a beam with 100 ns bunch spacing for the CNGS experiment OPERA [7], although with single-batch injection and different intensity requirements from the LHC, as well as one with 200 ns spacing (with re-bucketing $h =$

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10 → 20 replacing the splitting) for collisions with lead ions in the LHC. It was also the first high-brightness variant injected into the LHC to probe the behaviour of beams with very small transverse emittances up to collision.

BATCH COMPRESSION, BUNCH MERGING AND SPLITTING (BCMS)

In order to further reduce the splitting factor in the PS to increase beam brightness requires significantly more complex RF manipulations [2]. To avoid longitudinal acceptance limitations on the flat-bottom at 1.4 GeV (kinetic), the 8 bunches are first accelerated to an intermediate plateau at 2.5 GeV. This energy represents a reasonable compromise: bucket areas are twice as big for the same RF voltage at the price of half the synchrotron frequency. On this plateau the harmonic number is raised in 5 steps of one unit from $h = 9$ to $h = 14$ in a lengthy BC. Then a bunch pair merging ($h = 14 \to 7$) doubles the intensity per bunch while leaving the transverse emittance unaffected, doubling the brightness with this step. Finally, each bunch is triple-split and 12 bunches are accelerated on $h = 21$ to the flat-top. Fig. 6 shows a measurement of the entire process starting from the second injection. The evolution of longitudinal acceptance on the intermediate plateau is plotted in Fig. 7. Once again the RF manipulations are executed with phase and radial loops closed at all times, although their harmonic does not follow all harmonic number steps. In fact, $h_{\mathrm{PL}} = 9 \to 11 \to 13 \to 7 \to 21$. Despite the complexity, the uncontrolled longitudinal emittance blow-up of the process remains below 10 %.

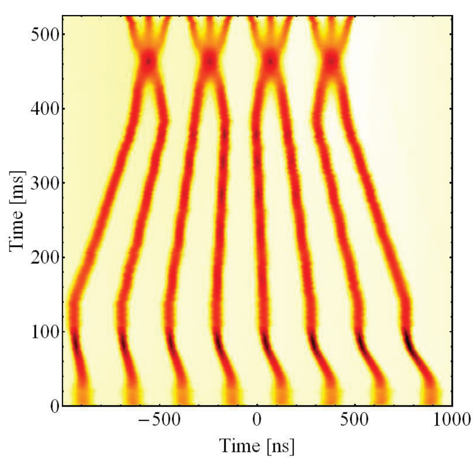

Figure 6: 4 + 4 bunches injected into $h = 9$, accelerated on $h = 9$ to an intermediate flat-top, followed by batch compression, bunch merging and splitting (BCMS).

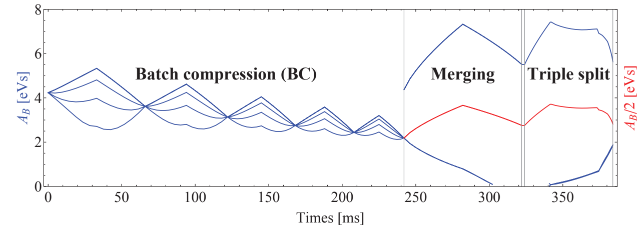

Figure 7: Bucket area along the BCMS RF manipulation. During BC, the bucket area is modulated from inner to outer buckets (multiple blue traces, cf. Fig. 2). During bunch merging, the upper blue trace shows the bucket area of the surrounding bucket, while the lower trace indicates the areas of the disappearing sub-buckets. Three sub-buckets emerge again during triple splitting (lower blue traces, cf. Fig. 4; upper trace: total area). The red trace is scaled to the area with respect to one initial bucket.

CONCLUSIONS

New production schemes for higher brightness LHC-type beams have been commissioned in the PS Complex and delivered to the LHC during the 2012 run. The brightness of the 25 ns BCMS beam was double that of its nominal counterpart at entry to the LHC [8]. Following various hardware improvements, the PS beam control system has been adapted to handle the significantly higher complexity required. The BCMS beam pushes the PS control system to its present limit, but the renovation of low-level RF controls during the current long shutdown (LS1) will allow even more complicated RF manipulations after the start-up in 2014. On the high-power side, the tuning group structure of the 10 accelerating cavities will be modified during LS1 to match present requirements, effectively increasing the available voltage for RF manipulations by 50 %.

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REFERENCES

[1] R. Garoby, S. Hancock, J.-L. Vallet, "Demonstration of Bunch Triple Splitting in the CERN PS," EPAC'00, Vienna, Austria, 2000, p. 304.

[2] H. Bartosik et al. "Performance Potential of the Injectors After LS1," LHC Performance Workshop 2012, Chamonix, France, 2012, p. 268.

[3] R. Garoby, "New RF Exercises Envisaged in the CERN-PS for the Antiprotons Production Beam of the ACOL Machines," PAC'85, Vancouver, Canada, 1985, p. 2332.

[4] H. Damerau et al. "Recent Improvements of the RF Beam Control for LHC-type beams in the CERN PS," IPAC'10, Kyoto, Japan, 2010, p. 2716.

[5] C. Carli et at., "Alternative/complementary Possibilities," LHC Performance Workshop 2011, Chamonix, France, 2012, p. 361.

[6] R. Garoby, "Multiple Splitting in the PS: Results and Plans," LHC Workshop, Chamonix, France, 2001, p. 32.

[7] E. Gschwendtner et al., "CNGS, CERN Neutrinos to Gran Sasso, Five Years of Running a 500kW Neutrino Beam Facility at CERN," these proceedings.

[8] S. Gilardoni et al., "The PS Upgrade Programme: Recent Advances," these proceedings.