RF MANIPULATIONS FOR SPECIAL LHC-TYPE BEAMS IN THE CERN PS

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Abstract

Beams with special longitudinal characteristics for the Large Hadron Collider (LHC) have been produced in the Proton Synchrotron (PS) and CERN. The flexibility of its RF systems consisting of in total 25 RF cavities at frequencies from 400 kHz to 200 MHz allows a variety of longitudinal beam manipulations. In particular the main RF system is split into three independent groups tunable from 2.8 MHz to 10 MHz. It is used to merge, split and change the spacing between bunches by applying different voltage and phase programs to the three groups of cavities at different harmonic numbers simultaneously. The batch compression, merging and splitting (BCMS) process has been operationally used for LHC fillings since 2016. To mitigate issues with long bunch trains in the LHC in 2017, short gaps of four bunch positions have been introduced between mini-batches of eight bunches (8b4e). A higher brightness version resulting in four mini-batches per PS extraction has been delivered for luminosity production in the LHC. This paper summarizes the operational experience and indicates possible future RF manipulation schemes.

INTRODUCTION

The PS accelerator is equipped with 5 different RF systems in the frequency range from 2.8 MHz to 200 MHz all of which are required for the production of LHC-type beams with 25 ns bunch spacing. The 10 (+1 spare) ferrite-loaded cavities cover a frequency range large enough to accelerate proton beams at any harmonic in the range of h = 7 to 21 (further harmonics, e.g., h = 6, are possible in a limited energy range). They are tunable in 3 groups and allow a large variety of RF manipulations resulting in a flexible bunch pattern for the LHC [1,2]. The cavities are driven by programmable beam-synchronous RF sources which compensate the time of flight between accelerating stations at any harmonic number [3].

Fixed-frequency RF systems at 20 MHz (h = 42) and 40 MHz (h = 84) are required for the bunch splittings at flattop energy to achieve 25 ns bunch spacing. To shorten the bunches prior to extraction to the SPS, 40 MHz (2 cavities) and 80 MHz (2 cavities + 1 spare) RF systems are operated for a non-adiabatic bunch rotation [4–6].

Emittance control is provided by a phase modulated RF system at 200 MHz. A wide-band Finemet cavity serves as longitudinal kicker for a coupled-bunch feedback system.

Thanks to the flexibility of the RF systems the parameters of LHC-type beams, mainly in terms of batch lengths and brightness can be switched between different variants. In 2016 an issue with an internal dump in the SPS limited the total intensity at the transfer to the LHC. The production scheme in the PS was moved from the standard beam with 72-bunch batches to BCMS, profiting from the almost doubled brightness from the injector chain. During the 2017 run, when vacuum related issues due to frozen air ("16L2") triggered a fast instability in the LHC [7], the beam for luminosity production was switched to the so-called 8b4e scheme in the PS. Mini-batches of 8 bunches spaced by 25 ns are followed by gaps of 4 empty bunch positions.

The production schemes of different LHC-type beams with regular 25 ns bunch spacing at PS extraction are summarized in Table 1. The transverse emittance of the beam at

Table 1: Longitudinal Manipulations for the Different Variants of LHC-type Beam with 25 ns Bunch Spacing. The standard beam with triple splitting [8] is compared to the BCMS variant [2] and batch compression (BC) from h = 9to h = 21, indicating the number of bunches (b).

LHC25ns	LHC25ns (BCMS)	LHC25ns (BC)
Inject 4 + 2	Inject 4 + 4	Inject 4 + 4
bunches	bunches	bunches
Acceleration to $E_{\rm kin} = 2.5 \rm GeV$		
h = 7	h = 9	
RF manipulations at intermediate flat-top:		
Batch compression		
	$h = 9 \dots 14$	
	Merging	Further
	$h = 14 \rightarrow 7$	batch
,	3-split	compression
h = 7, 14, 21		$h = 14 \dots 21$
Acceleration to flat-top		
18b, $h = 21$	12b, $h = 21$	8b, $h = 21$
Intensity accelerated for $1.3 \cdot 10^{11}$ ppb at extraction:		
$9.4 \cdot 10^{12} \text{ ppp}$	$6.3 \cdot 10^{12} \text{ ppp}$	$4.2 \cdot 10^{12} \text{ppp}$
RF manipulation at flat-top:		
Quadruple splitting (2×2-split), $h = 21 \rightarrow 42 \rightarrow 84$		
Bunch shortening on $h = 84 + 168$, final batch length:		
72b, <i>h</i> = 84	48b, $h = 84$	32b, $h = 84$
Overall splitting ratio from injection to extraction:		
<i>r</i> = 12	r = 6	r = 4

transfer from the PS Booster (PSB) to the PS is proportional to intensity [9]. At fixed intensity per bunch at PS extraction, the transverse emittance and hence the brightness is inversely proportional to the splitting ratio, *r*. The longitudinal emittance budget allows to tailor the emittance to a fixed $\varepsilon_1 = 0.35$ eVs per bunch at extraction by blow-up.

All RF manipulations other than the quadruple splitting at the flat-top are performed at an intermediate energy of

and DOI $E_{\rm kin} = 2.5 \,{\rm GeV}$. The energy has been chosen as a compro- $E_{kin} = 2.5 \text{ GeV}. \text{ Ine energy has been chosen as a compro-$ is mise between bucket area for a given RF voltage and theadiabaticity [10] defining the duration of the manipulation.**REGULAR 25 ns BUNCH SPACING** The beam variants with regular bunch spacing require $different RF manipulations (Table 1) at <math>E_{kin} = 2.5 \text{ GeV}.$ Triple Splitting (Nominal Beam)

For the nominal beam to the LHC, the triple-splitting of 6 author(s). bunches into 18 bunches at the intermediate flat-top results in a batch of 72 bunches at PS extraction [8], including the quadruple splitting at flat-top. Each bunch from the PSB contains 12 times the intensity per bunch at extraction.

Batch Compression, Merging, Splitting (BCMS)

naintain attribution to the The splitting ratio in the PS can be halved by introducing a bunch merging [2]. It doubles the bunch intensity and, as a longitudinal beam manipulation, preserves transverse emittance. Due to the injection of twice 4 bunches in buckets at h = 9, the scheme moreover profits from the brightness of all four PSB rings during both injections. The bunch $\stackrel{\star}{\equiv}$ merging, $h = 14 \rightarrow 7$ is preceded by a sequential increase of the harmonic number from h = 9 to h = 14. This batch $\stackrel{\text{s}}{=}$ compression [11] approaches all bunches from initially 8/9 $\stackrel{\text{t}}{=}$ of the circumference to a fraction of 8/14 = 4/7. Triple of the circumference to a fraction of 8/14 = 4/7. Triple splitting finally transforms the 4 bunches at h = 7 to 12 bunches at h = 21, the reference harmonic for acceleration (Fig. 1, left). The number of bunches per extraction from



Figure 1: Measured evolution of the bunch profiles at the ö intermediate flat-top for BCMS (left) and batch compression erms only beams (right).

the the PS reduces from 72 to 48. The BCMS scheme has been under used for the luminosity production during parts of the 2016 and 2017 runs.

be used Batch Compression (BC)

may Even further reduction of the splitting ratio, and consequently the transverse emittance at extraction, is achieved work by suppressing merging, as well as triple splitting and conis tinuing the batch compression up to h = 21 (Fig. 1, right). Following a proof-of-principle in 2014, the scheme has been rom commissioned in 2017. Again, increasing the brightness comes at the expense of a shorter batch of 32 bunches at PS Content extraction.

RF manipulation schemes have been proposed to create trains of mini-batches with gaps in the PS [1, 12]. These are interesting in view of reducing the built-up of electron-cloud instabilities [13]. Due to the quadruple splitting at the flattop (Table 1), common to all beam variants with 25 ns bunch

spacing, the bunch pattern can be controlled in multiples of

MINI-BATCHES WITH GAPS (8b4e)

four bunch positions. Splitting to 8b4e

Changing the triple splitting, $h = 7 \rightarrow 21$ (with additional h = 14 to redistribute equal intensity into the final buckets), into a direct splitting to h = 21 results in pairs of bunches with empty buckets between them (Fig. 2). The cor-



Figure 2: Measured bunch profiles during bunch direct splitting of 6 bunches from h = 7 to h = 21. Every third bucket remains empty after the process.

responding evolution of the longitudinal phase space during the manipulation is illustrated in Fig. 3. In the middle of the



Figure 3: Normalized longitudinal phase space for a pair of bunches during the splitting from $h_1 = 7$ to $h_2 = 21$. Time goes from top to bottom.

process, when the RF voltages at both harmonics are equal (Fig. 3, middle), two sub-buckets form at the center of the initial bucket, while a third, empty bucket is introduced. This RF manipulation, first demonstrated as a proof-of-principle in 2000 [1], has been operationally implemented during the 2017 run. The quadruple splitting at the flat-top converts the pairs of bunches into mini-batches of 8 bunches (b), followed by 4 empty (e) bunch positions, the 8b4e. Since the splitting ratio indicated in Table 1 is divided by a factor of 9th International Particle Accelerator Conference ISBN: 978-3-95450-184-7

1.5, a higher brightness at extraction is achieved. It is worth noting that the gap of about 120 ns between the mini-batches is already slightly longer than the rise time of the ejection kicker. Hence 4 + 3 bunches can be injected into h = 7. resulting in longer bunch trains with 7 mini-batches. The bunch pattern at PS extraction becomes $6 \times (8b + 4e) + 8b$.

Combining BCMS and 8b4e

In principle the direct splitting $h = 7 \rightarrow 21$ could replace the triple splitting in any production scheme of LHC-type beams. However, when combining the 8b4e bunch pattern with the BCMS scheme, there is no need to first merge pairs of bunches from h = 14 to h = 7 and then split them again to h = 21. Pairs of bunches can directly be moved from h = 14 buckets to adjacent h = 21 buckets. The normalized longitudinal phase space during the hand-over is sketched in Fig. 4. The RF voltage at h = 21 is increased until the



Figure 4: Normalized longitudinal phase space of two initial buckets during the handover from h = 14 to h = 21. Time goes from top to bottom.

voltages at both, h = 14 and h = 21, are equal (Fig. 4, middle). The voltage at h = 14 is then slowly removed. This RF manipulation can actually be understood as a single-step batch compression of two bunches, taking place seven times around the circumference. One empty bucket is inserted every second bucket (Fig. 4, bottom).

The evolution of the bunch profiles during the complete RF manipulation combining 8b4e with BCMS at intermediate energy in the PS is shown in Fig. 5, yielding 4 minibatches with 8 bunches. As no merging or splitting process is involved at intermediate energy, none of the manipulations requires tight control of the relative phases between RF harmonics. Additionally, thanks to the small splitting ratio, r = 4, the transverse emittance at PS extraction is only about 1 μ m for the nominal intensity per bunch, $N_{\rm b} = 1.3 \cdot 10^{11}$ ppb, the same as with the BC scheme. The bunch profile during



Figure 5: Combination of BCMS and 8b4e.

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Figure 6: Bunch profile and length at PS extraction for the combination of BCMS and 8b4e beam.

the last turn in the PS and the bunch length along the batch are plotted in Fig. 6. During the last 3 months of the 2017 run, this beam has been delivered for luminosity production in the LHC as a mitigation measure for the 16L2 issues [7].

CONCLUSIONS

Special LHC-type beams have been developed and commissioned. The flexibility of the RF systems in the PS on both, power and beam-control sides, allowed to set-up new RF manipulations in parallel to operation. To circumvent limitations in the downstream accelerators, the beams with specific bunch patterns and higher-brightness have been delivered to the LHC. Since July 2016 the BCMS variant with 48 bunches per extraction from the PS has been operationally deployed. As a contribution to the mitigation of 16L2 issues in the LHC during the second half of the 2017 run, the production scheme has been switched to the 8b4e beams allowing to recover a major fraction of integrated luminosity.

Possible RF manipulations for other bunch patterns like, e.g., mini-batches with 12 or 16 bunches are being studied.

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