PROPOSAL FOR THE CREATION AND STORAGE OF LONG BUNCHES IN THE LHC

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Abstract

Long bunches with a uniform longitudinal line density held by barrier buckets are considered for a future luminosity upgrade of the Large Hadron Collider (LHC). With such bunches, the luminosity is maximized for a fixed number of particles. Instead of conventional barrier buckets, periodic barriers are proposed. These are generated with multiple RF harmonics (e.g. multiples of 40 MHz). A possible scheme to create and hold long flat bunches in the LHC is described, and the resulting gain in luminosity is estimated.

INTRODUCTION

In the nominal scheme [1], both rings of the LHC will be operated with 2808 bunches each, kept in the buckets of an RF system working at 400 MHz (35640th harmonic, h of the revolution frequency). To increase the luminosity beyond 10^{34} cm^{-2}s^{-1} it has already been suggested to operate the machine with long bunches kept at low RF frequencies [2] or even so-called superbunches with a uniform longitudinal line density held by a sophisticated RF system based on induction cell cavities [3].

An easier approach is to reproduce barrier bucket like RF voltages by summing up the voltages of several RF systems working on multiple harmonics of each other [4]. Assuming 40 MHz as the fundamental harmonic for these long bunches, the final bunch length will be $4.5 - 5$ m (comprising 16 almost nominal LHC bunches with 1.5 eVs longitudinal emittance). Even in the case of only three RF harmonics more than 80 % of the particles are within a region of almost homogeneous line density. A possible scheme to confine the long bunches with a reasonable amount of additional RF installations is also proposed.

LUMINOSITY OPTIMIZATION

Neglecting other contributions, the dependence of the luminosity on the longitudinal particle distribution $\lambda(\phi)$ of the bunches can be described by

$$\mathcal{L} \propto N^2 \int \lambda^2(\phi)\, d\phi\,; \qquad (1)$$

it is assumed that all colliding bunches are equal and $\lambda(-\phi) = \lambda(\phi)$. Leaving the number of particles per ring, N constant, a square wave bunch would e.g. lead to an integral factor in Eq. (1) of one. This is the case for a perfect long bunch without any tails.

A square wave line density profile can be approached using RF systems working at multiple harmonics. As the nominal bunch distance in LHC is 25 ns (every tenth 400 MHz buckets can be populated), 40 MHz was chosen as fundamental frequency for the long bunch storage mode, meaning that the harmonics $n \cdot 3564$ are used to influence the longitudinal bunch distribution.

The squared integral over the line density as given in Eq. (1) and the resulting luminosity gain for an optimized ratio of RF amplitudes is shown in Tab. 1. Even with three

Table 1: Expected luminosity gain by using n RF systems at multiples of 40 MHz. Nominal LHC bunch, $n = 1$ for reference. The total RF voltage is also given.

of RF systems, n	1	2	3	4	5
$\int \lambda^2(\phi)\, d\phi$	0.51	0.70	0.81	0.84	0.88
Luminosity gain	1.00	1.44	1.58	1.66	1.72
Tot. voltage [MV]	16	2.6	1.5	1.1	1.2

RF systems working on $40/80/120$ MHz, the luminosity increases considerably compared to a nominal bunch. The longitudinal phase space and the line density for a matched elliptic distribution are illustrated in Fig. 1.

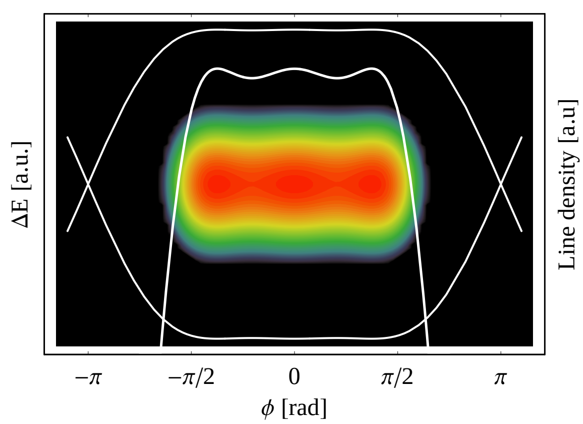

Figure 1: Longitudinal particle distribution and line density for a bunch kept in an optimized RF bucket generated by three harmonics. For $h = 3564$, 2π corresponds to 7.5 m.

GENERATION OF LONG BUNCHES

The generation of long bunches in the LHC can be achieved by an RF gymnastics scheme, which will start during ejection from the CERN SPS and whose main parts will be performed at flat-bottom and -top in the LHC:

1. Bunch lengthening by bunch rotation in the SPS and matched injection into the LHC.
2. Batch compression and bunch merging of $16 \rightarrow 2$ bunches at the flat-bottom in the LHC.

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3. Acceleration to 7 TeV with 3 MV at 40 MHz.
4. Final batch compression and formation of a long and flat bunch at flat-top.

An overview of the scheme including the longitudinal emittance budget is given in Fig. 2 and Tab. 2. It has been extensively modeled by numerical tracking calculations. The duration of the total procedure (excl. acc.) is about 1 min.

Injection

The 400 MHz superconducting cavities would generate intolerably large voltages due to transient beam loading so that they have to be removed. The SPS bunches ($h = 4620$) are injected directly into 40 MHz ($h = 3564$) buckets. If the longitudinal emittance is much smaller than the bucket area, the condition for a matched transfer from SPS (index 1) to LHC (index 2) is given by

$$\frac{V_1}{V_2} = \left(\frac{R_1}{R_2}\right)^2 \left|\frac{\eta_1}{\eta_2}\right| \frac{h_2}{h_1} \simeq 0.38\,\frac{h_2}{h_1}\,, \qquad (2)$$

where V is the RF voltage, η is the phase slip factor.

Even for a maximum RF voltage of 3 MV at 40 MHz Eq. (2) leads to an RF amplitude in the SPS which would be insufficient to keep the $0.6 - 0.8$ eVs bunches. Therefore, the bunches have to be stretched at the unstable fixed point [5] by switching the RF phase (8 MV/200 MHz) for some 20 turns. Changing the RF phase back again excites a rotation of the bunches in the longitudinal phase space. Finally, the bunches are transferred to the LHC when the bunch length is largest ($\simeq 2.6$ ns). The longitudinal emittance blow-up of 25 % is comparable to the blow-up caused by the nominal transfer scheme [6].

RF Gymnastics at Flat-Bottom

When the injection procedure is completed, LHC will be filled (excluding several kicker and the beam dump gaps) with short batches of 16 bunches separated by 2 empty bunch positions. The bunch spacing is 25 ns corresponding to $h = 3564$. By subsequent application of batch compression [8] and bunch pair merging [7], each batch is then confined to a batch consisting of only two dense bunches each of which contain 8 of the initial bunches.

Batch compression relies on the fact that bunches kept by an RF system operating on $h = h_1$ may be transferred to another RF system on a slightly larger harmonic number h_2. This can be done by simply decreasing the RF amplitude at h_1 and increasing it at h_2 simultaneously. As the RF wavelength shrinks with increasing frequency, the batch is compressed by a factor of h_2/h_1. Literally, $h_2 - h_1$ buckets have been inserted by such a procedure. This harmonic hand-over is repeated, starting from $h = 3564$, until $h = 7128$ is reached (in steps of $\Delta h = 3564/18 = 198$, 2.2 MHz). Batch compression only moves the bunches closer together, leaving the number of bunches constant. Therefore, the batch compression will be followed by bunch pair merging, so that the number of bunches is halved and their distance is again the initial bunch distance. Repetitive application of this combination of batch compression and bunch merging modifies the number of bunches (b) and empty bunch positions (e) from $16 \otimes b \oplus 2 \otimes e \rightarrow 8 \otimes b \oplus 10 \otimes e \rightarrow 4 \otimes b \oplus 14 \otimes e$ and finally $2 \otimes b \oplus 16 \otimes e$.

Acceleration

Due to the long acceleration time ($\simeq$ 20 min.) the average energy gain per turn needed in the LHC is only 0.485 MV. At a constant RF amplitude the bucket area is smallest about 1 min after the start of the acceleration cycle. For 3 MV RF voltage, the minimal bucket area is 26.2 eVs and offers a comfortable margin with respect to the expected longitudinal beam emittance (12.9 eVs, cf. Tab. 2).

Final Formation of Long Bunches

The final formation of the long bunch at flat-top energy consists of a further batch compression of the two bunches to $h = 7128$ and a subsequent procedure similar to a bunch merging. Starting from the single harmonic RF system at 80 MHz, all RF amplitudes are linearly changed to their final voltages, while the two dense bunches are merged into a single long and flat bunch (cf. Fig. 1).

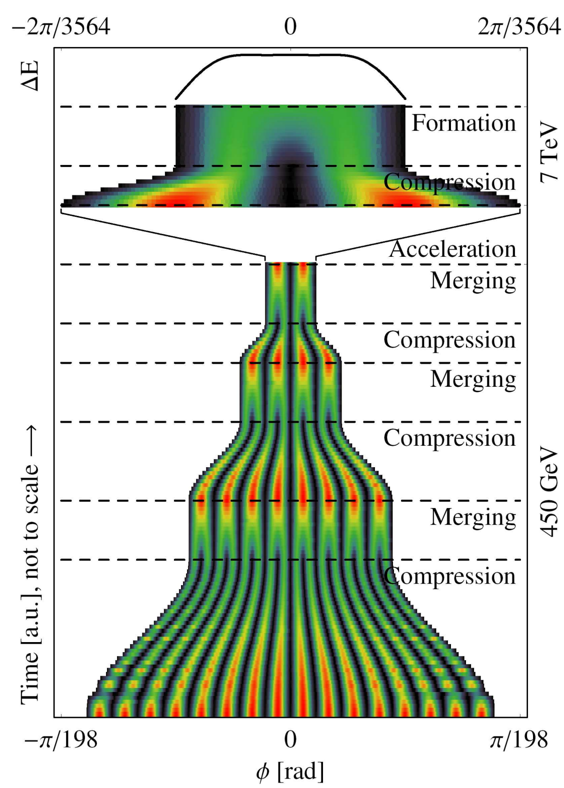

Figure 2: Mountain range plot of the separatrices (colour scale $\propto \Delta E(\phi)^2$) during formation of the long bunches.

Table 2: Emittance development during the proposed long bunch scenario for LHC ($16 \otimes b \oplus 2 \otimes e$).

	Energy, E	RF parameters	Emittance, ε_L	Blow-up
SPS ejection	450 GeV	8 MV at 200 MHz (SPS)	0.8 eVs	
Bunch rotation and LHC injection		3 MV at 40 MHz (LHC)	1.0 eVs	25 %
Blow-up by 400 MHz RF system		3 MV at 40 MHz	1.1 eVs	10 %
Batch compression to two bunches		2×1.5 MV at $40 \dots 80$ MHz	12.3 eVs	40 %
Acceleration to flat-top	7 TeV	3 MV at 40 MHz	12.9 eVs	5 %
Final formation of the long bunch		2×1.5 MV at $40 \dots 80$ MHz	28.5 eVs	10 %
Collision mode with long bunches		0.8/0.8/0.4 MV at 40/80/120 MHz	28.5 eVs	

LONGITUDINAL BEAM STABILITY

According to the analysis in [9], the beam is most prone to coupled bunch instabilities during the injection procedure (bunches are much smaller than buckets, meaning small synchrotron frequency spread, $\varepsilon_L/A_{\text{bucket}} \propto \Delta\omega_S/\omega_S$). The synchrotron frequency spread is at least one order of magnitude smaller than for a nominal bunch leading to loss of Landau damping due to the estimated broad band impedance [10] and coupled bunch mode excitation by any kind of narrow band impedance. A higher harmonic RF voltage around 400 MHz to increase $\Delta\omega_S/\omega_S$ and/or a longitudinal bunch-by-bunch feedback could be used to stabilize the bunches.

It is worth noting that, with respect to the present design of the beam crossing regions [11], the distance between bunches ($0.45\,\mu$s) is large enough that there are no parasitic beam-beam interactions between different bunches anymore.

HARDWARE REQUIREMENTS

As the initial bunch rotation in the SPS can be performed with the available 200 MHz RF cavities, the only major hardware upgrade for the proposed long bunch scenario is in the LHC. Two RF systems providing 1.5 MV each in the frequency range of $40 \dots 80$ MHz are required. The installation of fixed frequency RF systems at 120/160 MHz for an improved line density distribution could be considered and further harmonics may be added later if necessary. Assuming that some 300 kV can be obtained per cavity, the two frequency variable RF systems would consist of 5 cavities each. The cavity tuning is foreseen to be done with mechanical elements near the gap, similar to the pneumatic gap short circuits already operational in the PS at CERN [12, 13].

CONCLUSIONS

A possible luminosity upgrade scheme for the generation and storage of long and flat bunches in the LHC is proposed. Though sophisticated, it relies heavily on conventional RF gymnastics which are well proven to work up to highest beam intensities in smaller accelerators and the additional RF hardware is of reasonable size and performance.

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