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Alternative bunch filling schemes for the LHC

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Summary

The standard batches transfered from the PS to the SPS consist of 72 bunches each (in 3.6 s PS cycle). Alternative schemes with 48 bunches per batch (in 2.4 s PS cycle) have been investigated as backup solutions or in case of problems. The implications for the performance and the injector chain have been studied and are presented. Only filling schemes for proton operation are considered. Other filling schemes such as the bunch disposition for ion operation are not changed.

1 Motivation

The standard batches transfered from the PS to the SPS consist of 72 bunches each and the present LHC filling scheme was designed to accommodate the maximum number of bunches for highest luminosity [1, 2].
In 2004 it was possible to inject 4 stable batches of 72 bunches from the PS into the SPS. More recently it was observed that batches with 72 bunches can become unstable in the PS before extraction [3, 4]. The mechanism is not yet clear. Experimentally it was proofed that batches with 48 bunches can always be delivered to the SPS.
This triggered a question for alternative filling schemes for the nominal LHC beam using 48 bunches per batch from the PS [5]. We consider only options which do not require any additional resources, e.g. manpower or further machine experiments. Other options such as those for the ultimate LHC beam [6] are not the subject of this note.

2 Filling schemes

The LHC filling schemes [1] have been designed to accommodate the maximum number of bunches around the circumference of the LHC to obtain the highest luminosity. Boundary

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conditions imposed by the injector chain, beam dynamics and the LHC protection system have to be taken into account.

2.1 Boundary conditions

Some boundary condition must be fulfilled by any bunch filling scheme.

Total intensity in SPS

We assume that the SPS is able to accelerate up to $N_{tot} \leq 4 \cdot 10^{13}$ [1, 7] which limits the number of batches to maximum 7 batches with 48 bunches each, assuming the nominal intensity of $1.15 \cdot 10^{11}$ proton per bunch.

Length of bunch train

The maximum length of the flat top of the LHC injection kicker is assumed to be 7.86 μs, this limits the number of batches per train to 5. With minimum margin we could inject 6 batches, however under this condition some of the other boundary conditions cannot be fulfilled.

Injection and extraction gaps must be kept at least as large as in present case

In the present scheme, gaps are available to allow for the finite rise time of the injection, extraction and beam dump kickers. Any modification to the present scheme must not reduce these gaps.

Beam-beam effects require four-fold symmetry in LHC bunch train

The collision scheme depends on the bunch disposition in the LHC and in order to avoid undesirable beam-beam effects [8, 9, 10] a collision scheme which resembles an eight-fold symmetry should be maintained, which requires a quasi four-fold symmetry of the LHC bunch train.
Without a high degree of symmetry, the collision pattern can easily lead to a large number of missing head-on collisions.

Synchronization of beam dump

We follow the requirement that the last injection should be of the longest duration, i.e. 5 batches of 48 bunches. This last injection is followed by the gap for the beam dump.

For high luminosity the number of bunches should be as large as possible

The luminosity depends linearly on the total number of colliding bunches and therefore a maximum number of (colliding) bunches is wanted.

2.2 Present scheme

The present scheme with 72 bunches per batch allowed the transfer of up to four batches to the SPS and into the LHC. This was limited by the cycle length and the total intensity allowed in the SPS. The LHC filling scheme, written in the standard form, is.

$$\begin{aligned} & \{[(72b+8e)*2+30e]+[(72b+8e)*3+30e]+[(72b+8e)*4+31e]\} \\ & \{[(72b+8e)*3+30e]+[(72b+8e)*3+30e]+[(72b+8e)*4+31e]\}*3 \\ + & \{80e\} \quad = \quad 3564 \end{aligned}$$

where (b) indicates a position occupied by a bunch and (e) is an empty bunch position. This adds up to the total number of possible bunches, i.e 3564, corresponding to one tenth of the harmonic number.
This leads to a total number of 2808 bunches per beam. The gaps are necessary for the injector chain and the LHC beam dumping system and are:

- SPS injection: 8 missing bunches, 0.225 μs.
- LHC injection: 38/39 missing bunches, 0.975 μs.
- Abort gap: 119 missing bunches, 3 μs.

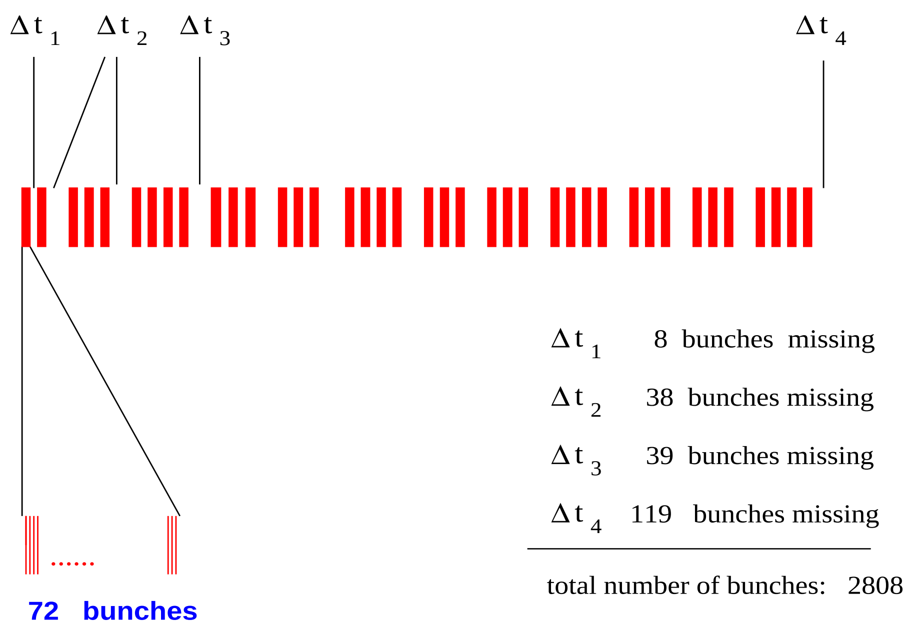

Figure 1: Current bunch filling scheme.

This actual bunch filling scheme is shown in Fig. 1 together with the various gaps in the train.

2.3 Alternative scheme

The alternative with 48 bunches per batch was developed to get the maximum number of bunches into the LHC, respecting the boundary conditions. The original idea [5] to transfer 6 batches of 48 could not fulfil the symmetry condition and would have required a different length of the flat bottom of the SPS supercycle. We therefore propose a scheme with maximum 5 batches per PS to SPS transfer.
Our proposal looks like:

$$\begin{aligned} & \{[(48b + 9e) * 2 + 31e] * 1 + [(48b + 9e) * 5 + 31e] * 2\} \\ + & \{[(48b + 9e) * 4 + 31e] * 1 + [(48b + 9e) * 5 + 31e] * 2\} * 3 \\ + & \{114e\} \quad = \quad 3564 \end{aligned}$$

The total number of bunches in the LHC is reduced to 2592, corresponding to 8% less and a corresponding loss of luminosity assuming the same bunch intensity. A small increase of about 4% of the bunch intensity would recover this loss, however this is already within the noise of intensity fluctuations which are expected to be around 10%.

The sizes of the gaps have slightly changed and are:

- SPS injection: 9 (previous 8) missing bunches, 0.25 μs.
- LHC injection: 40 (previous 38/39) missing bunches, 1.025 μs.
- Abort gap: 154 (previous 119) missing bunches, 3.875 μs.

The increased gaps for SPS and LHC injection follow from the symmetry requirement. The significantly increased abort gap is a result of dismissing two batches for the beam dump gap. Omitting a single batch of 48 bunches is not enough to generate the required length of the abort gap. Our proposed bunch filling scheme is shown in Fig. 2 together with the modifications to the gaps in the train.
Should it be necessary, the alternative scheme can be modified to allow a larger bunch spacing. A corresponding filling scheme for a bunch distance of 75 ns would be:

$$\begin{aligned} & \{[(16b + 2e) * 2 + 15e] * 1 + [(16b + 2e) * 5 + 15e] * 2\} \\ + & \{[(16b + 2e) * 4 + 15e] * 1 + [(16b + 2e) * 5 + 15e] * 2\} * 3 \\ + & \{36e\} \quad = \quad 3564/3 \quad = \quad 1188 \end{aligned}$$

For this scheme we have 864 bunches in the LHC, a loss of 8% of the bunches.

3 Implications

A changed bunch filling scheme has implications for the luminosity performance as well as the beam dynamics. Furthermore the different lengths of the batches imply changes to the injector chain.

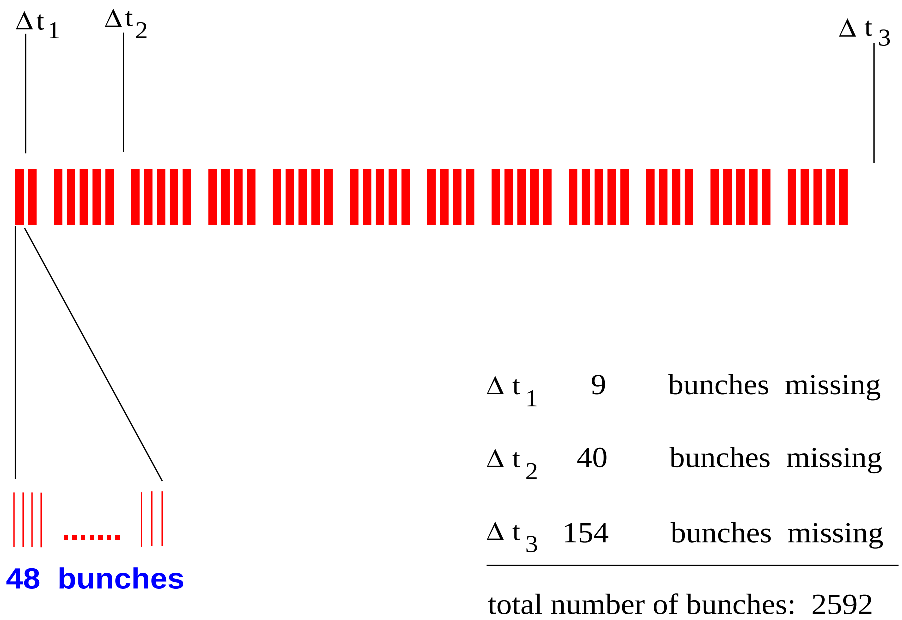

Figure 2: Proposal for an alternative LHC bunch filling scheme.

3.1 Performance

3.1.1 High luminosity interaction regions

In the high luminosity interaction regions in interaction points 1 and 5 all bunches collide head on. Since the total number of bunches is reduced from 2808 to 2592, the instantaneous luminosity is decreased by about 8%, assuming all other parameters unchanged. The more important integrated luminosity depends on operational efficiency and beam lifetime and presently cannot be quantified. A simplified operation could easily compensate for a reduced instantaneous luminosity.

3.1.2 Other interaction regions

The bunches number 1 collide in interaction points 1 and 5 due to the azimuthal symmetry of the two collision points. For the same reason the abort gaps in the two beams pass at the same time through interaction regions 1 and 5, not causing a loss of head-on collisions.
Since interaction points 2 and 8 are not symmetric with respect to the LHC bunch train, some bunches meet the abort gap and therefore miss head-on collisions.

For interaction point 2 (ALICE) two complete batches do not have head-on collisions, the number of collisions is therefore reduced from 2736 to 2496 compared to the scheme with 72 bunches. Since this is only the case for proton-proton interactions, this is not considered any problem.
Caused by the displaced collision point [8], the LHCb experiment will experience a further increased number of missing head-on collisions. The number of head-on collision is reduced from 2622 to 2340, corresponding to a loss of luminosity of 12%. However, the design luminosity in LHCb is much lower and any loss of head-on collisions can easily be compensated

by changing the optical functions, if necessary.

3.2 Beam-beam issues

The filling pattern has consequences for beam-beam effects since it has important implications for the collision schedule of the bunches [8, 10]. Already previous filling schemes were designed to maintain a high degree of symmetry [2]. In particular all PACMAN effects are strongly affected.

3.2.1 PACMAN effects

As PACMAN bunches we consider those which miss either long range or head-on collisions (or both).
Since the sizes of the gaps are not smaller than before and the batches are shorter, the number of PACMAN bunches increases slightly. The numerology is summarized in Tab. 1. The increased number of bunches with missing head-on collisions is caused by the larger

	present scheme	alternative
one head-on collision missed	252	336
two head-on collisions missed	3	6
min. number of long range	45	45
max. number of long range	120	120

Table 1: *Numerology of collisions for present and alternative bunch filling scheme.*

abort gap.

3.3 Injectors

The nominal 72 bunches in the PS are produced using a double-batch injection from the PS-Booster (PSB). More precisely, the PS receives 4 bunches from the PSB on RF harmonic number 7, keeps these bunches at low energy during 1.2 s and then receives another 2 bunches. These 6 bunches are then split into 18 at low energy (by means of one triple splitting), accelerated and then split into 72 at top energy (by means of two double splittings). The total magnetic cycle lasts 3.6 s. The new scheme would be to inject only the first batch, removing the long low-energy plateau, reducing therefore the cycle length to 2.4 s.
For the PSB there are no implications.

3.3.1 Implications for PS

This new type of beam has been produced for several years in the PS (the corresponding cycle is called TSTLHC), and was used in the SPS many times. The main advantages for the PS are the following:

- Less losses at low energy, as during the 1.2 s long flat bottom the large space-charge tune spread leads to space charge driven resonance trapping phenomena and subsequent beam losses located near the injection area (i.e. near the straight section 42), where activation problems have been encountered [4, 11].
- To damp the horizontal head-tail instability observed on the long injection plateau linear coupling is introduced. This is not required any more.
- Less multi-bunch effects: In the longitudinal plane, this required the use of a longitudinal coupled-bunch feedback with 72 bunches. In the transverse planes, as mentioned in Section 1, the beam has exhibited some signs of instabilities with 72 bunches during the 2006 PS run, which never appeared with the 48 bunches beam.
- Operationally, the new beam will be more robust since it does not require a constant tuning for the second batch injection. Indeed, due to the drift of the magnetic field, a radial steering has to be adjusted from time to time to compensate for the drift [4]. It also reduces a possible shot-to-shot and day-to-day variation caused by the non-reproducibility of the PS magnetic field [12].

It can be concluded that this beam provides more margin in the PS machine.

3.3.2 Implications for SPS

A test to inject 5 batches into the SPS was already successfully performed during a MD session in the 2006 run [5]. The new beam should be better concerning the electron cloud problems observed since many years in the SPS [13, 4]. The transverse coupled-bunch instabilities induced by the resistive wall are also less critical, leading to less stringent requirements on the transverse feedback systems [4].
Furthermore, the reduced maximum intensity of each SPS extraction (LHC injection) is advantageous for the machine protection, both for the SPS and LHC. A further advantage is the larger spacing between PS batches as the nominal rise time for the SPS injection kickers has not yet been achieved and demonstrated.

3.4 LHC filling time

For the nominal scheme [1, 2] one LHC beam is filled with 12 SPS cycles of 21.6 s each. The total filling time for both beams is therefore about 8 min 38!s. For the filling of the LHC with the ultimate beam about 30% more time is needed [6].
Due to the shorter flat bottom in the PS (and SPS) the total filling time for this alternative backup scheme is reduced to 8 min 10 s, i.e. by $\approx$ 5%.

4 Filling scheme for early commissioning and operation without crossing angle

For the LHC commissioning and for the special operation of the TOTEM experiment it is foreseen to run without crossing angles in the interaction points. This is feasible only when the bunch spacing is large enough that no parasitic interactions are possible within the range where the two beams share the same vacuum chamber. The separation of the two beams is achieved by the separation dipoles D1 and D2 in the experimental regions. Parasitic interactions can also be considered negligible when the beam separation provided by D1 and D2 is very large. This depends on the optical parameters as well as on the bunch spacing. For standard collision parameters a minimum bunch spacing of 600 ns can be considered safe, although slightly smaller spacings could be envisaged for special running conditions.

4.1 Filling scheme with 54 bunches

At present it is foreseen to operate with 43 equidistant bunches [1, 2]. Injecting a single bunch from the PSB into the PS and therefore replacing a batch by such a single bunch in the proposed scheme provides 54 bunches, although not equidistant around the LHC circumference.
The scheme can be written as:

$$\begin{aligned} & \{[(1b+56e)*2+31e]*1+[(1b+56e)*5+31e]*2\} \\ + & \{[(1b+56e)*4+31e]*1+[(1b+56e)*5+31e]*2\}*3 \\ + & \{114e\} \quad = \quad 3564 \end{aligned}$$

This gives 54 bunches, spaced by 1425 ns.

4.2 Filling scheme with 108 bunches

With a modified injection from the PSB into the PS, the batch can be replaced by 2 bunches as shown below.

$$\begin{aligned} & \{[(1b+27e+1b+28e)*2+31e]*1+[(1b+27e+1b+28e)*5+31e]*2\} \\ + & \{[(1b+27e+1b+28e)*4+31e]*1+[(1b+27e+1b+28e)*5+31e]*2\}*3 \\ + & \{114e\} \quad = \quad 3564 \end{aligned}$$

This gives 108 bunches, spaced by at least 700 ns.
For smaller bunch intensities and much smaller beam emittances as requested for TOTEM operation [14] the bunch spacing may be reduced further to approximately 450 to 500 ns, which we consider a hard limit. This would allow to replace one batch by 3 bunches in our proposal:

$$\begin{aligned} & \{[(3*(1b+18e))*2+31e]*1+[(3*(1b+18e))*5+31e]*2\} \\ + & \{[(3*(1b+18e))*4+31e]*1+[(3*(1b+18e))*5+31e]*2\}*3 \\ + & \{114e\} \quad = \quad 3564 \end{aligned}$$

and gives 162 bunches, spaced by 475 ns. Whether such a beam can be produced has not yet been investigated.
For an early commissioning with a larger β^* ($\beta^* \geq 4$ m) but nominal emittance this scheme provides sufficient beam separation without crossing angles.

4.3 Filling scheme for collisions in interaction point 8

The interaction point 8 (LHCb) is displaced by 11.25 m with respect to the symmetry point of the machine. Only for bunch spacings of 25 ns or 75 ns collisions occur in this interaction point. To allow collisions in interaction point 8 some of the bunches have to be displaced. Two options are feasible:

- Displace bunches in one beam only
- Displace bunches symmetrically in both beams

The resulting collision scheme for the two options is rather different: while for the first option the displaced bunches collide only in interaction point 8 and are offset in all other interaction points, the second option allows the displaced bunches to collide with their counterparts of the other beam in interaction points 1 and 5. This is however at the expense of an additional loss of collisions in interaction point 2. This is shown in Tab. 2 where the number of collisions

	no bunches displaced	bunches displaced in one beam	bunches displaced in both beams
collisions in IP1	54	49	54
collisions in IP2	52	47	42
collisions in IP5	54	49	54
collisions in IP8	0	5	5

Table 2: *Numerology of collisions for two displacement options, for filling scheme with 54 bunches.*

is shown for the different options and the filling scheme for 54 bunches per beam. Always 5 "batches" with a single bunch (i.e. one LHC injection) have been displaced, either in one or in both beams. The smaller number of collisions in interaction point 2 even without a displacement is due to the abort gap [9].

5 Summary

We have proposed an alternative bunch filling scheme for the LHC in case the present scheme with 72 bunches per batch exhibits problems in the PS as observed during the 2006 run, or elsewhere in the injector chain. All boundary conditions are fulfilled and the smaller number of bunches should not yield a substantially lower luminosity. Increased margin for the injection and extraction gap, and in particular for the beam abort gap, as well as beneficial effects for electron cloud instabilities and advantages for the operation of the injectors make it an interesting backup solution.

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