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LHC bunch filling schemes for commissioning and initial luminosity optimization

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Summary

In this note we explore the high degree of flexibility of the LHC bunch filling scheme to propose bunch configurations which allow to optimize the luminosity requirements in the four experiments for the commissioning and early running of the LHC.

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1 Motivation

The LHC is a proton-proton collider with an unprecedented number of bunches per beam. The large number is a consequence of the need for a large luminosity[1]. This very large number of bunches has strong implications for the machine, i.e. the beam dynamics, as well as for the operation of the experiments.

1.1 Implications for the machine

The bunch filling scheme in the LHC has strong implications not only on the LHC itself but also on the injector chain and various subsystems such as:

- Injector chain
- LHC collider issues:
  - Luminosity
  - Experimental conditions
  - Beam-beam effects
  - Other collective effects

- Diagnostics

The injector chain must be able to deliver the desired number of bunches with the required properties, i.e. mainly the emittances and intensities desired for high luminosity or dedicated high precision measurements. Furthermore, the acceleration, injection and extraction systems impose constraints on the arrangement of the bunches [2].

To maximise the luminosity and keep the number of interactions per crossing within acceptable limits, it is an advantage to operate with a large number of bunches, however other effects such as beam-beam effects and collective instabilities may impose limits on the total number of bunches, the bunch intensities or the total current in the machine.

A large number of bunches, in particular when they are not equidistant, may obscure the beam diagnostics systems.

All the above should be evaluated to ensure a successful operation of the machine.

1.2 Implications for the experiments

The LHC features 4 experiments in separate experimental areas around the rings plus additional special purpose detectors sharing these areas. Since the requirements from the experiments are rather different, an appropriate bunch filling scheme can help to optimize these requirements. The main issues are:

- 2 high luminosity experiments ➔ try to "maximize" number of useful collisions
- 2 special purpose experiments ➔ try to "optimize" number of collisions/s

While for two of the experiments the maximum possible luminosity is wanted, the two other main experiments have a narrow window for the optimum luminosity.

The proposed filling schemes are optimized for the following boundary conditions:

1. Deliver maximum luminosity to ATLAS (IP1) and CMS (IP5)
2. Deliver the largest possible number of collisions to LHCb (IP8) without exceeding $\sim 5 \times 10^{32}\ cm^2 s^{-1}$ and while keeping the average number of visible collisions per bunch crossing around 1. Note that IP8 is displaced by 11.25 m from the center of the cavern, towards IR7 .
3. Deliver to IP2 one of the two options:
   (a) average number of visible collisions per revolution around 1 ($\sim 10^{29}\ cm^{-2} s^{-1}$)
   (b) average number of visible collisions per revolution around 20 ($\sim 2 \times 10^{30}\ cm^{-2} s^{-1}$)
4. Conditions 2 and 3 should be implemented with minimal violation of condition 1.

1.3 Boundary conditions for filling scheme

With the RF frequency of 400.8 Mhz and a revolution frequency of 11.245 kHz we have 35640 buckets around the machine which could be filled with bunches. It is foreseen to operate with bunches spaced by 25 ns, i.e. 40 MHz, and therefore we have 3564 potential slots available.
The numbering of bunches is according to slot number (or equivalent: bucket number), for any spacing[1] . Slot number one is the first available slot of the first batch transferred from the SPS to the LHC (it may be empty, see 43 bunch scheme above). It is further assumed that slots number 1 in both beams collide in IP1 and IP5.
Considering a full 8-fold symmetry we count 445.5 slots between interactions points.
With our numbering rules we find that under these conditions we collide in IP1 and IP5 buckets with slot number parities **even-even** and **odd-odd** while in IP2 we have collisions of **odd-even** and **even-odd** slots.

For a bunch spacing of 25 ns as foreseen in the baseline both, the even and odd slot numbers are occupied, allowing collisions in all interaction points with the relevant collision parities. However it may become an issue for any bunch spacing $\neq$ 25 ns ! In particular in an equidistant filling pattern with 50 ns spacing it must be avoided to have only odd or only even slots occupied. The 75 ns automatically features alternating "even" and "odd" slot numbers.
A further complication comes from the fact that the collisions in IP8 do not occur at the symmetry point but shifted by 11.25 m, i.e. 1.5 slots. The symmetry point we call "DELPHI" since it has housed the DELPHI experiment during LEP operation.
In the 43 bunch filling scheme the distance between two neighbouring bunches is 81 slots, therefore no collisions can take place in IP8 for this scheme.
The filling scheme with 75 ns spacing allows collisions in all interaction points, including IP8 since the spacing corresponds to the shift of one bunch with respect to the symmetry point.
Considering protons only we can derive the following observations:

- Nominal 25 ns spacing - no trouble
- For 43 or 156 bunches, optimized for IP1, IP2 and IP5
- For 75 ns spacing - get good collision rate in all IPs (too much for IP2 ?)
- For 50 ns spacing - watch out for IP2 and IP8

1.3.1 Crossing and separation schemes

For a small number of bunches in the beam, i.e. 43 or 156, the bunches are separated fast enough into their separate vacuum chambers to avoid parasitic beam-beam encounters. Therefore a crossing angle is not needed.
For a larger number of bunches a crossing angle is always required [3].

[1] E.g. in the 43-bunch scheme we have the sequence (82, 163, 244, ...). It should be noted here that in this case we have alternating "even" and "odd" slot numbers occupied by the bunches.

1.3.2 Displacement of bunches

Operating with 43 or 156 bunches, it is required to displace some of the bunches to make them collide in IP8 and the collision accounting is:

- IP1,IP5: collide regular-regular, displaced-displaced
- IP2: collide regular-regular
- IP8: collide regular-displaced

To achieve this, two strategies are possible:

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

For the first option the number of collisions in the other interaction points IP1, IP2 and IP5 are reduced. Due to the symmetry between IP1 and IP5 this can be recovered by displacing bunches symmetrically in both beams. As a side effect the time between collisions is not a constant. Another side effect is a further reduction of the collisions in IP2. However a high luminosity is not required in IP2.
To define the necessary displacement, we make the following assumptions:

- It is possible to shift PS to SPS injection (one batch)
- It is possible to shift SPS to LHC injection (2, 3 or 4 batches)
- It is possible to replace SPS to LHC injection by single bunch

2 Filling schemes

In the following we discuss the various filling schemes and derive the number of collisions under the given conditions.

2.1 Standard filling schemes

2.1.1 Bunch spacing 25 ns

Usually the filling scheme is presented in a form like the nominal scheme below [4]:

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

Re-written in a different form it can be visualized as [5]:

72 0 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0

72 1 8 0 72 1 8 0 72 1 8 0 72 1 39 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 72 1 39 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 72 1 39 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 72 1 39 0

This form of representation is flexible and can be used as input format for multi-bunch simulations [8] and MAD-X auxiliary programs. Furthermore, it visualizes the injection schedule since each row represents one SPS to LHC transfer of either 3 or 4 batches.
The filling schemes for the two LHC beams may be different, however the total number of slots must be the same. A second input describing the collision points around the ring is required [5]. Programs exist to analyse the full collision schedule and provide the necessary information for injection, e.g. bucket numbers for first bunch in a train, etc. The same input is used for the computation of self-consistent bunch by bunch data such as tunes, orbits and luminosity, allowing fluctuations in the bunch intensities [6, 7].
In Tab.1 below we show the number of head-on collisions in the four interaction points with this nominal scheme and 25 ns spacing. The different numbers are caused by the various gaps in the bunch train which are symmetric between IP1 and IP5, but not for IP2 and IP8.

Interaction point	number of collisions
IP1	2808
IP2	2736
IP5	2808
IP8	2622

Table 1: Number of collisions for nominal filling scheme in the four collision points.

2.1.2 Bunch spacing 75 ns

The filling scheme for 75 ns spacing is shown below. Please note that in this example the number of slots is reduced to 1188 to simplify the description.

24 1 2 0 24 1 2 0 24 1 14 0 0 0 0 0
24 1 2 0 24 1 2 0 24 1 14 0 0 0 0 0
24 1 2 0 24 1 2 0 24 1 2 0 24 1 15 0

24 1 2 0 24 1 2 0 24 1 14 0 0 0 0 0
24 1 2 0 24 1 2 0 24 1 14 0 0 0 0 0
24 1 2 0 24 1 2 0 24 1 2 0 24 1 15 0
24 1 2 0 24 1 2 0 24 1 14 0 0 0 0 0
24 1 2 0 24 1 2 0 24 1 14 0 0 0 0 0
24 1 2 0 24 1 2 0 24 1 2 0 24 1 15 0
24 1 2 0 24 1 2 0 24 1 14 0 0 0 0 0
24 1 2 0 24 1 2 0 24 1 14 0 0 0 0 0
24 1 2 0 24 1 2 0 24 1 2 0 24 0 15 0

The table Tab.2 below shows the number of head-on collisions in the four interaction points with this scheme with 75 ns spacing.

Interaction point	number of collisions
IP1	936
IP2	912
IP5	936
IP8	874

Table 2: Number of collisions for 75 ns bunch spacing in the four collision points.

2.2 Commissioning filling schemes

The filling schemes for commissioning should allow collisions without crossing angles and long range interactions [3]. Therefore we consider the schemes with 43 and 156 bunches per beam for the commissioning. Here we show the numerology of the collisions and the proposed displacements to allow collisions in IP8.

2.2.1 Filling scheme with 43 bunches per beam

Depending on the number of displaced bunches, the luminosity in IP8 can be adjusted at the expense of luminosity in IP2. Below we show collisions in IPs with 43 equidistant bunches, different displacement strategies for IP8. Since collisions in IP8 require the meeting of a regular and a displaced bunch from the two beams respectively, this imposes a maximum number of 22 for the displacement. It corresponds to shifting 6 out of the 12 SPS to LHC transfers, not including the first one (in which case 21 bunches are shifted).

The number of collisions at the different interaction points and for the different strategies are shown in Tab.3.
The filling scheme corresponding to the column with 19 collisions in IP8 is shown as example below:

displaced	0	4 (asym)	4 (sym)	11 (sym)	19 (sym)
IP1	43	39	43	43	43
IP2	42	38	34	21	4
IP5	43	39	43	43	43
IP8	0	4	4	11	19

Table 3: Number of collisions for 43 bunches in the four collision points.

0 0 0 0 1 0 80 0 1 1 80 0 1 1 77 0
1 1 80 0 1 1 80 0 1 1 80 0 1 1 80 0
1 1 80 0 1 1 80 0 1 1 80 0 1 1 83 0
0 0 0 0 1 1 80 0 1 1 80 0 1 1 80 0
1 1 80 0 1 1 80 0 1 1 80 0 1 1 80 0
1 1 80 0 1 1 80 0 1 1 80 0 1 1 77 0
0 0 0 0 1 1 80 0 1 1 80 0 1 1 80 0
1 1 80 0 1 1 80 0 1 1 80 0 1 1 80 0
1 1 80 0 1 1 80 0 1 1 80 0 1 1 83 0
0 0 0 0 1 1 80 0 1 1 80 0 1 1 80 0
1 1 80 0 1 1 80 0 1 1 80 0 1 1 80 0
1 1 80 0 1 1 80 0 1 1 80 0 1 1 80 0

Changing the number of empty slots after the last injected batch (in this example a single bunch) displaces the next SPS to LHC injection. The example above shows the shift of altogether 19 bunches, leading to a large number of interactions in IP8 and a small rate in IP2. Shifting the theoretical maximum of 22 bunches allows 21 collisions in IP8 but none in IP2.

2.2.2 Filling scheme with 156 bunches per beam

	no bunches displaced	option 1	option 2
collisions in IP1	156	156	156
collisions in IP2	152	76	16
collisions in IP5	156	156	156
collisions in IP8	0	36	68

Table 4: Number of collisions for 156 bunches in the four collision points.

The number of collisions at the different interaction points and for the different strategies are shown in Tab.4.

The filling scheme corresponding to the column with 36 collisions in IP8 is shown as example below[2] :

1 0 20 0 1 0 20 0 1 0 20 0 1 0 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 37 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 37 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 40 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 37 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 37 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 34 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 37 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 37 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 37 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 37 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 37 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0

[2] Please note that in this example a SPS to LHC transfer does not correspond to a row

1 1 20 0 1 1 20 0 1 1 20 0 1 1 20 0
1 1 20 0 1 1 20 0 1 1 20 0 1 1 37 0
The careful reader will easily determine which injections need to be shifted to realise this option.

2.3 Special purpose filling schemes

2.3.1 Filling scheme with 43 bunches per beam for TOTEM operation

The operation of the TOTEM experiment (small angle scattering) requires to run with small emittances and without crossing angle. The foreseen scheme is the 43 bunch scheme also envisaged for early operation and was already discussed before.

2.3.2 Bunch spacing 50 ns

The 50 ns scheme was already mentioned before as an alternative to the 75 ns scheme. The 50 ns scheme has the advantage to provide a high luminosity with significantly reduced long range encounters as compared to the standard 25 ns scheme.
This scheme was discussed earlier since it is expected that the electron cloud effects are much less severe. It was discarded on the basis that it does not allow equally large number of collisions in all four interaction point, caused by the longitudinal shift of interaction point 8. Following a specification of the desired luminosities in the four experiments it has been re-discussed since a large number of collisions in all experiments is not the preferred scenario.
For equidistant bunches around the whole machine it would not provide collisions in IP2 and measures have to be taken to restore the interactions. To allow collisions in IP2 some bunches (or trains) must be displaced and this opens the possibility to adjust the relative collision rate between IP2 and IP8 in a rather wide range. This is in particular interesting since IP2 requires very low luminosity in proton-proton collisions while IP8 wants to keep the luminosity above 10 $^{32} cm^{-2} s^{-1}$.
Note that assuming symmetric displacement the collision rates in IP1 and IP5 are unaffected.
To construct the desired collision schedule we proceed as following:

- Start from nominal 25 ns spacing which maximises number of collisions in all interaction points.
- Remove every second bunch of a train, keep first bunch (no collisions in IP8).
- Shift selected trains (SPS/LHC transfers) by 1 slot to get desired sharing between IP2 and IP8.

We propose to study 5 scenarios with different strategies for displacing bunches. To simplify the operation we propose to shift only during the SPS to LHC transfer, i.e. always 2, 3 or 4 batches together.

a) No shift

b) Shift SPS/LHC transfers 4 - 6 (i.e. batches 10 - 19)

c) Shift SPS/LHC transfers 4 - 6, 10 - 12 (i.e. batches 10 - 19, 30 - 39)

d) Shift SPS/LHC transfers 1 - 3, 7 - 9 (i.e. batches 2 - 9, 20 - 29)

e) Shift SPS/LHC transfers 2 - 3, 7 - 9 (as d, but replace transfer 1 by one single bunch)

The number of collisions for the different scenarios are summarized in Tab. 5.

	a	b	c	d	e
IP1	1404	1404	1404	1404	1333
IP2	1368	684	0	72	2
IP5	1404	1404	1404	1404	1333
DELPHI	1368	684	0	72	2
IP8	0	655	1311	1242	1173

Table 5: Number of collisions with 50 ns spacing in the four collision points.

3 Expected impact on beam-beam performance

A consequence of a larger bunch spacing is the smaller number of long range interactions in the common part of the two beams. For a reduced number of long range interactions we expect a smaller beam-beam effect. As an illustration, we show in Fig. 1 the tune footprint for long range interactions only for 25 ns and 50 ns bunch spacing, with otherwise identical parameters.

Since the head-on contribution of the interaction does not depend on the bunch spacing, it is not considered here. Therefore Fig. 1 allows a direct comparison of the relevant parameters. The reduction of the footprint with the reduced number of interactions is significant and

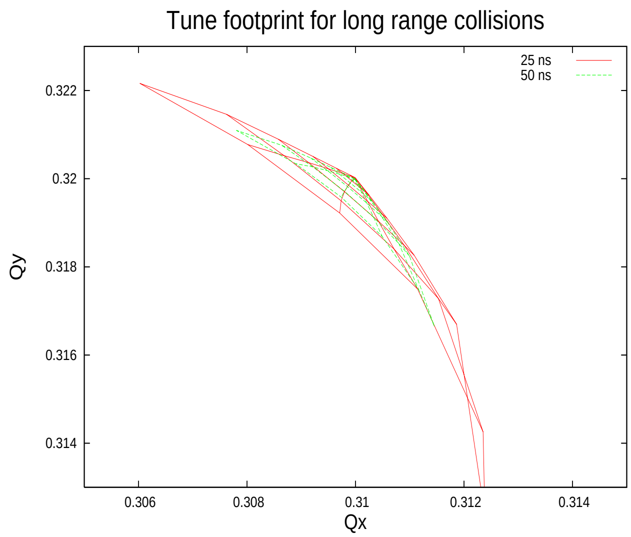

Figure 1: Tune footprint for long range beam-beam interactions. With $\beta^* = 0.55$ m, comparing 25 ns and 50 ns bunch spacing.

should reduce possible problems with long range interactions.

Adding the head-on interaction would show that for 50 ns spacing the tune spread is completely dominated by the head-on contribution.

4 Summary

The high degree of flexibility for the bunch filling schemes in the LHC allows to tailor the available luminosities in the four interactions points to the requirements of the experiments. It allows to adjust the luminosities in the ALICE and LHCb experiments without affecting the high luminosity experiments ATLAS and CMS.

The option with 50 ns bunch spacing allows such an adjustment with moderate loss of luminosity and at the same time with beneficial effects on the beam-beam interactions. In particular it is possible to reduce the number of collisions in ALICE by several orders of magnitude without changes to the optical parameters or partial beam separation.

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