LHC beam-beam effects- review and outlook

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Abstract

First experiences with colliding beams have been collected during the 2010 LHC run and some observations of beam-beam effects are reported. The observations are interpreted and critically compared with the expectations and strategies proposed at the previous workshop. Based on the available information, possible limitations are evaluated and strategies for the optimization are derived.

INTRODUCTION - WHAT IS A BEAM-BEAM LIMIT ?

To understand the possible problems related to the beam-beam interaction, it is worthwhile to consider the expected observations [1]. We have to distinguish between machines dominated by radiation and radiation damping such as LEP, and hadron machines mostly limited by non-linear effects and life time problems. In lepton colliders the transverse emittances are in general an equilibrium between excitation (e.g. through beam-beam effects) and the damping. Such an equilibrium emittance does not exist in a hadron machine.

- Possible problems in a lepton collider (e.g. LEP):
  - Increase of vertical equilibrium emittance with increasing intensity ($\mathcal{L} \propto N, \xi \approx const.$), the damping properties are all important, and the limit is very difficult to predict
  - The possible production of tails and bad life time is sometimes considered a "second beam-beam limit", however such problems can be (and are mostly) the result of other effects.
- Possible problems in a hadron collider (LHC):
  - May have slow emittance increase (over hours)
  - Will have beam losses (tails and dynamic aperture), bad life time, impossible to predict
  - Other possible effects are coherent beam-beam oscillations

The expected behaviour in LHC is very different from LEP and the lessons learned from LEP are of limited applicability.

REVIEW OF 2001 PROPOSALS

The main objective for proton running in 2010 was to get significant luminosity to the LHC experiments, details have been presented in [2]. The strategy proposed at the previous workshop [3] was closely followed.

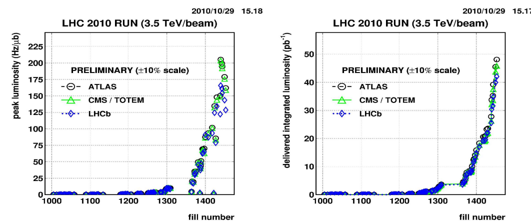

Figure 1: Peak and integrated luminosity in 2010.

The Fig.1 shows the evolution of the peak and integrated luminosity as a function of the fill number. The introduction of bunch trains and therefore the increased number of bunches is clearly visible.

COLLISIONS AT 450 GEV WITH NOMINAL BUNCH INTENSITY

Early in the run it was attempted to collide bunches with the nominal intensity around 10^{11} protons per bunch at the injection energy of 450 GeV. The purpose of this experiments was twofold: to explore the possibility to collide high intensity bunches and to test whether such bunches can be collided with a static offset, as foreseen for the ALICE experiment to control the luminosity. To simplify the test, only 2 bunches per beam have been injected to provide collisions in all four interaction points [4].

Head-on tune shift

The normalized emittances measured during the test were slightly smaller than nominal. When the collisions were adjusted, the life time was very reasonable and tune shifts close to nominal were achieved on this first attempt. These findings indicate little problems with the head-on beam-beam interaction and a small contribution from lattice non-linearities which was expected to be important at injection energy. As a result of this test, the bunch intensity was pushed close to nominal rather early for the following luminosity runs.

Offset collisions in IP2

The luminosity in IP2 has to be controlled to avoid a large pile up in the detector. One proposal was to collide the two beams with a static offset in the transverse plane. To test the feasibility of this procedure, the two beams were scanned against each other in the horizontal plane and the life time and possible emittance growth was recorded [4].

No significant effect was observed during this test in agreement with earlier tests at the SPS collider [5]. As a result of this study, the static offset became a standard operational procedure.
However, the number of long range interactions was small during the entire running period in 2009 and it remains to be demonstrated that additional long range encounters do not significantly change the dynamics.

OFFSET COLLISIONS

Discussing collisions with an offset, one has to distinguish different regimes with very different implications for the beam dynamics:

- Small offset ($\leq$ 0.5 σ), unavoidable due to PACMAN effects [1, 7].
- Medium offset ($\approx$ 1.0 σ), desired for luminosity levelling [2, 8].
- Large offset ($\approx$ 3.0 - 6.0 σ), desired for luminosity reduction.
- Very large offset ($\geq$ 10.0 σ), beam separation at parasitic encounters.

The different offsets can lead to quite different consequences such as e.g. emittance growth, reduction of dynamic aperture, excitation of coherent motion, orbit effects and other effects [1]. The study of the various effects requires different approaches and models and tools exist to evaluate and understand the implications [1, 15].

FILLING SCHEMES

One of the features of the LHC is its flexibility to use very different filling schemes, tailored to fulfill the requirements from the machine and the LHC experiments. This allows to slowly increase the number of bunches in the beam and provide the desired sharing of luminosity between the experiments. For the filling schemes used in 2010, we can distinguish two different periods:

- Initially: egalitarian filling schemes:
    - All IPs equal number of collisions.
    - At the beginning: maximum n collisions for $2n$ bunches per beam.
    - Improved with 3 bunch scheme (and other schemes derived from it).
- Later: maximize collisions in IP1 and IP5, non egalitarian
    - Achieved with bunch trains, mainly 150 ns spacing

When the number of bunches and therefore the luminosity was low, the filling schemes were designed to deliver equal number of collisions to all four experiments. Initally, the schemes were inefficient as they provided only n collisions per interaction point for $2n$ bunches per beam. A modified scheme based on 3 bunches per beam allowed a better yield and had some special features:

- The arrangement allowed two collisions per IP for 3 bunches per beam, i.e. the best ratio collision/bunches: $\frac{2}{3}$
- Special features (unwanted):
    - Parasitic encounters in IP1 and IP5 forced to introduce crossing angle earlier than foreseen
    - PACMAN effects: between 1 and 3 collisions per bunch !

Side effects of this scheme were parasitic encounters close to interaction points IP1 and IP5 which forced the introduction of crossing angles. The other side effect was a strong collision asymmetry: the bunches in the beam had between 1 and 3 head-on collisions, leading to a different integrated beam-beam effect. This is shown clearly in Fig.2 where

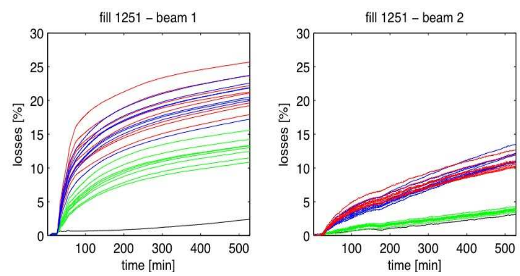

Figure 2: Beam losses for different bunches during fill with different collision schedules [6].

the losses during a fill are shown for the bunches separately and the colour code indicates the number of head-on collisions. It shows clearly that bunches with a larger number of collisions experience more losses that those with fewer interactions [6]. This is a strong indication of the expected PACMAN effects [7].
The scheme was easily extended by adding identical 3-bunch schemes, displaced longitudinally around the ring. Filling schemes with up to 50 bunches per beam have been developped using this strategy.
Since the LHC operated already with a crossing angle, the single bunches were replaced earlier than foreseen by bunch trains of 8 bunches per train, spaced by 150 ns within a train. The intermediate steps with 43 and 156 bunches per beam and without crossing angles have been skipped. Introducing these trains had no detrimental effect on the achievable head-on beam-beam tune shift. Adding more trains in small steps allowed to increase the number of bunches up to a maximum of 424. This procedure has an advantage for the beam dynamics. Once the maximum

number of bunches per train is established, the full complement of head-on and long range encounters is provided. Adding more trains of the same type does not affect the behaviour of the bunches already present before. Additional bunches behave like bunches already present in the machine. One therefore should expect that the performance is independent of the total number of bunches. This is demon-

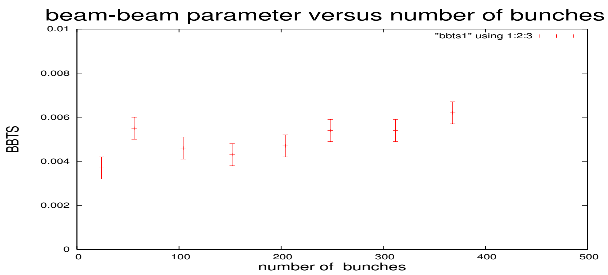

Figure 3: Beam-beam parameter as function of total number of bunches.

strated in Fig.3 where the head-on beam-beam tune shift is shown as a function of the total number of bunches in the machine. No dependence, and in particular no decrease can be observed. This is a unique feature of the bunch train and crossing angle geometry of the LHC. Colliders like SPS or Tevatron where the beam separation is provided by a "pretzel" scheme around the machine would no show this beneficial behaviour.

OPERATION WITH TRAINS AND 150 NS BUNCH SPACING

After the operation with trains and 150 ns spacing was established, the operation became routine with typical parameters like:

- Normalized emittances ≈ 2 to 3 μm.
- ξ per crossing ≈ 0.006 (i.e. up to 0.02 total for 3 collisions).
- Crossing angle (IP1/5) ± 100 μrad, β^* = 3.5 m, i.e. very small long range contribution [1].

Given the rather large β^* and the crossing angles of ± 100 μrad, the separation of the parasitic encounters in the drift space was approximately $d_{sep} \geq 13\ \sigma$, i.e. significantly larger than nominal (≈ 9.5 σ). Together with the smaller number of long range interactions due to the large spacing, the contribution from parasitic crossings to the overall beam-beam effect was very small in this configuration.

Angular scan

To probe the importance of long range interactions given the large separation and their small number, a test was performed at injection energy where the crossing angle between the beams was reduced from the nominal ± 170 μrad

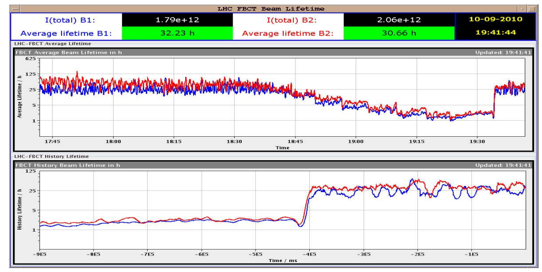

Figure 4: Beam intensity during angular scan. Upper curve shows beam intensities, lower curve zoomed to the last few minutes.

and the effect on the life time was recorded. The beam intensity during this scan is shown in Fig.4 and the steps of the crossing angle are clearly visible. During the entire scan the parallel separation at the central collision point was maintained at its nominal value, i.e. the separation was never smaller than ≈ 3.5 σ. The main observations can be summarized as:

- Little effect on life time between ± 170 μrad and ± 120 μrad
- First (very small) effect at ± 100 μrad
- First (significant) effect from ± 100 μrad to ± 90 μrad
- Final drop to less than 1 hr (parallel separation still on)
- Returning to ± 100 μrad restored the beam lifetime

The effect of long range interactions can clearly be observed when the separation becomes small enough, even with only a few encounters. A more detailed analysis

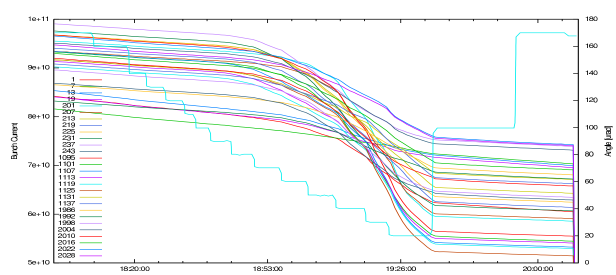

Figure 5: Losses per bunch during angular scan [13].

is shown in Figs.5 and 6 where the intensity is plotted for individual bunches as a function of the steps of the crossing angle also indicated in the figure. In particular in Fig.6 it is demonstrated that bunches with fewer long range interactions tend to have fewer losses and a better life time, indicating again the importance of PACMAN effects. Similar effects have been observed at the Tevatron [10] where the bunch position dependent emittance growth is related to the different long range interactions.

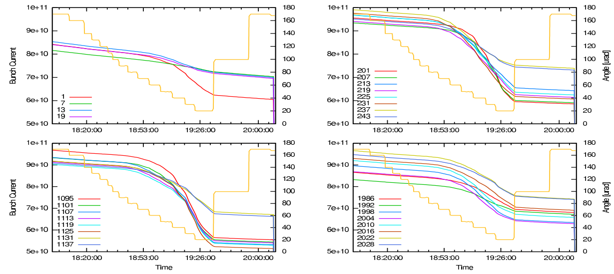

Figure 6: Losses per bunch during angular scan. Plotted per train [13].

EXPECTED BEAM-BEAM TUNE SHIFT

Some confusion is related to the maximum expected head-on beam-beam tune shift for the LHC. The nominal head-on tune shift was derived from SPS experience, taking into account possible contributions from the lattice nonlinearities and significant long range contributions. The nominal value of ξ = 0.0037 was defined to provide a coherent set of parameters to reach the target luminosity of $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. It should be considered as conservative and not as an expected upper limit, in particular in the absence of strong long range interactions. In the first collider runs, the SPS was operated with 3 p against 3 $\bar{p}$ bunches. In this configuration total tune shifts of 0.028 were obtained but the $\bar{p}$ life times at the beginning of a coast were poor. In the configuration with separated beams ("pretzel scheme"), i.e. in the presence of 3 head-on and 9 long range encounters, operating with a total tune shift of 0.02 was standard [9]. A typical tune shift per collision of 0.006 to 0.007 imposed no life time problems.
Similar numbers are reported from the Tevtron [10]. It should be expected that similar values can be reached at the LHC.

Optimization strategy

At the present stage of the commissioning, the LHC is not yet beam-beam limited and moreover it is unclear whether the limit will come from head-on or long range interactions. The strategy for optimization will crucially depend on which limit is encountered first.
The head-on tune shift depends only on the bunch intensity and the normalized emittance, i.e. is independent of β^* and the energy [1].

$$\Delta Q_{ho} \propto \frac{N}{\epsilon_n}$$

If the head-on interaction is the beam-beam limit, it is therefore advantageous to increase the bunch intensity together with the transverse emittance since this would keep the tune shift unaffected, but increases the luminosity proportional to the intensity. The luminosity is further increased by a reduction of β^*, without affecting the beam-beam parameter ξ.
The situation is very different for the contribution of long range interactions where the tune shift depends on the beam separation d_{sep}^2 and is proportional to [1]:

$$\Delta Q_{lr} \propto \frac{N}{d_{sep}^2} = \frac{N \cdot \epsilon_n}{\alpha^2 \cdot \beta^* \cdot \gamma}$$

i.e. depends on β^*. Any change of β^* or the energy γ requires to adjust the crossing angle α to keep the long range tune shift constant:

$$\alpha \propto \sqrt{\frac{N \cdot \epsilon_n}{\Delta Q_{max} \cdot \beta^* \cdot \gamma}}$$

This feature is again very different from a pretzel separation like SPS or Tevatron where a change of β^* does not affect the separation at long range encounters.

This has vital significance for the optimization strategy, i.e. whether a large number of bunches with a moderate β^* is preferred (in case of long range limits) or the focusing is pushed to smaller β^* when the machine is limited by head-on interactions.

Limits for optimization

It was proposed at this workshop [11] to squeeze to a minimum β^* of 1.5 m. This value is limited by the available aperture and the required crossing angle [11]. Given the dependence of long range contributions on β^*, the operation at this value has to be understood, in particular with the foreseen larger number of bunches with a small bunch spacing (75 ns or 50 ns). In case of problems, a slightly larger value of β^* may be desirable and can easily be implemented.
Much less flexibility is available to decrease or increase the size of the crossing angle since it must compromise two opposite requirements:

- Large enough for sufficient separation
- Small enough for aperture requirements

The ultimate limit must always come from beam dynamics and stability consideration and may eventually limit the minimum value of β^*.
Given the absence of any experience with a small β^* and many long range interactions, it is proposed to assume a conservative crossing angle at the start, providing a separation of at least 12 σ since such a separation proved workable for 150 ns bunch trains in 2010.
The increase of number of bunches per train as a consequence of a shorter bunch spacing has important consequences for long range beam-beam effects since it increases their number significantly. The numerology of the interaction count for different bunch spacings and configurations is summarized in Tab.1. A significant increase of all types of interactions is expected when the LHC is operated with the nominal filling scheme. As a demonstration of this strong effect, in Fig.7 the head-on and long range footprints (i.e. tune spread) are shown for different bunches

	25 ns 72b	150 ns 8b	50 ns 12b	50 ns 24b	75 ns 36b
bunches	2808	424	108	108	936
head on	4	3	3	4	4
long range	120	18	45	64	40

Table 1: Number of head-on and long range interactions for different spacings and configurations. First column are nominal parameters, second column operational scenario in 2010, following columns possible schemes for 2011.

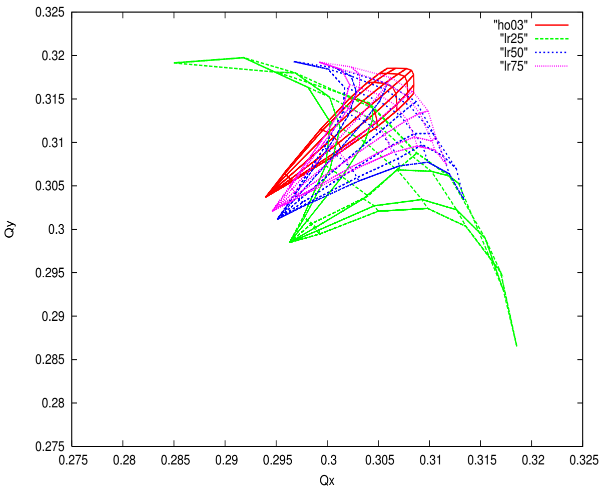

Figure 7: Tune footprint for different bunch spacings. Shown is a footprint for head-on collisions only as well as full footprints for head-on and long range interactions with different bunch spacings. All figures for 3.5 TeV and $\beta^* = 3.5$ m.

spacings with otherwise identical conditions. While for a large enough spacing the spread is dominated by the head-on contribution, for many bunches the long range spread is most significant, in particular for the nominal spacing of 25 ns between bunches. Although the tune spreads, i.e. the footprints in Fig.7, are not the main source of detrimental effects, they serve as a quantitative argument that a very significant change of behaviour may be expected for a change of spacing from 50 ns to 25 ns.

Test with 50 ns bunch spacing

A short test was done with trains of 12 bunches and a spacing of 50 ns. However 12 bunches per train do not provide the full number of long range encounters expected for this bunch spacing and the test was not fully relevant. A short test was made with beams offset by a few σ since a luminosity levelling is required by LHCb in 2011 to minimize the pile up [2, 8]. No life time effect was observed but the test should be repeated with the full long range contribution to draw reliable conclusions.

BEAM LOSSES

In the environment of superconducting magnets, beam losses are always a major concern. The understanding and minimization of these losses are therefore of vital importance.

Beam losses at beginning of a fill

The Fig.8 shows the losses at the beginning (first 6 minutes) of a typical high luminosity fill [6]. Losses of the

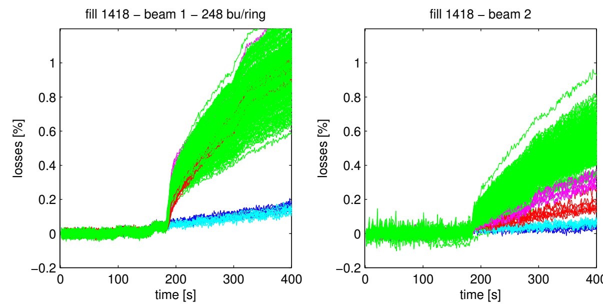

Figure 8: Beam losses at beginning of fill 1418 [6].

order of 1% can be expected and should not lead to beam aborts. A detailed understanding of the losses requires a bunch-by-bunch diagnostics [12] but the already well established dependence on the number of collisions is again visible. A very different picture is shown in Fig.9 where

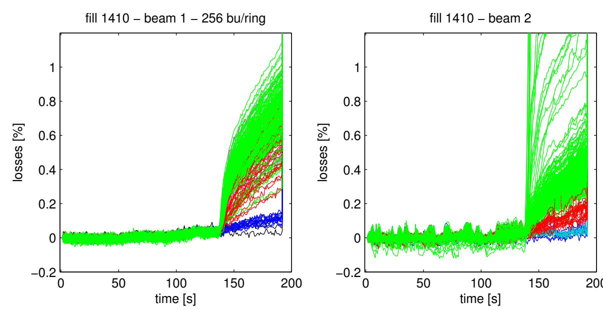

Figure 9: Beam losses at beginning of fill 1410 [6].

some bunches have lost several percent of the intensity after the beams were brought into collision. Such a behaviour is not typical and led to the loss of the fill. Possible sources are mismatched beams during some of the injections since only certain bunches of one train exhibited the bad lifetime. Additional diagnostics would allow to understand and possibly avoid such losses.

For comparison, the beginning of a fill at a well understood and "old" machine is shown in Fig.10 when beams were brought into collisions at RHIC [14]. Initial losses will be difficult to completely avoid since small mismatches or tails in the transverse plane will be swept away by the beam-beam effect. Such a behaviour is well known and observed in many other machines such as SPS or HERA.

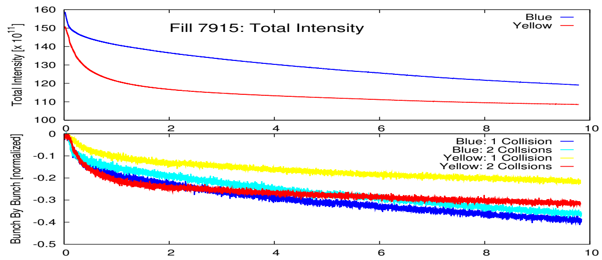

Figure 10: Beam losses at beginning of fill in RHIC [14].

Sudden beam losses during a fill

In the early days of luminosity production occasional sudden beam losses from one of the beams have been observed and have been a worry. In a window of a few minutes some bunches lost up to 10% of their intensities like shown in Fig.11, which displays a typical picture of these losses. In almost all cases the losses were closely related to

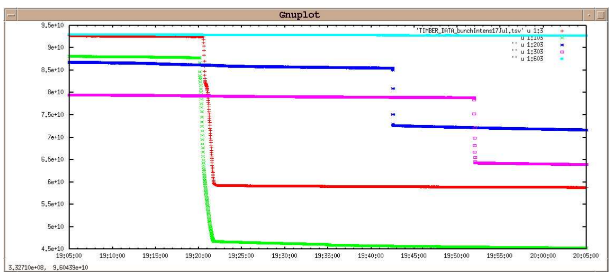

Figure 11: Sudden beam losses during fill.

the luminosity optimization procedure where the beams are moved against each other. The losses of Fig.11 are shown again in Fig.12 together with the steps of a luminosity optimization in IP2 [13]. The correlation is very strong and was observed at other occasions. Initially, when the LHC

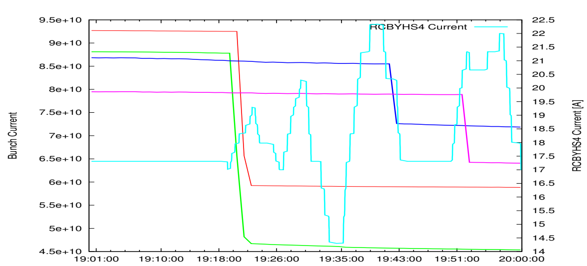

Figure 12: Sudden beam losses during fill and separation scan in IP2 [13].

was run with single bunches, the onset of coherent oscillations has been observed and as a cure a significant tune split between the two beams was introduced and kept.

In a test the tune split between the two beams was inverted and the losses moved to the other beam [6]. It is believed that the increased tune space required is responsible for the bad life time of one of the beams. After removing the tune split the problem did not re-occur.

OBSERVATION OF COHERENT BEAM-BEAM EFFECTS

Coherent oscillations have been reported which could be associated to coherent beam-beam modes. Such modes are expected when few bunches are in the machine or for bunches with very few (i.e. 1) collisions [1] because their excitation requires a high degree of symmetry. If present, they can be cured with a tune split between the two beams or a transverse damper [1]. The observation was however not clear since in many cases the coherent signal was present before the beams were colliding. A further investigation is foreseen to understand this signal. It is also expected that the presence of additional bunches, i.e. additional interactions, breaks the symmetry efficiently to avoid a collective motion [1, 15].

OUTLOOK AND PROPOSALS

Given the first significant experience with beam-beam effects in the LHC, one can attempt an outlook to running scenarios for the LHC in 2011.

Prospects for the head-on beam-beam tune shift

Small contributions of the lattice non-linearities as well as a careful setting of the machine allowed to quickly reach (and exceed) the nominal head-on beam-beam tune shift. The transverse emittances were significantly smaller than nominal and together with intensities slightly higher than nominal allowed head-on tune shifts around $\xi = 0.006$ per interaction point. It has to be seen whether this can be maintained in the presence of many more long range interactions. Yet there is no reason to assume that a head-on limit is reached and it is proposed to push the tune shift further by increasing the intensity with small emittances. The latter have the advantage to ease the provision of large enough separation at the long range encounters.

Possible strategy for maximum luminosity

Given that the limits are not yet reached, the full head-on limit should be explored with small emittances, i.e. values around 2.5 μm and below. Since a high luminosity can only be reached with the maximum number of bunches, the operation with more bunches and 50 ns or 75 ns spacing must be pursued. Using the argument as before, the maximum number of bunches per train should be explored at an early stage and the attainable β^* be found.
The levelling of the luminosity in IP8 [2] requires offsets in the order of 1 - 2 σ and needs to be studied, in particular in the presence of many long range interactions.

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