LUMINOSITY PERFORMANCE REACH AFTER LS1

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Abstract

Based on past experience (2010/2011), in particular expected limitations from beam-beam effects, and taking into account the expected beam quality from the LHC injectors, the peak and integrated luminosity at top energy is discussed for different scenarios (e.g. bunch spacing, beta*). In particular it will be shown which are the key parameters to reach the nominal luminosity and whether it is possible to exceed the nominal luminosity. Possible test in 2012 are discussed.

LESSONS FROM BEAM-BEAM STUDIES IN 2011 - IMPLICATIONS FOR PERFORMANCE

In all colliders, a significant limitation to the performance can come from beam-beam effects. This is also expected in the LHC. Based on the studies and observations in the first years of operation, we can estimate the possible implications for the operation at 7 TeV. Based on these observations and our experience we try to define a parameter set. The main observations can be summarized as [1]:

- High brightness beams not (yet) limited by head-on beam-beam effects
- Long range beam-beam effects strong as expected
  - Sufficient separation absolutely essential
  - PACMAN effects very strong
  - Number of collisions and number of bunches important (i.e. 25 ns vs 50 ns)
  - Small emittance highly desirable
- Luminosity levelling using transverse offsets is possible

Head-on beam-beam

In dedicated experiments [1] we have succeeded to obtain head-on beam-beam parameters several times the nominal value. Although not unexpected, such values can only be achieved in very clean conditions [1]. Whether such high brightness beams can be collided in the presence of many bunches and which are possible limitations, further studies are still needed and input during the studies in 2012 is expected on:

- Effect of noise
- Effect of bunch by bunch fluctuation
- Modulation effects

During normal operation, the beam-beam parameter is twice the nominal values, largely due to the smaller beam emittance available from the injectors. In the following we therefore assume that no limit comes from the head-on beam-beam effects.

Long-range beam-beam

From theoretical considerations and simulations, we expect that long-range beam-beam interactions reduce the dynamic aperture, i.e. leading to increased losses and lower lifetime. The expected dynamic aperture as a function of

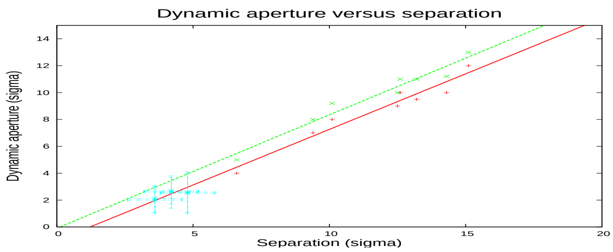

Figure 1: Dynamic aperture versus crossing angle [5].

the normalized beam-beam separation is shown in Fig.1. Also shown in Fig.1 are estimates from the long range beam-beam studies in 2011 [1]. The two lines correspond to the cases with 25 ns and 50 ns bunch spacing, i.e. correspond to a different number of long range interactions. The number of long range encounters is an important factor as demonstrated in [1]. From Fig.1 we can deduce that for a sufficient dynamic aperture under these conditions we require a separation of 10 σ for 50 ns and 12 σ for 25 ns spacing. The two simulations have been done for equal bunch intensities in the two cases and one must expect that an increase of the bunch intensity can change the picture. The estimates presented later are based on a normalized separation for 10 σ. Presently, no experimental data is available on the effect of intensity on the dynamic aperture due to long range beam-beam interactions and the estimates are based on scaling laws derived from an analytical model we have developed to assess the simulation results.

Long range scaling laws

For the scaling of the long range beam-beam tune shift ($\Delta\, Q_{lr}$) and the dynamic aperture (DA) we assume the dependence shown below.

$$\Delta\, Q_{lr} \;\propto\; N \;\; \text{(Intensity)}$$

$$\Delta\,Q_{lr} \;\propto\; n_b \;\;(\text{number of bunches})$$
$$\Delta\,Q_{lr} \;\propto\; \epsilon$$
$$\Delta\,Q_{lr} \;\propto\; \frac{1}{d_{sep}^2} \;\propto\; \frac{1}{\alpha^2}$$
$$\Delta\,Q_{lr} \;\propto\; \frac{1}{d_{sep}^2} \;\propto\; \frac{1}{\beta^*}$$

$$DA \;\to\; \frac{1}{n_b} \;\;(\text{number of interactions})$$
$$DA \;\to\; \frac{1}{\sqrt{\epsilon}}$$
$$DA \;\to\; d_{sep} \;\to\; \alpha$$
$$DA \;\to\; d_{sep} \;\to\; \sqrt{\beta^*}$$

$$DA \;\to\; \frac{1}{N} \;\;(\text{Intensity, still to be checked})$$

Conclusion: beam-beam effects

For the operation at 7 TeV we do not expect severe problems from head-on beam-beam effects. The long range beam-beam interactions behave as expected and provided a sufficient separation can be secured with a crossing angle, it can be kept under control. More input is expected from beam tests in 2012.

TOWARDS HIGHER LUMINOSITY

The operation of the LHC at higher energy after LS1 allows to aim for larger peak luminosities. The reduced emittances at larger γ allow for a smaller β^* and therefore contribute twice to a smaller beam size at the interaction points. The purpose is to provide the maximum useful integrated luminosities to the experiments. In this presentation we try to evaluate the possible performance reach within the given boundary conditions and the present experience with LHC operation. The questions how the machine is operated after the restart and the strategy to reach a high luminosity quickly are not addressed.

Assumptions for 2015 and beyond

- Energy 6.5 TeV (in 2015), 7 TeV later
- Aperture not worse than now
- Bunch spacing 25 ns or 50 ns

Performance issues in the LHC

The purpose of the LHC is to provide the maximum number of ”useful” luminosity to the experiments. The attainable peak luminosity is therefore only a secondary parameter and emphasis should be on the integrated luminosity.
However, the integrated luminosity is only useful when the detectors can make the maximum use and this requires to minimize the number of events per bunch crossing (event pile-up). This can easily be computed from the total inelastic cross section as:

$$PU = \frac{1}{f_{rev}}\frac{\mathcal{L}}{n_b} \cdot 72\,\text{mbarn}$$

Assume a maximum pile up limited to 42 events/crossing (twice nominal) this imposes limits for the maximum peak luminosity, depending on the number of bunches, and we arrived at the maximum luminosity as:

- N_b = 1380: $\mathcal{L}_{max}$ = 0.9 $10^{34}\text{cm}^{-2}\text{s}^{-1}$
- N_b = 2520: $\mathcal{L}_{max}$ = 1.75 $10^{34}\text{cm}^{-2}\text{s}^{-1}$

This shows the surprising result that the nominal luminosity cannot be achieved with a bunch spacing of 50 ns without exceeding significantly the limit for the event pile-up. The two options to avoid this are:

- Operation with 25 ns spacing
- Luminosity levelling for 50 ns spacing and loss of total integrated luminosity

At present the operation with 25 ns spacing is limited for reasons other than beam-beam effects and more input will come from 2012 operation.

How to get high luminosity ?

Given a fixed energy, we have several parameters which can be optimized to obtain the desired peak and integrated luminosity, given the boundary conditions discussed above. these are:

- Number of bunches (i.e. 25 ns versus 50 ns)
- Sufficient bunch intensity
- Small beam size (ϵ_n and β^*)
- Sufficient beam-beam separation (crossing angle α and ϵ_n)

For the beam-beam separation we assume 10 σ separation at the encounters in the drift space. This can be changed if required, although with possible implications for the reach in β^*.
In principle, the peak luminosity increases quickly with decreasing β^*, however the requirement for sufficient separation changes this picture.

In Fig.2 we show the relative luminosity as a function of β^* (solid line) and the reduced luminosity in the presence of a crossing angle providing a separation of 10 σ. It is clearly visible that below a β^* of approximately 0.50 m

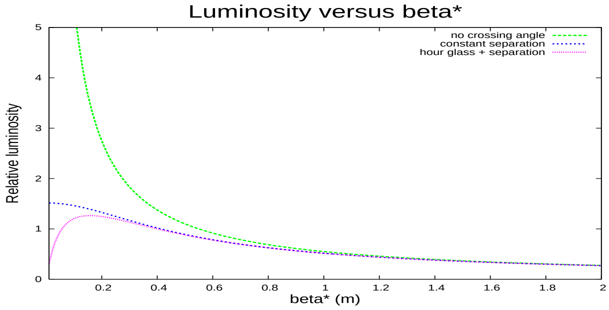

Figure 2: Luminosity versus β^*, including crossing angle (constant separation) and hour glass effect.

the increase of luminosity is very small. For even smaller β^* one has to expect that the hour glass effect reduces the luminosity further. From Fig.2 we conclude that operating with β^* smaller than approximately 0.50 m requires crab cavities to recover the geometric loss and since they are not foreseen before the high luminosity upgrade, we restrict ourselves to a minimum β^* of 0.50 m in the following calculations.
The emittance provided by the injector chain is of vital importance for the luminosity performance and below we show some of the scaling properties of separation (d), luminosity ($\mathcal{L}$), long range beam-beam tune shift (ΔQ_{LR}) and the required crossing angle (α):

$$d \propto \frac{1}{\sqrt{\epsilon_n}} \qquad \mathcal{L} \propto \frac{1}{\epsilon_n} \qquad \Delta Q_{LR} \propto \epsilon_n$$

$$\alpha = \frac{d \cdot \sqrt{\epsilon_n}}{\sqrt{\beta^*} \cdot \sqrt{\gamma}}$$

A smaller transverse emittance is an advantage in all cases and we suggest to keep the emittance as small as possible, provided it is allowed for other effects, i.e. collective instabilities or emittance growth.

Boundary conditions - injectors

It was experienced in 2011 operation that a small emittance is closely related to smaller bunch intensities, in particular for the case of 25 ns spacing.

Possible scenarios

Given the boundary conditions, the preferred scenario are compromises between conflicting requirements and options, such as:

- High intensity:
  - + Possible with spacing 50 ns (at present)
  - + High peak luminosity
  - – High event pile up
- Small emittance:
  - + Possible with spacing 50 ns and 25 ns (lower intensity)
  - – Smaller crossing angle required, smaller β^* possible
  - – Smaller peak luminosity
  - + Smaller event pile up

An optimum choice is difficult to foresee since some of the dependencies are still unknown and some mitigation procedures (e.g. e-cloud) not predictable on a reliable basis. Therefore we have several options and follow basically two strategies:

- Assume little improvement on beam quality (very conservative) compared to 2011
- Assume improved beam brightness from injectors [2, 3]

It was shown [2, 3] that manipulations of the beam preparation process in the injectors and the choice of related filling schemes, possibly with reduced number of bunches, can lead to an improved brightness for both, 50 ns as well as for 25 ns spacing. Under the assumption that smaller emittances are tolerable for collective effects and an emittance increase in the LHC can be understood and controlled, we can derive different parameter sets which we consider realistic.
Since the possible parameter space is very large, given the number of possible parameters and options, we restrict ourselves to a few options which can be scaled within limits and should give a good hint for the target performance. In Tabs.1 and 2 we show the parameters and luminosity for different sets of parameters, for 50 ns and 25 ns options. The parameters for bunch intensities and emittances

Δt/nb$^{*)}$	ϵ_n (μm)	Nb (10^{11})	$\mathcal{L}_{peak}$ (10^{34})	α (μrad)	PU
50/1404	2.0	1.4	1.35	±120	61
25/2808	3.0	1.2	1.30	±150	30
50/1404	2.0	1.7	1.90	±120	87
25/2520	1.3	0.7	1.00	±100	23
25/2592	1.4	1.15	2.30	±120	63

Table 1: Peak luminosity for different sets of parameters (PU = events per crossing).

Δt/nb$^{*)}$	ϵ_n (μm)	Nb (10^{11})	$\mathcal{L}_{peak}$ (10^{34})	α (μrad)	$\int \mathcal{L}$dt (fb^{-1})
50/1404	2.0	1.4	1.35	±120	40
25/2808	3.0	1.2	1.30	±150	38
50/1404	2.0	1.7	1.90	±120	56
25/2520	1.3	0.7	1.00	±100	29
25/2592	1.4	1.15	2.30	±120	70

Table 2: Peak luminosity for different sets of parameters.

are compatible with those presented in [2, 3]. In all cases considered the head-on beam-beam tune shift is in the same order as achieved in operation in 2011. The integrated luminosity in Tab.2 assumes a simplified form using a global factor (0.23) of efficiency. A more refined model requires a better understanding of the luminosity behaviour together with a well defined procedure for levelling.

The first surprising result is that the nominal luminosity of $1.0 \cdot 10^{34}$ cm^{-2} s^{-1} is in reach already with parameters achieved in the 2011 operation. On first sight an operation with 50 ns spacing provides higher peak luminosity, but at the expense of a large event pile-up. The required luminosity levelling would reduce the useful luminosity significantly.

Assuming that for both spacing options a levelling is required eventually, the option for 50 ns provides only half the luminosity. The potential for (useful) improvement is much larger for the 25 ns option and should therefore get high priority.

Further possible improvements

Under the conditions that smaller emittances can be produced and conserved, additional measures can be conceived to improve the performance.

The smaller emittance allows for a smaller β^* due to less strict aperture requirements. However, due to the required crossing angle (see Fig.2) the loss due to the geometric factor is 30 -40 %, depending on the exact configuration. A possible option to avoid this loss is the use of "pseudo-flat" beams. The feature unequal β-functions in the two planes, i.e. $\beta^*_x \neq \beta^*_y$. Such beams have been used in the $Sp\bar{p}S$ in the last years of operation with great success. It is easy to compute that e.g. beams with (β^*_x,β^*_y) = (0.5m, 0.3m) result in a larger luminosity that round beams with 0.4 m in both planes. The crossing angle would be in the plane of larger β^*, resulting in a smaller minimum angle for the desired separation and a smaller loss of luminosity. It was usually considered a (unproven) disadvantage that for pseudo-flat beams the head-on beam-beam tune shifts are not equal in the two planes, i.e. $\Delta Q_x \neq \Delta Q_y$. Accidentally, a crossing angle providing a 10 σ separation reduces the tuneshift in the crossing plane sufficiently to make them practically equal.

A further advantage of such a scheme is that a levelling with β^* is simplified since it may be done only in one plane and a change of the crossing angle is not required.

LUMINOSITY LEVELLING

It was speculated that a luminosity levelling is required to provide the maximum useful luminosity. It is certainly the case for 50 ns spacing but most likely also required at high performance with 25 ns beams. Different levelling options have been discussed. The requirement that any levelling must be local (single experiment) excludes global levelling options (such as change of bunch length) and a levelling with crossing angle provides only a small range unless crab cavities are used. The basic options left are transverse offsets as used during 2011 in IP2 and IP8 and levelling by changing β^*. The latter has not been tried and may be facilitated by the use of pseudo-flat beams.

SUMMARY

The analysis of possible operational scenarios after LS1, including the expected improvements from the injectors, have shown that:

- Nominal luminosity is clearly in reach
- Preservation of emittances should be high priority
- Peak luminosities two times larger than nominal (or higher) are possible

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