How does the number of experiments affect the maximum luminosity of the LHC?

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Abstract

The maximum luminosity of the LHC is the result of a careful optimization process and gives the highest possible value for two high luminosity experiments and an energy of 7.0 TeV. Any change of these parameters can strongly affect the maximum intensity and therefore the reachable luminosity. Additional experiments can change the balance between the different effects which limit the beam intensity. In particular, when the intensity is limited by beam-beam effects, any additional experiment can lead to a significant reduction of the luminosity in the other experiments. In this report it will be demonstrated how the different contributions depend on the number of experiments and how the parameters are optimized to achieve the highest possible luminosity. Further it will be shown that a third interaction region in the LHC, independent of its luminosity, will lead to a loss of about 35% of the luminosity for the two other experiments. This significant loss will also occur during the startup period when the LHC is operated with a luminosity around $1.0 \cdot 10^{33} \text{cm}^{-2}\text{s}^{-1}$.

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1 General considerations

One of the basic intensity limitations for a high luminosity hadron collider is the beam-beam interaction. For the already existing and planned hadron colliders this has led to schemes where the unwanted, i.e., parasitic beam-beam effects are minimized and the "useful" beam-beam effects, i.e., collisions used by the experiments are the main contribution. It can therefore be expected, that the number of experiments plays a crucial role for the determination of the maximum intensity where a collider can operate (beam-beam limit). The current beam-beam limit for the LHC has been determined for two experiments and an energy of 7.0 TeV.

1.1 Beam-beam limit and maximum tunespread criterion

This beam-beam limit cannot easily be derived from basic principles and a widely accepted, useful criterion is the overall tune shift and tune spread of the whole beam. It should be small enough that the tune space occupied by the whole beam can be placed into the working diagram such that low order resonances are avoided.

From experience with the SPS proton-antiproton collider and from the Tevatron we can define a total tunespread of $|\Delta Q_{x,y}^{\text{max}}| \leq 0.015$ as the acceptable limit.

For two experiments and an energy of 7 TeV this would lead in the LHC to a beam-beam limited luminosity of $2.3 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. However, the LHC is a larger and more complicated machine than the SPS or the Tevatron, and is likely to be less tolerant to beam-beam resonances. For this reason in defining its nominal parameters, we have assumed a more conservative value for $|\Delta Q_{x,y}^{\text{max}}| \leq 0.010$, leading to a luminosity of $1.0 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

1.2 Contributions to the tune spread

The overall beam-beam induced tune spread in the LHC is caused by different types of beam-beam interactions and this total spread has to include:

- Head-on beam-beam collisions from all experiments
- All long range beam-beam collisions near the interaction points
- Effects from PACMAN bunches

The first two points add for all bunches in the same way, while the bunches near a gap in the bunch train experience fewer long range collisions (PACMAN bunches) and will therefore have a different beam-beam interaction than the nominal bunches. Consequently, their shift is smaller and they occupy a slightly different place in the tune diagram. The overall tune spread $\Delta Q^{\text{tot}}$ for the beam is therefore larger than the tune spread for a single bunch.

The parameters of the LHC (intensity, crossing angle, $\beta^*$, bunch spacing, crossing schemes etc.) have been chosen to optimize the luminosity with the constraint $|\Delta Q_{x,y}^{\text{max}}| \leq 0.010$ for both planes.

*The tune spread is a consequence of the non-linear nature of the beam-beam force*
1.3 Simplest case

In the simplest case all experimental regions are identical and contribute equally to the total spread: \( \Delta Q^{\text{tot}} = n_{\text{exp}} \cdot \Delta Q^{\text{exp}} \). This tune spread is proportional to the beam intensity and when the maximum spread is kept constant, the maximum acceptable beam intensity is inversely proportional to the number of experiments: \( N_{\text{max}} \propto \frac{1}{n_{\text{exp}}} \).

Because the luminosity is proportional to \( N^2 \), the maximum luminosity is therefore inversely proportional to the number of experiments squared: \( L_{\text{max}} \propto \frac{1}{n_{\text{exp}}^2} \).

Such a simple estimate is only valid when all interaction regions are identical, in particular the different contributions mentioned above are identical. This is however rarely the case. Moreover, in the case of the LHC, the interaction regions are deliberately made different to reduce the overall spread by a partial compensation with alternating crossing angles \([2, 3, 5]\). This compensation effect can be destroyed by adding interaction regions.

It is therefore not simple to extrapolate the luminosity as a function of the number of experiments, in particular when the interaction regions have a significantly different set of parameters or a different geometry.

In the following I shall try to summarize the dependence of the beam-beam effects on these parameters and in particular how the relative importance of the different types of contributions changes with these parameters.

2 Head on and long range interactions

The two main contributions to the tune shift and tune spread are the head on collisions in the centre of the interaction regions and the so-called long range interactions near the collision point where the separated beams travel in a common vacuum chamber and experience parasitic interactions.

2.1 Head on collisions

The contribution from the head on collision is easy to estimate: the linear beam-beam tune shift \( \xi \) can easily be written as:

\[
\xi \propto \frac{N_b}{\epsilon^*}
\]  

(1)

where \( N_b \) is the bunch intensity and \( \epsilon^* \) the normalized emittance. The beam-beam effect is a non-linear phenomenon and the particles at different amplitudes experience different tune shifts, leading to a tune spread in the beam. The maximum tune shift for a head on collision is experienced by the central particles and is equal to \( \xi \). This parameter is independent of \( \beta^* \) and therefore the contribution from a high luminosity region (low \( \beta^* \)) and a low luminosity region (high \( \beta^* \)) are the same. The crossing angle \( \alpha \) slightly changes this parameter since the effective beam size depends on the crossing angle. The number of bunches and the bunch spacing have no effect on \( \xi \).
2.2 Long range interactions

Long range interactions occur in the common part of the vacuum chamber where the beams are separated by a small crossing angle $\alpha = 200 \mu\text{rad}$. For the total effect the separation of the two beams and the number of these encounters are both important and the geometry of the interaction region plays an important role. Furthermore, the crossing can occur in one or two planes and in the first case the symmetry between the planes is broken and the effect is significantly different in the two transverse planes.

2.2.1 Separation

When the beams are separated by means of a small crossing angle $\alpha$ the separation increases linearly with the distance in the driftspace between the interaction point and the first focussing elements: $x(s) = \alpha \cdot s$ and the normalised separation $d_{\text{sep}}$ can be expressed as [2, 4]:

$$d_{\text{sep}} = \frac{x(s)}{\sigma(s)} = \frac{\alpha \cdot s}{\sigma^*} \approx \frac{\alpha \cdot \beta^*}{\sqrt{\epsilon \gamma}} = \frac{\alpha \cdot \sqrt{\beta^*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon}} = \text{const.}$$  \hspace{1cm} (2)

where the transverse beam size is $\sigma^*$, the emittance is $\epsilon$ and the $\beta$-function at the interaction point is $\beta^*$. The distance from the interaction point is $s$.

It has been shown [2] that the tune spread increases approximately as

$$\Delta Q_{\text{long range}} \propto d_{\text{sep}}^{-2}$$  \hspace{1cm} (3)

and the long range contribution to the overall tune spread depends strongly on the parameters of the interaction region.

From equations (2) and (3) it can be seen that the long range contribution is approximately proportional to $\frac{1}{\beta^*}$ and it can be shown [4] that the proper choice of a larger $\beta^*$ can even increase the luminosity when the long range interactions are the dominating factor.

2.2.2 Number of parasitic interactions

The number of parasitic encounters in the common part of the beam pipe is proportional to the total number of bunches $n_b$ and the length $L$ of the common part. Given a constant separation, the long range induced tune spread is proportional to the number of long range interactions and the bunch intensity: $\Delta Q \propto (N, n_b)$ whereas the luminosity is proportional to the squared intensity and the number of bunches $L \propto (N^2, n_b)$. It may therefore be an advantage to operate with a smaller number of bunches and a large bunch intensity [3]. This would increase the head on contribution and reduce the contribution from parasitic encounters.

With the currently chosen spacing of 25 ns between the bunches, the head on contribution dominates.

\(^1\alpha\) is the full crossing angle.
2.2.3 Crossing scheme

For beams separated in one plane, the tune shifts have a different sign in the two planes for a separation larger than \( \approx 1.5 \sigma \); it is negative in the plane of separation and positive in the other plane. A scheme with alternating crossing angles, i.e. crossing in the horizontal plane in one interaction region and vertical crossing in the other, can be used to compensate a large fraction of the long range effects. Such an alternating scheme has been proposed and is essential to reach the highest possible luminosity [3, 4]. A possible alternative with a simultaneous crossing in both planes has been discussed [5] and has some very attractive properties. In particular, it does not require an even number of interaction points to get a compensation effect.

2.3 Optimum parameters

The present luminosity for the LHC is the result of a very careful optimization process of all parameters involved. This optimization concerns all parameters such as crossing angle, \( \beta^* \), bunch spacing and intensity, i.e. linear beam-beam tune shift \( \xi \). The result of this optimization strongly depends on the number of experiments and the beam energy [4]. The current parameters are optimized for two experiments and an energy of 7.0 TeV. For the optimum solution the contribution from head on and long range interactions are approximately comparable or the head on effect slightly larger. Any change of these parameters would therefore require another iteration process to optimize the luminosity. For some of the possible scenarios this optimization was done and is summarized in various reports [3, 4, 5].

3 Experiments with different luminosity

It is rather obvious now that any change to the number of experiments or layout of the interaction region can change the possible luminosity strongly. Adding an identical third experiment would reduce the luminosity by a factor \((2/3)^3\) in the best case where the experiments are identical or all long range contributions are negligible. In the case the long range contribution is large, this reduction factor can be much larger since the compensation effect from alternating crossings is not present for the third interaction region.

In the case of an additional experiment with a low luminosity some qualitative estimates can be made more easily. Two possible scenarios can be used to decrease the luminosity: separated beams at the interaction point for a luminosity reduction of several orders of magnitude and a high \( \beta^* \) for a moderate luminosity decrease. For separated beams the luminosity would be reduced by the factor:

\[
\frac{L}{L_0} = e^{-\sigma^2/\sigma^2} \quad (4)
\]

where \( d \) is the separation and \( \sigma \) the beam size at the interaction point. Separated beams would reduce the head on contribution to an insignificant value and hardly change the long range effects.

A significantly higher \( \beta^* \) would not change the head on effect (1) but according to equation (2) reduce the long range effects. In the case the long range effects play no role in any of the interaction regions, the reduction factor due to a third experiments would be the usual factor \((2/3)^2\), i.e. the luminosity in the other two experiments is reduced by more than a factor two,
independent of the $\beta^*$ and the luminosity of the third experimental region. For the LHC high luminosity interaction regions however, the long range interactions contribute significantly and this factor must be slightly modified.

For a $\beta^*$ of more than 10 or 20 m the long range effects for the third experiment can be neglected. The luminosity decrease would then be approximately $\approx (4/5)^2$ or $\approx 35\%$ assuming the head on and long range contributions are comparable for the two other interaction regions. The above result is confirmed by detailed calculation and by tracking.

4 Conclusion

It has been shown that the number of experiments or interaction regions have a very strong effect on the maximum reachable luminosity of the LHC. Further it has been demonstrated that, except for the trivial case of identical experiments, it is rather difficult to scale this luminosity with the number of interaction regions. Any reliable estimate has to take into account the relative contribution of the different effects, their dependence on the parameters, the layout of the interaction regions and a possible new optimization of the parameters.

For the case of a third, low luminosity experiment with a high $\beta^*$ it has been calculated that a luminosity decrease of approximately 35% has to be expected for the other two high luminosity experiments. Although the additional experiment is designed for a low luminosity with a high $\beta^*$ and the long range effects are smaller, the luminosity reduction is significant since the head on beam-beam effects do not depend on the luminosity nor $\beta^*$.

In the start up period it is foreseen to operate the LHC with a much smaller beam intensity than nominal[6], but to optimize the luminosity by reducing the transverse emittance so as to remain in the regime of the beam-beam limit. In this case the above conclusion is equally valid for the start up period, with a luminosity around $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ for the high luminosity experiments.

References

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