POTENTIAL OF REDUCED TRANSVERSE EMITTANCES FOR INCREASING THE LHC LUMINOSITY

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Abstract

The use of smaller than nominal beam transverse emittances ($\varepsilon_N <$ 3.75 mm.mrad) is a means for increasing LHC luminosity which is especially worth investigating while future injectors are being designed. Possible scenarios are drafted in this paper, together with their potential performance.

INTRODUCTION

The maximum tolerable head-on beam-beam tune shift of ~0.01 sets a fundamental limit to the operation of the LHC. In the case of round beams filling similarly both rings with alternating planes crossing at two interaction points, the total head-on beam-beam tune shift can be written as [1]:

$$\Delta Q_{bb} \cong -\frac{N_b}{\varepsilon_N}\frac{r_p}{2\pi\sqrt{1+\phi^2}}\,, \qquad (1)$$

where N_b is the number of protons per bunch, ε_N the normalized rms transverse emittance and ϕ the "Piwinski parameter" defined as:

$$\phi = \theta\sigma_z/(2\sigma^*)\,, \qquad (2)$$

σ* being the rms transverse beam size at the interaction point, σ_z the rms bunch length and θ the crossing angle.

The luminosity can be expressed as:

$$L \cong \frac{f_{rev}\gamma}{2r_p} n_b \frac{1}{\beta^*} N_b \Delta Q_{bb} F_p F_{hg}\,, \qquad (3)$$

where f_{rev} is the revolution frequency, n_b the number of bunches, β* the beta function at the interaction point, F_p a form factor resulting from the longitudinal bunch profile (1 for a Gaussian and $\sqrt{2}$ for a uniform profile) and F_{hg} the factor resulting from the "hourglass" effect (<1 when bunch length > β*).

To limit the long range beam interactions between beams to an acceptable level, a separation d_{sep}~9σ is needed, which corresponds to a crossing angle θ of 285 µrad in the nominal case [2]. Keeping the same criteria with different machine parameters, results in:

$$\theta \propto \sqrt{\frac{\varepsilon_N}{\beta^*}}\,, \qquad (4)$$

For given beam characteristics, this requirement reduces the gain in luminosity resulting from a smaller β*, because it leads to a higher crossing angle θ and hence to a larger Piwinski parameter and a reduced ΔQ_{bb}. Means of compensation involve severe complications to the lay-out of the interaction regions, using dipoles inside the detector magnet and/or Crab cavities [3].

Using smaller than nominal beam transverse emittances ($\varepsilon_N <$ 3.75 mm.mrad), smaller crossing angles are acceptable and the full benefit of the reduced β* can be obtained.

FIRST IR UPGRADE

Applying Eq. 1, 2 and 3, the nominal beam and machine parameters in the LHC at 7 TeV give the nominal luminosity of 10^{34} cm^{-2}s^{-1}. (Table 1 - 2nd column).

The new optics which is being prepared in the frame of the first IR upgrade [3] is aimed at reducing β* by more than a factor of two, from 0.55 down to 0.25 m. Its effect is illustrated in the 3rd column of Table 1. The crossing angle must increase like the inverse of $\sqrt{\beta^*}$ by a factor 1.48 to 423 µrad according to Eq.4. It results in a reduced ΔQ_{bb} of 0.68 and a luminosity increased up to 1.5×10^{34}cm^{-2}s^{-1}, much less than the inverse ratio of β*.

However, if the beam emittance is simultaneously reduced to 2.56 mm.mrad, a crossing angle of 349 µrad is sufficient to compensate for the β* of 0.25 m. It results in the same head-on beam-beam tune shift than in the nominal case, and in a luminosity of 2.2×10^{34} cm^{-2}s^{-1}, drawing the full benefit from the smaller β* (Table 1 - 4th column).

A very interesting feature of this option is that the corresponding beam brightness N_b/ε_N is the same than for the "ultimate" beam (N_b =1.7×10^{11} protons within ε_N =3.75 mm.mrad), which should be feasible in the injectors once Linac4 is in operation.

Table 1: LHC Luminosity with nominal beam intensity

	Initial IR triplet	**IR phase 1 triplet**	**IR phase 1 triplet + reduced ε_N**
N_b (x 10^{11})	1.15	1.15	1.15
ε (mm)	3.75	3.75	**2.56**
β*	0.55	0.25	0.25
σ* (mm)	16.58	11.18	9.24
Crossing angle θ (mrad)	0.285	0.423	0.349
σ_z (mm)	75.50	75.50	75.50
Piwinski parameter ϕ	0.65	1.43	**1.43**
ΔQ_{bb}* head-on	1.00	0.68	**1.00**
Luminosity (×10^{34}cm^{-2}s^{-1})	1.00	1.50	**2.20**
Luminosity lifetime (h)	22.00	14.62	**9.98**

* ΔQ_{bb} is normalized to the value of the nominal beam

CASE OF SLHC

Using the same formulas, Table 2 illustrates more ambitious possibilities with higher beam current.

Table 2: SLHC Luminosity

	Ultimate N_b with β^*=0.5 m	**Ultimate N_b with β^*=0.25 m**	**Ultimate N_b with β^*=0.25 m and reduced emittance**	**> Ultimate N_b with β^*=0.15 m and reduced emittance**
N_b ($\times 10^{11}$)	1.70	1.70	1.70	2.36
ε (mm)	3.75	3.75	**2.65**	**2.60**
β^*	0.50	0.25	0.25	0.15
σ^* (mm)	15.81	11.18	9.40	7.21
Crossing angle θ (mrad)	0.299	0.423	0.355	0.454
σ_z (mm)	75.50	75.50	75.50	75.50
Piwinski parameter ϕ	0.71	1.43	**1.43**	**2.38**
ΔQ_{bb}* head-on	1.43	1.01	**1.43**	**1.37**
Luminosity ($\times 10^{34}$ cm^{-2}s^{-1})	2.33	3.29	**4.65**	**10.29**
Luminosity lifetime (h)	13.94	9.89	**6.99**	**4.39**

* ΔQ_{bb} is normalized to the value of the nominal beam

The case of the ultimate beam with β^*=0.5 m is shown in the second column. The nominal head-on beam-beam tune shift is brought up to 1.43, and the luminosity reaches 2.3×10^{34} cm^{-2}s^{-1}. This is the same performance than achieved with a smaller beam current and ΔQ_{bb} in the 4th column of Table 1, using an emittance of 2.56 mm.mrad combined with β^*=0.25 m.

With the ultimate beam and β^*=0.25 m, a higher luminosity is attainable (3.3×10^{34} cm^{-2}s^{-1}) with a reduced ΔQ_{bb} (Table 2 – column 3).

For the same ultimate intensity but with a reduced emittance of 2.65 mm.mrad that re-establishes a similar ΔQ_{bb} than in the first case of Table 2, the luminosity can be brought up to 4.65×10^{34} cm^{-2}s^{-1} (Table 2 – column 4). The corresponding brightness is largely within the capability of the future injector complex made up of SPL, PS2 and SPS.

To reach a peak luminosity of 10^{35} cm^{-2}s^{-1} with the same number of bunches, the combined effect of a β^* reduced to 0.15 m and an intensity increased to 2.36×10^{11} protons/bunch within an emittance of 2.6 mm.mrad is used in the 5th column of Table 2. This brightness is the design value of the future injectors, and the circulating intensity is slightly smaller than in the Large Piwinski Angle option envisaged in reference [3].

CONCLUSION

A smaller emittance is capable to increase the luminosity of the LHC by an order of magnitude while keeping a time interval of 25 ns between bunches and without neither inserting magnets inside the detectors nor using Crab cavities. It also reduces the required aperture.

A more detailed analysis of the pros and cons of such an approach is clearly worth the effort, especially at a time where the specifications of the new injectors can still evolve.

REFERENCES

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