SYNCHRO-BETATRON EFFECTS IN THE PRESENCE OF LARGE PIWINSKI ANGLE AND CRAB CAVITIES AT THE HL-LHC *

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Abstract

The reduction of β^* at the collision points for the high luminosity LHC (HL-LHC) requires an increment in the crossing angle to maintain the normalized beam separation to suppress the effects of long-range beam-beam interactions. However, an increase in the crossing angle may give rise to synchro-betatron resonances which may negatively affect the beam emittance and lifetime. 6D weak-strong and strong-strong simulations were performed to study the effect of synchro-betatron resonances in the context of the HL-LHC layout and its suppression via crab crossing.

INTRODUCTION

The LHC interaction region (IR) employs a common focusing channel for both beams. Due to the 25ns bunch spacing, the two beams encounter each other in about 30 places on the left and the right of the collision point. Therefore, a crossing angle is required to physically separate the beams by approximately $10\,\sigma$ to avoid head-on encounters in unwanted locations. The HL-LHC aims to squeeze the collision point β^* by a factor of about 3 below the design value of 0.55 m as shown in Table 1. This requires an increase in the crossing angle to maintain the normalized beam to beam separation near the IR. Consequently the effective luminosity gain is reduced due to the larger crossing angle θ (see Tab. 1). In addition, large crossing angles in the presence of beam-beam interactions can induce coupling between the transverse and longitudinal planes and excite synchro-betatron (SB) resonances when:

$$k\,Q_x + l\,Q_y + m\,Q_s = n, \tag{1}$$

where k, l, m, n are integers, $k, l, m \neq 0$ and Q_x, Q_y, Q_s are the tunes in the horizontal, vertical and longitudinal planes. These effects have been studied in various contexts reported in Refs. [1, 2].

To fully exploit the beam size reduction a compensation of the crossing angle and leveling of luminosity with crab cavities is required [5, 6]. The achievable peak luminosity with crab compensation is $2.0\,10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and the target leveled luminosity is $5.0\,10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Crab cavities will then gradually restore the head-on collision and reduce the synchro-betatron effects which may lead to improved lifetime and losses. In this paper we study the effect of the Piwinski angle on the synchro-betatron resonances and their suppression with crab cavities. Both nominal and HL-LHC beam and lattice parameters with beams colliding in IP1 and IP5 only are used to characterize and compare the dependence.

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Table 1: Relevant LHC nominal and upgrade design parameters [3, 4]. The peak luminosity is quoted without crab compensation and the crossing angle is calculated for a normalized separation of about $10\,\sigma$.

	Nominal	Upgrade
Energy [TeV]	7	7
Protons/Bunch [10^{11}]	1.15	2.0
ϵ_n [μm]	3.75	2.5
σ_z [cm]	7.55	7.55
IP$_{1,5}$ β^* [cm]	55	15
Tunes (Q_x, Q_y, Q_s)	0.31 0.32 0.002	
Crossing Angle [μrad]	285	475
Geometric Reduction	0.83	0.37
Number of LR / IP	30	18-24
Peak luminosity [$10^{34}\,cm^{-2}s^{-1}$]	1.0	7.4

CROSSING ANGLE

Detailed tracking simulations have been performed to determine the optimum value of the crossing angle to achieve the maximum luminosity while keeping the dynamic aperture above a certain level. A minimum normalized separation at the location of the long-range encounters of about $10\,\sigma$ from these studies [7].

Even though the HL-LHC will be operated with smaller emittances, the bunch intensity and number of parasitic encounters per IP will be increased. The combined effects of these new parameters result in a significant increase of the beam-beam tune spread and the crossing angle should be re-evaluated as illustrated in Fig. 1.

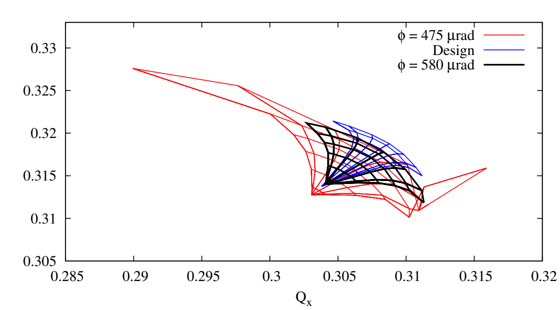

Figure 1: Tune footprints for nominal and HL-LHC beam parameters derived with MADX [8].

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Using the design HL-LHC beam parameters, the tune footprint overlaps a large number of betatron resonances and shows distortions which could indicate a poor dynamic aperture (DA) and lifetime. An increase of the crossing angle to 580 μrad was necessary to bring the tune spread down to similar level to what was obtained for the nominal LHC beam parameters.

Frequency Map Analysis (FMA) gives complementary information on possible lifetime and DA issues by looking at tune changes of single particles over time [9]. This method was implemented in the weak-strong version of BeamBeam3D [10] and used to confirm the estimates derived from the tune footprints. In this case, all the long-range interactions were lumped at a single location assuming a phase advance of $\pm\pi/2$ from the IP.

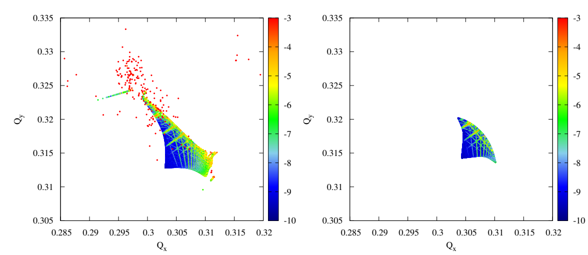

Figure 2: FMA of HL-LHC with crossing angles of 475 μrad (left) and 580 μrad (right) the colors illustrate the amplitude of the tune changes going from blue to red in increasing amplitude. Red indicates a tune change of 10^{-3} between two samples of 2048 turns.

Figure 2 shows a comparison of FMA with crossing angles of 475 μrad and 580 μrad. A clear improvement is observed when increasing the crossing angle to 580 μrad which confirms the results obtained with the tune footprints. This value of the crossing angle corresponds to a normalized separation at the location of the parasitic encounter of about 12.2 σ and a reduction of the peak luminosity to $6.2\,10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ from $7.4\,10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ with 10 σ separation. The Piwinski angle which reflects the strength of the synchro-betatron coupling is increased from 2.5 to 3.0 which is to be compared to 0.7 with LHC parameters. Adding the crab cavities compensation did not excite additional resonances in these simulations.

Running at $\beta^* = 15$ cm and a crossing angle of 580μrad will require very large aperture in the triplets. Large orbit offsets in the triplets where the β-functions are very large could also result in poor dynamic aperture and lifetime due multipole field errors. It is therefore interesting to consider a scenario with relaxed β^*. For example, a crossing angle of 410μrad was derived from the same analysis at $\beta^* = 0.3$ m. The normalized separation remains at 12.2σ and the peak luminosity is reduced to $5.4\,10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Operating with relaxed β^* would then result in a loss of flexibility for luminosity leveling but also in a significant gain in aperture. The required voltage in the crab cavities being proportional to the crossing angle this would also allow for a design with reduced voltage.

Long term tracking and DA studies are required to determine the exact value of the optimum crossing angle. However, these preliminary estimates indicate that the normalized separation should be increased with respect the nominal LHC and will be used as input for the the following sections of this paper.

SYNCHRO-BETATRON COUPLING

Past studies have shown that not only the luminosity and beam-beam parameter would be recovered with crab compensation but also that the synchro-betatron coupling would be reduced [11]. The synchro-betatron coupling is dominated by the head-on interactions. Long-range encounters have a minor contribution to these effects and will not be considered in the following simulations.

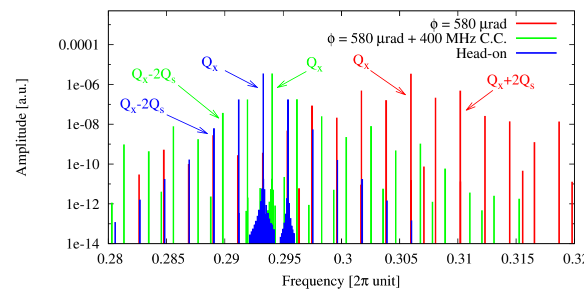

Figure 3: Horizontal spectrum comparison for head-on, crossing angle and crab compensation for a particle with initial amplitude 1 σ_x and 1 σ_s.

Figure 3 illustrates a comparison between particles with initial amplitude (1 σ_x, 1 σ_s) colliding head-on and particles with crab compensation. The beam-beam parameters is not fully recovered due to the finite RF curvature which reduces the overlap between the beams with respect to a fully head-on collision. For collisions with a crossing angle the synchrotron sidebands are excited by the beam-beam force. This effect appears to be stronger for the second sidebands. Once the crab compensation is applied, this excitation is reduced to a level similar to the head-on case.

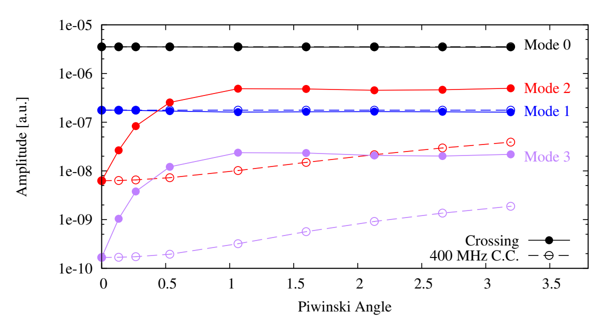

Figure 4: Amplitude of the sidebands as a function of the Piwinski angle.

Figure 4 shows the amplitude of the first three sidebands as a function of the Piwinski angle. The dashed lines represent the same sidebands with crab compensation. We

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observed a clear dependency of the amplitude of the sidebands on the value of the Piwinski angle reaching a maximum for an angle of about 1.0 and partial compensation with crab cavities. The LHC is currently running with a Piwinski angle of about 0.4 and should reach a value of about 0.7 for design parameters. The regime at which the HL-LHC will be operated is well above these value in the region where the amplitude of the sidebands are close to their maximum ($\Phi \approx 2.0 - 3.0$).

The most likely operating scenario is to level the luminosity with the crab cavities. This implies an increase of the crossing angle at the beginning of stores. For this reason, the damping properties of the cavities will probably not be used when the beam-beam parameter is the strongest. This is illustrated in Fig. 5 where the damping of the synchrotron sidebands is only observed once the bunch intensity has significantly dropped.

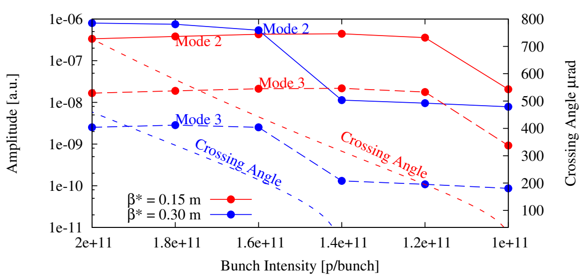

Figure 5: Simulated amplitude of the sidebands through a store assuming luminosity leveling with a crossing angle.

The operating mode currently considered for the crab cavities, i.e. luminosity leveling, would make it impossible to profit from their damping properties. However, the presence of the crab cavities will allow the flexibility to choose the best initial crossing angle and leveling scenario. From these simulations it is difficult to assess the real impact of the sidebands excitation, dynamic aperture and experimental studies would be desirable to predict eventual negative effects.

COHERENT BEAM-BEAM EFFECTS

All the previous simulations were performed in the weak-strong approximation where only one beam feels the beam-beam force while the other remains unaffected. In reality, the two beams couple through the beam beam force and coherent modes arise as observed in Fig. 6 for the head-on case. The main modes are the so-called σ and π separated by $Y \cdot \xi$ where ξ is the beam-beam parameters and Y is the yokoya factor.

Theoretical predictions [12] showed that in the presence of strong betatron coupling and for a beam-beam parameter of the order of the synchrotron tune, the sidebands of the incoherent tune spread could overlap the π-mode and provide Landau damping. This was observed in our 6D strong-strong model as shown in Fig. 6 where the π-mode is fully suppressed for $\Phi \approx 3.0$. The crab compensation restores the head-on conditions. The synchro-betatron coupling becomes weaker while the beam-beam parameters is increased, the π-mode is therefore also restored.

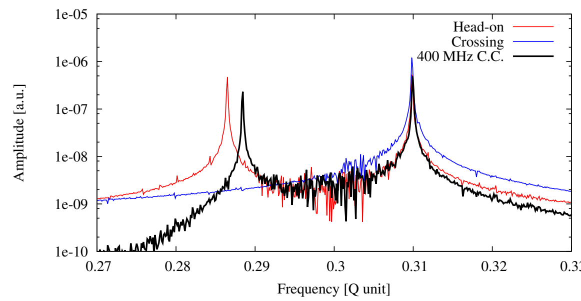

Figure 6: 6D Strong-strong simulation with and without crossing angle and crab cavities for $\Phi \approx 3.0$.

SUMMARY

We have studied the impact of synchro-betatron effects for operation with large Piwinski angle and crab cavities as relevant for the HL-LHC. Preliminary results indicate that a $10\,\sigma$ separation at the long range encounter predicted for nominal LHC may not be valid for the HL-LHC beam parameters and should be increased either with a larger crossing angle or a larger β^*.

We showed that the amplitude of the synchrotron sidebands is dependent on the value of the Piwinski angle and that in any of the scenarios considered, the HL-LHC would be operated close to their maximum amplitude which could be of some concern for lifetime and emittance. The crab compensation would damp the synchrotron sidebands but will be used for luminosity leveling at the beginning of stores. Therefore, damping with crab cavities is probably not applicable. Strong betatron coupling provides damping to the coherent beam-beam modes. In the case of HL-LHC the large bunch-to-bunch spread due to long-range interactions would in any case suppress the coherent modes which are therefore not currently considered as an issue. These preliminary studies did not identify clear detrimental effects from strong synchro-betatron coupling, but should be verified by long term tracking, dynamic aperture and emittance simulation and validated experimentally.

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