MEASUREMENT OF BETA-BEATING DUE TO STRONG HEAD-ON BEAM-BEAM INTERACTIONS IN THE LHC

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Abstract

The LHC operation relies on a good knowledge of the optics, usually corrected in absence of beam-beam interactions. In a near future, both the LHC and the HL-LHC will need to cope with large head-on beam-beam parameters, the impact on the optics needs to be understood and, if necessary, corrected. The results of a dedicated experiment performed at injection energy are discussed in this paper.†

INTRODUCTION

The current beam-beam parameter in the LHC is slightly higher than design (ξ_{bb}=0.0037 per head-on collision) and it is increasing as the quality of the beams delivered by the injectors as well as the brightness preservation in the LHC improve (end of 2016: 0.0046 per Interaction Point (IP)). Future projects such as the HL-LHC and the FCC-hh rely on total beam-beam parameters of 0.02 or larger depending on its IPs. In such configurations, the quadrupolar component of the beam-beam force introduces a β-beating in the order of 15% - 23% depending on the number of collisions (IP1 and 5 - IP1,5 and IP8) [1], potentially resulting in luminosity imbalance between IPs, deteriorated cleaning efficiency and machine protection issues. Since such a β-beating goes beyond tolerances, the effect of the beam-beam interactions needs to be understood and if possible corrected. Due to the strong non-linearity of the beam-beam interactions, they introduce a significant amplitude detuning and a corresponding amplitude dependent β-beating as described in [1]. An optimized correction scheme needs to be investigated.

In this report, we explore the possibility of measuring for the first time the β-beating coming from the head-on beam-beam interaction at one IP using forced oscillations with AC dipoles in the LHC. The impact of possible corrections to the β-beating and on dynamic aperture is investigated in [2].

EXPERIMENTAL SET-UP

The Machine Development (MD) study was carried out the night between the 29th and the 30th of October 2016.

The first part of the MD consisted in two fills (fill number 5478 and 5479) with three bunches per beam aiming to collision at the IP, test the reproducibility of the separation bumps and setup the ADT [3] and AC dipole [4] as exciters.

In the second part of the MD (fill number 5480), one pilot bunch was injected at slot 3080 with corresponding damper settings in Beam 1 and two nominal bunches (at slots 2100 and 3080) were injected in Beam 2. Tests were performed at injection energy (450 GeV) since the head-on interaction is independent of the energy and a higher beam-beam parameter could have been reached. The intensities of Beam 1 and Beam 2 were respectively about $7 \cdot 10^9$ ppb and $1.05 \cdot 10^{11}$ ppb and their transverse normalized emittances around 0.8 µm in both planes. The separation was collapsed at IP1 and the transverse damper was turned off on Beam 1. Through the five fills constituting the second part of the MD, AC dipole or ADT excitations with different excitation frequencies and amplitudes were applied. The length of excitations was about 6600 turns for the AC-dipole and 29000 turns for the ADT. Prior to this, the excitation amplitude was ramped during approximately 1100 turns to ensure the adiabaticity of the ramping process [5].

The horizontal and vertical beam tunes before collision were 0.31 and 0.32, respectively, the full crossing angle at IP1 and IP5 was 340 µrad and β^*=11 m.

PRELIMINARY RESULTS

Through the five fills, the horizontal and vertical computed beam-beam parameter ξ_{bb} from Beam 2 parameters had a value between 0.022 and 0.013. Plots in Fig. 1 show Beam 1 horizontal spectrum from data acquired with the Base-Band Tune (BBQ) [6] while exciting with the ADT at two different amplitudes (top plot with an amplitude of 0.55 σ_x and 0.15 σ_y, lower plot with an amplitude of 1.19 σ_x and 0.15 σ_y, in the x-y plane) at a frequency of (0.28, 0.285) in the x-y plane. The excitation amplitudes are given in units of the Root Mean Square (RMS) beam size σ.

Before the excitation (blue lines in Fig. 1), the tune spread starts at about 0.292, meaning that the measured beam-beam parameter should be $\xi_{bb} \simeq 0.018$ which is smaller than what was computed. We compare the beam spectra with excitation (red lines in Fig. 1) in order to put in evidence the beam range for a full head-on collision. For the top plot (0.55 σ_x), the continuum spectra from the beam is seen in the tune range 0.295 to 0.31. For a larger excitation amplitude (1.19 σ_x in lower plot), the continuum spectra is reduced in range (0.3 to 0.31) as qualitatively expected. In the limit of very large excitation, the frequency spectrum would reduce to a single line at the natural tune as the beam-beam tune shift tends to zero while separation increases.

The complete analysis of the BBQ spectrogram showed that assuming a correction factor of 1.2 to the emittance of

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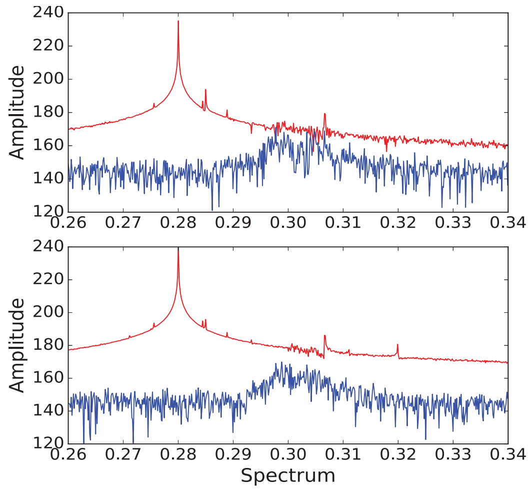

Figure 1: Horizontal spectra of Beam 1 for different ADT excitation amplitudes: the vertical excitation is kept constant at 0.15 σ_y while the horizontal one is 0.55 σ_x (top) and 1.19 σ_x (bottom). The blue curves correspond to the spectrum of the beam just before the ADT excitation and the red ones to the spectrum during the excitation. The horizontal and vertical ADT frequencies were (0.28, 0.285). Beam 1 intensity was $7.8 \cdot 10^9$ ppb (top) and $7.5 \cdot 10^9$ ppb (bottom). Beam 1 emittances on x-y plane were (0.53 µm, 0.76 µm) for top case and (0.50 µm, 0.71 µm) for bottom case.

Beam 2 in both planes leads to a smaller beam-beam parameter (between 0.0185 and 0.011) that is more consistent with the measured spread of the beam as visible in the spectrogram of Fig. 2 where the white line shows the expected beam-beam tune shift assuming emittances larger by 20%. This is in line with BSRT measurement uncertainties due to the impact of the β-beating at the BSRT itself and to the fact that the measured emittances were below 1.5 µm [7]. Detailed analysis is needed to address this discrepancy.

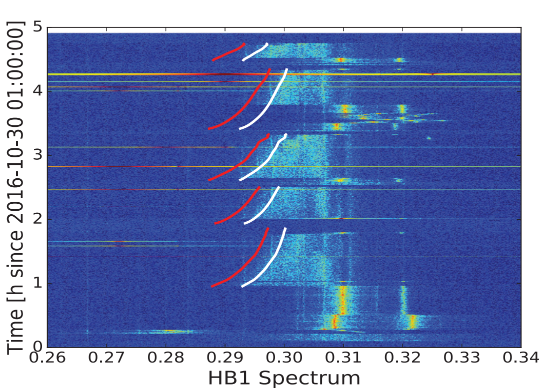

Figure 2: Horizontal Beam 1 spectrum from BBQ as a function of time during the MD. The red and white curves represent the tune shift due to beam-beam collision, i.e. $Q_x - \xi_x$, based on the measured emittance and if a 20% larger emittance is assumed respectively.

Forced oscillations differ from free oscillations and to reconstruct the free β-functions (without excitations and with beam-beam collision), a correction is required depending on the distance between the natural and the excitation frequencies [8]. Three approaches based on the Beam Position Monitors (BPM) were used in order to deduce the natural tune at collision: (i) direct observation of the natural tune in Beam 1 spectrum, (ii) deviation of the RMS β-beating (from reconstructed β-function with and without beam-beam collision) on both sides of the AC/ADT location and (iii) phase advance deviations after AC/ADT location in the segment-by-segment analysis [9, 10]. Beam optics were computed using the N BPM method [11].

An example of Beam 1 spectrum for the largest AC-dipole excitation from the BPMs data is given in Fig. 3. The signal coming from the AC-dipole on both planes provides the strongest signal in the horizontal spectra. There is also a peak at 0.288 on the horizontal spectrum that is not yet understood. Apart from these excitation peaks, there is another signal that may correspond to the beam natural tune at the frequencies (0.307, 0.317). However, the beam natural tune signal does not appear in any other spectrum of the experiment.

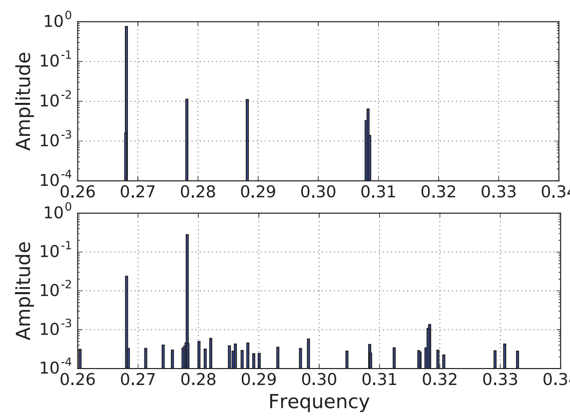

Figure 3: Horizontal (top) and vertical (bottom) Beam 1 spectra for AC-dipole excitation with 1.8 σ_x and 1.84 σ_y respectively. Excitation frequencies were $f_{excit} = (0.268, 0.278)$ and the value of the natural tunes seen on the spectra are (0.307, 0.317) on the x-y plane.

The RMS method uses the fact that the largest β-beating source for forced oscillations in IP4 (s≃3332 m) should be the AC dipole itself. The best guess of the natural tune should correspond to minimizing the difference of the RMS β-beating between both sides of IP4. This method provides consistent results for every excitation in the sense that stronger is the excitation amplitude the closer to the initial tunes is the natural tune. Examples of scans with two different excitation amplitudes are given in Fig. 4. In the case of the strongest AC-dipole excitation (1.8 σ_x and 1.84 σ_y on the x-y plane), the natural tunes provided by this method (i.e. green plot in Fig. 4) are (0.31, 0.3163), which are similar to the ones from the spectra in Fig. 3, i.e. (0.307, 0.317).

The phase advance method aims at finding the natural tune that minimizes the phase advanbce beating originating

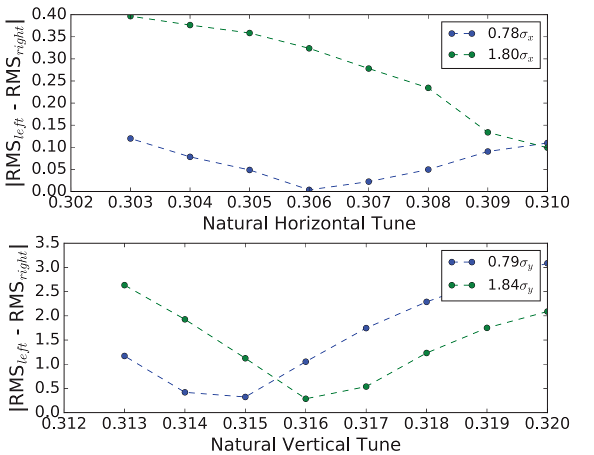

Figure 4: Horizontal (top plot) and vertical (bottom plot) scan of the natural tune where the RMS of the β-beating was computed for two different AC dipole excitations.

in IP4. This method is applied to the IR4 segment which is treated as an independent transfer line, meaning that the measured optics are used as initial conditions for the simulations and that machine errors occurring in this segment are neglected in the phase propagation. Scans with different natural tunes in the simulations were performed. This method always provided the same results indicating that the best natural tunes were (0.31, 0.32). Further analysis about the simulations and limitations of the model are still in progress.

The β-beating introduced by the beam-beam collision at IP1 (s≃20 000 m) computed from the BPMs data at the moment of the strongest AC dipole excitation is shown in Fig. 5. For this measurement, Beam 1 had an oscillation amplitude of 1.8 σ_x and 1.84 σ_y and the frequencies of the forced oscillations were 0.268 and 0.278 on the horizontal and vertical plane respectively. Beam 1 and Beam 2 intensities were $6.2{\cdot}10^9$ ppb and $1.1{\cdot}10^{11}$ ppb and their emittances (1.1 μm, 1.3 μm) and (1.0 μm, 0.9 μm), respectively. The β-beating due to beam-beam collision remains below 10%.

For the vertical plane, one also notices an important unexpected contribution from IP5 (s≃6665 m in Fig. 5). Further investigations are needed to understand its source.

The predicted β-beating for the zero amplitude particles is shown in Fig. 6 for the above beam parameters where one sees that the maximum β-beating is between 10-8% without and with the correction factor to the emittance respectively. However, for a 2 σ oscillation amplitude, a reduction of the β-beating of roughly 30% is expected as estimated in [1] leading to a maximum of β-beating of about 8-6%.

The comparison of the β-beating from Fig. 5 and Fig. 6 shows that the simulations and the mesurements are of the same order of amplitude. The 20% correction factor to the emittance provides a smaller β-beating as expected that is also more consistent with Fig. 5.

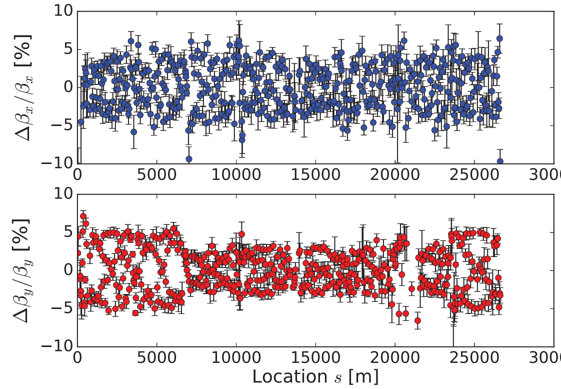

Figure 5: Measured β-beating for 1.8 σ_x and 1.84 σ_y amplitude particle due to beam-beam interaction at IP1 along the machine computed from BPMs data. This case corresponds to the AC dipole excitation shown on Fig. 3 and to the green plot on Fig. 4. The longitudinal coordinate starts at IP3.

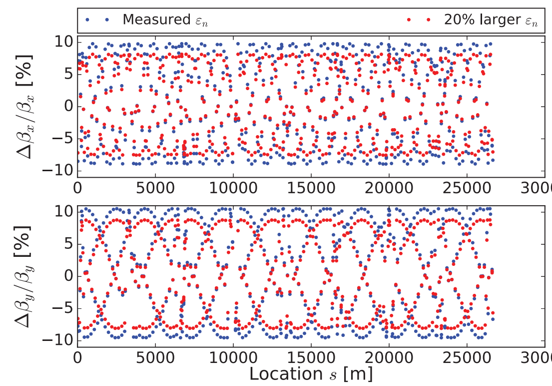

Figure 6: Simulation of β-beating in the LHC due to head-on beam-beam interaction at IP1 at injection energy for zero amplitude particles. Blue points were computed based on the measured normalized transverse emittance and the red ones assuming a 20% larger emittance. The longitudinal coordinate starts at IP3.

CONCLUSIONS

Forced oscillations have been induced for the first time in the presence of beam-beam head-on collisions in the weak-strong regime with the aim of measuring optics parameters. No emittance growth or particle losses were observed for a wide range of excitation amplitudes up to about 2 σ. The main difficulty to achieve an accurate optics measurement at low excitations is the identification of the natural oscillation frequency. At large amplitude however a clear natural frequency is observed and optics measurements could be accomplished.

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