TUNE STUDIES WITH BEAM-BEAM EFFECTS IN LHC*

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Abstract

In high brightness colliders the tune spread due to the collisions has a significant impact on the quality of the beams. The impact of the working point on emittance growth and beam lifetime has been observed in beam experiments in LHC. Strong-strong beam-beam simulations that were accomplished to better understand such observations are shown. Compared to experiments, wide ranged parameter scans can be done easily. Tune footprints and scans of the emittance growth obtained from simulations are discussed. Three cases are considered: Very high intensity, moderate intensity and collisions with separated beams.

INTRODUCTION

The beam-beam force between colliding beams acts like a non-linear lens. In circular colliders, high brightness beams cause both a notable shift and spread of the single particle tunes, which may move the particles onto tune resonances. The consequences were visible in the LHC before the maintenance shutdown and will be more severe after the High Luminosity upgrade.

In order to avoid emittance growth and a reduction of the beam lifetime, the working point needs to be chosen such that the effective tune of the beams is not on resonances. Experience with tunes and resonances in LHC have been gained in beam experiments. In this paper, we summarize simulations accomplished to gain understanding of observations in the LHC. An experiment with intense beams is described in the first section. In the second section, a measured reduction of beam lifetime is related to tune resonances and emittance growth. The third section highlights the impact of an offset between the colliding bunches. For the future high Luminosity LHC, beam-beam effects will be even more important. However, due to space constraints, we refer to Ref. [1, 2] for a discussion of future scenarios

BEAM EXPERIMENT WITH HIGH INTENSITY

Possible problems arising from head-on collisions with maximal beam-beam parameter was searched for in a dedicated experiment in May 2011 [3]. The experiment was

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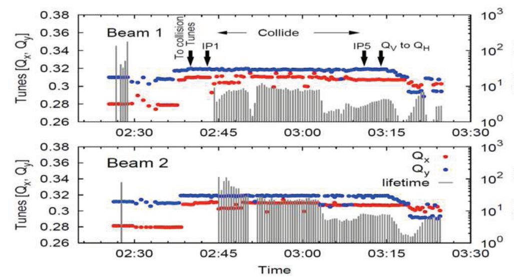

Figure 1: Tunes and beam life time as a function of time in the 4^{th} fill of the experiment. Markers highlight the actions of the operators.

carried out at injection energy E=450 GeV, and with the injection optics, i. e. β^*=11 m. The LHC was filled 5 times, but here we limit our discussion to the last two fills. For a full description of the experiment we refer to Ref. [3].

In fill 4, two bunches with an intensity of 1.7×10^{11} protons were colliding in two interaction points (IPs). The history of the fill is sketched in Fig. 1, along with the measurement of the tune and beam life time. At about 3:18 h, the vertical tune was decreased from 0.32 to 0.31.

Figure 2 shows the emittances of beam 1 as a function of time. The data from 02:30 to 3:25 on the horizontal scale correspond to fill 4. The emittances changed significantly during the lengthy optimization procedure. Of particular interest is the simultaneous jump up of the horizontal and down of the vertical emittance at 03:18 h, when the tune was changed. In beam 2, the emittance behaved similar but changing less in the vertical plane.

Fill 5 started with 1.8×10^{11} protons per bunch. An optimization of the collisions was not necessary this time because the settings from the previous fill were used. The vertical tune was set to 0.31 from the beginning this time. Again the beams were put into collision in IP1 first and IP5 second. Figure 2 shows that the emittance growth was almost constant during the store, i. e. it was not accelerated by the collisions.

Simulations were run to investigate the role of the tune for the emittances. Maps showing the emittance growth as a functions of the horizontal and vertical tune were generated to identify the optimal values. The goal of this work was not quantitative predictions of emittance growth and due to numerical noise, these resulting growth rates may be too large. But for the comparison of working points, a high accuracy is not required. The maps for fill 4 of the ex-

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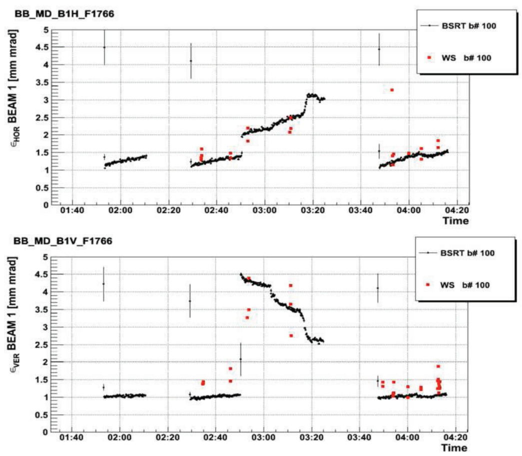

Figure 2: Evolution of the horizontal (top) and vertical (bottom) emittance of beam 1 in fills 3 to 5.

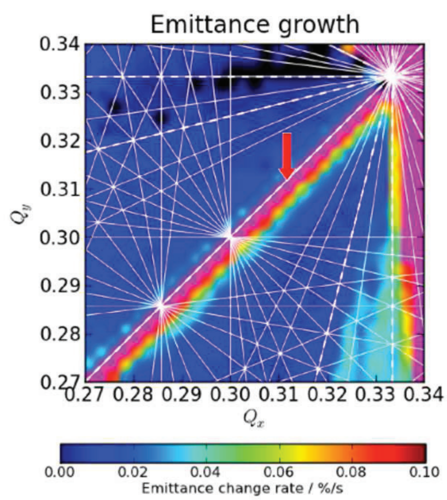

Figure 3: Simulated horizontal emittance change as a function of the horizontal and vertical tune in fill 4. Black represents emittance decrease, while magenta illustrates growth exceeding 0.1 %/h. The red arrow indicates the shift of the tune. The white lines visualize resonances. Clearly visible are 3^{rd} and higher order resonances in the upper right corner and the 2^{nd} order resonance on the diagonal. The lines crossing in the center of the picture correspond to 10^{th} order.

periment are shown in Fig. 3 and Fig. 4, for the horizontal and vertical plane, respectively.

The simulation does not reproduce the emittance exchange already measured with $Q_y = 0.32$, but it confirms a strong coupling for $Q_x = Q_y$. In Fig. 2, this corresponds to the slump at about 3:18 h. In fill 5 no emittance exchange was observed though the tunes were still equal. As Fig. 5 and 6 reveal, the change of the beam parameters, in particular smaller emittances, changed the conditions enough to suppress emittance exchange.

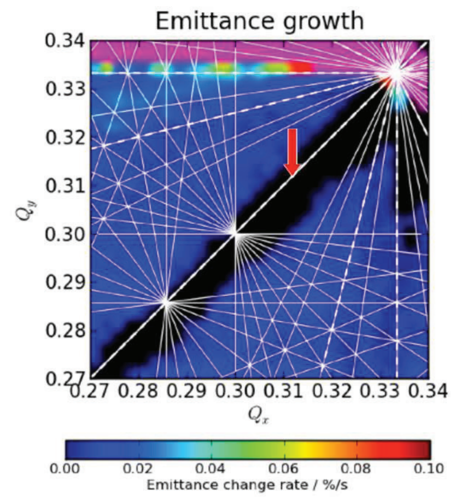

Figure 4: Simulated vertical change in fill 4. The color code is the same as in Fig. 3.

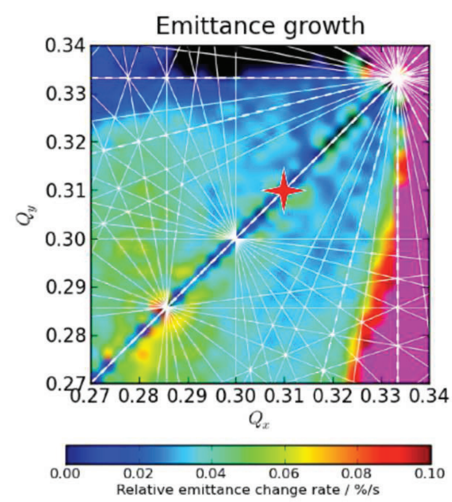

Figure 5: Simulated horizontal change in fill 5. The color code is the same as in Fig. 5. The star marks the new working point.

LIFETIME

The impact of tune variations on the beam lifetime has been probed by small tune variations. In the case discussed here, the normalized emittance was 2 μm, β^*=1.5 m, crossing angle = 0.28 mrad, and $N = 1.15 \times 10^{11}$ at 3.5 TeV. The working point was set to (Q_x, Q_y)=(0.308, 0.318), to (0.31, 0.32), and to (0.312, 0.322). Increasing the working point increased the beam lifetime [4]. Simulations were run with the these settings to understand the underlying mech-

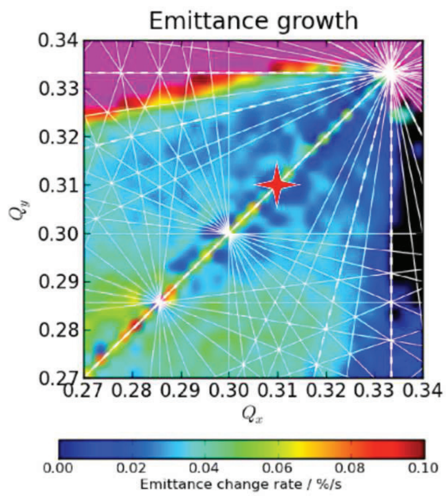

Figure 6: Simulated vertical change in fill 5. The color code is the same as in Fig. 5. The star marks the new working point.

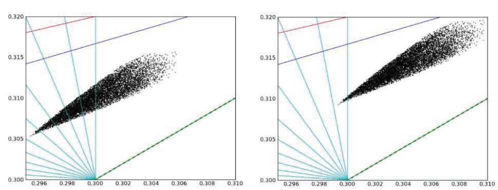

Figure 7.

anism. Figure 7 shows the simulated tune footprint for the lowest and highest working point.

Obviously, increasing the working point moves the beam away from 10^{th} order resonances. The simulations did not provide information about the lifetime that could have been compared to the observation. However, they generate emittance data, and emittance growth is also an indicator for the excitation by higher order resonances. As Fig. 8 demonstrates, the emittance growth is indeed larger when the beam is deeper in the resonance. Therefore, 10^{th} order resonances can be held responsible for beam degradation.

COLLISION WITH OFFSET

Separation of the colliding beams has been investigated as an option to level luminosity. An experiment to test this idea [5] has been carried out successfully and simulations yielded a very good agreement [6]. From these simulations, tune footprints of beams colliding with an offset were gained. Fig. 9 shows that the tune footprint is shifted and distorted in the expected way [5], when the beams are separated. This modification of the footprint may have a significant impact on the dynamics of beams in the High Luminosity LHC, if beam separation should be employed there. A separation is expected to alter the optimization of the working point.

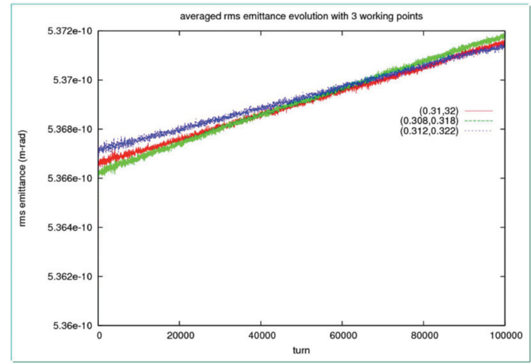

Figure 8.

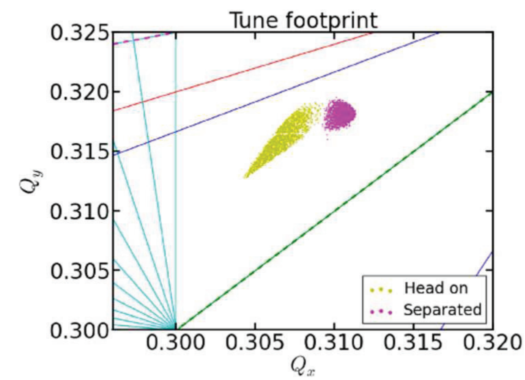

Figure 9: Simulated tune footprint of bunches colliding head-on and with a separation of 2.5 σ.

CONCLUSION

Strong-strong beam simulations have been applied to simulate colliding beams in LHC. Simulated tune footprints and tune maps indicating of the emittance growth are a useful tool to better understand the behavior of colliding beams. They can help to optimize the working point for present and future beam parameters.

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