OBSERVATION OF COHERENT BEAM-BEAM EFFECTS IN THE LHC

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Abstract

Early collisions in the LHC with a very limited number of bunches with high intensities indicated the presence of coherent beam-beam driven oscillations. Here we discuss the experimental results and compare with the expectations.

INTRODUCTION

Indications of coherent beam-beam modes during operation of the Large Hadron Collider (LHC) with a limited number of bunches motivated dedicated experiments in order to confirm their presence and study their stability. It has been shown [1] that in some cases, due to loss of Landau damping, the beam-beam interaction could cause dipolar oscillations to appear. Without damping, they are very sensitive to any close frequency component. In particular, they can become unstable while moving the beams against each other. As no clear observation of these modes has been done yet at LHC, a series of experiment was performed in which the parameters of the machine and the beams were chosen to be highly symmetric and to maximize the head-on beam-beam parameter ξ. This allows to enhance the possibility to observe coherent modes and study their behavior. Implications for operation are then discussed.

SETUP

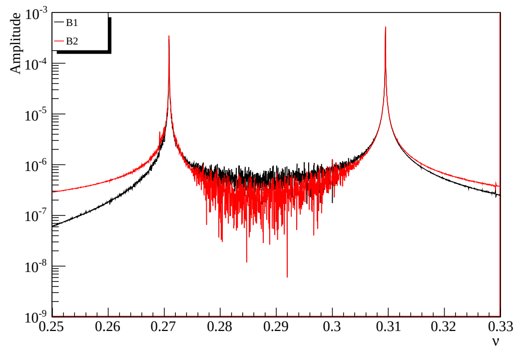
Four similar experiments were performed, two of them will be detailed here, the beam parameters of which are shown in Table 1. Two beams, each containing one bunch of high intensity and small emittance, were put into collision in interaction point (IP)1. In the first experiment, the orbit was then optimized for luminosity. The same procedure was then applied to IP5, which is located symmetrically at the other side of the ring. As the effect of coherent motion is not dependent on the energy, the study was performed at injection energy with unsqueezed beams.
In such conditions, two coherent modes are expected, the first one is known as the σ-mode and has the frequency of the unperturbed tune. The second one, the π-mode, has a smaller frequency, $\nu_\pi = Q - Y \cdot \xi$, where Y is the Yokoya factor [2]. Whereas the σ-mode corresponds to the two beams oscillating in phase, i.e. always colliding head-on, the π-mode correspond to the two beams colliding out of phase, i.e. colliding with an offset.
The base band tune (BBQ) pickups were used to measure independently the position of both beams turn by turn [3]. The analysis of the amplitude of the signal provides information about the presence, or not, of an instability. It is also used to identify the presence of the two coherent modes, by comparing the FFTs of the sum and the difference of the measured positions of the two beams. Indeed, the peak of the σ-mode is enhanced in the sum of the two signals, whereas the π-mode will be suppressed, as the beams are oscillating in phase for the former and out of phase for the latter. The opposite is true for the subtracted signals.
In order to be able to observe the development of coherent motion, no transverse damper was used during the experiments.

SIMULATIONS

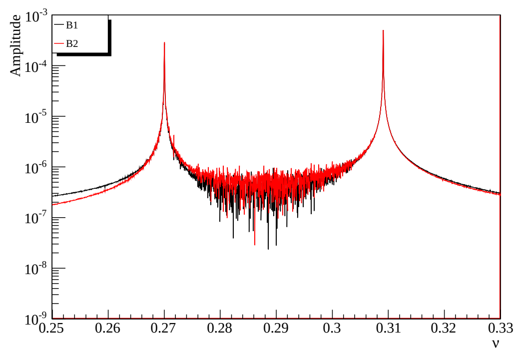
We are considering the beam-beam force in the strong strong regime, self consistent simulations are required to compare the measurements with expectations. The code BeamBeam3D [4] was used, it allows for self consistent field calculation of arbitrary distributions using the three dimensional particle-in-cell method. The transport between IPs is done with a linear transfer map, the only non-linear element is therefore the beam-beam force. The beam parameters used for the simulations are the ones described in Table 1. The transfer maps were derived from the nominal LHC lattice. Two bunches of $2 \cdot 10^6$ macro-particles with 5 longitudinal slices per bunch were tracked over 2^{14} turns. The spectrum is then derived by performing an FFT of the motion of the center of mass. The spectrum obtained for the first experiment are shown in Fig. 1, showing the two coherent modes.

Table 1: Beam Parameters

	Experiment 1		**Experiment 2**	
	B1	**B2**	**B1**	**B2**
Energy [GeV]	450		450	
$\beta^*_{IP1/IP5}$ [m]	11		11	
N [10^{11} p/bunch]	1.95	1.76	1.90	1.86
ϵ^{norm}_{hor} [μm]	1.3	1.5	1.3	1.5
ϵ^{norm}_{ver} [μm]	1.2	1.5	1.3	1.5
Q_{hor}	0.31		0.31	
Q_{ver}	0.31		0.32	
$\phi/2$ [μrad]	170		170	
ξ	$\sim 2 \cdot 0.016$		$\sim 2 \cdot 0.015$	



(a) Horizontal



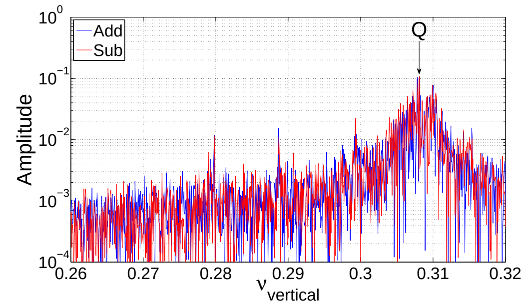
(b) Vertical

Figure 1: Simulation of coherent spectrum for the experiment 1. A tune shift of $\Delta Q_{\text{sim}} = 0.040$ is observed between the two coherent modes.

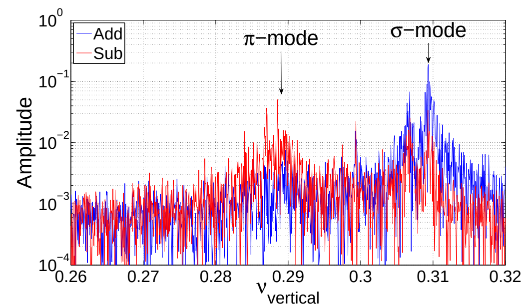
RESULTS

Stable Coherent Motion

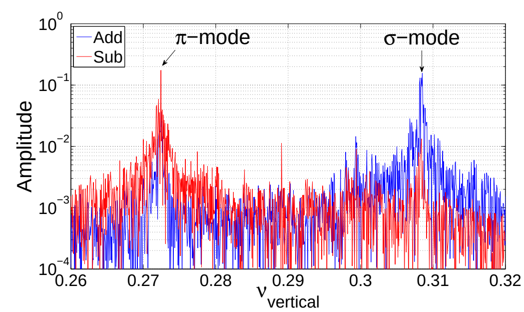
During experiment 1, no instabilities were observed, however, the signal from the coherent motion is clear on the plots from Fig. 2. A similar effect is seen on both planes, for clarity, only the vertical plane is shown. When the beams are not colliding, only the peak from the tune is visible, as the two signals are independent, neither the added or subtracted signal has enhanced peaks. However, when colliding in IP1, the peak from the added signals sitting at the tune is enhanced, indicating the presence of a σ-mode, whereas a peak in the subtracted signals, corresponding to a π-mode, is visible at $\nu_\pi = 0.289 \pm 10^{-3}$. The tune shift is then around half the one expected with two colliding IPs, which is indeed the tune shift expected [5]. When colliding both IP1 and IP5, a π-mode is clearly visible at $\nu_\pi = 0.272 \pm 5 \cdot 10^{-4}$, leading to a measured tune shift of $\Delta Q_{\text{meas}} = 0.036 \pm 10^{-3}$, which is consistent with the simulated one (Fig. 1b), assuming an error margin of $\pm 4 \cdot 10^{-3}$ on the simulated tune shift caused by the uncertainty on the emittance measurements , 10%, which dominates the error on the inputs for the simulation.



(a) No Collision



(b) Collision in IP1



(c) Collision in IP1 and IP5

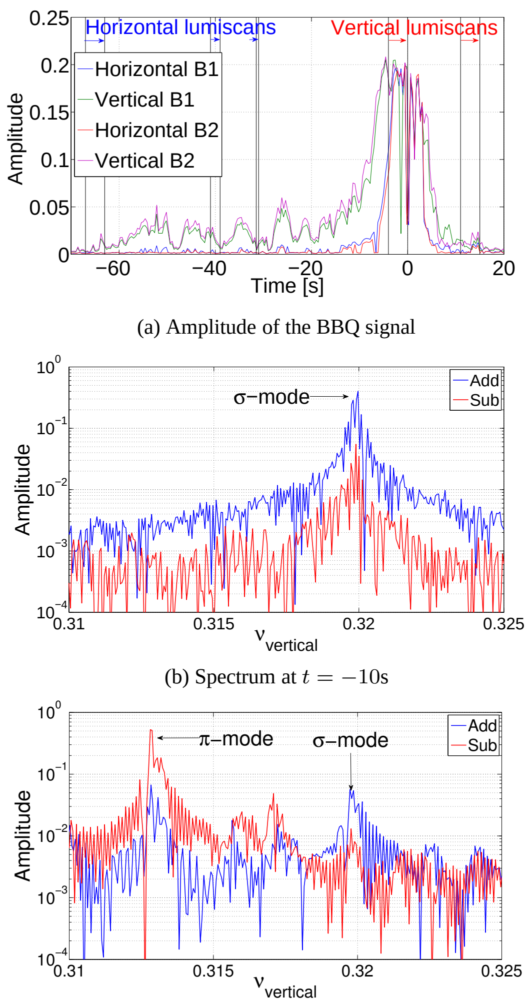
Figure 2: The Fourrier transform of the addition and subtraction of the beam position measured by the BBQ pickups.

Unstable Coherent Motion

Table 2: Emittance Growth Observed during the Instability

	Horizontal		Vertical	
	B1	B2	B1	B2
$\Delta\epsilon$ [μm]	0.6	3.5	1.3	1.2

Whereas stable when kept in a steady state, the beams have become unstable in some cases during optimization of the orbit, in particular during experiment 2. An instability was observed during optimisation of IP1, as shown by the amplitude of the BBQ signal on Fig. 3a. The driving mechanism of the instability is not fully understood, however, the tune spectra measured during the development of the instability 3b shows that the σ-mode in the vertical plane is driven unstable with a rise time of $\tau = 7.8s$, which is then transmitted to the horizontal plane. The first



(a) Amplitude of the BBQ signal

(b) Spectrum at $t = -10$s

(c) Spectrum at $t = 1$s

Figure 3: Amplitude of the BBQ signal during the instability and spectrum of the added and subtracted signals during the instability. $t = 0$ is defined at the time of the observed emittance growth.

step of the optimisation of the orbit in the vertical plane causes a significant emittance growth (Table 2). Moreover, it drives the π-mode, as can be seen on Fig. 3c, the σ-mode has almost disappeared to the profit of the π-mode. It is important to note that this does not necessarily indicates a beam-beam driven instability, it is however a good candidate. Further investigations are needed to determine if the coherent modes can become unstable and if so, in which conditions.

This kind of behaviour has not been observed during standard operation for physics, as the transverse damper is turned on systematically, shadowing relevant signal from the BBQ. Yet simulations have shown that the breaking of symmetries is highly unfavorable for the appearance of coherent motion [5], therefore, it is believed that the numerous symmetry breaking parameters in the LHC, such as unequal phase advance between the IPs or bunch by bunch differences [6], in particular due to PACMAN effects, will allow a suppression of the coherent modes. The observations of stable coherent motion presented in this paper motivate future experimental investigations to test it, in order to determine to what extend coherent beam-beam modes could become detrimental to operation for physics. In particular, the different suppression techniques will be investigated.

CONCLUSION

Coherent dipolar beam-beam modes have been observed in dedicated experiments at the LHC, with very high brightness beams, inducing a head-on beam-beam parameter per IP four times higher than nominal. In these symmetric conditions extremely favorable for the development of coherent motion, the modes have shown to remain mostly stable, even without a transverse damper. This suggests that, coherent beam-beam modes will not be an issue during operation for physics. Future dedicated experiments with decreasing symmetry will help to shed light on this effect.

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