COHERENT INSTABILITY DUE TO BEAM-BEAM INTERACTION IN HADRON COLLIDERS*

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Abstract

Beam-beam effects can excite coherent modes in circular colliding beams and can thereby cause coherent instabilities. Nevertheless the beams in LHC have been well behaved and no fundamental limitation to the beam-beam parameter has been found in head-on collisions. In this paper we consider beams with much higher intensities than ever collided in any hadron collider. By virtue of 3D strong-strong computer simulations, we investigate the coherent stability and emittance growth of proton beams in head-on collision. The impact of a crossing angle between the beams and of a transverse damper is examined.

INTRODUCTION

In lepton colliders, a changed scaling of the luminosity and the beam-beam parameter with intensity has been observed when the intensity exceeded a threshold [1]. The dynamics of colliding hadron beams differs qualitatively from that of electron beams because radiation damping is negligible for hadrons. Therefore hadron beams are assumed to be more prone to instabilities. In the LHC however, the intensity or beam-beam parameter have not been limited by beam-beam effects due to head-on collisions [2]. Beam-beam effects at the highest beam-beam parameter achieved in LHC are discussed in Ref. [3, 4]. In this paper we consider the coherent stability at intensities well beyond the performance of present colliders to identify possible inherent beam-beam limitations for future colliders.

Analytic models of the coherent stability apply only to simplified cases, like assuming linear self-fields and no crossing angle [5, 6]. These models predict unstable regions in the parameter space. Head-tail modes, on the other hand, have been found to be generally stable as long as impedances are neglected [7]. The computer simulations discussed here are not subject to the limitations of the analytic models. In the next section the setup of our simulations is outlined. A discussion of results and conclusions follow in the subsequent sections.

SETUP

The beam parameters chosen for our simulations loosely follow the LHC setup, except for the intensity. The intensity of the beams in our simulations was increased until strong coherent effects were observed. Table 1 lists the simulation parameters. Initially, the particle distribution was Gaussian. One pair of bunches collided once per turn. The corresponding beam-beam parameter without crossing angle is 0.067. According to the linear model developed in Ref. [6], these bunches will experience a quadrupolar instability.

Table 1: Simulation Parameters

Parameter	Value	Unit
N	21×10^{11}	-
ϵ	0.512	nm
β^*	0.5	m
σ_L	0.077	m
δ_p	1.11×10^{-4}	-
Q_x, Q_y, Q_z	0.31, 0.32, 0.00212	-
E	7	TeV
N_m	1,000,000	-
Slices	10	-

Table 2: The Four Cases Discussed in This Paper

Case	Crossing angle	Damper
A	0	off
B	0	on
C	0.15 mrad	off
D	0.15 mrad	on

The beam-beam kicks were computed self-consistently using a Green's function method [8]. The numerical noise in self-consistent simulations can drive emittance growth [9, 10]. However, in the cases considered here, the physical emittance growth is so large that the numerical contribution is negligible. In fact, using 4 times more macro particles in a simulation of case D changed the emittance growth by about 3 % only. Impedances and electron clouds have been neglected because they would obscure the pure beam-beam effects.

Collisions with and without crossing angle as well as with and without transverse damper are discussed. In the following section these 4 cases will be referred to by the letters specified in Tab. 2. The damper model is described in Ref. [10].

RESULTS

First we consider the case A. The offset and emittance are shown as a function of time in Fig. 1. The centroid motion is unstable and the emittance grows by several 10 %/s. From 12,000 to 50,000 turns, the horizontal oscillation is damped while the emittance growth is accelerated. A list of emittance growths after different time intervals for all cases is provided in Fig. 3. For either plane, the average growth of both beams is given.

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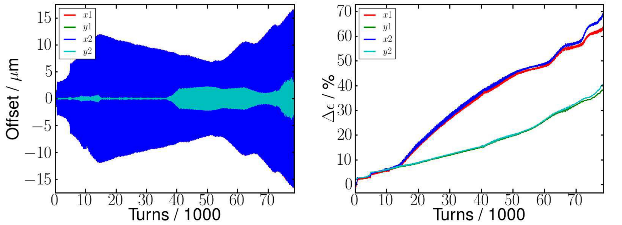

Figure 1: Case A, offset (left) and emittance growth (right) versus time.

Table 3: Emittance Growth (with respect to initial value) at Different Times for Cases A Through D. The simulation of case C did not arrive at 70,000 turns.

Turns	5000	25,000	70,000
A, hor.	8 %	26 %	61 %
A, ver.	7 %	13 %	35 %
B, hor.	33 %	35 %	41 %
B, ver.	13 %	16 %	21 %
C, hor.	7 %	43 %	-
C, ver.	6 %	22 %	-
D, hor.	78 %	116 %	134 %
D, ver.	43 %	70 %	81 %

The envelope spectrum of 2048 turns at the beginning of the simulation and after 30,000 turns is shown in Fig. 2. At the beginning there are peaks at 0.2 and 0.4, indicating a 5^{th} order envelope resonance. These peaks disappear, however, within 10,000 turns and several peaks close to 0 and 0.5 rise. Due to the large beam-beam parameter, the tune footprint is quite large and spreads over many resonance, as Fig. 3 illustrates.

Setting the damper gain to 0.02 (case B) stabilized the centroid, as Fig. 4 demonstrates. Larger gains yielded more emittance growth. The horizontal oscillation is quite large initially, with an amplitude of about 10 μm, and damped very slowly, though. The difference between the planes is attributed to the tunes since all other parameters are equal in both planes. There is a rapid emittance growth initially, which suddenly slows down, as shown in Fig. 4. The final growth rate is on the order of 1 %/s, presumably due to diffusion. Compared with case A, the emittance growth is enhanced initially (s. Tab 3), but after a short time the damper proves beneficial.

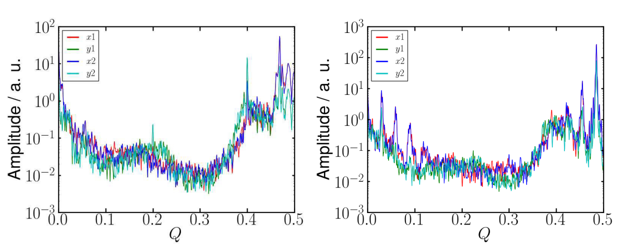

Figure 2: Case A, envelope spectrum after at the beginning and after 30,000 turns.

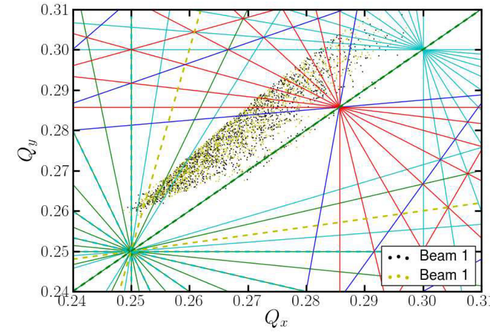

Figure 3: Case A, tune footprint. The visible resonance lines include 4^{th} order (cyan dashed), 6^{th} order (yellow dashed), 7^{th} order (red), 8^{th} order (green), 9^{th} order (blue) and 10^{th} order (cyan solid).

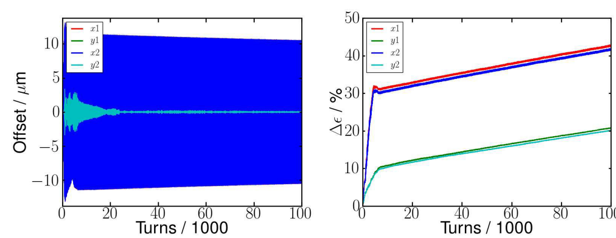

Figure 4: Case B, offset (left) and emittance growth (right) versus time.

The spectra of the offsets and envelopes during the fast growth period are shown in Fig. 5. There is a series of peaks in the spectra, indicating the excitation of the beams. After a few 1000 turns, when the beams stabilized, they mostly disappear. As a consequence of coupling, the spectra look all quite similar, despite the differences between the vertical and horizontal planes in the time domain.

Next we let the bunches collide with the nominal crossing angle, without damping (case C). The resulting centroid motion and emittance growth are displayed as a function of time in Fig. 6. The beams obviously suffer a dipolar instability. The emittance grows modestly at the beginning but accelerates as the instability evolves.

The spectrum of the centroid motion is shown in Fig. 7.

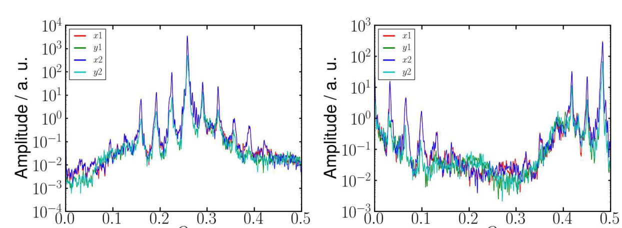

Figure 5: Case B, offset and envelope spectrum after 3000 turns.

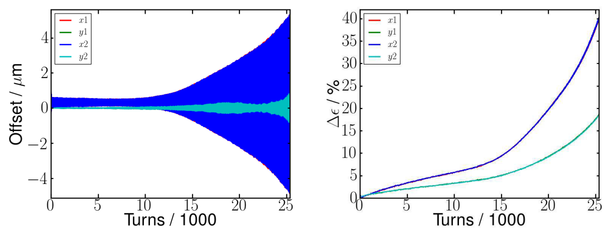

Figure 6: Case C, offset (left) and emittance growth (right) versus time.

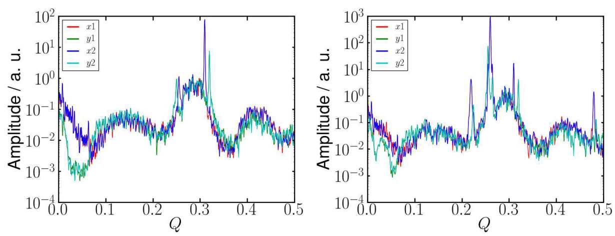

Figure 7: Case C, offset spectrum after 1000 turns and 20,000 turns. The π and σ beam-beam modes are clearly visible.

The spectra clearly reveal the σ (at Q_x and Q_y, respectively) and π (at lower frequency) BB modes. As the instability progresses, the π modes increase, which proves that they are driving the oscillation, but also new modes appear.

Finally the damper was turned on while the beams were colliding with crossing angle (case D). In this case the damper gain was set to 0.2. The corresponding offset and emittance are shown in Fig. 8. The damper stabilizes the centroids within 30.000 turns. By this time the emittance has already grown by 40 % to 50 %, respectively, in each plane. After the offset is under control, the emittance keeps growing at a decreasing rate. Similarly to the situation without crossing angle, the damper accelerates the initial emittance growth but mitigates it later on. The growth rate will possibly converge towards a constant determined by diffusion.

The spectra of the offset and envelope are shown in Fig. 9. Here we see one coherent mode at $q \approx 0.262$ in both planes. It appears that the π mode of both planes coupled to an oscillation with a single frequency while the damper completely suppresses the σ mode. The envelope spectrum features peaks at q, $1 - 2q$ and a broad band around $1 - 2$ times the working point.

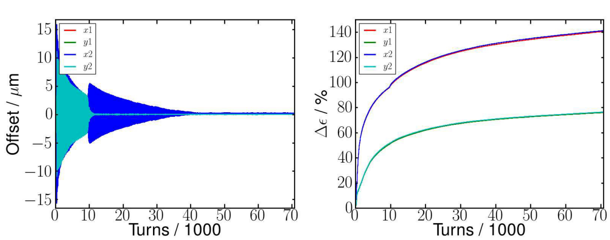

Figure 8: Case D, offset (left) and emittance growth (right) versus time.

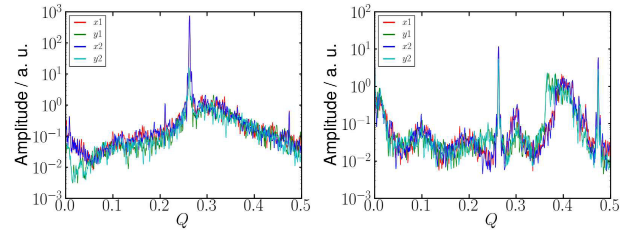

Figure 9: Case D, offset (left) and envelope (right) spectra after 20,000 turns.

CONCLUSIONS

At extremely high intensity beams colliding head on experience dipolar instabilities in our simulations. A transverse damper has proven able to suppress these instabilities, although the damping time can be very long. Employing the damper causes a short, drastic emittance growth, several 10 % within a few 10,000 turns, and cannot avert a subsequent continuous emittance growth with a rate of about 1 %/s. Although a crossing angle (without crab cavities) reduces the effective beam-beam parameter, the beams are stronger affected by beam-beam effects with a crossing angle. At a sufficiently large intensity, beam-beam effects severely challenge the control of the beams even in the absence of external perturbations.

ACKNOWLEDGMENT

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