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Performance Limitations in the LHC due to Parasitic Beam-beam Encounters- Parameter Dependence, Scaling, and PACMAN Effects

R. Giachino, W. Herr, E. Metral, G. Papotti, T. Pieloni (CERN, Geneva), G. Trad

X. Buffat (EPFL, Lausanne; CERN, Geneva), D. Kaltchev (TRIUMF, Vancouver, Canada)

Abstract

A novel type of 2.76 m long slotted, or perforated, strip-line pick-up, or kicker electrode structure, for CSRe stochastic cooling of non-relativistic particle beams with $\beta \sim 0.7$ is presented. It is installed inside a bending vacuum chamber with the output signal taken from the downstream end. This slotted structure features a sufficiently broad bandwidth, good beam coupling impedance, low losses and a comparatively easy mechanical construction and installation into the CSRe dipole chamber. In this paper the electrode structure and pickup tank, as well as the beam test results will be presented.

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Abstract

We studied possible limitations due to the long-range beam-beam effects in the LHC. With a large number of bunches and collisions in all interaction points, we have reduced the crossing angles (separation) to enhance long-range beam-beam effects to evaluate their influence on dynamic aperture and losses. Different β^*, number of bunches and intensities have been used in several dedicated experiments and allow the test of the expected scaling laws.

STUDIES OF LONG RANGE INTERACTIONS

Contrary to the head-on beam-beam effects, the long range beam-beam interactions is expected to play an important role for the LHC performance and the choice of the parameters [1, 2]. To study the effect of long range beam-beam interactions we have performed two dedicated experiments. In the first experiment, the LHC was set up with single trains of 36 bunches per beam, spaced by 50 ns. The bunch intensities were $\approx 1.2\ 10^{11}$ p/b and the normalized rms emittances $\epsilon_n \approx 2.5\ \mu$m. The trains collided in IP1 and IP5, leading to a maximum of 16 long range encounters per interaction point for nominal bunches. First, the crossing angle (vertical plane) in IP1 was decreased in small steps and the losses of each bunch recorded. The details of this procedure are described in [3].
In the second experiment we injected 3 trains per beam, with 36 bunches per train. The filling scheme was chosen such that some trains have collisions in IP1 and IP5 and other collide only in IP2 or IP8.

Losses due to long-range interactions

From simulations [4] we expected a reduction of the dynamic aperture due to the long-range beam-beam encounters and therefore increased losses when the separation is decreased. To estimate the losses, we have shown in Fig.1 the expected dynamic aperture as a function of the normalized separation [4] for two different bunch spacings (50 ns and 25 ns). The separation was varied by changing the crossing angle as well as the β^*. From this figure we can determine that visible (i.e. recordable) losses can be expected for a dynamic aperture around 3 σ and therefore when the separation is reduced to values around 5 σ.

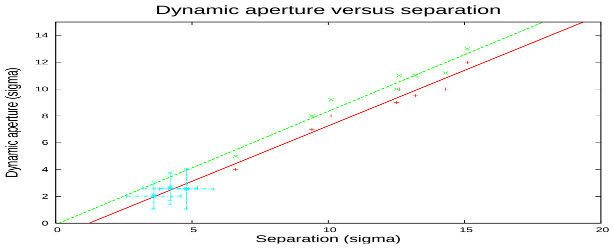

Figure 1: Dynamic aperture versus full separation. Comparison with results from experiment.

We have performed two measurements and the results of the first experiment are shown in Fig.2 where the integrated losses for the 36 bunches in beam 1 are shown as a function of time and the relative change of the crossing angle is given in percentage of the nominal (100% $\equiv$ 240 μrad). The nominal value corresponds to a separation of approximately 12 σ at the parasitic encounters.

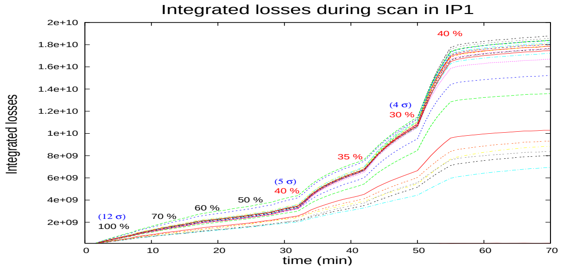

Figure 2: Integrated losses of all bunches as a function of time during scan of beam separation in IP1. Numbers show percentage of full crossing angle.

The losses per bunch observed in the second experiment showed a very similar behaviour. From Fig.2 and from the second experiment we observed significantly increased losses for some bunches when the separation is reduced to about 40%, i.e. around 5 σ. The emittances, mainly determined by the core of the beam, are not affected by the reduced separation and we interpret this as a reduction of the dynamic aperture as expected from the theory and simulations.

Bunch to bunch differences and PACMAN effects

Not all bunches are equally affected. At a smaller separation of 30% all bunches experience significant losses ($\approx$4 σ). Returning to a separation of 40% reduces the losses significantly, suggesting that mainly particles at large amplitudes have been lost during the scan due to a reduced dynamic aperture. Such a behaviour is expected [4]. The different behaviour is interpreted as a "PACMAN" effect and should depend on the number of long range encounters, which varies along the train. This is demonstrated in Fig.3 where we show the integrated losses for the 36 bunches in the train at the end of the experiment. The maximum loss is clearly observed for the bunches in the centre of the train with the maximum number of long range interactions (16) and the losses decrease as the number of parasitic encounters decrease as clearly visible in Fig. 3. The smallest loss is found for bunches with the minimum number of interactions, i.e. bunches at the beginning and end of the train [5, 6].

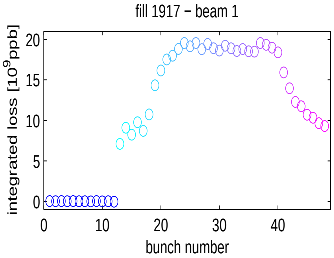

Figure 3: Integrated losses of all bunches along a train of 36 bunches, after reducing the crossing angle in IP1.

In the second part of the experiment we kept the separation at 40% in IP1 and started to reduce the crossing angle in the collision point IP5, opposite in azimuth to IP1. Due to this geometry, the same pairs of bunches meet at the interaction points, but the long range separation is in the orthogonal plane. This alternating crossing scheme was designed to compensate first order effects from long range interactions [5]. Figure 4 shows the evolution of the luminosity in IP1 as we performed the scan in IP5. The numbers indicate again the relative change of separation, this time the horizontal crossing angle in IP5. The luminosity seems to show that the lifetime is best when the separation and crossing angles are equal for the two collision points. It is worse for smaller as well as for larger separation. This is the expected behaviour for a passive compensation due to alternating crossing planes, although further studies are required to conclude. The alternating crossing scheme was implemented in the LHC [6] to avoid a tune shift of PACMAN bunches relative to the nominal bunches as well as chromaticity variations. The effect of the alternating crossing scheme on the tune along a bunch train is shown in Fig.5. Without the alternating crossing, the PACMAN bunches exhibit a strong dependence of their tunes on their position in the bunch train. Depending on the intensity, bunch spacing and separation, this spread can exceed $2 \cdot 10^{-3}$. The alternating crossing scheme compensates completely for this spread. This compensation is incomplete when bunch to bunch fluctuations are taken into account, but in all cases the compensation is efficient [6]. This compensation is largely helped by the design feature that the two low β^* experimental regions are exactly opposite in azimuth [7] and the same bunch pair collide in the two regions with alternating crossings and the same optical parameters. This requires that the contribution to the long range beam-beam effects from the other two experiments is small. Due to the larger β^* this is guaranteed under nominal operational conditions.

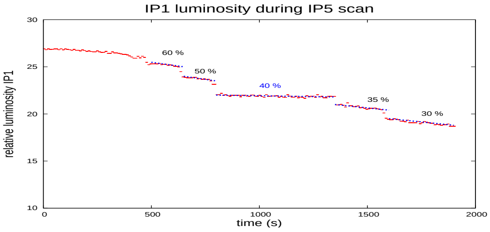

Figure 4: Luminosity in IP1 as a function of time during scan of beam separation in IP5.

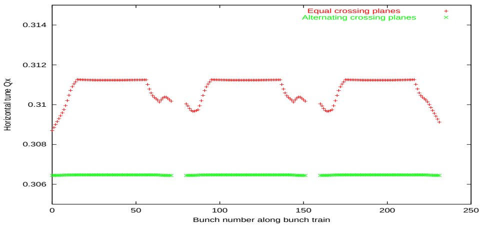

Figure 5: Computed tune along bunch train for equal and alternating crossing planes [5, 6].

PARAMETRIC DEPENDENCE OF LONG RANGE LOSSES

In order to study the dependence of long range effects on the parameters of the beam-beam interaction, we have performed the experiments with different parameters, in particular different β^* and intensities. In the first experiment we wanted to evaluate how the long range losses are affected by higher intensities (compared to previous experiments). Trains with 36 bunches and 1.6 10^{11} p/b with transverse emittances around 2 - 2.5 μm have been brought into collision and the crossing angle α in IP1 and IP5 were reduced in steps from 145 μrad half crossing angle. The normalized separation in the drift space we used for comparison is measured in units of the transverse beam size at the corresponding encounter. For small enough β^* and round beams it can be written as a simple expression

$$d_{sep} \approx \frac{\sqrt{\beta^*} \cdot \alpha \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}}.$$

Beyond the drift space the exact separation has to be computed with an optics program. For our $\beta^* = 0.6\ m$, the initial separation in the drift space was therefore around 9 - 9.5 σ. In a first step the crossing angle (vertical plane) was slowly decreased in IP1 until visible and measurable losses were observed. In a second step the crossing angle in IP5 (horizontal plane) was decreased. In the second test we evaluated the effect of the reduced β^* (compared to previous experiments in 2011) and same intensity (1.2 10^{11} p/b). Since the separation depends on β^* and the crossing angle we can test whether the normalized beam separation at the encounters is the relevant parameter. The relevant parameters of the three experiments are found in Tab.1. The experimental procedure was the same as before: the separation (crossing angle) was reduced until visible losses were observed. The results of a first separation scan with lower intensity are shown in Fig.6. The main observations are that for the case with β^* = 0.60 m and intensity of 1.2 10^{11} p/b starting with separation of $\approx$ 9 - 9.5 σ we observe significant losses at $\approx$ 5 σ separation. The results of a second separation scan with higher intensity are shown in Fig.7. The main observations are that for the case with β^* = 0.60 m and intensity of 1.6 10^{11} p/b starting with separation of $\approx$ 9 - 9.5 σ we observe significant losses at $\approx$ 6 σ separation. The experiments summarized in Tab.1 have been analysed using a recently developed technique to parametrize the strength of the long range non-linearity, based on the evaluation of the invariant and the emittance smear [8, 9]. This method has been used to compare different configurations [9] and allows to derive scaling laws for the dynamic aperture. The onset of losses can be defined as a percentage of the emittance smear at a defined amplitude. For same intensities the losses onset is determined by the normalized separation of the encounters and by the total number of encounters. While the deterioration in the loss onset for higher intensities is explained by an equivalent smear percentage at a defined amplitude. Details can be found in [9].

experiment	emittance(μm)	$\beta^*(m)$	Intensity p/b
2011 (50 ns)	2.0 - 2.5	1.5	1.2 10^{11}
2012 (50 ns)	2.0 - 2.5	0.6	1.2 10^{11}
2012 (50 ns)	2.0 - 2.5	0.6	1.6 10^{11}

Table 1: Parameters for three long range experiments

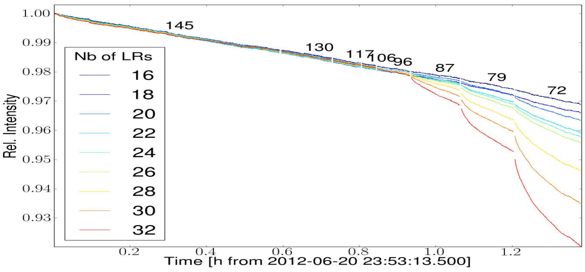

Figure 6: Separation scan with low intensity.

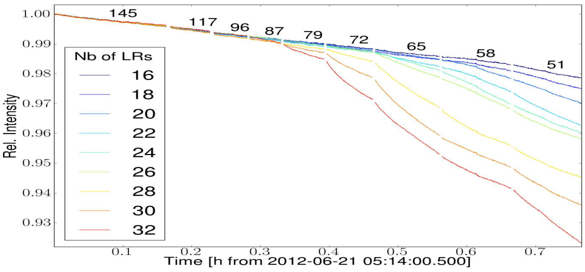

Figure 7: Separation scan with high intensity.

SUMMARY

We have reported on studies of beam-beam effects in the LHC with high intensity, high brightness beams and can summarize the results as: The effects of the beam-beam interaction on the beam dynamics clearly established, effects on the beam lifetime and losses (dynamic aperture) are clearly visible. The number of head-on and/or long range interactions is important for losses and all predicted PACMAN effects are observed. All observations are in good agreement with the expectations and an analytical model [9]. From this first experience we have confidence that beam-beam effects in the LHC are understood and should allow to reach the target luminosity for the nominal machine at 7 TeV beam energy. The analytical model [9] should allow to extrapolate the results to different configurations of future projects and allow an optimization of the relevant parameters.

ACKNOWLEDGEMENTS

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