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OBSERVATIONS OF BEAM-BEAM EFFECTS AT HIGH INTENSITIES IN THE LHC

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First observations with colliding beams in the LHC with bunch intensities close to nominal and above are reported. In 2010 the LHC initially operated with few bunches spaced around the circumference. Beam-beam tune shifts exceeding significantly the design value have been observed. In a later stage crossing angles were introduced around the experiments to allow the collisions of bunch trains. We report the first experience with head-on as well as long range interactions of high intensity bunches and discuss the possible performance reach.

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STUDIES OF HEAD-ON COLLISIONS

The layout of experimental regions in the LHC is shown in Fig.1. The beams travel in separate vacuum chambers

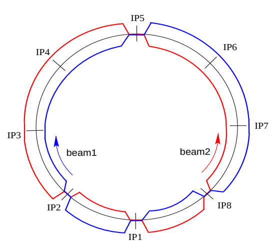

Figure 1: Layout of the experimental collision points in the LHC [1].

and cross in the experimental areas where they share a common beam pipe. In these common regions the beams experience head-on collisions as well as a large number of long range beam-beam encounters [2]. This arrangement together with the bunch filling scheme of the LHC as shown in Fig.2 [2, 3] leads to very different collision pattern for different bunches, often referred to as "PAC-MAN" bunches. The number of both, head-on as well as

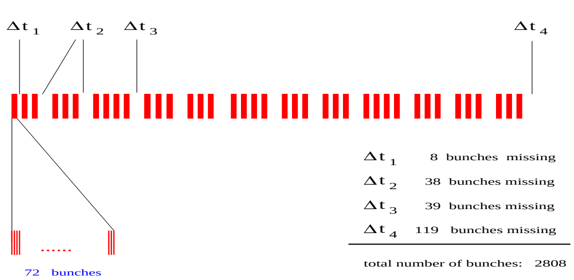

Figure 2: Bunch filling scheme of the nominal LHC.

long range encounters, can be very different for different bunches in the bunch trains and lead to a different integrated beam-beam effect [3]. This was always a worry in the LHC design and the effects have been observed in an early stage of the commissioning. Strategies have been provided to minimize these effect, e.g. different planes for the crossing angles [2, 3].

Head-on beam-beam tune shift

The nominal LHC parameters have been chosen to reach the design luminosity of $1.0 \cdot 10^{34}$ cm^{-2}s^{-1} [1]. The main parameters relevant for beam-beam effects are summarized in Tab.1. At a very early stage of the LHC op-

Table 1: LHC nominal parameters and achieved during operation and experiments in 2010/2011.

Parameter	nominal	achieved
Intensity (p/bunch)	$1.15 \cdot 10^{11}$	$2.3 \cdot 10^{11}$
Emittance	3.75 μm	$\leq$ 2.00 μm
β^*	0.55 m	1.5 m
ξ/IP	0.0035	0.0170
Bunch spacing	25 ns	50 ns
Bunches/beam	2808	1380

eration it was tested whether the nominal beam-beam parameters can be achieved. After this has been successfully demonstrated, we have performed a dedicated experiment to test the achievable beam-beam tune shift. To that purpose we have filled the LHC with single bunches per beam, colliding in IP1 and IP5 (see Fig.1). We have used bunch intensities of $\approx 1.9 \cdot 10^{11}$, i.e. well above the nominal and the emittances have been reduced to $\leq$ 1.20 μm in both planes. It was shown that such bunches can be collided in both interaction points without significant losses or emittance increase [7] and we have demonstrated that a beam-beam tune shift of 0.017 for a single interaction and an integrated tune shift of 0.034 for both collision was possible. These tune shifts have been obtained in the absence of any long range encounters and it should be expected that the operationally possible tune shifts are lower.

Effect of number of head-on collisions

Due to the filling pattern in the LHC, different bunches experience different number of head-on as well as long range interactions. Details are given in another contribution [4]. In Fig.3 we show as illustration the losses of bunches with very different (0 - 3) number of head-on collisions. The data was taken during a regular operational fill of 10 hours duration. The correlation between losses and number of head-on collisions is apparent and a more detailed analysis is found in [4]. The transverse emittances

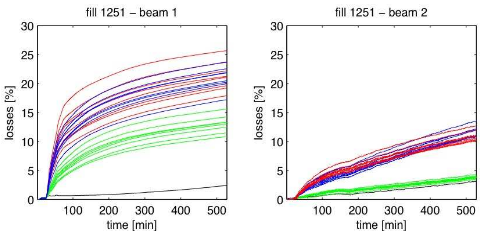

Figure 3: Losses of bunches with different number of head-on collisions [4]. Numerology: blue (3 collisions), red (2 collisions), green (1 collision), black (no collision).

during normal operation are larger ($\approx$ 2.5 μm) than in the head-on test. In a second experiment we increased the bunch intensity further to $\approx 2.3 \cdot 10^{11}$ with emittances $\approx$ 1.80 μm. Although the tuneshift was slightly lower than in the previous experiment (0.015), the lifetime was worse. We interprete these results as losses of particles at large amplitudes. This is supported by the observation that the strongest losses occur at the very beginning of a fill (Fig.3).

STUDIES OF LONG RANGE INTERACTIONS

To study the effect of long range beam-beam interactions we have performed a dedicated 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} protons and the normalized emittances around 2.5 μm. 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 [10] and the results are shown in Fig.4 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. From Fig.4 we observe significantly increased losses for some bunches when the separation is reduced to about 40%, i.e. around 5 σ. 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 [8]. 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.5 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. The smallest loss is found for bunches with the minimum number of interactions, i.e. bunches at the beginning and end of the train [2, 3]. This is a very clear demonstration of the expected different behaviour, depending on the number of interactions.

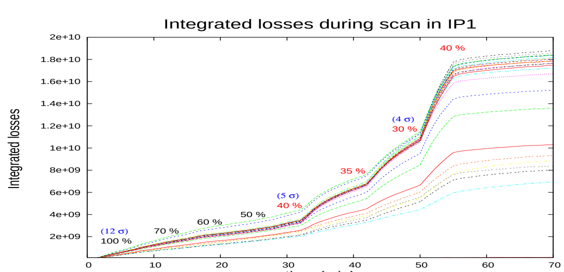

Figure 4: Integrated losses of all bunches as a function of time during scan of beam separation in IP1. Numbers show percentage of full crossing angle.

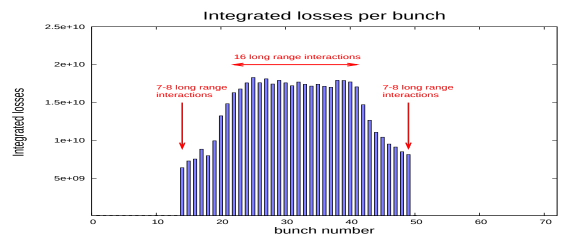

Figure 5: Integrated losses of all bunches along a train of 36 bunches, after reducing the crossing angle in IP1.

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 (Fig.1). 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 [2]. The Fig.6 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

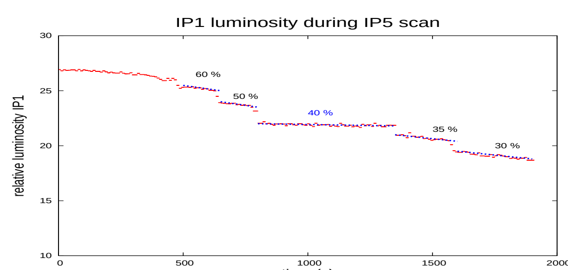

Figure 6: Luminosity in IP1 as a function of time during scan of beam separation in IP5.

compensation due to alternating crossing planes, although further studies are required to conclude.

Further observations of PACMAN effects

Another predicted behaviour of PACMAN bunches are the different orbits due to the long range interactions. To study these effects, a fully self-consistent treatment was developed to compute the orbits and tunes for all bunches in the machine under the influence of the strong long range beam-beam interactions [9]. In Fig.7 we show a prediction

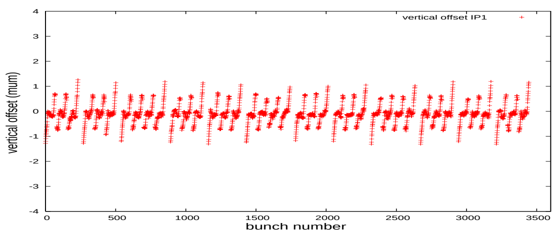

Figure 7: Computed orbit offsets in IP1 along the bunch train [2, 3].

for the vertical offsets in IP1 [2, 3]. The offsets should vary along the bunch train. Although the orbit measurement in the LHC is not able to resolve these effects, the vertex centroid can be measured bunch by bunch in the experiment. The measured orbit in IP1 (ATLAS experiment) is shown

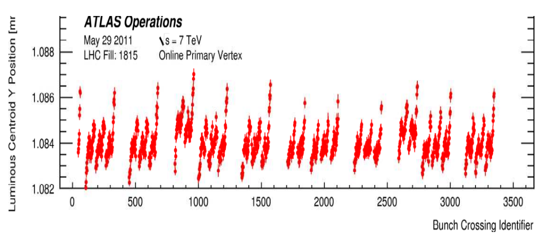

Figure 8: Measured orbit offsets in IP1 along the bunch train [5, 6].

in Fig.8 and at least the qualitative agreement is excellent. This is a further strong indication that the expected PACMAN effects are present and understood and that our computations are reliable.

OPERATION WITH STATIC OFFSETS

Since the LHC experiments have very different requirements, it is necessary to keep the luminosity at a constant and lower level in interaction points IP2 and IP8, while the highest possible luminosities are required in IP1 and IP5. The necessary reduction in IP2 and IP8 cannot be achieved by a larger β^* and the "leveling" is more problematic. As an easy solution it was proposed to collide the beams in these experiments with a small transverse offset between 1 and 4 σ. Although it was thought to be the source of possible problems, this scheme was tested in the machine [11] and found possible. It is now an operational procedure. More details can be found in another contribution to this conference [11].

SUMMARY

We have reported on the first studies of beam-beam effects in the LHC with high intensity, high brightness beams and can summarize the results as:

- Effect of the beam-beam interaction on the beam dynamics clearly established
- LHC allows very large head-on tune shifts above nominal
- Effect of long range interactions on the beam lifetime and losses (dynamic aperture) is clearly visible
- Number of head-on and/or long range interactions important for losses and all predicted PACMAN effects are observed

All observations are in good agreement with the expectations. 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.

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