OPTIMIZATION OF THE LHC SEPARATION BUMPS INCLUDING BEAM-BEAM EFFECTS

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Abstract

The LHC beams will cross each other and experience perturbations as a result of the beam-beam effect at the interaction points, which can result in emittance growth and halo creation. The beam-beam force is approximately linear for small offsets and highly non-linear for larger offsets with peaks in growth close to 0.3 and 1.5 σ separation. We present a study of the process of going into collisions in the LHC and use simulations to investigate on possible emittance blow-up. We analyze how the crossing scheme can be optimized to minimize the collapsing time of the separation bumps for given hardware constraints.

INTRODUCTION

The nominal LHC will be filled with two beams of 2808 bunches colliding in four interaction points. The crossing schemes were designed [1, 2] using a crossing angle in one plane to avoid parasitic collisions outside the interaction points. During injection, ramp and squeeze, beams are also kept separated at the interaction points by parallel separation in the other transverse plane. The time which is required to put the beams into collisions is given by the collapsing time for these parallel separation bumps.

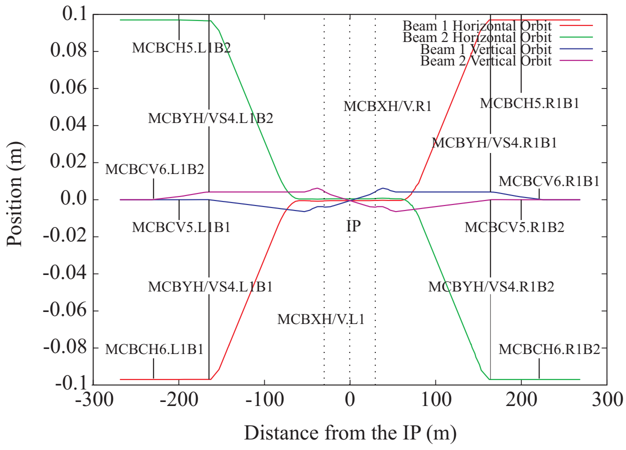

Figure 1: Crossing scheme in both planes at IP5.

Figure 1 shows as example the crossing scheme used at IP5 (CMS) in the horizontal and vertical plane. It is realized using six dipole corrector magnets per plane and beam and involves three different hardware types, called MCBC, MCBY and MCBX. The MCBC and MCBY magnets are further away from the interaction point and are installed as separated magnets in the horizontal and vertical plane acting individually on each beam. The MCBX magnets closer to the IP are special nested magnets which affect both the horizontal and vertical plane and are common for the two beams.

Table 1: Characteristics of the Orbit Corrector Magnets Around the IP

Magnet	Nominal I [A]	dI/dt [A/s]	d^2I/dt^2 [A/s^2]
MCBX	550	5	0.5
MCBY	72	0.67	0.25
MCBC	80	0.67	0.25

Table 1 shows the nominal settings of those orbit correctors. Those values were not achieved for all MCBX in the first hardware commissioning campaign. Collapsing the separation bumps consists of ramping all the correctors fields down to zero. In this process we will assume the ramp with a parabolic-linear-parabolic ramp. The parabolic phases depend on an acceleration term and the linear phase on dI/dt. The separation at the IP varies linearly with the current applied to the correctors.

OPTIMIZING THE COLLAPSING TIME VIA OPTICS REMATCHING.

It is possible to find the minimum collapsing time by varying the strength of the MCBX. This was done using the matching procedures of the MAD-X program [3].

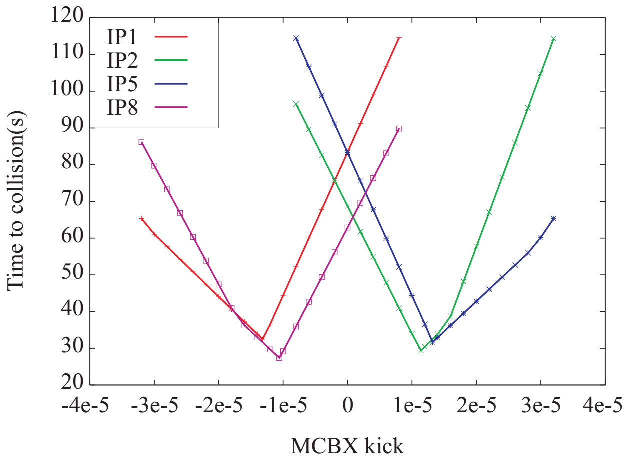

Figure 2: Evolution of the collapsing time with the MCBX strength. LHC version 6.503, collision optics at 7TeV.

Figure 2 shows the evolution of the collapsing time versus the MCBX angular kick at the four IPs for the nominal 7 TeV LHC optics (full separation at the four IPs). Given the actual hardware settings, the limitation comes from the

MCBX and the collapsing time only depends on its acceleration and ramping rate. Table 2 summarizes the results for the nominal LHC optics. In the case of low β^*, the time is limited by the deceleration (10s to go from the maximum dI/dt to zero for a ΔI of 25A). It is likely that the LHC will be operated in the first year at 5 TeV with β^*=2m and a nominal separation of 2 mm. The optimized collapsing time in this case would be approximately 60 s from full separation and 18 s from 14 σ.

Table 2: Summary table. t represents the expected collapsing time in seconds for full separation (1 mm at 7 TeV) and 14 σ separation.

	β^* [m]	t_{full} [s]	$t_{14\,\sigma}$ [s]
IP1	0.55	33	11
IP2	10	27	27
IP5	0.55	32	11
IP8	10	29	29

BEAM-BEAM EFFECTS WHILE BRINGING THE BEAMS INTO COLLISIONS.

In the process of collapsing the separation bumps to bring beams into collision, each beam will be influenced through the beam-beam interactions by the bunches of the counter-rotating beam. The forces depend on the actual, dynamically varying separation and beam shapes and influence the trajectories of the particles in each beam.

Simulation model and observations

Many detailed beam-beam simulations have been performed for the LHC for the static case with fixed offsets [4, 5]. A first study of dynamic effects was presented in [6]. Many details on beam-beam effects in the LHC can found in [7]. Here we describe recent studies in which we dynamically change the separation between the colliding beams. We know that emittance blow up and lifetime in the presence of beam-beam may critically depend on many parameters and may substantially vary in a real machine from fill to fill. The studies presented her are mostly intended as a guidance for further work with optimization on the actual machine. For the dynamic simulations discussed here, we found it convenient to start from the object oriented program BeamTrack [8]. Beams are described as ensembles of macroparticles and the accelerator as a set of 6D transformations acting on the beam. The code has a simple, easily expandable input/output interface and optional display. We recently added the simulation of beam-beam effects with programmable, time dependent separation. The number and spatial distribution of macroparticles in each beam can be specified separately and allows for both strong-weak and strong-strong simulation. The beam-beam kicks are calculated using the actual average beam positions and rms beam sizes and the analytical Bassetti-Erskine field calculation. Both central and parasitic (long range) collisions are simulated. In the work reported here, we allow for collisions in two interaction points, IP1 (ATLAS experiment) and IP5 (CMS). If not stated otherwise, we use nominal LHC parameters at 7 TeV/c beam momentum. For the 25 ns nominal bunch spacing, parasitic encounters occur at multiples of 12.5 ns (3.747 m) up about 58 m on either side of the IP. The phase advance between the interaction points and the parasitic collisions is close to 90°. This allows in good approximation to simulate the n parasitic collisions around each IP by a single, n times stronger kick. We checked that the tune footprint of our simulation matches quite well with the expectations of the detailed MAD-X based model, see Fig. 3.

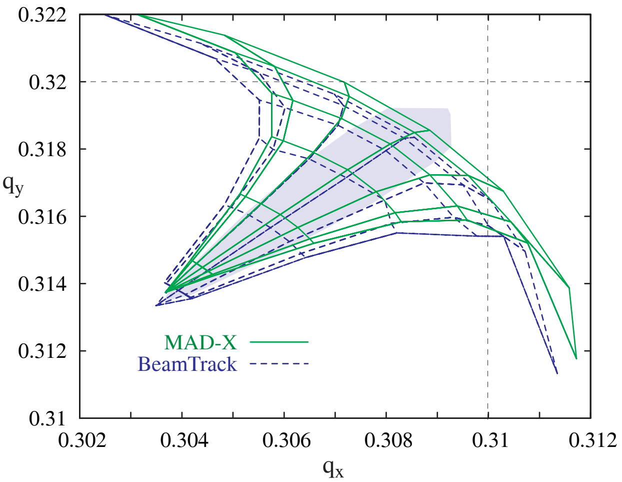

Figure 3: Comparison of tune footprints for 0, 1, .. 6 $\sigma_{x,y}$ obtained with detailed MAD-X simulation and our simplified model (dashed blue lines), for nominal LHC beam parameters with central and parasitic collisions in IP1&5. The shaded area shows the 0-6 σ tune fooprint from BeamTrack without parasitic collisions.

The strong-strong simulation is restricted to Gaussian-beams for the calculation of the beam-beam kick. The weak-strong approximation allows for some limited checks on the effect of the opposite beam on non-Gaussian distributions. We expect the simulations to still be approximately valid for situations in which we consider the effect of one gaussian beam and a non-Gaussian witness beam or for cases with a small contribution of extended tails in addition to a gaussian core. From tests with a flat probe beam colliding with a gaussian beam, we find that particles with amplitudes above 7 σ will be stripped off within seconds by the parasitic beam-beam encounters of the gaussian beam.

The early operation of the LHC will be without crossing angle, for the nominal 2808 bunches per beam, the crossing angle is required and there will be 30 long range beam-beam interactions around each interaction point. The two scenarios, no parasitic crossings (as for the early operation) and full nominal parameters with 30 parasitic crossings per IP were studied by tracking 10^6 macro-particles for each beam. The collapsing of the separation bumps was modelled by a linear function in time which underestimates by a factor two the time spent at small separation (deceleration of the magnets). All the simulations were performed with the nominal LHC intensity (1.15×10^{11} p/bunch) and collision tunes ($Q_x = 64.31$ and $Q_y = 59.32$). The first step in our recent simulation campaign was to look at runs without parasitic encounters, just with head-on collisions. In this case, the simulations did not produce any significant emittance increase, in agreement with static case simulations [4]. In shorter test runs, we also simulated the head-on case with a tenfold increase in intensity or by placing one of the tunes close to the third order resonance. This both resulted in significant blow-up.

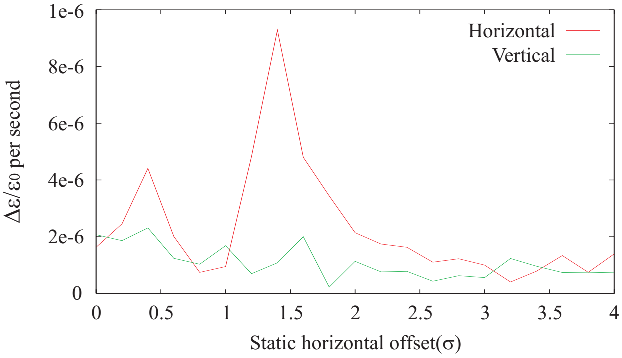

Figure 4: Emittance growth for different horizontal static offsets with beams colliding head-on in one IP .

With the long-range beam-beam effects added, we started to see emittance growths for nominal parameters on the level of a few percent over time scales of seconds as relevant for bringing beams into collisions.This is shown in Fig. 5 for going into collisions in 1, 5 or 10 seconds starting from 14 σ separations.

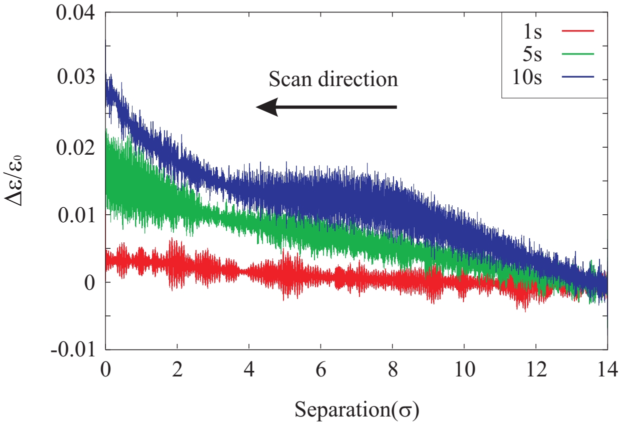

Figure 5: Emittance growth from simulations for different collapsing speeds in the case of two IPs with long range.

In the example shown, beams collide in IP5 and the parallel separation is ramped down to zero in IP1. The blue curve which has the largest effect corresponds to what is actually anticipated for the collapsing time based on the parameters as given in Table 1. Even with optimistic input conditions simulations show a sizeable emittance blow-up that could be reduced by going faster into collisions. Emittance exchange can occur between beams and planes. We quadratically add the emittances of the two planes according to

$$\varepsilon_i = \sqrt{\frac{\varepsilon_{xi}^2 + \varepsilon_{yi}^2}{2}}, \quad (1)$$

to allow to refer to a single number for the emittance increase. Towards smaller separation, the growth appears to increase. This can be expected from the shape of the beam-beam forces which become more non-linear and is also seen in static simulations at fixed separation [4].

Discussion

We studied the dynamics of bringing beams into collisions in the LHC. On the more practical side, we have shown that we have some flexibility to minimize the time needed to bring beams into collisions by choosing an optimal distribution of strengths between the magnets involved. These studies were complemented by beam-beam simulations. For nominal LHC beam parameters with both central and parasitic beam encounters the simulations show a sizeable emittance increase when beams are brought into collisions, which can be minimized by a further reduction of the time in which beams are brought into collisions. The studies presented here are mostly intended as a preparation and basis for the work with actual first colliding beams in the LHC, expected later this year. Only a comparison with observations in the machine can tell what the amplitude of the effect will be but simulations showed that it is desirable to have more flexibility in terms of how fast we can collapse the separation bumps. In addition, we may have significant non-gaussian tails which are hard to predict and simulate, but which may be quite important for machine protection and experimental conditions and cause machine induced backgrounds visible in the detectors.

Acknowledgement

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