Beam-beam issues for LHC upgrade phases 1 and 2

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Abstract

While long-range beam-beam interaction will not be the limiting effect in the first years after LHC start-up, it will definitely become one in the upgrade scenarios. Upgrade phase 1 will include an exchange of the triplet magnets allowing for a $\beta^* = 25$ cm optics. Phase 2 is an even more ambitious upgrade that will include a modification of the detectors. Currently two phase-2 upgrade scenarios are proposed: the "Dipole Zero" (D0) and the "Large Piwinski Angle" (LPA) option.

After some general notes and a brief description of the applied simulation model, the upgrade phase 1 issues and optics will be discussed with regard to beam-beam performance. The following two sections will deal with upgrade phase 2.

GENERAL

BBTrack [5], a weak-strong 6D tracking code, was used to track (linear transfer matrices between nonlinear elements, interaction points (IPs) 1 & 5 only) particle distributions (initial energy offset $\delta p/p = 2.7 \times 10^{-4}$) for 300,000 turns in LHC at top energy (7 TeV) and determine the particle stability with help of the Lyapunov exponent. The dynamical aperture (DA) is defined as the amplitude at which 40% of the particles in a radial range of width $\delta r = 0.2\sigma$ are chaotic.

For comparison, the main beam-beam parameters of the nominal LHC are: 15 LR collisions at each side of the IP ($\beta^* = 0.55$) with a full crossing angle $\theta = 284\mu$rad (average separation $\bar{d} \approx 9.5\sigma$) at 1.15 p/bunch. This crossing angle was chosen to obtain an acceptatble long-range beam-beam effect [4]. Namely with this crossing angle a dynamic aperture (DA) of 5.4σ is expected that could be improved to $DA = 7.2\sigma$ by a wire compensation [6].

LHC UPGRADE PHASE 1

By 2013 the whole triplet will need to be exchanged and a new interaction region (IR) scheme with $\beta^* = 25$ cm will be implemented in order to boost the luminosity. In the following, 3 different optics - "low β max", "modular" and "compact" - as proposed by R. de Maria et al in [7] - are briefly discussed. A forth option, similar to the low β max one, called "symmetric" was proposed by J.P Koutchouk, E Todesco et al in [2]. In order to keep an average beam-beam separation of $\bar{d} \approx 9.5\sigma$ the crossing angle in all three options is increased with respect to the nominal LHC (from $\theta = 284\mu rad$ to 450μrad). Given the same magnet technology, the stronger focussing requires a longer triplet and hence it introduces more long-range beam-beam encounters (LRBBIs). The number of long range beam beam encounters (LRBBIs) and other important parameters are summarized in Table 1 and Fig. 1. In order to cope with these additional LRBB encounters and potentially also with a higher beam current or simply to improve the nominal beam-beam performance a wire compensator (BBLR) is foreseen. A wire compensation does not interfere with the IR design as it only requires a) that the wire be placed at a position with equal β-function in both transverse planes, b) a reasonably large β to allow accommodating a wire compensator with a practical wire diameter and c) a small phase advance between the wire and the LRBBIs. Suitable positions can be found in all scenarios. Simulations showed that the simple criterion of minimizing the number of LRBBI is a reasonable guide for optimisation, and that accordingly the low β-max optics performs best. Its DA for 1.15×10^{11} p/bunch is 5.1σ. For 1.7×10^{11}p/bunch the DA shrinks to 3.8σ. Figure 3 a) shows the stability diagram of the low β max optics. Subfigure b) shows that a wire compensation can reduce the tune footprint to the head-on one. Figure 4 demonstrates the enhanced DA due to the wire compensator.

variable	nominal	low β max	Compact	modular
β^* [m]	0.55	0.25	0.25	0.25
#LRBBIs	16	19	22	23
wire @ [m]	104	136	170	160
β_{wire} [m]	1780	3299	2272	3000
σ_{dsep}	1.6	3.6	2.2	X

Table 1: Comparison of three proposed phase 1 upgrade optics with respect to their long-range beam-beam (LRBB) performance.

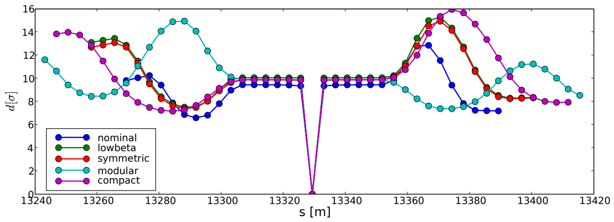
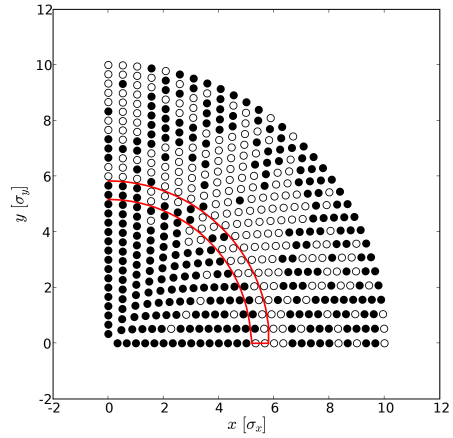
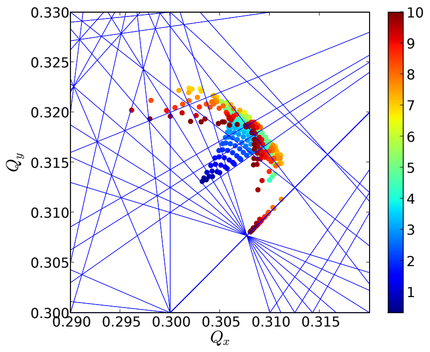


Figure 1: Comparison of the normalized beam-beam separation at IP5 for the nominal LHC and four upgrade scenarios.



(a) Stability. black=stable, white=chaotic



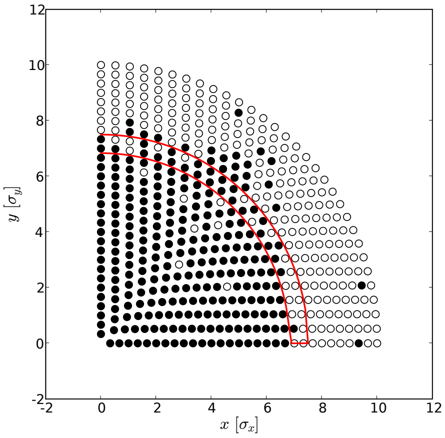
(b) Tune footprint

Figure 2: Low β max optics for $1.15 \cdot 10^{11}$ p/bunch

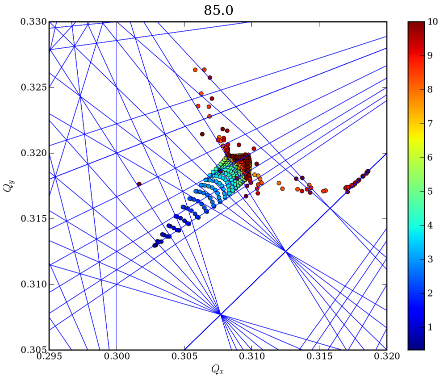
LHC UPGRADE PHASE 2 - 'DIPOLE ZERO' (D0)

General notes

One scenario for the phase-2 upgrade foresees the installation of an “early separation” dipole “D0” about 6m from the collision point and a reduced crossing angle [3]. This scheme implies two long range encounters at a reduced separation of about 5σ on each side of the two high-luminosity IPs. Unfortunately no consistent optics was made available for this scheme, so we have added a D0 to the low β max optics. While this allows to study beam-beam issues realted to close encounters, it may not properly model two essential components of the whole picture: 1) Although the HO collision is scale invariant, the reduced spot size ($\beta^* \approx 8cm$) at the IP causes a large increase of the sensitivity to noise created within the focussing system. As the D0 is part of the latter and its adequate mounting is challenging this issue could be important. 2) As mentioned above, also a decrease in β^* causes an increase of triplet length and it requires a larger crossing angle in order to keep the same normalized beam-beam separation. For those two reasons it is not possible to reduce the problem to the simple question “can we stand two close encounters?”



(a) Stability

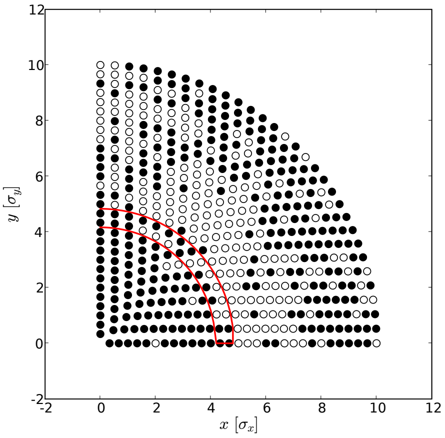


(b) Tune footprint

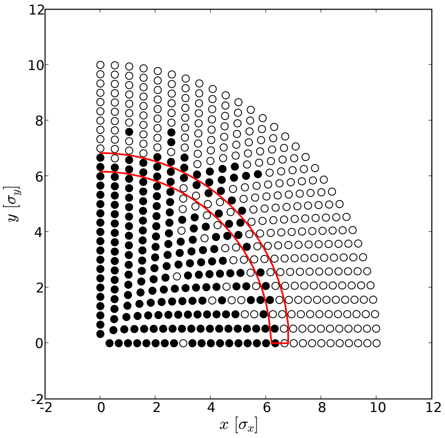
Figure 3: The low β^* max optics: A wire compensator could eliminate the long-range beam-beam tune spread and increase the DA to 7σ.

Studies

Figure 5 a) shows the beam-beam separation of our model and b) compares the footprint with and without the D0 activated. Though the footprint appears to be smaller with D0, the stability is worse: While the tunes of high and low amplitude particles are shifted equally, intermediate amplitude particles behave differently: With D0 present the footprint folds at lower amplitudes. This tune footprint folding (which unfortunately could not be reproduced in the SPS or RHIC machine studies so far due to the lack of a head on collisions) proved to be one of the main instability-contributions in simulations. Fig. 6 demonstrates that this folding at lower amplitueds indeed reduces the DA already for nominal beam current. Going to the ultimate intensity of $1.7 \cdot 10^{11}$ p/bunch - as foreseen for this optics - leaves an unbearably small stable region. In this case no wire compensation can be used, since the wire has a finite diameter, only functions in hte 1/r regime of the beam-



(a) The DA of the compact optics is $\approx 4.2\sigma$



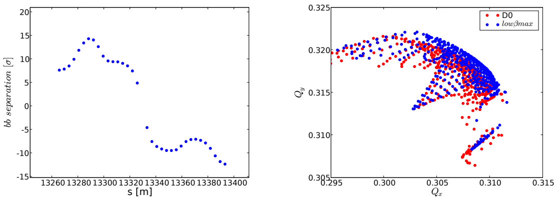
(b) A wire compensation could increase the DA of the compact optics to $\approx 6.2\sigma$

Figure 4: Stability diagrams for the "compact" optics with and without wire compensator.

beam force and must be placed in the shadow of the collimators at amplitudes above 7σ. Only an electron lens used "as wire" would be an option. Figure 8 shows a stability study considering only the head-on interaction and two long-range encounters per side of each IP at a variable distance. The minimal acceptable beam-beam separation seems to be around 6.5σ.

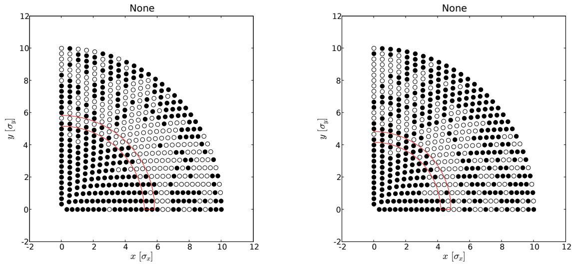
RHIC

Experiments at RHIC and at the CERN SPS have been performed in order to study the effect of close encounters [8]. While the results of these experiments help to understand the loss mechanisms and to benchmark simulations, they must be treated with caution when extrapolating to the LHC due to the lack of head-on collisions. For example the phase-1 upgrade optics "low β max" produces in simulations a DA of 3.8σ for 1.7×10^{11}p/bunch including HO while without HO at 2.5×10^{11} a DA of 5σ!



(a) Normalized beam-beam separation in the D0 considered optics (b) Tune footprint of the low β max optics with and without D0 model

Figure 5: Beam-beam separation and tune footprint for our model D0 option.



(a) Stability in the base line low β max optic (b) Stability with the D0 activated

Figure 6: Stability diagram for the DO option with the nominal bunch charge of 1.15×10^{11} p/bunch

Figure 9 shows two typical results of the RHIC beam-beam experiments with a single long-range encounter at varying beam-beam distance. First losses are observed at about 7σ separation. Results of parameter scans obtained with the RHIC wire compensator (Fig. 10) show an onset of beam loss at 6σ for a wire strength euqivalent to 2 LR encounters.

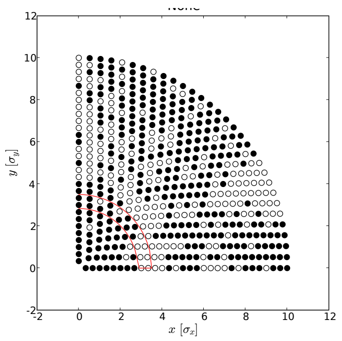
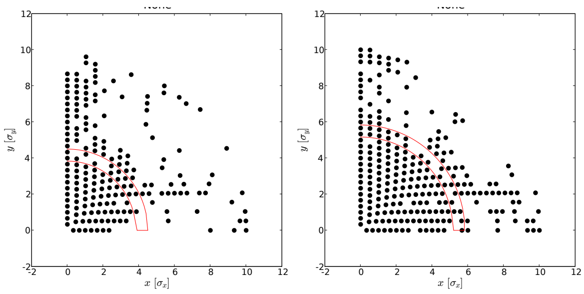
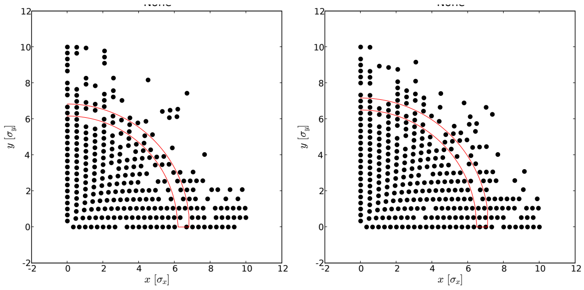


Figure 7: Stability diagram for the D0 upgrade scenario with $1.7 \cdot 10^{11}$p/bunch

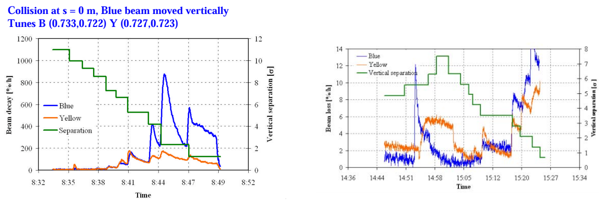


(a) 5σ (b) 6σ



(c) 7σ (d) 8σ

Figure 8: Stability diagram for the D0 model with HO and 2 LR encounter per side per IP at 1.7×10^{11} p/bunch and varying separation(crossing angle)



(a) Injection energy. (b) Top energy

Figure 9: RHIC Beam-Beam experiments with a single long-rang ebeam-beam encounter and a bunch population of 1.5×10^{11}p/bunch. shown are the loss reates for both beams and the normalized distance as a function of time.

D0 - CONCLUSION

While the idea of separating the two beams as early as possible seems to be an obvious aproach to take, it faces potentially severe long-range beam-beam issues in addition to detector integration issues. With few exceptions the - due to the lack of HO - optimistic experiments at RHIC and the CERN SPS indicate a drastically perturbed beam-stability already with a single long-range encounter at 6-7 σ separation. In addition numerous issues such as the crab cavity, likely required in this scheme, and the electron lens for compensation must be addressed. To study these questions in detail, it is of great importance to develop a realistic optics as soon as possible.

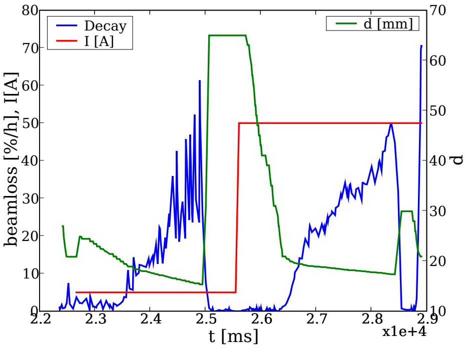


Figure 10: Distance scan with RHIC BBLR at top energy (100 GeV Ions) with transverse beam size $\sigma = 4mm$. Shown are the beam loss and the absolute beam-wire distance as a fucntion of time.

LHC UPGRADE PHASE 2 - LARGE PIWINSKI ANGLE (LPA)

The second proposed upgrade scenario is the LPA [1] comprising $4.9{\cdot}10^{11}$ p/bunch with flat beams at 50 ns bunch spacing corresponding to an LR effect enhanced by a factor of 2.5 compared to nominal LHC. Figure 11 shows the stability region and the tune footprint of this option. Only a wire compensation can make the LPA viable (Fig. 12)

LPA - conclusions

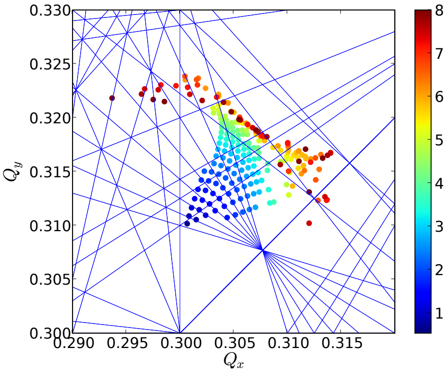
The LPA option has the advantage of being predictable. As its optics layout will be very similar to that one of upgrade phase 1 and not too different from nominal LHC, experimental tests can be performed at the original LHC. The wire compensation can be installed without any risk at any time and its effectiveness can be proven already in the nominal LHC. In case crab cavities become indeed operational they can be installed as a complement. The impact of the synchro-betatron resonances, more strongly excited at a large Piwinski angle, must be studied in more detail but it is not expected to be a severe issue for the low synchrotron tune of the LHC.

CONCLUSION

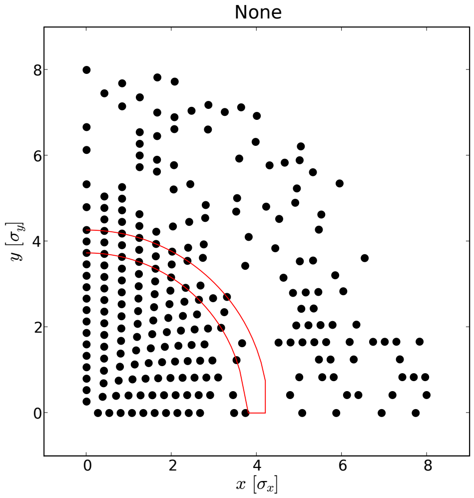
The preferred optics for phase 1 is the low β max optics as it features the lowest number of long-range beam-beam encounters. Seen from the LRBB point of view the LPA option appears more robust and more predictable for the LHC upgrade phase two.

Thanks

The authors want to thank R. de Maria for his continuous support with the upgrade optics, R. Calaga, R. Tomas, J.P Koutchouk and G. Sterbini for the fruitfull co-operation and the RHIC BBLR team for helpfull input.

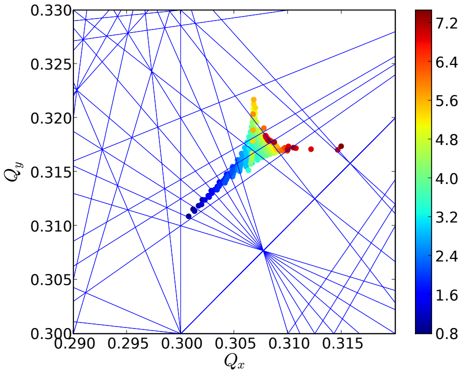


(a) Tune footprint

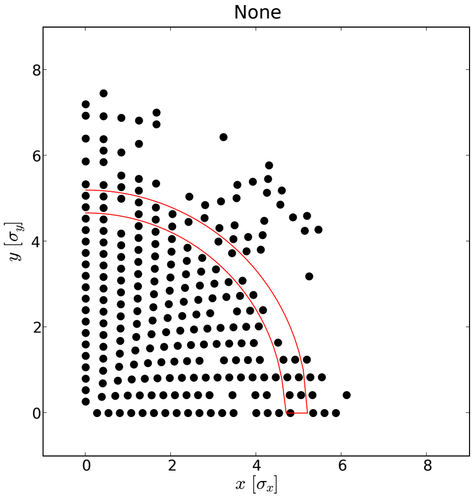


(b) Stability diagram

Figure 11: Tune footprint and stability diagram for LPA



(a) Tunefootprint



(b) Stability diagram

Figure 12: Tune footprint and stability diagram for LPA for LPA with wire compensation

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