Analytical studies of beam-beam effects for the HL-LHC

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Around the experimental regions of the Large Hadron Collider (LHC) beams travel in a common vacuum chamber and therefore experience the fields of the opposing beams, so-called long range interactions. The number of these parasitic encounters depends on the lengths of the common regions before the beams are sufficiently separated by dipole magnets, and on the bunch spacing. For a fixed encounter, the effect of the long-range interaction depends on the beam separation normalized to transverse beam size.

The TRIUMF-CERN collaboration on High-Luminosity Upgrade of the LHC (HL-LHC) is focused on investigations of these beam-beam interactions and their influence on beam quality which in turn affects the maximum achievable luminosity. Although beam-beam effects are dominant to decrease the available dynamic aperture of the HL-LHC beams at collision, for correct calculation of dynamic aperture they must be considered in combination with the other nonlinearities present.

Our main activity remains particle tracking in a latest version HL-LHC lattice which includes beam-beam effects and field errors. The aim is to compute the dynamic aperture (DA), its dependence on parameters and tune-scans: DA values for a dense set of points in horizontal/vertical tune space allowing to see decremental effects of betatronic resonances.

Another important objective is advancing the theory of motion in presence of multiple long-range beam-beam interactions. This should allow to understand better the combination of factors influencing DA. Most promising are analytical calculations of the combined action of all long-range collisions (as an effective Hamiltonian, or approximate invariant of motion) and the interpretation of the distortion of this invariant (emittance smear) as early indicator of chaotic motion, The one-dimensional version of this theory, developed and reported in the past, was recently confirmed to explain the resonance locations: [1] and [2].

The above, in terms of Hamiltonian mappings, is in fact equivalent to finding the lowest order “normal form”. It therefore requires a two-dimensional beam-beam Hamiltonian to be expressed in the so called resonance (action-angle) basis. As this was done, the resultant Fourier-expansion coefficients appeared to be nearly identical to some little known mathematical objects – two-dimensional Bessel functions. Low-order such functions were shown to describe the tune shift with amplitude, beam-beam footprint, in exact agreement with HL-LHC tracking, [3]. The higher-order ones possess, same as their standard 1D counterparts recursive properties that were used in [3] to compute them fast numerically. Finally, the symmetries and recursions obeyed by the beam-beam Hamiltonian coefficients may be of direct interest since the combined effect of all long-range encounters around the ring depends strongly on the left-right (anti) symmetries of the HL-LHC insertions.

References

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[2] D. Kaltchev, *Tune-scans and working point optimization for colliding beams in HL-LHC*, Presentation at the Beam-Beam Effects Workshop, Berkeley CA, Feb 5 – 7, 2018

[3] D. Kaltchev, *Fourier Coefficients of Long-Range Beam-Beam Hamiltonian via Two-Dimensional Bessel functions*, Proc. of IPAC 2018, Vancouver BC, Canada