Strong Head-on Beam-Beam Interactions

GPU Accelerated Modelling of Nonlinear Effects

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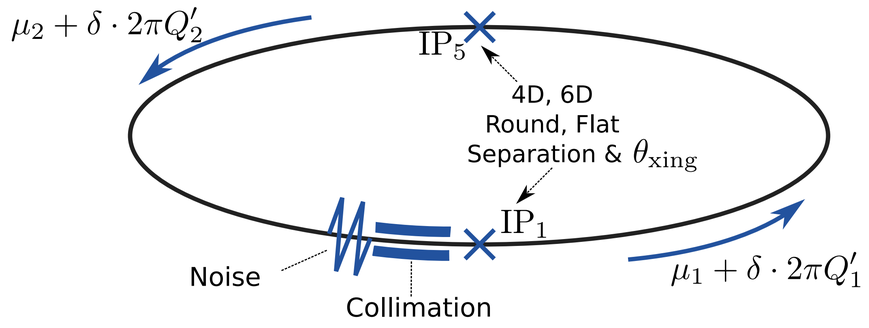
Summary

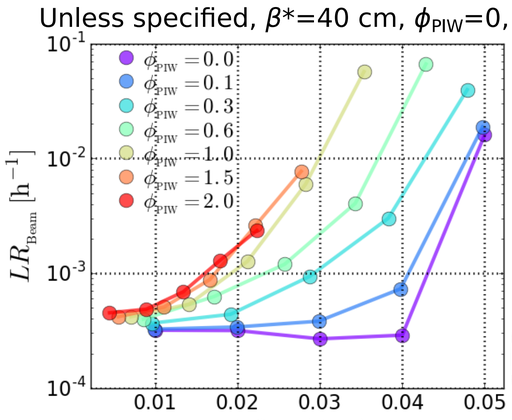
We study limitations caused by strong incoherent head-on beam-beam interactions, using a GPU-based code (CABIN) achieving a speedup of more than 1000. The emittance and intensity are monitored to study the impact quantitatively. A new initial distribution in 6D phase space has been developed to study both with a limited number of macroparticles. FMAs are applied to study the impact qualitatively. Simulation results show agreement with an MD in the LHC. With the FCC baseline parameters, based on the LHC tunes, a realistic maximal total beam-beam tune shift has been found to be approximately 0.02. There are modifications that allow for the ultimate FCC-hh tune shift of 0.03 [1,2].

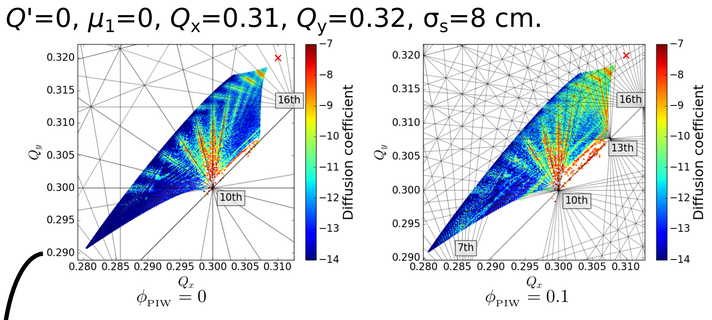
The model (figure below) consists of two interaction points, where the interaction can be 4D or 6D, round or flat, and with a separation and crossing angle in opposite planes.
The IPs are separated by two independent stretches of lattice inflicting a linear phase advance dependent on chromaticity, such that $(\mu_1+\mu_2)/2\pi=Q$ is the tune in the ring.
In the end of each turn, a gaussian, incoherent noise is applied, and all particles beyond an elliptical limit in transverse cartesian space are counted as lost to model the collimation.



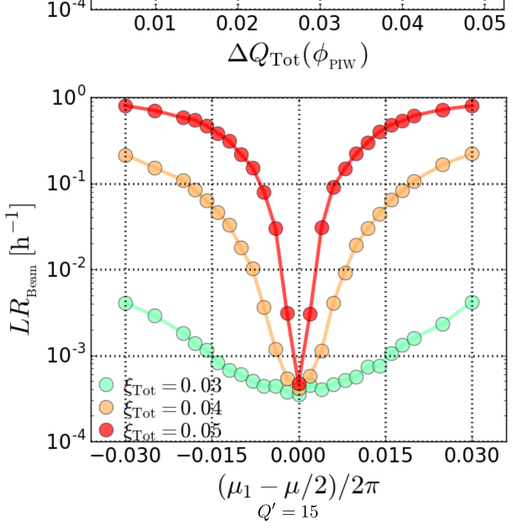
Dynamical effects

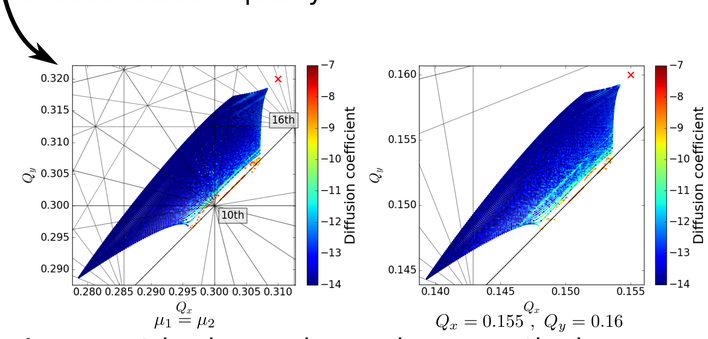
Unless specified, β*=40 cm, ϕ_{PIW}=0, Q'=0, μ_1=0, Q_x=0.31, Q_y=0.32, σ_s=8 cm.



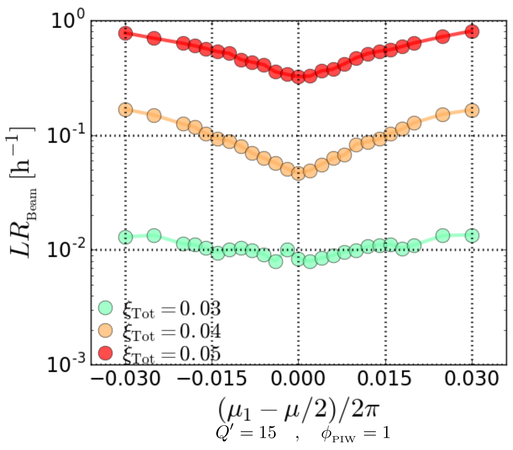


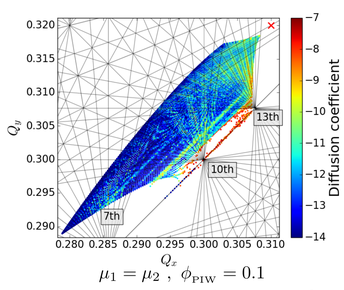
A crossing angle activates odd resonances. For large beam-beam parameters, these resonances strongly affect the beam quality.



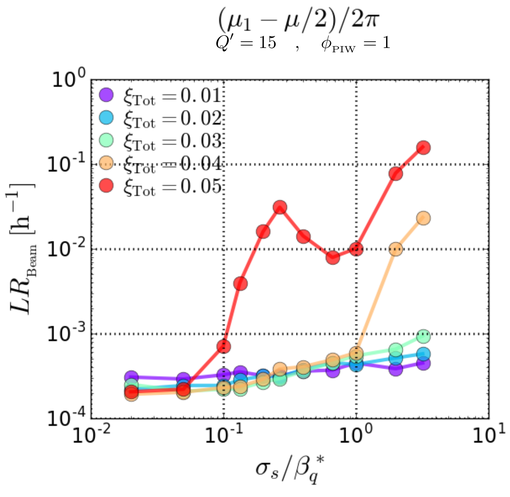


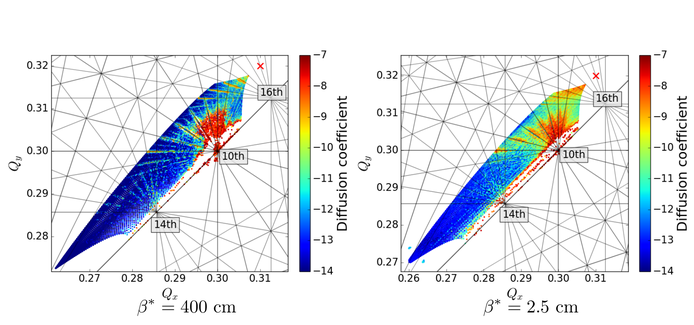
A symmetric phase advance improves the beam quality. This setup is equal to a shorter ring with half the fractional tune and beam-beam tune shift. The required phase accuracy increase with ξ_{Tot}.



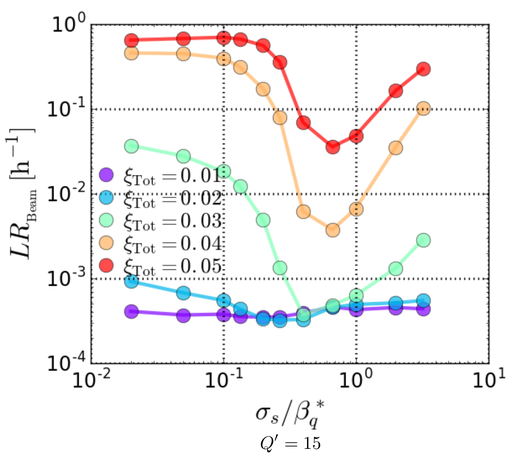


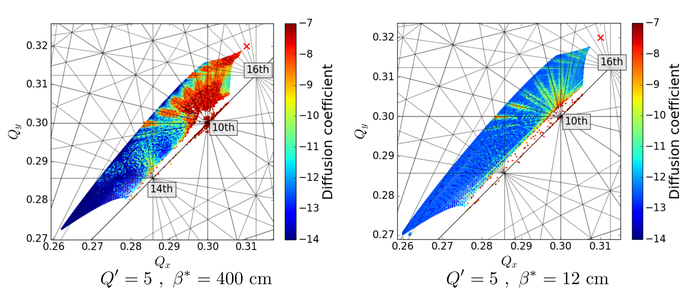
A nonzero crossing angle destroys the symmetry, the improvement is negligible compared to the case with zero crossing angle.





The hourglass effect causes mixing of the longitudinal and transverse dof, and activates beta-synchrotron resonances. The odd resonances are not affected.

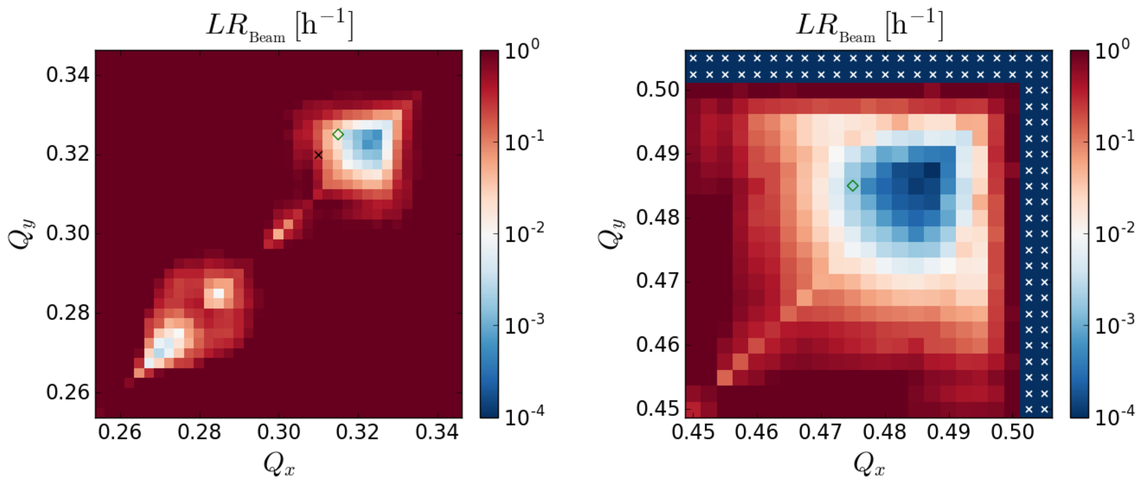




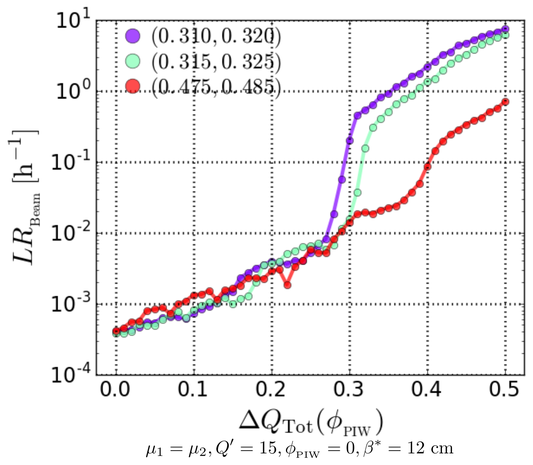
Chromaticity activates beta-synchrotron resonances. The effects of the hourglass effect and chromaticity seem to cancel, leaving an optimal β*≈12 cm.
This is not affected significantly by a crossing angle.

Tune scan

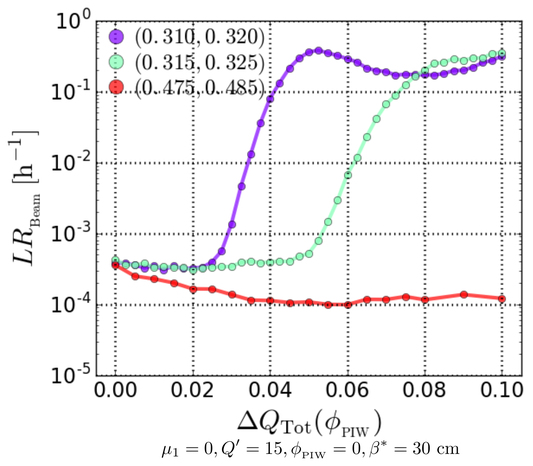
An attempt to find better working points than (0.31,0.32) (x), requiring $|Q_x\text{-}Q_y|\geq 0.01$.
The tune scan was done for β*=40 cm, σ_s=8 cm, Q'=15, μ_1=0, θ_{xing}=300 µrad, ΔQ_{Tot}=0.03.
We found two good alternative working points; (0.315,0.325) and (0.475,0.485) (◇).



Maximal beam-beam tune shift



With symmetric phase advance, optimal β* and zero crossing angle, the system is optimized to keep good beam quality, even with the assumed necessary large chromaticity. This setting allows for beam-beam tune shifts up to ΔQ_{Tot}=0.25. The required precision on μ_1 will not be attainable for that large ΔQ_{Tot}. Even with crab cavities, it is not probable to counter all nonsymmetrical effects driving odd resonances. Tune shifts this large would make the beam vulnerable to resonances driven by the lattice sextupoles. The configuration and performance is not considered realistic.



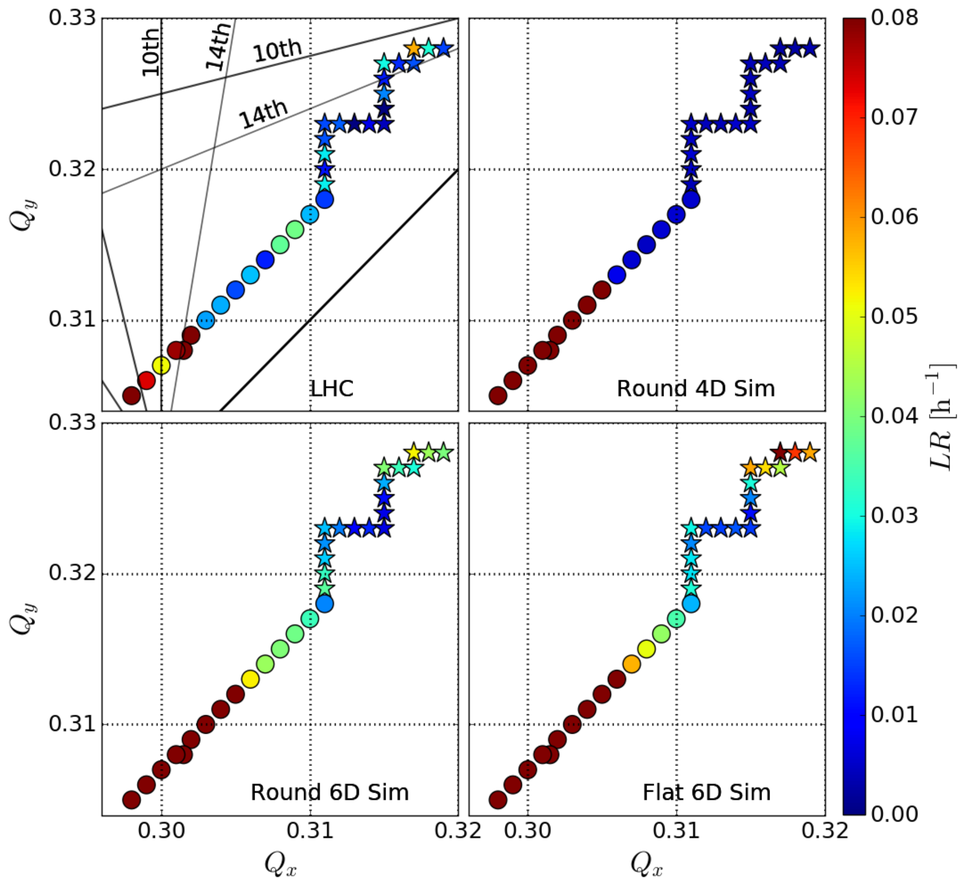
Setting μ_1=0 and using the FCC design β*, drastically reduces the maximal ΔQ_{Tot}. From the LHC tunes, the limit is approximately 0.035. This is with zero asymmetrical effects in the beam-beam interaction, and thus no odd resonances.

The limits on ΔQ_{Tot} for different scans are given in the table below for (0.31,0.32) and (0.315,0.325).

(Q_x, Q_y)	β_q^* [cm]	ΔQ_{Tot} $(\phi_{\mathrm{PIW}} = 0)$	ΔQ_{Tot} $(\phi_{\mathrm{PIW}} = 1)$
$(0.31, 0.32)$	12	0.043	0.028
$(0.31, 0.32)$	30	0.035	0.018
$(0.315, 0.325)$	12	0.067	0.036
$(0.315, 0.325)$	30	0.060	0.026

Comparison to LHC

A dedicated MD was performed to test high-intensity, single bunches, and the impact of the beam-beam interaction. The total beam-beam tune shift was just below 0.02.
The configurations have been reenacted with CABIN, presented below.
The 6D implementation was required to understand the impact of the 14th/7th order resonance around (0.317,0.328). The flat implementation did not alter the dynamics significantly, but it did increase the simulation time more than a factor 20.



References

[1] S. V. Furuseth. “Head-On Beam-Beam Interactions in High-Energy Hadron Colliders. GPU-Powered Modelling of Nonlinear Effects”. CERN-THESIS-2017-279. , 2017.
[2] S. V. Furuseth and X. Buffat. “GPU-powered Modelling of Nonlinear Effects due to Head-on Beam-Beam Interactions”. PRAB. To be published.