

6D beam-beam modeling in Xsuite

Overview and status update

P. Kicsiny, X. Buffat, D. Schulte

Many thanks to D. Shatilov, M. Zobov, G. Iadarola, F. Zimmermann, K. Oide, S. White, K. Ohmi, F. Carlier, A. Latina, R. Bruce, A. Ciarma, A. Abramov, Y. Zhang, M. Hofer, M. Boscolo, T. Pieloni, M. Seidel

Overview

- Introduction
 - Beam-beam effects in FCC-ee
 - Overview of existing simulation tools for circular machines
- Xsuite development status for beam-beam studies
 - Beam-beam models
 - Benchmark studies
 - Summary and next steps

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Beam-beam effects in FCC-ee

- Beam-beam interaction:
 - Dynamic, nonlinear force
 - Simulations with large crossing angles (30 mrad)
 - Beamstrahlung
- We know from past studies, that beam-beam effects can lead to:
 - 3D flip-flop [1]
 - Interplay with wakefield [2]
 - Reduction of dynamic aperture [3]
 - Interplay with lattice nonlinearities and imperfections [4]
 - 6D collective instabilities [5]
 - Beam background
- Our ultimate goal is to simulate FCC-ee luminosity & beam losses with relevant mechanisms (e.g. crab-waist, tilted solenoid, bootstrap, top-up injection)

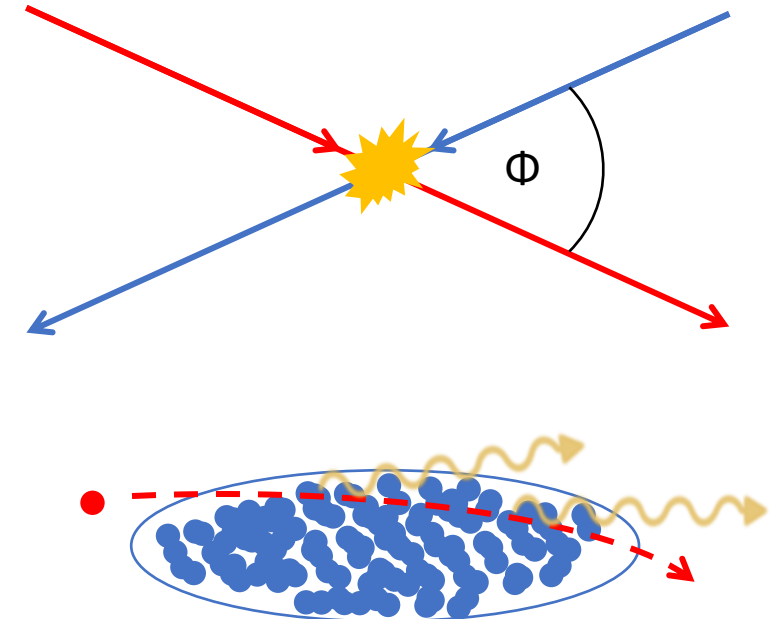
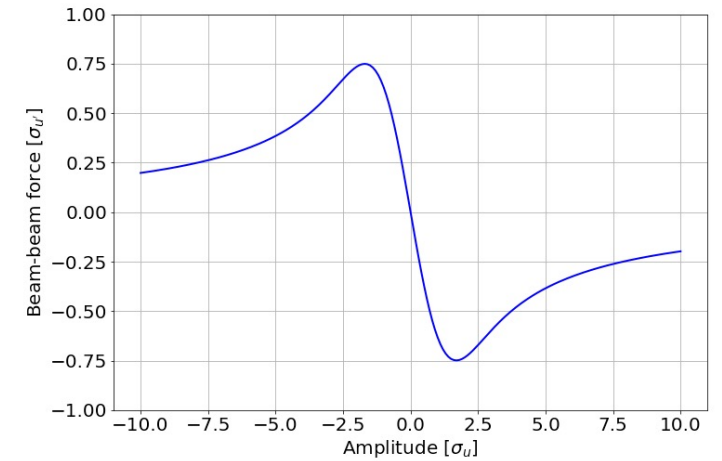
[1] D. Shatilov [<http://www.icfa-bd.org/Newsletter72.pdf>]

[2] Y. Zhang [<https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.23.104402>]

[3] D. Shatilov [https://indico.cern.ch/event/1084323/contributions/4570411/attachments/2332376/3975032/ODM-146_shatilov.pdf]

[4] D. Zhou [https://kds.kek.jp/event/39142/contributions/194651/attachments/146544/182494/20210824_BB_Simulations_SKB.pdf]

[5] K. Ohmi [<https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.119.134801>]



Overview of existing simulation tools for circular machines

	Weak-strong 6D	Quasi strong-strong 6D	Strong- strong 6D	Beamstrahlung	Transverse wakefields	Longitudinal wakefields	Tracking with simplified maps	Tracking element-by-element	Background generation	Crab waist of the strong beam	Synchro-beam mapping with solenoid field
GUINEA PIG [1]	Available	Not available	Available	Available	Not available	Not available	Not applicable	Not applicable	Available	Not applicable	No info
COMBI [2]	Available	Available	Available	Not available	Available	Not available	Available	Not available	Not available	Not available	Not available
BBWS [3]	Available	Not available	Not available	Available	Available	Available	Available	Available	Not available	Not available	Not available
BBSS [4]	Not available	Not available	Available	Available	Available	Available	Available	Available	Not available	Not applicable	No info
IBB [5]	Not available	Not available	Available	Available	Available	Available	Available	Not available	Not available	No info	Not available
LIFETRAC [6]	Available	Available	Not available	Available	Not available	Not available	Available	Available	Not available	Available	Not available
BeamBeam3D [7]	Available	Not available	Available	Available	Available	Not available	Available	Not available	Not available	Not applicable	Not available
	Available		Not available		No info		Not applicable				

- Several codes have been used for beam-beam simulations in various colliders
 - They were used for different kinds of studies with different models
 - No cross-framework communication

- [1] D. Schulte [<https://cds.cern.ch/record/331845/files/shulte.pdf>]
 [2] T. Pieloni, W. Herr [<https://accelconf.web.cern.ch/p05/PAPERS/TPAT078.PDF>]
 [3] K. Ohmi [<https://indico.cern.ch/event/438918/contributions/1085290/attachments/1147002/1644777/BenchBBcodes.pdf>]
 [4] K. Ohmi [https://oraweb.cern.ch/pls/hhh/code_website.disp_code?code_name=BBSS]
 [5] Y. Zhang [<https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.23.104402>]
 [6] D. Shatilov [<http://cds.cern.ch/record/1120233/files/p65.pdf>]
 [7] J. Qiang [<https://amac.lbl.gov/~jigiang/BeamBeam3D/>]

Overview of existing simulation tools for circular machines

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	Available		Not available		No info		Not applicable				

- We are participating in the effort towards a new design (**Xsuite**) featuring a single general software framework for beam dynamics studies. See: **G. Iadarola** @ this workshop, Tuesday 30. Nov.

- Modularity, sustainability, performance
- CHART: Accelerator design and simulation framework for FCC-ee: see **F. Carlier** @ this workshop, Tuesday 30. Nov.

[1] D. Schulte [<https://cds.cern.ch/record/331845/files/shulte.pdf>]

[2] T. Pieloni, W. Herr [<https://accelconf.web.cern.ch/p05/PAPERS/TPAT078.PDF>]

[3] K. Ohmi [<https://indico.cern.ch/event/438918/contributions/1085290/attachments/1147002/1644777/BenchBBcodes.pdf>]

[4] K. Ohmi [https://oraweb.cern.ch/pls/hhh/code_website.disp_code?code_name=BBSS]

[5] Y. Zhang [<https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.23.104402>]

[6] D. Shatilov [<http://cds.cern.ch/record/1120233/files/p65.pdf>]

[7] J. Qiang [<https://amac.lbl.gov/~jigiang/BeamBeam3D/>]

Overview

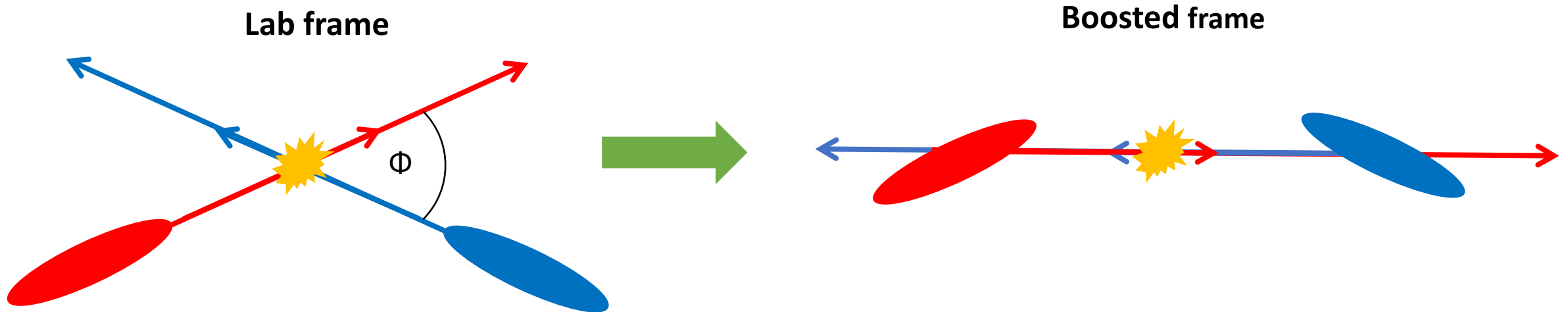
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Xsuite development status for beam-beam studies

- Implemented:
 - 6D weak-strong model (based on Sixtrack implementation)
 - Tracking through the arcs/injection lines with a simplified map (including linear chromatic effect, without coupling)
 - Element-by-element tracking through the arcs (based on Sixtrack implementation)
 - Transverse and longitudinal wakefields (PyHEADTAIL)
 - 6D strong strong model with soft Gaussian approximation
- Ongoing
 - Synchrotron radiation (A. Latina)
 - Beamstrahlung
- Plans
 - 6D strong-strong with field solver and Beamstrahlung (adapting field solvers already implemented in xsuite)
 - Synchro-beam mapping including solenoid field
 - 6D weak-strong model with non-Gaussian distributed charges (crab-waist of the strong beam)
 - Background (Beamstrahlung photons, Bhabha scattering, pair production)
 - GUINEA PIG interface for direct benchmarks

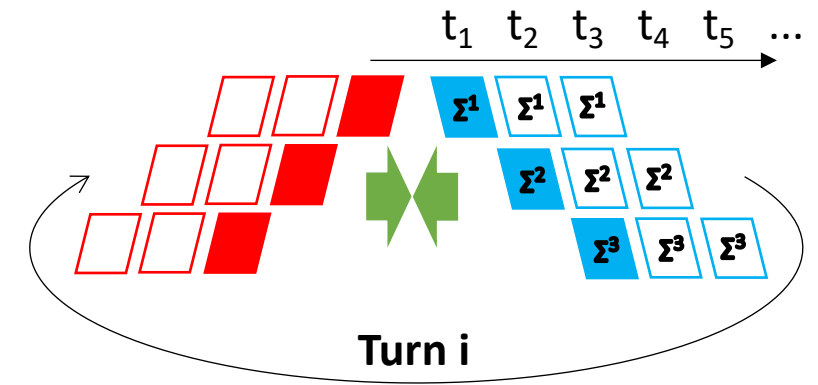
6D beam-beam models: eliminating the crossing angle

- FCC-ee features large crossing angles
 - Transform beams into a boosted frame where they collide head-on to simplify the computation of beam-beam kick [1]



[1] K. Hirata [<http://cds.cern.ch/record/271786/files/SCAN-9411248.pdf>]

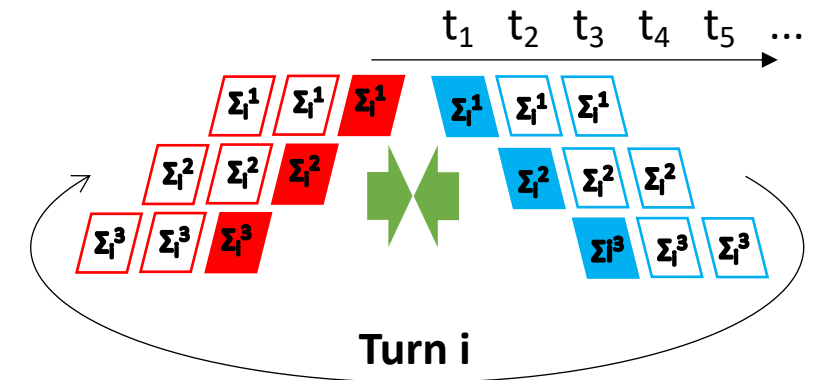
6D beam-beam models: Weak-strong



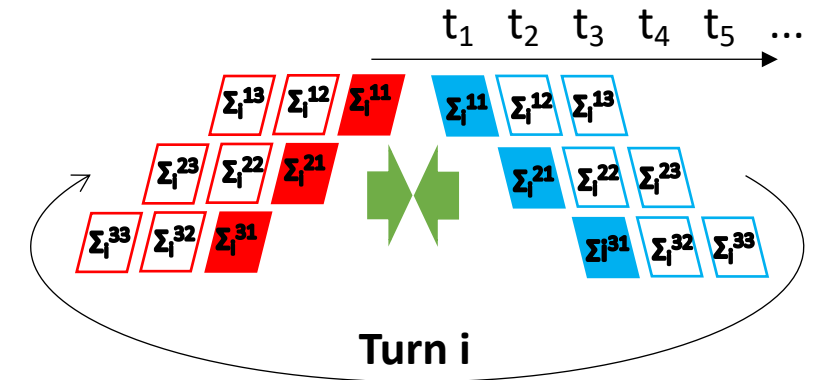
- **Weak beam** represented by a set of **macroparticles**
- **Strong beam** represented only by its **statistical moments** ($\langle x \rangle$, Σ) and **not tracked**
- Σ^j : each strong beam slice j has its own moments that are computed before the whole simulation and remain constant over the turns
- Computationally cheap (for N slices: compute stat. moments N times per turn)
- Cannot model collective dynamics, such as 6D instabilities, 3D flip-flop, interplay with wakefields

6D beam-beam models: Quasi (frozen) strong-strong

- Both beams are tracked
- **Each slice** is represented by a set of **macroparticles**
- Σ_j = stat. moments of each slice **j** are recomputed each turn **i** at the IP and transported w/o update to the collision points
 - Possibility to update every N turns instead to reduce computation cost when studying slow mechanisms
- Computationally more expensive (for N slices: compute stat. moments 2N times per turn)
- Can model fast instabilities, but neglects the variation of the beam-beam force due to the kicks within one interaction (low disruption parameter). Likely to be the most efficient for FCC-ee configurations (accuracy to be validated).



6D beam-beam models: Strong-strong



- Both beams are tracked
- **Each slice** is represented by a set of **macroparticles**
- Σ_i^{jk} = each turn **i**, slice **j** of beam 1 interacts with slice **k** of beam 2 and moments are recomputed before each slice-slice interaction
- Computationally most expensive (for N slices: compute stat. moments N^2 times per turn)
- Closest to reality

6D beam-beam models: Slice-slice interaction

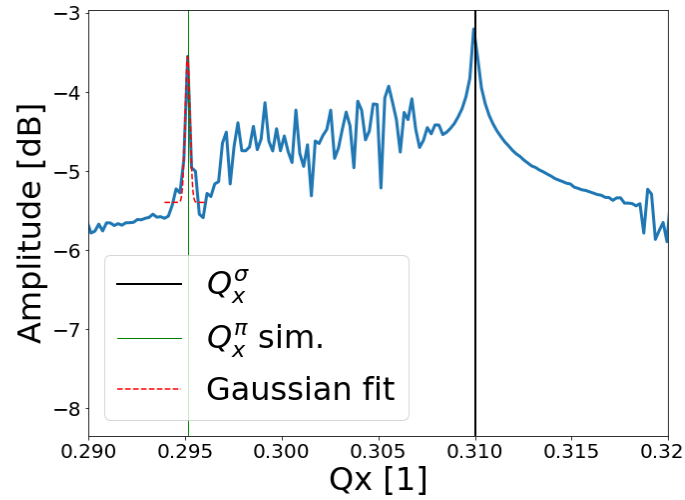
- In Xsuite the **single slice-slice interaction is the same algorithm**, independent of the model
 - It is extendible with features, such as Beamstrahlung, Bhabha scattering etc.
- EM field and beam-beam kick is for now calculated with the Bassetti-Erskine formula (**soft-Gaussian approximation**) [1]

$$\Delta y' + i\Delta x' = \frac{Nr_0\sqrt{2\pi}}{\gamma\sqrt{\sigma_x^2 - \sigma_y^2}} \left(w \left[\frac{x + iy}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \right] - \exp \left[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} \right] \cdot w \left[\frac{x\frac{\sigma_y}{\sigma_x} + iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \right] \right)$$
$$\Delta r' = -\frac{2Nr_0}{\gamma} \cdot \frac{1}{r} \cdot \left[1 - \exp \left(-\frac{r^2}{2\sigma^2} \right) \right] \quad w[t] = \exp[-t^2] \left(1 + \frac{2i}{\sqrt{\pi}} \int_0^t \exp[u^2] du \right)$$

- The goal is to enable also the use of **self-consistent EM field solvers** for more accurate simulation of the charge density
 - Efficient field solvers are available in Xsuite (based on PyHEADTAIL, PyECLOUD and COMBI implementations)

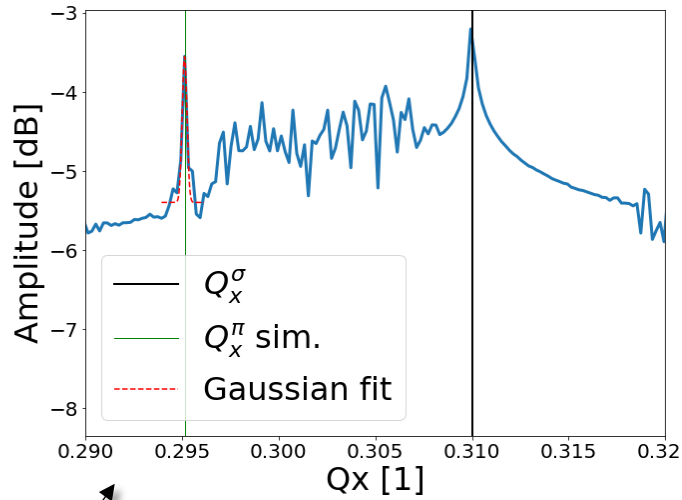
[1] M. Bassetti, G. A. Erskine [<https://cds.cern.ch/record/122227/files/198005132.pdf>]

Benchmark studies: collective motion at HL-LHC

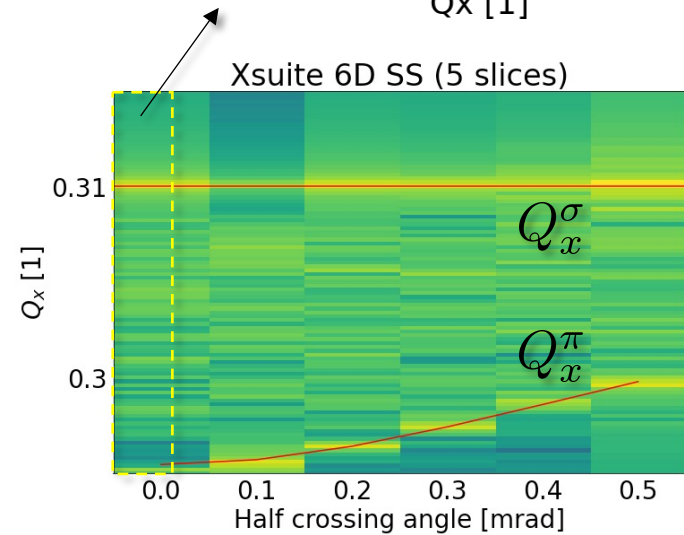


- First test of 6D strong-strong beam-beam interaction using Xsuite w/o beamstrahlung and synchrotron radiation
- Collective modes in **soft-Gaussian approximation** are reproduced correctly (Yokoya factor: 1.1)

Benchmark studies: effect of crossing angle at HL-LHC



- First test of 6D strong-strong beam-beam interaction using Xsuite w/o beamstrahlung and synchrotron radiation
- Collective modes in **soft-Gaussian approximation** are reproduced correctly (Yokoya factor: 1.1)



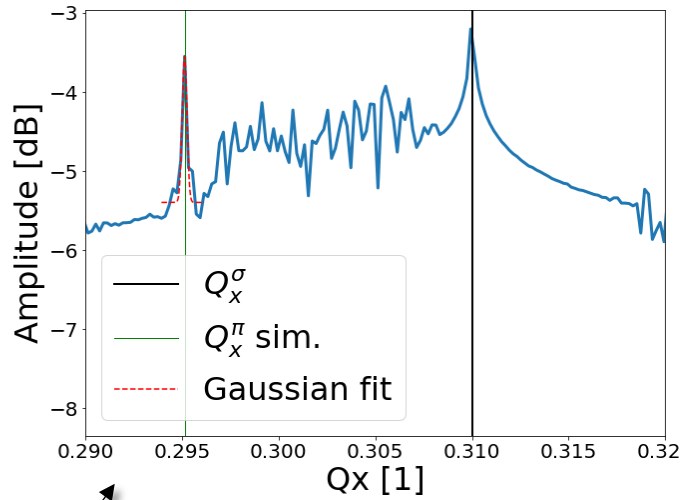
$$Q_{x,y}^\pi = Q_{x,y}^\sigma + Y \cdot \Delta Q_{x,y}$$

$$\Delta Q_{x,y} = \frac{1}{2\pi} \arccos[\cos(2\pi Q_{x,y}^\sigma) - 2\pi \xi_{x,y} \sin(2\pi Q_{x,y}^\sigma)] - Q_{x,y}^\sigma$$

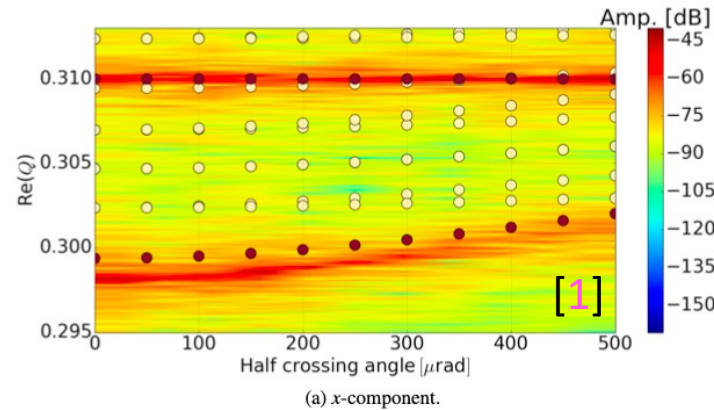
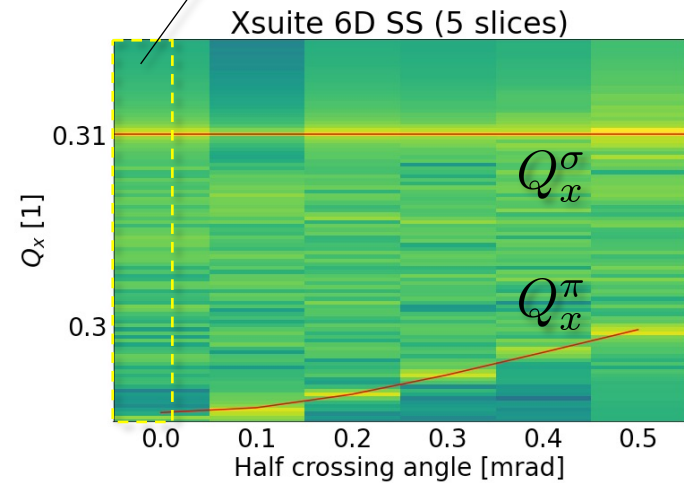
$$\xi_x = \frac{Nr_0\beta_x^*}{2\pi\gamma\sigma_x \sqrt{1 + \left(\frac{\sigma_z}{\sigma_x} \tan(\Phi)\right)^2} \left(\sigma_x \sqrt{1 + \left(\frac{\sigma_z}{\sigma_x} \tan(\Phi)\right)^2} + \sigma_y\right)}$$

$$\xi_y = \frac{Nr_0\beta_y^*}{2\pi\gamma\sigma_y \left(\sigma_x \sqrt{1 + \left(\frac{\sigma_z}{\sigma_x} \tan(\Phi)\right)^2} + \sigma_y\right)}$$

Benchmark studies: effect of crossing angle at HL-LHC



- First test of 6D strong-strong beam-beam interaction using Xsuite w/o Beamstrahlung and synchrotron radiation
- Collective modes in **soft-Gaussian approximation** are reproduced correctly (Yokoya factor: 1.1)
- Dependence of π mode with crossing angle matches past studies and theory



$$Q_{x,y}^{\pi} = Q_{x,y}^{\sigma} + Y \cdot \Delta Q_{x,y}$$

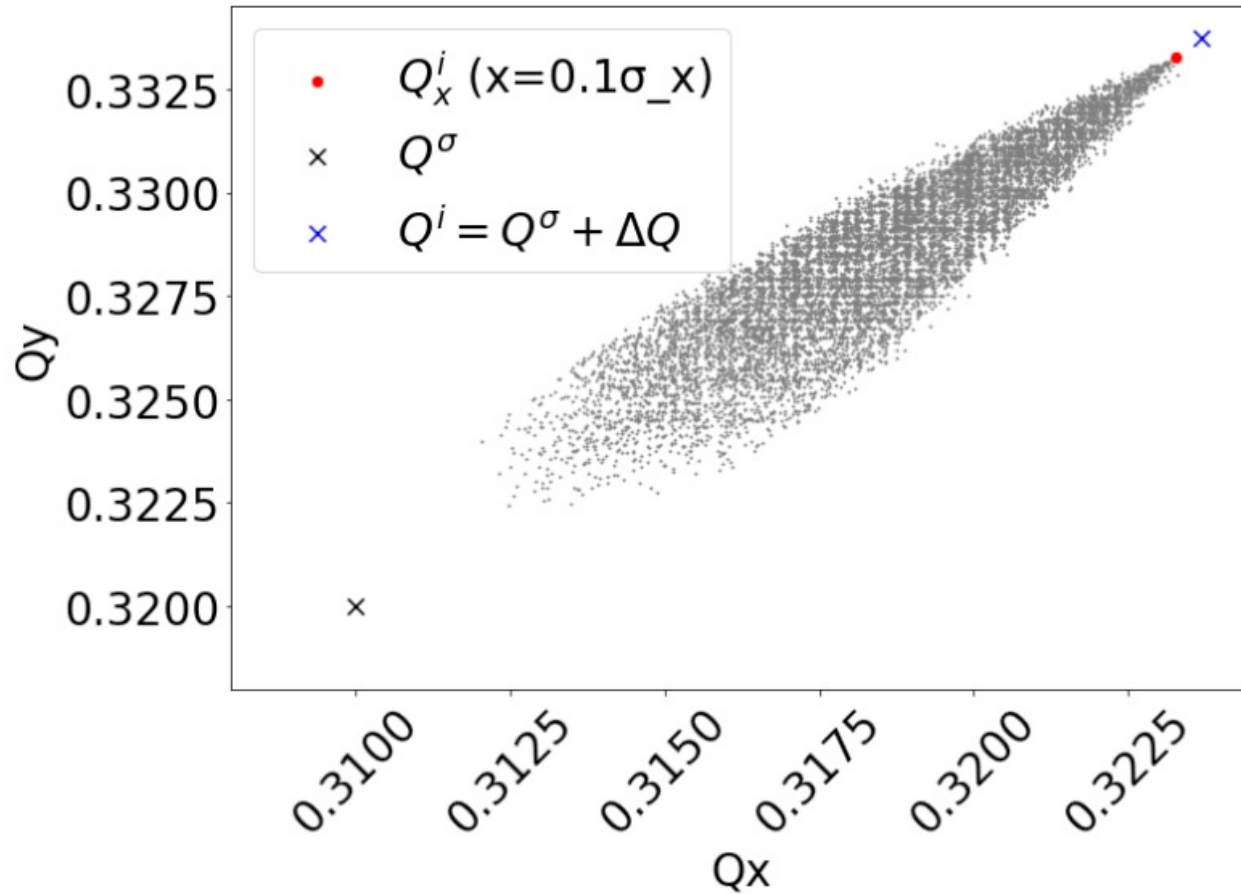
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[1] L. Barraud [<https://cds.cern.ch/record/2684699/files/CERN-ACC-NOTE-2019-0032.pdf>]

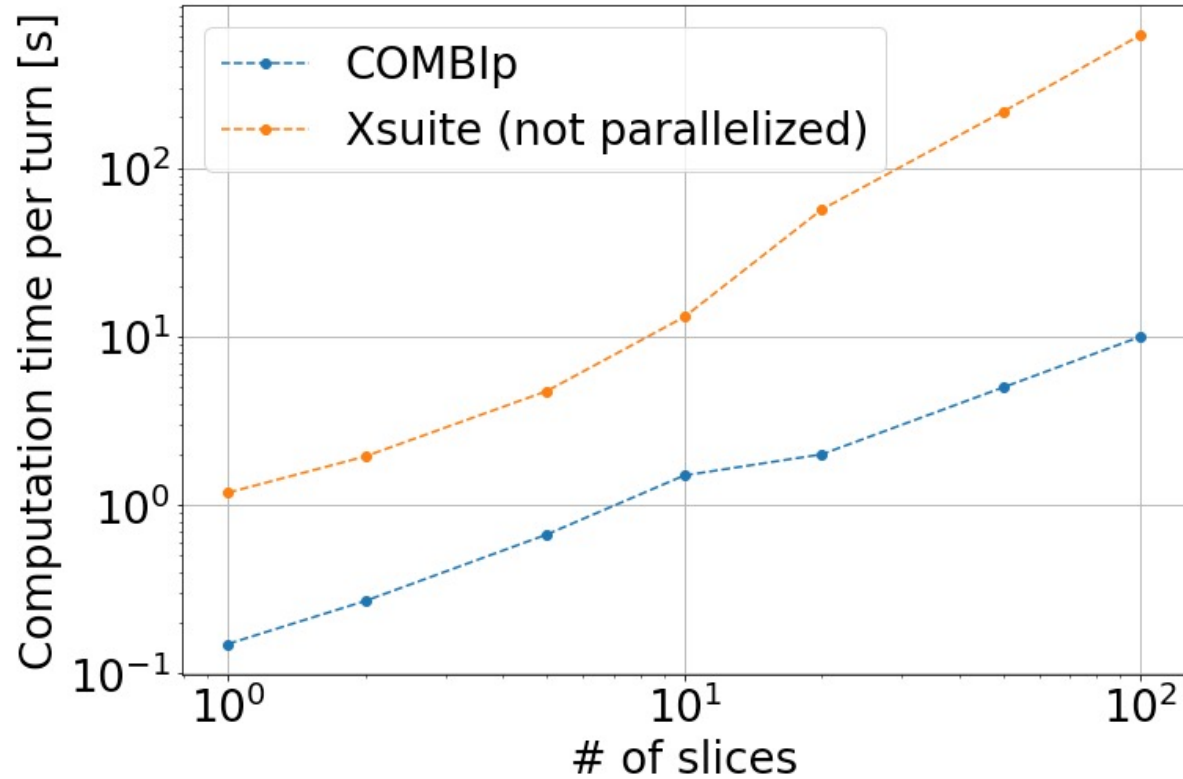
Benchmark studies: Incoherent tune



- First test of tune footprint driven by beam-beam interaction using Xsuite 6D strong-strong model
- Tune footprint of particles matches expectations
 - Small amplitude test particle's tune shift comparable to theory

$$Q_{x,y}^i = \frac{1}{2\pi} \arccos[\cos(2\pi Q_{x,y}^\sigma) - 2\pi \xi_{x,y} \sin(2\pi Q_{x,y}^\sigma)]$$

Benchmark studies: first runtime estimates



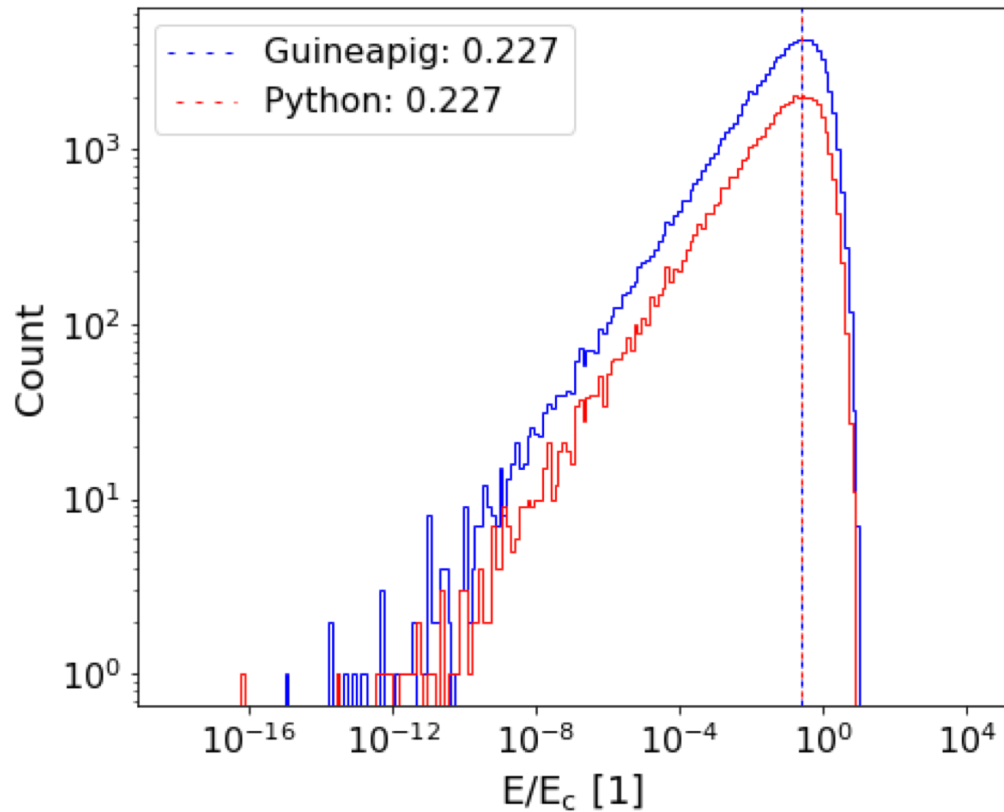
- 1.000.000 macroparticles per beam (round beams)
- Estimated runtime per turn of strong-strong simulation scales with the number of slices
- Code optimization is ongoing to meet the performance of existing optimised codes
- Parallelization
 - OpenMP and GPU acceleration are available in Xsuite, to be tested and qualified
 - Additional MPI parallelization on-going

Summary and next steps

- Development of a software framework with a modular approach featuring multiple beam-beam, lattice and wakefield models to address the relevant beam degradation mechanisms affecting the FCC-ee performance with the same toolset
- 6D strong-strong model in Xsuite has been implemented and first benchmarks performed, further benchmarks are in progress:
 - Tune footprints, frequency map analysis and dynamic aperture with flat beams + crossing angle
 - Beamstrahlung spectrum
 - 3D flip-flop
 - 6D instabilities
- Code development:
 - 6D Weak-strong with Beamstrahlung to enable MDI and collimation studies (A. Ciarma, A. Abramov)
 - Implementation of other beam-beam models
 - Analysis tools (frequency map analysis, dynamic aperture)
- Physics studies targeted:
 - Interplay with real lattice model (simplified map -> element by element tracking)
 - Crab sextupoles
 - Impact of lattice imperfections (misalignment, orbit and optics corrections)
 - Top-up injection
 - Multiple IPs
 - Monochromation
 - Wakefields

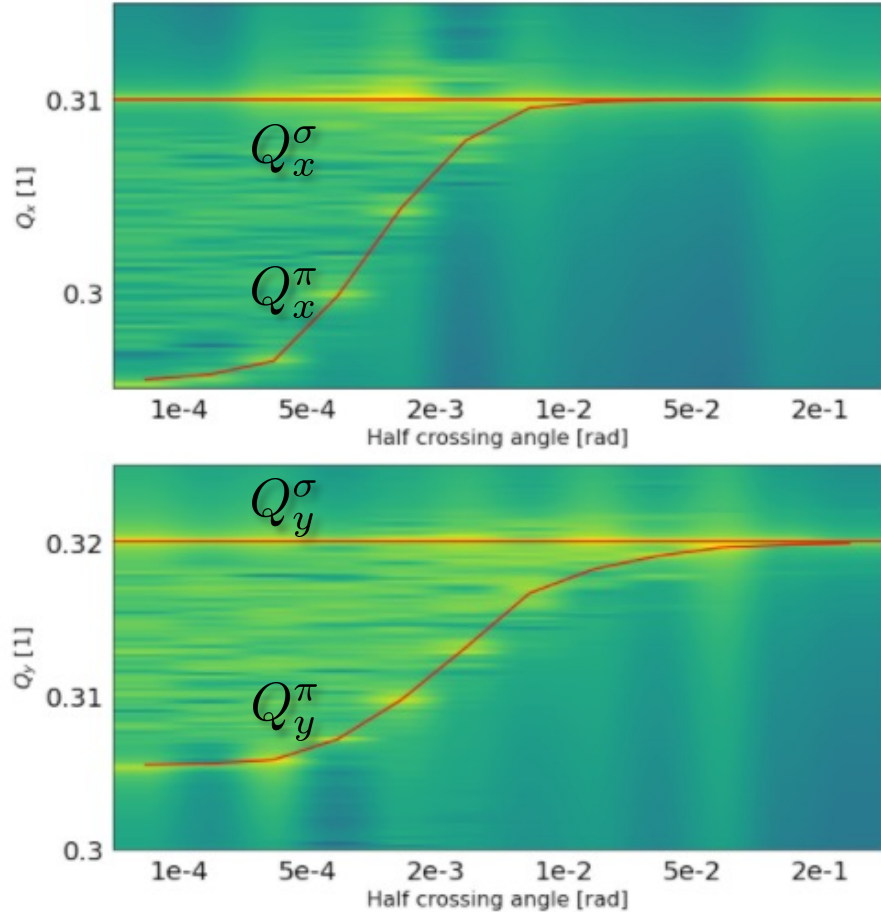
Backup

Beambeam with PyHEADTAIL + xsuite: current status



- Work on a tool based on PyHEADTAIL [6] and xsuite [7] is ongoing
- Highlight: plot of the distribution of emitted beamstrahlung photons as a function of energy in units of the “critical energy” $E_c = 2.22e-6 \times E^3/\rho$ [GeV]
- Benchmark shown against GUINEA PIG
- Only one beam slice
- Reasonable but not fully accurate, differences are related to slicing
- Plan is to go full 6D with many slices, then redo clear benchmark

Benchmark studies: Effect of crossing angle: HL-LHC



- HL-LHC with FCC-ee-like crossing angle (\sim mrad)
- Benchmark between theory and simulation is good also on crossing angles comparable to FCC-ee

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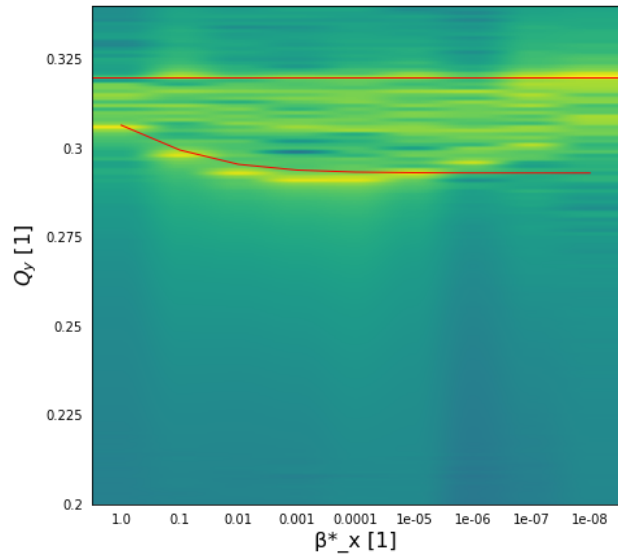
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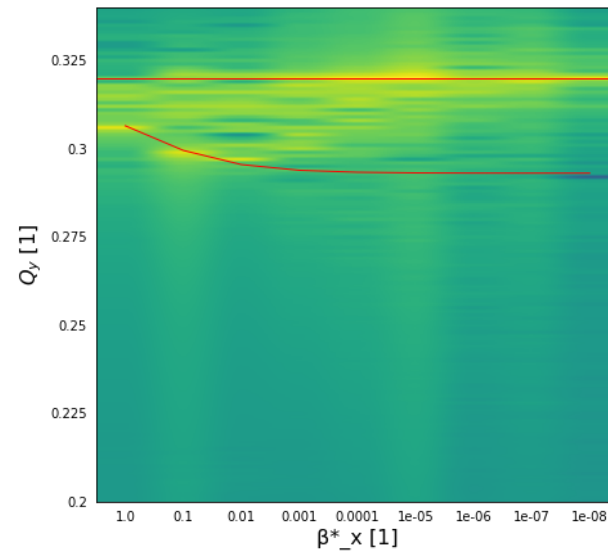
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Backup – Effect of bunch length

$\sigma_z = 8e-4$ m



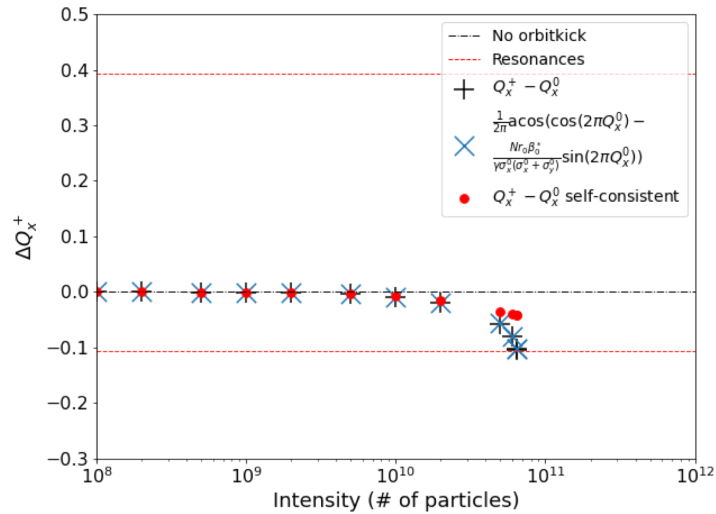
$\sigma_z = 8e-2$ m



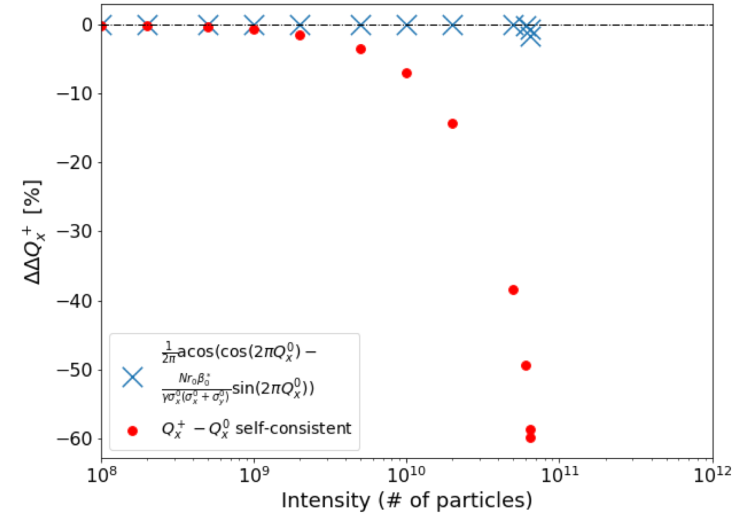
- Xsuite 6D strong-strong model
- EM field computed with Soft-Gaussian approximation
- HL-LHC parameters
- π mode deviates from theory for flat beams when increasing bunch length
- Could be linked to hourglass effect

Backup – MadX simulations: beam-beam tune shift

Tune shift w.r.t unperturbed nominal tune Q_y^0 as a function of beam intensity



Difference between tune shifts always compared to the Twiss output (black cross on left plot), in percentages as a function of beam intensity



- Twiss of MadX (black) gives accurate estimates until close to the resonance, compared to the analytical solution (blue)
- Self-consistent solution (red) does not match with the (weak-strong) model of MadX
- Correctly estimating beam dynamical properties from beam-beam interactions requires self-consistent (strong-strong) simulation