FCC

DEVELOPMENTS ON XSUITE BEAM-BEAM SIMULATIONS FOR FCC-EE

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Special thanks to:
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FCCIS Workshop
6th December 2022

Overview

1. xsuite simulation setup for simplified tracking
   - First results
2. FMA
   - FCCee tune footprints
   - Comparison of various codes
   - Slicing algorithms
3. Benchmark against analytical formula ξ
   - Studies of hourglass effect with reduced bunch intensity
4. Strong-strong simulations
   - Tune scan
   - 3D flip-flop
5. Summary

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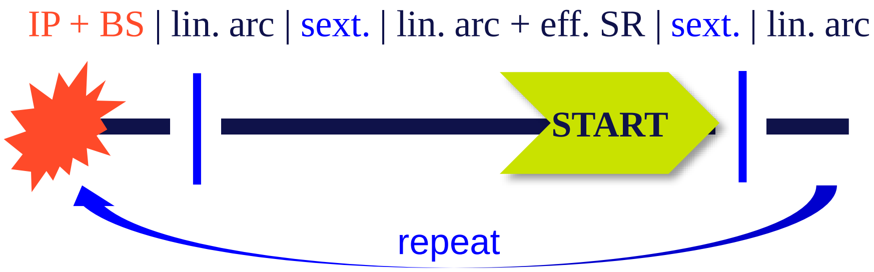
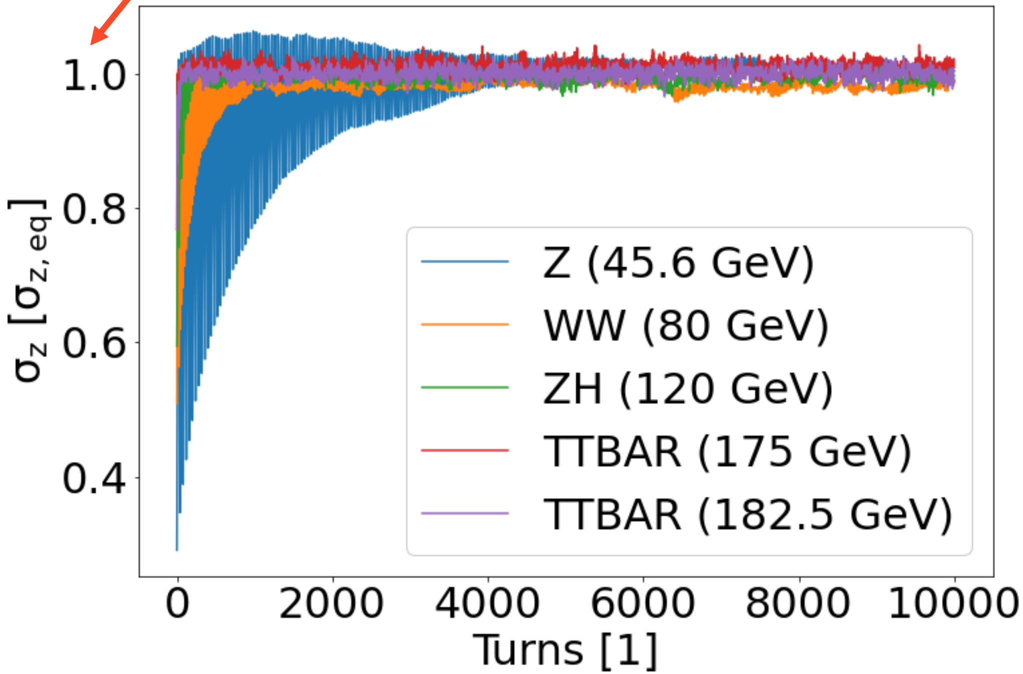
Simplified tracking simulations with xsuite

- Exploit superperiodicity of machine (2 IP case)
- In code:
  - 1 IP + tracking over half arc with linear transfer matrix
  - Arc split into 3 segments
  - 2 crab sextupoles between arc segments (β_x=3 m, β_y=5000 m)
  - A «turn» begins in front of the right sextupole:
    - Observation point for coordinates
  - Effective radiation (damping+noise) in arc, beamstrahlung in beam-beam
    - No radiation for FMA



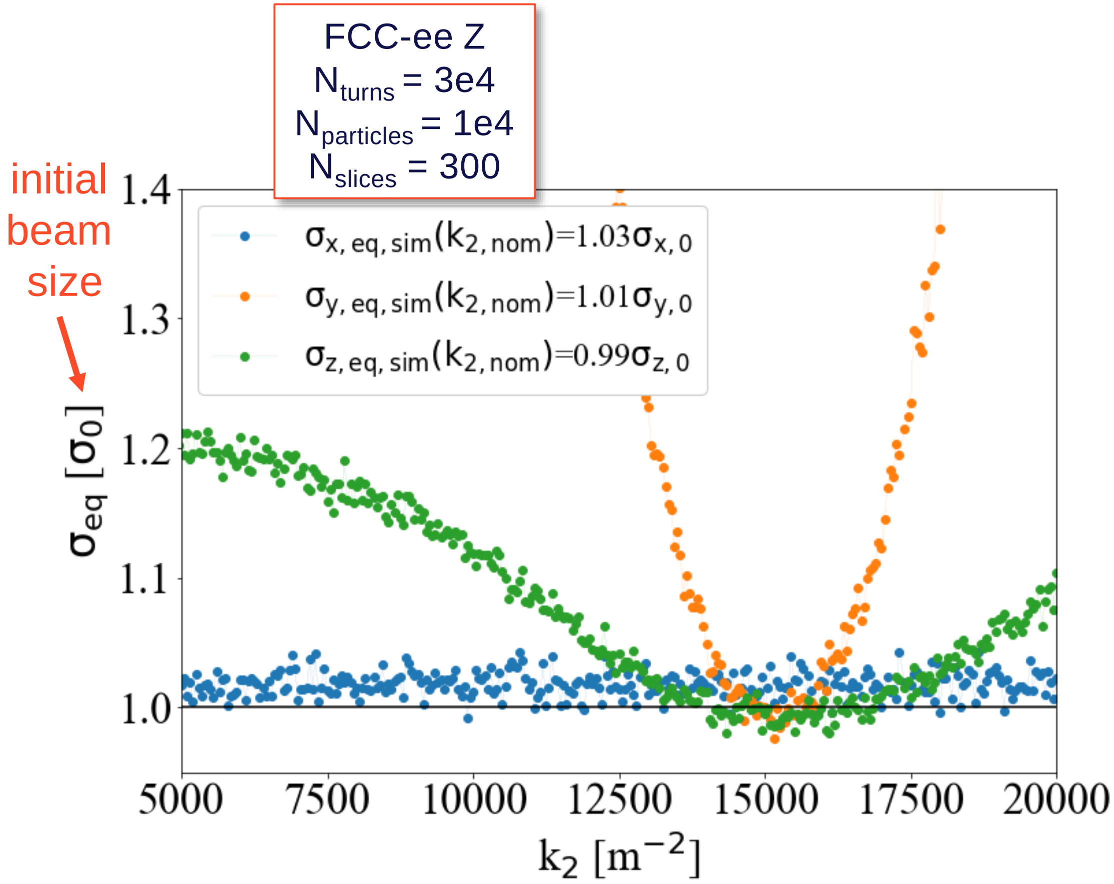
Equilibrium bunch length

normalized to design report values (SR+BS)



- **Weak-strong** model (1e4 particles)
- Equilibrium bunch length agrees with design report value for all resonances

Crab waist & transverse blowup



- **Weak-strong** model
- Optimum k_2 close to nominal value (~0.97*$k_{2,nom}$ for Z resonance)
- No transverse blowup in optimum setting

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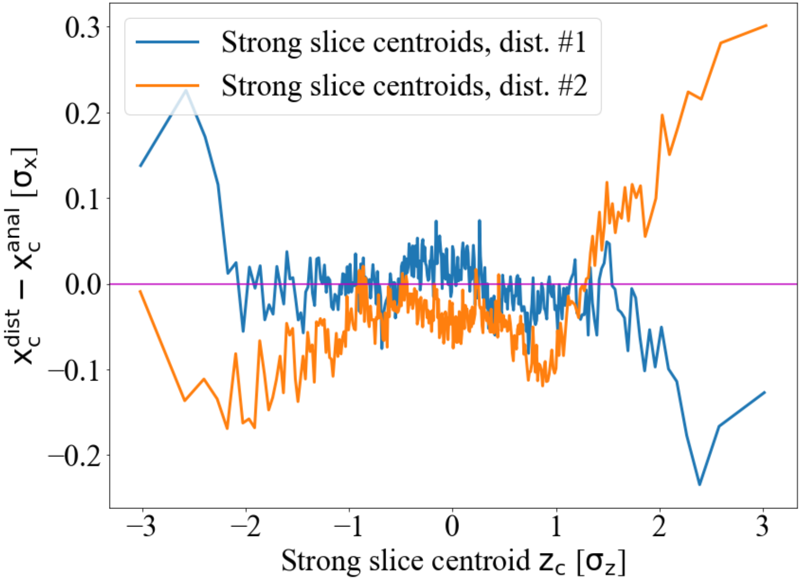
FMA – FCCee Z tune footprint

- In the **weak-strong** model, the strong bunch slice moments can be computed from:
  - Analytical Gaussian
  - Distribution of macroparticles → slice centroid coordinates are noisy
    - Random offset affects tune shift → noise on footprint



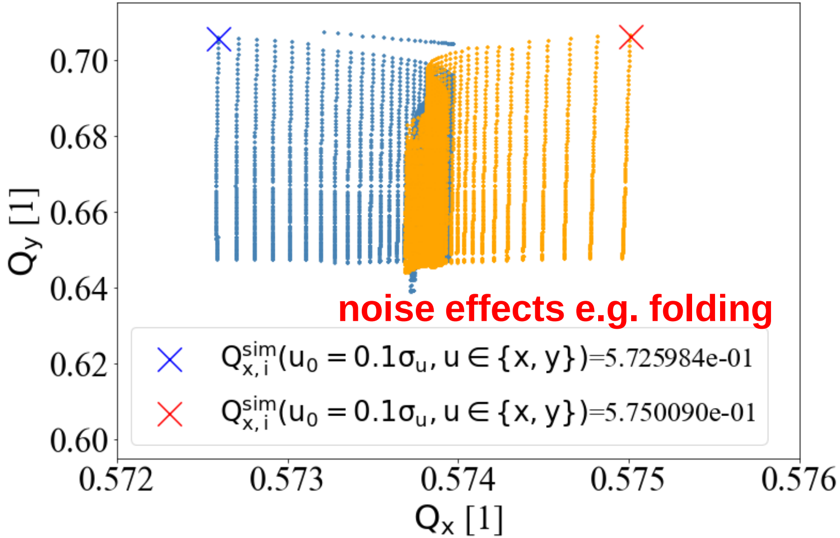
1e6 macroparticles
301 slices (uniform charge)
3333 macroparticles / slice

compared to slices from analytical Gaussian (Hirata's slicing)

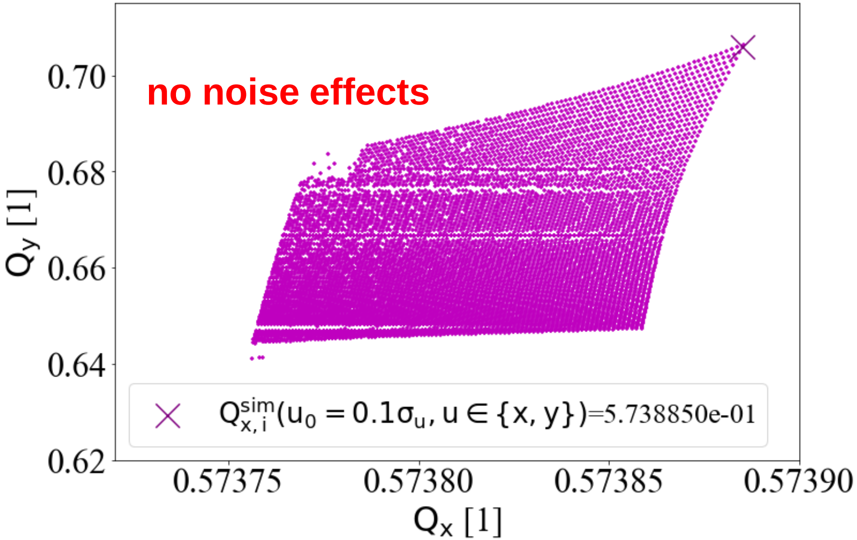
FMA – FCCee Z tune footprint

- Random offset affects tune shift ➡ noise on footprint
- Better to use moments from slicing an analytical Gaussian to avoid noise effects
  - Possible in WS but not in SS!

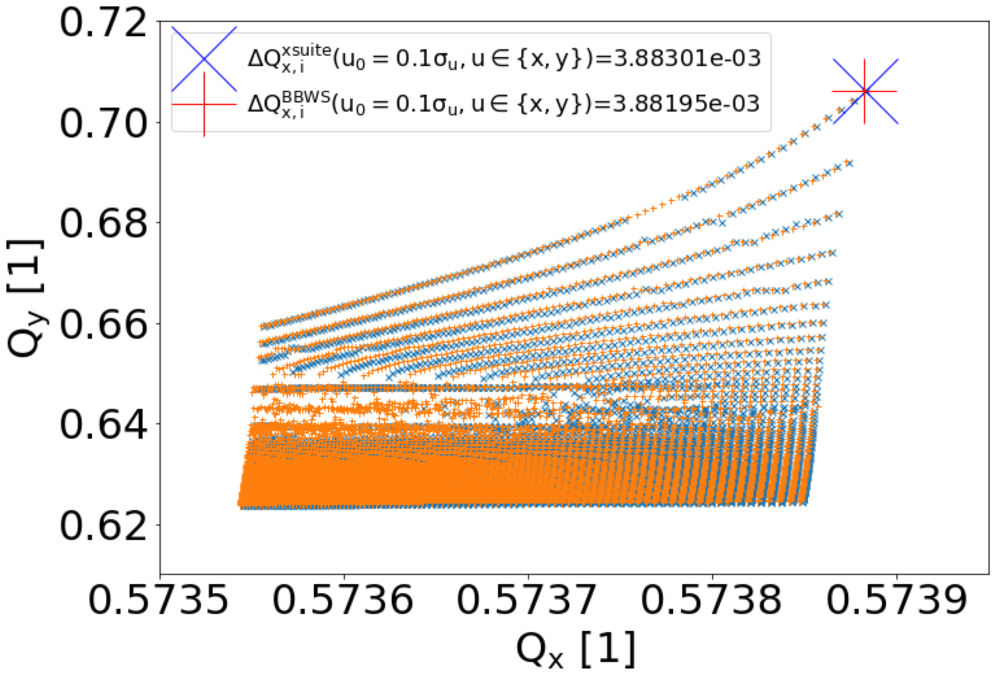
using moments from dist. of 1e6 particles



using moments from analytical Gaussian



FMA - Benchmark of xsuite and BBWS footprint



- Good agreement (1e-6 accuracy) between BBWS and xsuite
- 1e-4 discrepancy in ΔQ_x compared to LIFETRAC

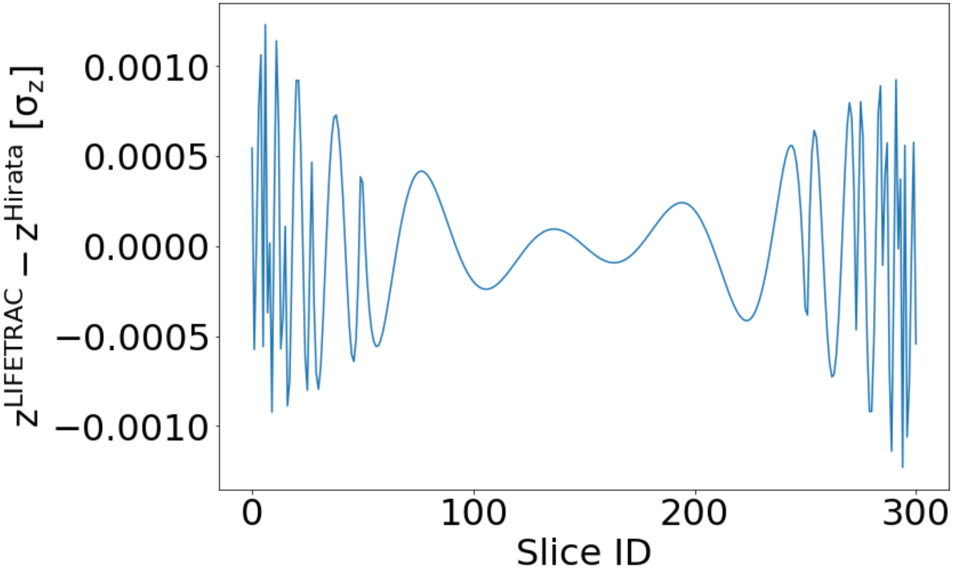
Code	ΔQ_x
xsuite / BBWS	3.88e-3
LIFETRAC	3.806e-3

- xsuite/BBWS both use slicing algorithm form Hirata (SBC) [1]

[1] K. Hirata et al. A symplectic beam-beam interaction with energy change [https://cds.cern.ch/record/243013?ln=en]

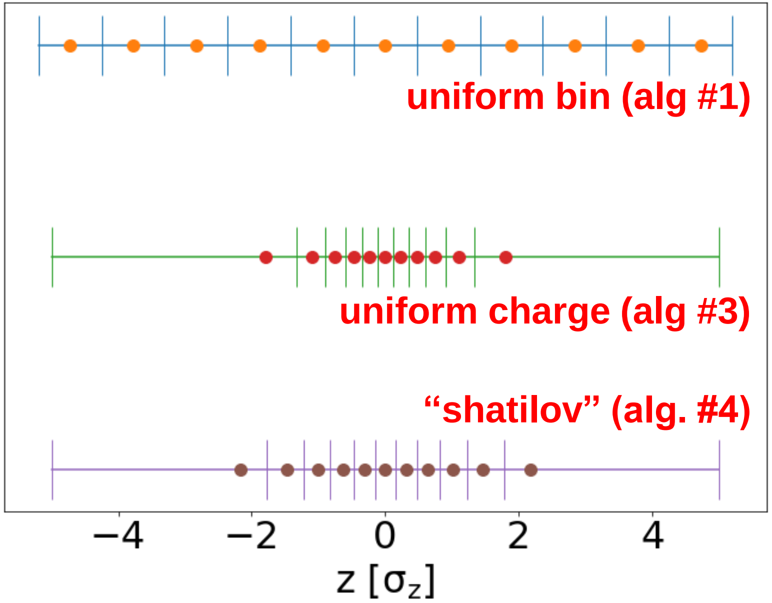
FMA – slicing algorithms

- Hirata's algorithm has a lower accuracy for slice positions (precomputed table for error function, single precision)
- Comparison of strong slice z centroids, 301 slices, uniform charge



FMA – slicing algorithms

- Switch to slicing algorithms used in LIFETRAC



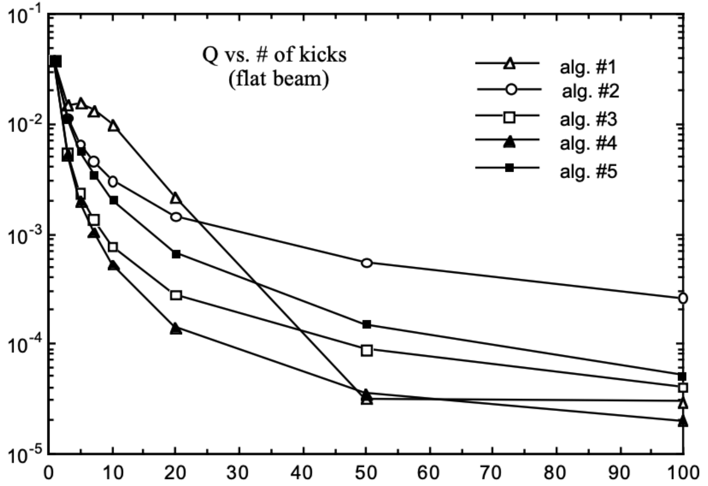


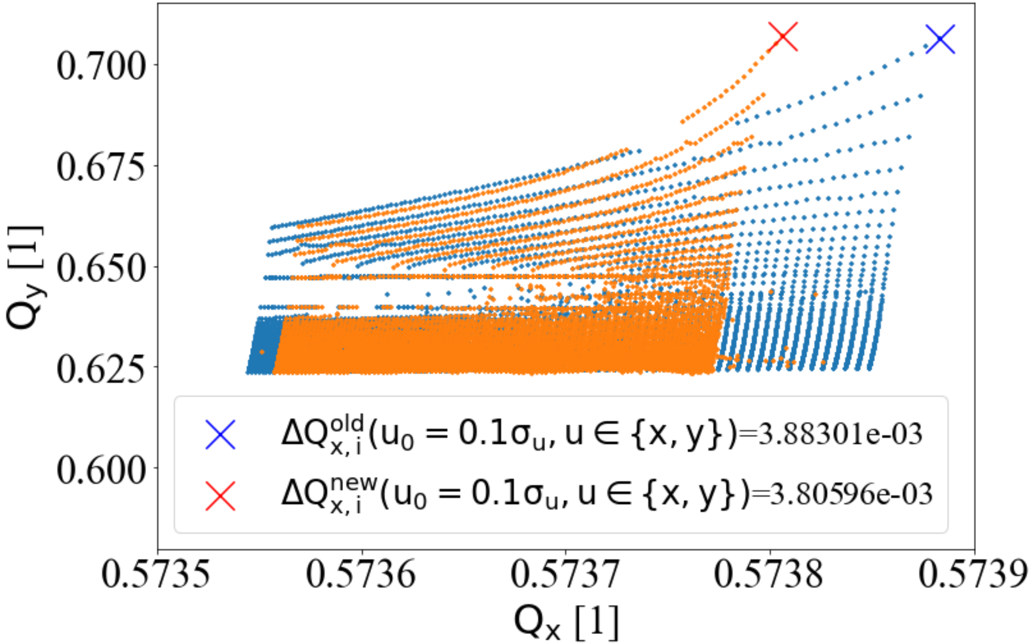
Figure 1: Convergence of the slicing algorithms: Q plotted vs. number of kicks N_s for flat beams (PEP-II-like parameters; see Table 2).

[2]

[2] M. Furman, A. Zholents, T. Chen, D. Shatilov; Comparisons of Beam-Beam Simulations [https://escholarship.org/uc/item/8nd6g4pv]

FMA – slicing algorithms

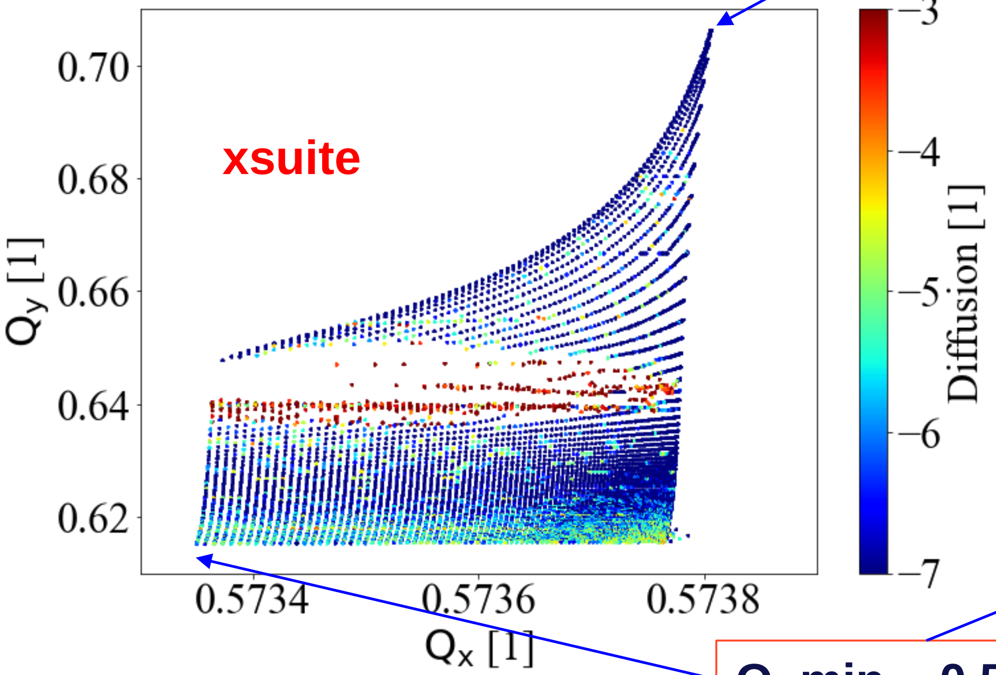
- Compare FCCee Z footprint with old (Hirata's) and new (LIFETRAC) slicing
- All 3 slicing algorithms produce ΔQ_x=3.806e-3 (~1e-7 accuracy)

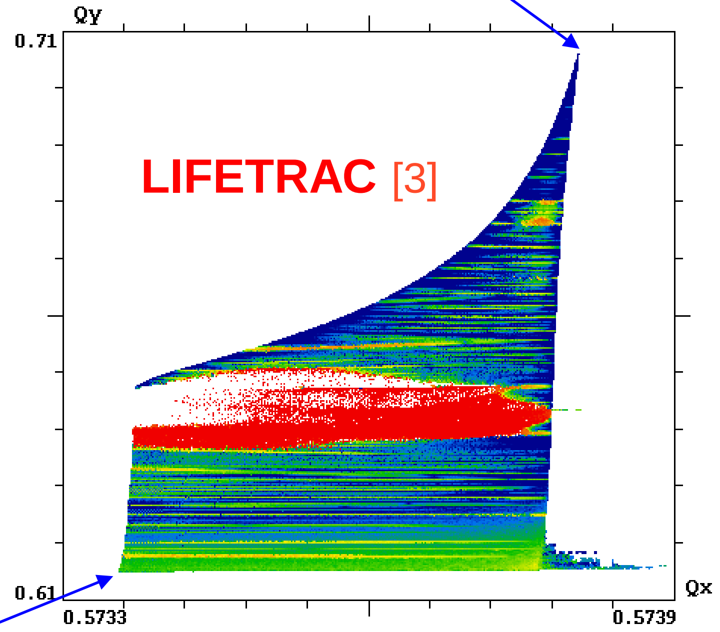


FMA – diffusion

$$D = \log_{10}\left[\sqrt{\sigma^2_{Q_{x,i}} + \sigma^2_{Q_{y,i}}}\right]$$

Q_x max ~ 0.573806

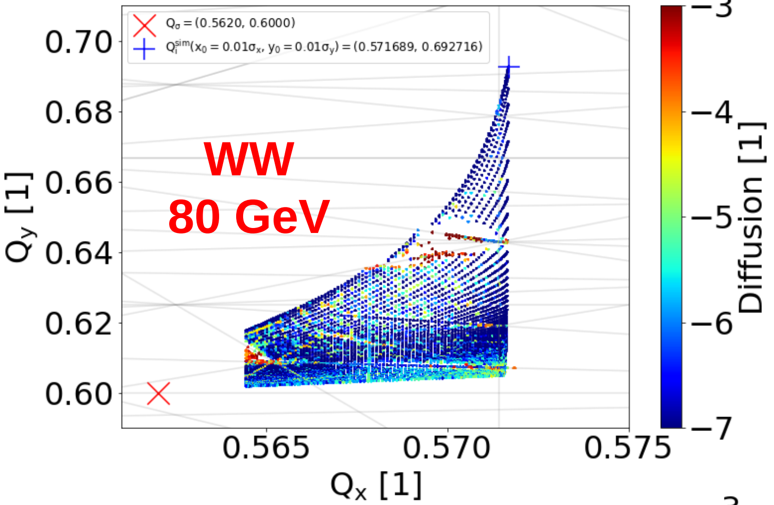


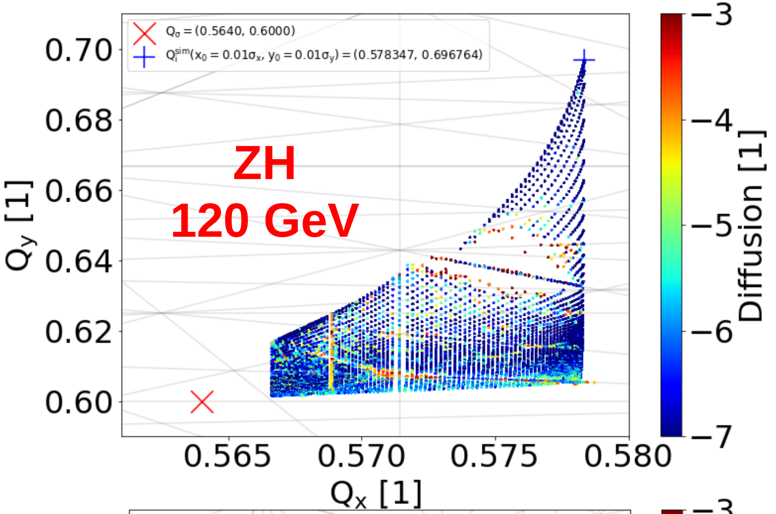


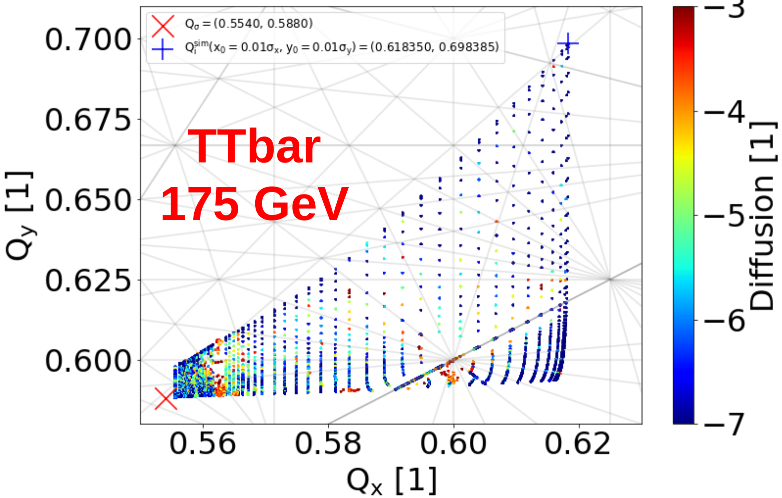
Q_x min ~ 0.57335

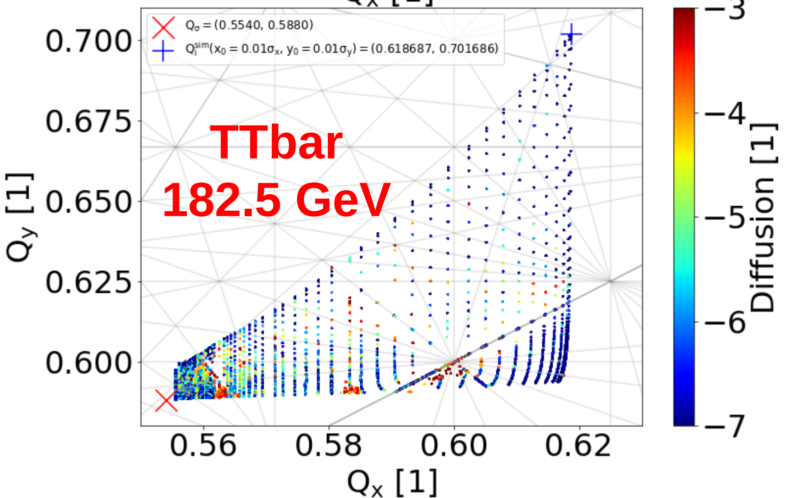
[3] courtesy of D. Shatilov

FMA – Footprint of other FCCee energies









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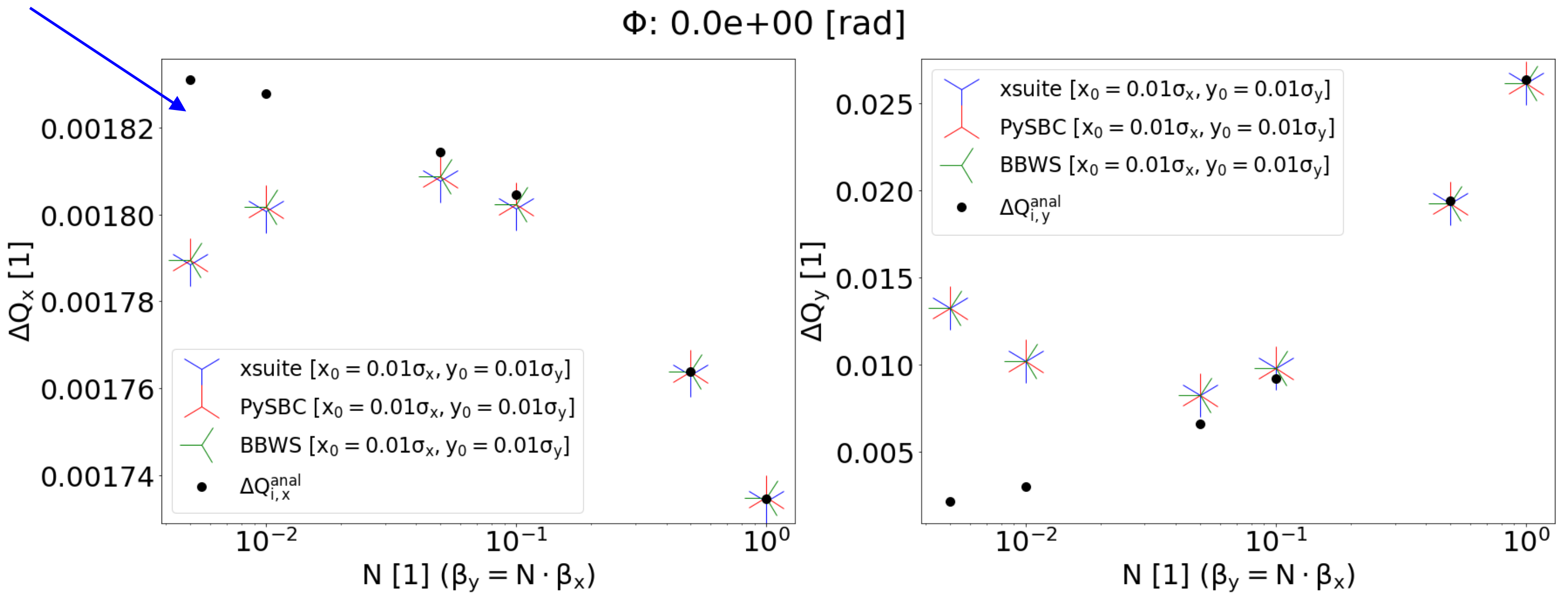
Benchmark against analytical formula ξ

- Head on collision with flat beams (N_b = 1e8)
    - All codes agree (xsuite, PySBC, BBWS)
    - Analytical estimate does not account for hourglass effect

$$Q^i_{x,y} = \frac{1}{2\pi}\arccos[\cos(2\pi Q^\sigma_{x,y}) - 2\pi\xi_{x,y}\sin(2\pi Q^\sigma_{x,y})]$$

FCC-ee Z



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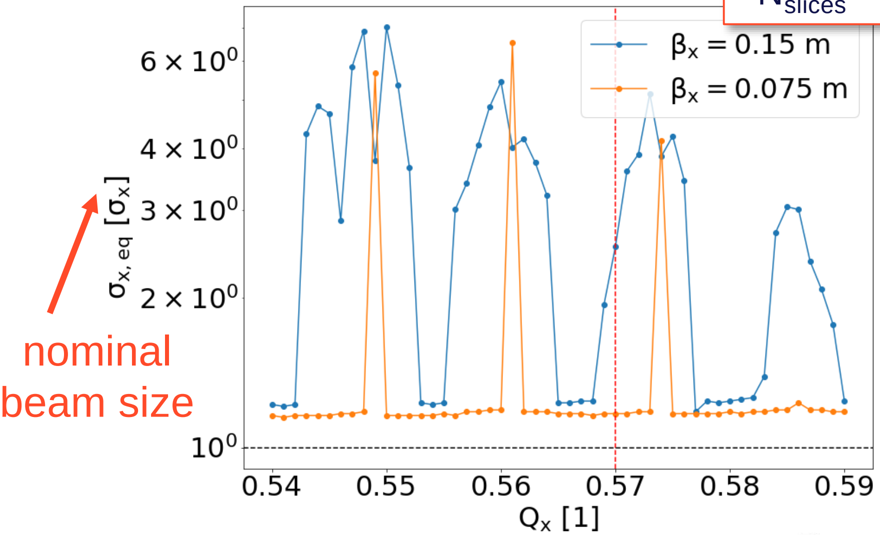
Tune scan

FCC-ee Z
N_{turns} = 3e4
$N_{particles}$ = 1e4
N_{slices} = 300



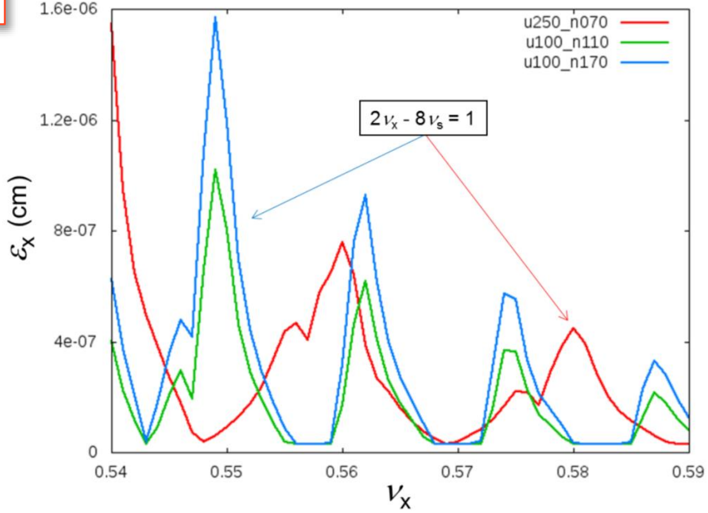


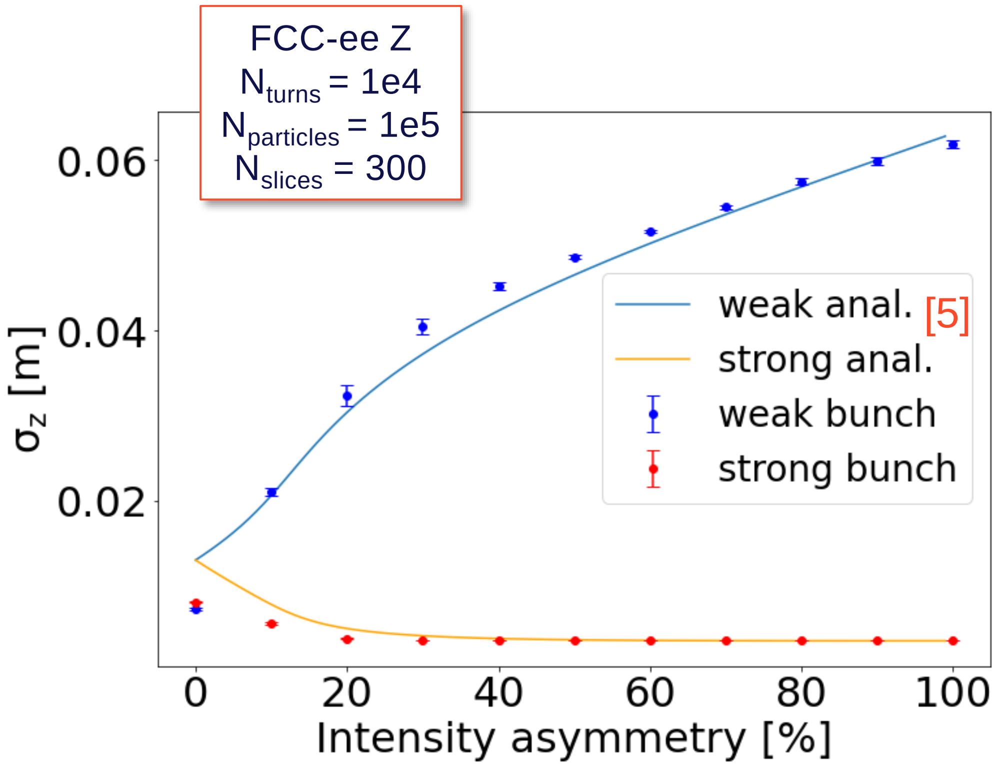
Figure 7: Growth of ε_x due to coherent X-Z instability, as a function of ν_x. Red line corresponds to U_{RF} = 250 MV, $N_p = 7\cdot10^{10}$, green and blue lines – U_{RF} = 100 MV, $N_p = 1.1\cdot10^{11}$ and $1.7\cdot10^{11}$.

[4]

- Nominal working point is unstable in xsuite
- Reason to be investigated

[4] D. Shatilov; FCC-ee Parameter Optimization [https://cds.cern.ch/record/2816655]

xsuite benchmark of 3D flip-flop



- First results are promising
- Need more particles and turns
- Improvement of parallelization ongoing
- Symmetric case instability to be understood
- Study ongoing

[5] See talk of K. Le Nguyen Nguyen @ this workshop

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Summary

- Successful code benchmarks in weak-strong case
  - xsuite benchmarked against several existing tools, such as GUINEA-PIG, LIFETRAC, PySBC, BBWS
  - Beamstrahlung (feature released on Github [6]), tune footprint
- Ongoing benchmarking and simulations of 3D flip-flop and coherent head-tail instability with the strong-strong model
- Next steps:
  - Link element by element lattice (SAD / MAD-X) to xsuite beam-beam
  - Bhabha scattering

Thank you!

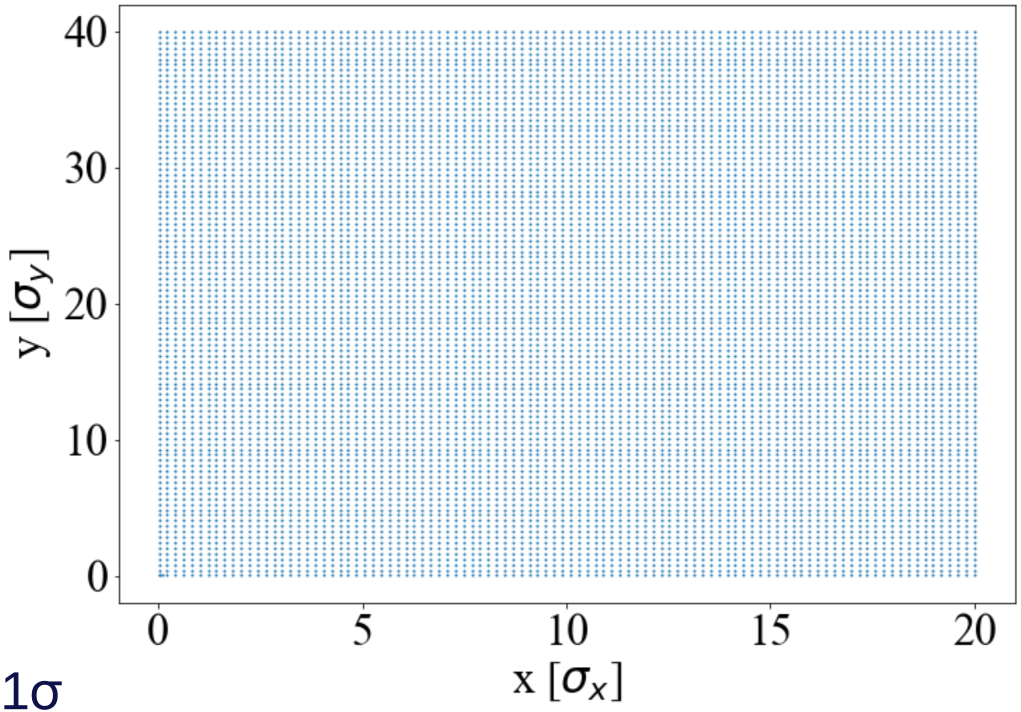
WORK SUPPORTED BY THE SWISS ACCELERATOR RESEARCH AND TECHNOLOGY (CHART)

[6] https://github.com/xsuite/xfields

BACKUP

FMA – test particle grid

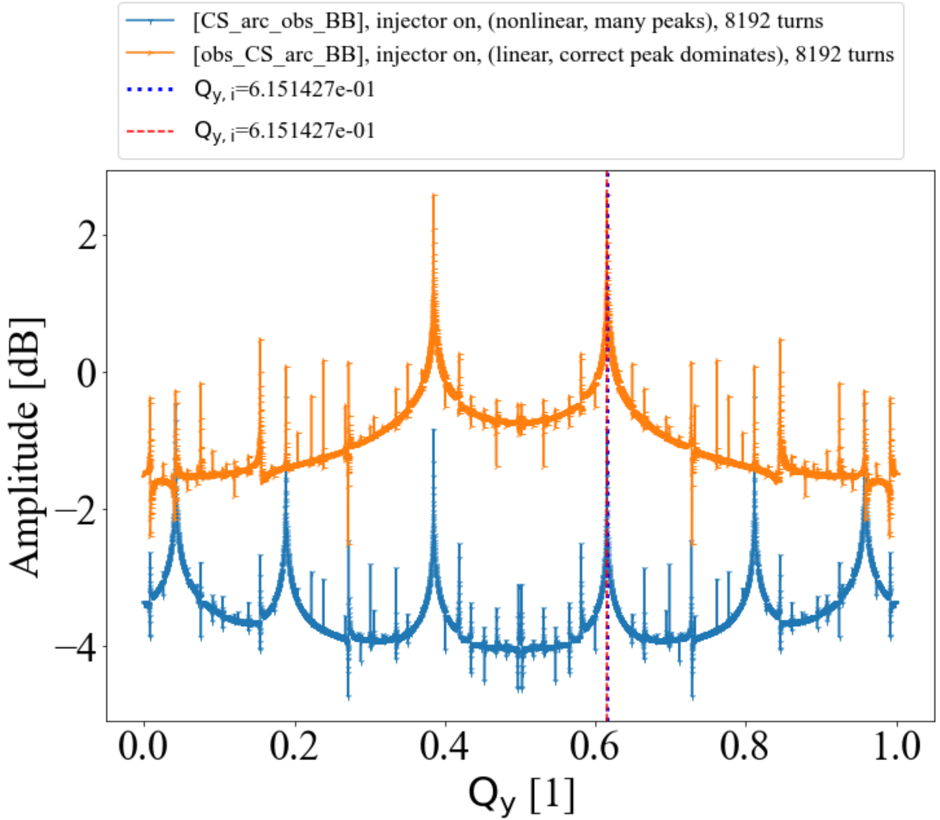
```
n_j = 100  # n_j x n_j particles
j_min = 1e-4
j_max = 10
j_vec_x = np.linspace(0,2*j_max, n_j)**2/2
j_vec_y = np.linspace(0,4*j_max, n_j)**2/2
j_vec_x[0] = j_min
j_vec_y[0] = j_min
x_test_vec = np.sqrt(2*j_vec_x)
y_test_vec = np.sqrt(2*j_vec_y)
```



- 10002 particles:
  - 100 x 100 grid
  - Extra test particles: 0.01σ, 0.1σ
- FMA with 8192 turns
- FFT window for diffusion: 4096, stride: 409 (5%), D=std of 11 tunes
- Observation point before CS: [obs, CS, small arc, IP, small arc, CS, long arc]

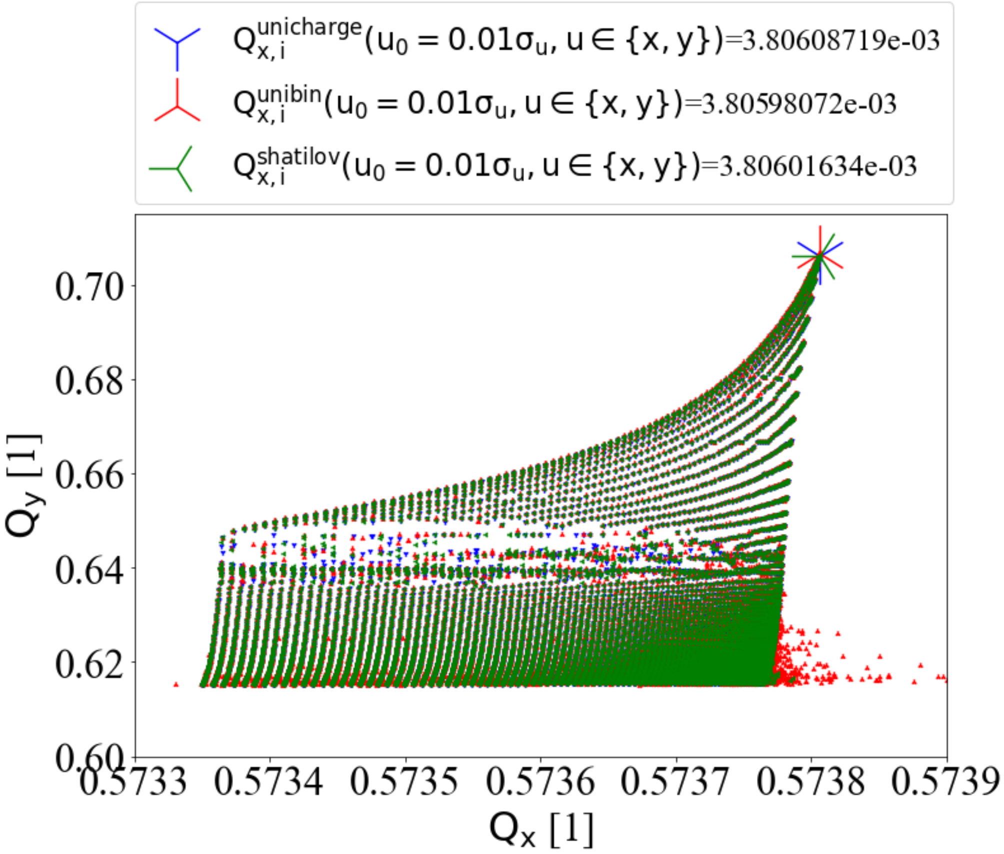
FMA – choice of observation point

- Observation point in linear part of lattice, outside CS (orange): spectrum less noisy
- Observation point before/after IP in nonlinear part (blue): spectrum more noisy due to CS nonlinearities
- There is no impact on incoh. tune
- But: in the second case for large amplitude particles the peak finder can more easily trigger on wrong peak

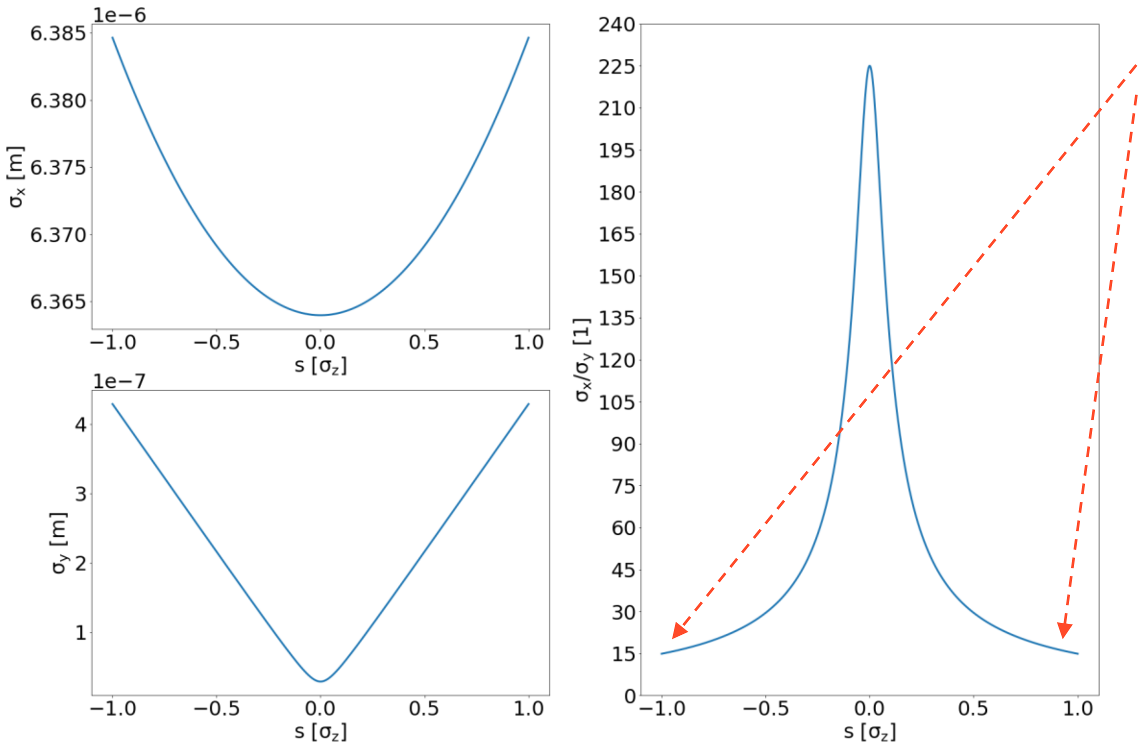


FMA – footprint with all 3 slicing algorithms

- Observation point in linear part of lattice: [obs, CS, arc, BB, arc, CS, arc]
- Injector element before tracking
  - Turn starts with CS
  - Need to match optical functions
- Same settings on slide #12, #13



Benchmark against analytical formula ξ

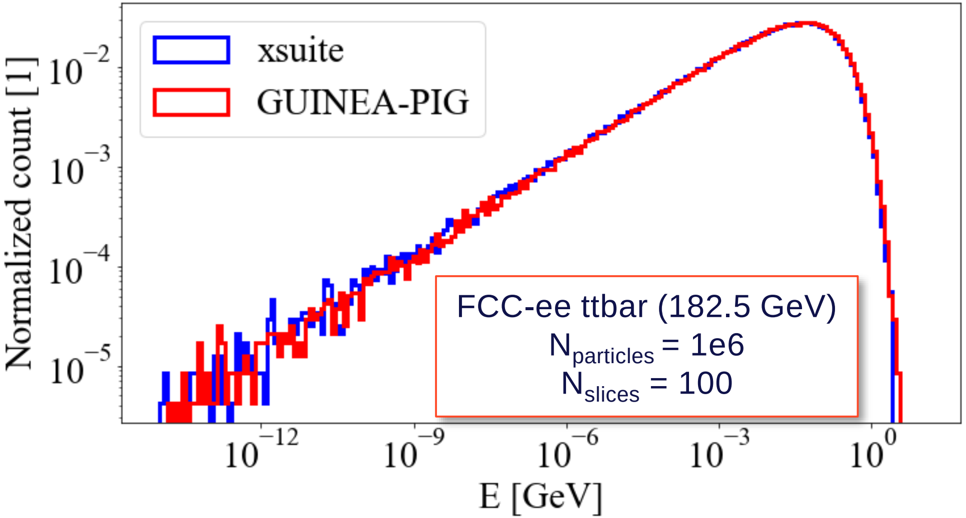


- For FCC-ee Z: σ_x/σ_y ~15 at **$s = \sigma_z$**
- Therefore $\sigma_x >> \sigma_y$ starts to break
- $\Delta Q_x \sim \xi_x \sim \beta_x / (\sigma_x(\sigma_x + \sigma_y))$
- ΔQ_x still depends on σ_y
- ΔQ_x smaller than w/o hourglass

Beamstrahlung benchmark

- Benchmark against reference code GUINEA-PIG [1]
  - Beamstrahlung model OK
- xsuite: **weak-strong**
- GUINEA-PIG: **strong-strong**
  - More photons emitted
    for extremely flat beams (Z)

Beamstrahlung photon spectrum / coll.

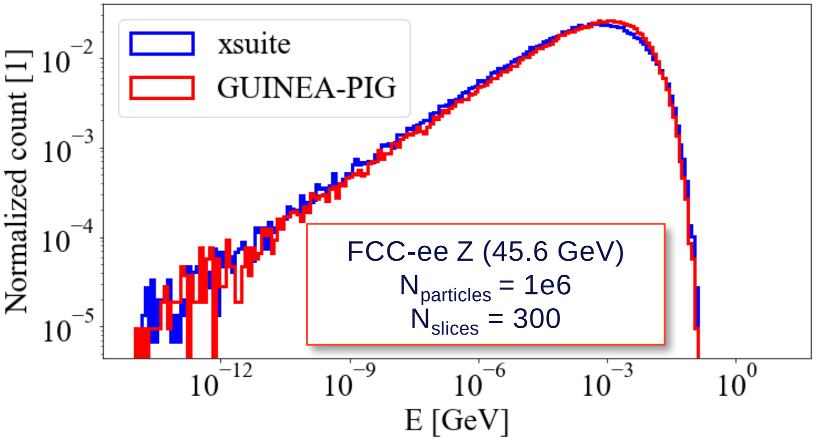


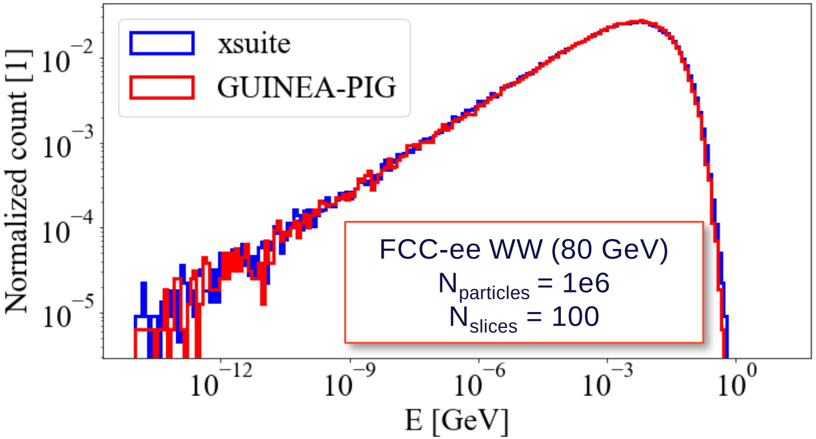
- Possibility to generate photons
  for external use (collimation, MDI) [2]

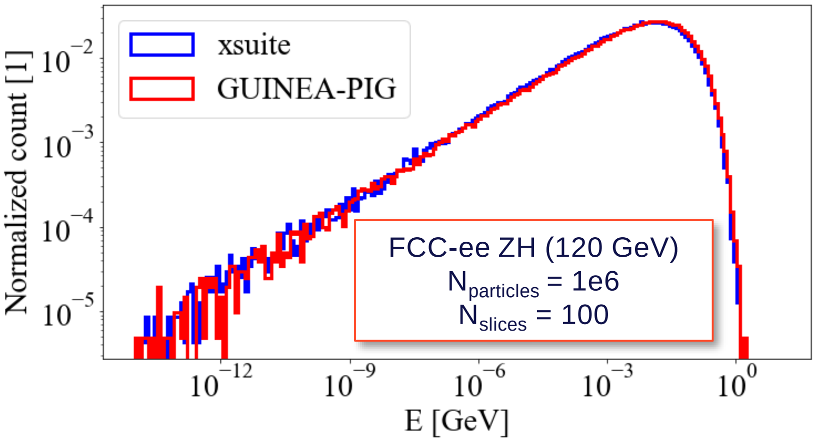
- TODO: come up with an efficient model of Bhabha scattering

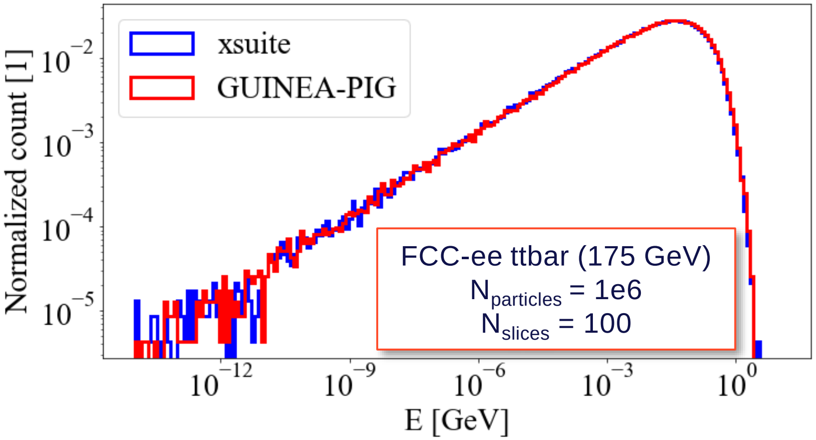
[1] https://twiki.cern.ch/twiki/bin/view/ABPComputing/Guinea-Pig
[2] https://xsuite.readthedocs.io/en/latest/internal_record.html#internal-record-for-elements-used-in-standalone-mode

Beamstrahlung benchmark – other FCCee energies

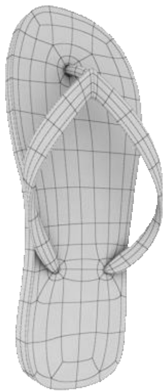






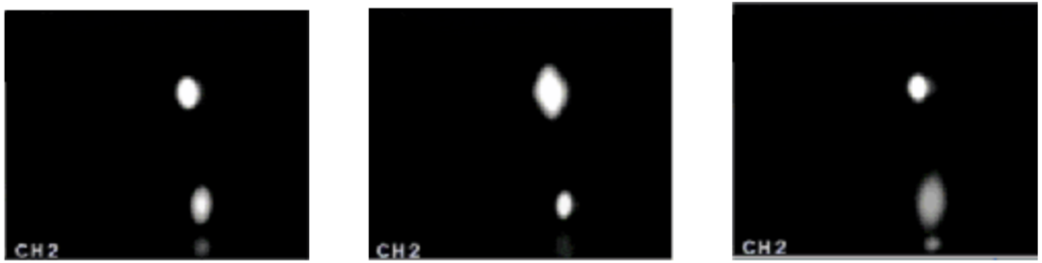


3D flip-flop [1]



- Occurs only in presence of BS
  1. BS leads to asymmetry in the bunch length σ_z due to asymmetry of bunch currents (which are never exactly the same)
  2. Asymmetry in σ_z leads to amplified synchro-betatron resonances of the longer σ_z bunch
  3. Tune footprint expands and can cross more resonance lines
  4. Increase of both transversal emittances of the longer bunch
     - Increased emittances cause asymmetry in transversal beam size. This asymmetry increases BS and σ_z for the longer bunch but decreases BS and shrinks σ_z for the shorter bunch:
       - ➢ σ_z asymmetry increases even more
  5. Repeat from 2.

➢ One bunch blows up, the other shrinks



(a) Equal (b) Blown-up positron beam (c) Blown-up electron beam [2]

[1] D. Shatilov [http://www.icfa-bd.org/Newsletter72.pdf]
[2] X. buffat [https://e-publishing.cern.ch/index.php/CYRSP/article/view/265/277]