SIMULATION OF FCC-EE BEAM-BEAM EFFECTS WITH XSUITE

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Outline

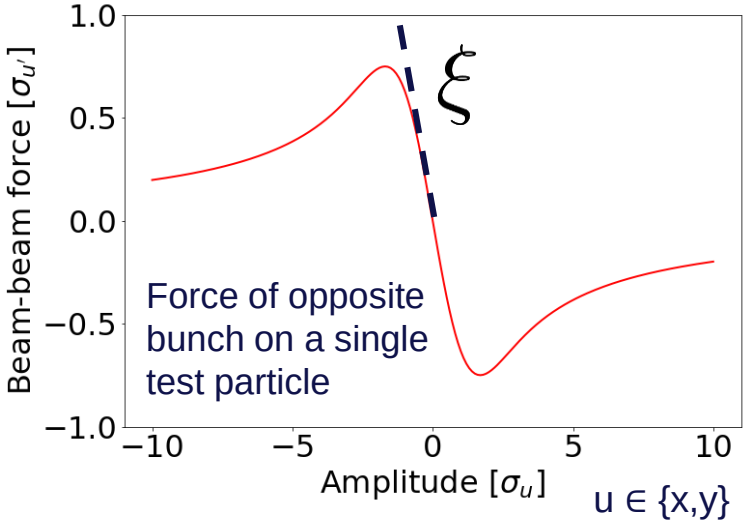
1. Beam-beam effects and modeling
2. Benchmark highlights
3. Summary

Beam-beam interaction

- A particle beam represents an electromagnetic potential for other charges

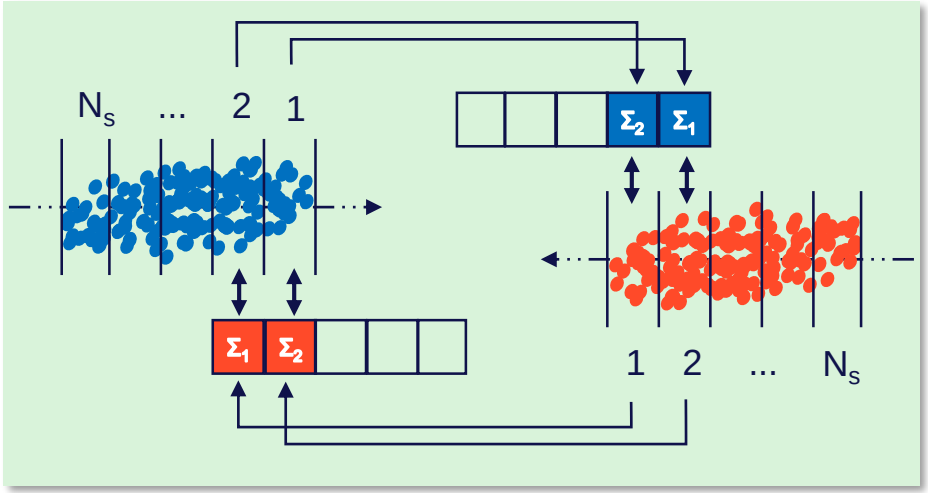
$$\xi_x = \frac{N r_0 \beta_x^*}{2\pi\gamma\sigma_x \sqrt{1+\left(\frac{\sigma_z}{\sigma_x}\mathrm{tg}(\Phi)\right)^2}\left(\sigma_x \sqrt{1+\left(\frac{\sigma_z}{\sigma_x}\mathrm{tg}(\Phi)\right)^2}+\sigma_y\right)}$$

- Beam acts with a force on other beam
  - Beam-beam kick: **highly nonlinear**
  - Harmful consequences for beam dynamics
  - Linear strength characterized by beam-beam parameter (ξ)
  - No complete theory, simulations have to be used



Beam-beam models

- ~10^4-10^7 particles per bunch
- Longitudinal slicing (simplecticity)
- Interaction of slice pairs
  - Compute kick using slice moments (Σ)
  - Update dynamical variables



multi-turn effects | low disruption parameter | high disruption parameter

single particle effects | slow instabilities | fast instabilities, wakefield & lattice interplay

fastest & least accurate — **slowest & most accurate**

never
weak-strong [**WS**]

periodically
quasi strong-strong [**QSS**]

after each slice-slice interaction
strong-strong [**SS**]

Frequency of recomputing slice moments

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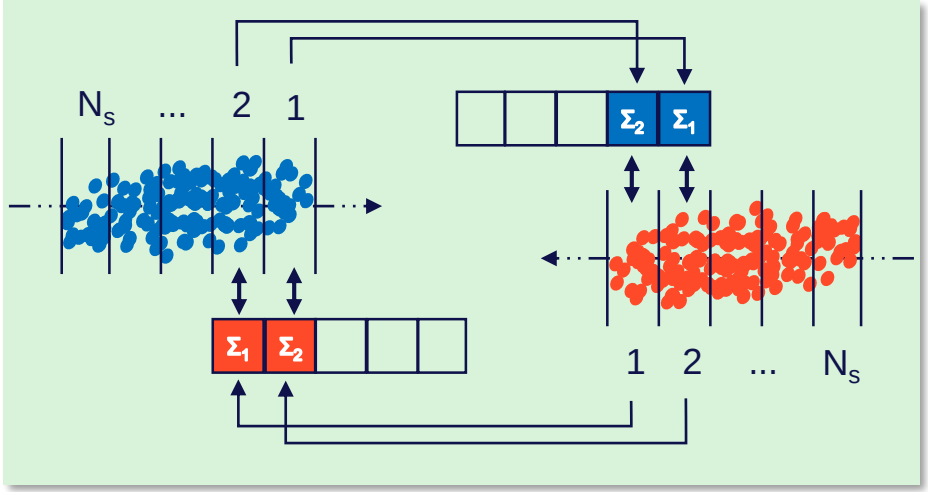
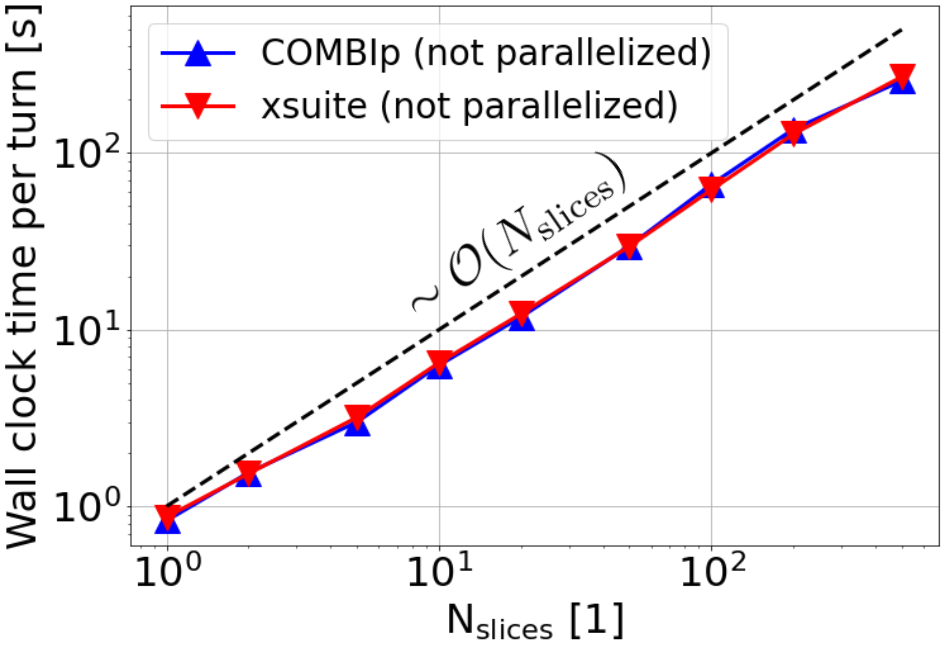


In xsuite:

- Core algorithm: single slice-slice interaction
- Choice between models done by user: specifying update frequency of slice moments
- Force: soft-Gaussian kick by Bassetti-Erskine formula [1] (field solvers to be tested in future)
- Extendible with features e.g. Beamstrahlung, Bhabha scattering

[1] https://cds.cern.ch/record/122227/files/198005132.pdf



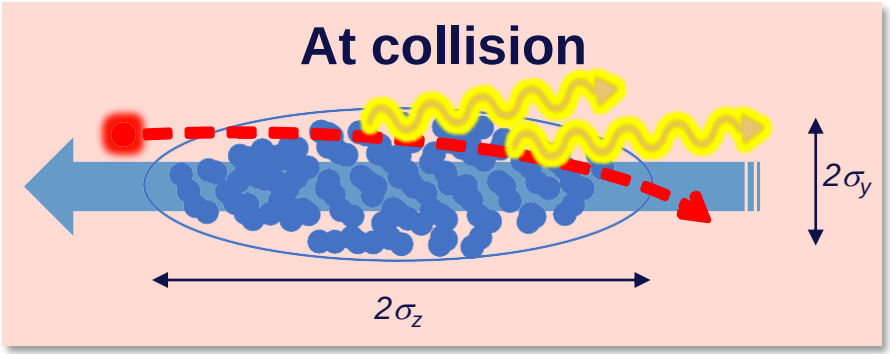
- Benchmark of computation (wall clock) time using reference code COMBIp [1]
  - Beam-beam (**strong-strong**)
  - Linear tracking
- Avg. time per turn scales approximately with the number of longitudinal slices
- xsuite runtimes comparable to state of the art
- OpenMP and GPU acceleration are available in xsuite, to be tested in future
  - Will be needed for full scale simulations

[1] https://twiki.cern.ch/twiki/bin/view/ABPComputing/COMBI

Beamstrahlung

- Radiation emitted at collision due to deflection in the collective EM field of the opposite bunch

- Harmful effect
  - Increases bunch length (σ_z) & energy spread (σ_δ)
  - Decreases luminosity & beam lifetime



Main limiting factor of FCC-ee luminosity

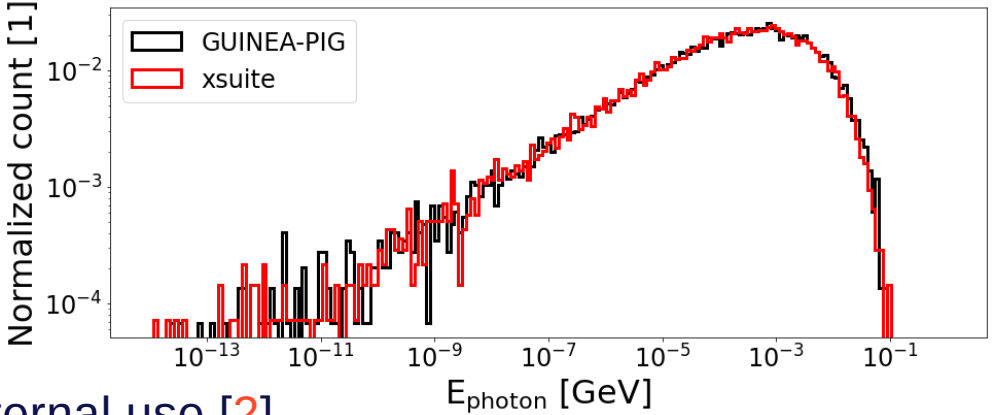
- Proposed setup [1]:
  1. Large Piwinski angle + crab waist scheme
     - ➢ Small beam size, crossing angle, crab sextupoles
  2. Top-up injection scheme: continuous injection of new bunches
     - ➢ Maintains luminosity levels & compensates for decreased beam lifetime

[1] https://cds.cern.ch/record/2651299/files/CERN-ACC-2018-0057.pdf

Beamstrahlung benchmark

- Benchmark against reference code GUINEA-PIG [1]
  - FCC-ee Z
  - Half crossing angle: 15e-3 [rad]
  - Beamstrahlung model OK
  - xsuite: **weak-strong**
  - GUINEA-PIG: **strong-strong**

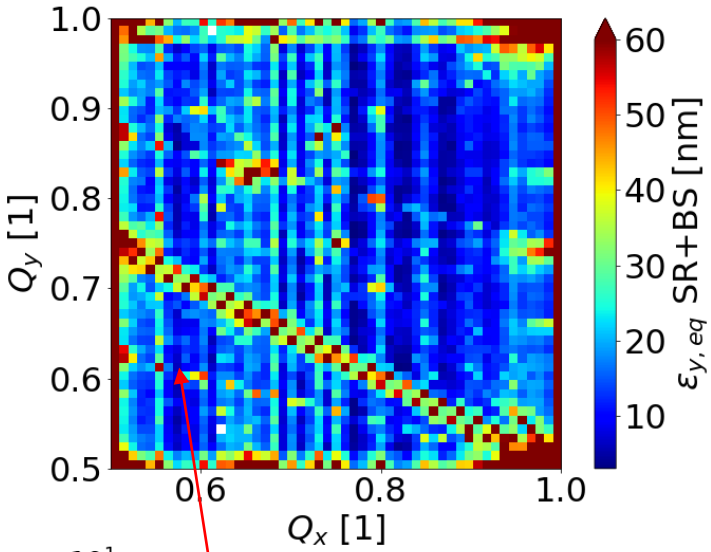
Beamstrahlung photon spectrum / coll.

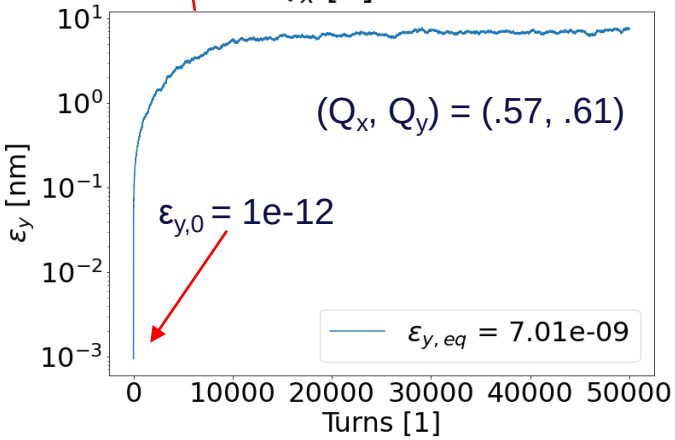


- Possibility to generate photons for external use [2]

- 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





- Finding optimal working points:
  - Tune scans: FCC-ee Z **weak-strong** tracking including synchrotron radiation + Beamstrahlung
- Blowup of transversal emittances due to beam-beam (crab sextupole to be added)

Work ongoing!

Summary

[1] https://github.com/xsuite

Work so far

- Beam-beam model development & benchmarks
- Beamstrahlung: photon generation available
- Update github repository [1] expected in a few days

Work ongoing

- Crab sextupoles
- Interplay with real lattice model
- Bhabha scattering
- Top-up injection
- 3D flip-flop

More on xsuite by T. Pieloni & F. Carlier @ this workshop

Other xsuite features targeted

- Impact of lattice imperfections (misalignment, orbit and optics corrections)
- Multiple IPs
- Monochromatization
- Wakefields

Thank you!

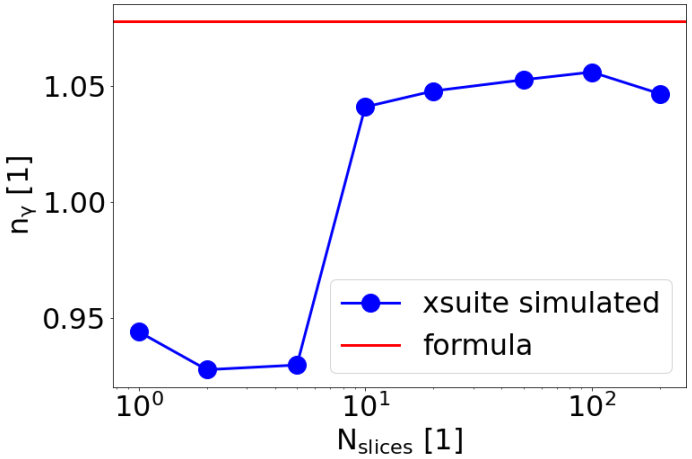

BACKUP

Simulation parameters

	Runtime benchmark (slide #5)	Beamstrahlung energy spectrum (slide #7)	Tune scan (slide #8)
N slices	scanned	200	200
N macroparticles	1e6	1e5	1e3
N turns	10	1	5e4
Half crossing angle [rad]	0	15e-3	15e-3
$\varepsilon_x/\varepsilon_y$ [m]	2.68e-10 / 2.68e-10	2.7e-10 / 2.7e-12	2.7e-10 / 1e-12
β_x/β_y [m]	1 / 1	0.15 / 0.15	0.15 / 8e-4
Beamstrahlung	OFF	ON	ON
Beam profile	HL-LHC round Gaussian	FCC-ee flat Gaussian	FCC-ee flat Gaussian
xsuite beam-beam model	strong-strong	weak-strong	weak-strong

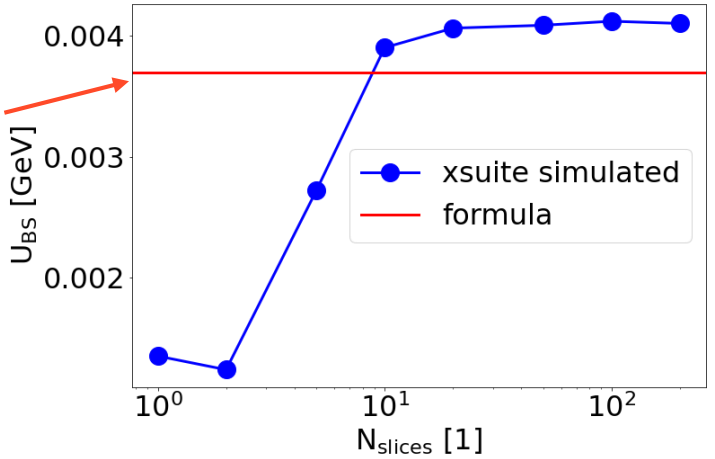
Beamstrahlung benchmarks

Avg. num. of emitted BS photons / e⁻ / coll.



Valid for weak-strong case

Avg. E loss / e⁻ / coll.



- Single **weak-strong** beam-beam collision; look at num. of emitted photons & E loss
- xsuite simulated quantities converge (within 10%) to analytical estimates [1]

[1] https://accelconf.web.cern.ch/ipac2016/papers/wepmw010.pdf