TOWARDS BEAM-BEAM SIMULATIONS FOR FCC-EE

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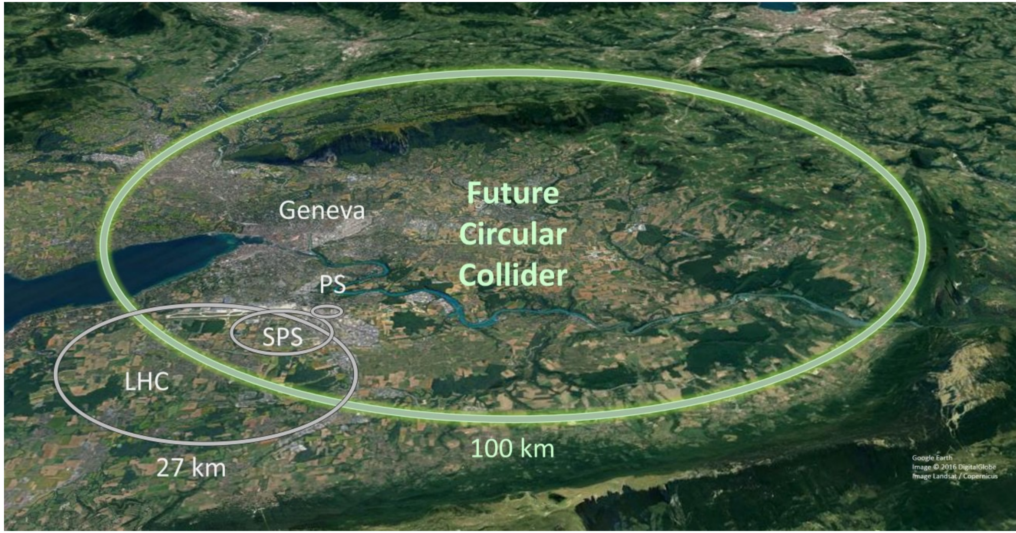
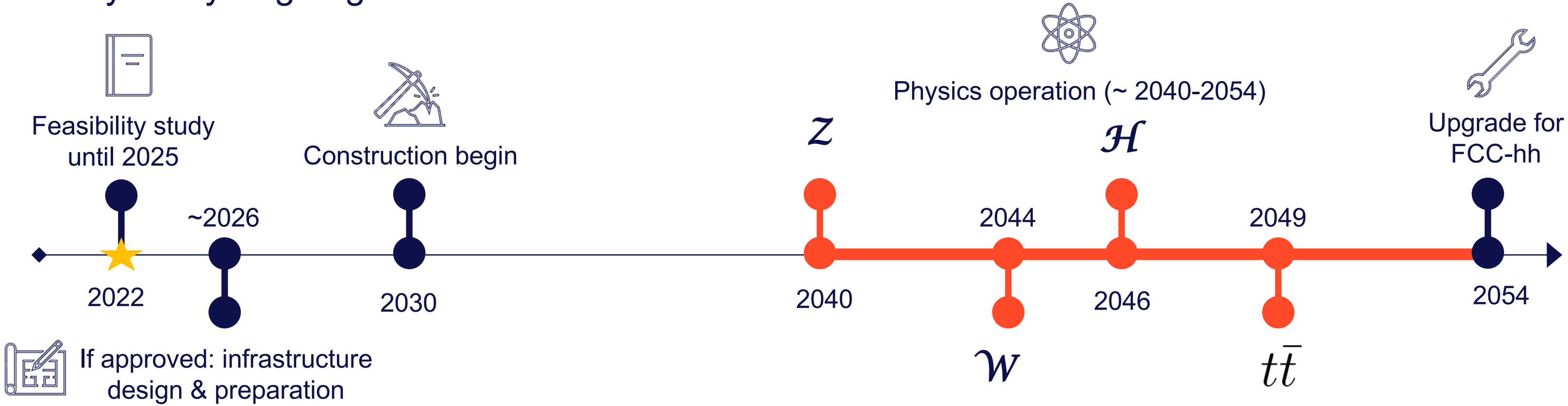
Overview

1. Introduction to FCC-ee
2. Beam-beam effects in FCC-ee
3. Overview of existing simulation tools for circular machines
4. Beam-beam models
5. First studies
6. Summary & next steps

FCC-ee

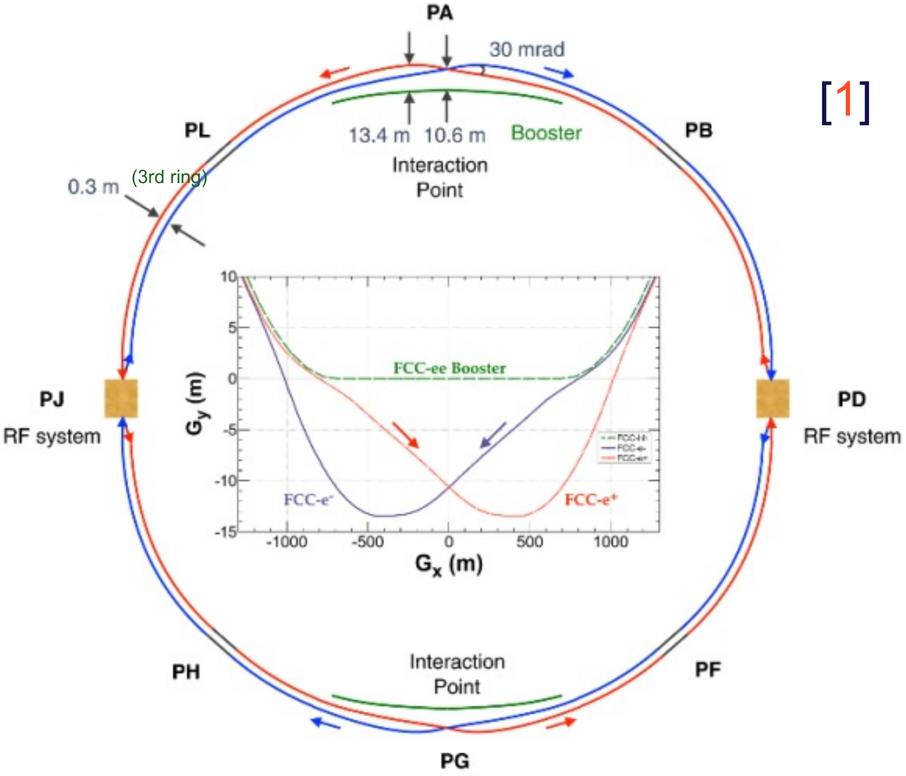
- The FCC-ee (Future Circular Collider): currently one of the most favored next colliders at CERN
- Study properties of standard model particles with unprecedented precision, up to 350 GeV
- A first stage towards a possible 100 TeV hadron collider (FCC-hh)
- Feasibility study ongoing





Layout

- Baseline with 2 IP
- 4 IP configuration under study
- Accelerator design aims to maximize luminosity and reduce beam-beam effects



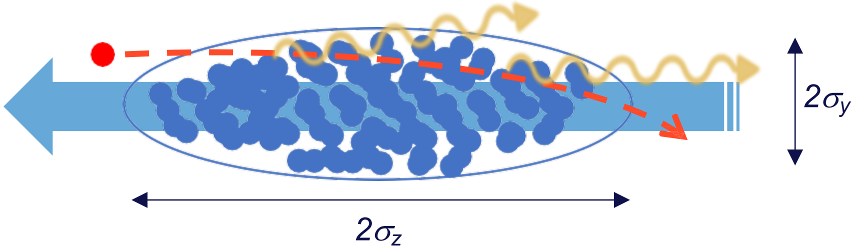
[1]

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

Beam-beam effects in FCC-ee

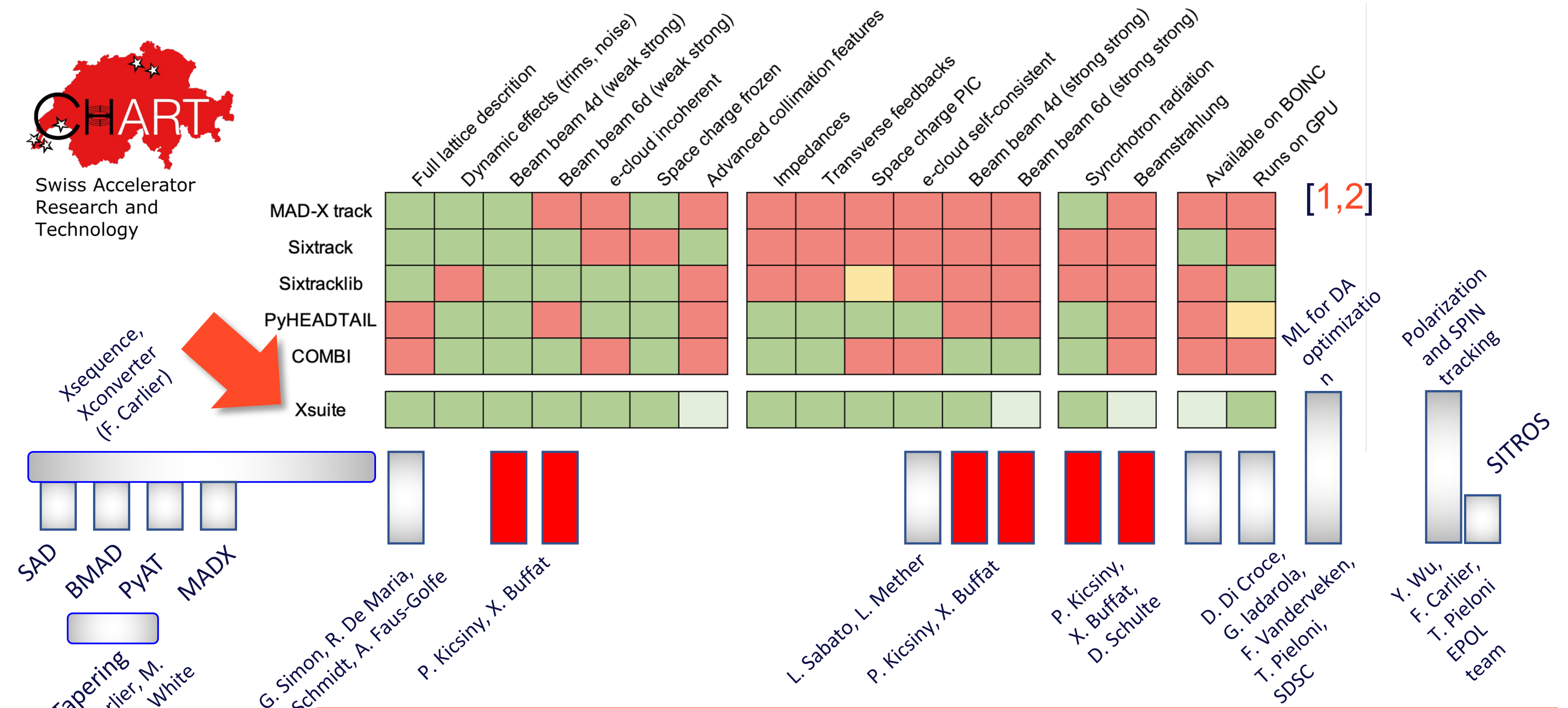
- Nonlinear kick
- No complete theory, simulations have to be used
- Beamstrahlung:
  - ➢ Increases bunch length (σ_z) & energy spread (σ_δ)
  - ➢ Decreases luminosity & beam lifetime

At collision



- Proposed setup to increase luminosity [1]:
  1. Large Piwinski angle + crab waist scheme [2]
     - ➢ 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
[2] https://arxiv.org/pdf/1608.06150.pdf

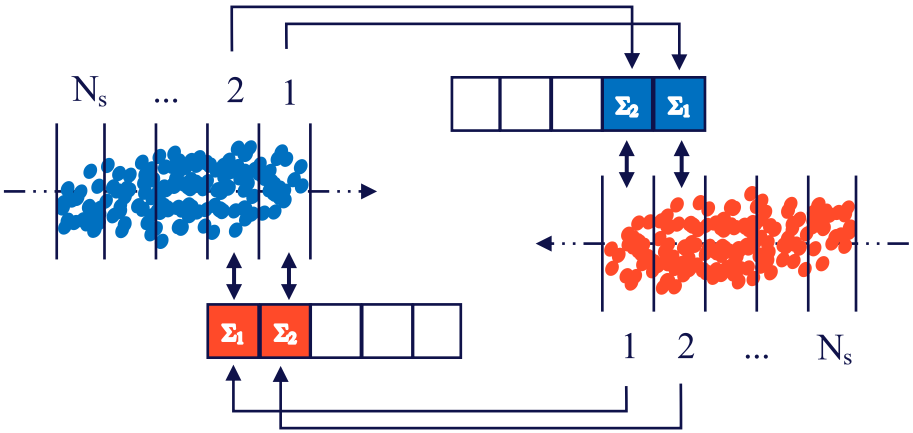


FCC-ee high complexity: need to simulate interplay of different effects

[1] G. Iadarola https://indico.cern.ch/event/1066779/contributions/4485729/attachments/2301867/3915592/019_Xsuite.pdf
[2] T. Pieloni https://indico.cern.ch/event/1064327/contributions/4893328/attachments/2454297/4206242/FCC%20Software%20framework%20developments.pdf

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

single particle effects

low disruption parameter

slow instabilities

high disruption parameter

fast instabilities

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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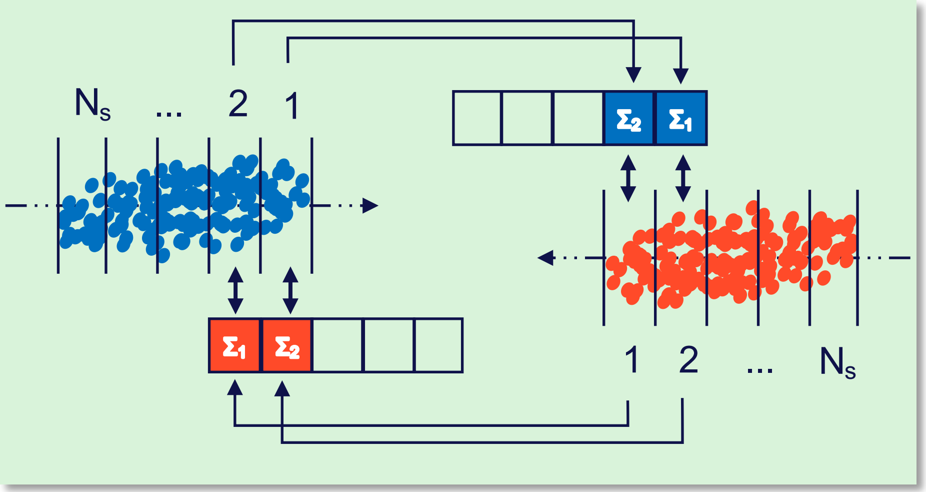
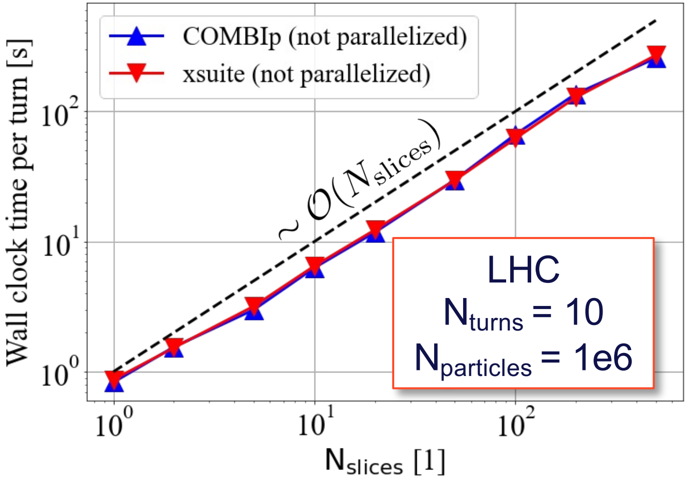


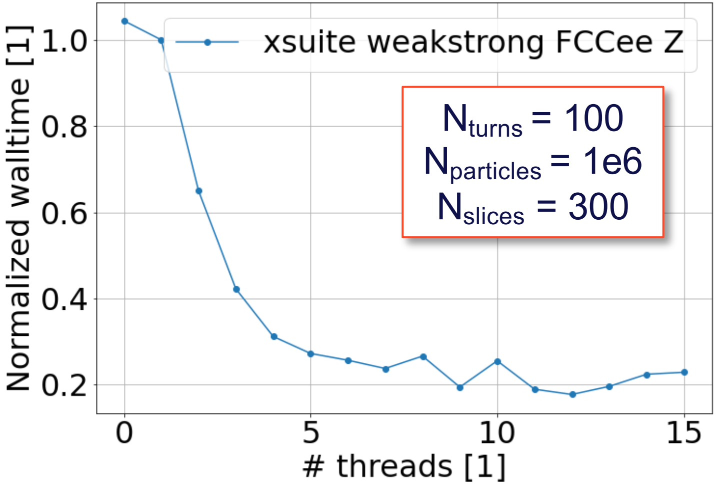
In xsuite:

- Core algorithm: single slice-slice interaction
- Flexible choice of model
- Force: soft-Gaussian kick by Bassetti-Erskine formula [1] (field solvers to be tested in future)
- Extendible: e.g. Beamstrahlung, Bhabha scattering

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



- Benchmark of computation time for beam-beam (**strong-strong**) + linear tracking against reference code COMBIp [1]
- Time per turn scales approximately with the number of longitudinal slices



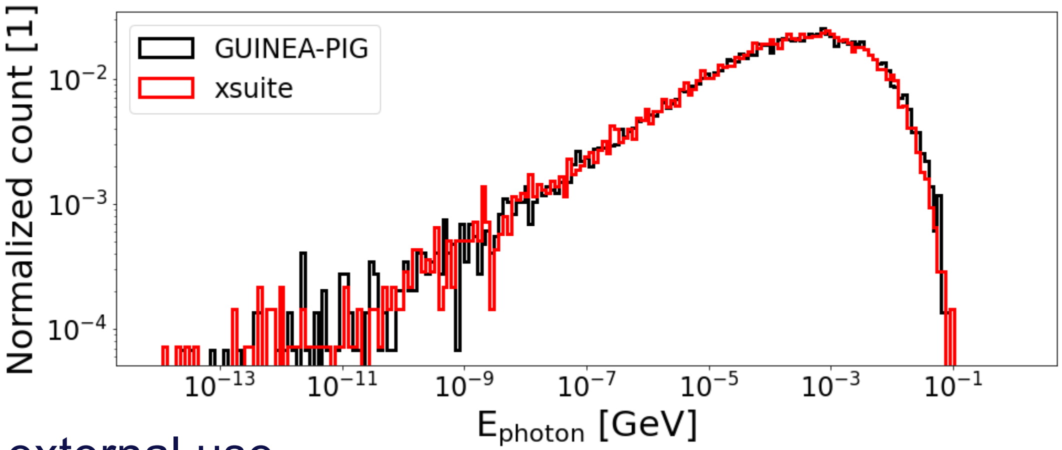
- Multithreading: ~x5 speedup
- GPU acceleration is available in xsuite
  - To be tested
  - Will be needed for full scale simulations

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

Beamstrahlung benchmark

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

Beamstrahlung photon spectrum / coll.



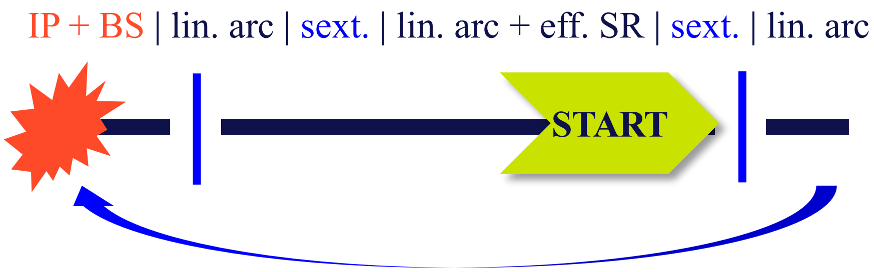
- Possibility to generate photons for external use (collimation, MDI) [2]

- 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

Simplified tracking simulations with xsuite

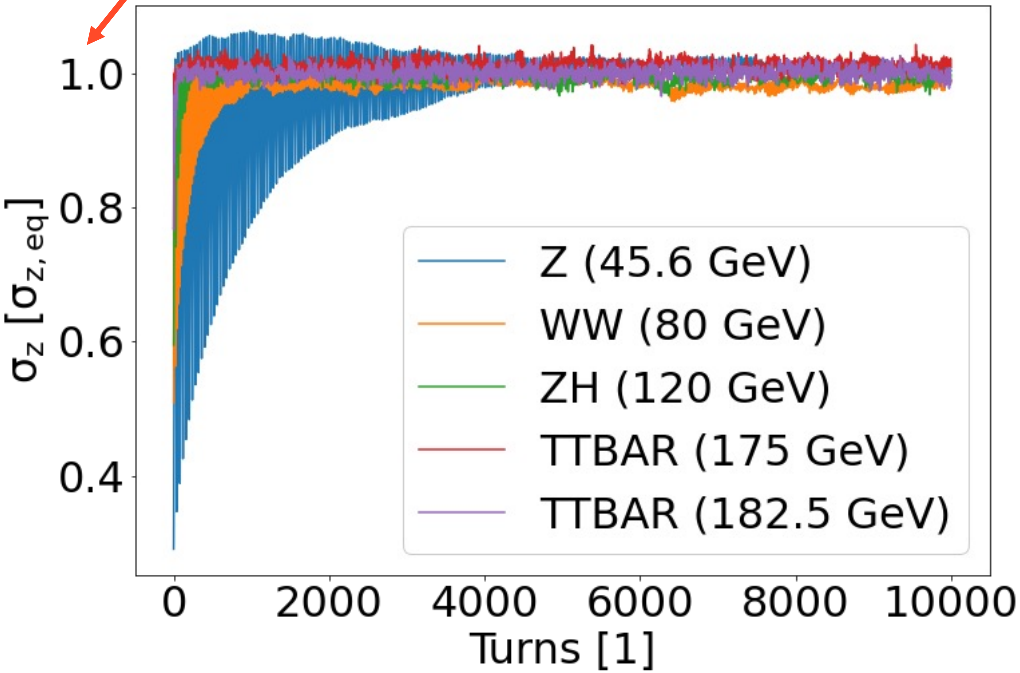
- Exploit superperiodicity of machine (2 IP case)
- In code:
  - 1 IP + tracking over half arc with linear transfer matrix



  - Arc split into 3 segments
  - 2 crab sextupoles between arc segments
  - A «turn» begins in front of the right sextupole:
    - Observation point for emittances (by stat. definition from normalized coordinates)
  - Observation point for raw coordinates is before IP
  - Effective radiation (damping+noise) in arc, beamstrahlung in beam-beam

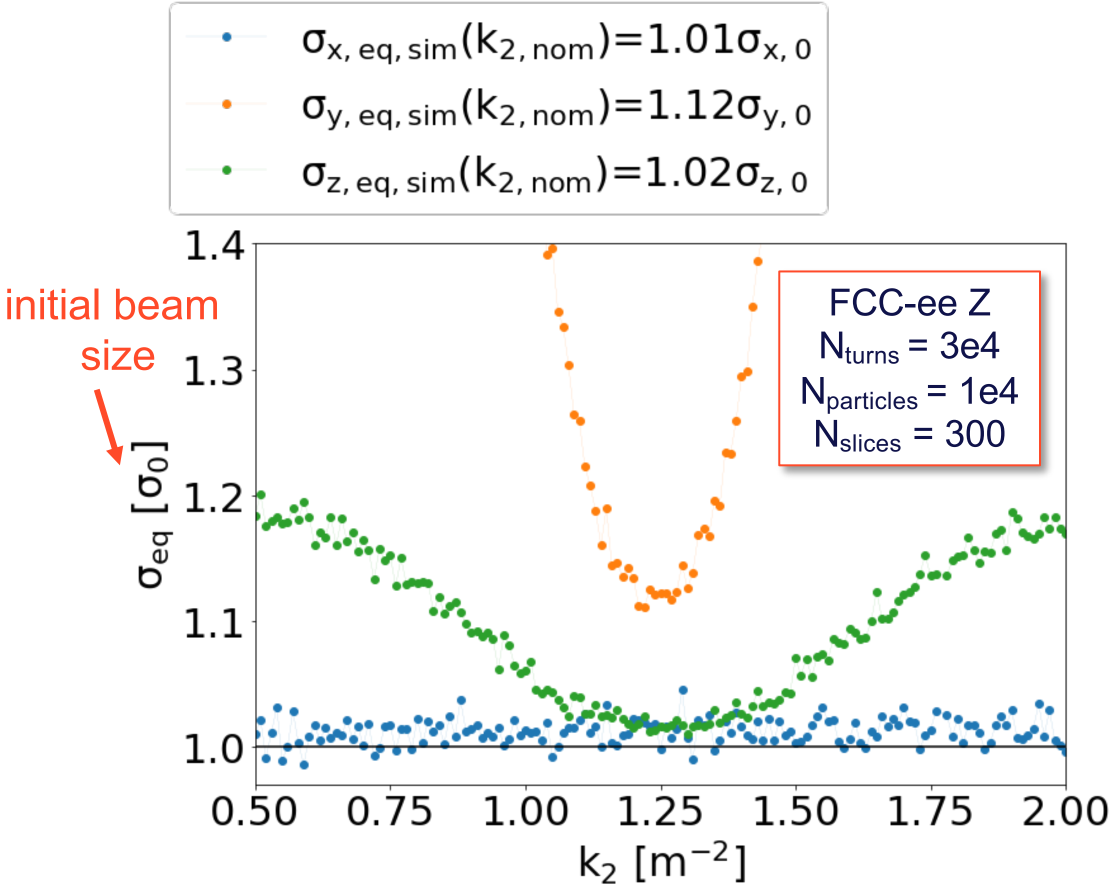
Equilibrium bunch length

normalized to design report values (SR+BS)



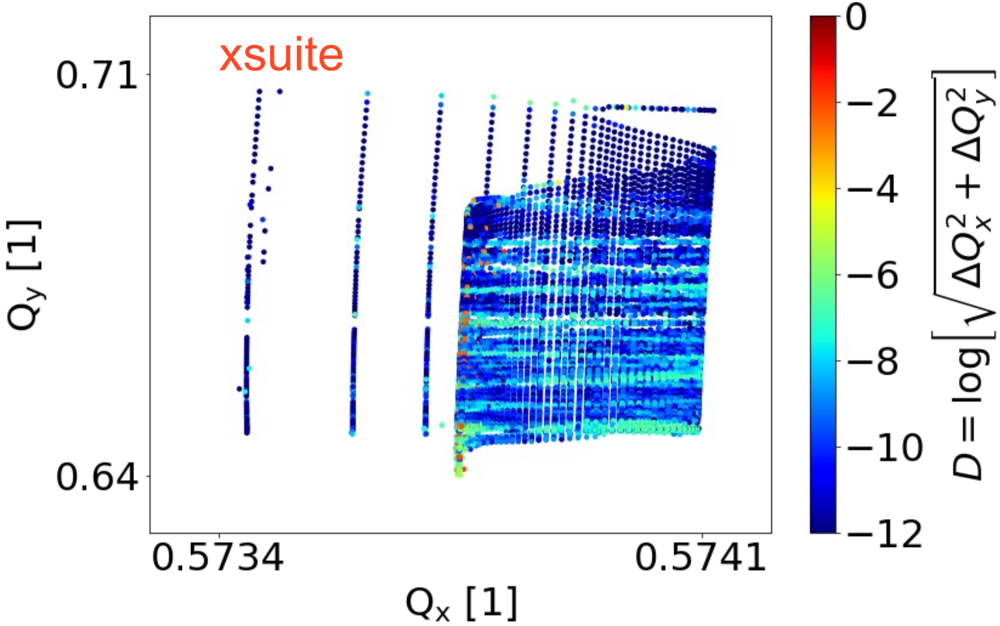
- **Weak-strong** model (1e4 particles)
- Equilibrium bunch length agrees with design report value for all resonances

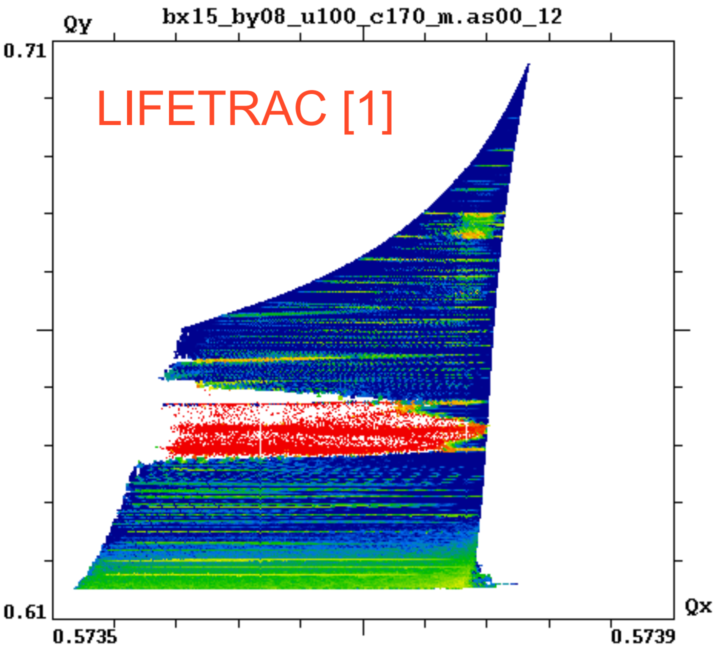
Crab waist & transverse blowup



- **Weak-strong** model
- Optimum k_2 close to nominal value (~0.97*$k_{2,nom}$ for Z resonance)
- ~10% blowup of vertical beam size (stat. errors ~1%)
- Not observed in other codes
- Investigation in progress

Understanding transverse blowup & benchmarking

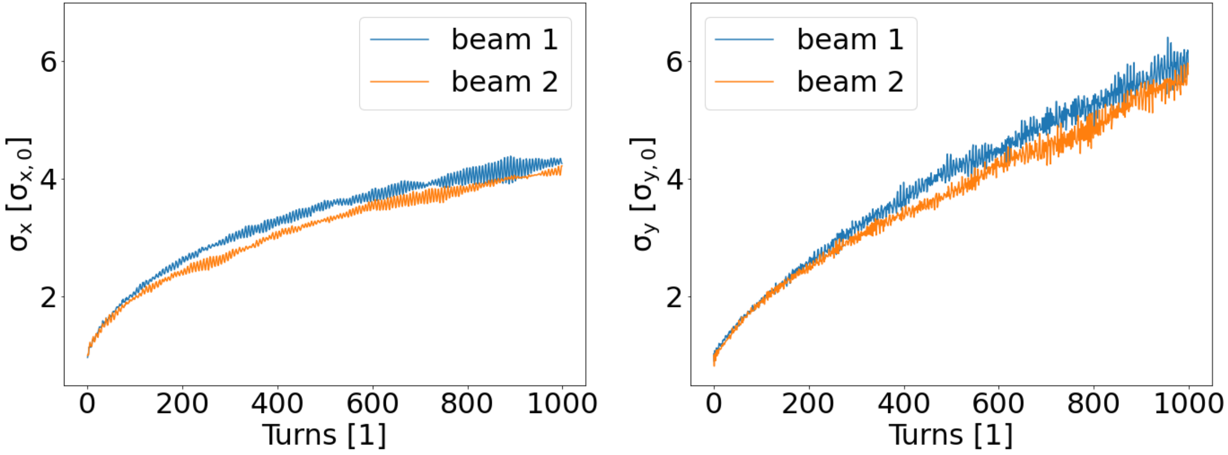




- FCCee Z tune footprint
- Differences to be understood

[1] Courtesy of D. Shatilov

Strong-strong simulations



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

- Fast blowup in x and y size (not observed in other codes)
- Coherent beam-beam instability? [1]
- Investigation in progress

[1] https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.119.134801

Summary

Work so far: xsuite code development & benchmarks for FCC-ee

- Flexible beam-beam models (weak-strong, quasi strong-strong, strong-strong)
- Beamstrahlung: photon generation available
- Weak-strong benchmarks (understaning vertical blowup, FMA benchmark)
- Strong-strong benchmarks (understand blowup, reproduce coherent instability)

Work ongoing

- Bhabha scattering
- 3D flip-flop
- Top-up injection

Other xsuite features targeted

- Impact of lattice imperfections
- Interplay with real lattice model
- Multiple IPs
- Monochromation
- Wakefields

Thank you!

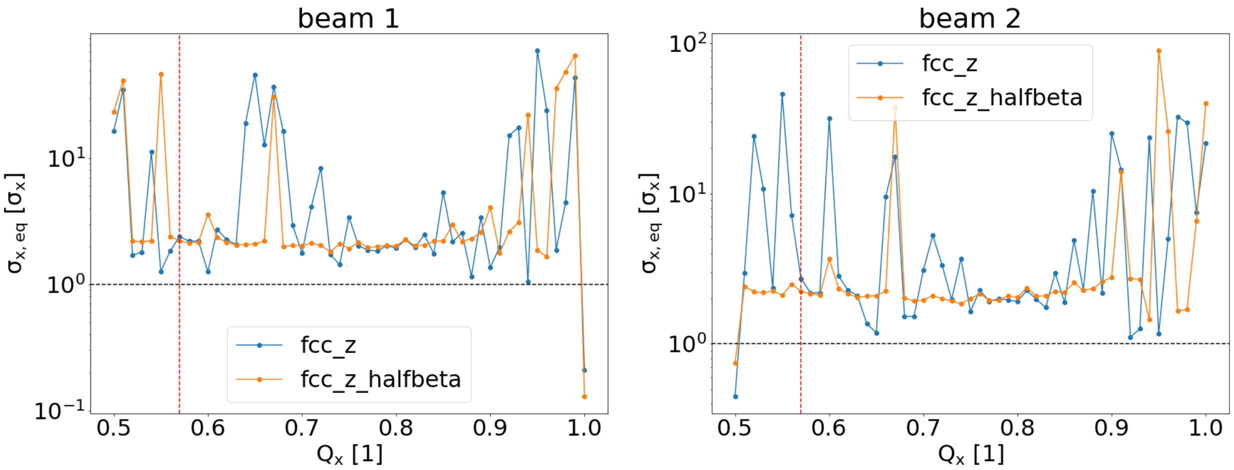
This work was performed under the auspices and with support from the Swiss Accelerator Research and Technology (CHART) program (www.chart.ch).

BACKUP

Simulation parameters

	Runtime benchmark	OpenMP benchmark	Beamstrahlung energy spectrum	CW scan
N slices	scanned	300	100	300
N macroparticles	1e6	1e6	1e5	1e4
N turns	10	100	1	3e4
Half crossing angle [rad]	0	15e-3	15e-3	15e-3
$\varepsilon_x/\varepsilon_y$ [m]	2.68e-10 / 2.68e-10	2.7e-10/1e-12	2.7e-10 / 2.7e-12	2.7e-10/1e-12
β_x/β_y [m]	1 / 1	0.15 / 8e-4	0.15 / 0.15	0.15 / 8e-4
Beamstrahlung	OFF	ON	ON	ON
Beam profile	LHC round Gauss	FCC-ee Z	FCC-ee flat Gauss	FCC-ee Z
xsuite beam-beam model	strong-strong	weak-strong	weak-strong	weak-strong

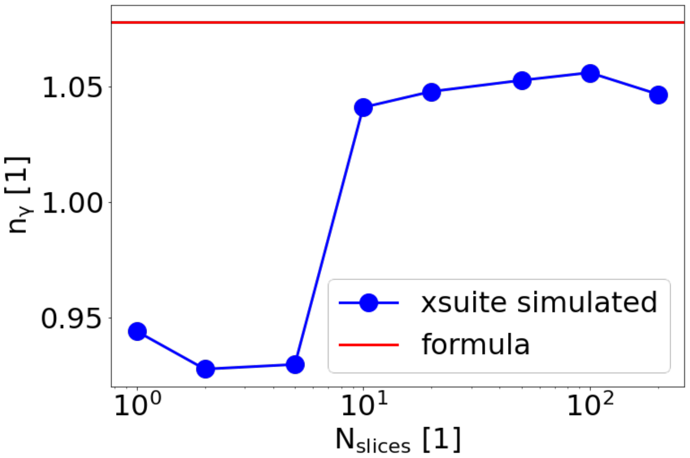
Investigating transverse blowup



- black lines: starting value (no blowup)
- red lines: FCCee Z working point
- working point is not on a peak but rather the baseline is higher than expected

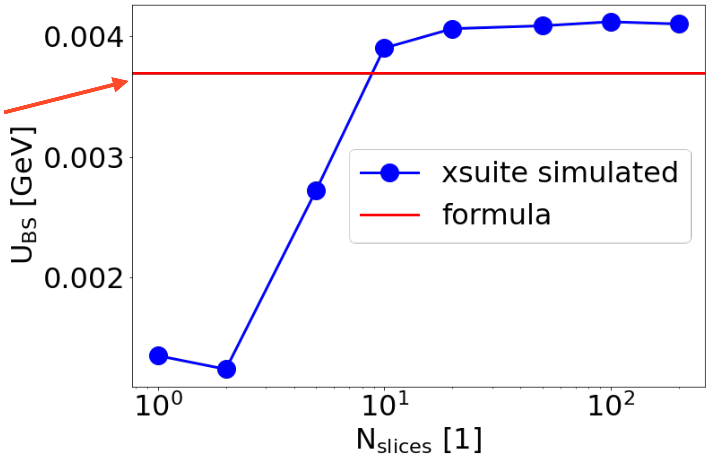
Beamstrahlung benchmarks

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



Valid for weak-strong case

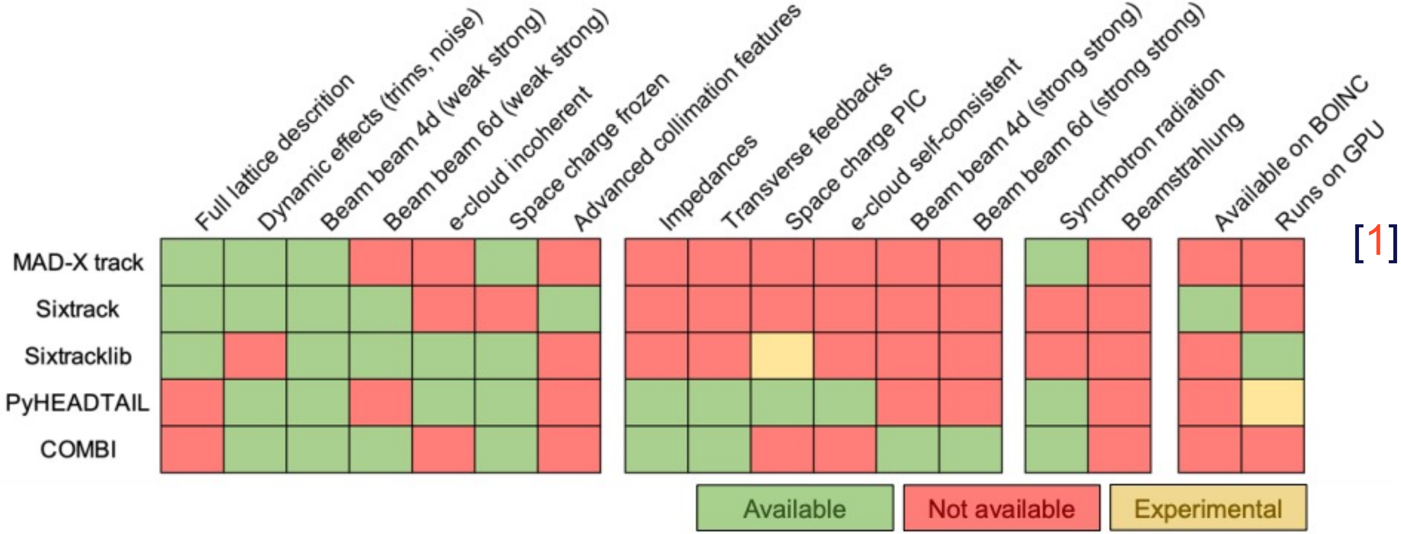
Avg. E loss / e⁻ / coll.



- 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

Overview of existing simulation tools for circular machines



[1]

- Different multiparticle tracking codes are used for different kinds of studies
  - e.g PyHEADTAIL: impedance modeling; SixTrack: beam background simulations; etc.

- FCCee high complexity: need to simulate interplay of different effects

[1] G. Iadarola https://indico.cern.ch/event/1066779/contributions/4485729/attachments/2301867/3915592/019_Xsuite.pdf

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 with different models
  - No cross-framework communication
  - Expensive to maintain and develop

[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/~jiqiang/BeamBeam3D/

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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

- Efforts towards a new design (**Xsuite** [1]) featuring a single general software framework for beam dynamics studies
  - Modular, sustainable, performant
  - Part of the larger project CHART: Accelerator design and simulation framework for FCC-ee

Swiss Accelerator Research and Technology

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