BEAM-BEAM STUDIES FOR FCC-ee

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for the beam-beam working group, with special thanks to:

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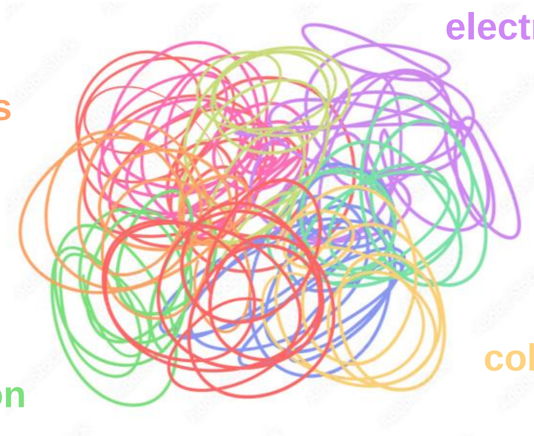
Overview

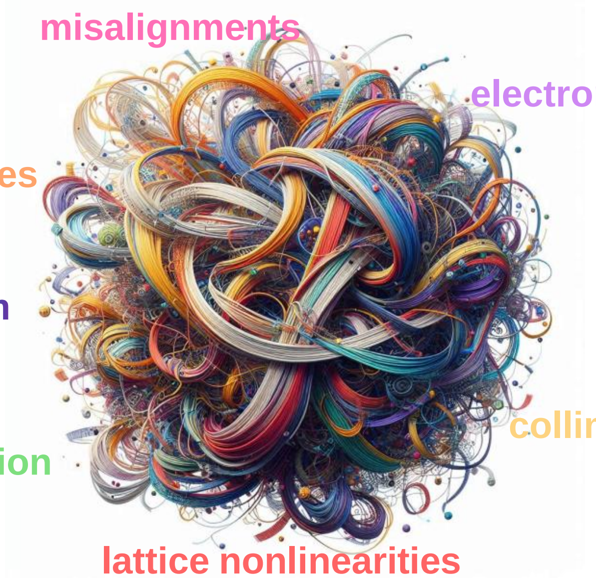
- FCC-ee will be a highly complex machine

- Interplay of various effects



Overview

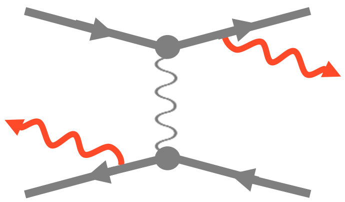
- FCC-ee will be a highly complex machine
- Interplay of various effects
- Presence of beam-beam collisions further complicates beam dynamics
- Self-consistent simulations are challenging



Radiation at FCC-ee collisions

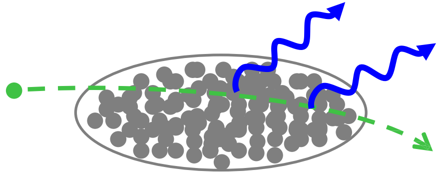
Incoherent

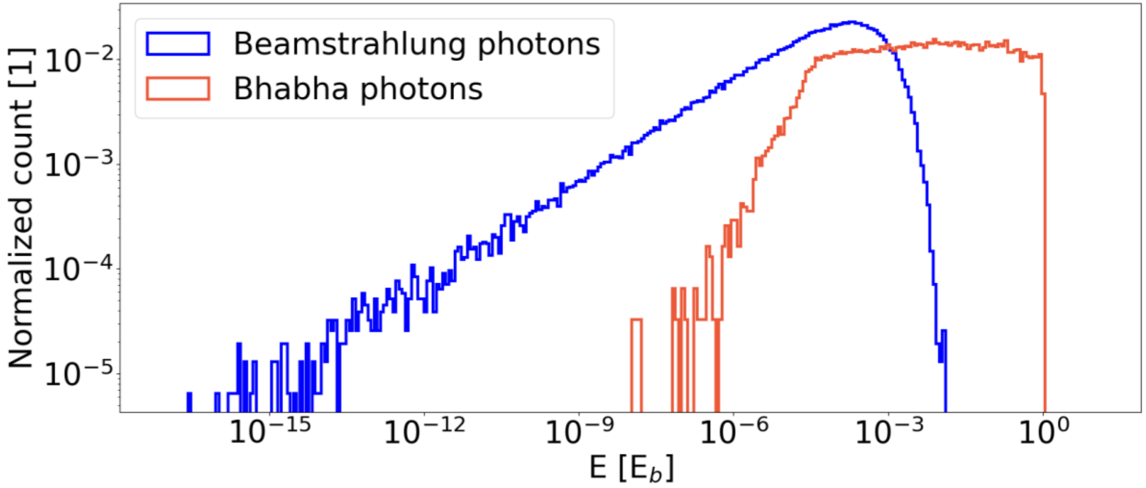
- Radiative Bhabha scattering
- Deflection in field of single particle of opposite bunch



Collective

- Beamstrahlung
- Deflection in collective field of opposite bunch





- Radiation ➡ particle losses

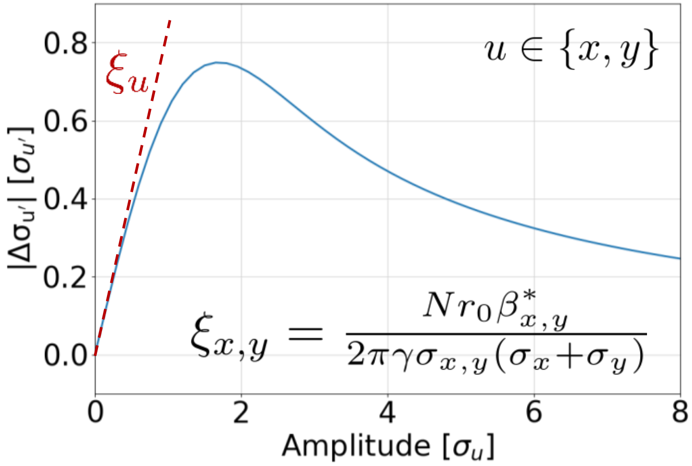
$\tau \mathcal{L}$ ⬇ $\sigma_z \sigma_\delta$ ⬆

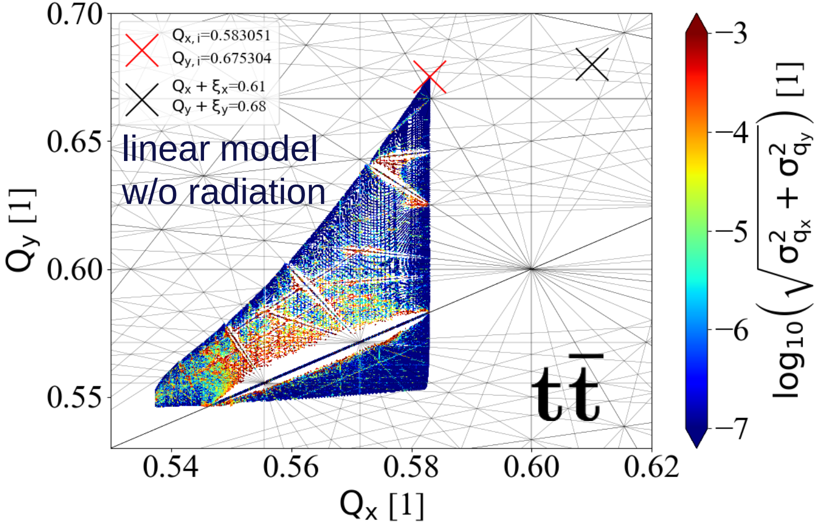
lifetimes:
BS ~100 min
BH ~30 min

Beam-beam force

High lumi ➡ strong beam-beam force

$$L = \frac{\gamma}{2er_e} \cdot \frac{I_{tot}\xi_y}{\beta_y^*} \cdot R_{hg}$$





Consolidation...

- Radiation (synchrotron radiation, beamstrahlung, Bhabha)
- IP tuning & feedback
- Beam asymmetries
- Top-up injection

Tools

	Weak-strong 6D	Quasi-strong-strong 6D	Strong-strong 6D SG	Strong-strong 6D PIC	Beamstrahlung	Bhabha-scattering	Transverse wakefields	Longitudinal wakefields	Linear tracking	Lattice tracking	Open source	Runs on GPU
GUINEA-PIG [2]	Available	Not available	Not available	Available	Available	Available	Not available	Not available	Not available	Not available	Available	Not available
COMBI [3]	Available	Available	Available	Available	Not available	Not available	Available	Not available	Available	Not available	Available	Not available
BBWS [4]	Available	Not available	Not available	Not available	Available	Not available	Available	Available	Available	Available	Not available	Not available
BBSS [5]	Not available	Not available	Available	Available	Available	Not available	Available	Available	Available	Not available	Not available	Not available
SCTR [6]	Not available	Not available	Available	Available	Available	Not available	Available	Available	Available	Available	Not available	Available
IBB [7]	Not available	Not available	Available	Not available	Available	Not available	Available	Available	Available	Not available	Not available	Not available
LIFETRAC [8]	Available	Available	Not available	Not available	Available	Not available	Not available	Not available	Available	Available	Not available	Not available
BeamBeam3D [9]	Available	Not available	Available	Available	Available	Not available	Available	Not available	Available	Not available	Available	Not available
Xsuite [10]	Available	Available	Available	Not available	Available	Available	Available	Available	Available	Available	Available	Available

Available | Not available

- Different beam-beam codes exist, with different features
- FCC-ee: self-consistent & fast modeling needed including many effects
- Xsuite: development driven by needs for FCC-ee

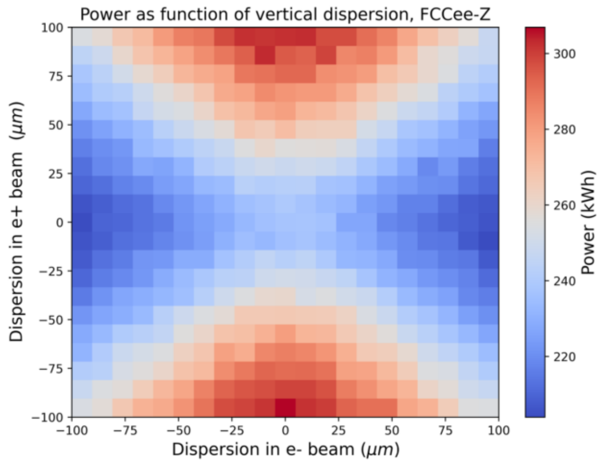
IP tuning & optimization

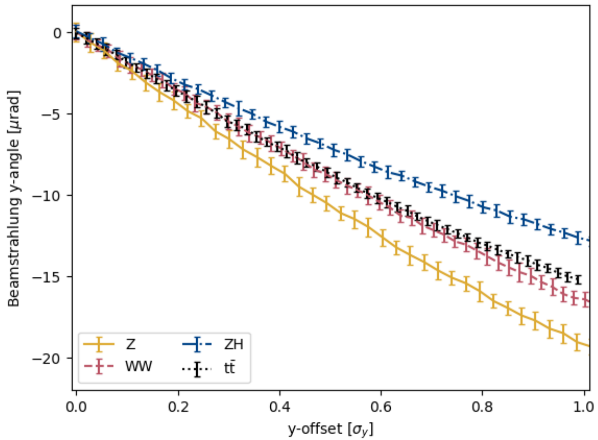
Design schemes to infer and correct for imperfections based on different signals (radiation, orbit measurements, ...)

- Waist & dispersion shifts, beam offsets (fast IP feedback)
- Using GUINEA-PIG (single passage), multiturn effects with Xsuite need to be considered

V. Gawas, poster @ this conference

J. Salvesen, poster @ this conference

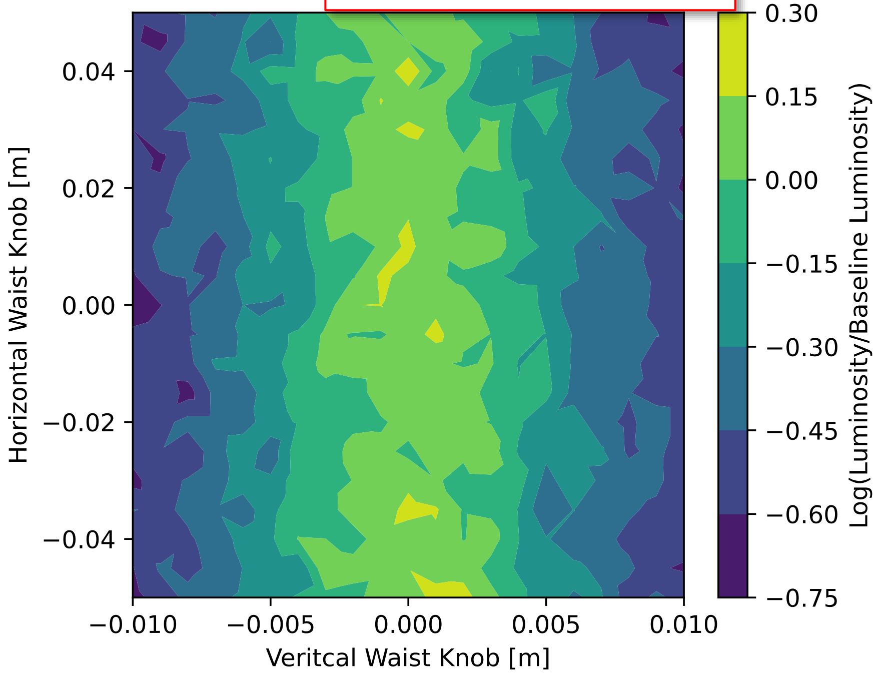




IP tuning & optimization

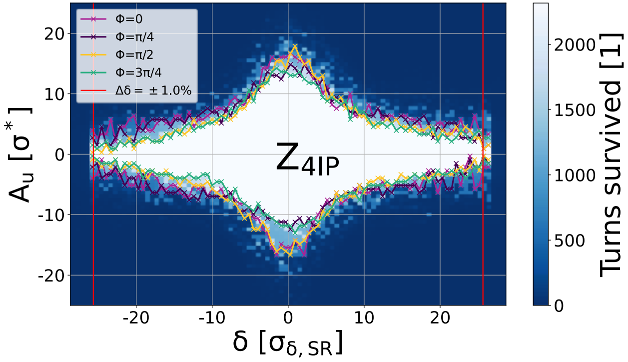
- Development of tuning knobs to vary beam configuration at the IP (waist)
  - Determine whether optics can be relaxed for better performance (e.g. easier startup)
  - Design experimental methods for waist correction based on luminosity
- Larger sensitivity in luminosity for vertical but smaller in horizontal waist
- Tests with machine errors in progress

Xsuite, FCC ttbar
relaxed optics [11]
300 turns
1e5 macroparticles



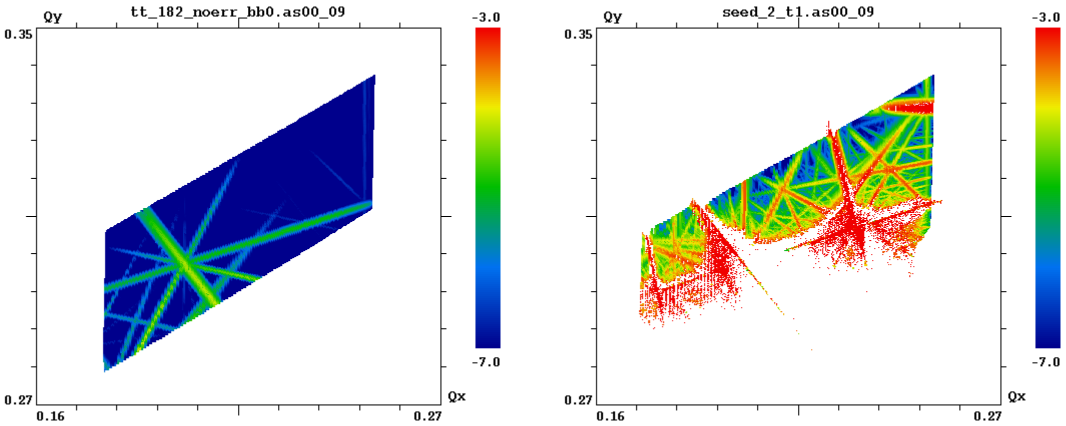
Dynamic aperture

$$u \in \{x, y\} \qquad A_u = \sqrt{\left(\frac{u}{\sigma_u^*}\right)^2 + \left(\frac{p_u}{\sigma_{p_u}^*}\right)^2}$$



w/o errors

- Negligible reduction from beam-beam
- Compares well with SAD results from K. Oide [12]



D. Shatilov [13]

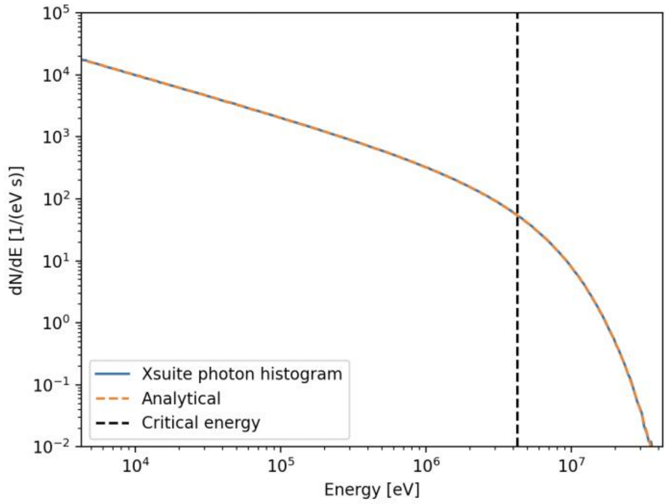
w/ errors & corrections

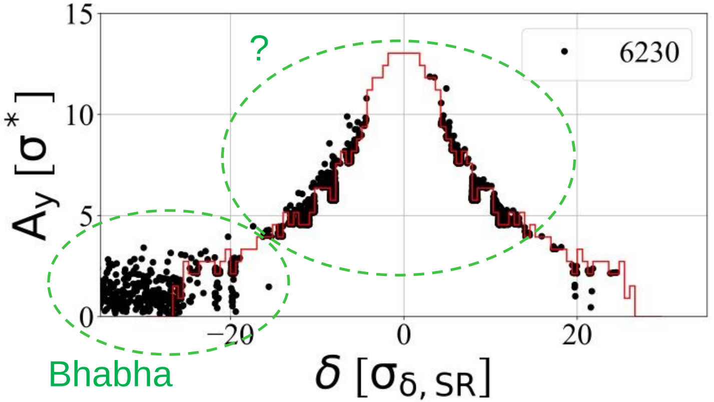
- More lattice induced resonances are seen with beam-beam due to large amplitude detuning
- Full lattice needs to be optimized with beam-beam included
- Tools are ready, requires work with tuning working group to establish correction strategies

Benchmarking radiation in Xsuite

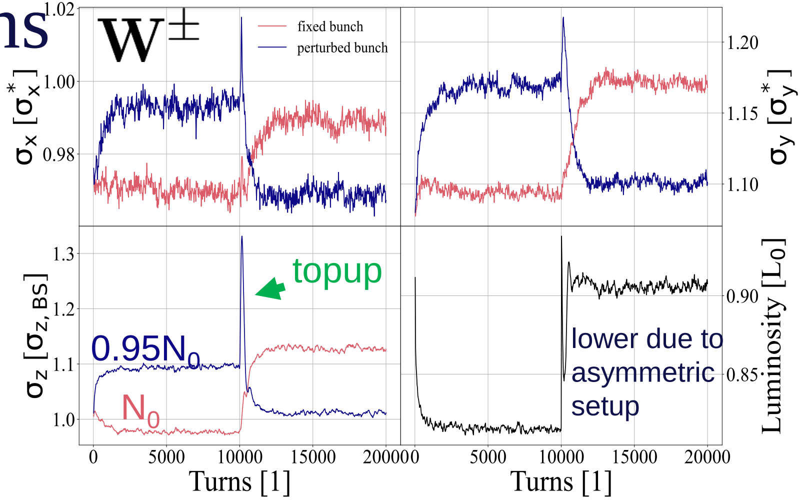
Several benchmarks

- ✓ Synchrotron radiation with MAD-X and SAD [14]
- ✓ Optics, orbit, energy with and without errors
- ✓ Quantum excitation and damping
- ✓ Equilibrium emittance w/ vertical wiggler
- ✓ Tracking and matrix methods
- ✓ Bhabha + beamstrahlung lifetimes
- Loss rate from unknown mechanism to be investigated (comparison with SAD to be refined)



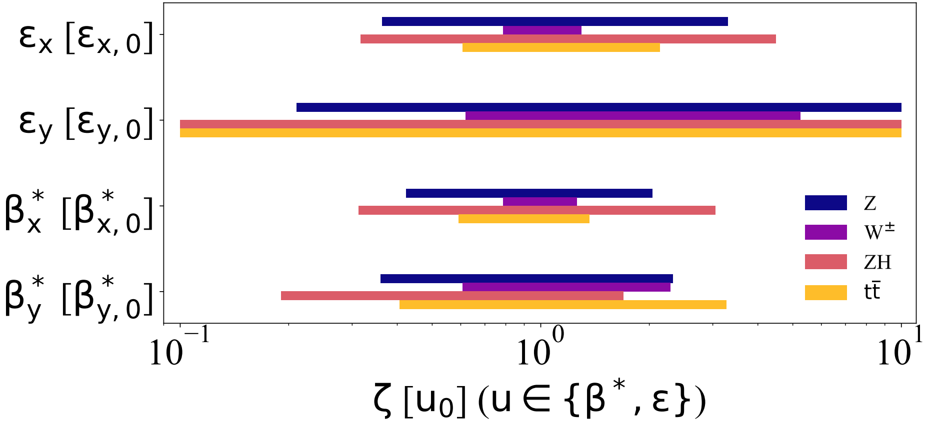


Top-up injection & asymmetry scans



Longitudinal top-up simulated with Xsuite

- Perturbed bunch init. with 95% intensity
- Track till equilibrium & top-up
- Luminosity lower than in symmetric case (L_0) due to vertical blowup
  - Should be avoided (e.g. working point optimization)

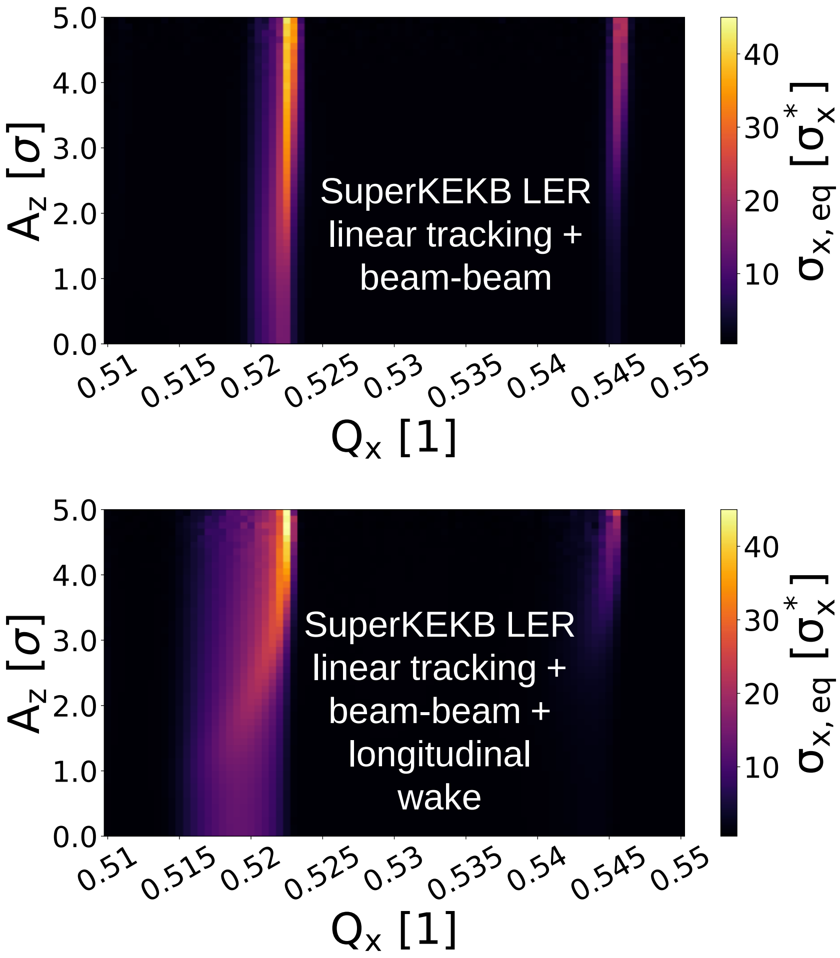


- Evaluate asymmetries in emittance/beta leading to 50% vertical blowup
- Derived coarse tolerances for machine tuning

Case study at the SuperKEKB

- Beam-beam excites synchro-betatron resonances (collective [15], here single particle)
- Interplay with longitudinal wakefield enhances amplitude dependent incoherent x-z resonance
  - Impact on FCC-ee W? (high Q_s)
- Successful Xsuite benchmarks against BBWS, BBSS, PyHEADTAIL
- Transverse impedance + beam-beam @ FCC-ee

R. Soos, talk @ this conference



Summary

<u>Work so far</u>

- Xsuite beam-beam model developed:
  - Benchmarked against other codes GUINEA-PIG, BBWS, BBSS, PyHEADTAIL, COMBI, BBBREM, SAD, MAD-X
  - Tools are ready to combine beam-beam + lattice / IP + errors & tuning
  - Consolidated tolerances for asymmetries (bunch intensity, emittance, beta)

<u>Lots of work still ahead...</u>

- Understand lifetime discrepancy (not beam-beam related)
- Lattice tuning w/ errors @ beam-beam
- Beam-beam + longitudinal impedance @ FCC-ee W
- IP tuning with multiturn tracking
- Beam-beam + transverse impedance
- Monochromatization + beam-beam

Thank you!

References

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

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

[9] J. Qiang https://amac.lbl.gov/~jiqiang/BeamBeam3D/

[10] Xsuite 10.18429/JACoW-HB2023-TUA2I1

[11] L. van Riesen-Haupt https://www.jacow.org/ipac2024/pdf/WEPR04.pdf

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[13] D. Shatilov, FCC Week 2022 https://indico.cern.ch/event/1064327/contributions/4893272/

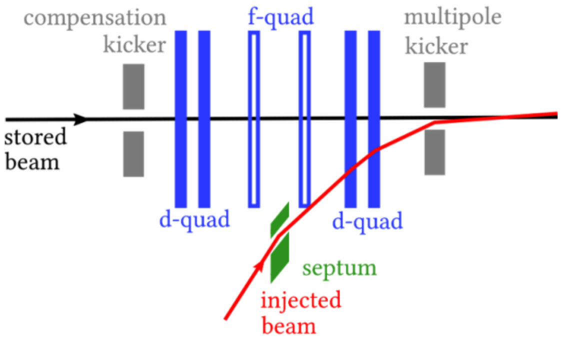
[14] L. van Riesen-Haupt https://www.jacow.org/ipac2024/pdf/WEPR05.pdf

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

BACKUP

Top-up injection

- Maintains luminosity levels & compensates for decreased beam lifetime
- Single booster feeds both beams



Longitudinal top-up simulated with Xsuite

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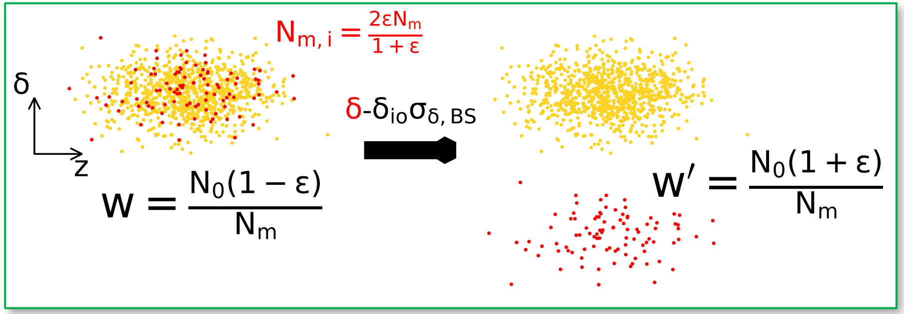
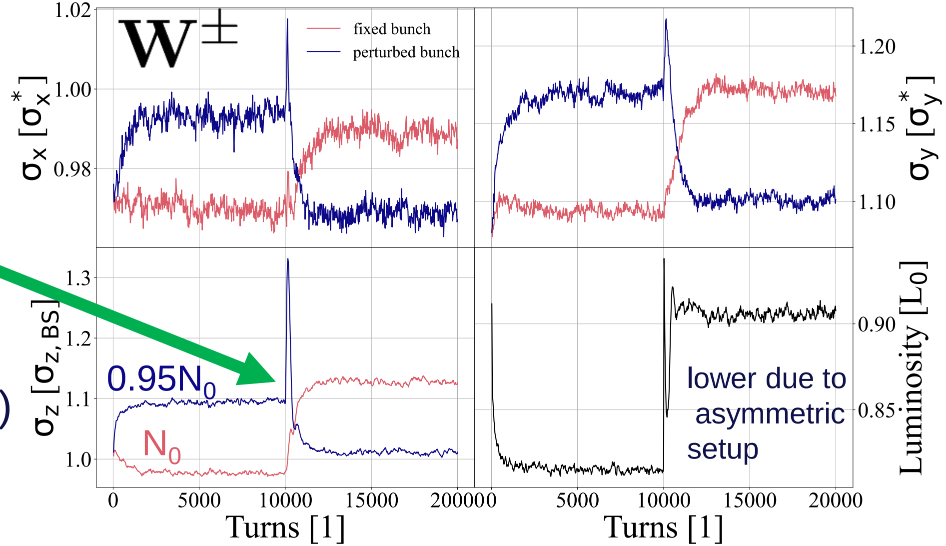
- Track till equilibrium & top-up



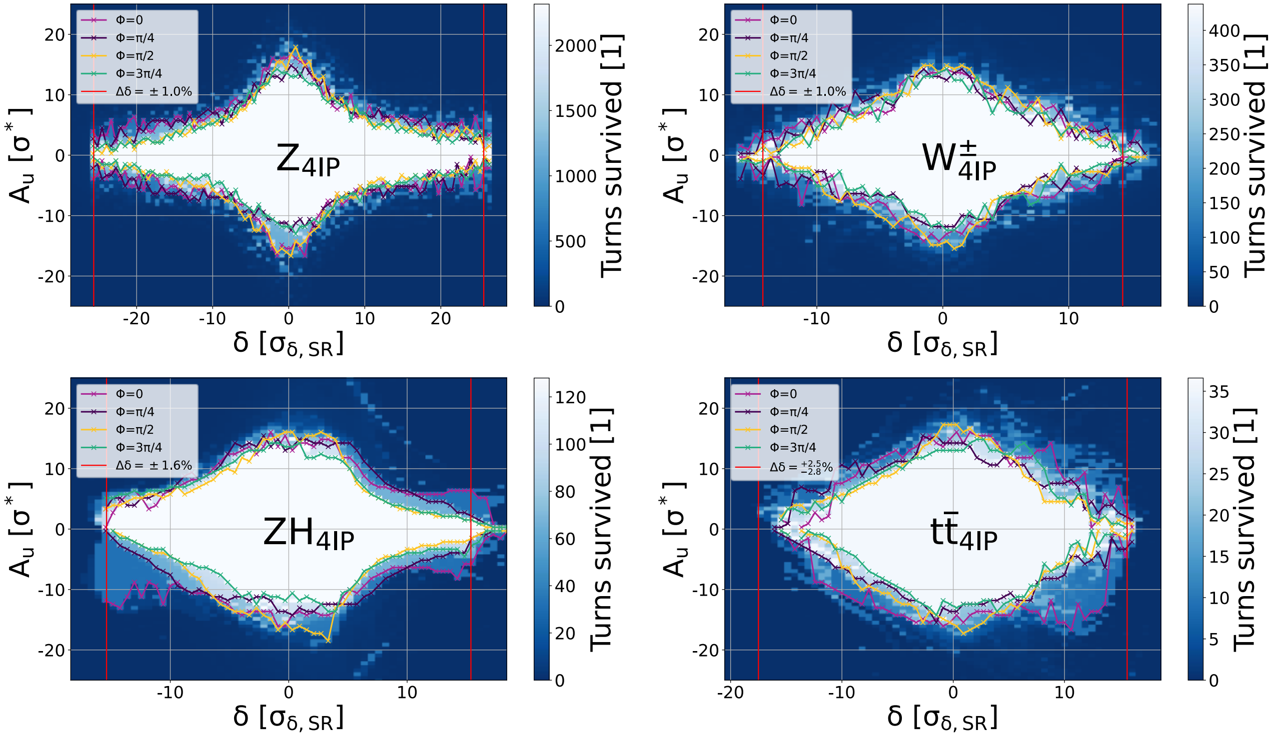


- Luminosity lower than in symmetric case (L_0)
  - This reduction cannot be avoided but currently not taken into account in design

Simulation parameters

Slide #	9	11/upper	11/lower	12
Machine setup	FCC 4 IP baseline	FCC 4 IP baseline, W	FCC 4 IP baseline	SuperKEKB LER
Lattice model	nonlinear	linear	linear	linear
Beam-beam model	weak-strong	1st part: quasi-strong-strong (f_{update}=100), 2nd part: strong-strong	quasi-strong-strong (f_{update}=100)	strong-strong
# slices in beam-beam	100 (300 for Z)	100	100 (300 for Z)	100
# macroparticles	4e4	1e5	1e5	1e5
# turns	2x SR damping time	2e4	1e4 (Z, W), 5e3 (H, T)	2e4

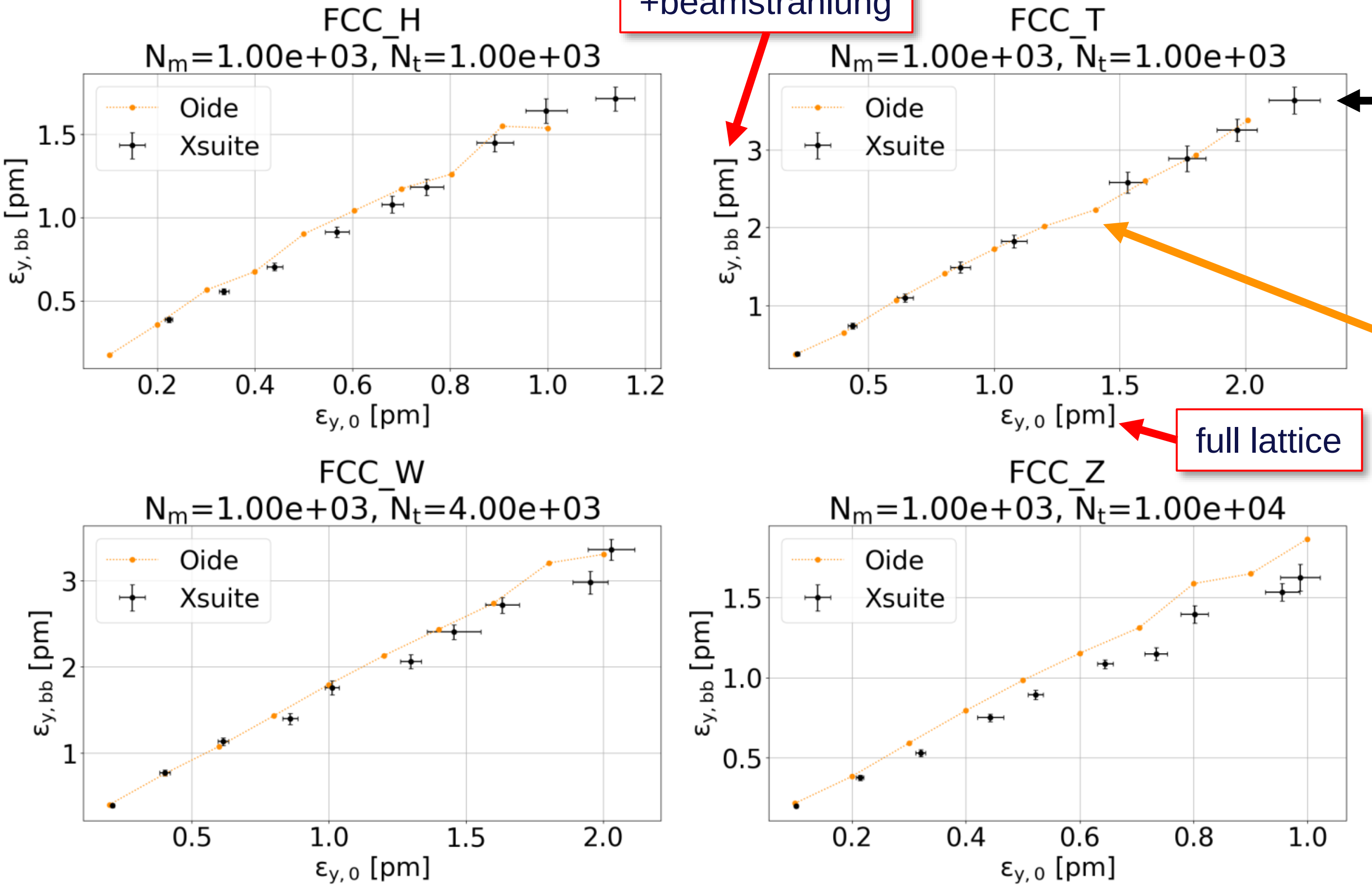
Dynamic aperture with beam-beam



$$A_u = \sqrt{\left(\frac{u}{\sigma_u^*}\right)^2 + \left(\frac{p_u}{\sigma_{p_u}^*}\right)^2}$$

$$u \in \{x, y\}$$

Vertical emittance

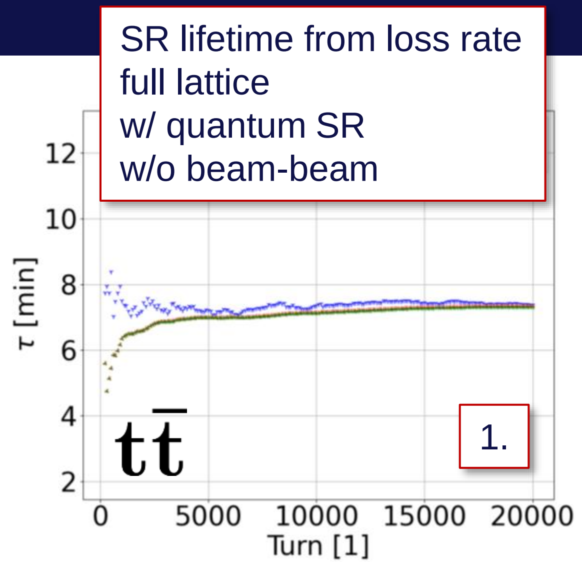


- Independent benchmarks with SAD & Xsuite
- Good agreement

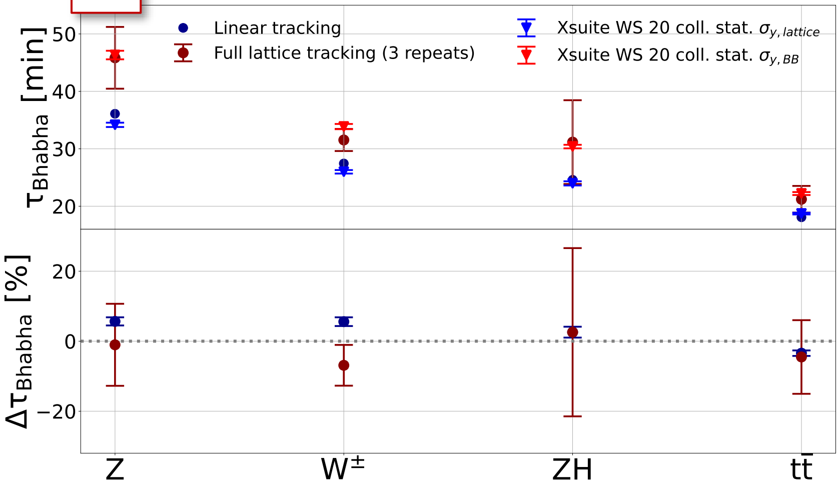
Beam lifetime

1. Synchrotron radiation seems to be dominating
   - Discrepancy w.r.t. SAD results from K. Oide
   - Work in progress

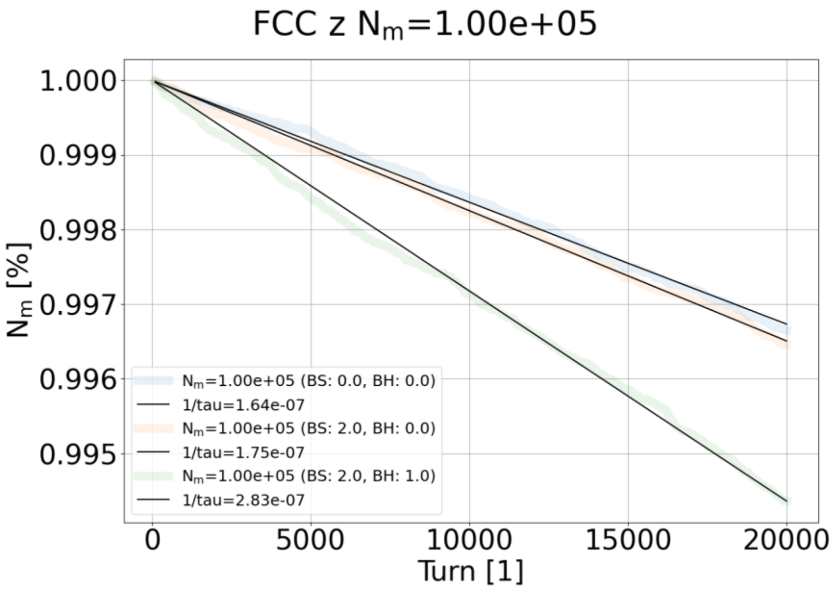
2. Bhabha lifetimes simulated & compare well to reference estimates (GUINEA-PIG + BBBREM)

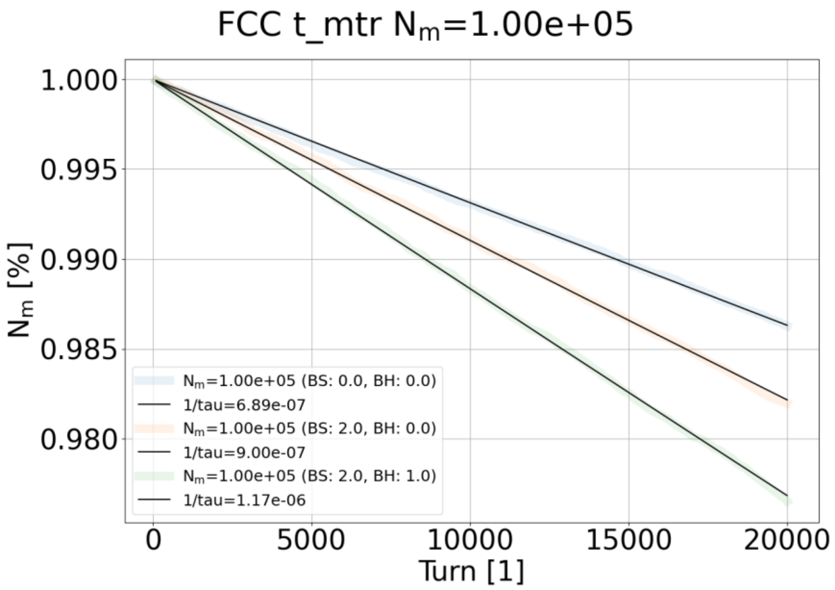


2.



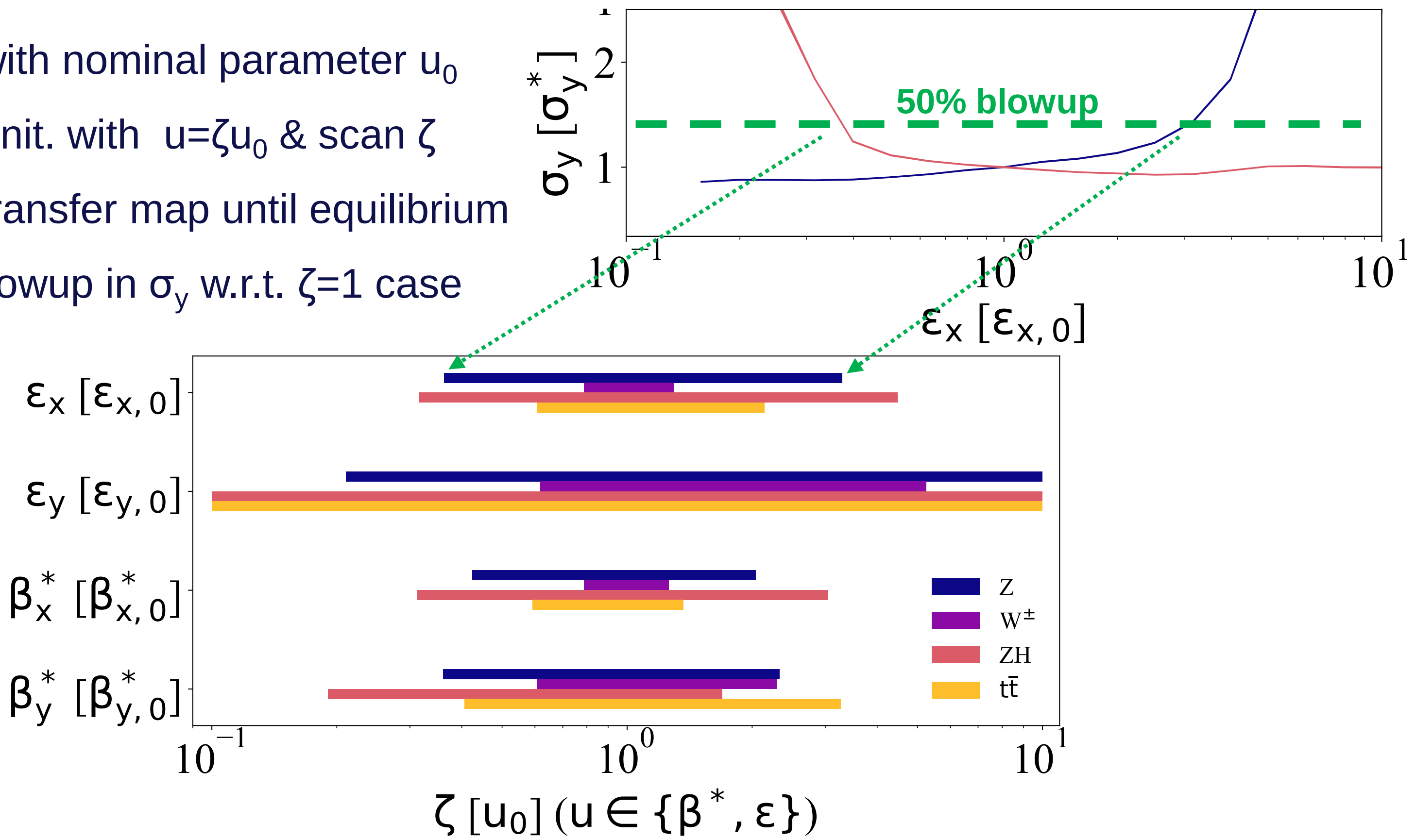
Bhabha lifetime: loss rates



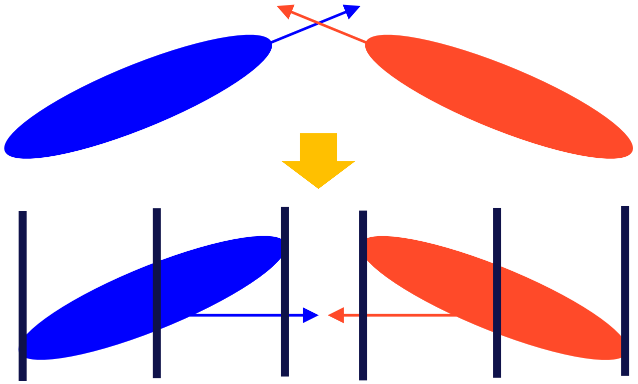


Tolerances to parameter asymmetries

- fixed bunch: init. with nominal parameter u_0
- perturbed bunch: init. with $u=\zeta u_0$ & scan ζ
- Track with linear transfer map until equilibrium
- Tolerance: 50% blowup in σ_y w.r.t. $\zeta=1$ case



Beam-beam in Xsuite



1. Lorentz transform into head-on frame
2. Longitudinal slicing
3. Beam-beam kick in soft-Gaussian approximation [4]

$$\Delta y' + i\Delta x' = \frac{N r_0 \sqrt{2\pi}}{\gamma\sqrt{\sigma_x{}^2 - \sigma_y{}^2}} \left(\mathrm{w}\left[\frac{x+iy}{\sqrt{2(\sigma_x{}^2 - \sigma_y{}^2)}}\right] - \exp\left[-\frac{x^2}{2\sigma_x{}^2} - \frac{y^2}{2\sigma_y{}^2}\right] \cdot \mathrm{w}\left[\frac{x\frac{\sigma_y}{\sigma_x} + y\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x{}^2 - \sigma_y{}^2)}}\right]\right)$$

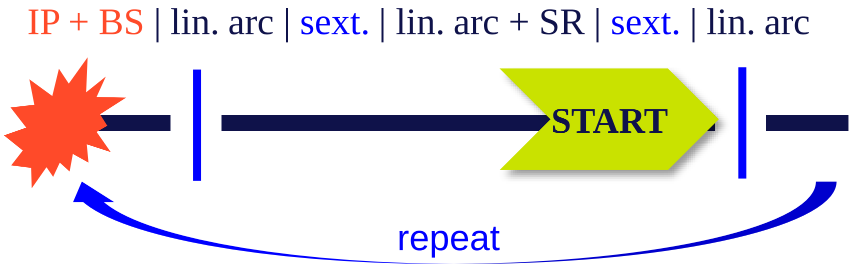
$$x' \leftarrow x' + \Delta x'$$
$$y' \leftarrow y' + \Delta y'$$

$$\mathrm{w}[t] = \exp\left[-t^2\right]\left(1 + \frac{2\mathrm{i}}{\sqrt{\pi}}\int_0^t \exp\left[u^2\right] \mathrm{d}u\right)$$

Simplified tracking simulations with Xsuite

- First studies with 2 IP baseline from CDR [5]
- Recent studies with 4 IP design from [6]

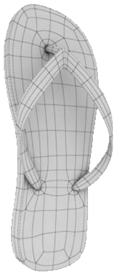
- Xsuite tracking setup:
  - 1 IP + tracking over arc superperiod with linear transfer matrix

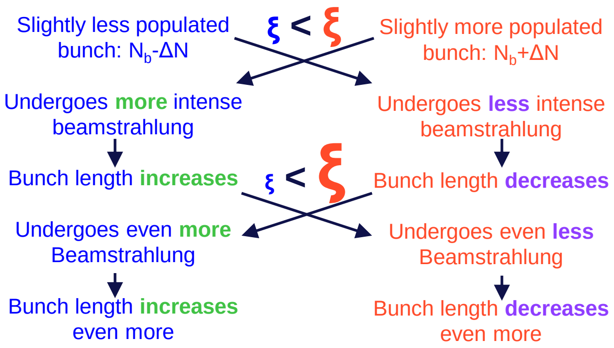


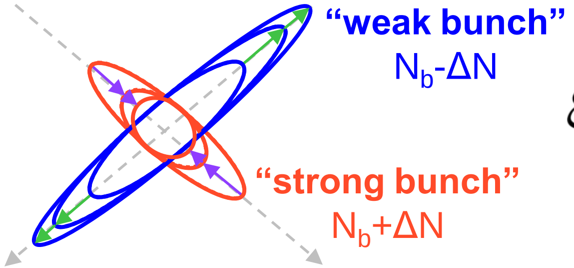
  - Arc split into 3 segments
  - 2 crab sextupoles between arc segments (β_x=3 m, β_y=500 m)
  - Each iteration begins in front of the right sextupole
    - Observation point for coordinates
  - Synchrotron radiation (damping+noise) in **arc**, beamstrahlung+bhabha scattering in **beam-beam element**

Flip-flop

- Flip-flop instability (1D) observed in other colliders (VEPP-2000) [7]
- For FCC-ee: 3D flip-flop - direct consequence of **beamstrahlung**, triggered by an initial asymmetry in **bunch intensity** [8]







$$\xi \sim \frac{1}{\sigma_z}$$

- Inflation of one bunch ➡ beam loss
- Above a threshold ξ_0 longitudinal blowup drives transverse diffusion ➡ 3D flip-flop
- Relevant for FCC-ee top-up injection

Workflow for emittance scan – everything in Xsuite

Prepare Xtrack line once [6]:

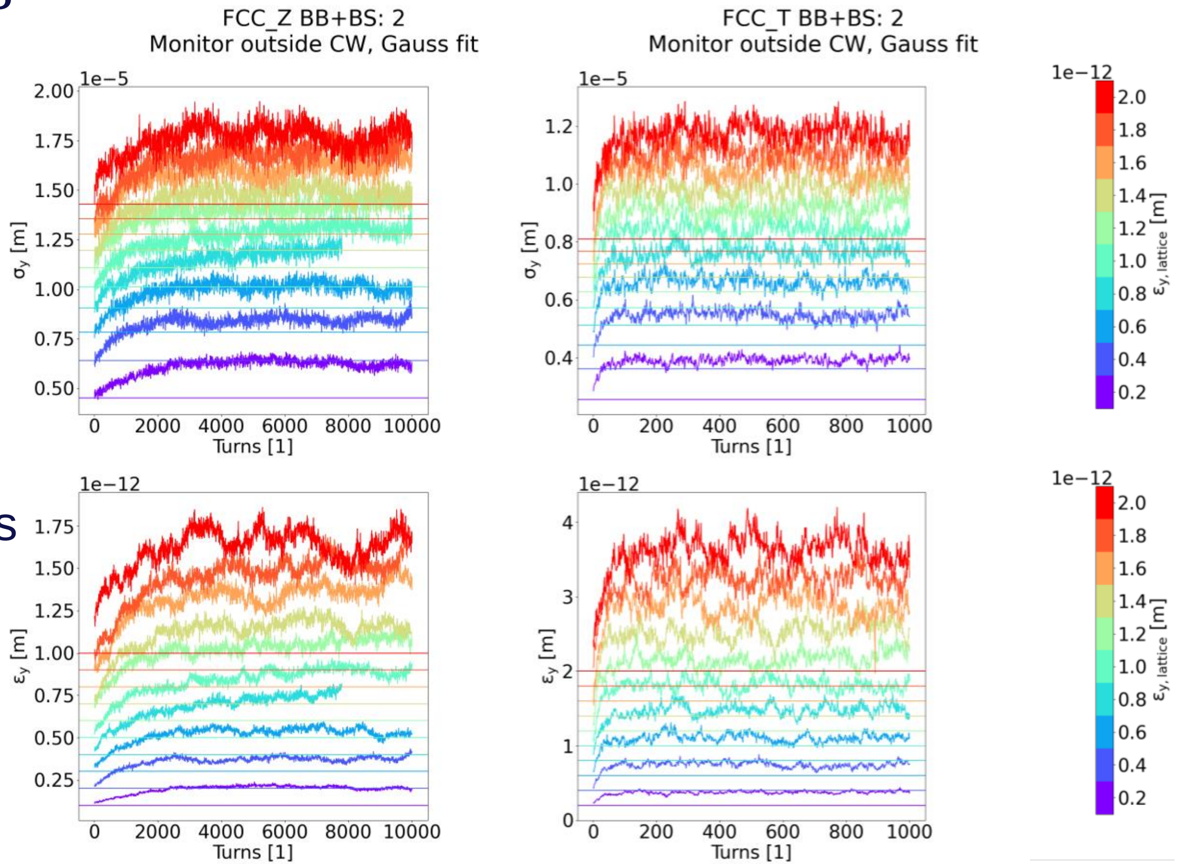
- load MAD-X sequence [7]
- add wigglers
- convert to Xtrack line
- build + twiss 4D
- slice sequence
- build + twiss 4D
- save Xtrack line

Loop over a range of ε_y values:

- load Xtrack line
- add observation point @ RF
- build + twiss 4D
- twiss 6D mean synrad + tapering
- match ε_y
- twiss 6D mean synrad + tapering
- ⋮
- add beam-beam element (optional)
- build
- set quantum synrad
- track
- repeat with next ε_y

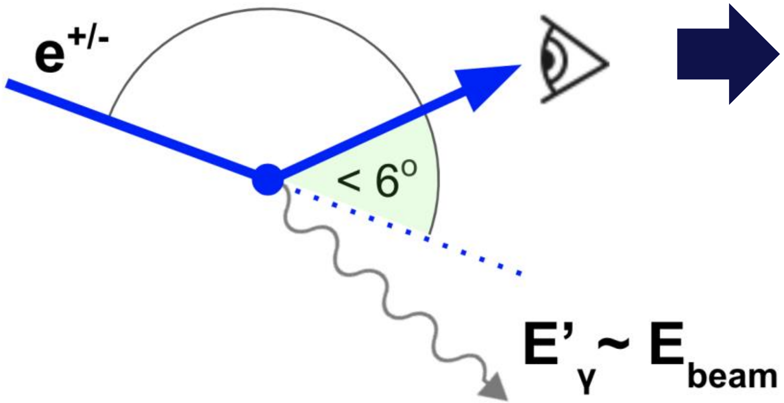
Emittance scan results

- Small discrepancy compared to SAD results
- Xsuite likely not yet converged
- Need more turns to see fully converged emittances



Small angle Bhabha scattering [6]

- Dominated by t-channel (scattering) process



→ **luminosity** in lepton colliders

→ primary particles lost within a turn

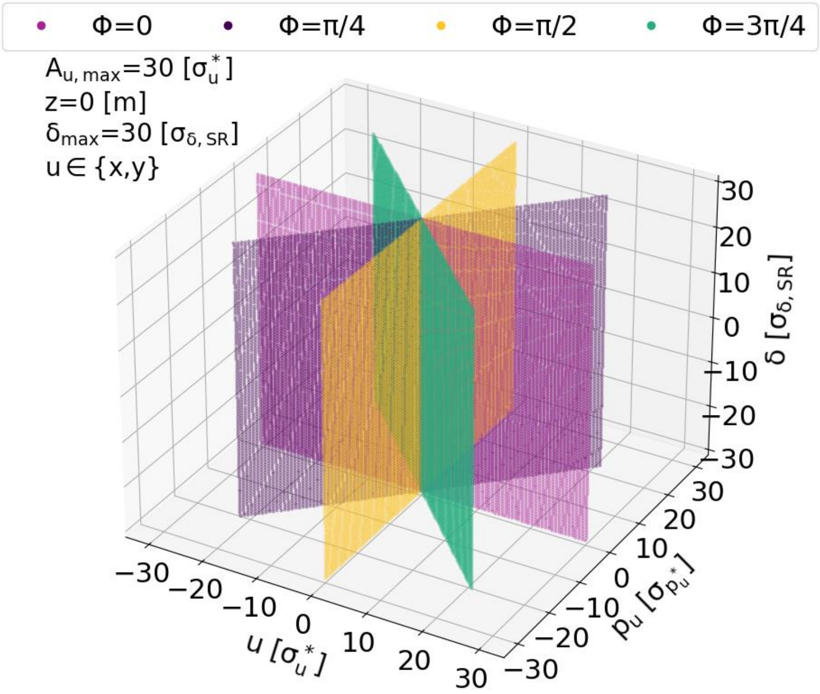
- Main limitation of FCC-ee **beam lifetime** (alongside beamstrahlung)

Bhabha lifetimes

$$\frac{1}{\tau} = \frac{1}{N_b}\frac{dN_b}{dt} = \frac{1}{N_b}\sigma_{Bhabha} L_{inst} \cdot N_{IP} = \frac{1}{N_b} R_b \cdot f_{rev} \cdot N_{IP}$$

- τ: Bhabha lifetime [s]
- N_b: bunch intensity [1]
- σ_{Bhabha}: Bhabha cross section [m^2]
- N_{IP}: number of Ips [1]
- $L_{inst}=L*f_{rev}$: instantaneous lumi of 1 bunch crossing [m^-2 s^-1]
- L: integrated lumi of a single collision (luminosity per bunch crossing) [m^-2]
- f_{rev}: revolution frequency [s^-1]
- $R_b= \sigma_{Bhabha}*L$: number of emitted Bhabha photons with E above mom. acceptance [1]

Dynamic aperture test grid



Beam-beam in Xsuite

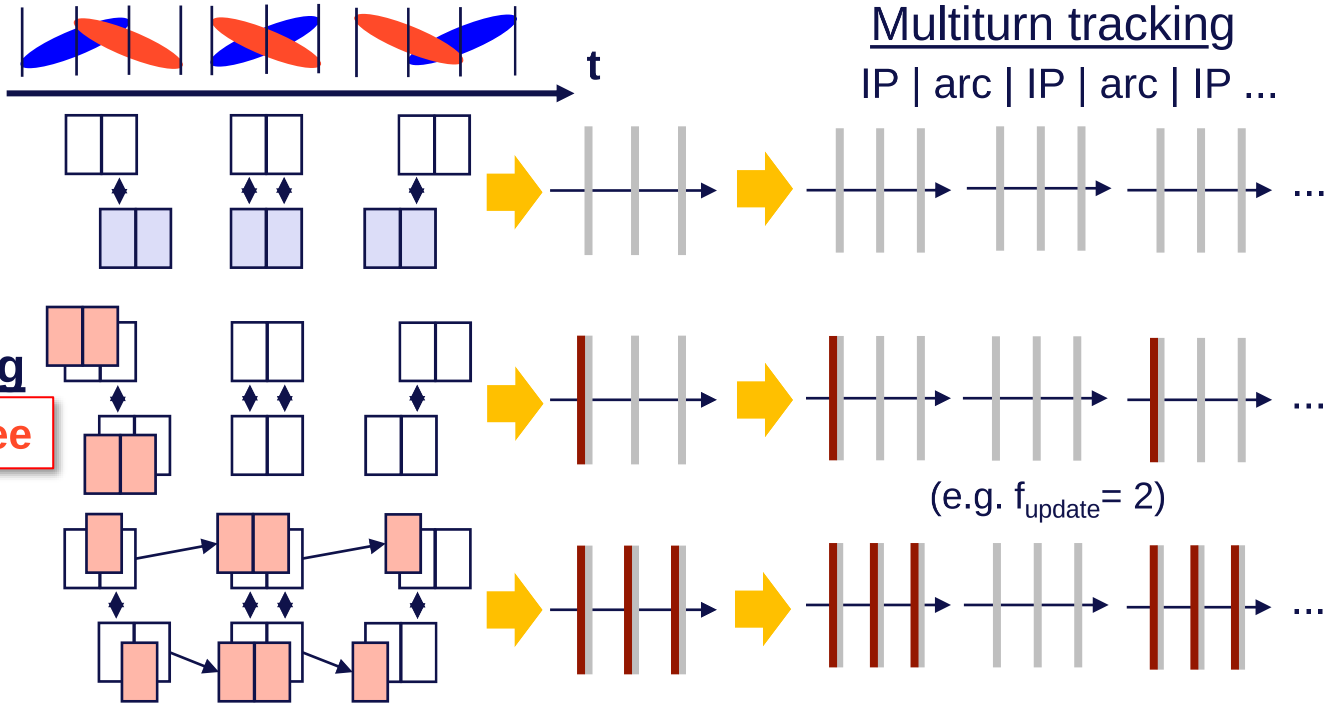
Faster & less accurate

Weak-Strong (WS)

Quasi-Strong-Strong (QSS) FCC-ee

Strong-Strong (SS)

Slower & more accurate



: untracked bunch with fixed moments

: bunch slice with macroparticles

: soft-Gaussian kick

: compute statistical moments of slice