BEAM-BEAM EFFECTS AT THE FCC-ee

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

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ICFA mini workshop: Beam-Beam Effects in Circular Colliders BB24
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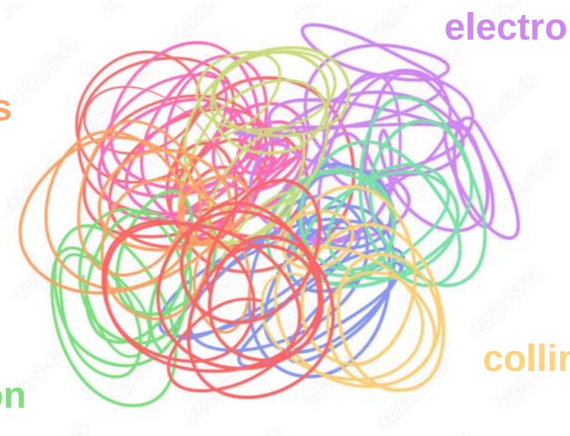
This work was performed under the auspices and with support from the Swiss Accelerator Research and Technology (CHART) program.

Overview

- FCC-ee will be a highly complex machine
- Interplay of various effects



errors & misalignments

electron cloud

impedances

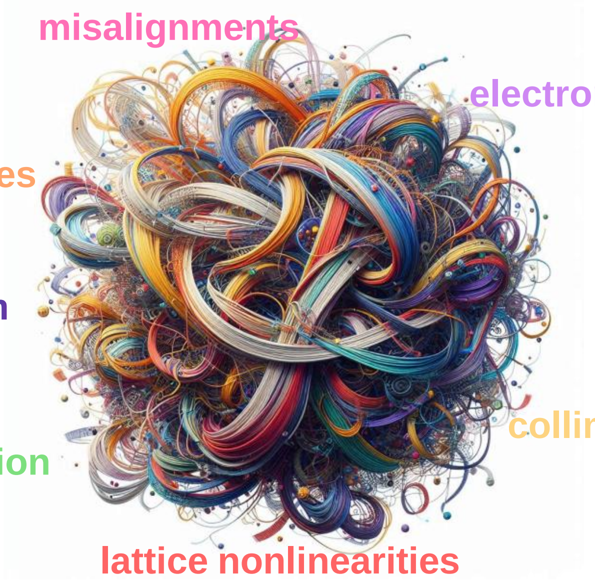
collimation

radiation

lattice nonlinearities

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



errors & misalignments

electron cloud

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beam-beam

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lattice nonlinearities

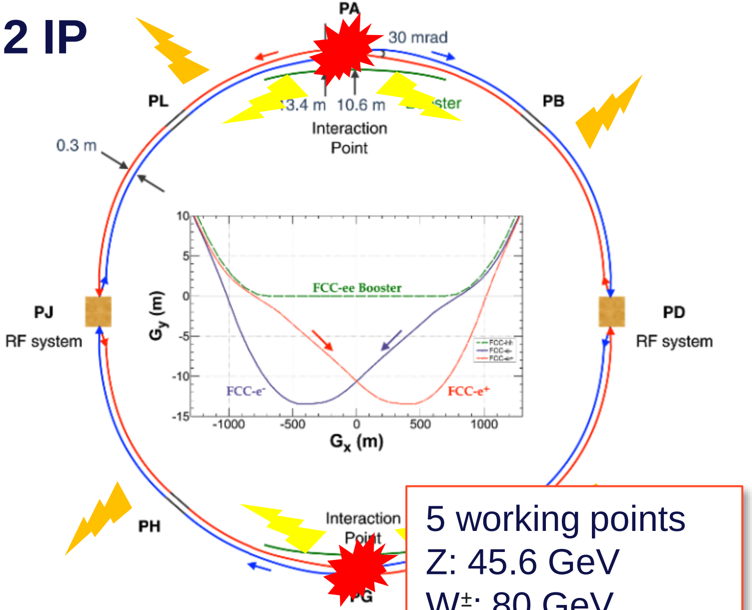
FCC-ee design

Interaction point (IP)

Synchrotron radiation

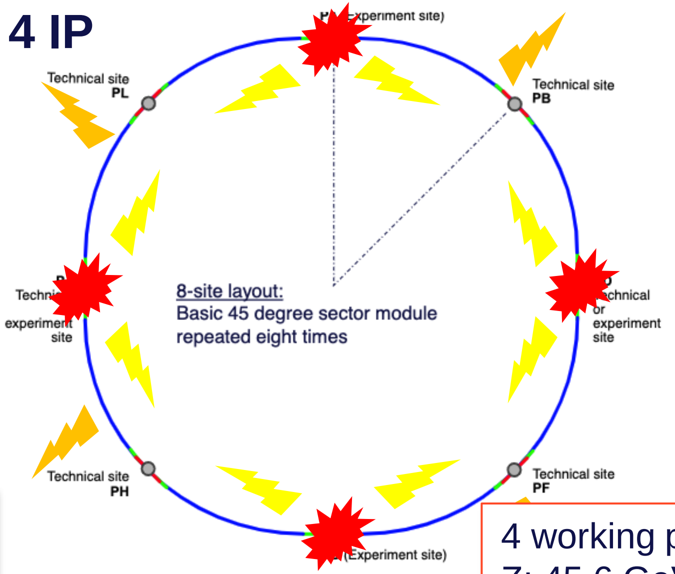
Beamstrahlung + radiative Bhabha scattering

2 IP



5 working points
Z: 45.6 GeV
W±: 80 GeV
ZH: 120 GeV
ttbar 1: 175 GeV
ttbar 2: 182.5 GeV

4 IP



4 working points
Z: 45.6 GeV
W±: 80 GeV
ZH: 120 GeV
ttbar: 182.5 GeV

Design studies so far

- Design strategy: balancing several effects
  - Past studies on parameter optimization [1,2]
- Constraint on beam current: 50 MW synrad power
  - Constrains beam parameters at IP
  - Different challenges at each energy
- In general: high energy & charge density

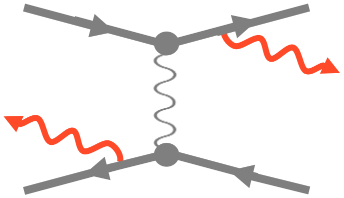
beamstrahlung
non-Gaussian tails
reduced beam lifetime

- Goal: increase lumi by keeping lifetime long enough & avoid instabilities
- This talk: overview of ongoing studies

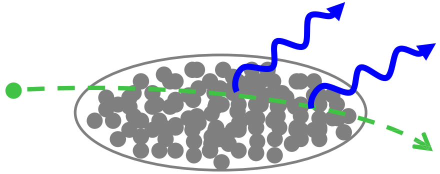
Radiation at FCC-ee collisions

Incoherent

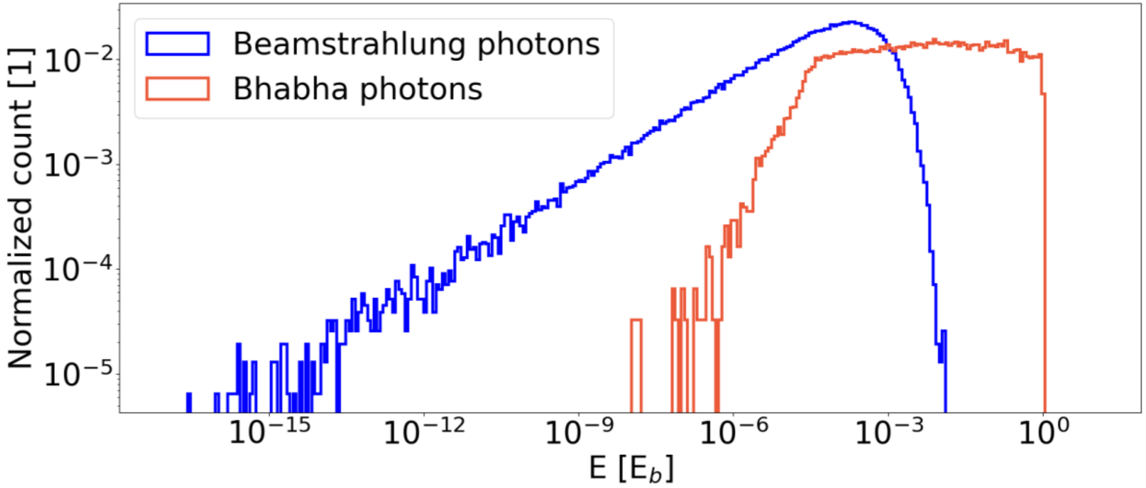
- Radiative Bhabha scattering
- Deflection in field of single particle of opposite bunch



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

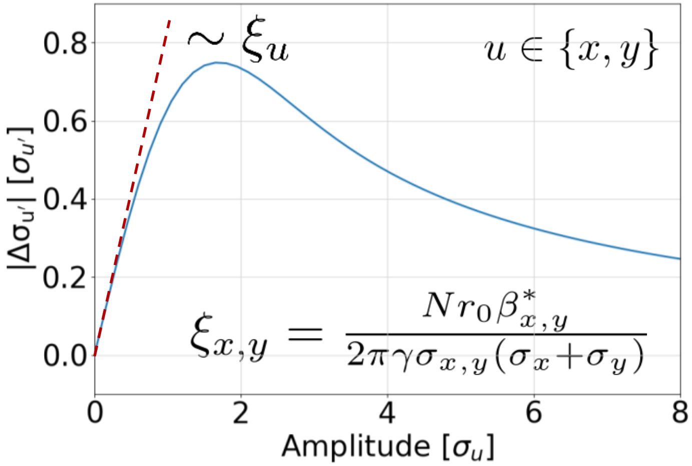
Beam-beam force

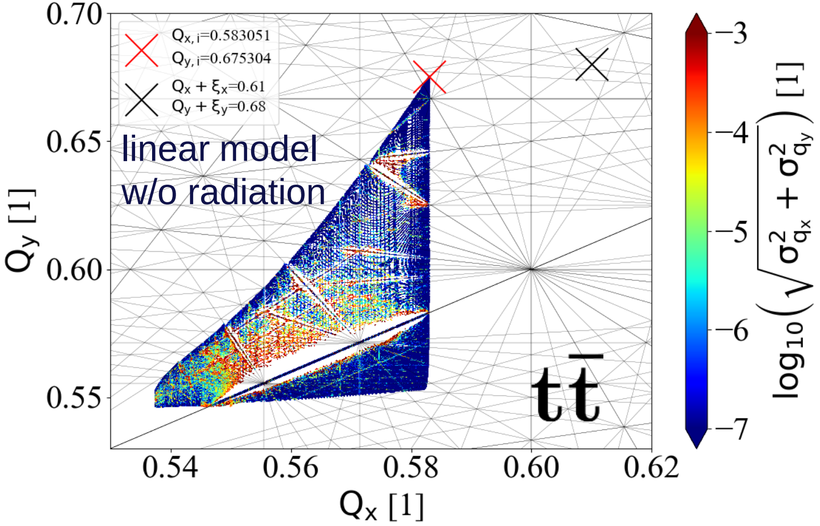
High lumi → strong beam-beam force

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

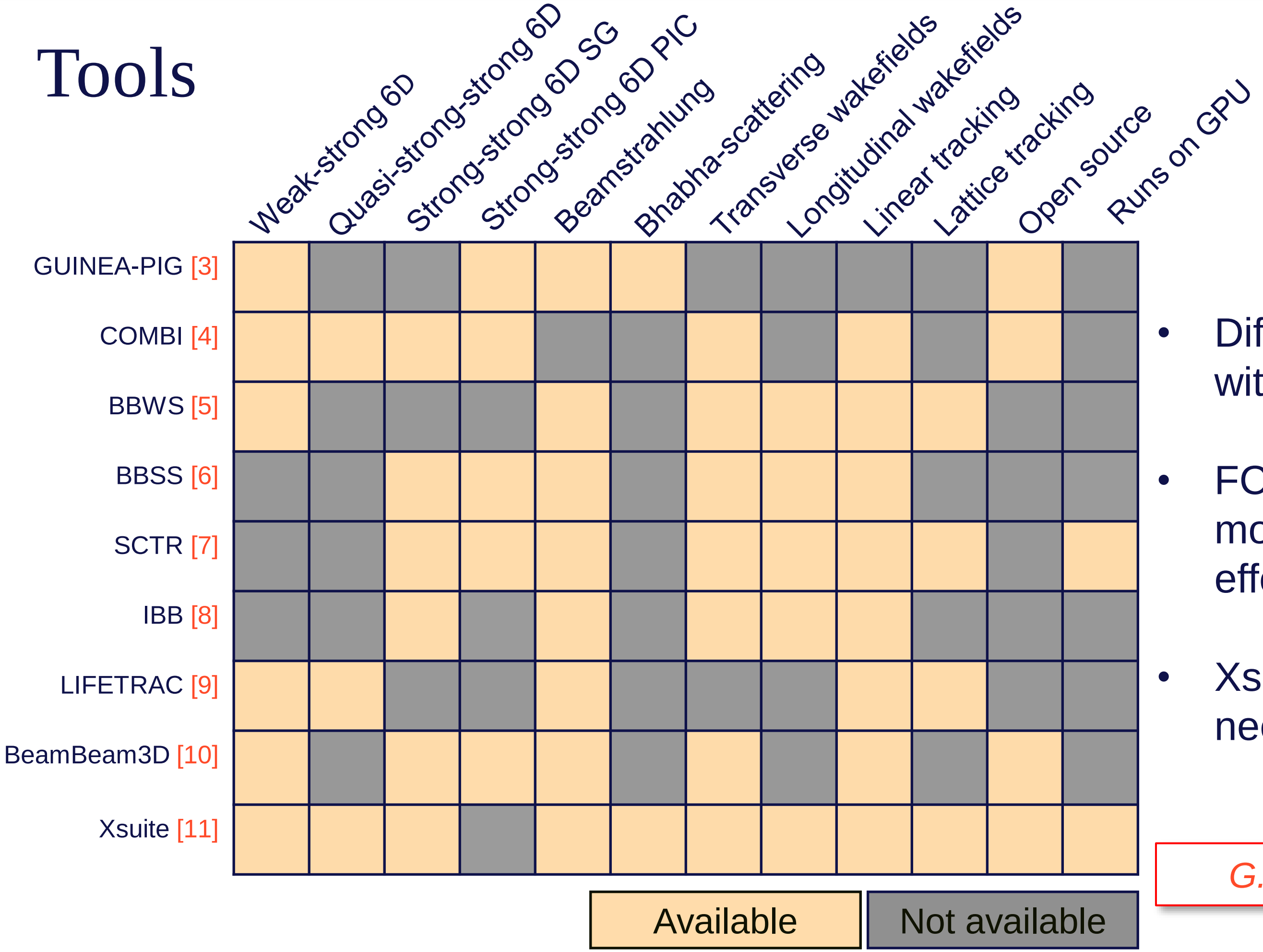
Consolidation...

- 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 [3]	🟧	⬛	⬛	🟧	🟧	🟧	⬛	⬛	⬛	⬛	🟧	⬛
COMBI [4]	🟧	🟧	🟧	🟧	⬛	⬛	🟧	⬛	🟧	⬛	🟧	⬛
BBWS [5]	🟧	⬛	⬛	⬛	🟧	⬛	🟧	🟧	🟧	🟧	⬛	⬛
BBSS [6]	⬛	⬛	🟧	🟧	🟧	⬛	🟧	🟧	🟧	⬛	⬛	⬛
SCTR [7]	⬛	⬛	🟧	🟧	🟧	⬛	🟧	🟧	🟧	🟧	⬛	🟧
IBB [8]	⬛	⬛	🟧	⬛	🟧	⬛	🟧	🟧	🟧	⬛	⬛	⬛
LIFETRAC [9]	🟧	🟧	⬛	⬛	🟧	⬛	⬛	⬛	🟧	🟧	⬛	⬛
BeamBeam3D [10]	🟧	⬛	🟧	🟧	🟧	⬛	🟧	⬛	🟧	⬛	🟧	⬛
Xsuite [11]	🟧	🟧	🟧	⬛	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧

🟧 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

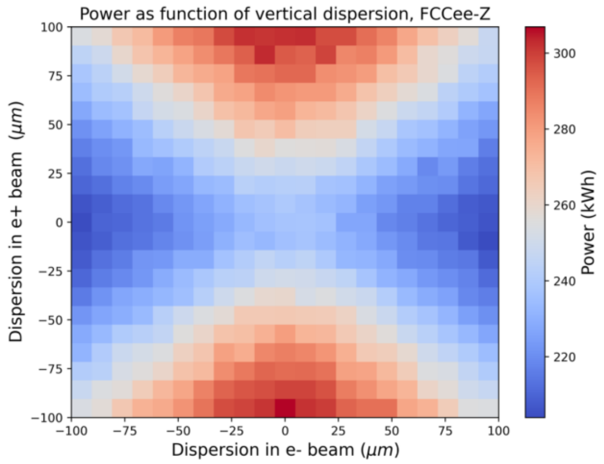
G. Iadarola, talk @ this workshop

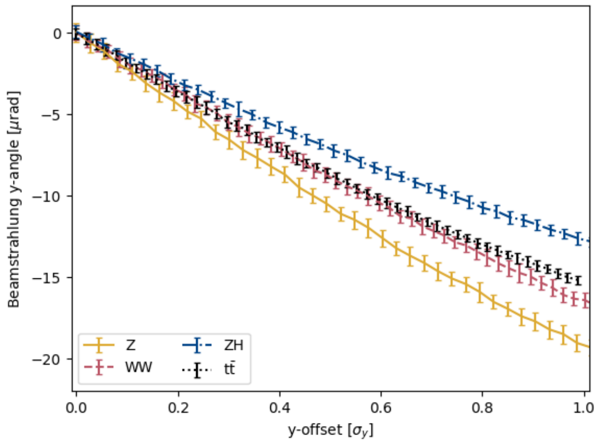
IP tuning & optimization

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, talk @ this workshop

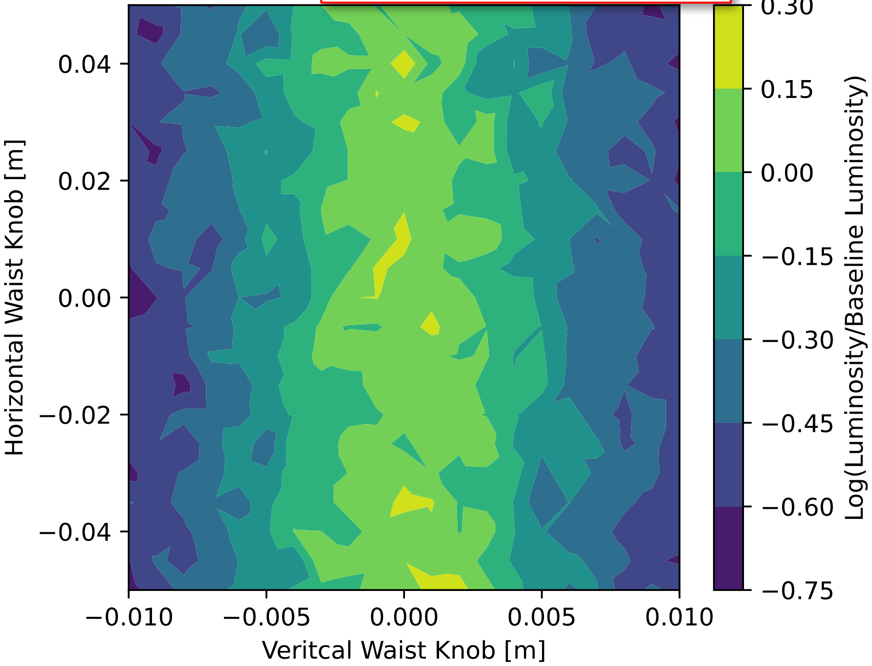




IP tuning & optimization

- 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 [12]
300 turns
1e5 macroparticles

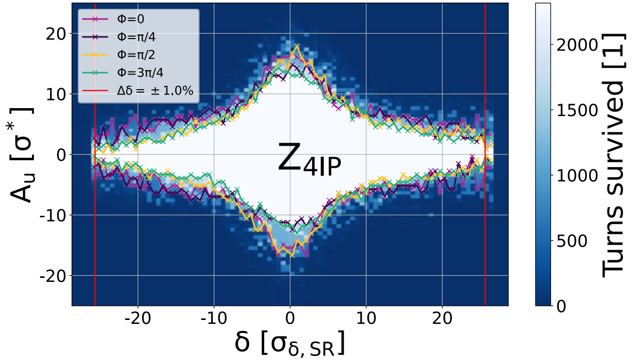


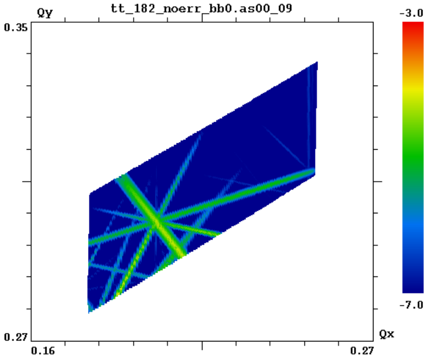
Dynamic aperture

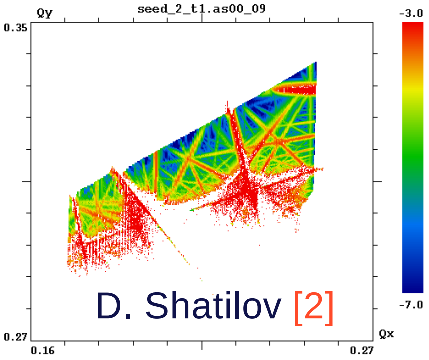
w/o errors

- Negligible reduction from beam-beam
- Compares well with SAD results from K. Oide [13]

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







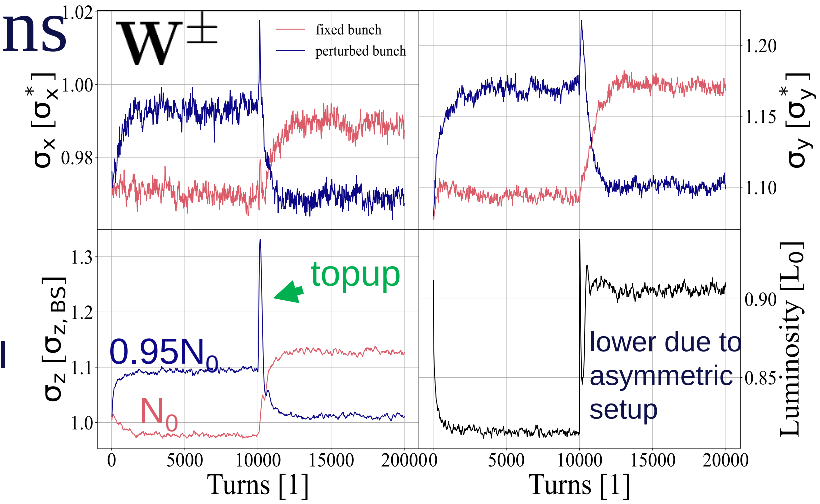
D. Shatilov [2]

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

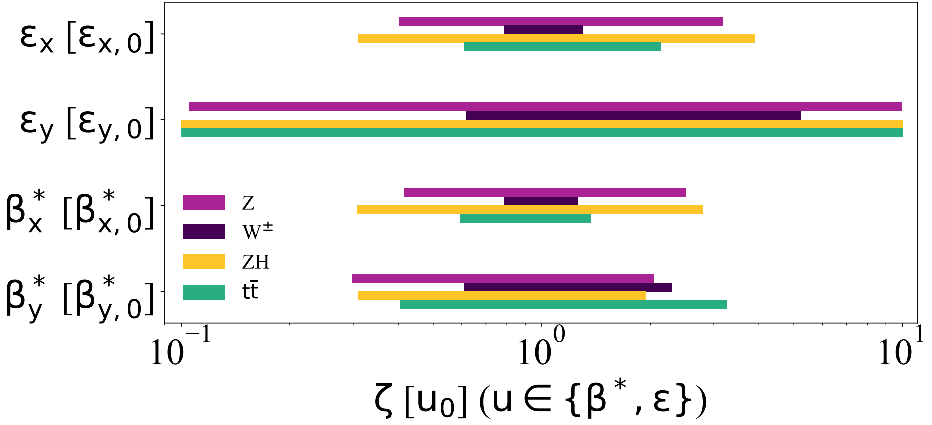
L. van Riesen-Haupt, talk @ this workshop

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
  - Some seem hard to reach e.g. for W
  - Working point needs to be optimized

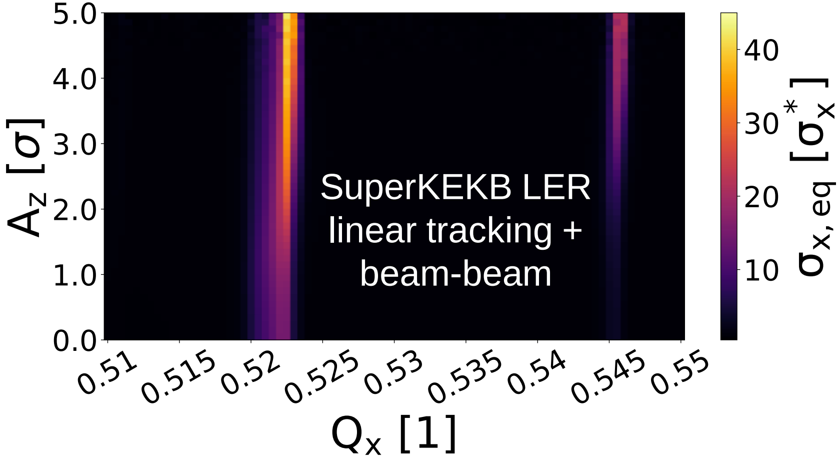
Case study at the SuperKEKB

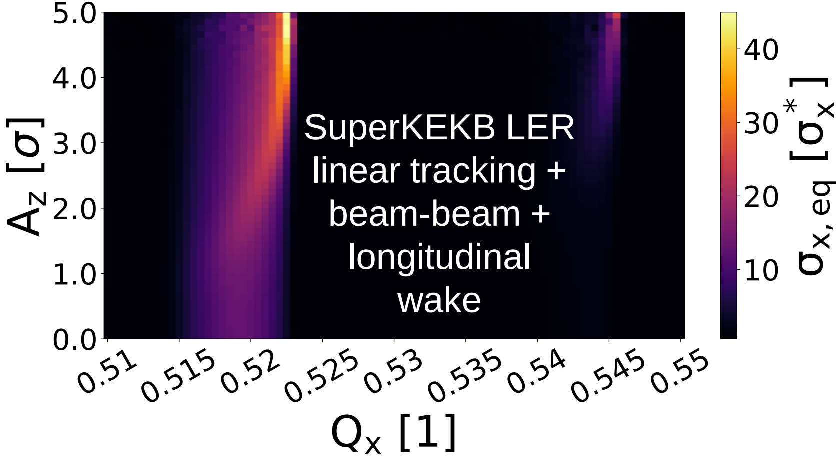
- Beam-beam excites synchro-betatron resonances (collective [14], here single particle)
- Interplay with longitudinal wakefield enhances amplitude dependent incoherent x-z resonance
  - Impact on FCC-ee W [15]? (high Q_s)
- Successful Xsuite benchmarks against BBWS, BBSS, PyHEADTAIL
- Crab-waist imperfections

D. Zhou, talk @ this workshop

- Transverse impedance + beam-beam @ FCC-ee

R. Soos, talk @ this workshop





Summary

Work so far

- 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)

Lots of work still ahead...

- Errors & misalignments + beam-beam: needed for realistic estimates
- Parameter optimization of FCC-ee W
- IP tuning with multiturn tracking
- Beam-beam + transverse impedances

Thank you!

References

[1] D. Shatilov, https://cds.cern.ch/record/2816655/files/9999999_30-41.pdf

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

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

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

[5] K. Ohmi https://indico.cern.ch/event/438918/contributions/1085290/attachments/1147002/_1644777/BenchBBcodes.pdf

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

[7] K. Ohmi https://indico.cern.ch/event/1398060/contributions/5876155/attachments/2831376/4947208/Beam-beamFCCee_ohmi.pdf

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

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

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

[11] Xsuite 10.18429/JACoW-HB2023-TUA2I1

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

[13] K. Oide, FCC-ee Collider Optics
https://indico.cern.ch/event/1202105/contributions/5408583/attachments/2659051/4608141/FCCWeek_Optics_Oide_230606.pdf

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

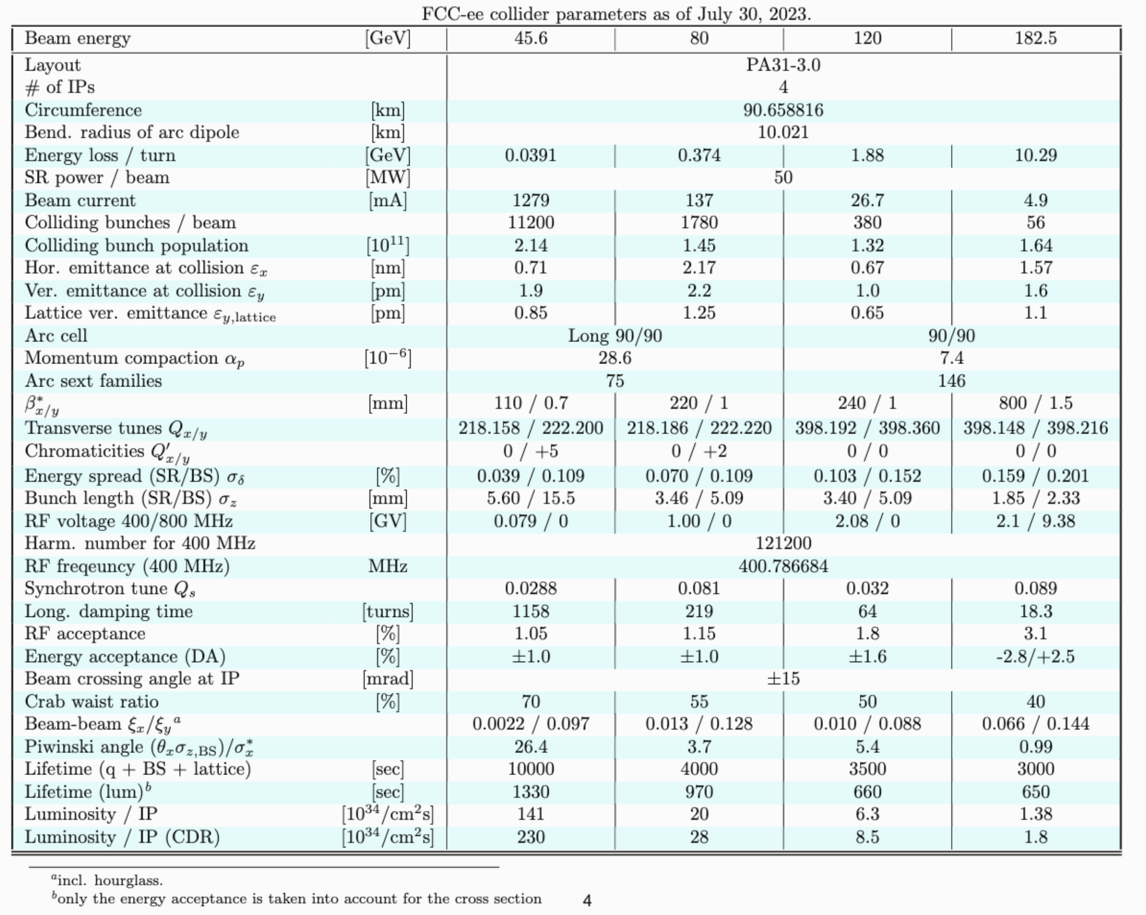
[15] K. Oide, FCC Week 2024, https://indico.cern.ch/event/1298458/contributions/5977859/attachments/2873388/5034194/Optics_Oide_240611.pdf

BACKUP

Simulation parameters

Slide #	**11**	**12/upper**	**12/lower**	**13**
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 (200 for Z)	100	100 (200 for Z)	100
# macroparticles	4e4	1e5	1e5 (1e6 for Z)	1e5
# turns	2x SR damping time	2e4	1e4 (Z, W), 5e3 (H, T)	2e4

Previous parameters (July 2023 almost for MTR)



FCC-ee collider parameters as of July 30, 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0391	0.374	1.88	10.29
SR power / beam	[MW]	50			
Beam current	[mA]	1279	137	26.7	4.9
Colliding bunches / beam		11200	1780	380	56
Colliding bunch population	[10^{11}]	2.14	1.45	1.32	1.64
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.67	1.57
Ver. emittance at collision ε_y	[pm]	1.9	2.2	1.0	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.85	1.25	0.65	1.1
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	800 / 1.5
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.360	398.148 / 398.216
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.109	0.070 / 0.109	0.103 / 0.152	0.159 / 0.201
Bunch length (SR/BS) σ_z	[mm]	5.60 / 15.5	3.46 / 5.09	3.40 / 5.09	1.85 / 2.33
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.089
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	3.1
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP	[mrad]	±15			
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y[a]		0.0022 / 0.097	0.013 / 0.128	0.010 / 0.088	0.066 / 0.144
Piwinski angle $(\theta_x\sigma_{z,\mathrm{BS}})/\sigma^*_x$		26.4	3.7	5.4	0.99
Lifetime (q + BS + lattice)	[sec]	10000	4000	3500	3000
Lifetime (lum)[b]	[sec]	1330	970	660	650
Luminosity / IP	[10^{34}/cm^{2}s]	141	20	6.3	1.38
Luminosity / IP (CDR)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

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[a] incl. hourglass.

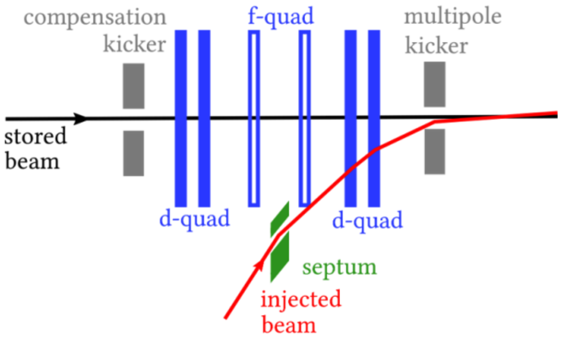
[b] only the energy acceptance is taken into account for the cross section

4

Nov. 13, 2023, K. Oide

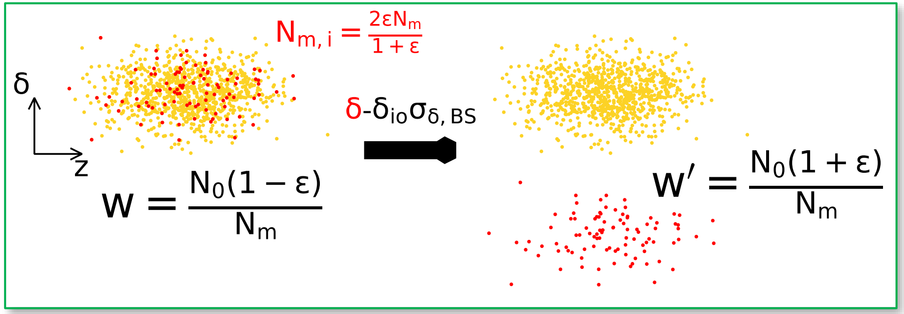
Top-up injection

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



Longitudinal top-up simulated with Xsuite

- Perturbed bunch init. with 95% intensity
- Track till equilibrium & top-up



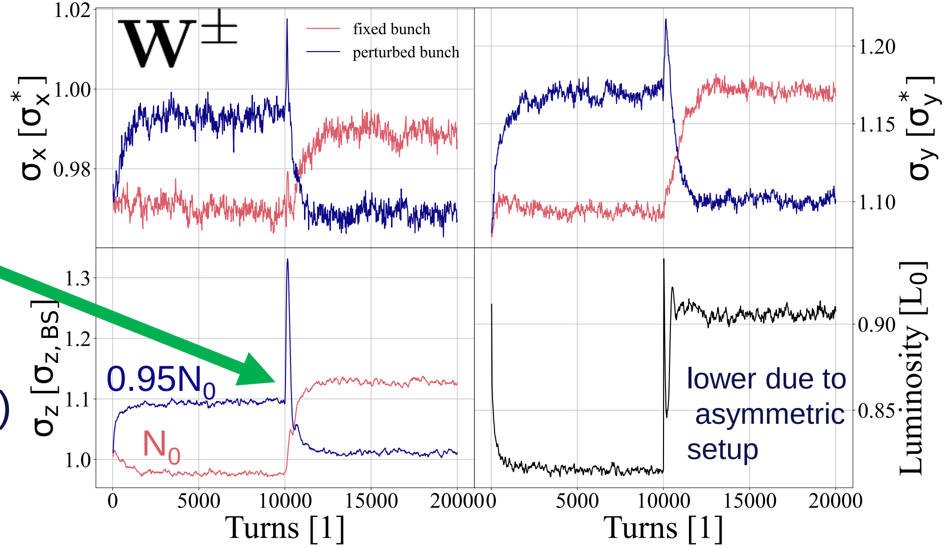
$$N_{m,i} = \frac{2\varepsilon N_m}{1+\varepsilon}$$

$$\delta\text{-}\delta_{io}\sigma_{\delta,\,BS}$$

$$w = \frac{N_0(1-\varepsilon)}{N_m}$$

$$w' = \frac{N_0(1+\varepsilon)}{N_m}$$

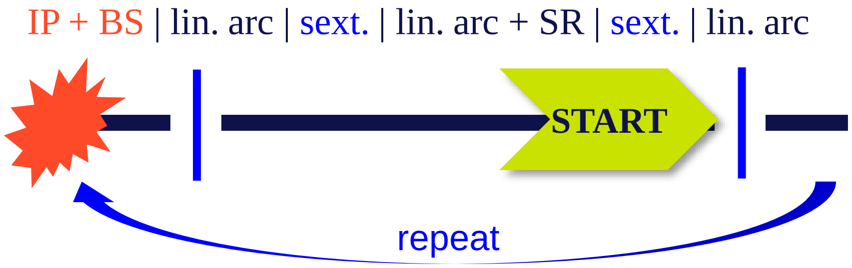
- Luminosity lower than in symmetric case (L_0)
  - This reduction cannot be avoided but currently not taken into account in design



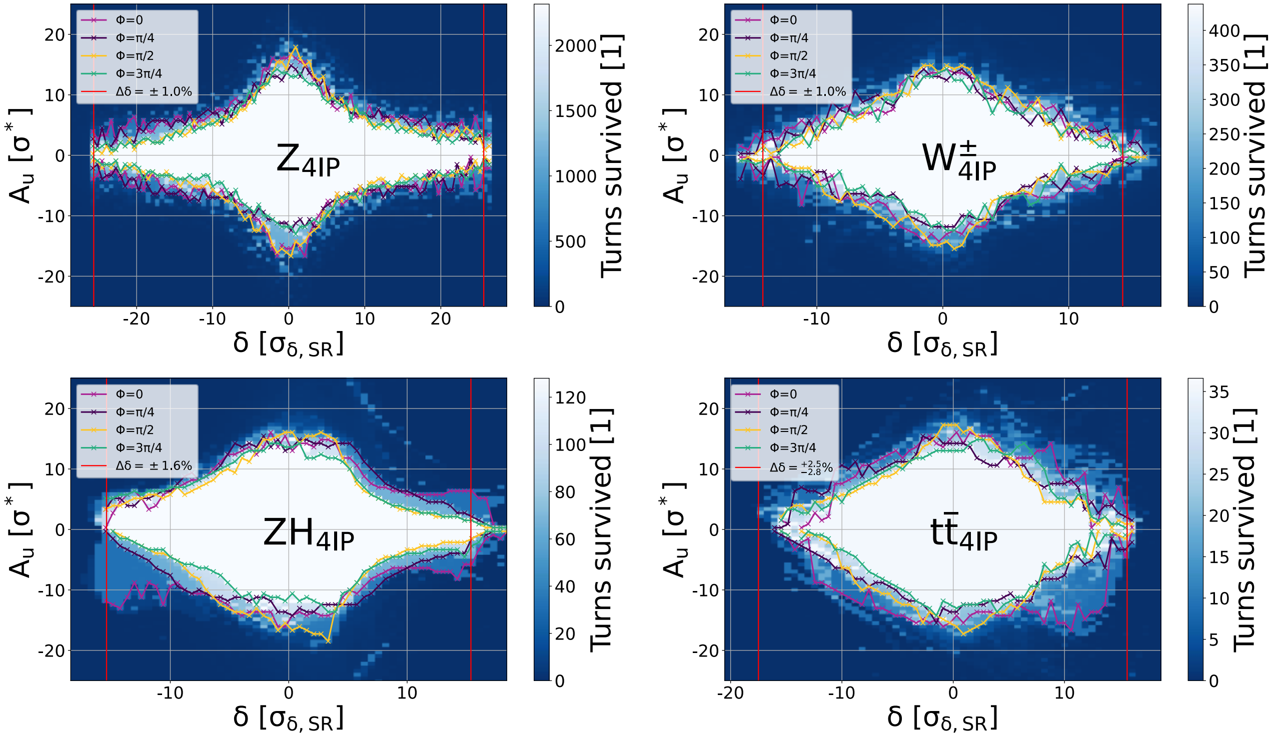
Simplified tracking simulations with Xsuite

- First studies with 2 IP baseline from CDR
- Recent studies with 4 IP design

- 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**



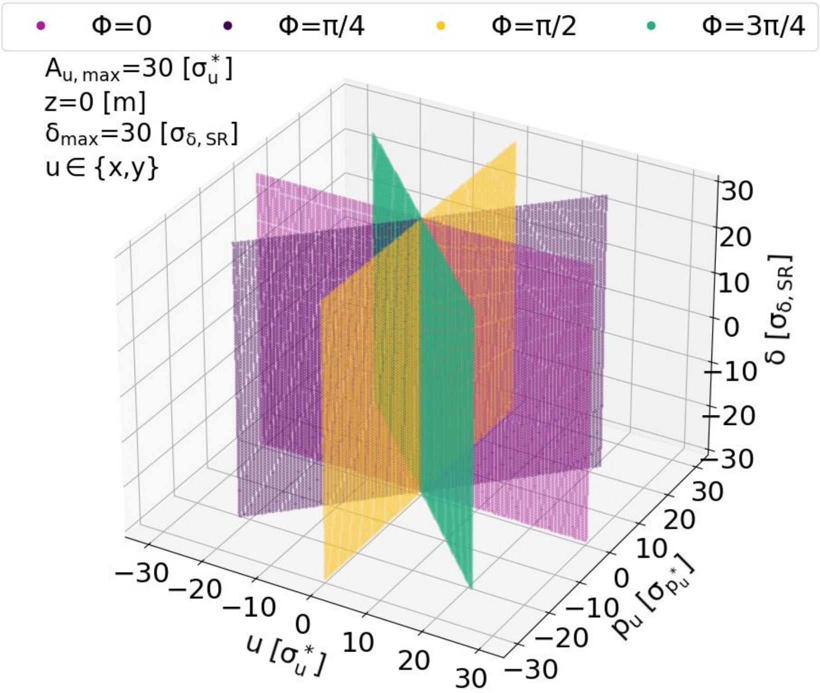
Dynamic aperture with beam-beam



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

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

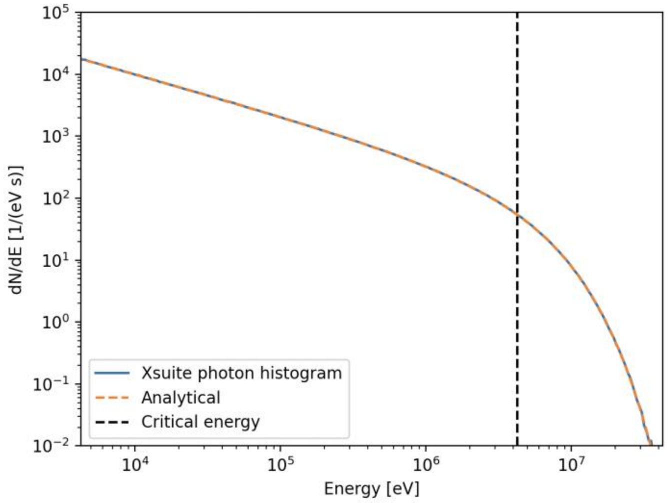
Dynamic aperture test grid

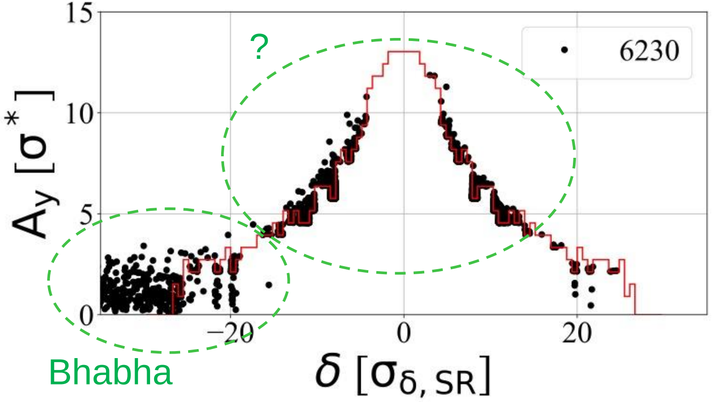


Benchmarking radiation in Xsuite

Several benchmarks

- ✓ Synchrotron radiation with MAD-X and SAD
- ✓ Optics, orbit, energy with and without errors
- ✓ Quantum excitation and damping
- ✓ Equilibrium emittance w/ vertical wiggler
- ✓ Tracking and matrix methods
- ✓ Bhabha + beamstrahlung lifetimes
- ✓ Issue with synchrotron radiation loss rate resolved





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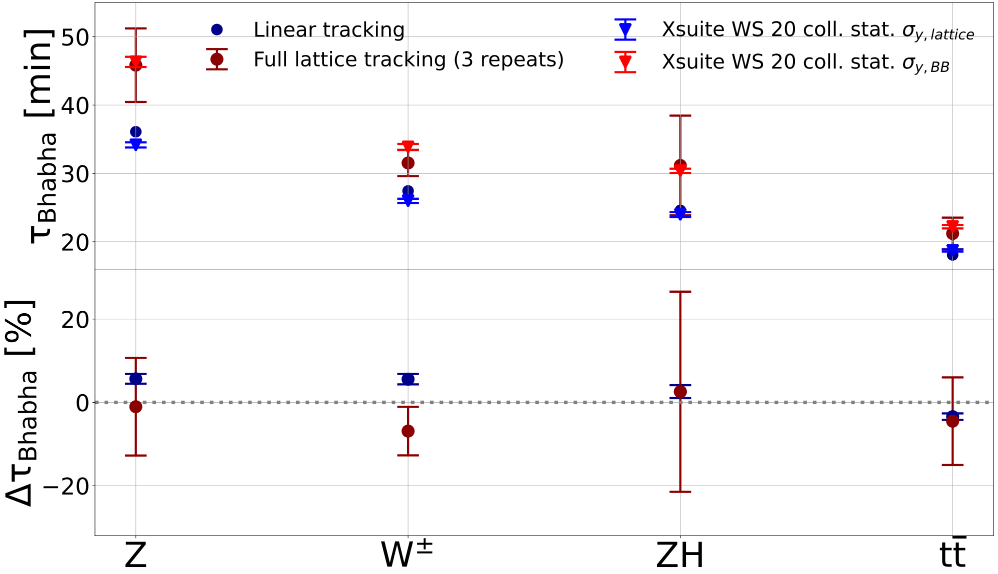
Bhabha

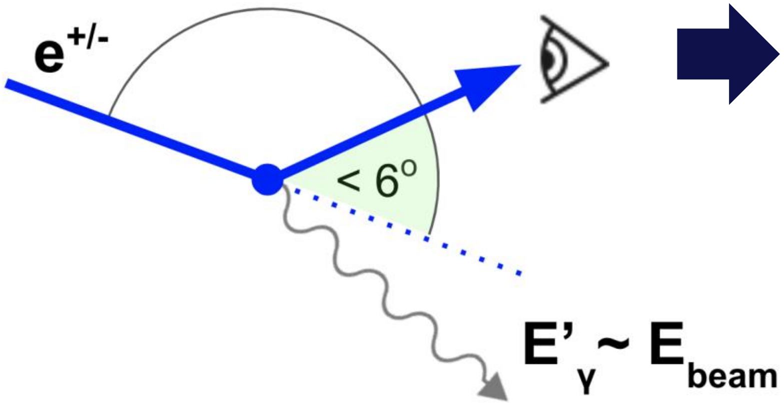
Beam lifetime

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



Small angle Bhabha scattering

- Dominated by t-channel (scattering) process



➡ **luminosity** in lepton colliders

➡ primary particles lost within a turn

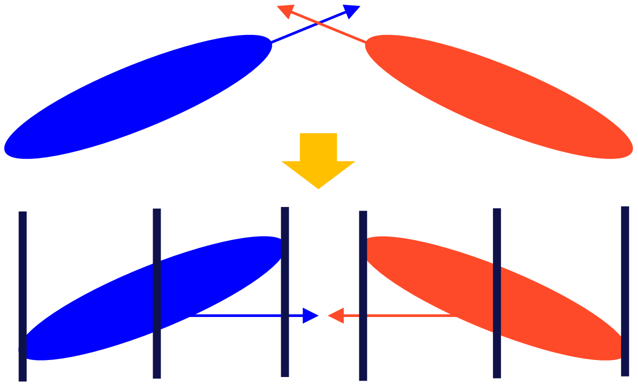
- Main limitation of FCC-ee **beam lifetime** (alongside beamstrahlung)

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= σ_{Bhabha}*L: number of emitted Bhabha photons with E above mom. acceptance [1]

Beam-beam in Xsuite



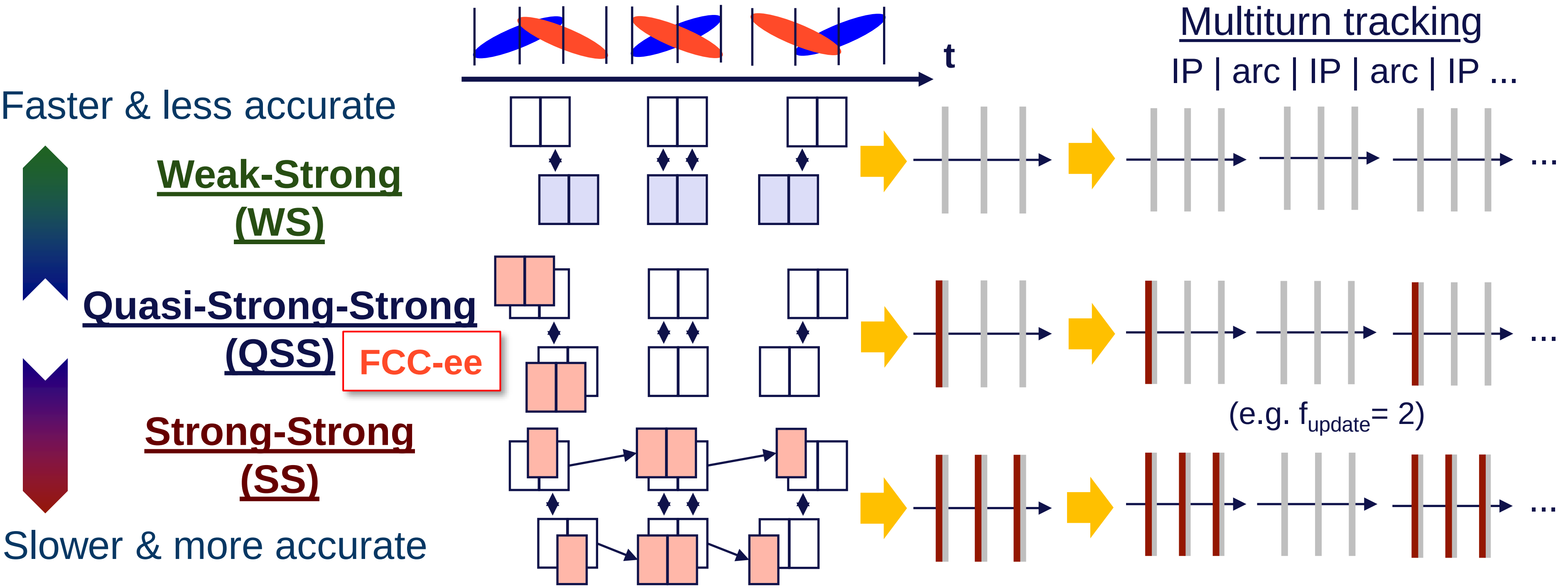
1. Lorentz transform into head-on frame
2. Longitudinal slicing
3. Beam-beam kick in soft-Gaussian approximation [4]

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

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

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

Beam-beam in Xsuite



Multiturn tracking

IP | arc | IP | arc | IP ...

Faster & less accurate

Weak-Strong (WS)

Quasi-Strong-Strong (QSS) FCC-ee

Strong-Strong (SS)

Slower & more accurate

🟦 : untracked bunch with fixed moments

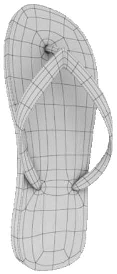
▢ : bunch slice with macroparticles

▢ ◆ ▢ : soft-Gaussian kick

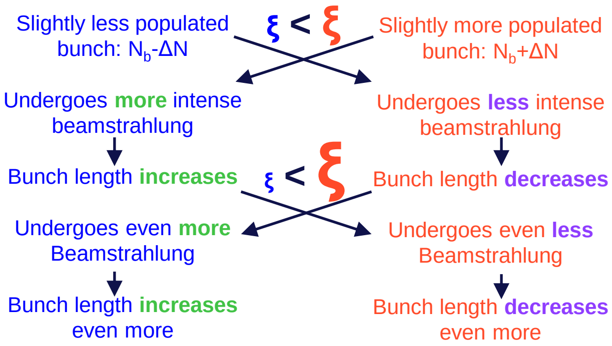
🟥 : compute statistical moments of slice

Flip-flop

- Flip-flop instability (1D) observed in other colliders (VEPP-2000)



- For FCC-ee: 3D flip-flop - direct consequence of **beamstrahlung**, triggered by an initial asymmetry in **bunch intensity**



Slightly less populated bunch: N_b-ΔN

$\xi < \xi$

Slightly more populated bunch: N_b+ΔN

Undergoes **more** intense beamstrahlung

Undergoes **less** intense beamstrahlung

Bunch length **increases**

$\xi < \xi$

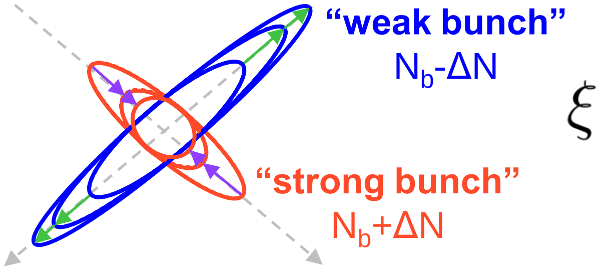
Bunch length **decreases**

Undergoes even **more** Beamstrahlung

Undergoes even **less** Beamstrahlung

Bunch length **increases** even more

Bunch length **decreases** even more

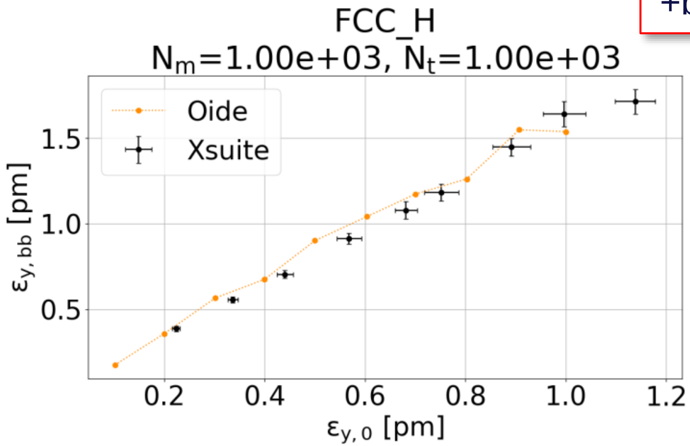


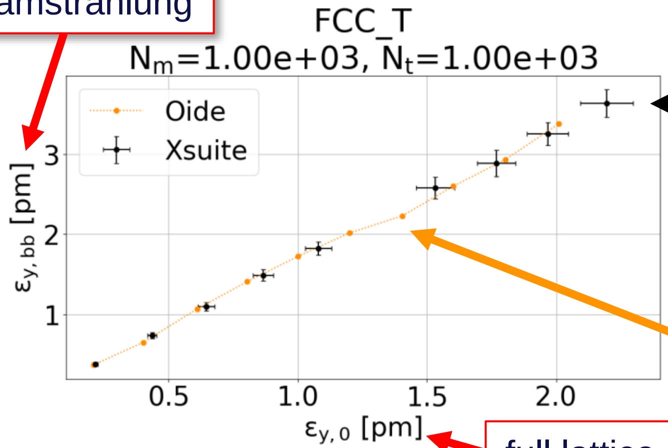
$$\xi \sim \frac{1}{\sigma_z}$$

- 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

Vertical emittance

w/ beam-beam
+beamstrahlung



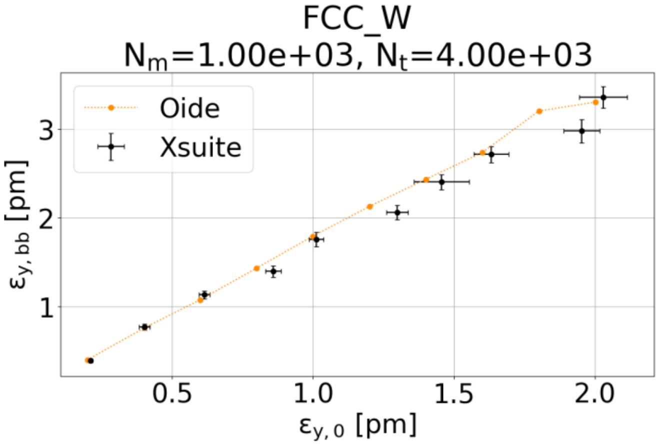


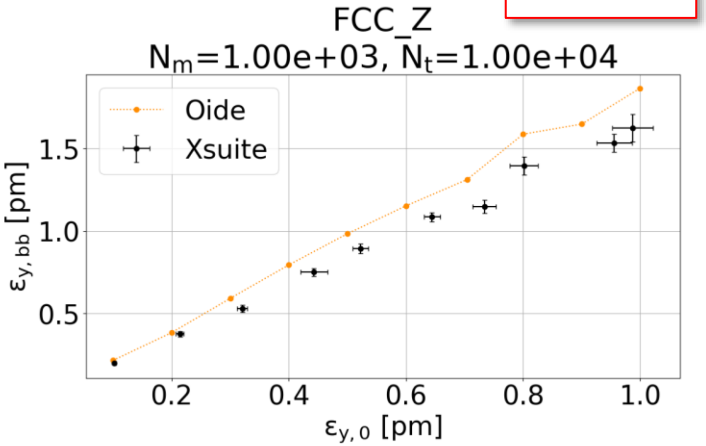
Xsuite tracking

error bars:
stat. of last 2500 turns

Reference data
by K. Oide

full lattice





- Independent benchmarks with SAD & Xsuite
- Good agreement

Workflow for emittance scan – everything in Xsuite

Prepare Xtrack line once:

- load MAD-X sequence
- 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