FCC

BEAM-BEAM CODE PROGRESS

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FCC-week
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Outline

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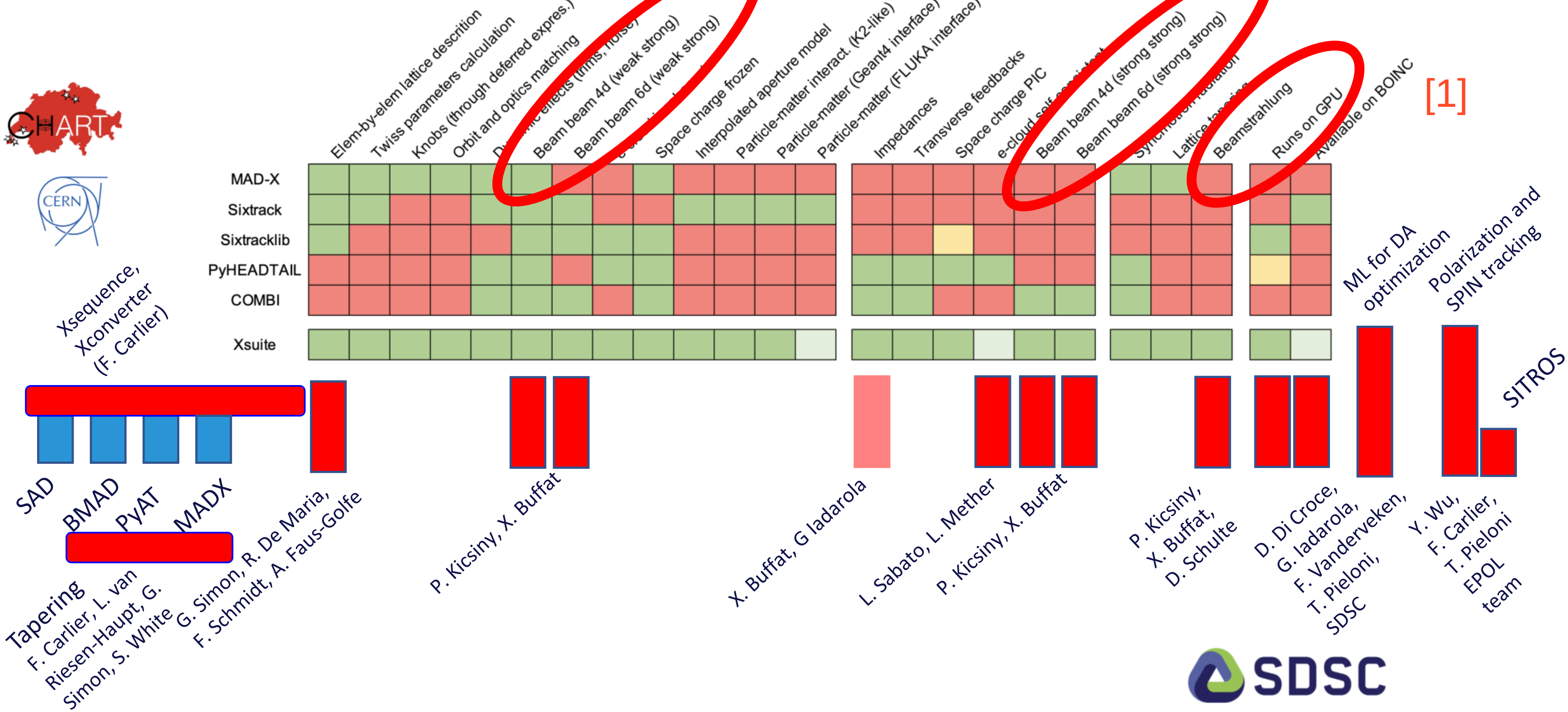
1. Introduction
2. Performance of the Xsuite beam-beam model
3. Scan of x-z instability
4. 3D flip-flop instability
5. Bhabha scattering
6. Summary

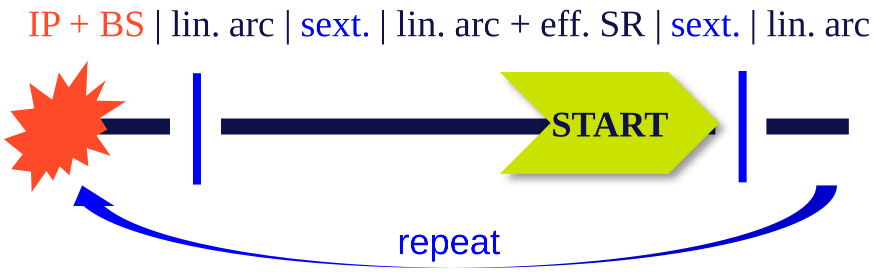
Synergies and New Developments



Simplified tracking simulations with Xsuite

- Exploit superperiodicity of machine (2 IP baseline from CDR)

- 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=500 m)

  - A «turn» begins in front of the right sextupole:
    - Observation point for coordinates

  - Effective radiation (damping+noise) in **arc**, beamstrahlung in **beam-beam element**

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Performance of the Xsuite beam-beam models

Time 1 collision on CPU
(AMD EPYC 3 GHz, single core)

Model	WS	QSS	SS
Runtime [s]	~40	~90	~110

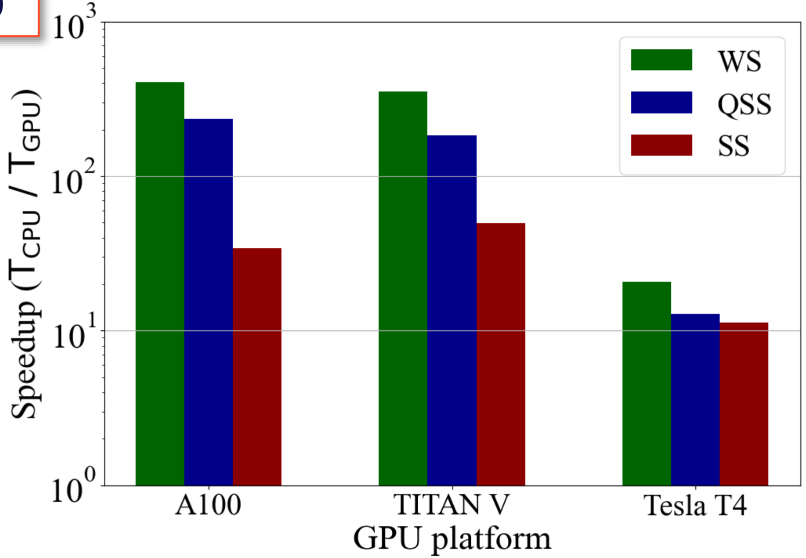
FCC-ee Z
$N_{particles}$ = 1e6
N_{slices} = 100

Only 1 beam tracked

Number of calls to the 3 main operations over a single collision

Beam-beam with N_s slices	WS	QSS	SS
Assign slices	0	1	$2N_s - 1$
Compute stat. moments	0	1	$2N_s - 1$
Synchrobeam kick	1	$2N_s - 1$	$2N_s - 1$

Scaling on GPU



- Before: typical setup with single CPU (~ 1 week)
- GPU significantly reduces computational cost (< 1 day)

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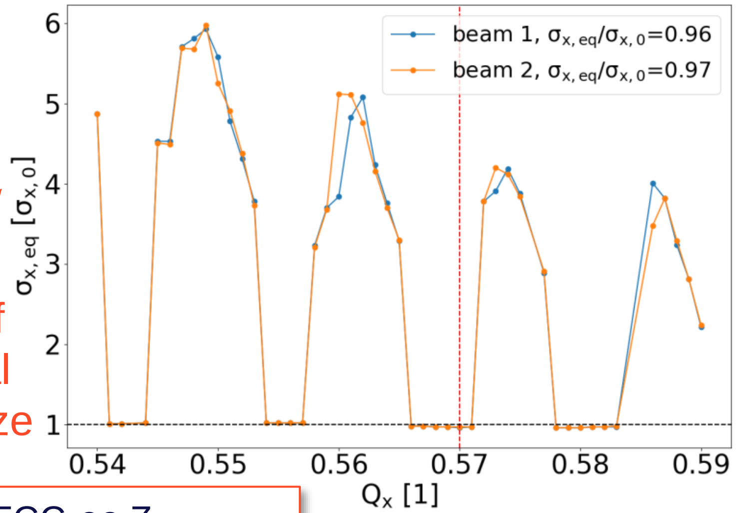
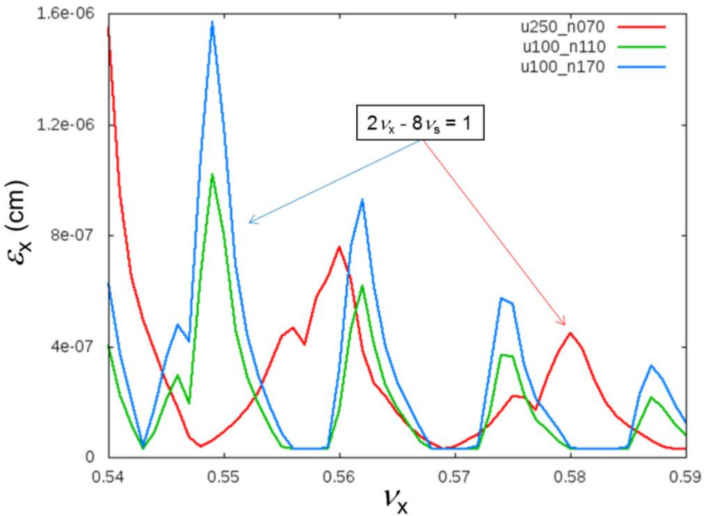
x-z instability

- x-z instability regions reproduced in QSS simulation





[2]

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 $1.7\cdot10^{11}$.

FCC-ee Z
Quasi strong-strong (f=1)
N_{coll} = 1e4
$N_{particles}$ = 1e6
N_{slices} = 300

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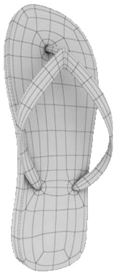
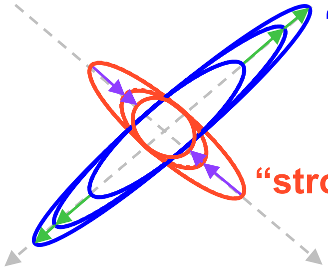
Flip-flop

- Flip-flop instability (1D) observed in other collides (VEPP-2000) [3]



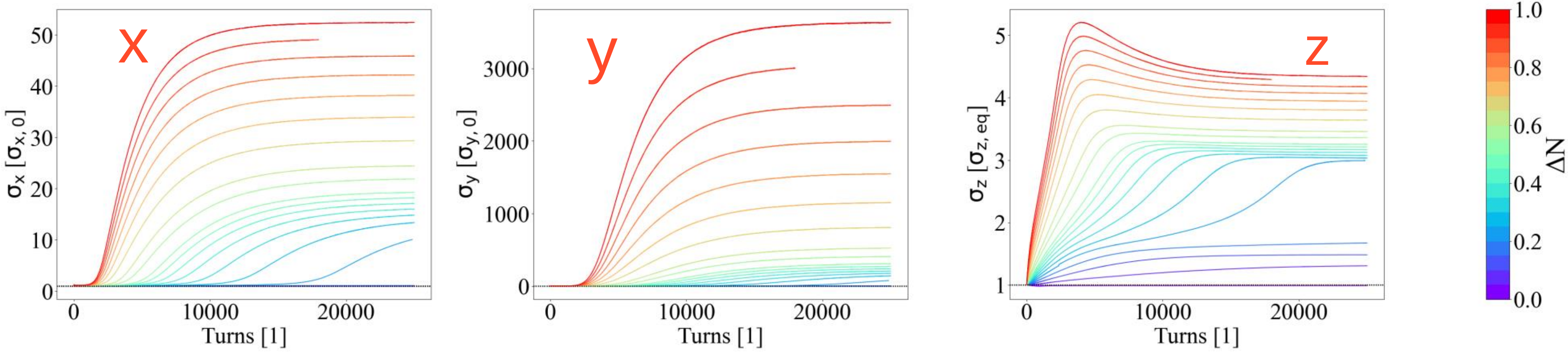
- For FCC-ee: 3D flip-flop - direct consequence of beamstrahlung, triggered by an initial asymmetry in bunch intensity [4]

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



- 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

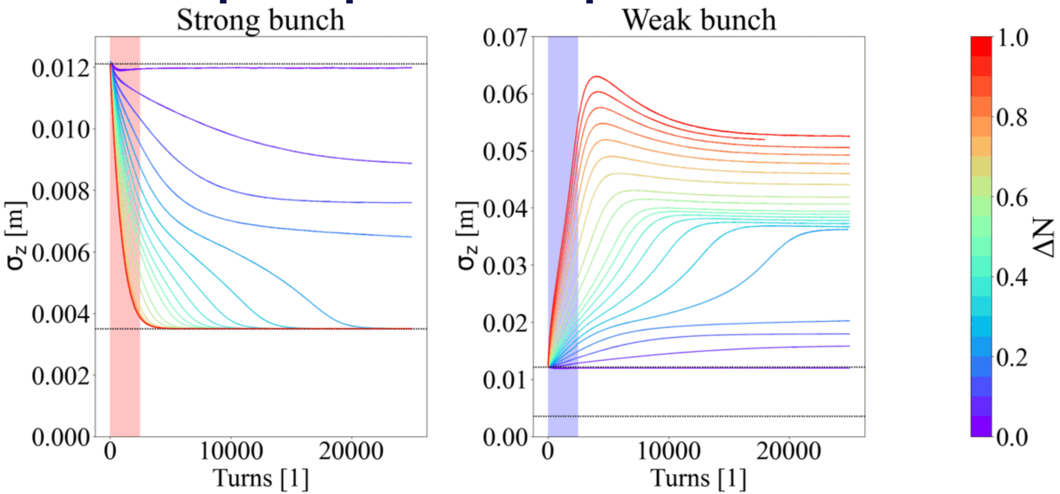
3D flip-flop



- Scanned asymmetry in bunch intensity: $N_{w,s} = N_0 \cdot (1 \pm \Delta N)$ (ΔN ∈ [0,1])
- Observed expected blowup of weak bunch

FCC-ee Z
Quasi strong-strong (f=100)
N_{coll} = 5e4
$N_{particles}$ = 1e7
N_{slices} = 300

3D flip-flop – comparison to a 1D model



FCC-ee Z
Quasi strong-strong (f=100)
N_{coll} = 5e4
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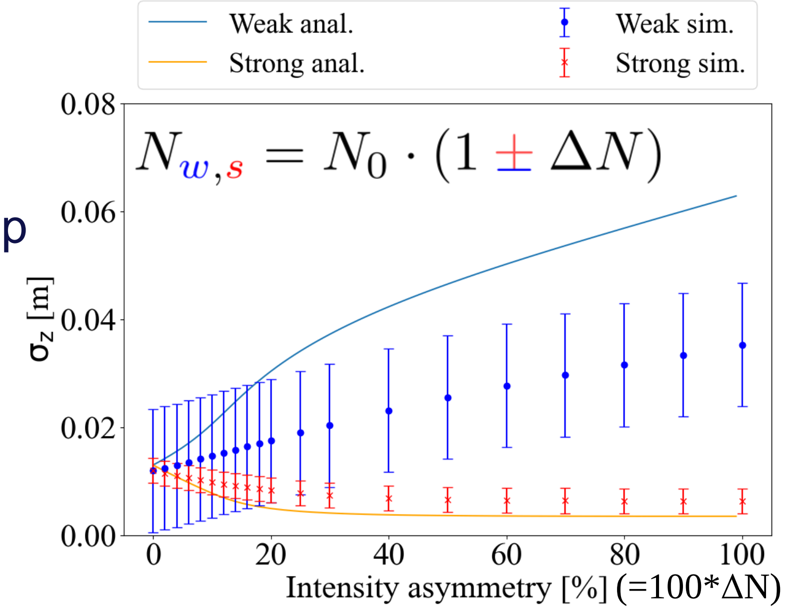
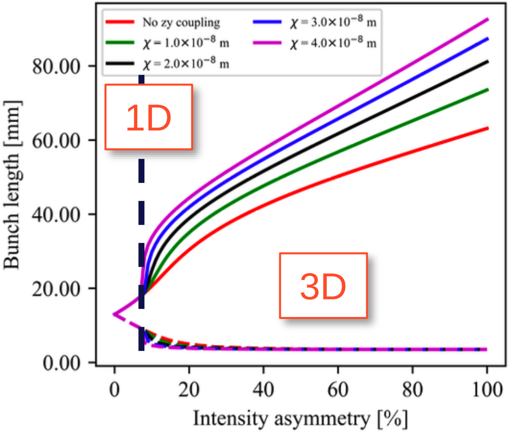
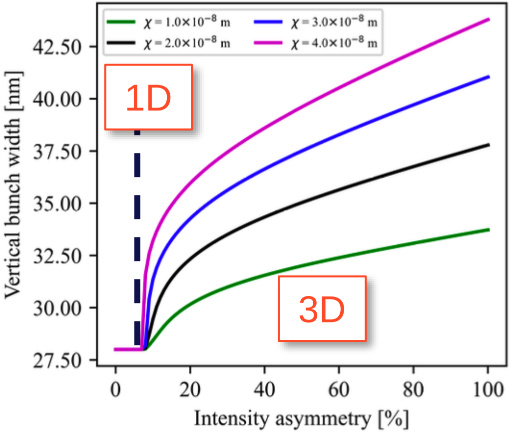


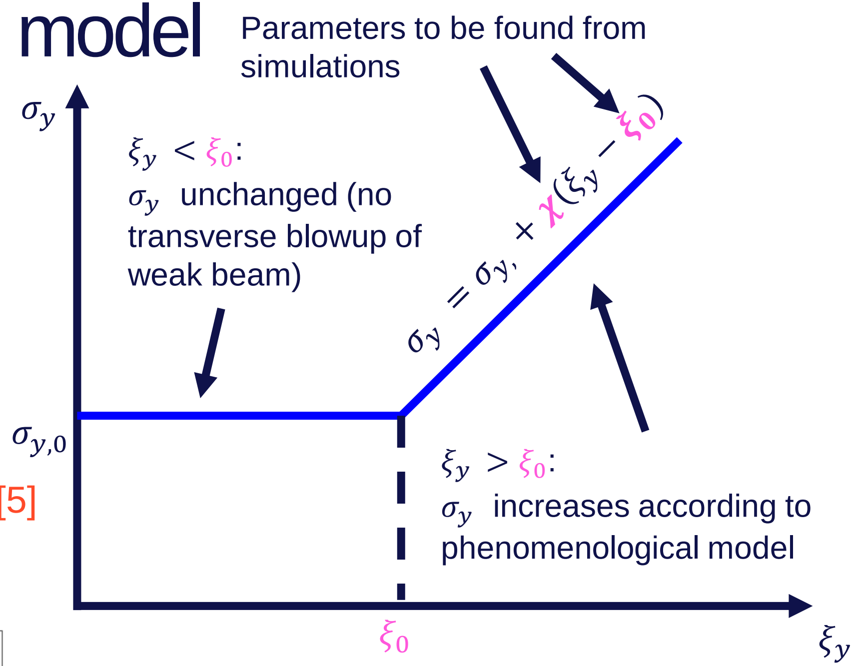
- Analytical model (Khoi's model) to estimate blowup
- Khoi's 1D model [5] does not take into account nonlinear diffusion at high asymmetries
- Khoi's 3D [5] model includes diffusion in a phenomenological way

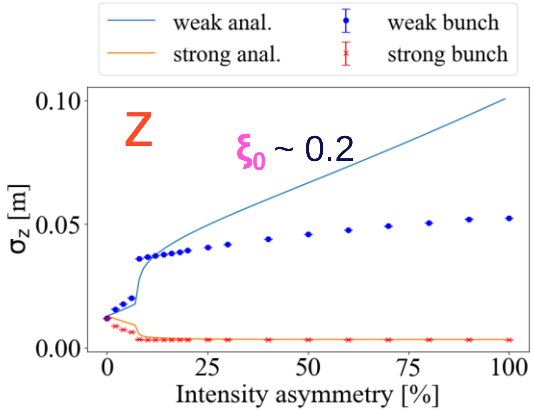
3D flip-flop – comparison to a 3D model

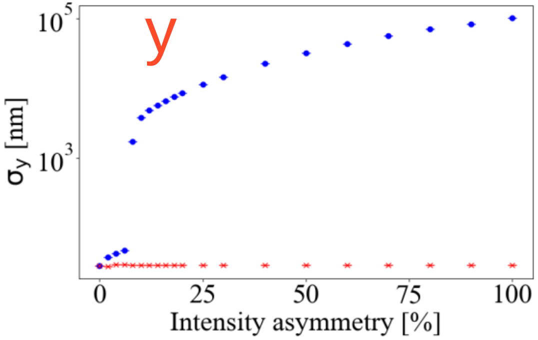




[5]







- Model validates tracking
- Good predictions at small ΔN
- Allows fast parameter scan for first estimates of blowup

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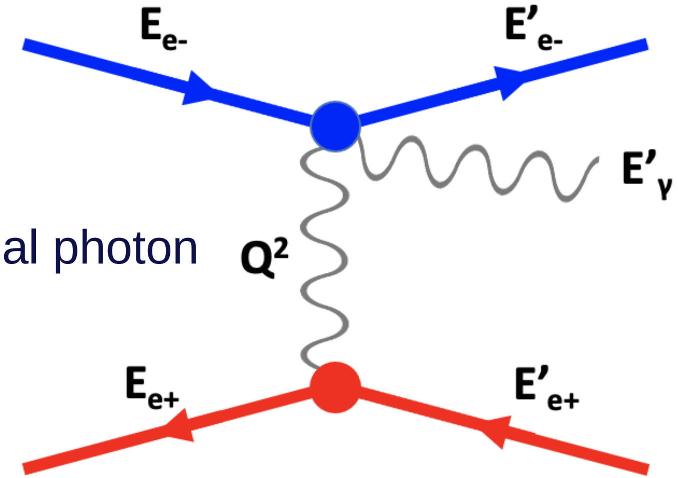
Bhabha scattering

- Coulomb scattering of relativistic charges of opposite sign

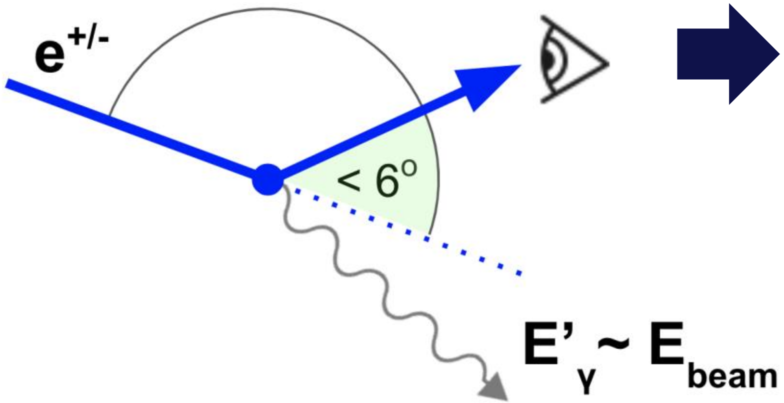
virtual photon



occasional bremsstrahlung (radiative Bhabha) photons

Small angle Bhabha scattering [6]

- Dominated by t-channel (scattering) process

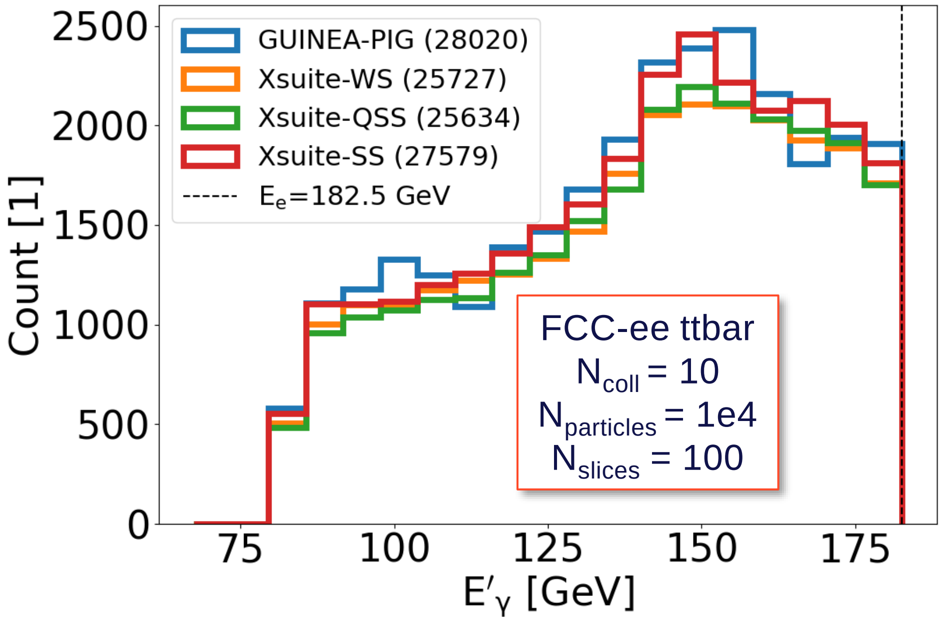


luminosity in lepton colliders

primary particles lost within a turn

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

Bhabha scattering event generator in Xsuite



- Modeled with the method of equivalent photons [7]
- Successful benchmark of event generator against GUINEA-PIG [8]
- Ready to simulate beam lifetime

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Summary

Progress so far

- Development progress in the Xsuite beam-beam model (https://github.com/xsuite)
  - Beamstrahlung, Bhabha scattering, luminosity (soft-Gaussian)
- Successful benchmark of all approximations (WS, QSS, SS)
  - FMA, x-z instability, 3D flip-flop (including validation of Khoi's model)

Ongoing work

- Combination of beam-beam + full lattice
- Beam lifetime studies

Thank you!

Next steps

- Simulations with updated FCC-ee parameters (4 IPs)
- Impact of lattice imperfections (misalignment, orbit and optics corrections)
- Top-up injection
- Benchmark at SuperKEKB

References

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https://cds.cern.ch/record/2816655

[3] D. Shwartz et al., Recent Beam-Beam Effects at VEPP-2000 and VEPP-4M
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[4] D. Shatilov, Beam-beam Effects at High Energy e^+e^- Colliders
https://doi.org/10.18429/JACoW-eeFACT2018-TUYBA02

[5] K. Le Nguyen Nguyen, Analytical Description of the Impact of Intensity Asymmetry in Colliders with Strong Beamstrahlung
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[6] S. Jadach et al., Bhabha process at LEP: theoretical calculations
doi:10.1016/S0920-5632(96)90021-3

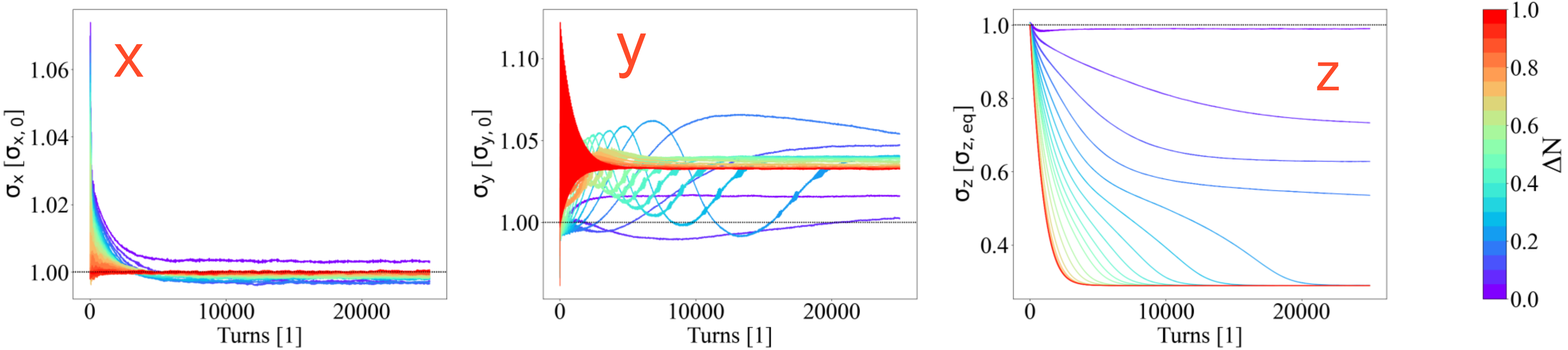
[7] C. Weizsäcker, E. Williams
doi:10.1007/BF01333110, http://gymarkiv.sdu.dk/MFM/kdvs/mfm%2010-19/mfm-13-4.pdf

[8] D. Schulte, GUINEA-PIG
https://gitlab.cern.ch/clic-software/guinea-pig

BACKUP

3D flip-flop

Driven by asymmetry in bunch intensity: $N_{w,s} = N_0 \cdot (1 \pm \Delta N)$



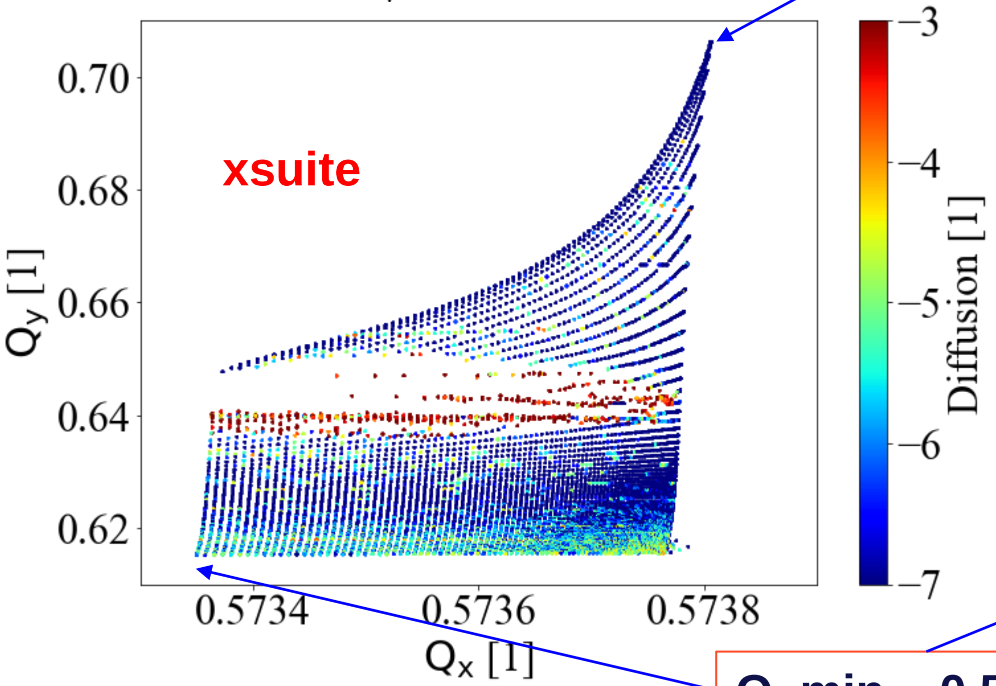
- Strong bunch shrinks
- 1D variant previously observed in VEPP-2000 [3]
- FCCee: 3D flipflop [4] – interplay of longitudinal and transversal beam sizes

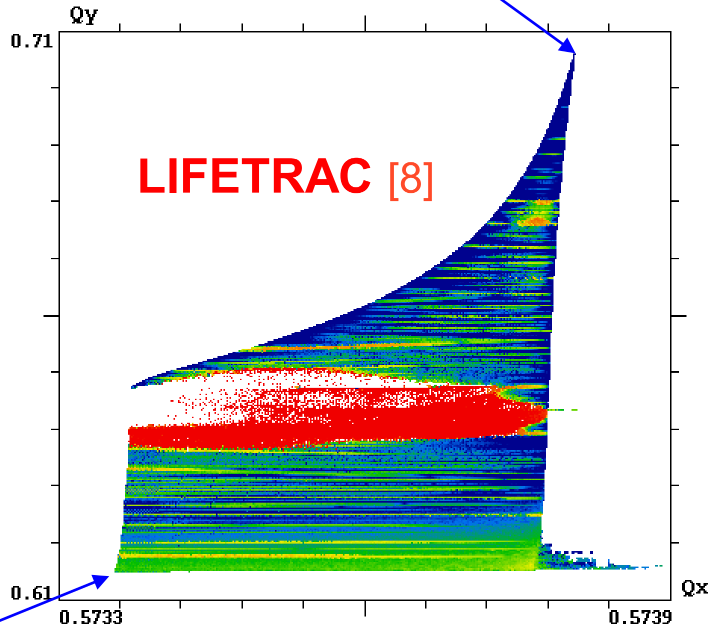
FCC-ee Z
Quasi strong-strong (f=100)
N_{coll} = 5e4
$N_{particles}$ = 1e7
N_{slices} = 300

FMA – FCC-ee Z footprint

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

Q_x max ~ 0.573806

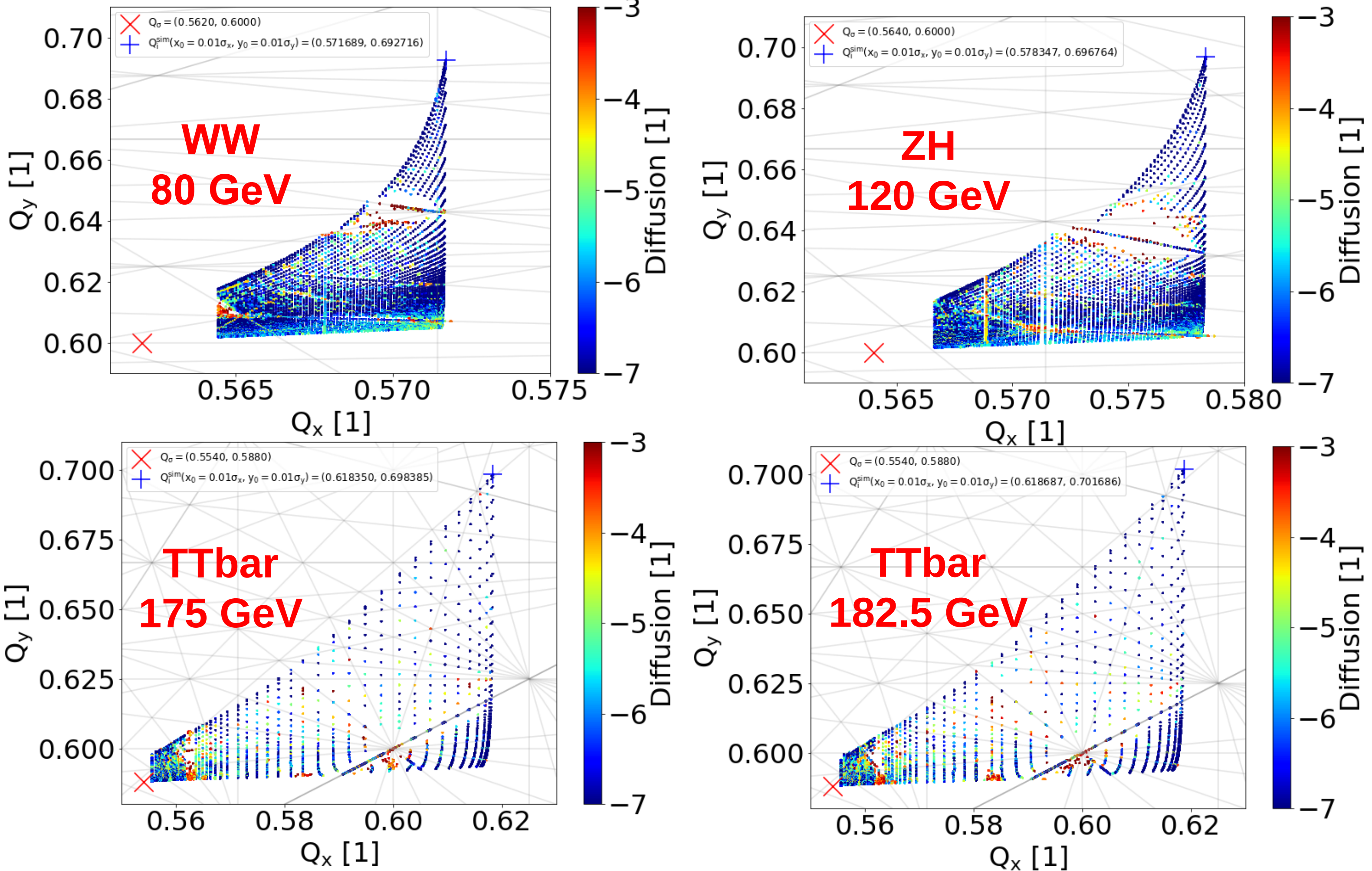




Q_x min ~ 0.57335

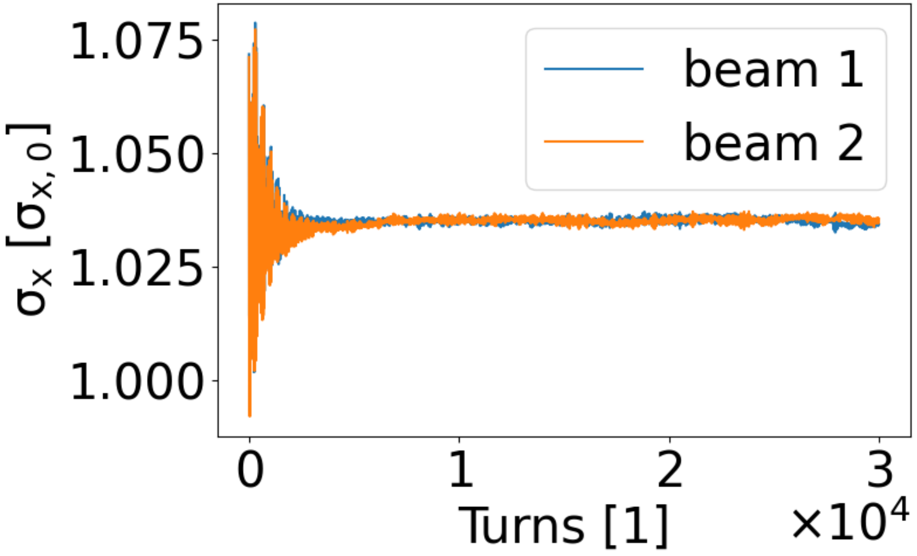
- Validation of Xsuite weak-strong model

FMA – Footprint of other FCCee energies

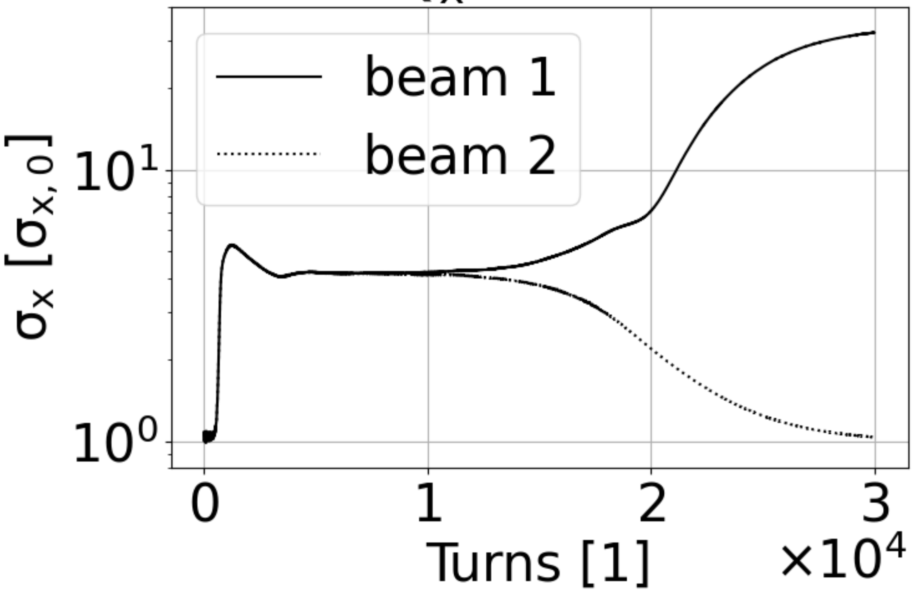


x-z instability

Stable Qx=0.57

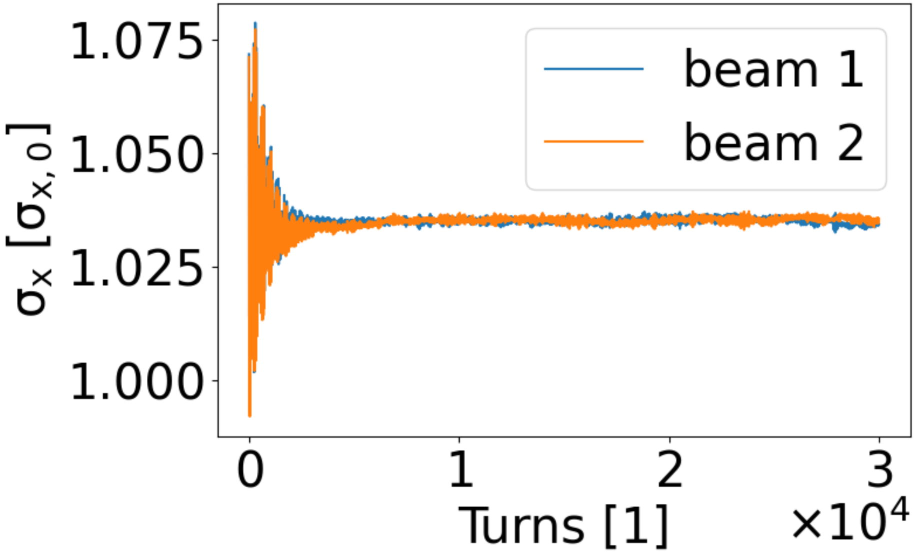


Unstable Qx=0.575



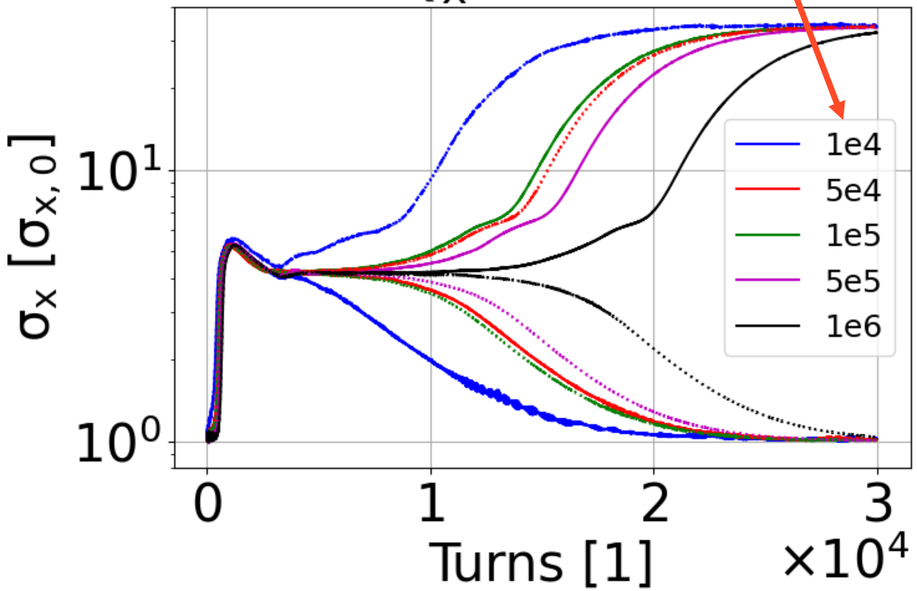
x-z instability

Stable Qx=0.57



num. macroparticles

Unstable Qx=0.575



- Flip-flop driven by numerical noise
  - Irrelevant as it happens only in unstable configurations

- Successful benchmark of (quasi-)strong-strong model