TOP-UP INJECTION STUDIES

Peter Kicsiny, X. Buffat, K. Le Nguyen Nguyen, T. Pieloni, M. Seidel

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What has been done:

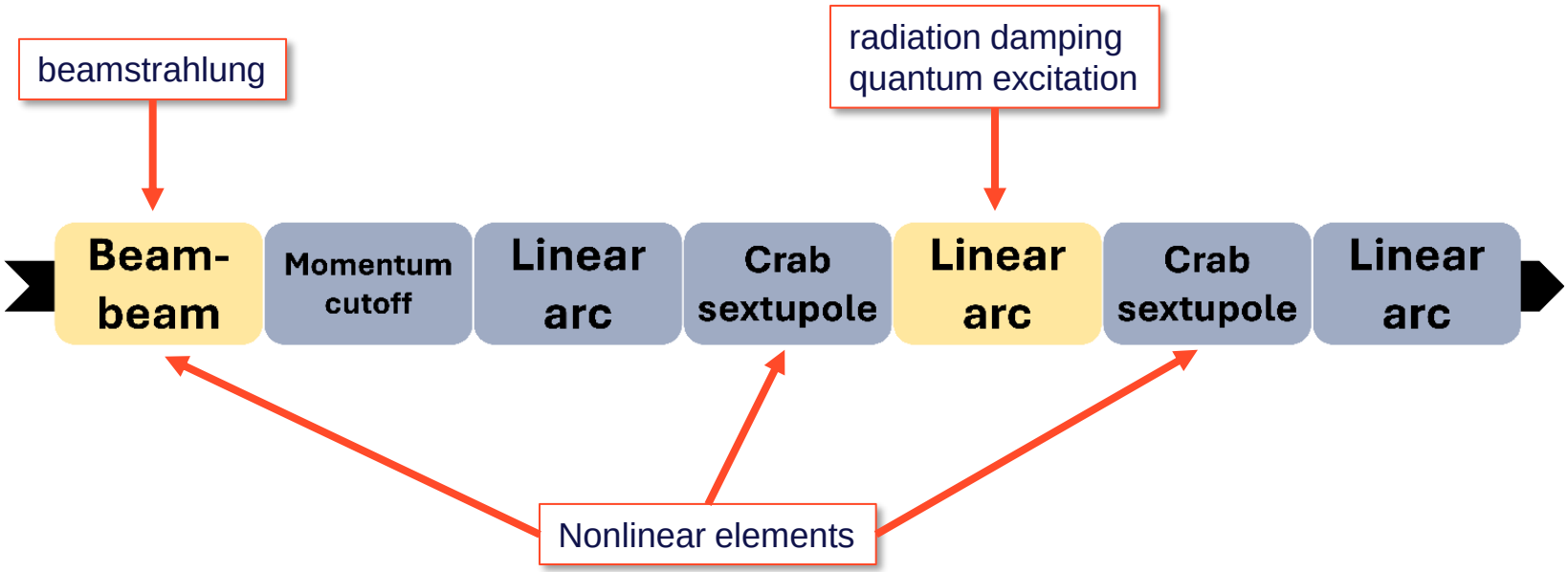
- Tracking with linear transfer map + beam-beam
  - Single top-up injection of one beam
  - Scan of injection offset
  - Scan of bunch intensity asymmetry
  - Scan of beam parameters at the IP (in backup slide)

What hasn’t been done:

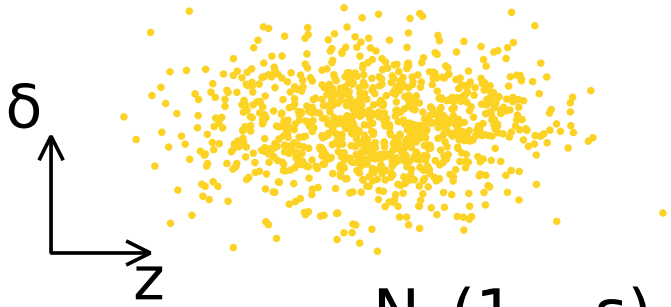
- Tracking & top-up with the full lattice
- Optimization of booster parameters

Simplified tracking setup

- 4 IP baseline design [1]
- Iterate over ¼ superperiod of machine



Longitudinal top-up injection



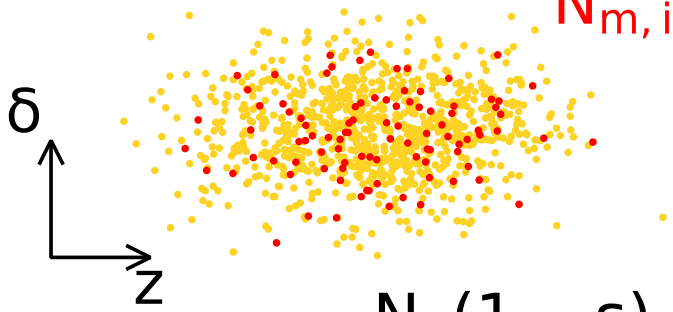
$$w = \frac{N_0(1-\varepsilon)}{N_m}$$

- N_0: nominal bunch intensity
- N_m: # macroparticles
- ε: bunch intensity asymmetry factor: e.g. ε=0.05 for 5% asym.: top-up beam from $0.95N_0$ to $1.05N_0$
- w: “weight” of each macroparticle = # real charges represented by it
- δ_{io}: injection offset in units of the rms rel. energy spread

Longitudinal top-up injection

1. Select $N_{m,i}$ macroparticles

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



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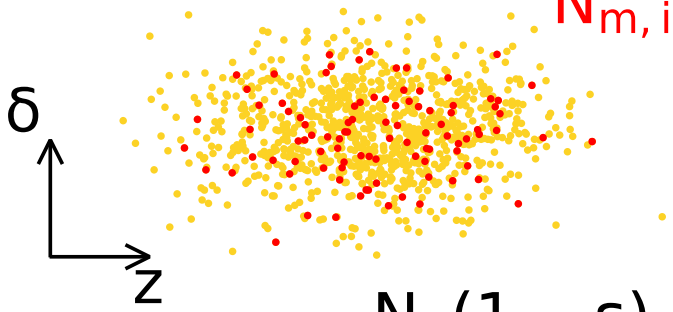
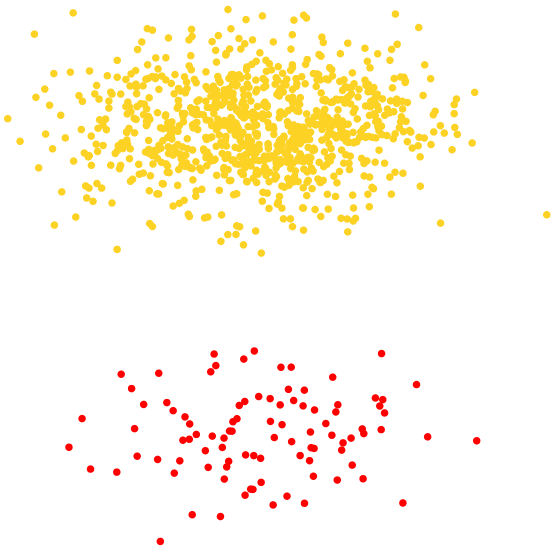
Longitudinal top-up injection

1. Select $N_{m,i}$ macroparticles
2. Offset δ of these macroparticles

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



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



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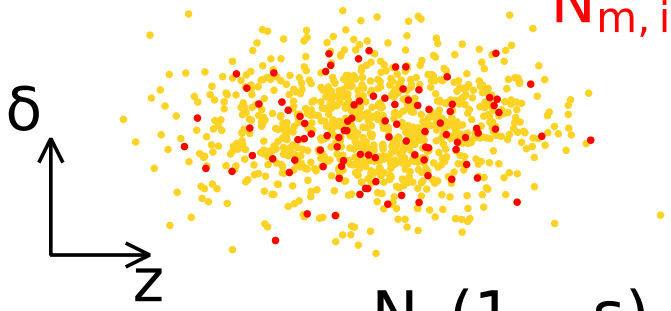
Longitudinal top-up injection

1. Select $N_{m,i}$ macroparticles
2. Offset δ of these macroparticles
3. Update weight of all macroparticles

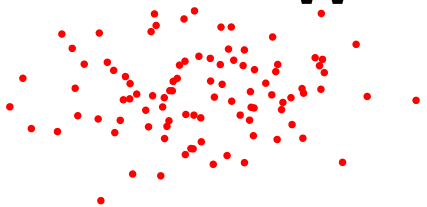
$$N_{m,i} = \frac{2\varepsilon N_m}{1+\varepsilon}$$



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

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

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



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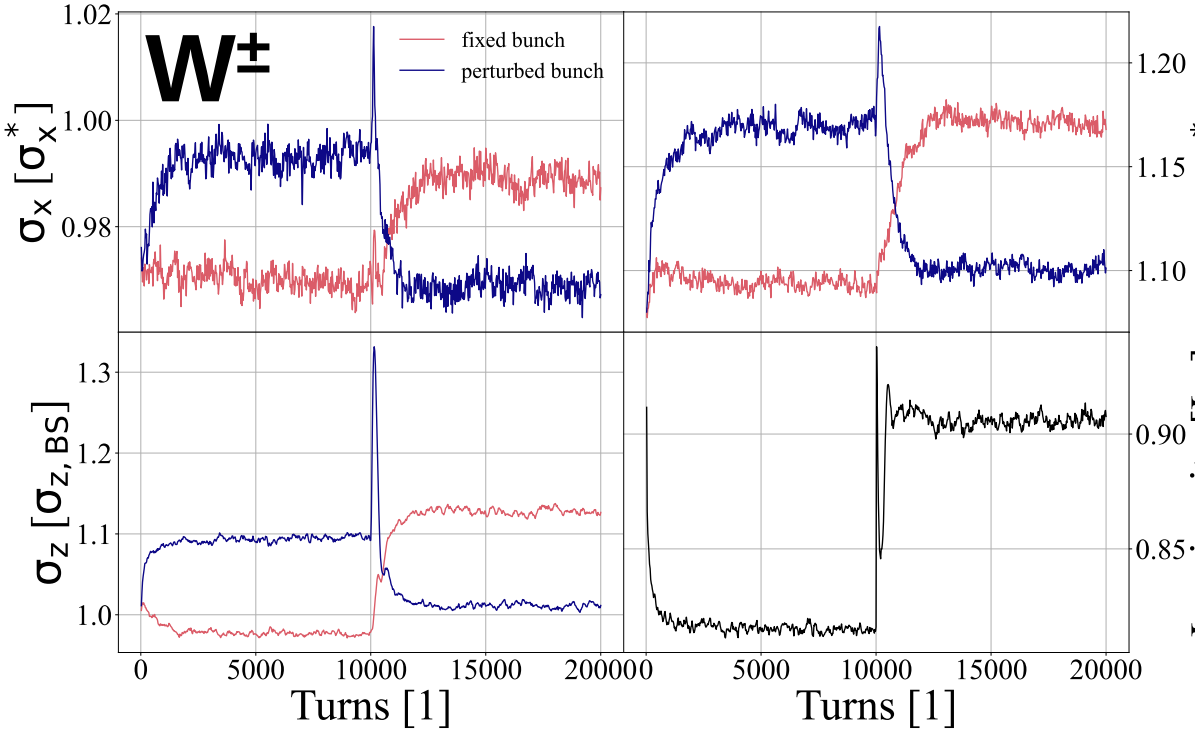
Strong-strong simulation of top-up injection

Fixed bunch: nominal parameters

Perturbed bunch: start with $0.95N_0$ (ε=0.05, δ_{io}=7)

1. Track till equilibrium
2. Top-up perturbed bunch to $1.05N_0$
3. Track till equilibrium



Nominal rms bunch sizes from [1]

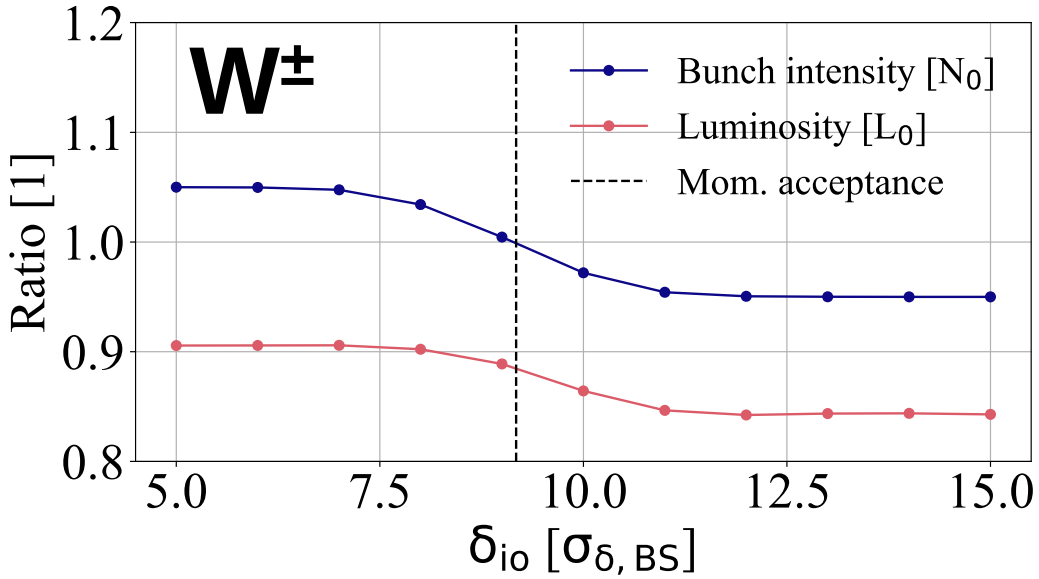
L_0: lumi per bunch crossing, from a single strong-strong collision simulation with Xsuite

Eq. reached in ~1.5 s (=5e3 turns)

Strong-strong simulation of top-up injection

1. Fix bunch intensity asymmetry to ε=0.05
2. Scan injection offset
3. Record equilibrium luminosity after top-up

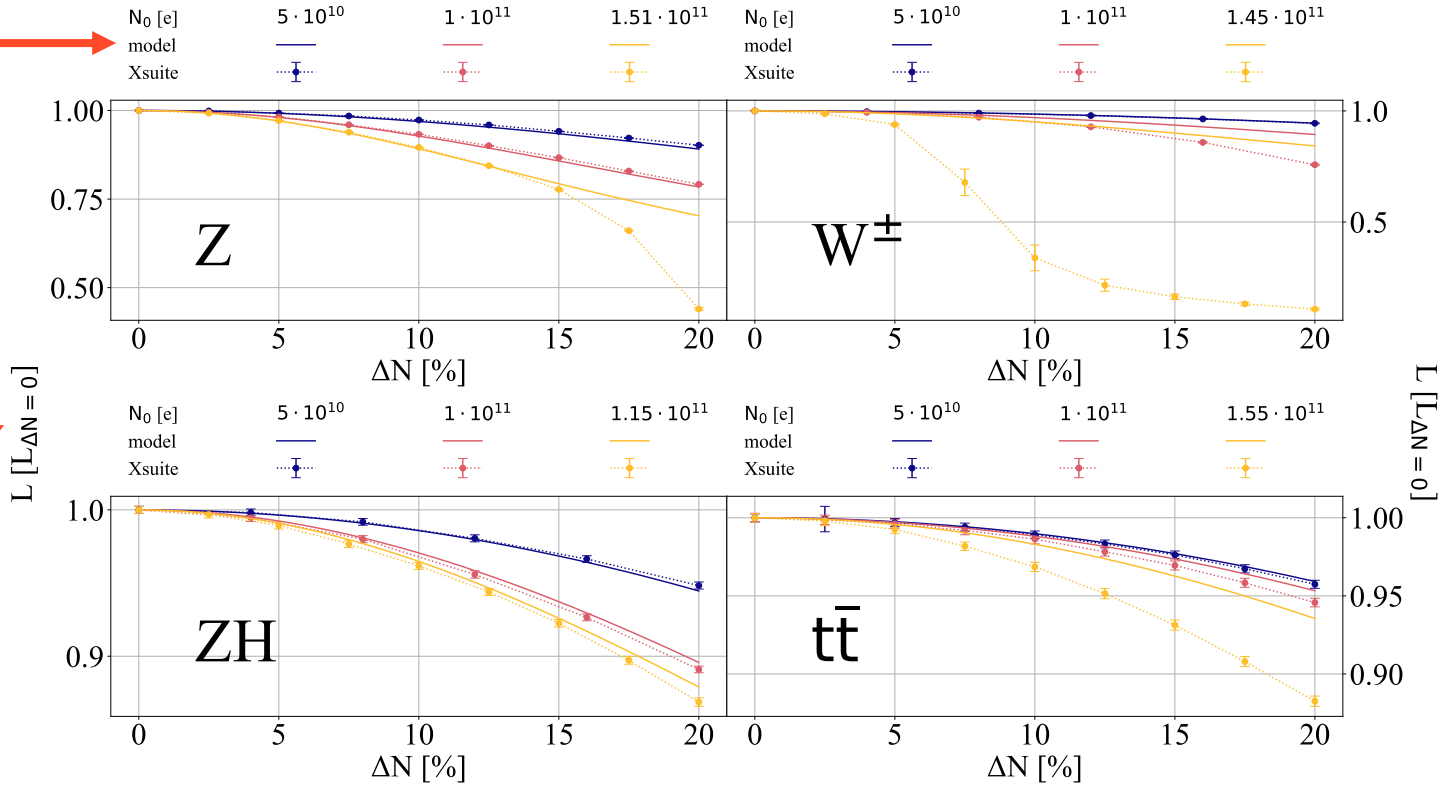
- No unexpected effects were observed



Quasi-strong-strong simulation of luminosity (no top-up here)

1. Scan mean bunch intensity N_0
2. For each N_0 scan ΔN:
   $N_\pm = N_0(1 \pm \Delta N)$
3. Track beams till equilibrium

Comparison with analytical model [2]



Luminosity normalized to symmetric simulation (ΔN=0)

Summary

- Several parameter scans have been done with **linear tracking**
- Flip-flop mechanism results in new equilibrium with reduced luminosity
- Reaching new equilibrium is fast (~synchrotron radiation damping rate)
- No reduction of injection efficiency/beam loss was observed due to beam-beam
- Simulation details can be found in [3]
- Tracking with full lattice (proper DA) needs to be performed for more realistic beam dynamics during/after injection

References

[1] K. Oide, FCC-ee collider optics, FCC week (2023)
https://indico.cern.ch/event/1202105/contributions/5408583/attachments/2659051/4608141/FCCWeek_Optics_Oide_230606.pdf

[2] Impact of bunch intensity asymmetry in colliders featuring strong beamstrahlung
K. Le Nguyen Nguyen, X. Buffat, P. Kicsiny, T. Pieloni, 2024
arXiv preprint https://arxiv.org/abs/2404.09012

[3] Impact of beam asymmetries at the Future Circular Collider $e+e-$
P. Kicsiny, X. Buffat, K. Le Nguyen Nguyen, T. Pieloni, M. Seidel, 2024
Phys. Rev. Accel. Beams 27, 121001 https://doi.org/10.1103/PhysRevAccelBeams.27.121001


BACKUP

Simulation parameters

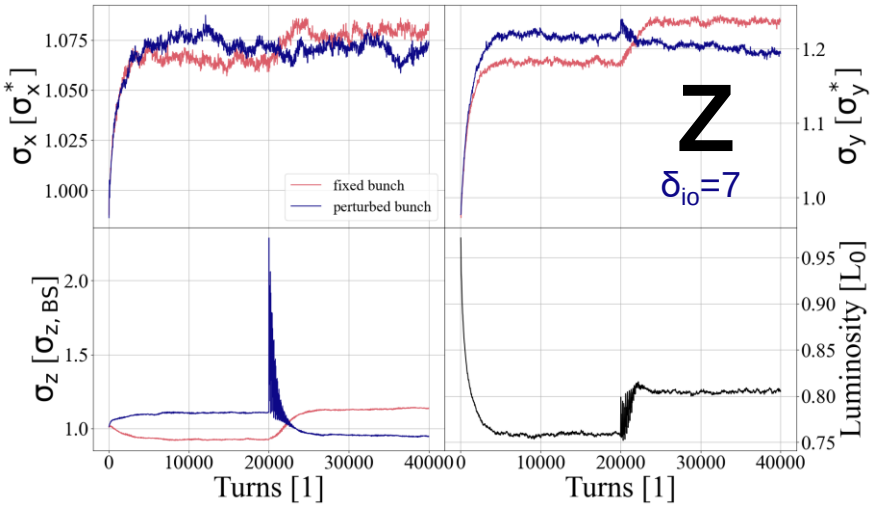
Slide #	7	8	9	10
Machine setup	FCC 4 IP from 2023 FCC week, W	FCC 4 IP from 2023 FCC week, W	FCC 4 IP from 2023 FCC week	FCC 4 IP from 2023 FCC week
Lattice model	linear	linear	linear	linear
Beam-beam model	QSS f=100 (before top-up) SS f=1 (after top-up)	QSS f=100 (before top-up) SS f=1 (after top-up)	QSS f=100	QSS f=100
# slices in beam-beam	100	100	100 (200 for Z)	100 (200 for Z)
# macroparticles	1e5	1e5	1e5 (1e6 for Z)	1e5 (1e6 for Z)
# turns	1e4 each stage (4e4 superperiod iterations)	1e4 each stage (4e4 superperiod iterations)	Z: 8e4, W: 4e4, H: 2e4, T: 2e4 superperiod iterations	Z: 8e4, W: 4e4, H: 2e4, T: 2e4 superperiod iterations

f: update frequency of stat. moments in beam-beam in every X superperiod iterations

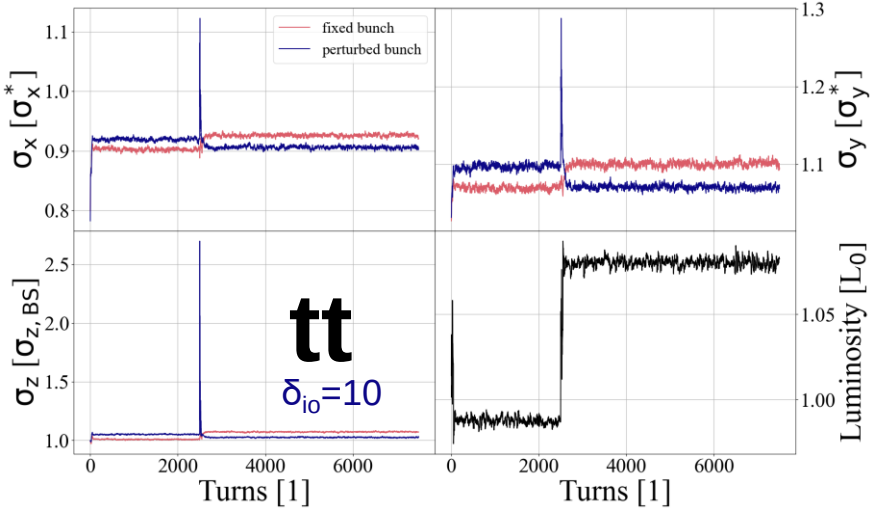
Strong-strong simulation of top-up injection

- Equilibrium reached with a rate proportional to radiation damping time

Eq. reached in ~3 s (=1e4 turns)

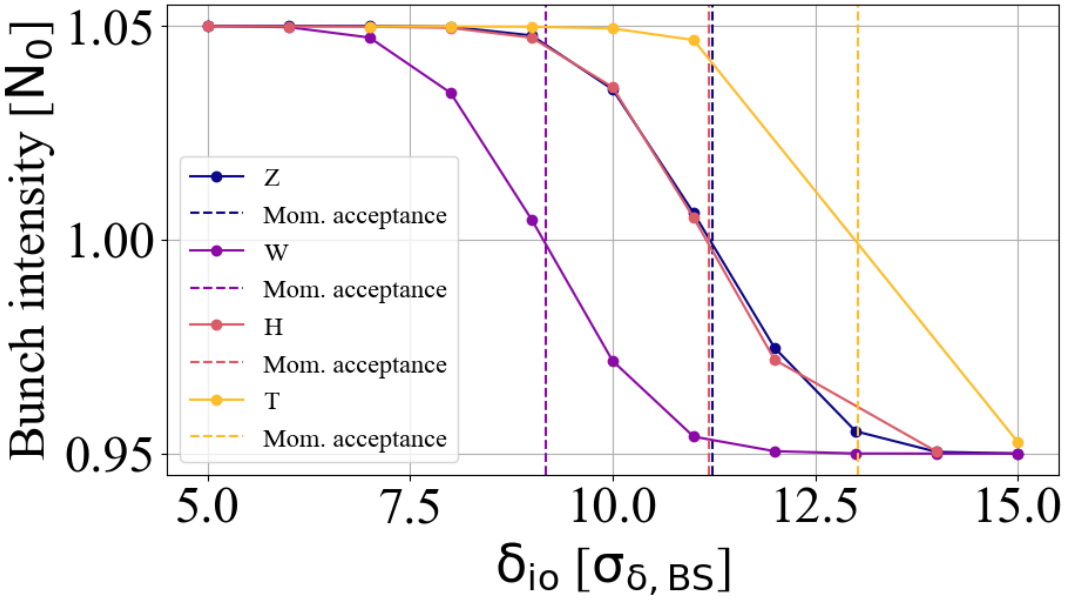


Eq. reached in ~0.03 s (=100 turns)



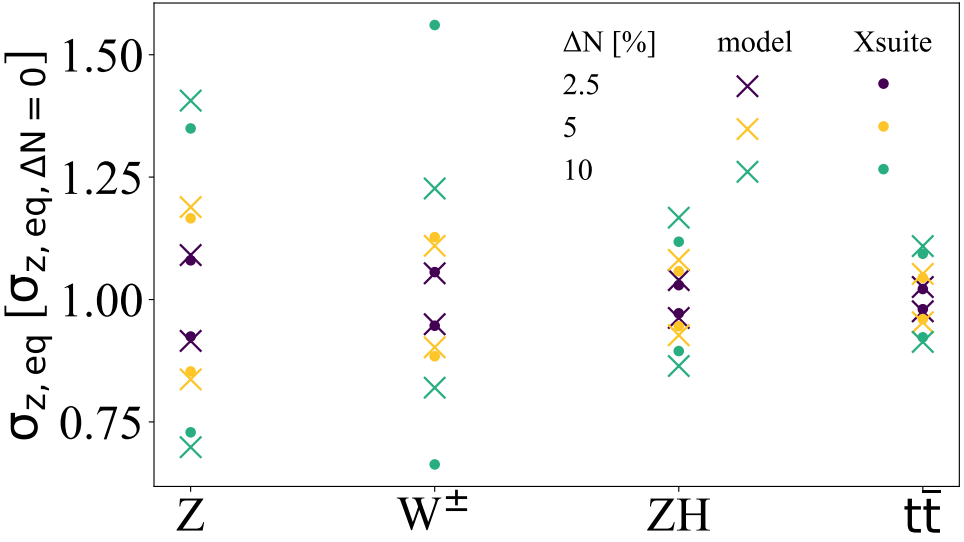
Strong-strong simulation of top-up injection

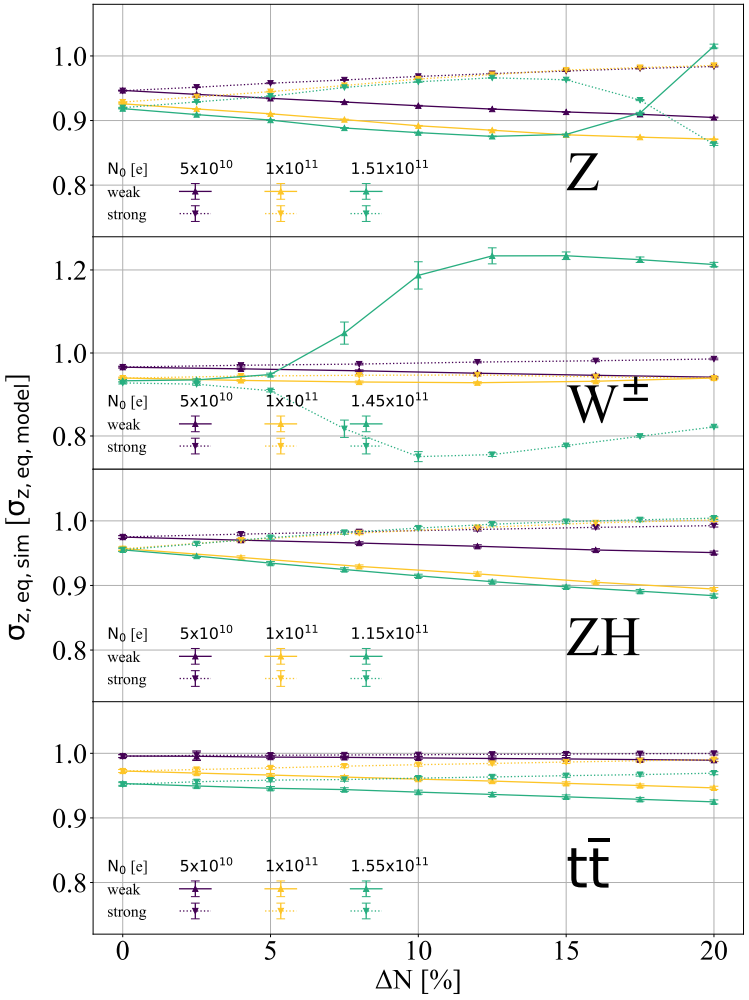
- Trivial limit to injection efficiency is the momentum acceptance
- No other limits observed



Equilibrium bunch length

- W: significant vertical blowup due to 3D flip-flop





Quasi-strong-strong simulation of beam parameter perturbations

- Fixed bunch: nominal parameters
- Perturbed bunch: scan variable u (β_x, β_y, ε_x, ε_y) in range of 0.1-10x nominal value
- All other parameters of the perturbed bunch kept at their nominal value
- Track till euilibrium & observe vertical rms bunch size σ_y at IP of both beams
- Threshold: $\sigma_y < 1.5\ \sigma_{y,\,\mathrm{nominal}}$