Kick Strength and Phase Advance

- Relative rms phase advance error with respect to the model used for defining the quality of TbT measurements
- First TbT tracking over 500 turns for FCC-Z mode and 360 installed BPMs
- Without synchrotron radiation
- Gaussian BPM noise applied

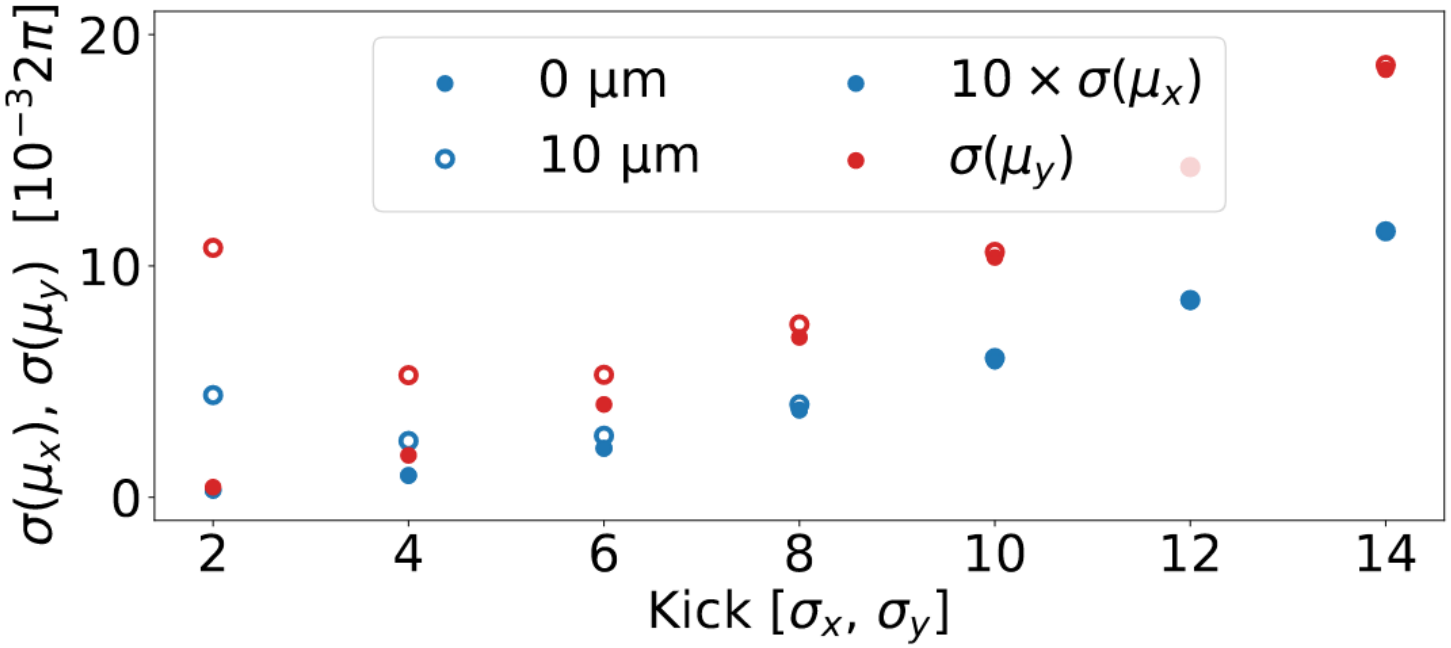
Without BPM noise phase error increases with increasing excitation strength

With BPM noise (here 10 µm) optimum kick strength found at 4 σ_x, 4 σ_y

Excitation needs to be sufficiently large to compensate for BPM noise

Effect on vertical plane 20 times more severe

FCC-Z mode at 45.6 GeV single particle tracking



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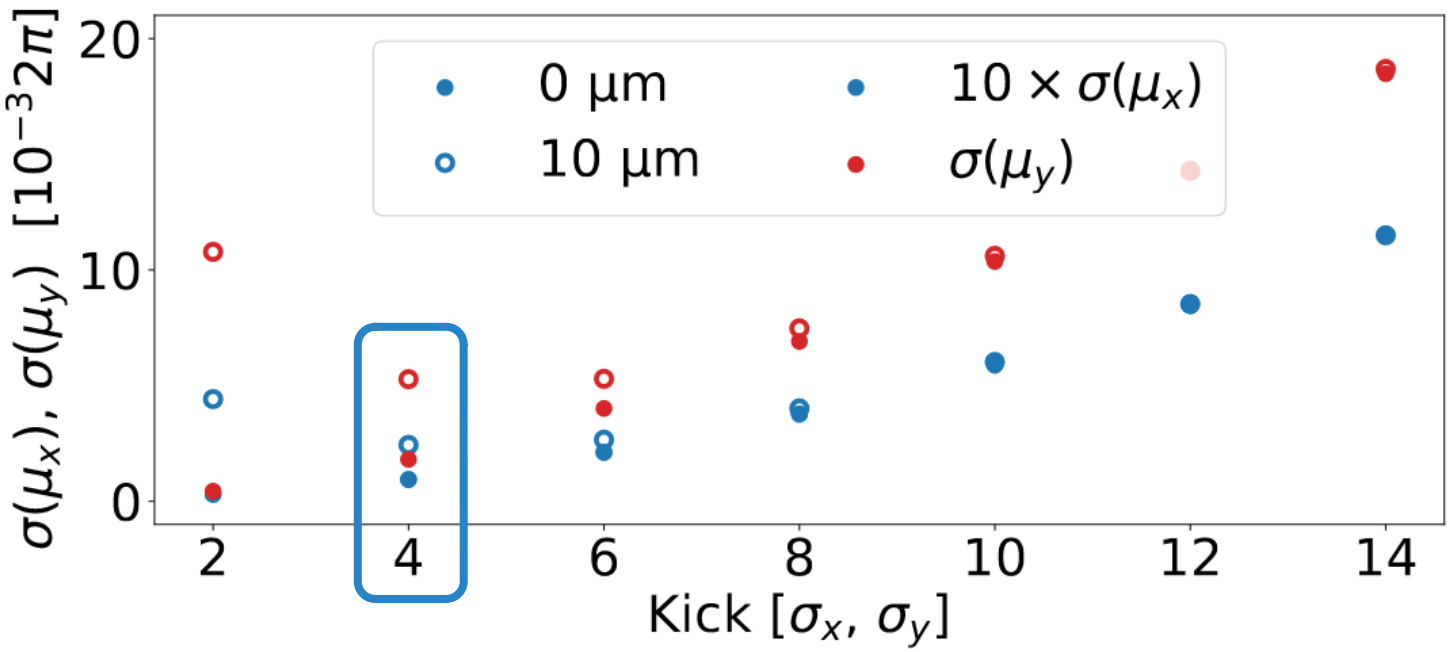
FCC-Z mode
500 turns, no synchrotron radiation
Minimum hor and ver. phase advance error with
10 µm BPM noise: 0.24 x 10^{-3} (2π) and 5.28 x 10^{-3} (2π)

Comparison LHC
6600 turns, AC-dipole
Minimum hor and ver. phase advance error, ~100 µm
BPM noise: < 1 x 10^{-3} (2π)

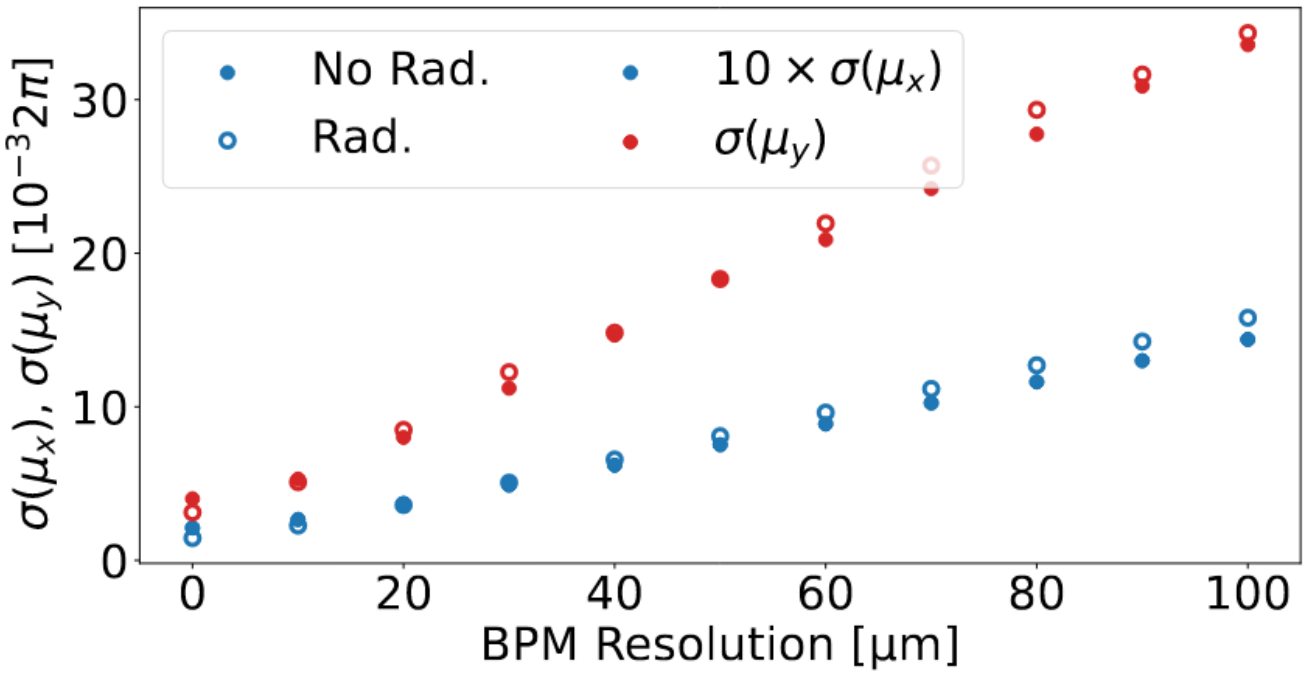
FCC-Z mode at 45.6 GeV single particle tracking



Phase Error

- Relative rms phase advance error figure-of-merit for measurement quality
- Error increases with BPM noise
- Kick amplitude 6 σ_x, σ_y
- Effect of radiation damping negligble
- BPM noise 20 times larger for vertical plane

FCC-Z mode with 45.6 GeV beam energy
Single particle tracking in SAD



FUTURE CIRCULAR COLLIDER

FCC hh ee he

CERN

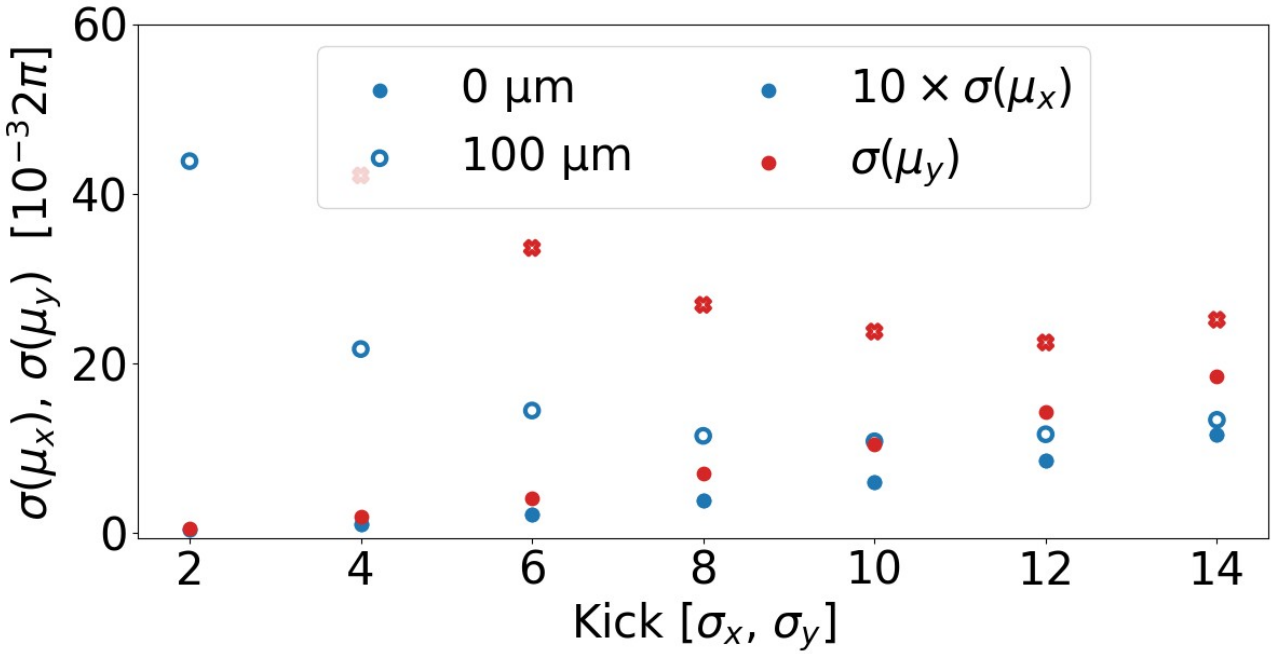
Back-up

Phase Error – No Damping

- Relative rms phase advance error figure-of-merit for measurement quality
- 500 turns, only 350 BPMs, 1 seed → to be improved in future studies
- Various kick amplitudes
- Without noise: Smaller kick lower error
- With noise: Optimum kick strengths
  - 20 µm: 6 σ_x, σ_y
  - 100 µm: 12 σ_x, σ_y

Amplitude must be large enough to compensate for BPM noise

FCC-Z mode with 45.6 GeV beam energy
Single particle tracking in SAD
No radiation damping

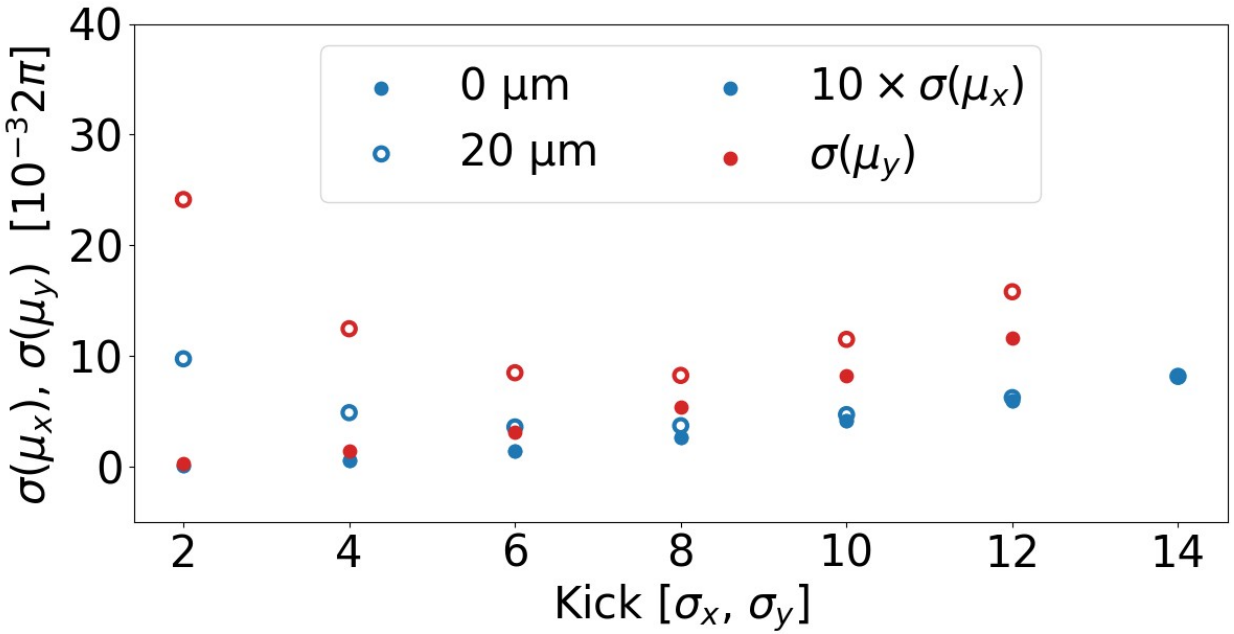


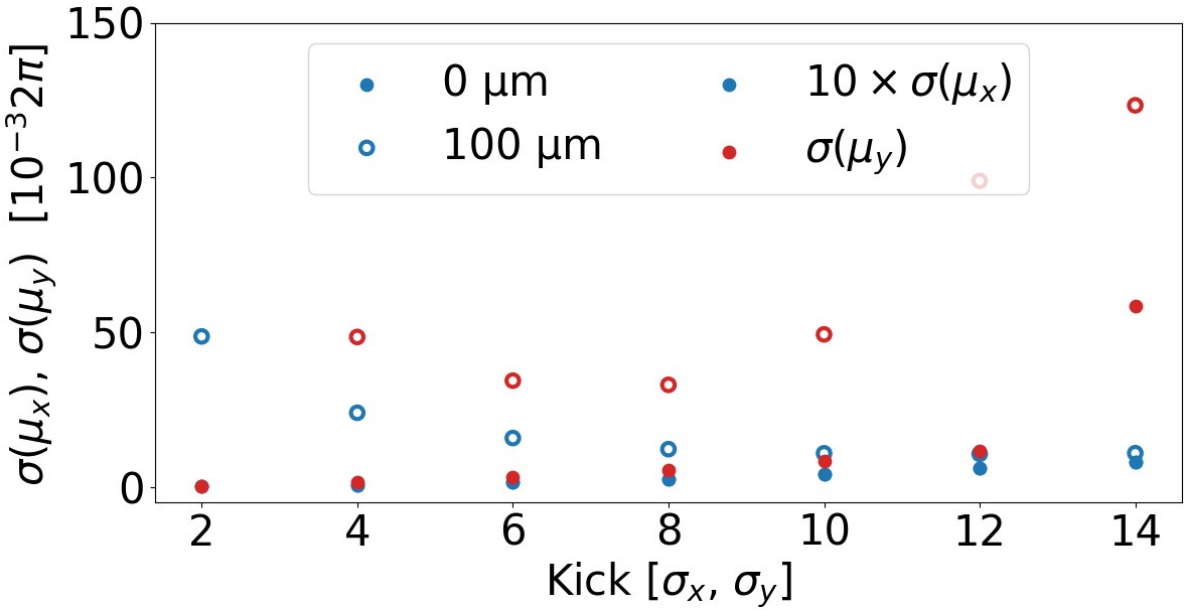
Phase Error – Damping

- Including synchrotron radiation damping
  - 20 µm: 6-8 σ_x, σ_y
  - 100 µm: 6-8 σ_x, σ_y

FCC-Z mode with 45.6 GeV beam energy
Single particle tracking in SAD
With radiation damping

The optimum kick strength changes if single kicks and damping or constant amplitude is used for optics measurements





Phase Error – No Damping

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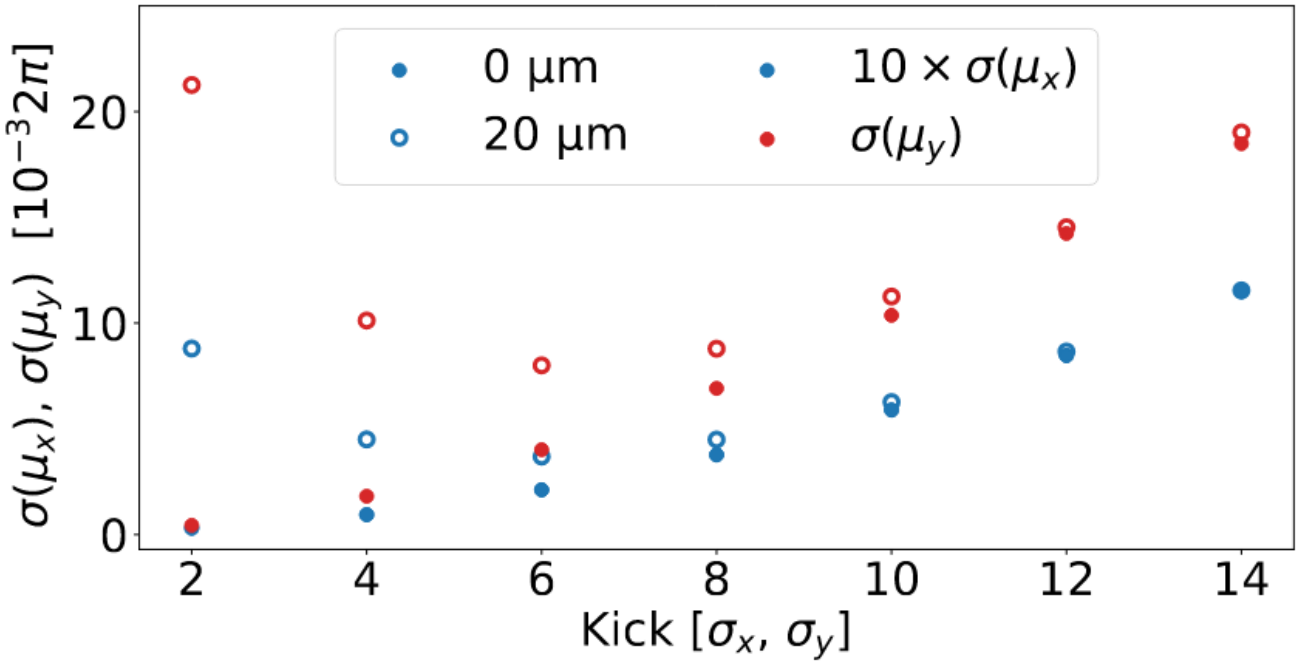
- 500 turns, only 350 BPMs, 1 seed → to be improved in future studies
- Various kick amplitudes
- Without noise: Smaller kick lower error
- With noise: Optimum kick strengths
  - 20 µm: 6 σ_x, σ_y

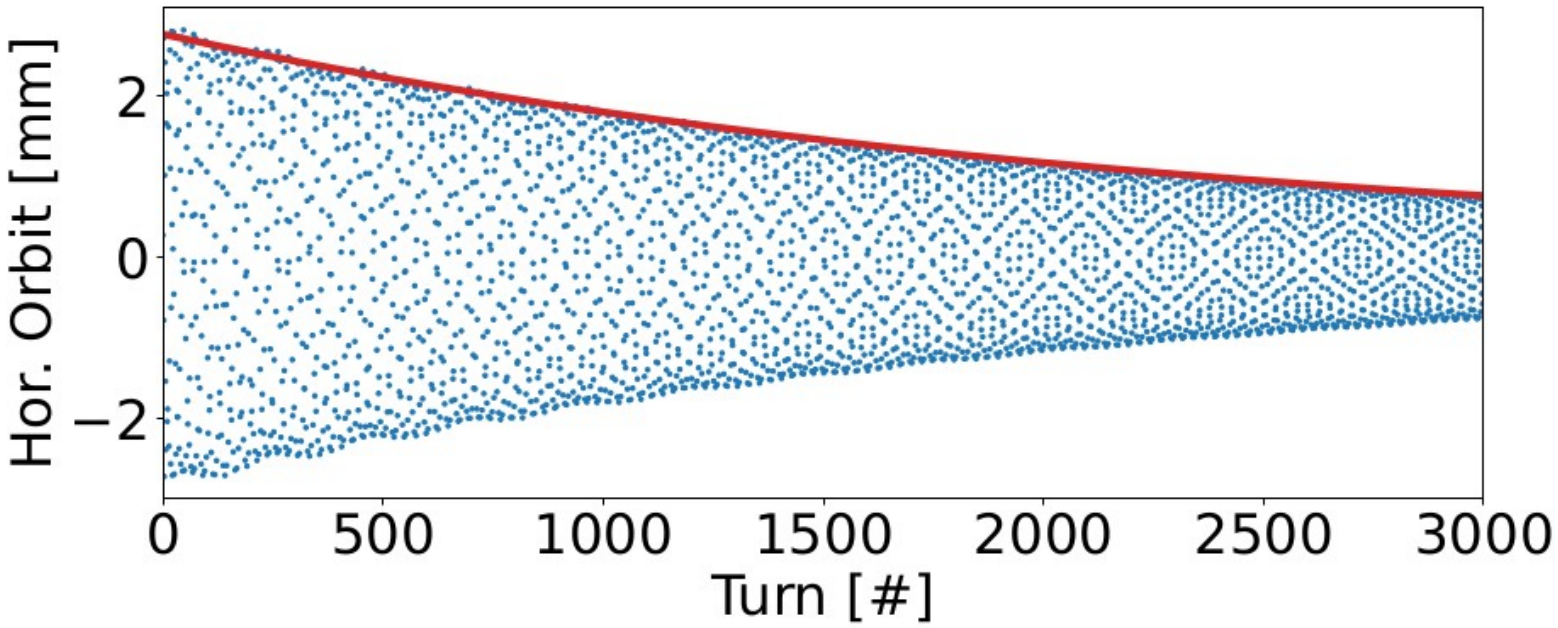
FCC-Z mode with 45.6 GeV beam energy
Single particle tracking in SAD
No radiation damping



Single Kicks for TbT Z-Mode

- Orbit recorded in every turn
- Beam excited
- Orbit damps after single kick
- Equal H and V damping

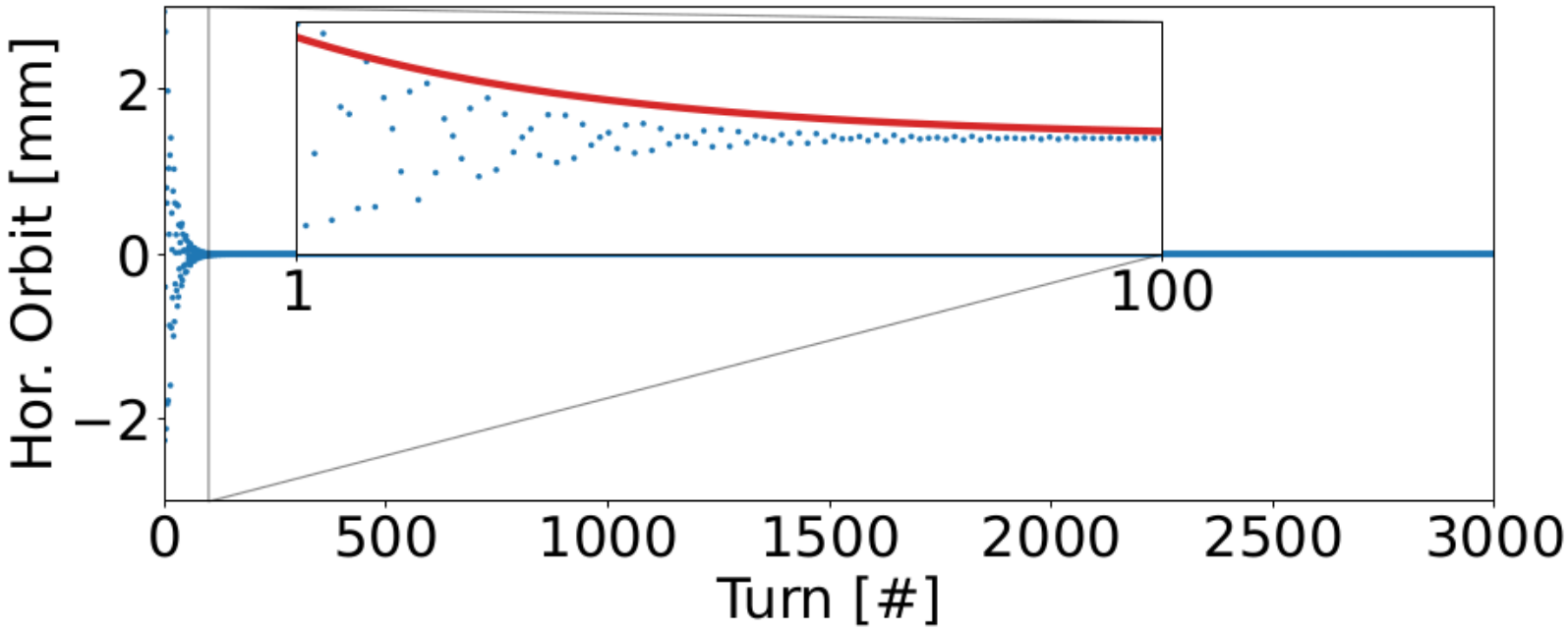
FCC-Z mode with 45.6 GeV beam energy
Single particle tracking in SAD after 6 sigma kick
Damping time about 2300 turns, 40 MeV radiation losses per turn
→ ***Slow enough to be used for optics measurements***



Single Kicks for TbT ttbar-Mode

- Orbit recorded in every turn
- Beam excited
- Orbit damps after single kick
- Equal H and V damping

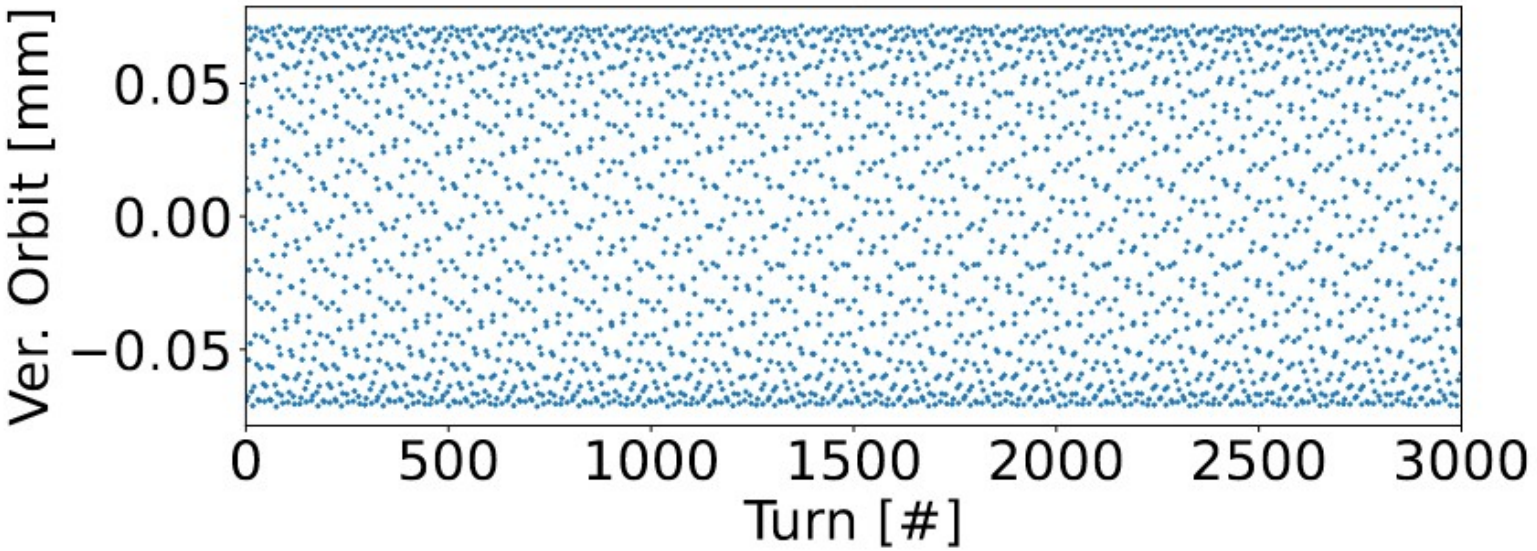
FCC-ttbar mode with 182.5 GeV beam energy
Single particle tracking in SAD after 6 sigma kick
Damping time about 40 turns, 10 GeV radiation losses per turn
→ ***Too fast to be used for optics measurements***



Continous Excitation

- Orbit recorded in every turn
- Beam excited continously
  - Transverse feedback and amplification → Driving on the natural tune

FCC-Z mode with 45.6 GeV beam energy
Single particle tracking in SAD without radiation damping

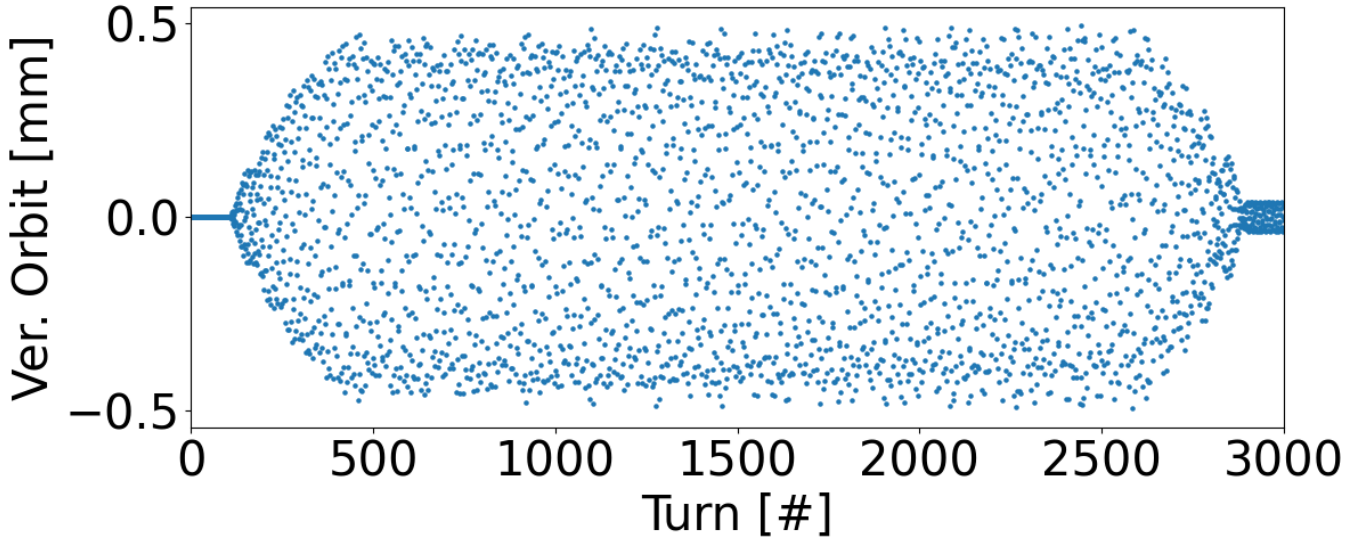


Continous Excitation

- Orbit recorded in every turn
- Beam excited continously
  - Transverse feedback and amplification → Driving on the natural tune
  - AC-Dipole → can also drive at tune different from the natural one
  - Radiation damping remains to be included

FCC-Z mode with 45.6 GeV beam energy
*Single particle tracking in MAD-X **without radiation damping***

$$u(s,N) = \frac{BL}{4\pi\, B\rho\, \delta_u} \sqrt{\beta_u(s)\beta_{u,0}} \times \cos\left(2\pi Q_u^{\mathrm{dr}} N + \phi_u(s) + \phi_{u,0}\right)$$



Harmonics Analysis

- Fourier Transformation including cleaning based on SVD performed
- → Yields tunes, phases between BPMs, amplitudes, noise estimates, …
- Optics then measured using harmonics analysis output

SuperKEKB electron ring
SVD cut of 20 modes

Fewer modes: Less noise, might loose some information

More modes: More noise, lower risk of loosing information