FUTURE CIRCULAR COLLIDER

Measurement Techniques

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On behalf of the FCC-ee Optics Tuning Team

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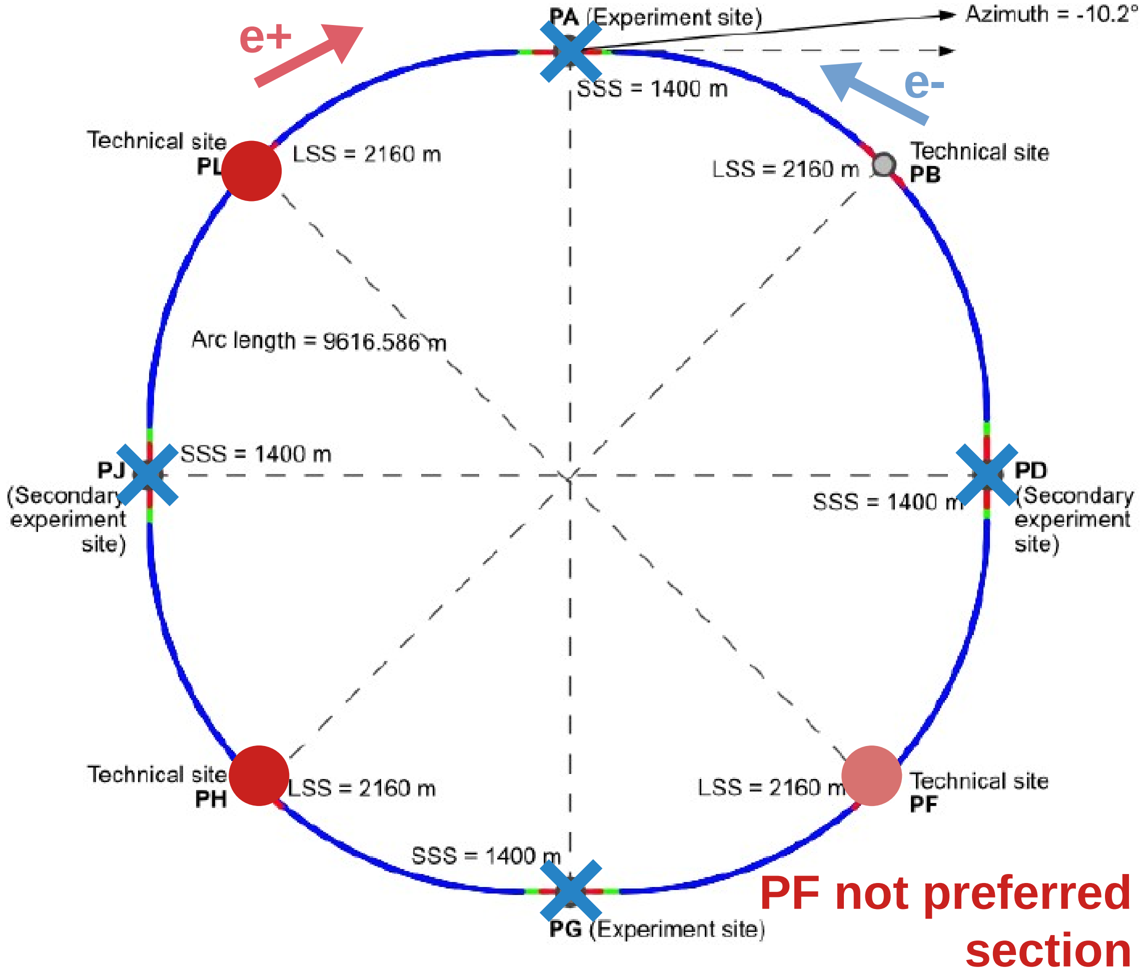
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

Motivation

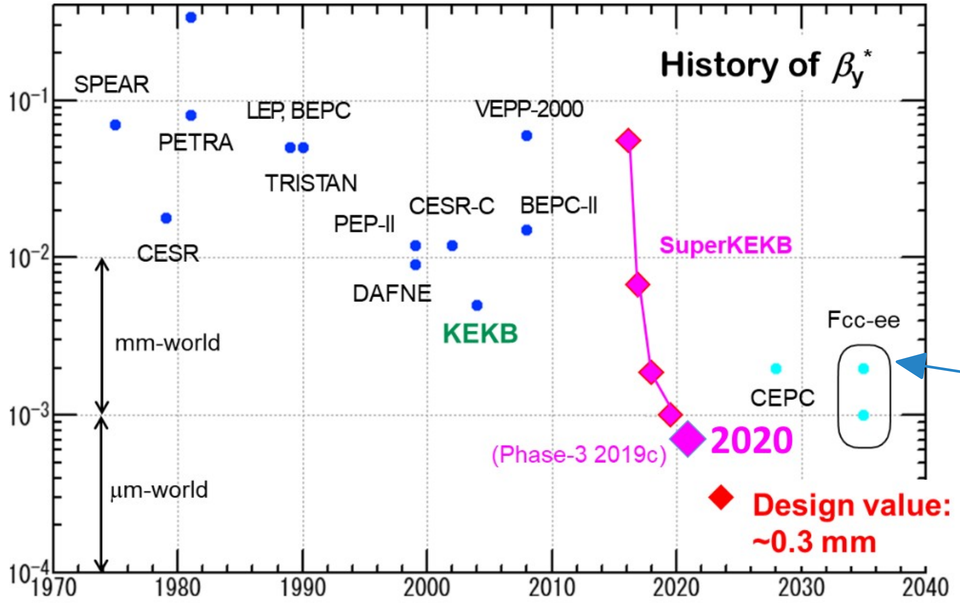
- FCC-ee designed with 4 IPs (✕)
- 4 different energies
  - Z: 45.6 GeV, 1 RF
  - W: 1 RF
  - H: 1 RF
  - ttbar: 2 RFs
- Demands precise optics control
- → Optics measurements and corrections
- → Evaluation of best suitable techniques
- → A lot to be learned from existing facilities such as SuperKEKB, etc.



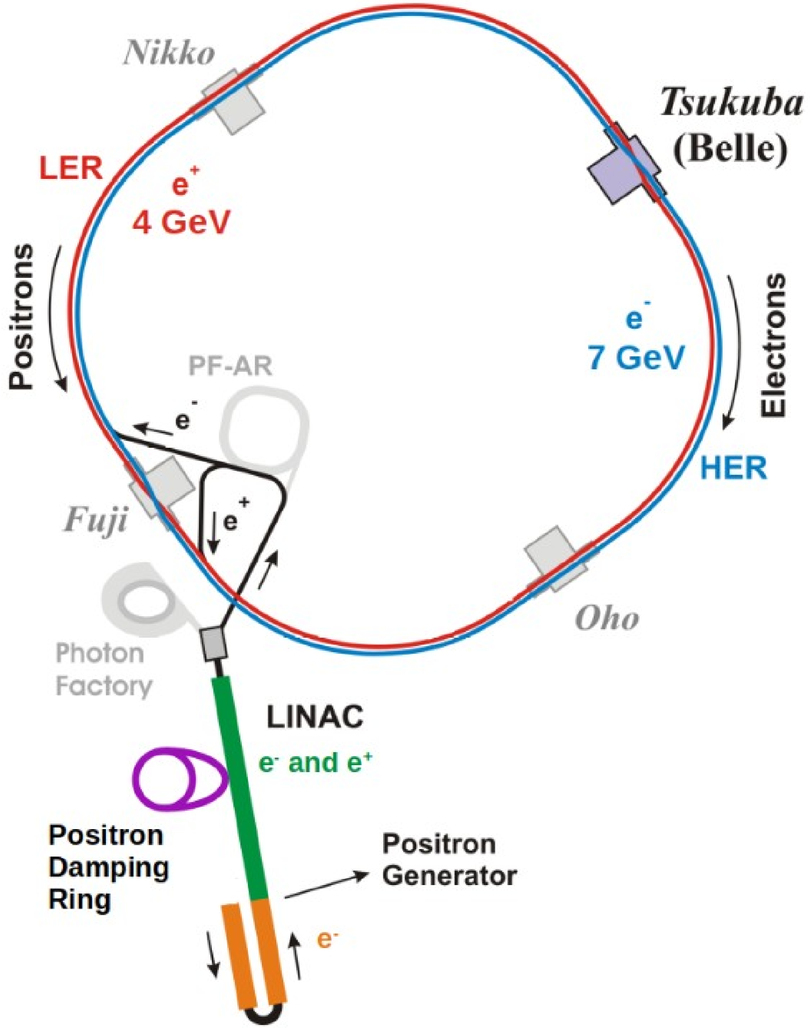
SuperKEKB

- Lepton double ring collider and 1 interaction point
- 7 GeV electron ring (HER)
- 4 GeV positron ring (LER)
- Record low β_y^* of 0.8 mm

SuperKEKB is a small FCC



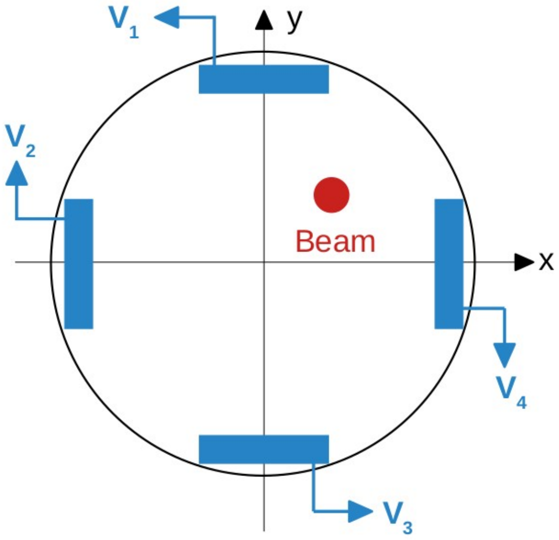
Lowest βy for FCC-ee already reached in SuperKEKB*



Beam Position Monitors I

- Crucial devices which record the centroid orbit data of a particle bunch
- Pick-ups most common type, electrode locations different, e.g:

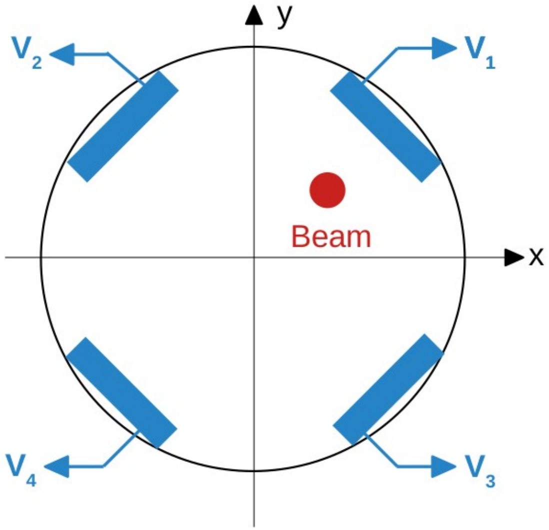
LHC:



$$x = \frac{V_1 - V_3}{V_1 + V_3}$$

$$y = \frac{V_4 - V_2}{V_4 + V_2}$$

SuperKEKB:



$$x = \frac{V_1 + V_4 - (V_2 + V_3)}{V_1 + V_2 + V_3 + V_4}$$

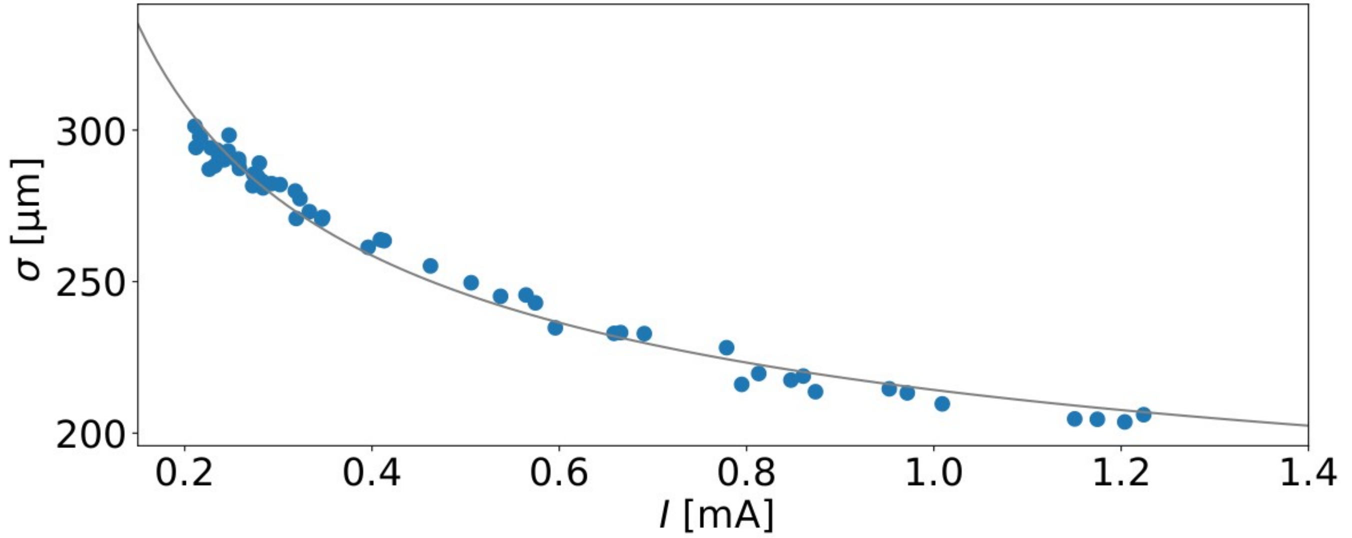
$$y = \frac{V_1 + V_2 - (V_3 + V_4)}{V_1 + V_2 + V_3 + V_4}$$

Beam Position Monitors II

- Resolution also depends on number of bunches and bunch populations
- Improves for
  - Using average over several turns compared to Turn-by-Turn measurements
  - Higher bunch current
  - More bunches
- Other imperfections affect signal
  - Non-linearity, calibration, etc.
- Typically installed next to quadrupoles

Assuming a BPM next to every quadrupole would require about 1800 BPMs

Single bunch measurements for SuperKEKB positron ring with 4 GeV



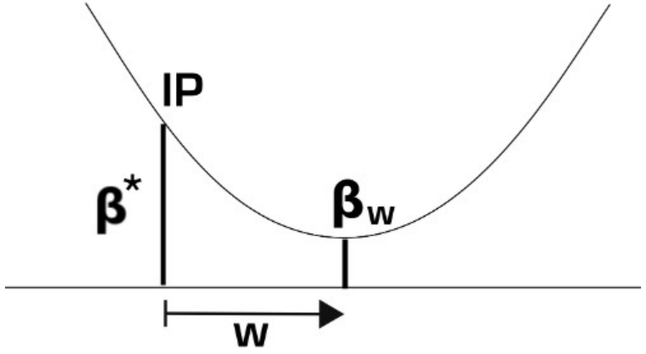
K-Modulation

- Successfully performed in SuperKEKB, LHC, …
- Used to determine β* by varying quadrupole strength
- β-function at quadrupoles estimated by tune change

ΔKL … relative change of integrated quadrupole strength
ΔQ … relative change of tune

$$\overline{\beta} \approx \pm \frac{4\pi \Delta Q}{\Delta KL}$$

Minimum β-function not always at IP but shifted by waist w



- β_w propagated from β_0 at the final focus quadrupoles and β* given by $\beta^* = \beta_w + \frac{w^2}{\beta_w}$

L … distance from IP to first quadrupole*

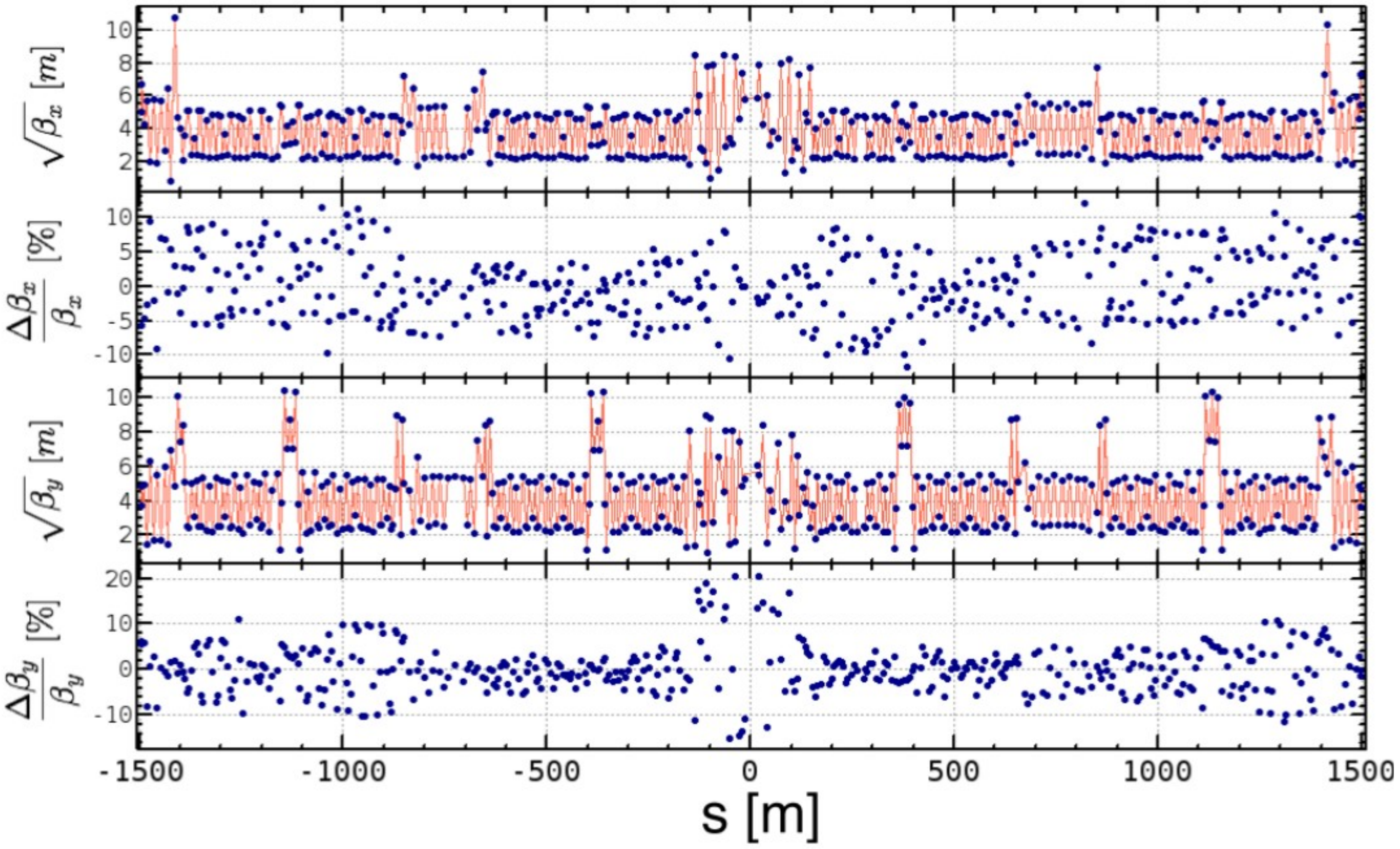
$$\beta_0 = \beta_w + \frac{(L^* \pm w)^2}{\beta_w}$$

- Main limitation is tune accuracy measurement

P. Thrane et al., Phys. Rev. Accel. Beams 23, p. 012803, 2020.
P. Thrane et al., CLIC-Note-1077, 2017.

Closed Orbit Distortion

- SuperKEKB 3 pairs of orbit correctors generate redundant set of 6 closed orbit distortions
- Average orbit over several turns
- Large matrix generated
- Optics retrieved by analytical equations
-
- **Rather time consuming** (20 mins in SuperKEKB)
- **Impact of radiation damping in FCC-ee needs to be evaluated**

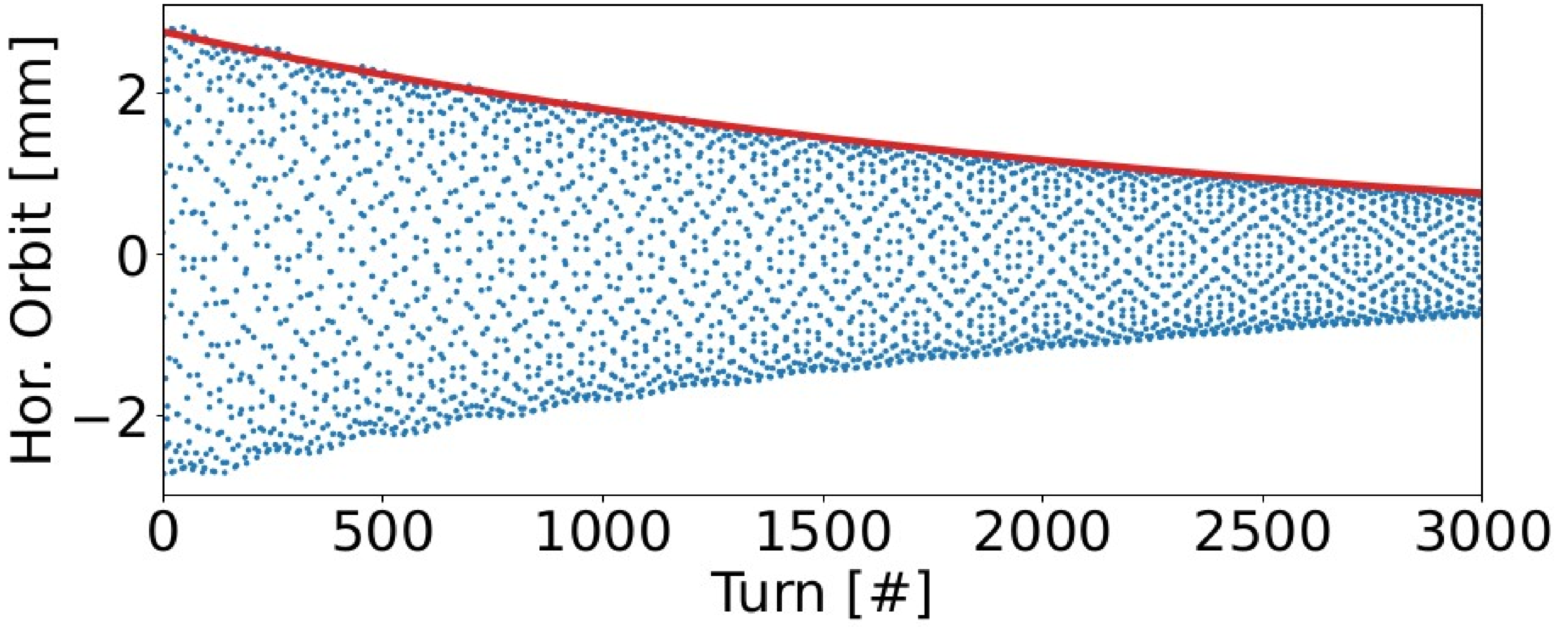


Y. Ohnishi et al., IPAC'16, THPOR007, 2016.

Single Kicks for TbT Z-Mode

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

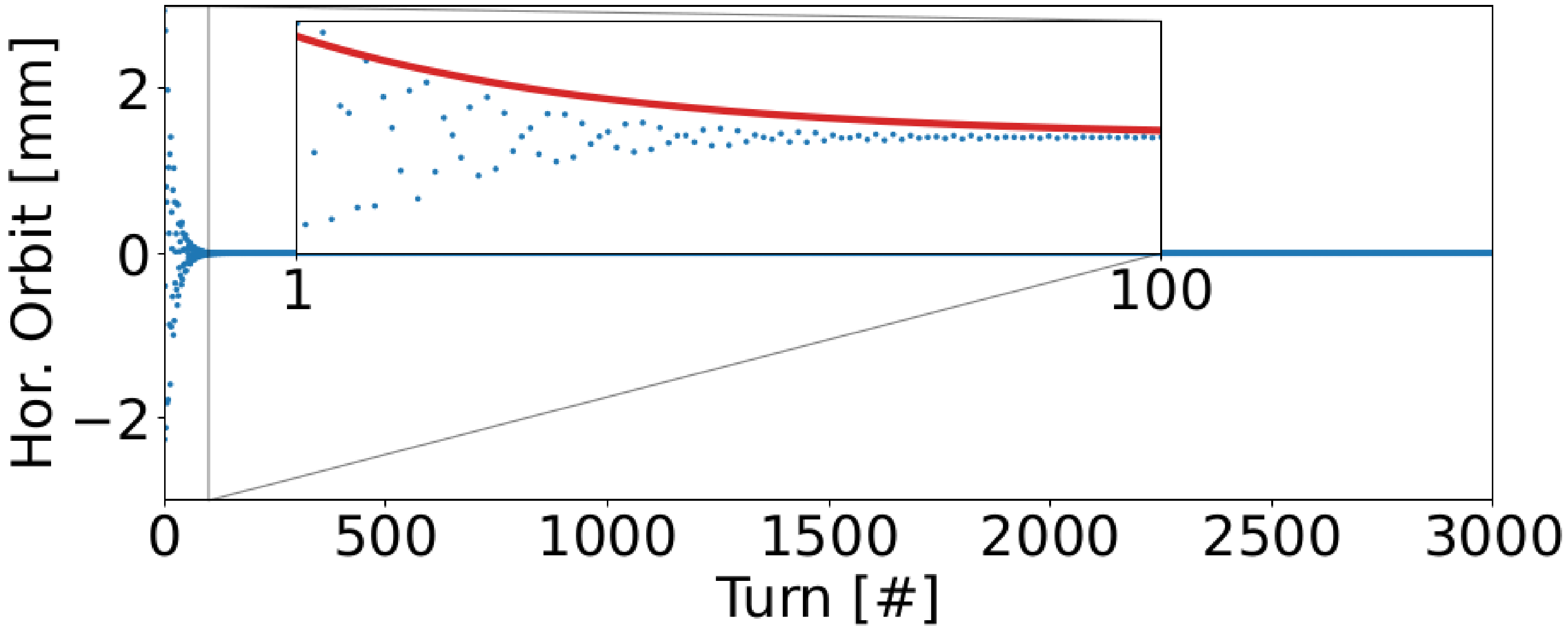
FCC-Z mode with 45.6 GeV beam energy
Single particle tracking in SAD after 6 sigma kick
Damping time about 2300 turns, 40 MeV radiation losses per turn
→ ***Slow enough to be used for optics measurements***



Single Kicks for TbT ttbar-Mode

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

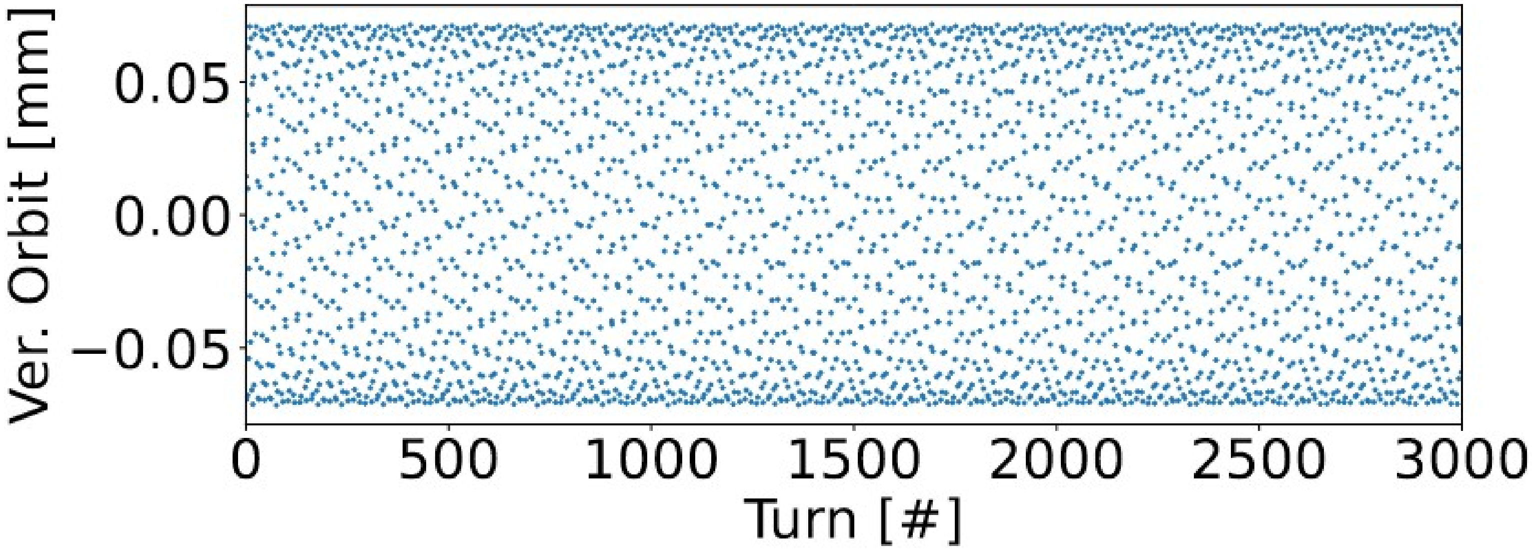
FCC-ttbar mode with 182.5 GeV beam energy
Single particle tracking in SAD after 6 sigma kick
Damping time about 40 turns, 10 GeV radiation losses per turn
→ ***Too fast to be used for optics measurements***



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

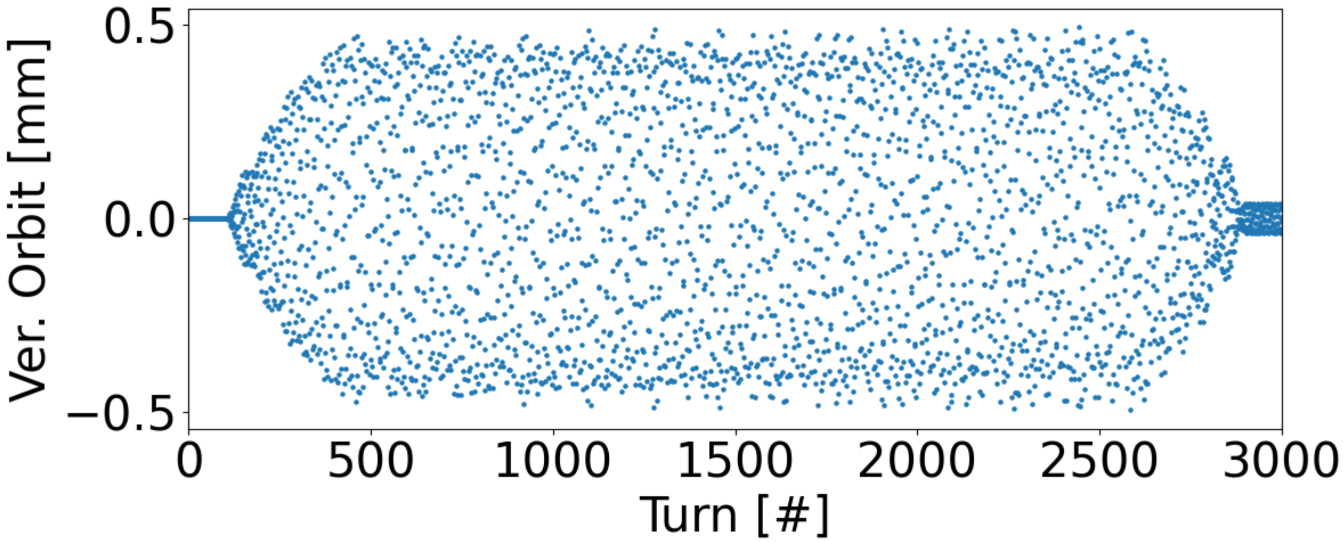


Continous Excitation

- 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***

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



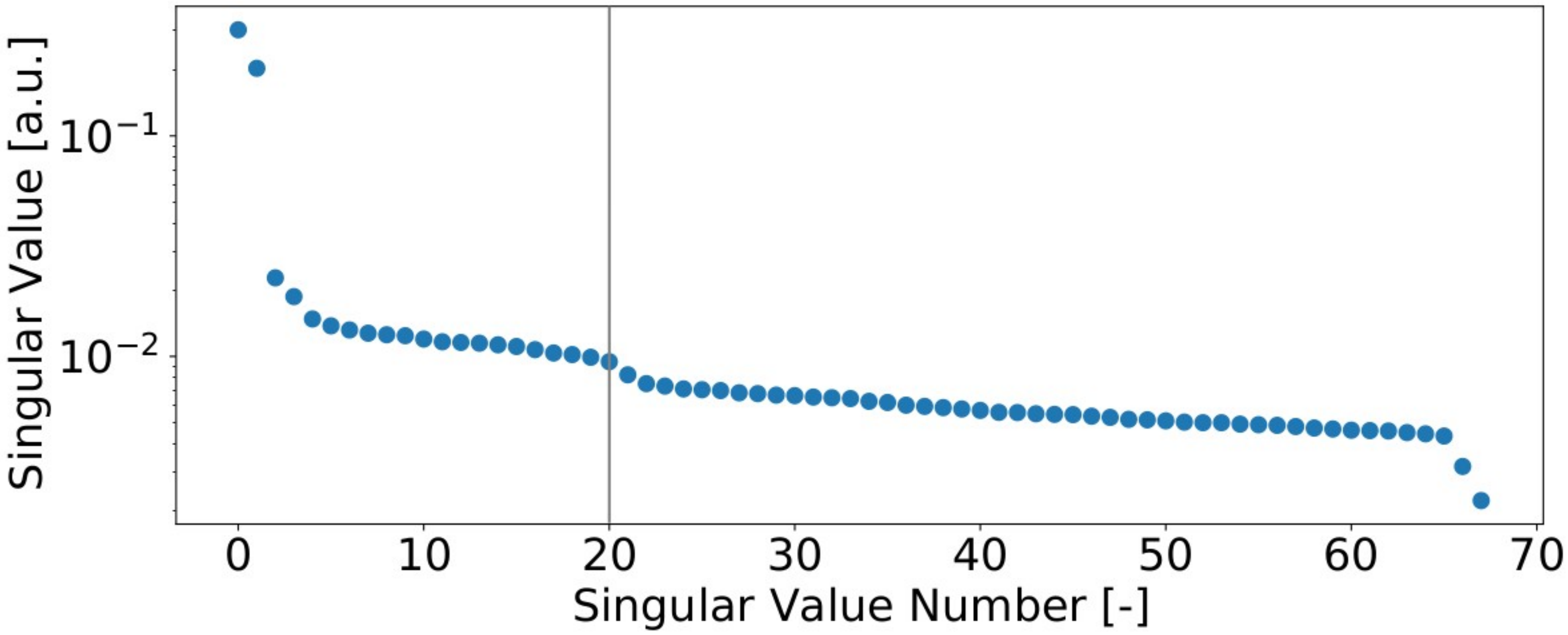
Harmonics Analysis

- 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

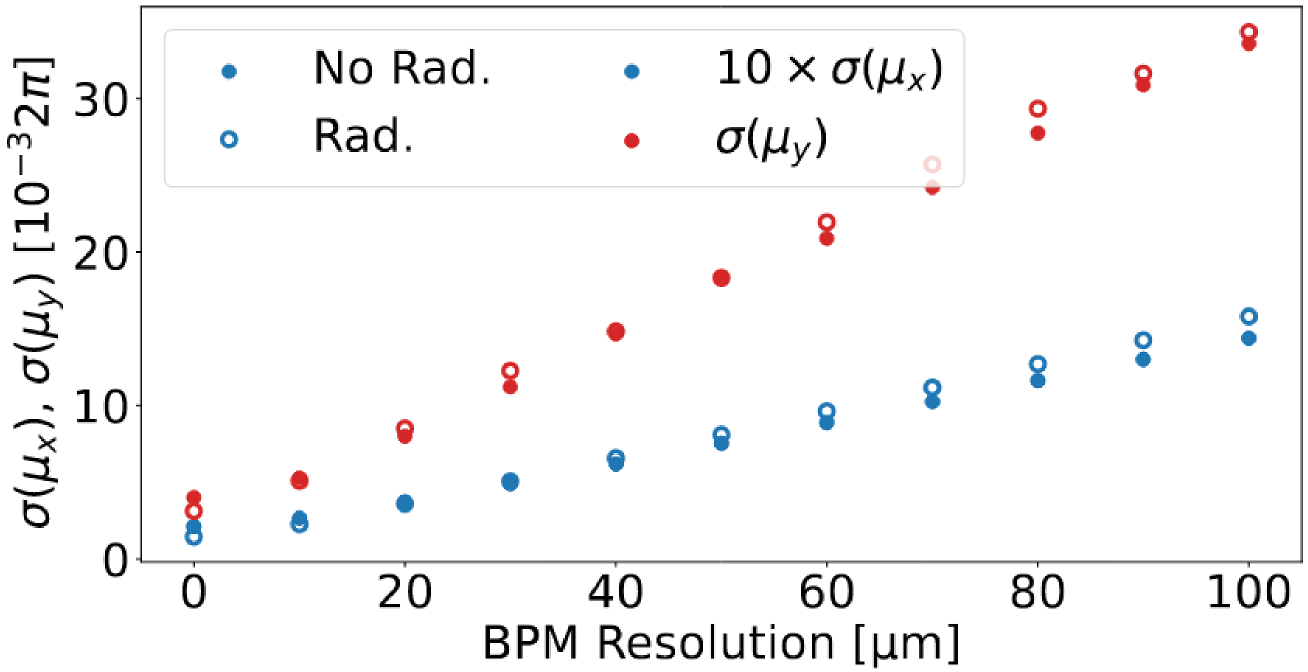
More modes: More noise, lower risk of loosing information



Phase Error

- Relative rms phase advance error figure-of-merit for measurement quality
- Error increases with BPM noise
- 500 turns, only 350 BPMs, 1 seed → to be improved in future studies
- Kick amplitude 6 σ_x, σ_y
- Effect of radiation damping negligible
- BPM noise 20 times larger for vertical plane

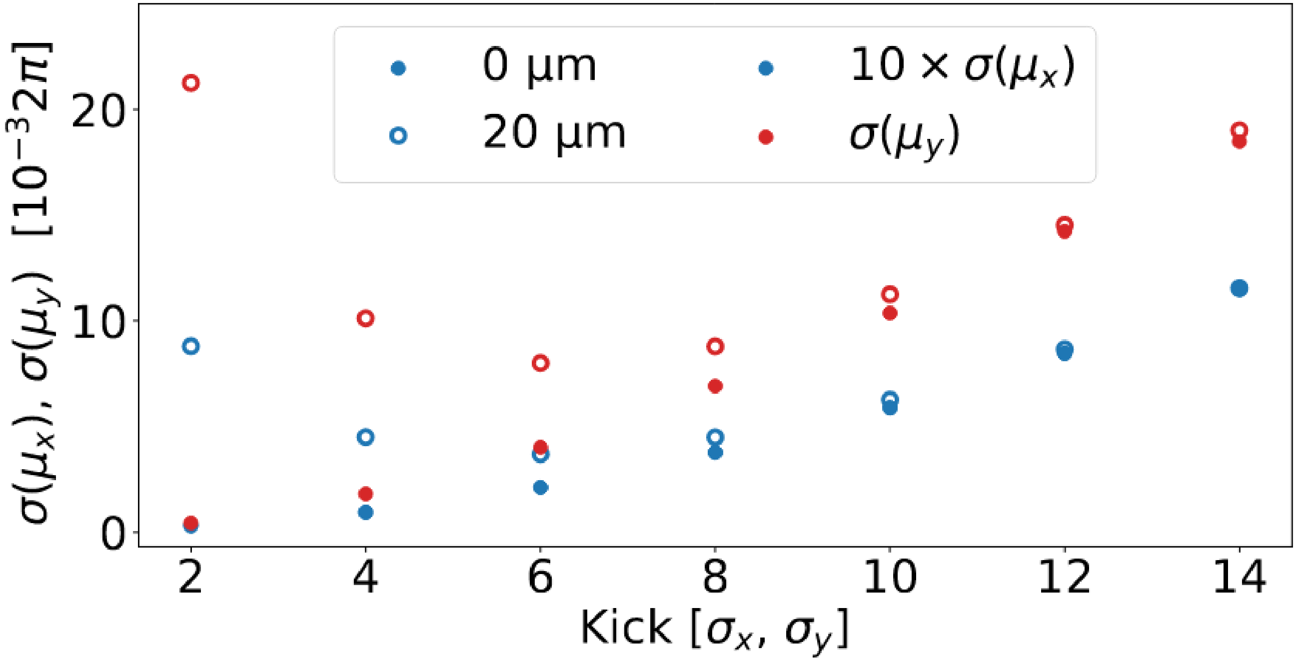
FCC-Z mode with 45.6 GeV beam energy
Single particle tracking in SAD



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

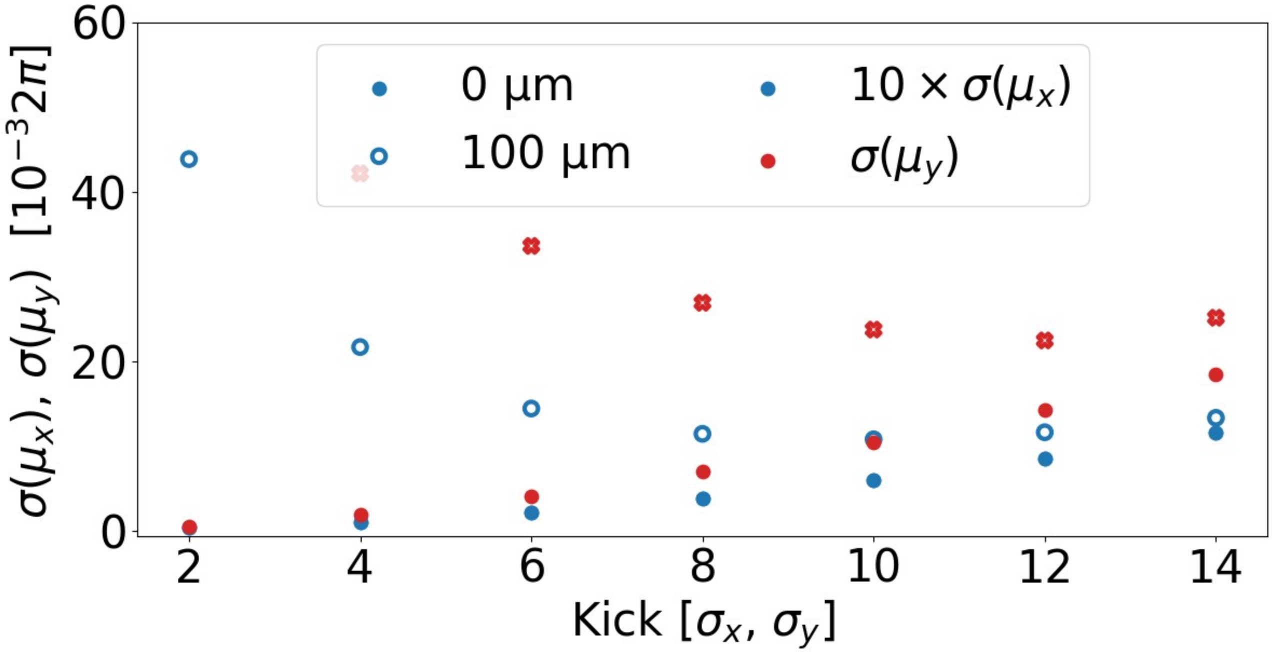
FCC-Z mode with 45.6 GeV beam energy
Single particle tracking in SAD
No radiation damping



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

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



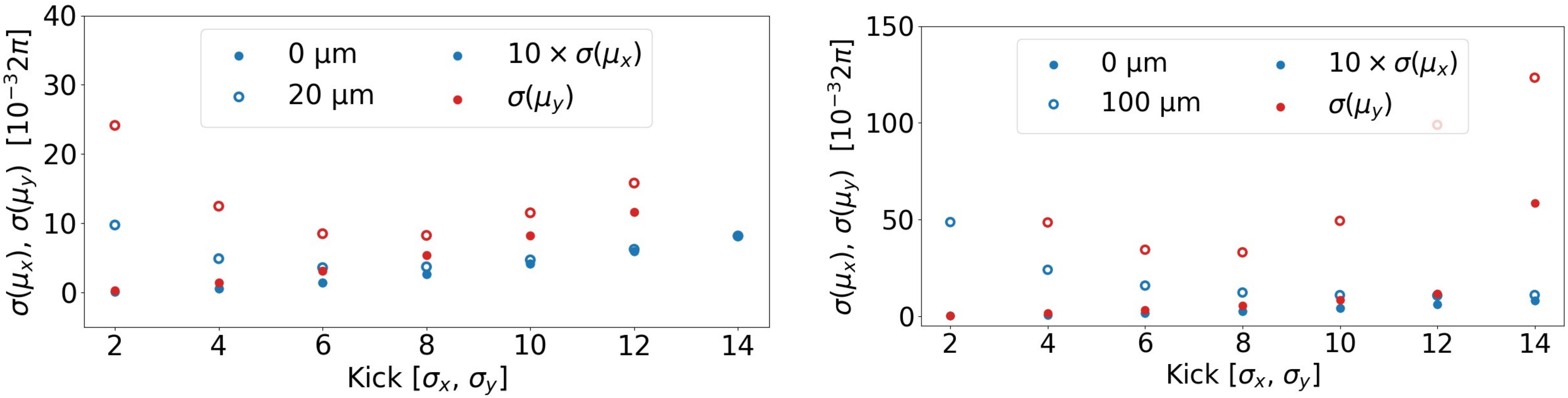
Amplitude must be large enough to compensate for BPM noise

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

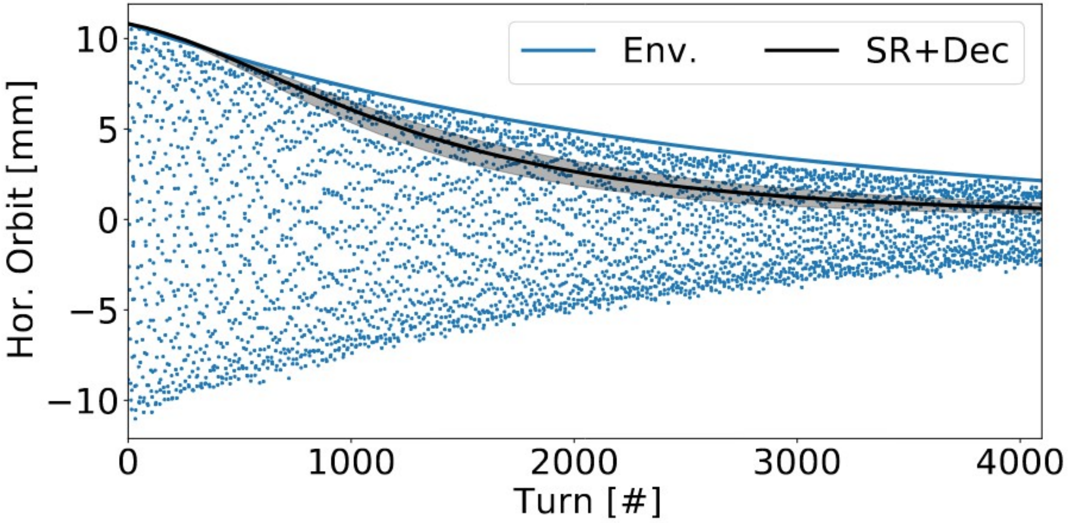
The optimum kick strength changes if single kicks and damping or constant amplitude is used for optics measurements



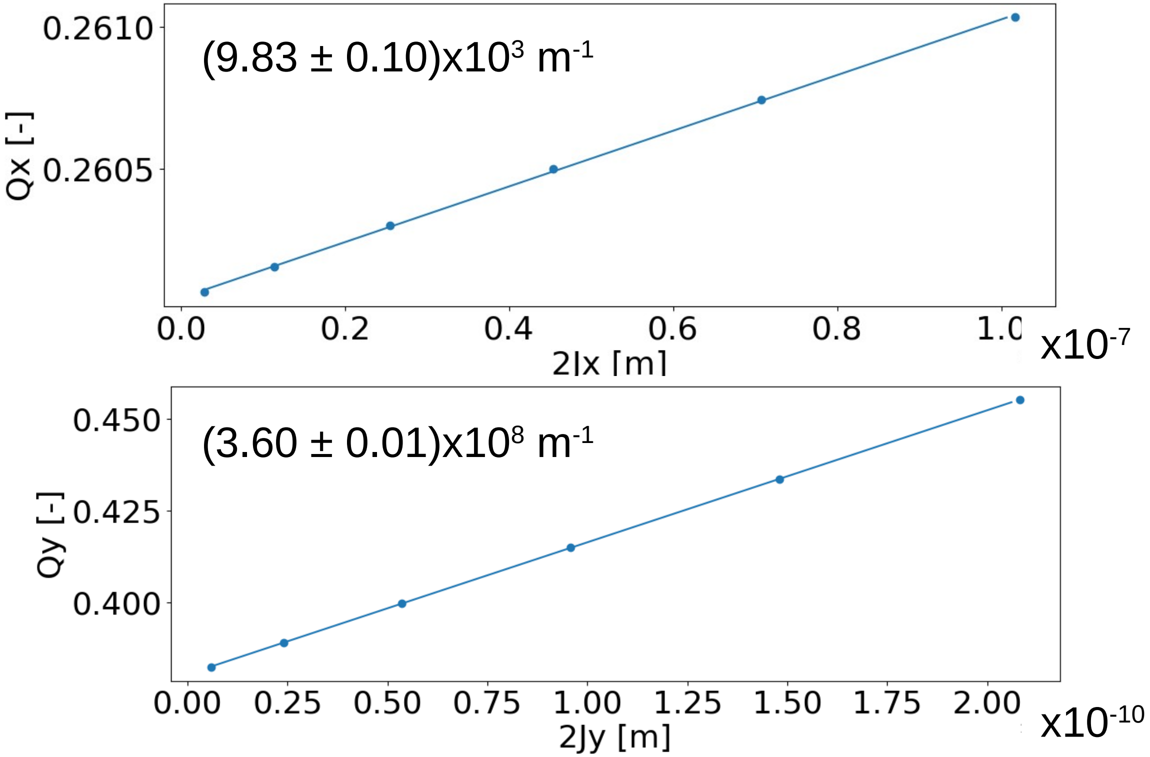
Single Kicks in SuperKEKB

- In addition to radiation damping orbit affected by decoherence, head-tail, etc.
- Method to measure decoherence from one single TbT file with damping developed
- Applicable for FCC-ee
- Understanding SuperKEKB essential

TbT single bunch orbit SuperKEKB positron ring



FCC-Z mode amplitude detuning



Summary and Outlook

- First promising studies for TbT measurements in FCC-ee
- Strong synchrotron radiation damping influences measurement techniques
- Lessons to be learned from existing machines such as SuperKEKB

- Future studies:
  - AC-dipole with synchrotron radiation for particle tracking
  - Use AC-dipole tracking data with compensation techniques for optics measurements
  - Run more seeds and more BPMs for more realistic estimates on accuracy
  - See impact of field and misalignment errors on measurement techniques
  - Combine measurement techniques with tuning algorithms
  - ...

Thank you!

Measurement Techniques

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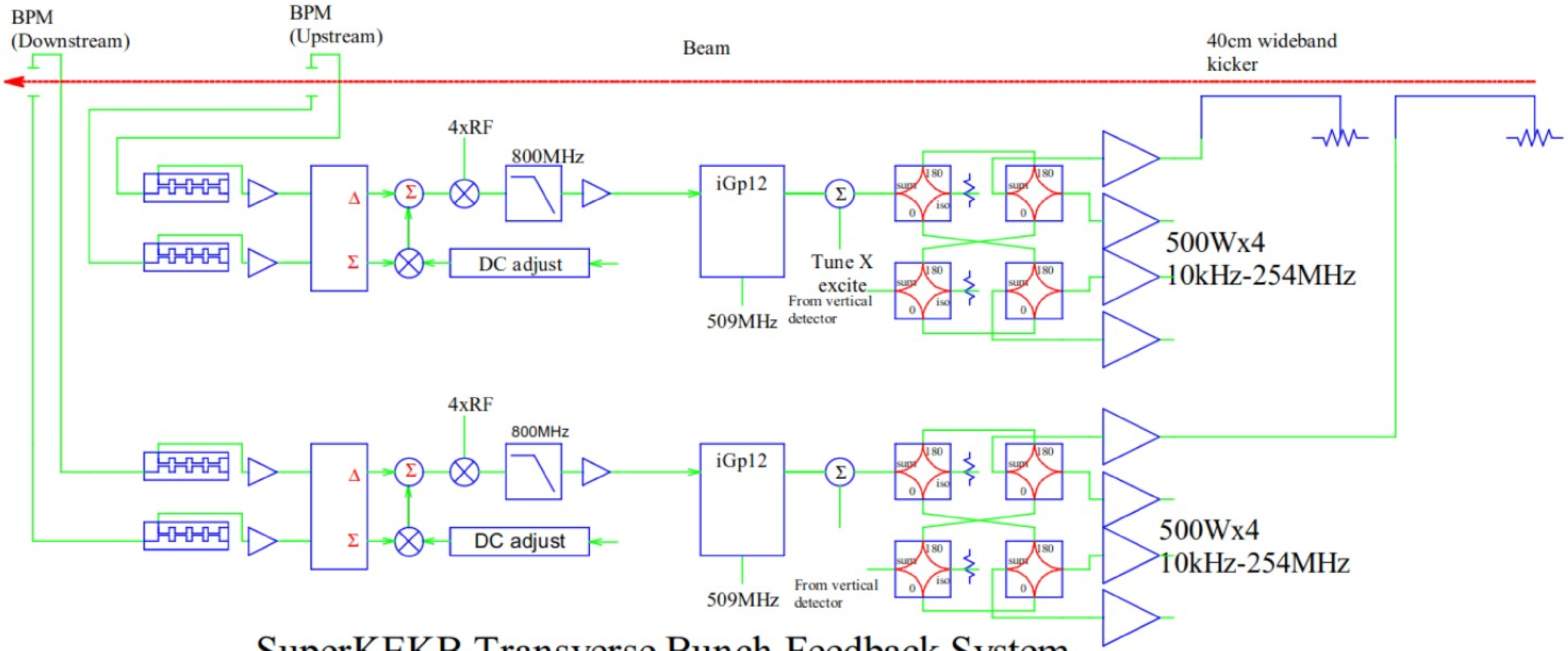
Transverse Feedback System



SuperKEKB Transverse Bunch Feedback System