Optics measurements at SuperKEKB

Jacqueline Keintzel

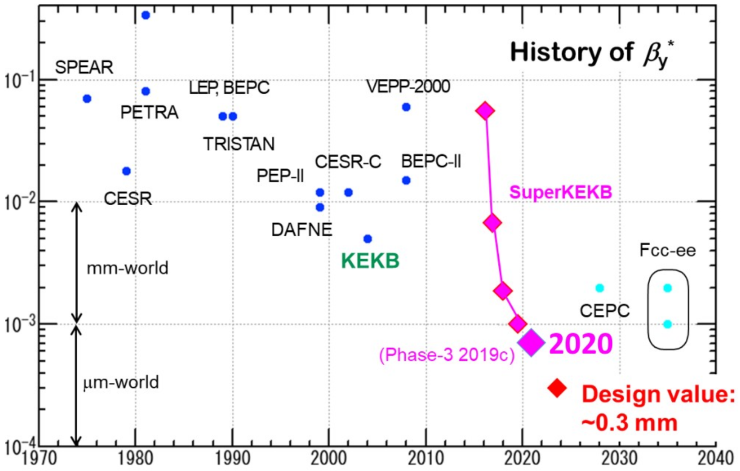
Acknowledegements:
M. Benedikt, Y. Funakoshi, T. Ishibashi, H. Koiso, G. Mitsuka, A. Morita, Y. Ohnishi, K. Ohmi, K. Oide, S. Terui, M. Tobiyama, H. Sugimoto, R. Tomás, R. Yang, F. Zimmermann, D. Zhou

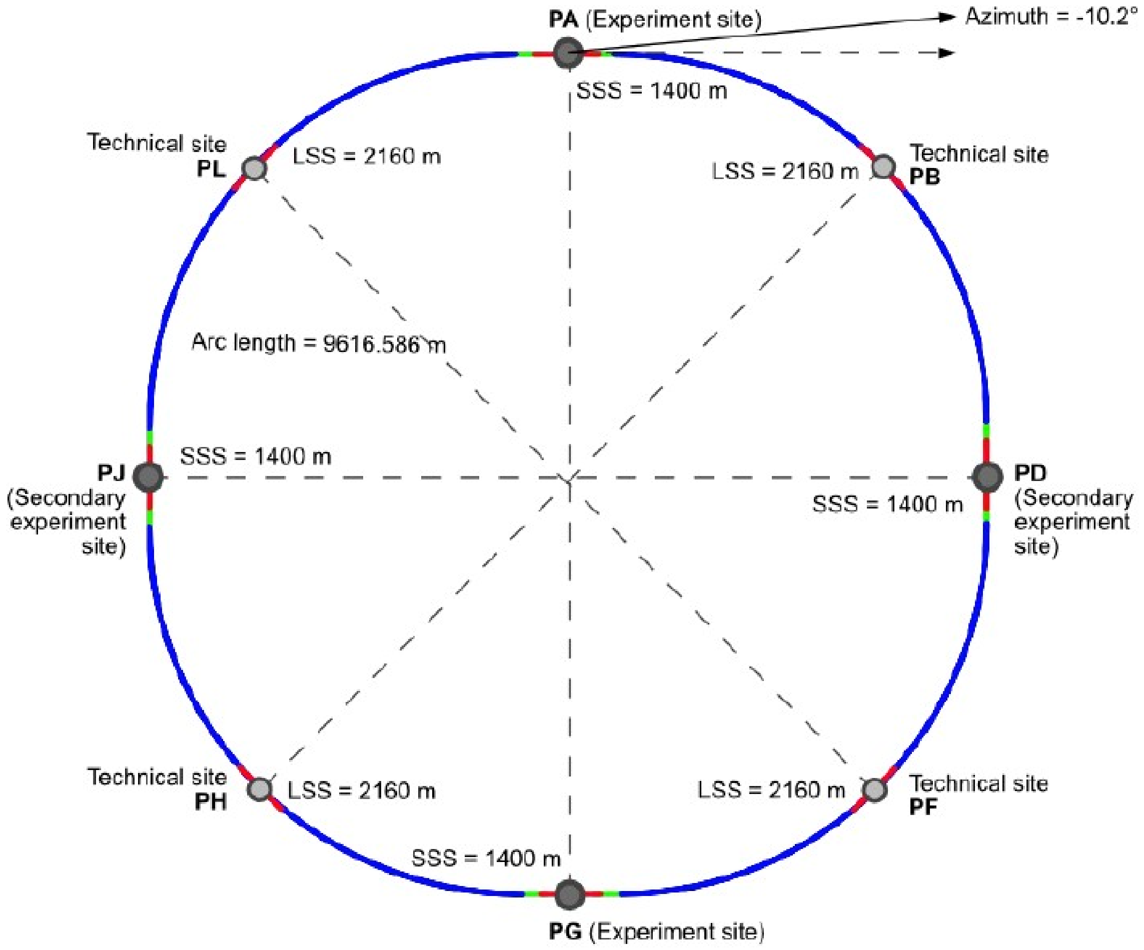
FCC WP 2 Workshop
Optics Correction and Beam Measurement
6th December 2021

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.

FCC-ee

- Electron-positron double ring collider
- Virtual crab-waist collision scheme
- -I transformation between sextupoles
- Top-up injection at collision energy
- Record low βy* of 0.8 mm





K. Oide, https://indico.cern.ch/event/1077162/, 2021.

SuperKEKB – A small FCC-ee?

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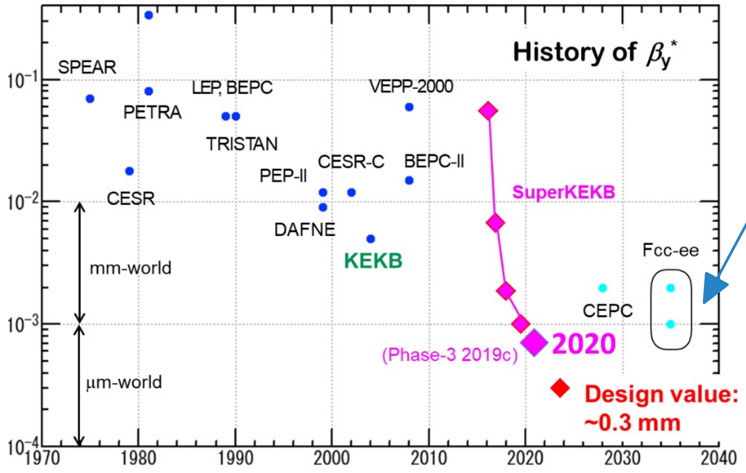
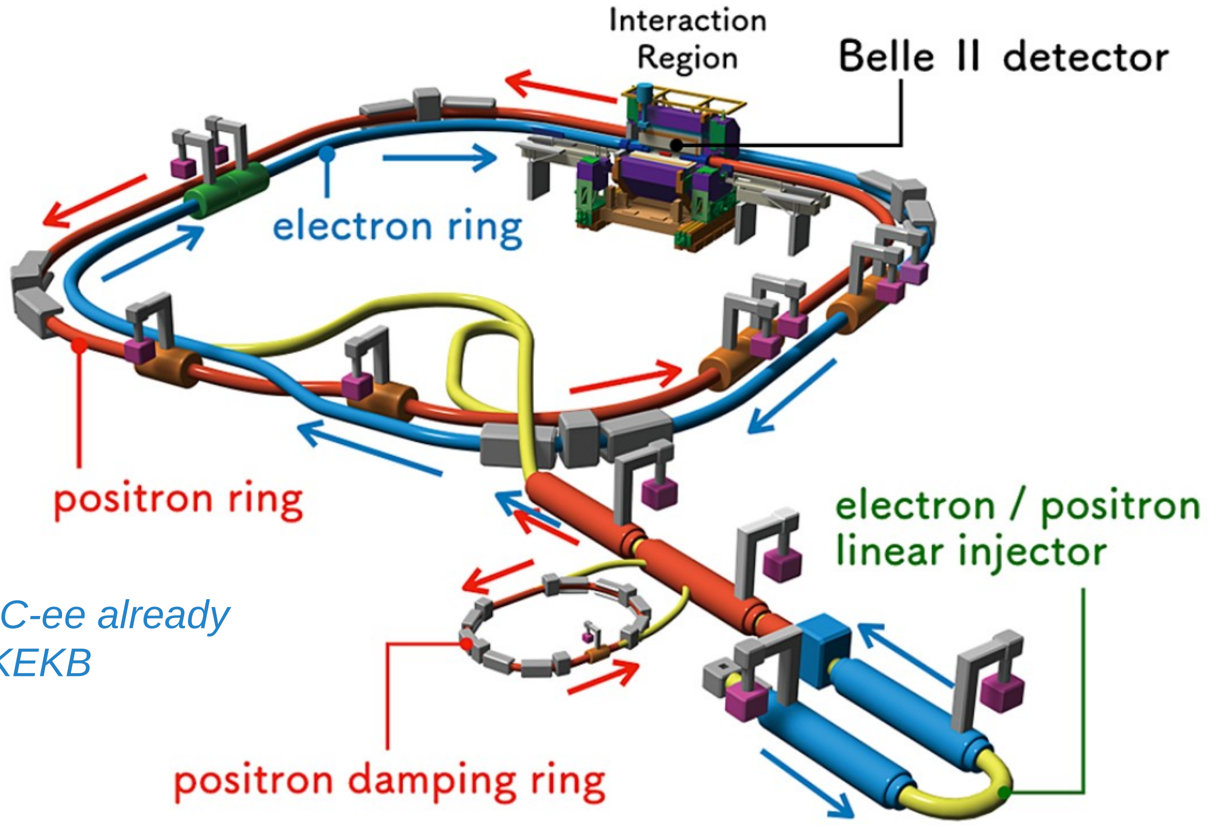


Lowest βy for FCC-ee already reached in SuperKEKB*



SuperKEKB is a small version of FCC-ee!
Understanding SuperKEKB essential for FCC-ee!

K. Akai et al., SuperKEKB Collider, arXiv:1809.01958v2, 2018.

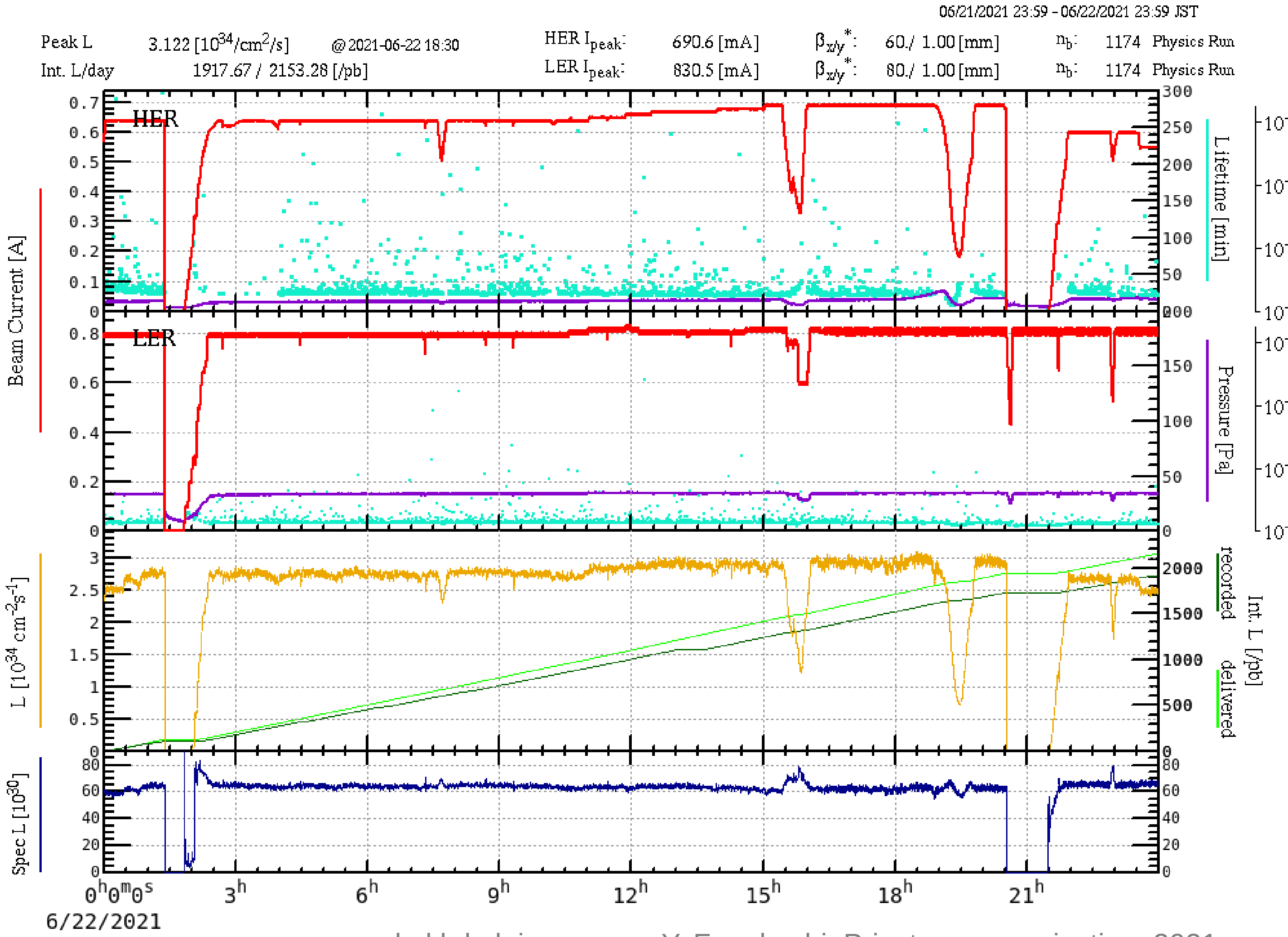
Record Luminosity

- Positron ring with 4 GeV (LER) and $\beta x^*/\beta y^*$ = 80/1 mm with 80% CW
- Electron ring with 7 GeV (HER) and $\beta x^*/\beta y^*$ = 60/1 mm with 40% CW

- Record luminosity in June 2021
- About **3.1 x 10^{34} cm^{-2}s^{-1}**

- Specific luminosity defined as

$$L_{SP} = \frac{L}{n_b I_+ I_-}$$

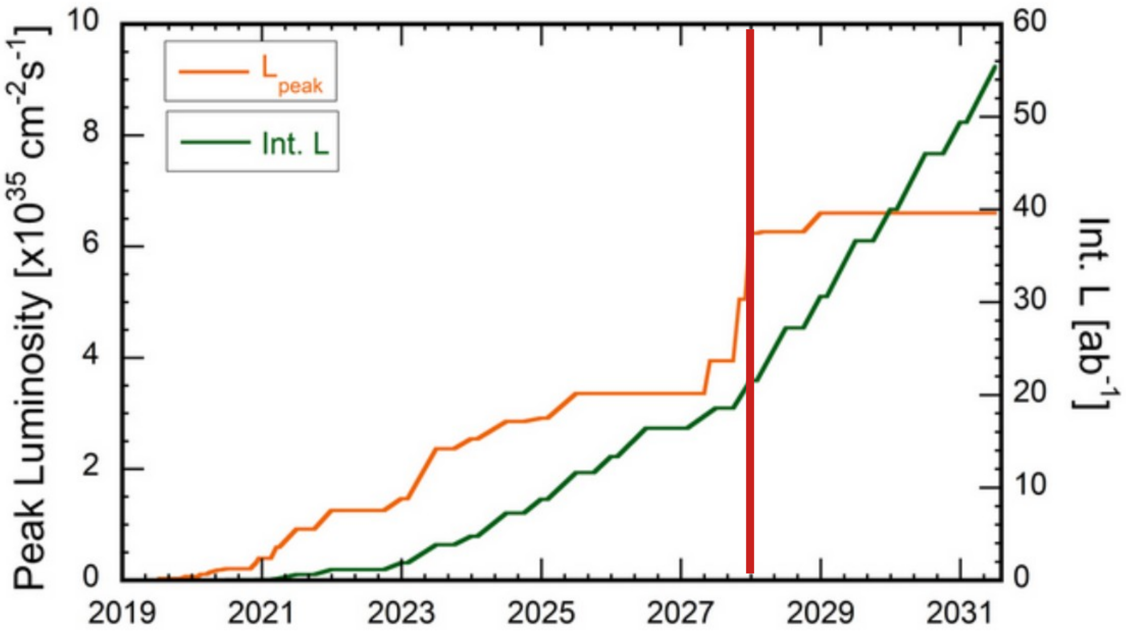


www-superkekb.kek.jp Y. Funakoshi, Private communication, 2021.

SuperKEKB Goals

- 3 times lower βy* functions
- 20 times higher luminosity

*An **international task force** has been formed to help achieving design goals in various subgroups*
Kick-off meeting in July 2021:
https://kds.kek.jp/event/38899/



Design goal foreseen around 2028

www-superkekb.kek.jp

Parameter	June 2021		Design	
	LER	HER	LER	HER
Beam energy [GeV]	4	7	4	7
Number of bunches [-]	1174		1761	
Beam current [mA]	790.3	686.6	2800	2000
β_x^* [mm]	80	60	32	25
β_y^* [mm]	1	1	0.27	0.3
σ_x^* [µm]	24	22	10.1	10.7
σ_y^* [µm]	0.26	0.23	0.048	0.062
$\mathcal{L}_{\max}$ $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	3.12		60	

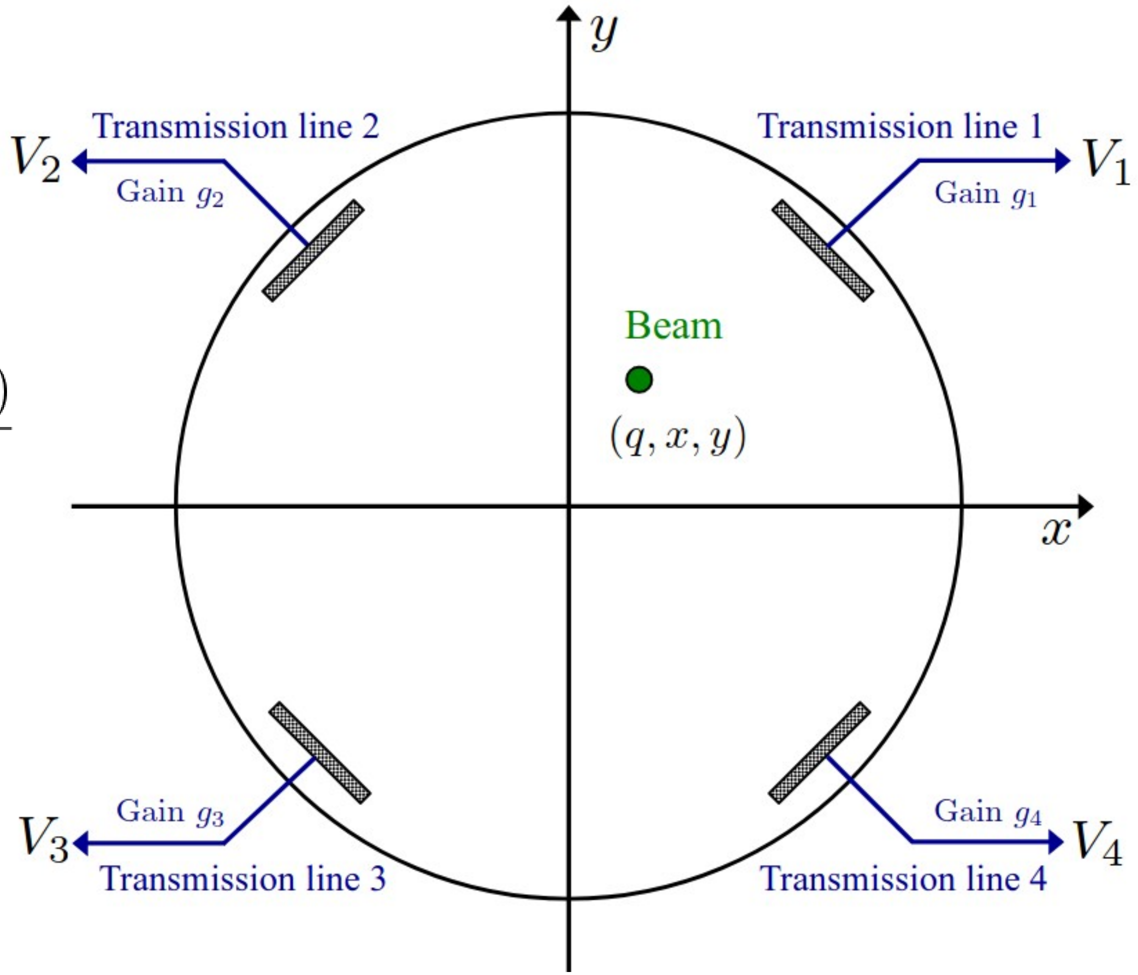
N. Taniguchi, kds.kek.jp/event/34739, 2020. Y. Funakoshi, Private communication, 2021.

Optics Measurements

- Beam Position Monitors (BPMs) crucial
- Axis rotated by 45° due to synchrotron radiation
- Record horizontal and vertical orbit by

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

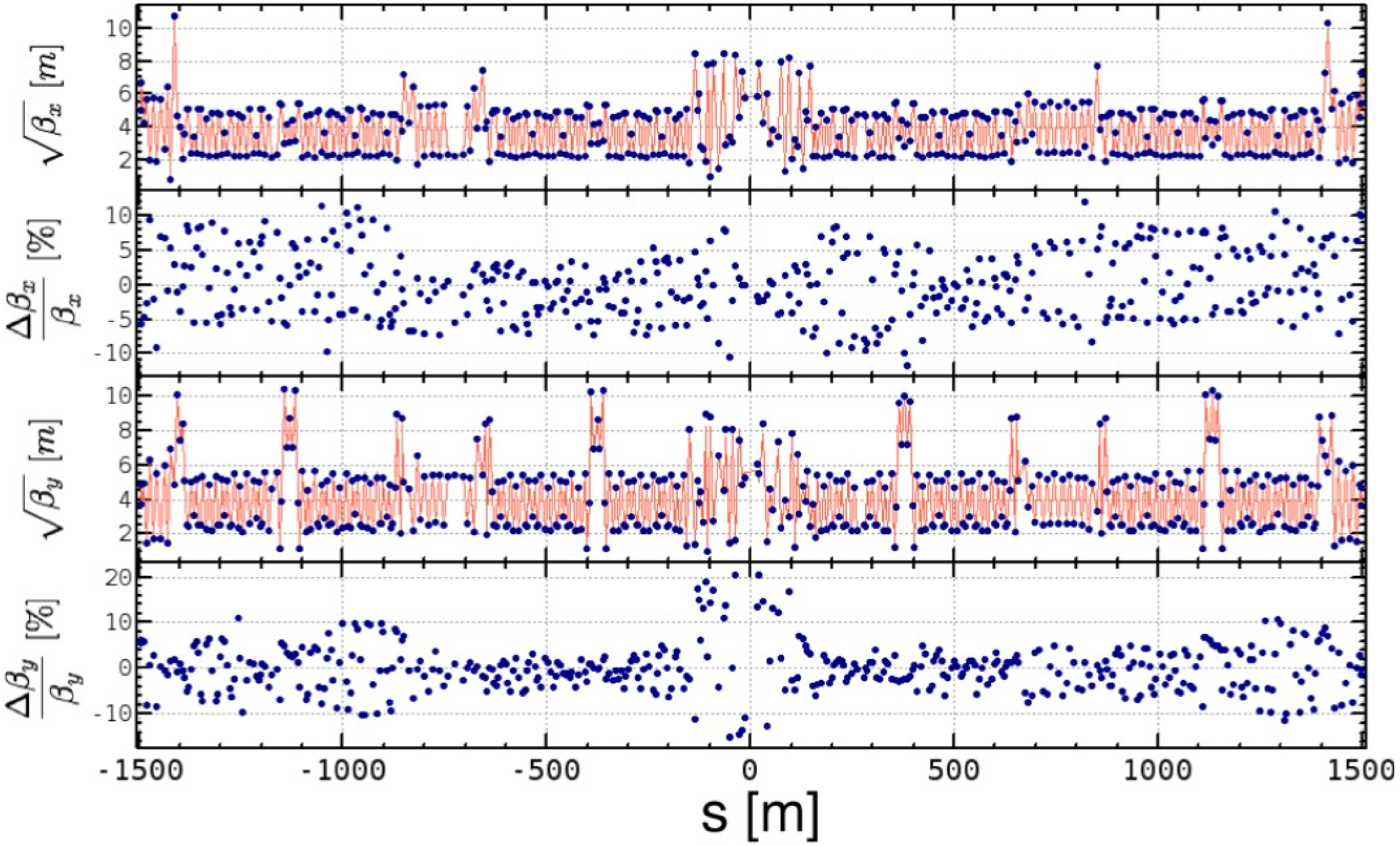
- Two recording possibilities
  - Average for Closed Orbit Distortion (COD)
  - Turn-by-Turn mode (TbT)



H. Sugimoto et al., IPAC'19, TUZPLM2, 2019.

Closed Orbit Distortion

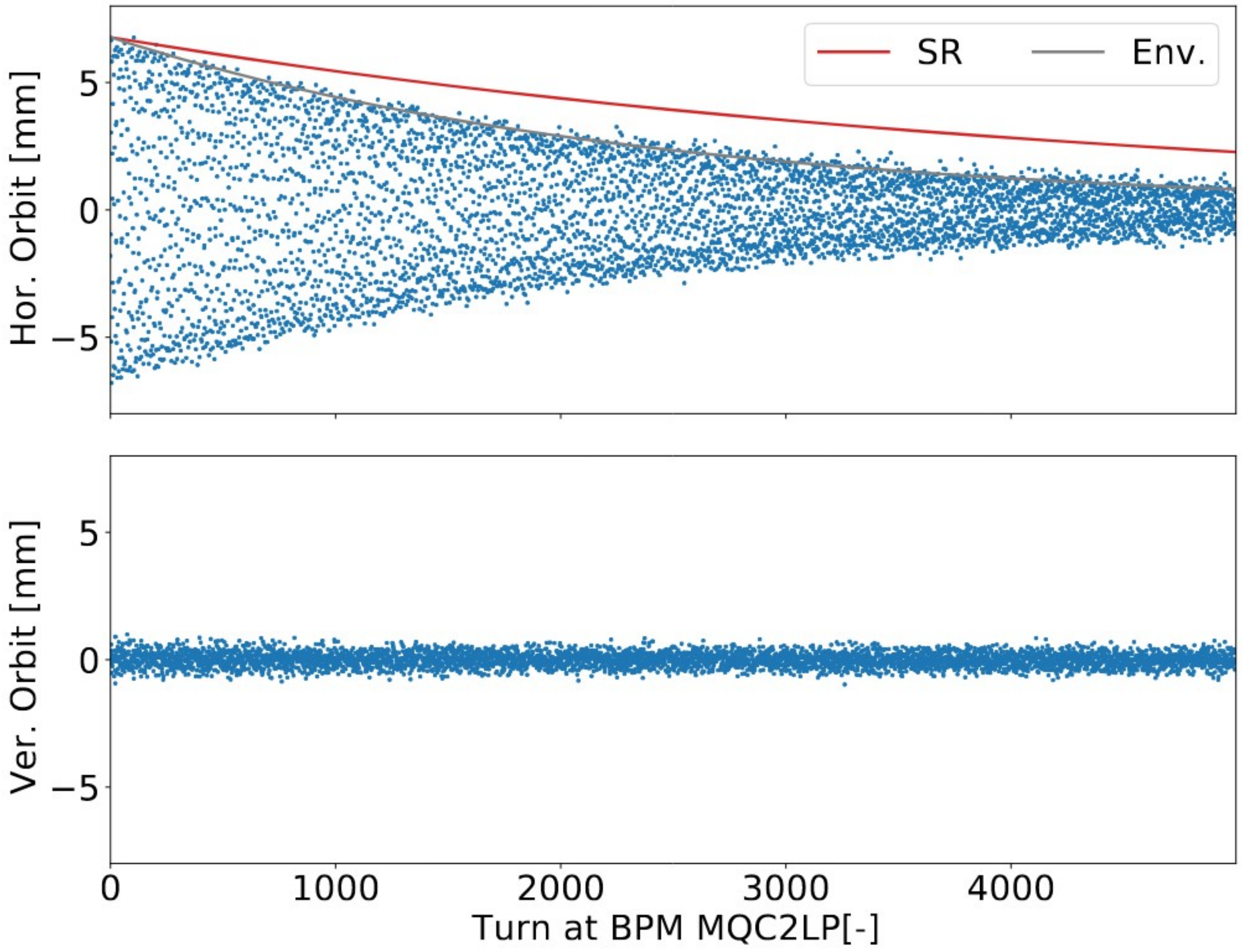
- 3 pairs of orbit correctors generate redundant set of 6 closed orbit distortions (CODs)
- Average orbit over several turns are recorded at about **450 BPMs**
- Large matrix generated
- Optics retrieved by analytical equations
- Optics measurements with COD used for optics corrections
- Regularly performed



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

Turn-by-Turn

- About **70 BPMs** record TbT data
- Demands beam excitation
  - Single kick with injection kicker (IK)
    - Only horizontal kicks



Turn-by-Turn

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- Demands beam excitation
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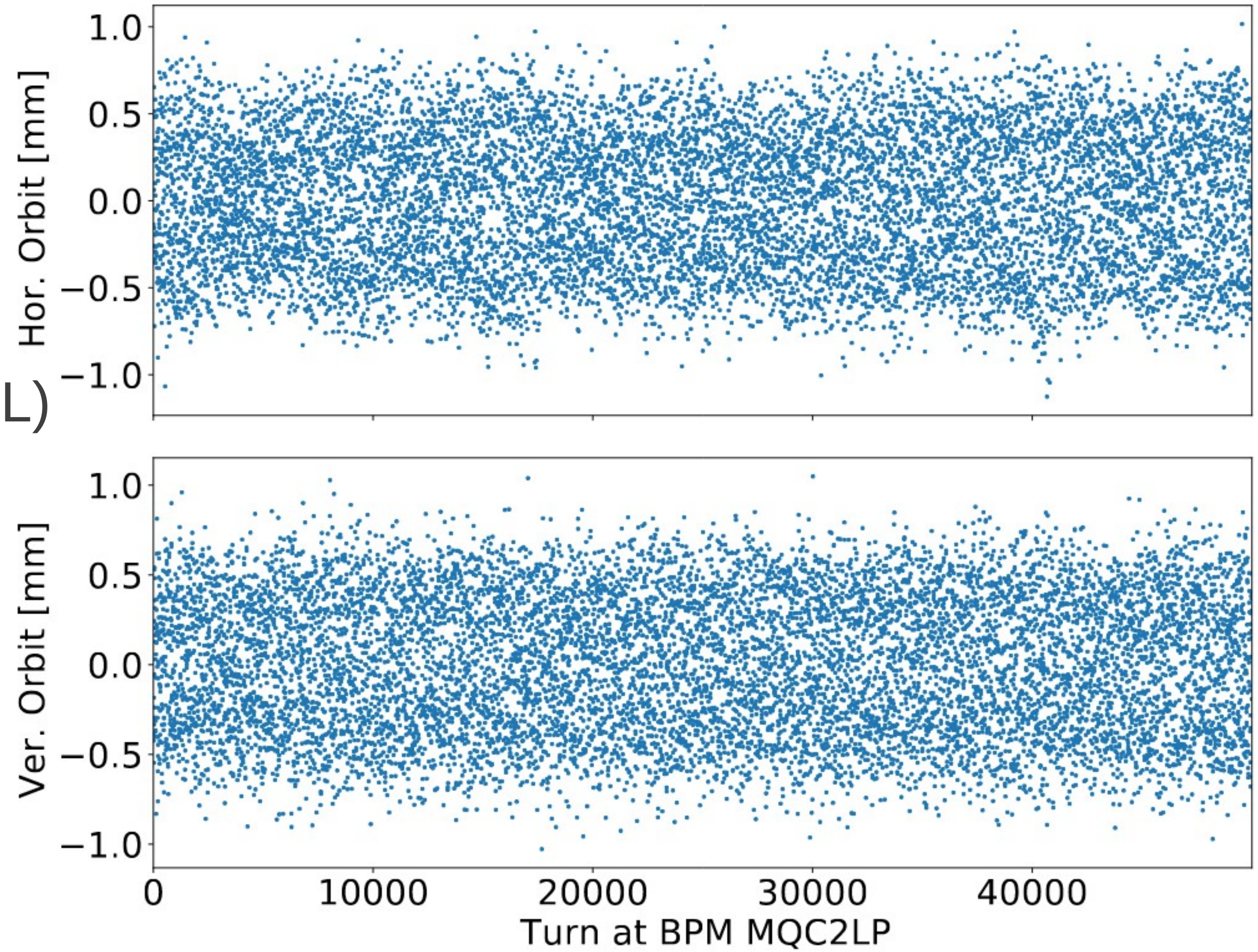
  - Driven motion with phase lock loop (PLL)
    - AC-dipole like
    - Can excite both planes
    - Essential for vertical plane
    - Improvements ongoing



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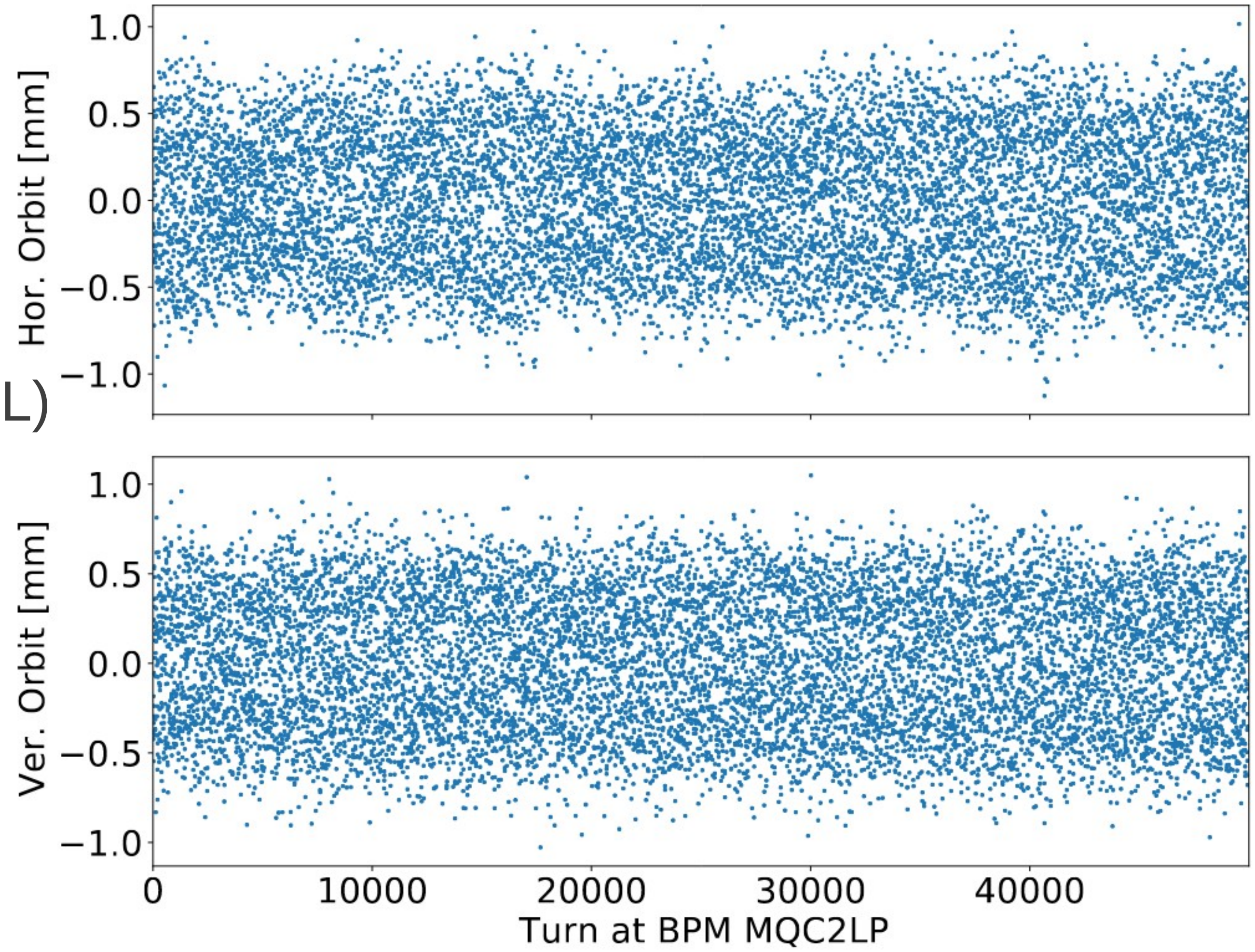
    - Improvements ongoing
- Stored in SDDS format

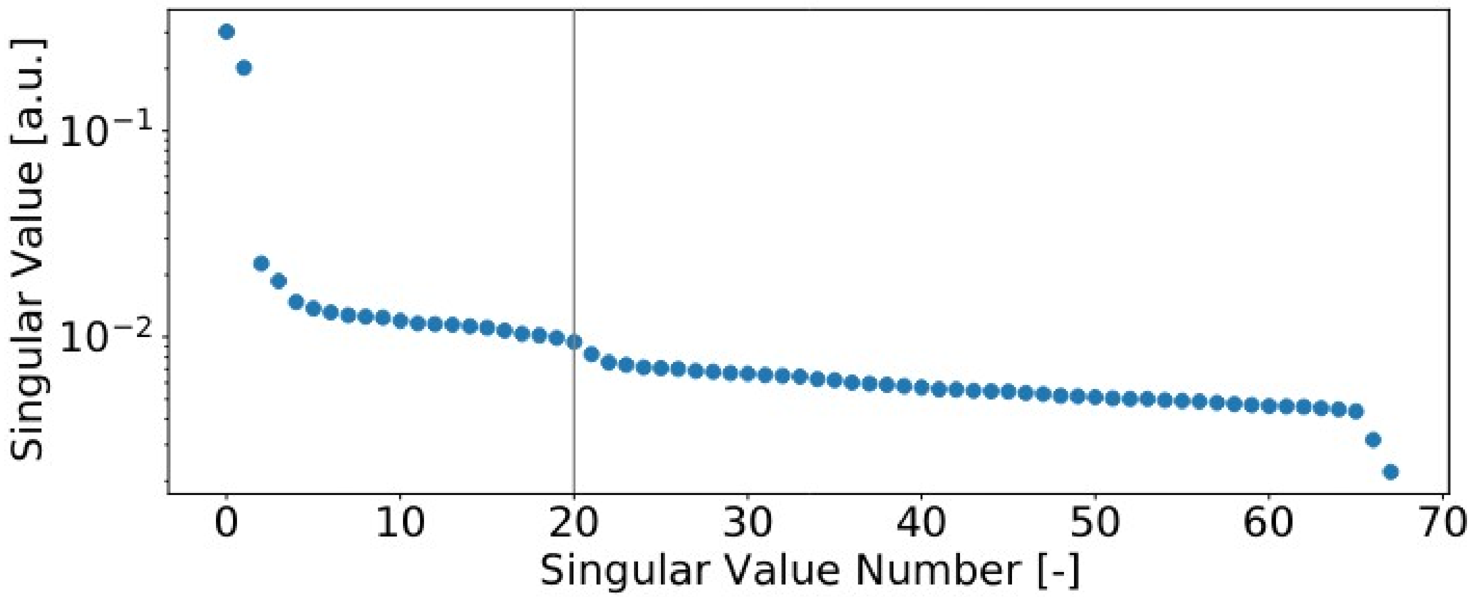


Harmonic Analysis

- Performed with codes developed by the Optics Measurement and Correction (OMC) team
- Requires model for analysis

OMC3: github.com/pylhc/omc3   Beta-Beat.src: github.com/pylhc/Beta-Beat.src.

- Cleaning based on Singular Value Decomposition (SVD) → **20 modes kept for SKEKB**



Using fewer modes

Better noise reduction

Information might get lost

Using more modes

Less noise reduction

Fewer information lost

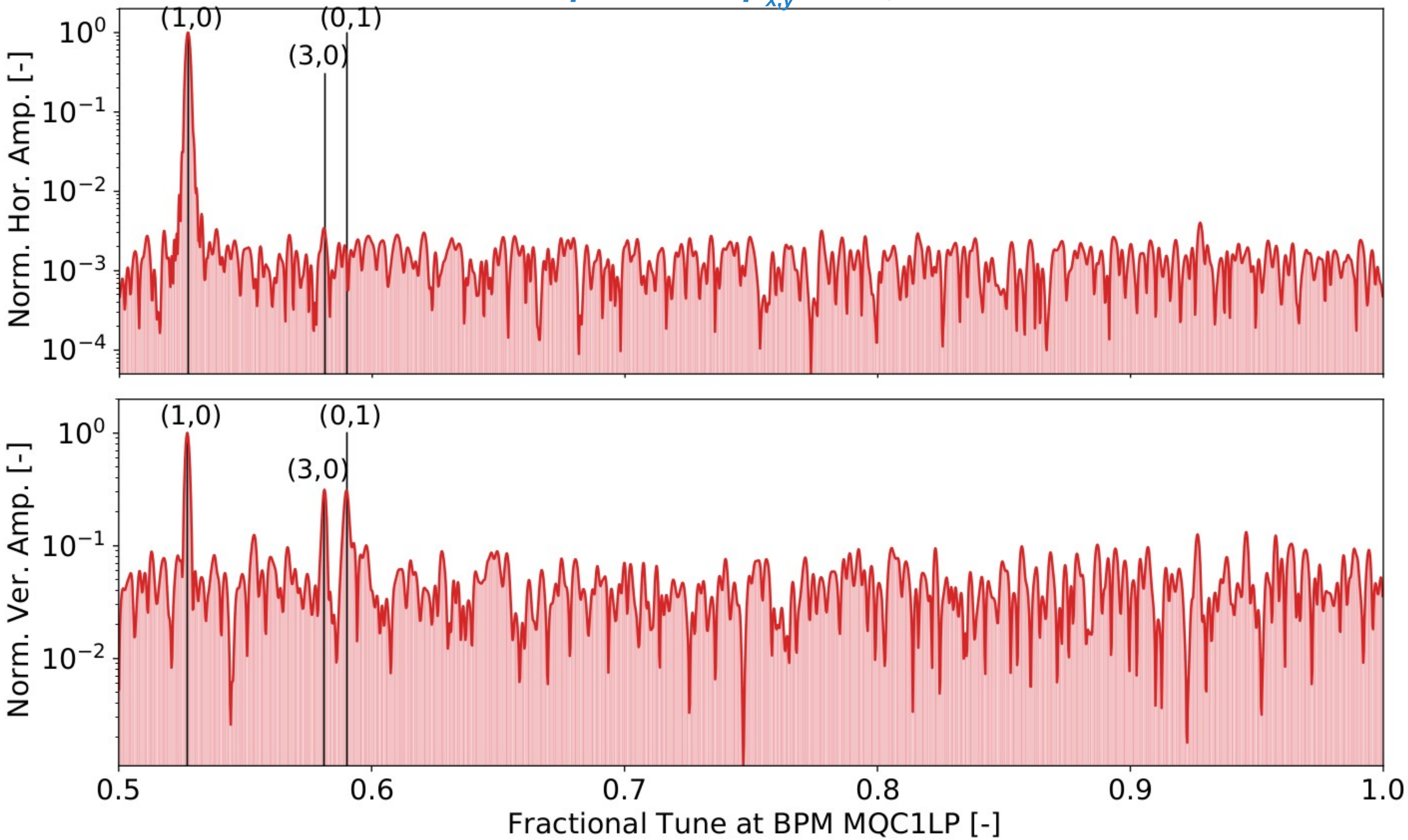
Trade-off individual for every machine and measurement

Harmonic Analysis

- Output is the harmonic spectrum in both planes
- Shows tunes and higher order resonances
- In example
  - (1,0) Hor. Tune Q_x
  - (0,1) Vert. tune Q_y
  - (3,0) 3 Q_x

Possible skew optupoles errors or octupoles in combination with coupling?

LER optics with $\beta_{x,y}^*$ = 80, 2 mm



Optics Analysis

- Codes also used for e.g. LHC
- On-momentum measurements
- Off-momentum measurements
- Relative momentum offset by
  - Measured closed orbit (CO_x)
  - Model dispersion (η_x)

$$\delta_p = \frac{\langle \eta_x^{\mathrm{mdl}} CO_x \rangle}{\langle (\eta_x^{\mathrm{mdl}})^2 \rangle}$$

TbT results benchmarked with optics obtained using COD

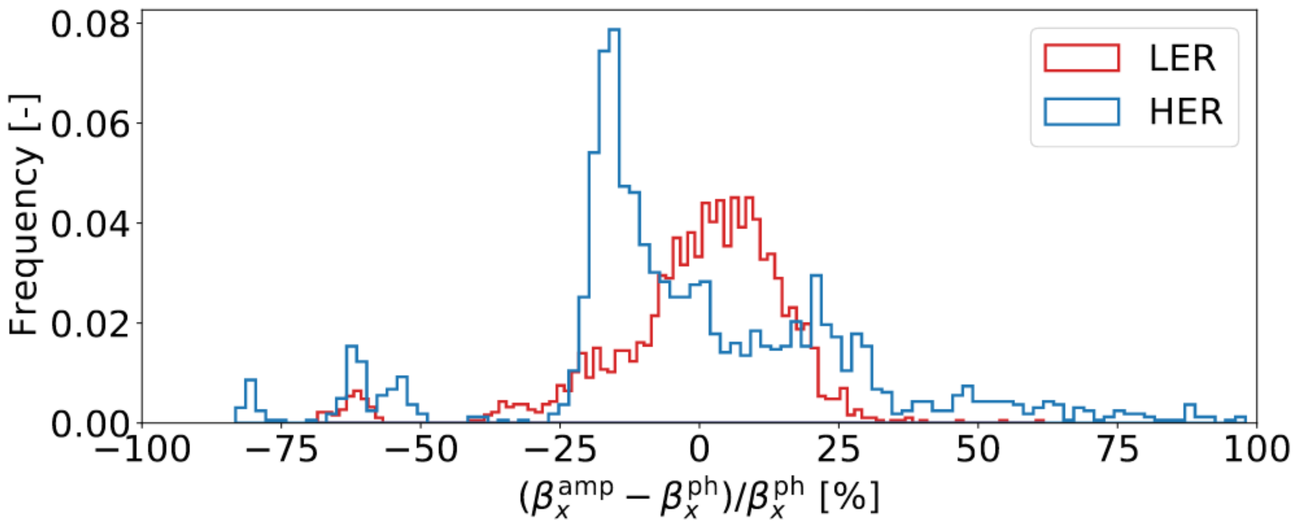
β-functions either

measured from amplitude (calibration dependent)

measured from phase advance (calib. independent)

and compared

Possible BPM calibration errors → only phase used



COD or TbT?

Closed Orbit Distortion

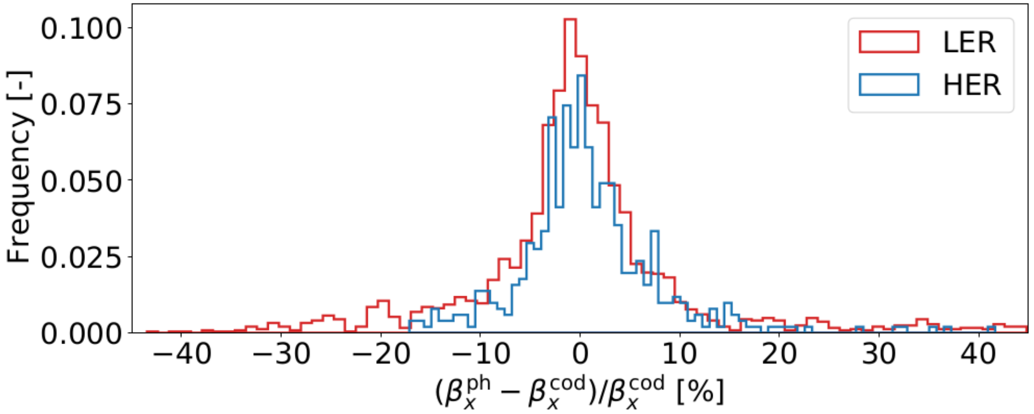
- 450 BPMs per ring (~ 5 µm resolution)
- Used for optics corrections
- Double plane measurements
- Lower orbit distortion feasible for smaller β* (below 80 mm)

→ poorer measurement quality for more queezed optics

Turn-by-Turn

- 70 BPMs per ring (~ 200 µm resolution)
- Typically faster than COD
- Improvements ongoing
- PLL required for vertical optics
- Identification of resonance driving terms

Optics beating between TbT and COD



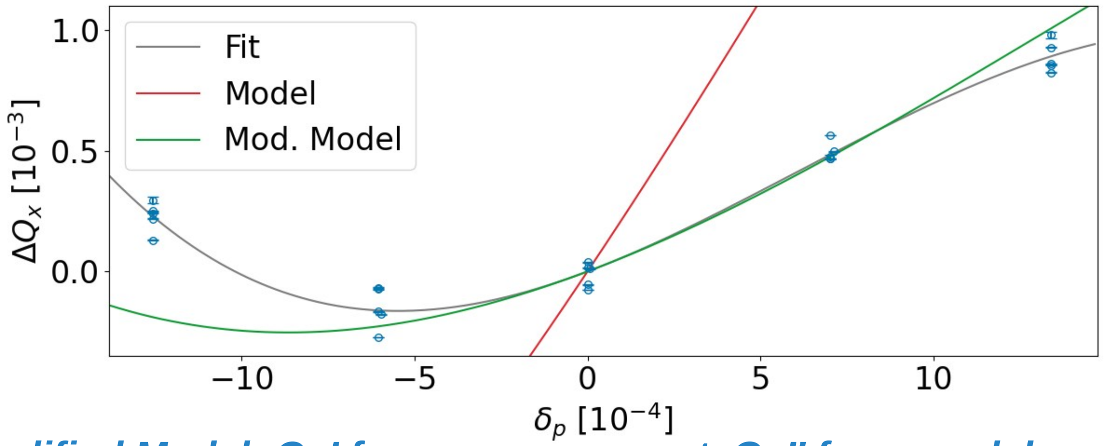
*Relative horizontal error between COD and TbT-IK is about **6% rms***

Each method shows different merits and limitations

Chromaticity

- Injection kicker used for off-momentum optics measurements
- LER linear chromaticity about 1.7 for all measurements, no second-order chromaticity
- Second-order chromaticity in HER measurements with $\beta_{x,y}^{*}$ = 80,2 mm
  - Measurements Q_x' = 0.54 +/- 0.04, Q_x'' = 680 +/- 35
  - Model Q_x' = 2.14, Q_x'' = 470
- Different Q_x' could be from sextupole settings
- **Larger second-order chromaticity** than model
  - Possible **octupole** sources
  - Second-order contributions from **sextupoles**

HER optics with $\beta_{x,y}^{*}$ = 80,2 mm

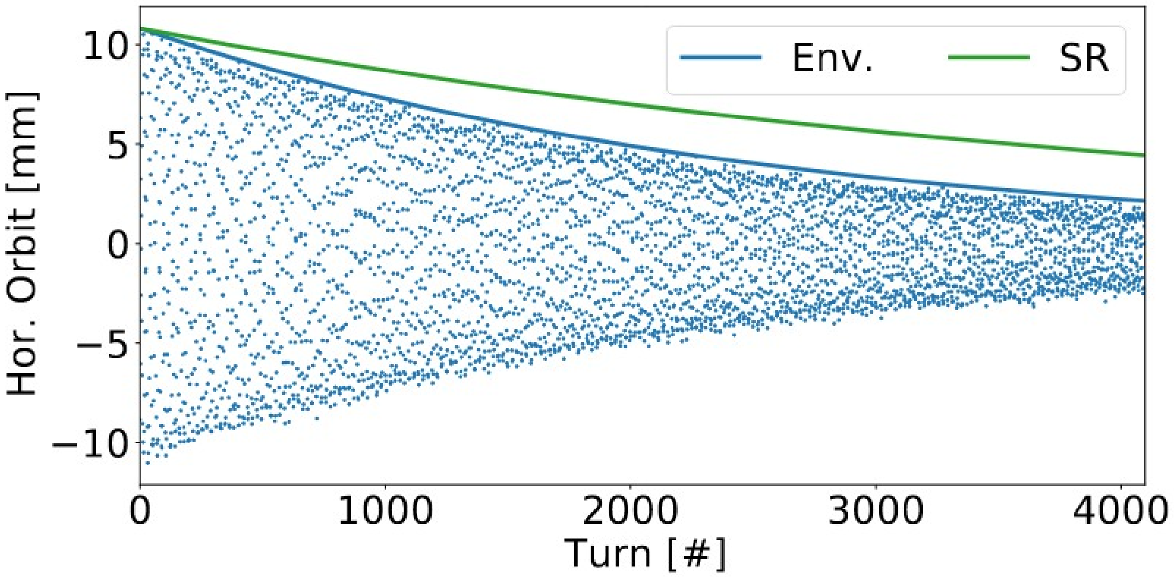


Helps finding non-linearities in lattice

Modified Model: Qx' from measurement, Qx'' from model

Horizontal Betatron Damping

LER optics with $\beta_{x,y}^*$ = 80,1 mm
Single bunch in ring
0.3 mA bunch current



- Faster damping of TbT data than expected from synchrotron radiation (SR)
- Faster damping from…
- … orbit errors?
  - Usually orbit well corrected
- … head-tail?
  - Expected to be small as low bunch current
- … decoherence?

Decoherence

- Originates from finite tune spread
- Particles do not oscillate synchronously
- After applying a kick particles start to decohere
- Not observable for AC-dipole excitation

Linear chromatictiy

Decoherence and recoherence

R.E. Meller, SSC-N-360, 1987.

Second-order chromaticity

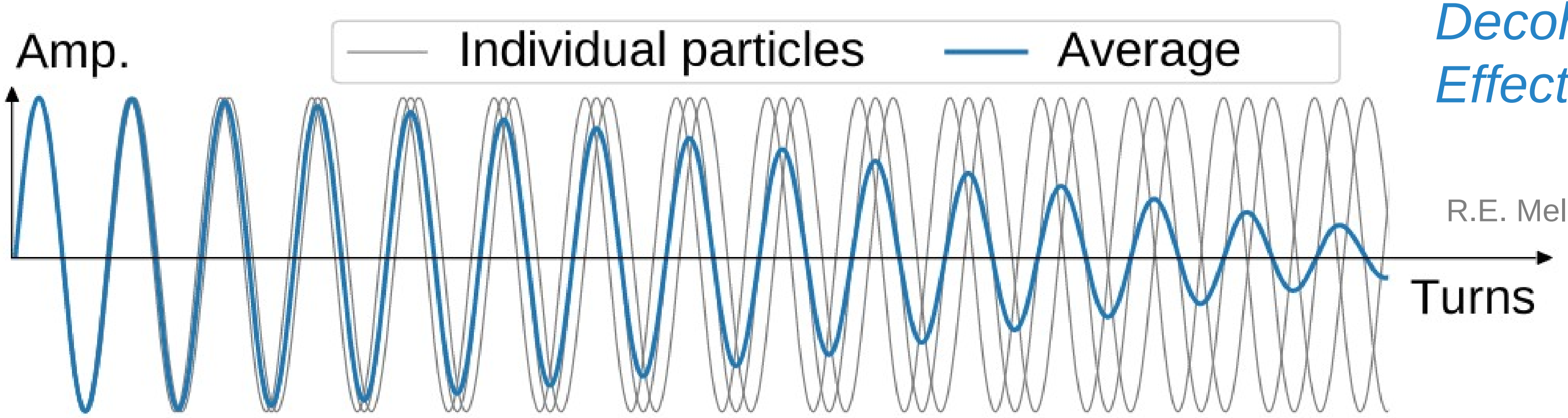
Decoherence

G.Rumolo and R. Tomas, NIMA 03, p. 206, 2004.

Amplitude detuning

Decoherence

Effect different for hadrons and leptons



R.E. Meller, SSC-N-360, 1987.

Decoherence illustrated for hadrons
Individual amplitudes remain constant over time

Strong synchrotron radiation damps amplitude of each particle

Hadrons and Leptons

$$A_{\mathrm{Dec}} = \frac{1}{1+\theta^2}\exp\left\{-\frac{Z^2}{2}\frac{\theta^2}{1+\theta^2}\right\}$$

R.E. Meller, SSC-N-360, 1987.

Hadrons:

$$\theta = 4\pi\mu N$$

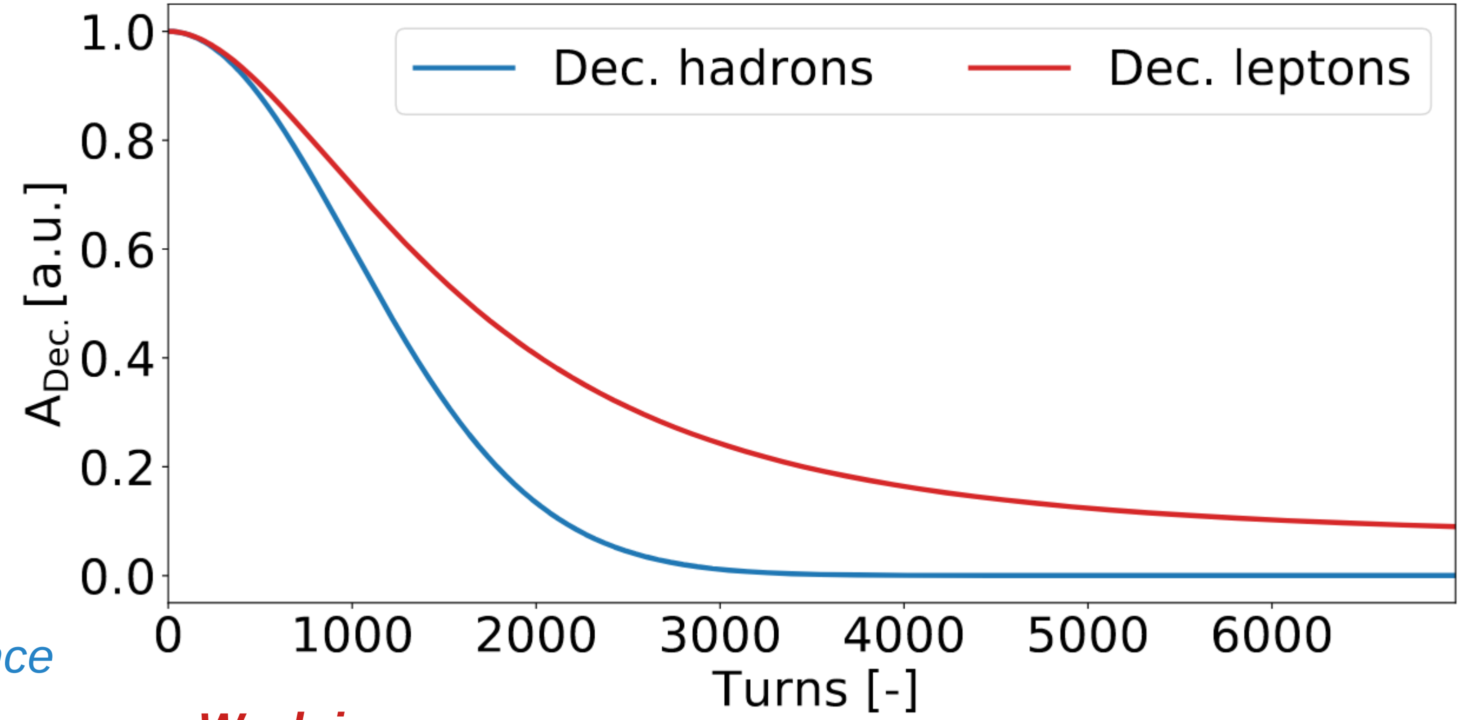
R.E. Meller, SSC-N-360, 1987.

Leptons:

$$\theta = 2\pi\mu\,\tau_{\mathrm{SR}}\left(1 - e^{-2N/\tau_{\mathrm{SR}}}\right)$$

N … Turns
Z … Initial kick
μ … Amplitude detuning normalized by emittance

Decoherence factor over estimated when synchrotron radiation damping is not included



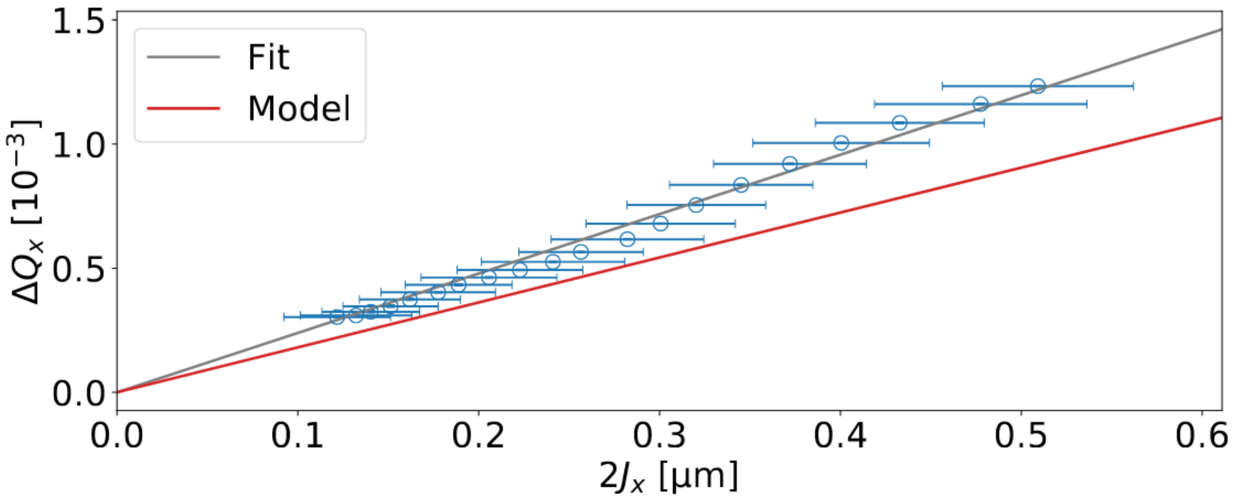
Work in progress

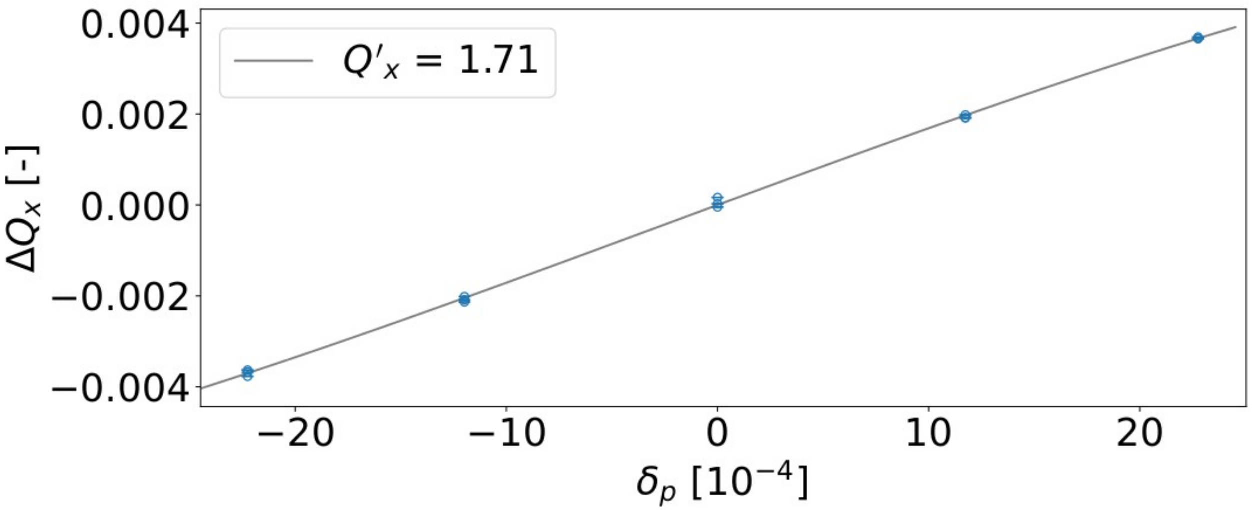
Decoherence Measurements

- Evaluation of amplitude detuning and chromaticity needed
- Q_x' = 1.7 ± 0.04 (Model: 0.04) Q_x'' = -22 ± 18 (Model: -199)

LER optics with $\beta_{x,y}$ = 80,1 mm*
Single bunch in ring
0.3 mA bunch current

- Amplitude detuing $dQ_x/d2J_x$
- Measured: (1.925 ± 0.050) x 10^3 m^{-1}
- Model: 1.758 x 10^3 m^{-1}



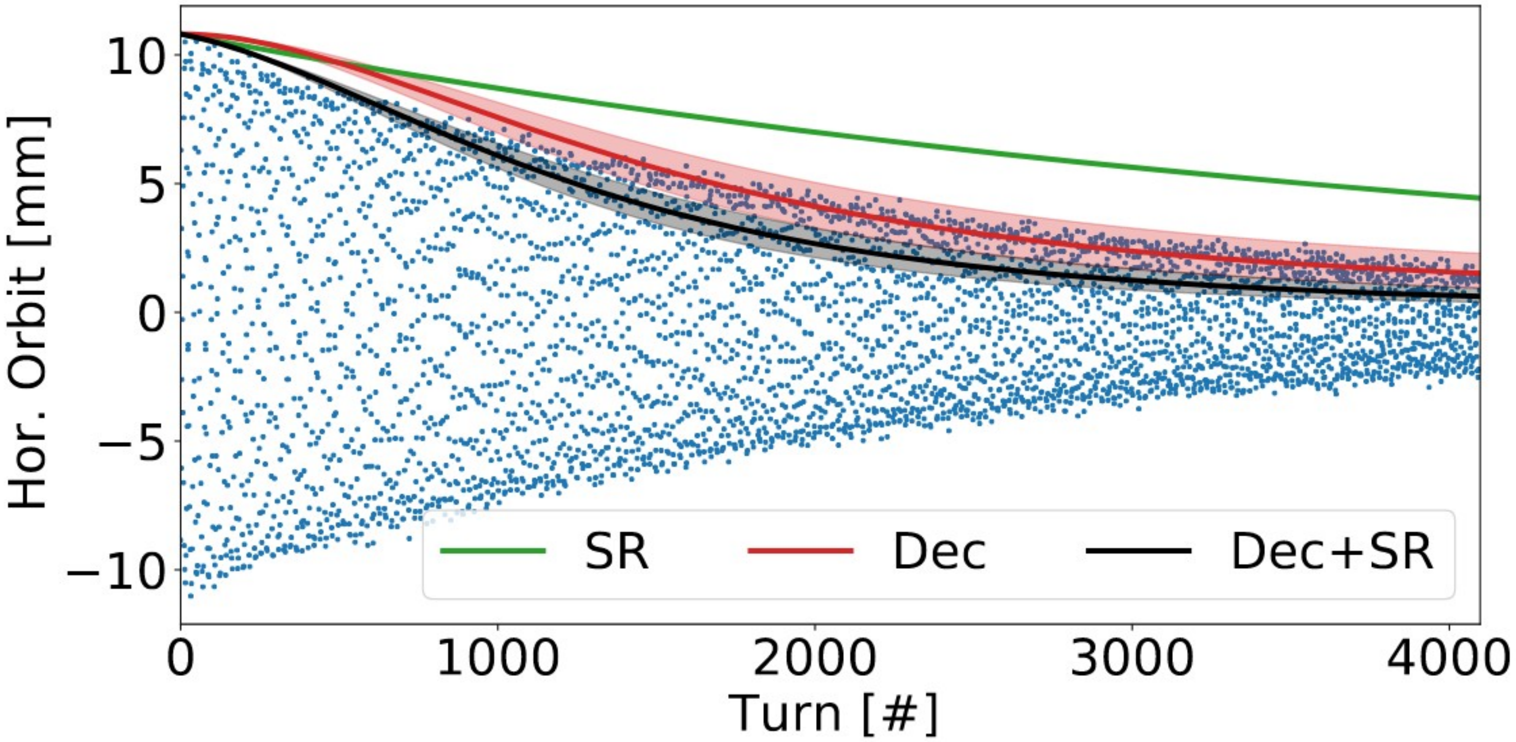


- Emittance during measurement unknown
- Estimated 2 nm

Decoherence Measurements

- TbT closed orbit measurements with IK single kick used
- Equations over-estimate damping
  - Emittance unknown
  - BPM reading could be spoiled by calibration and resolution
  - Additional growth mechanisms
  - Possible closed orbits could lead to different damping

LER optics with $\beta_{x,y}^*$ = 80,1 mm
Single bunch in ring
0.3 mA bunch current



Many things to be understood
Work in progress

Summary

- SuperKEKB is demonstrating FCC-ee key concepts
  - Crab-waist optics, similar lattice and optics, top-up injection, tilted solenoid, etc.

- Studies and results at SuperKEKB will influence the FCC-ee design
  - Help defining beam optics measurement system (TbT with single kick, AC-dipole, etc.)
  - Understand commissioning challenges and might help avoiding them

- Numerous future studies could be performed
  - Optics corrections and measurements
  - Impedance studies
  - Hands-on experience in control and operation
  - Etc.

SuperKEKB is small FCC-ee

Understanding SuperKEKB challenges is inevitable for FCC-ee design

Thank you!

Optics measurements at SuperKEKB

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