Beam Tests for FCC-ee at SuperKEKB and PETRA III

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On behalf of

The FCC-ee collaboration

Acknowledgements: Gero Kube

FCC-IS Workshop 2022

WP2: Accelerator

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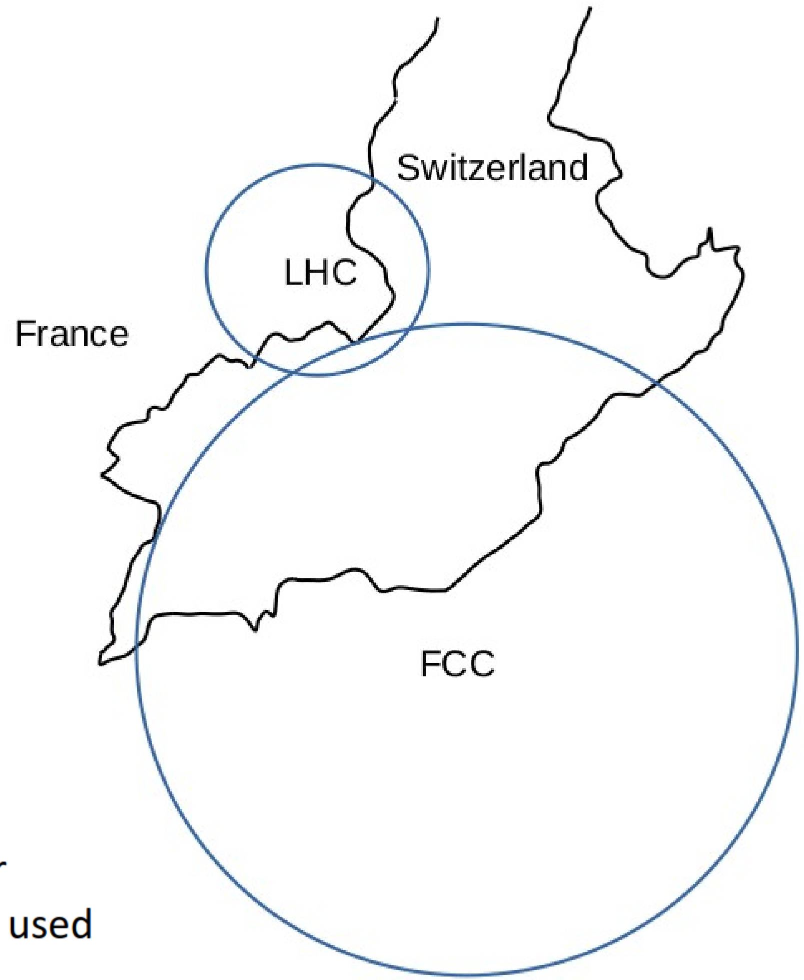
Introduction

- Integrated FCC project spans over this century
- FCC-ee first stage with commissioning in 2040s
- FCC-ee requires
  - Emittance tuning techniques
  - Understanding alignment tolerances
  - Robust and fast optics measurement techniques
- M. Benedikt:

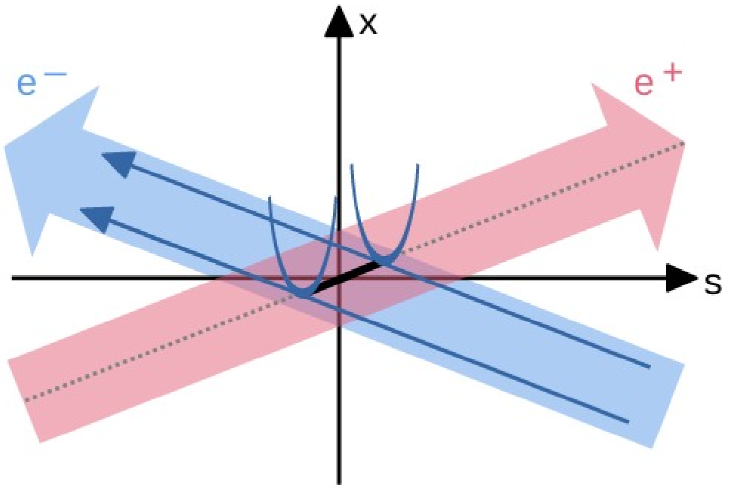
- **Low-risk technical solution** based on 60 years of e^+e^- circular colliders and particle detectors ; R&D on components for improved performance, but no need for “demonstration” facilities; LEP2, VEPP-4M, PEP-II, KEKB, DAΦNE, or SuperKEKB already used many of the key ingredients in routine operation

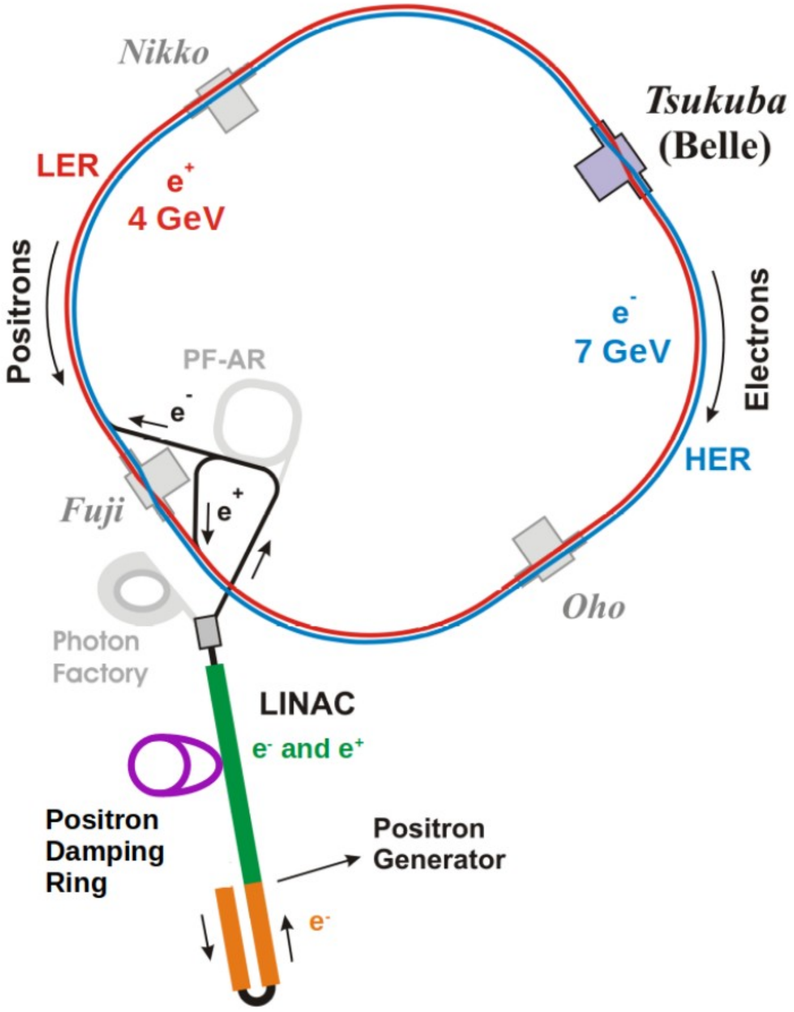


Requires beam tests at existing machines to test FCC-ee challenges
Here: SuperKEKB and PETRA III / IV

SuperKEKB

- Collider with 3 km circumference
- Record luminosity of 4.65 x 10^{34} $cm^{-2}s^{-1}$
- Very similar to FCC-ee
  - Non-interleaved sextupoles with -I transformation
  - Crab-waist collisions
  - Top-up injection
  - ...





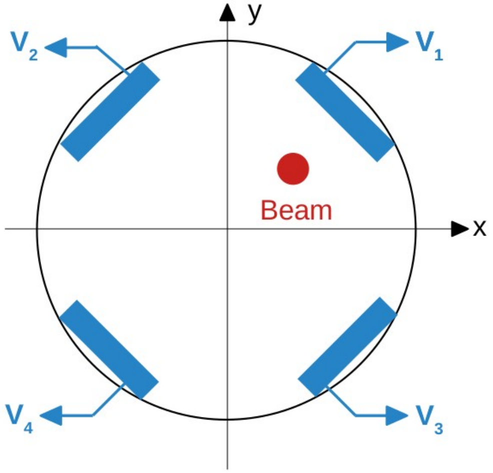
SuperKEKB is small FCC-ee

M. Wendt

Beam Position Monitors

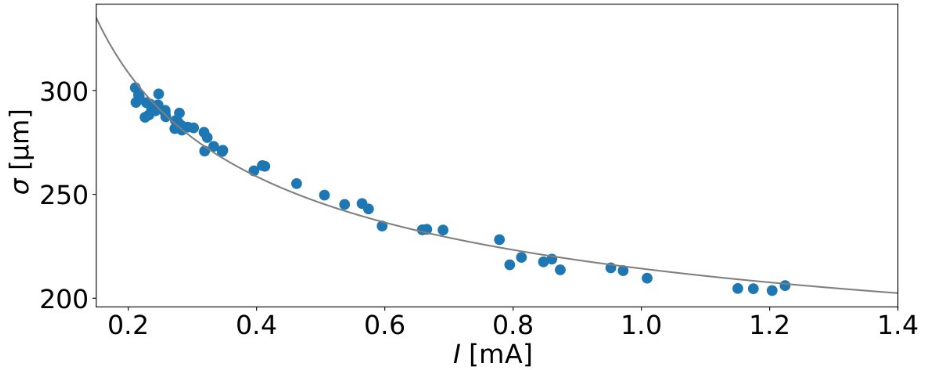
- Beam Position Monitors (BPMs) are crucial devices for beam optics measurements
- Button BPMs are the most common type, spoiled by resolution, calibration, non-linearity, ...

Leptons:



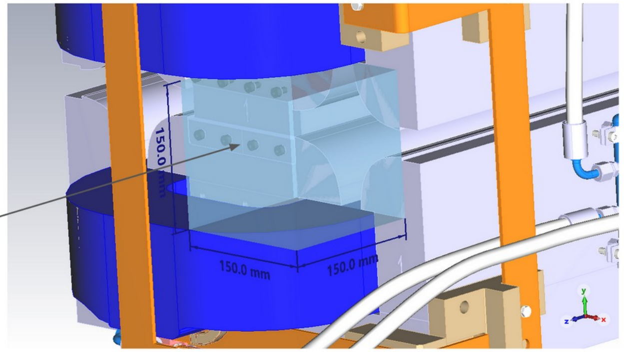
Buttons typically rotated by 45° due to strong synchrotron radiation

Single bunch measurements for SuperKEKB positron ring
Estimated BPM resolution improves with bunch intensity
→ Probably similar for FCC-ee
→ Requires specifications for single bunch/multi bunch and average orbit and turn-by-turn



BPMs could be installed next to every quadrupole
No additional space presently presumed
How would it look for placement next to sextupoles?

BPM fits in
this blue box

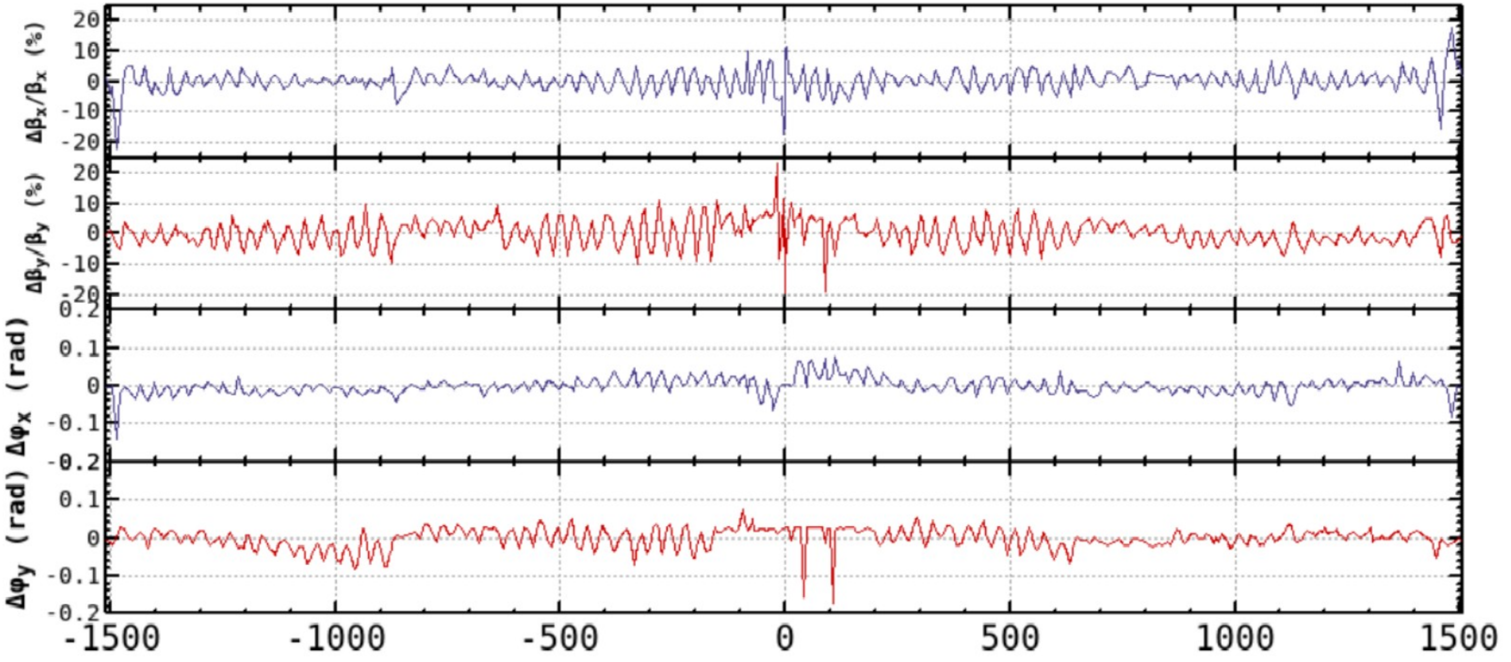


H. Sugimoto

Orbit Response Matrix SKEKB

- Explore Orbit Response Matrix (ORM) approach for FCC-ee
- Including Closed Orbit Distortion (COD) method with fewer correctors as in SKEKB

In SuperKEKB:
Closed Orbit Distortion (COD) performed
3 pairs of orbit correctors generate 6 closed orbit distortions
+ Routinely performed and used to calculate corrections
+ Very good resolution of about 5 µm
- Rather time consuming procedure
- Orbit limited to 10-20 µm to avoid distortions from interaction region quadrupoles and sextupoles



Orbit Response Matrix FCC-ee

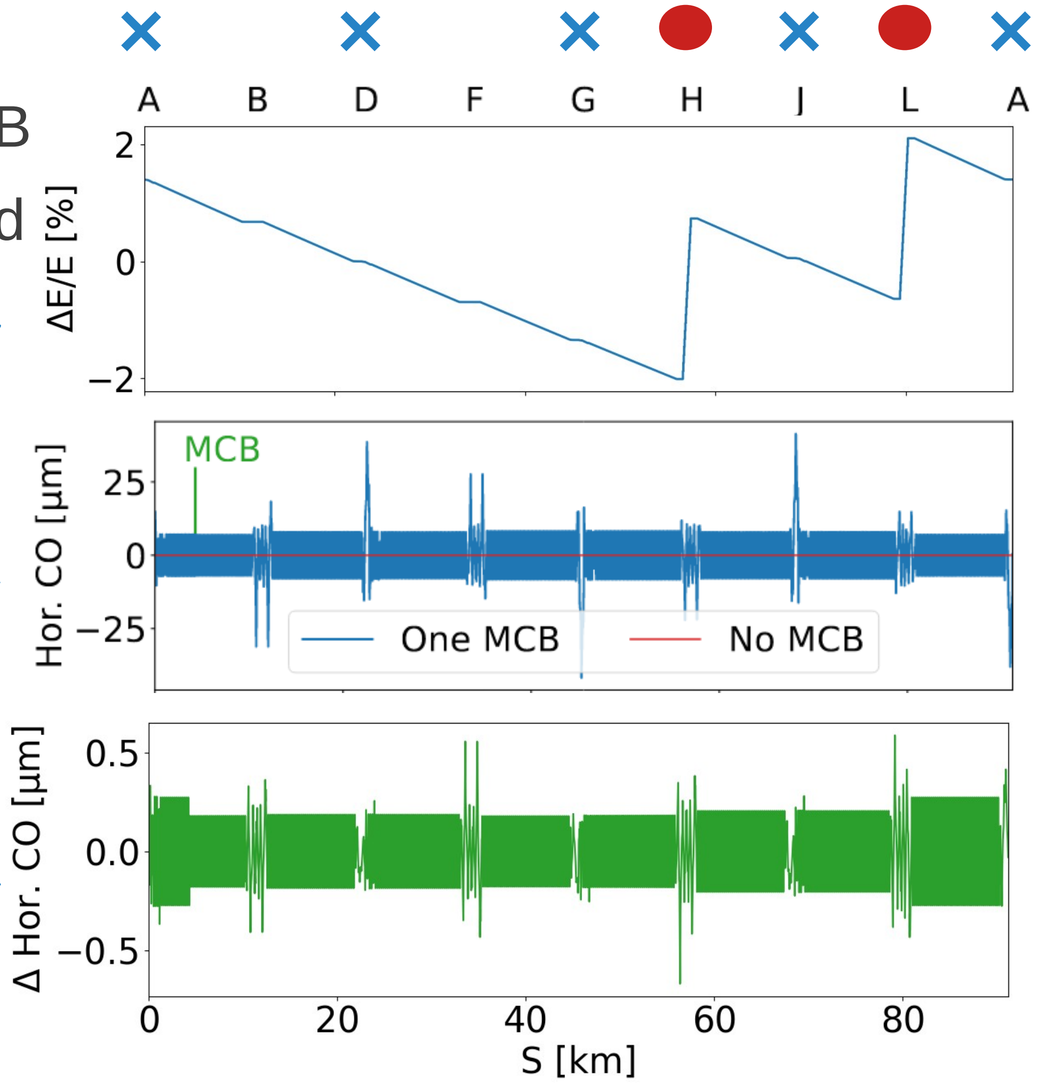
- Explore orbit response matrix approach for FCC-ee
- Including closed orbit distortion method as in SKEKB
- Strong synchrotron radiation needs to be considered

In FCC-ee ttbar mode:
Beam energy 182.5 GeV
Radiation losses/turn about 10 GeV
Effect on ORM with strong synchrotron radiation to be studied

Large energy variation of about ± 2 %, tapering applied

Example of generated closed orbit with one kicker (MCH)
Including radiation and 2 RF sections

Difference of closed orbit with radiation to closed orbit without radiation or RF sections using same MCB
0.5 µm maximum difference and 0.12 µm rms



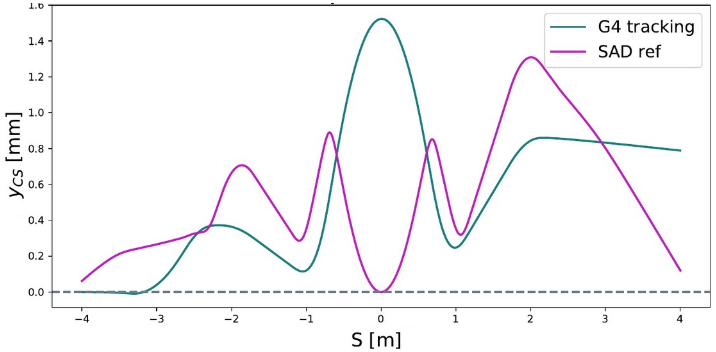
H. Burkhardt, M. Lückhof, H. Nakayama

Background and Models

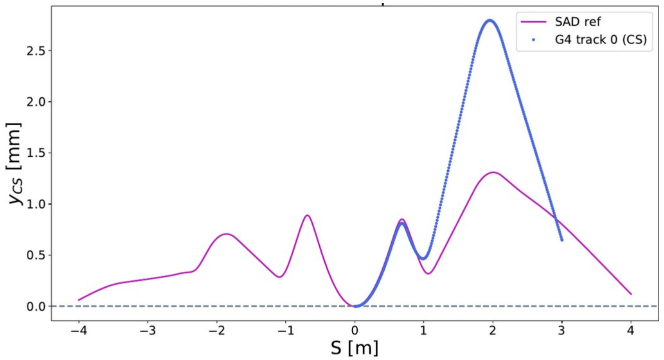
- MDISIM developments: rebuilt SuperKEKB interaction region based on SAD
  - Simulate SAD-model vertical closed orbit in the presence of solenoid and quadrupoles

Aim to measure orbit using e.g. beam-gas vertex in SuperKEKB

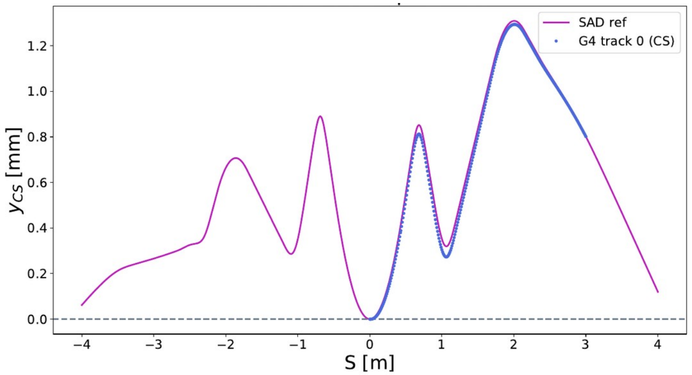
Start



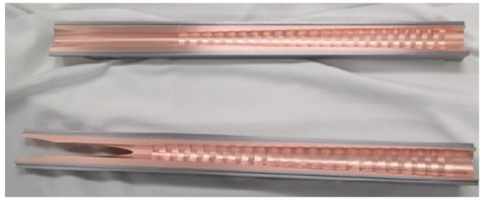
Intermediate



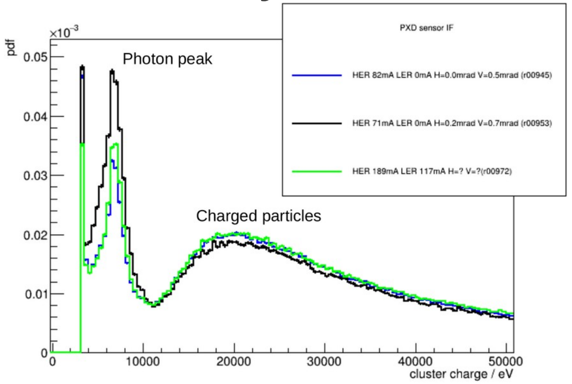
Final



- Strong 10 keV photon line in synchrotron radiation background



Beam pipe next to interaction point

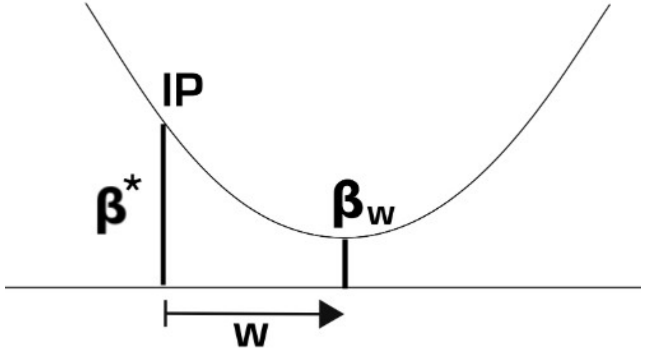


FCC-ee:
- Code development driven by SuperKEKB experience
- Accurate model of the interaction region with solenoids
- Help to determine number of collimators in interaction region

K-Modulation

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

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



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

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

- 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

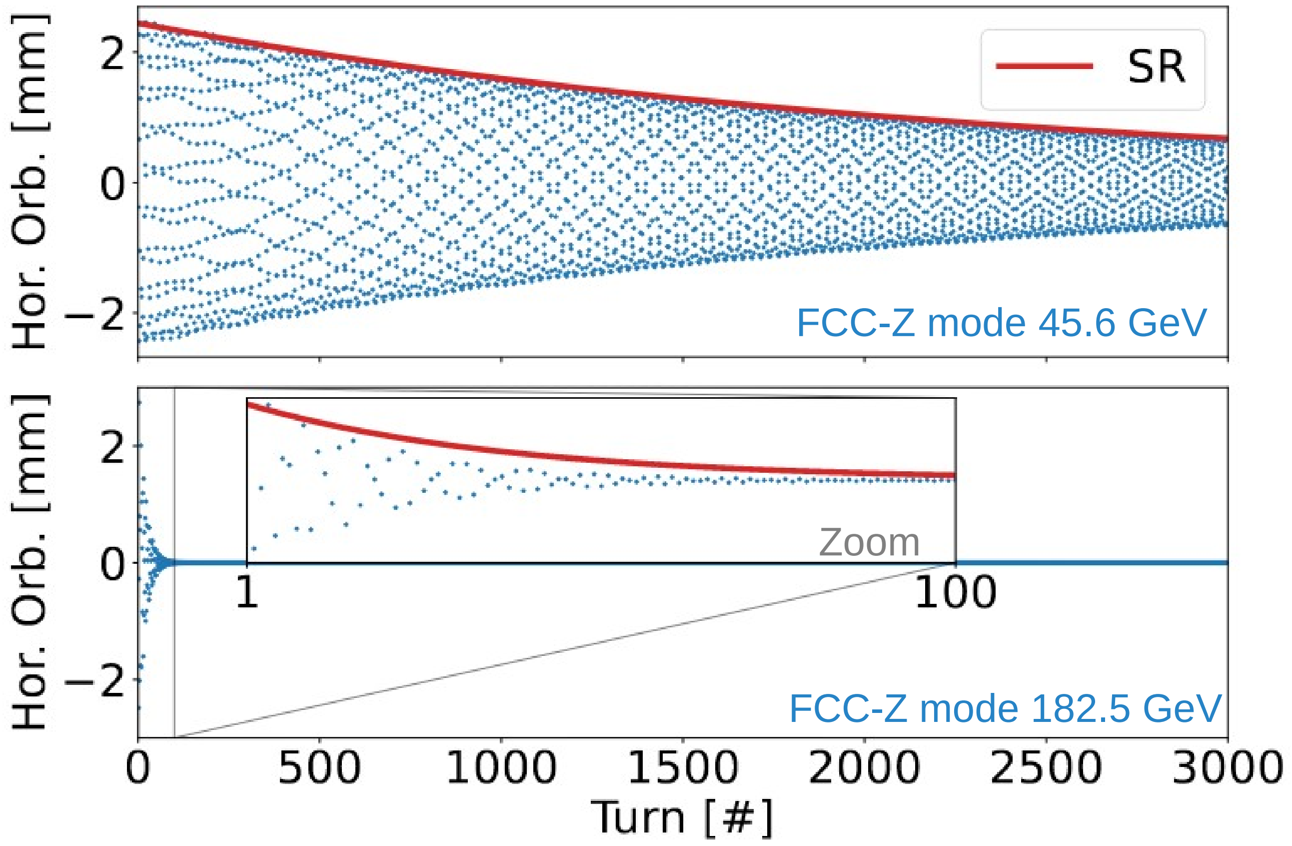
Hysteresis from magnets could disturb optics
Fewer problem with superconducting magnets

Turn-by-Turn Measurements

- Orbit recorded ideally horizontally and vertically Turn-by-Turn (TbT)
- Requires beam excitation
  - Single kick

Top: FCC-Z mode 45.6 GeV beam energy
Damping of single particle tracking orbit after $10\sigma_x$, $10\sigma_y$ kick
2300 turns damping time
→ **Slow enough to be used for TbT measurements**

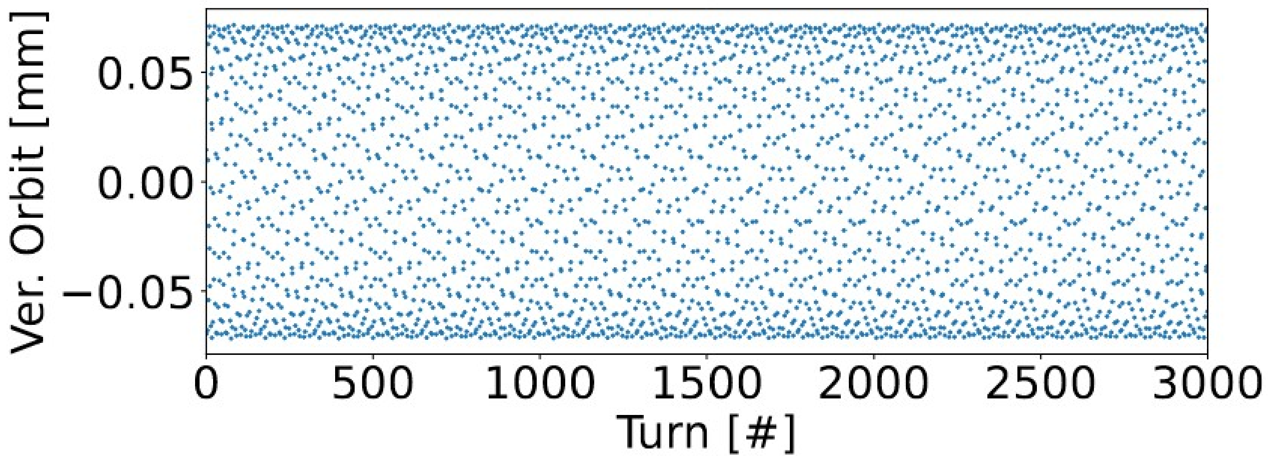
Bottom: FCC-ttbar mode 182.5 GeV beam energy
Damping of single particle tracking orbit after $10\sigma_x$, $10\sigma_y$ kick
40 turns damping time
→ **Too fast to be used for TbT measurements**

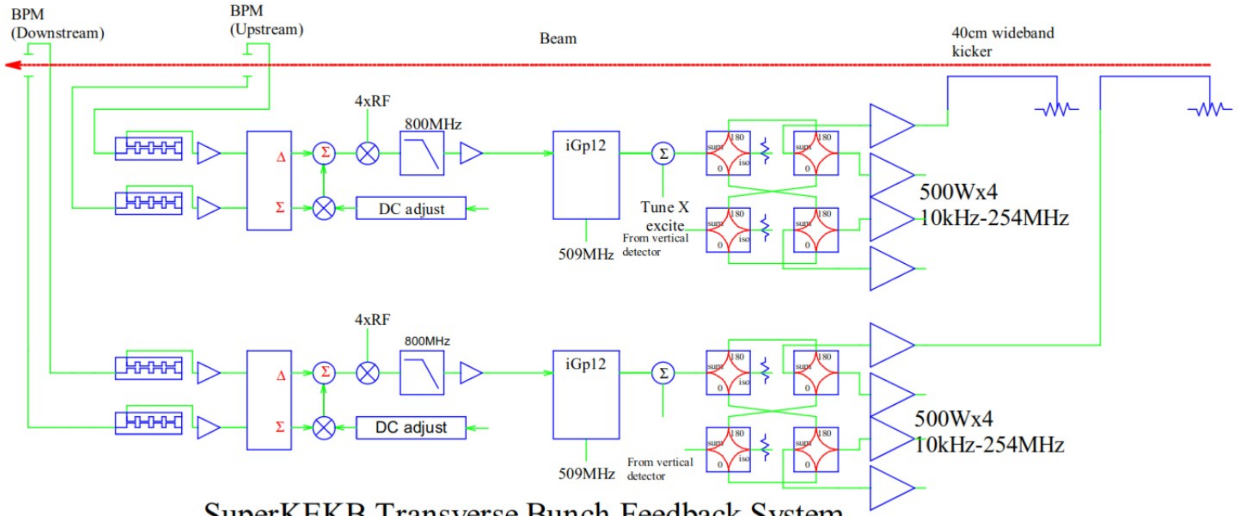


Turn-by-Turn Measurements

- Orbit recorded ideally horizontally and vertically Turn-by-Turn (TbT)
- Requires beam excitation
  - Single kick
  - Driven motion

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





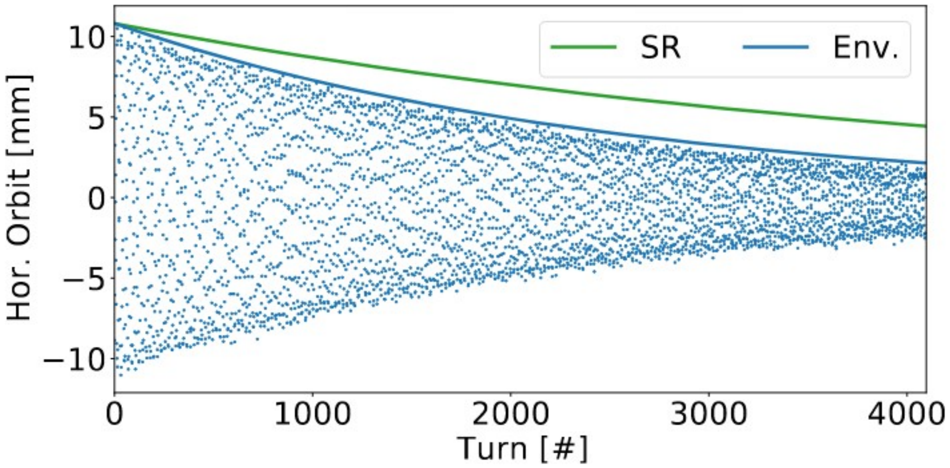
SuperKEKB Transverse Bunch Feedback System

Continous excitation achieved in SuperKEKB using transverse feedback system and amplification
+ Drives the beam at the natural tune (no compensation)
- Typically limited in amplification (low excitation)

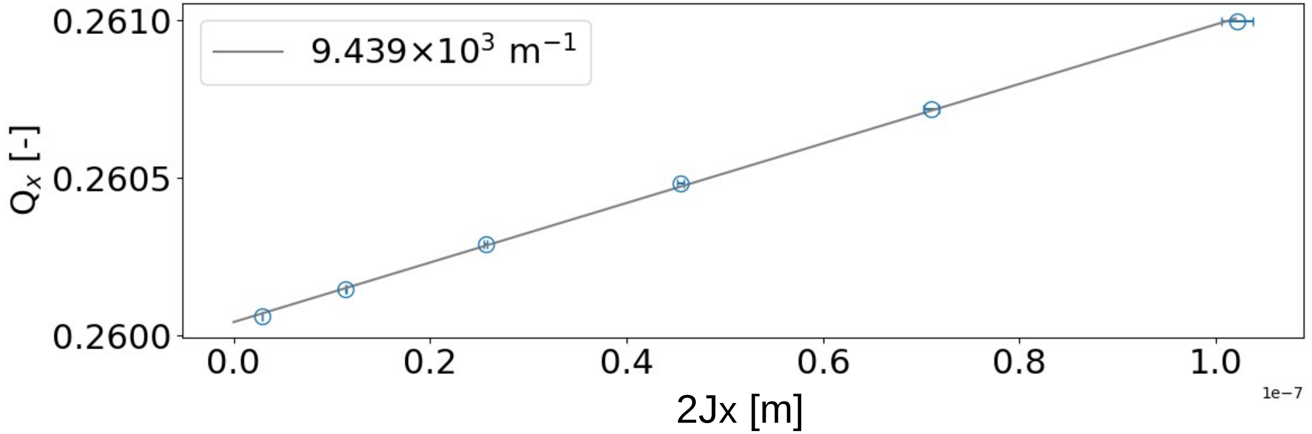
Single Kicks in Measurements

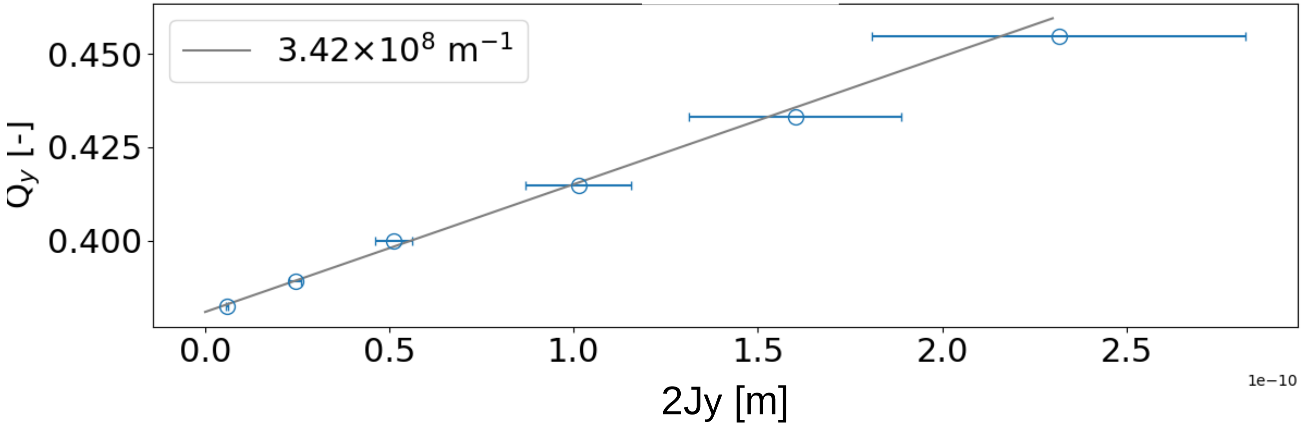
- After kick is applied, orbit is affected by
  - Synchrotron radiation (SR)
  - Decoherence from amplitude detuning
  - Head-tail effect and impedance
- Detailed analysis of SKEKB TbT data

Qx' = 1.70 ± 0.04 , Qx'' = -22 ± 18



Amplitude detuning for FCC-ee Z-mode also needs to be considered in addition to SR

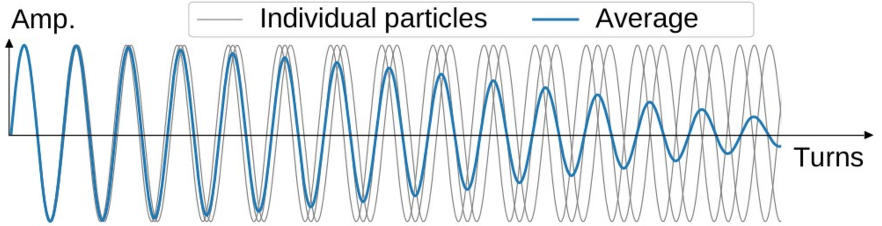




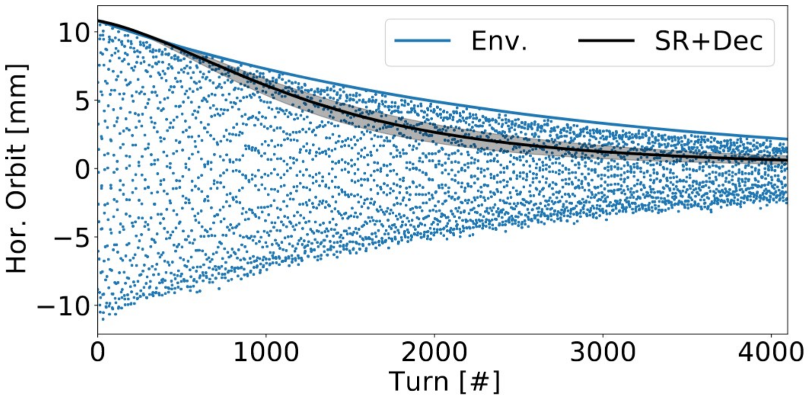
Lepton Decoherence

- Decoherence from amplitude detuning enhances damping of center-of-charge
- Only pseudo-damping → amplitude of individual particles not affected by decoherence

Decoherence illustrated for 3 hadrons
Leptons: individual amplitudes damp over time too



Synchrotron radiation and decoherence over-estimate damping → growth contributions



Existing theory for hadrons:

μ … Amplitude detuning   N … Turns
Z … Kick strength

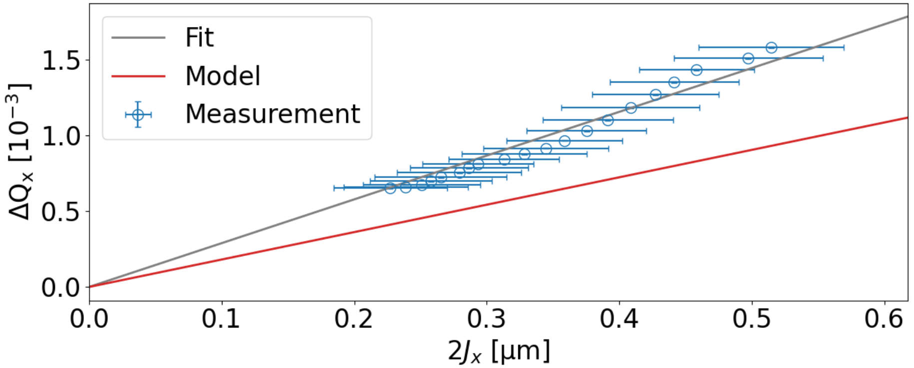
$$A_{\mathrm{Dec}} = \frac{1}{1+\theta^2}\exp\left\{-\frac{Z^2}{2}\frac{\theta^2}{1+\theta^2}\right\} \quad \theta = 4\pi\mu N$$

Here extended for leptons:

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

Damping explained by synchrotron radiation and decoherence
→ TbT orbit data scaled to reproduce radiation damping
→ Measure tune for various actions and fit gives amplitude detuning
Method applicable for all lepton storage rings such as FCC-ee

SuperKEKB LER amplitude detuning measurement

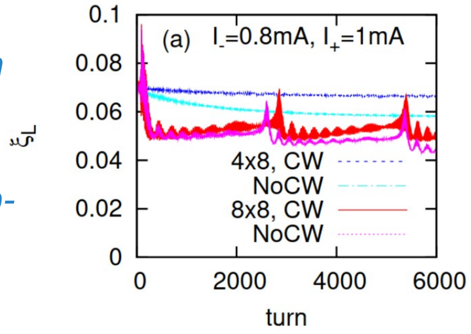


D. El Khechen

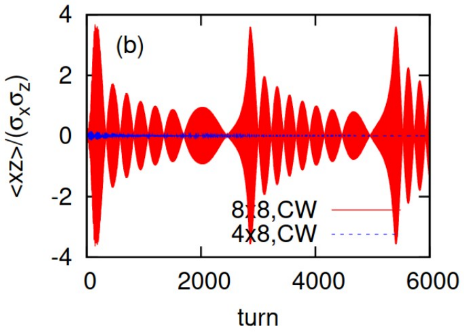
Beam-Beam and Luminosity Dither

- Beam-beam simulations
  - Emittance blow up
  - Benchmark codes

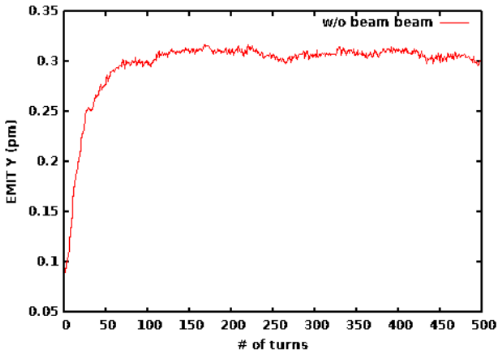
Beam-beam parameter with and without crab-waist in SuperKEKB

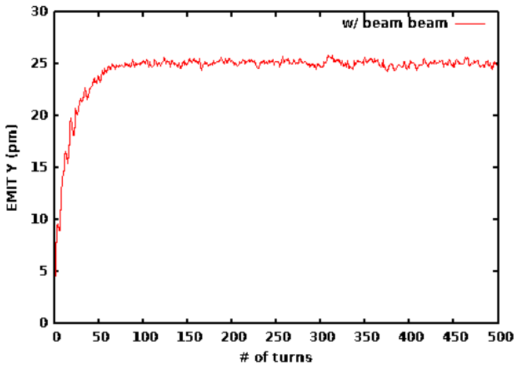


*Head-tail motion during SuperKEKB commissioning (8x8 β*x,y = 8xdesign)*



Vertical emittance blow-up due to beam-beam in FCC-ee





- Luminosity dither system
  - Increase luminosity

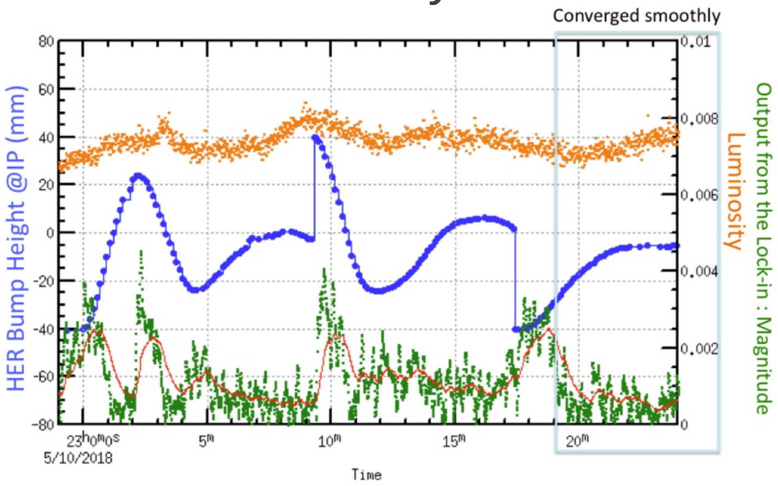


Figure 8: V_x (green) and bump height at the IP (blue) are plotted with luminosity (orange) during the dither feed-back test.

With feedback improve beam-beam position at the IP using bumps to increase luminosity

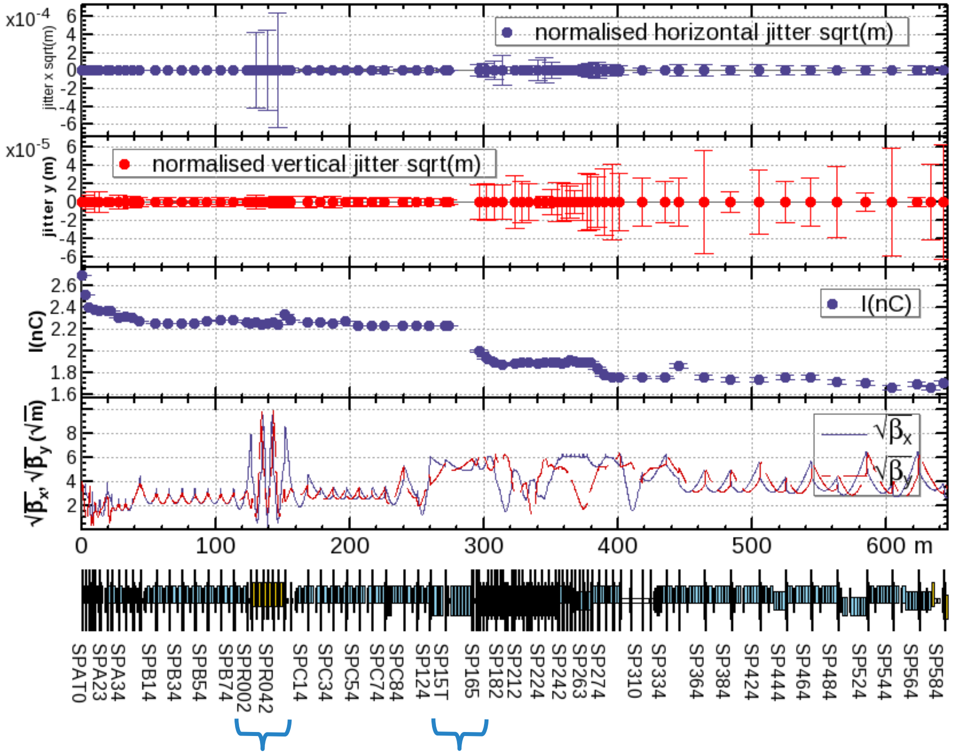
FCC-ee:

- *Gain experience with possible similar luminosity dither system*
- *Benchmark beam-beam simulation codes*
- *Rebuild possible emittance blow-up challenges*

S. Ogur

Studies at Injectors

- Beam jitter studies in electron mode
  - Result of mismatch in linac arc



Fluctuation starts in linac arc

Target for positron prodction

- Beam based misalignment determination in quadrupoles
  - Avoid emittance blow-up
  - RMS alignment precision of 37 µm

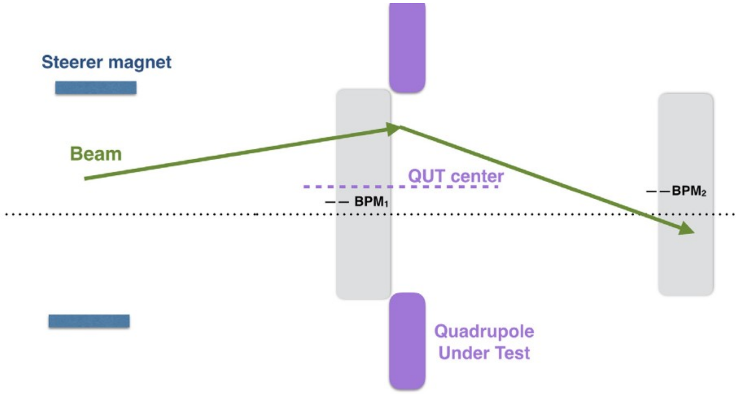


Fig. 5. A sketch of the orbit change caused by the dipolar kick from a displaced quadrupole.

Precise alignment also possible with virtual BPMs

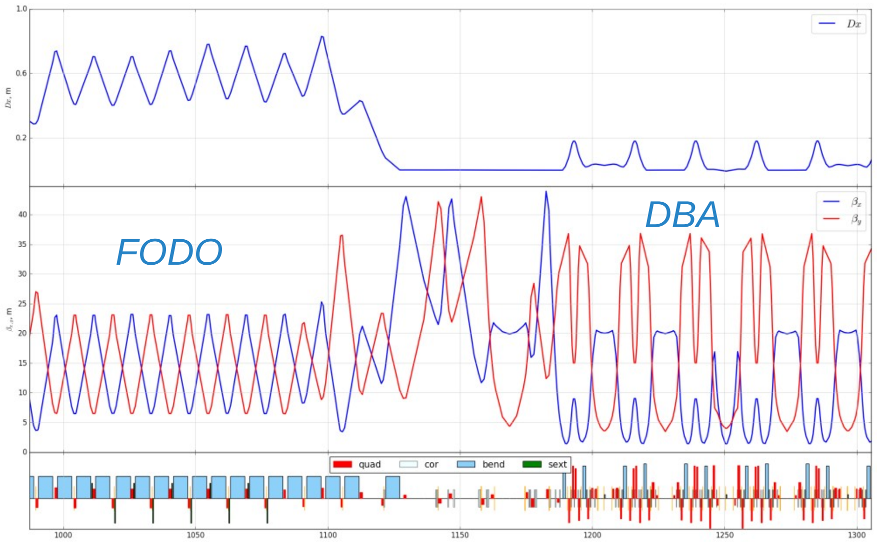
Applicable to other machines to improve misalignments

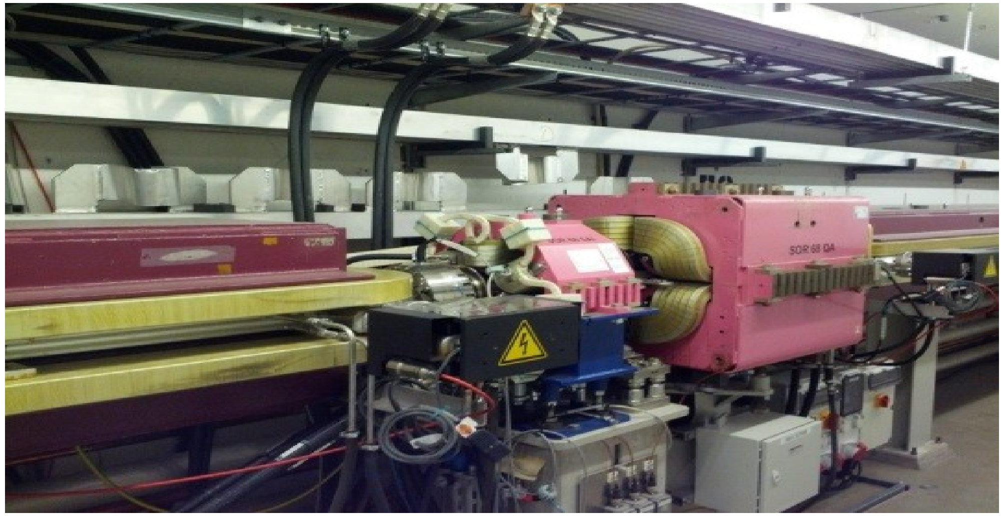
FCC-ee:
- Gain experience for injector optics
- Improve magnet alignments and determine number of required BPMs

I. Agapov

PETRA III

- Light source with 2.3 km circumference
- Hybrid between FODO and DBA

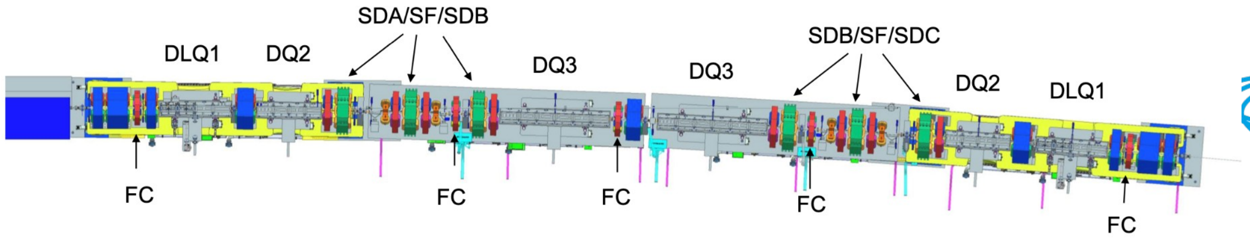


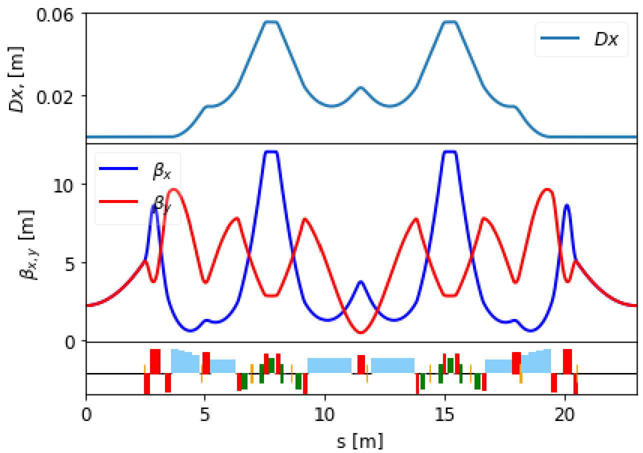


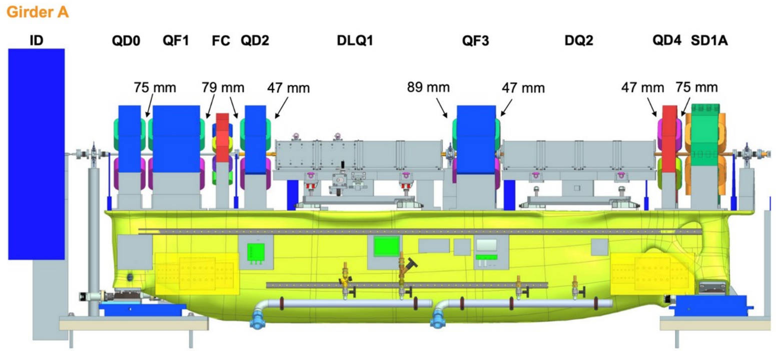
PETRA IV

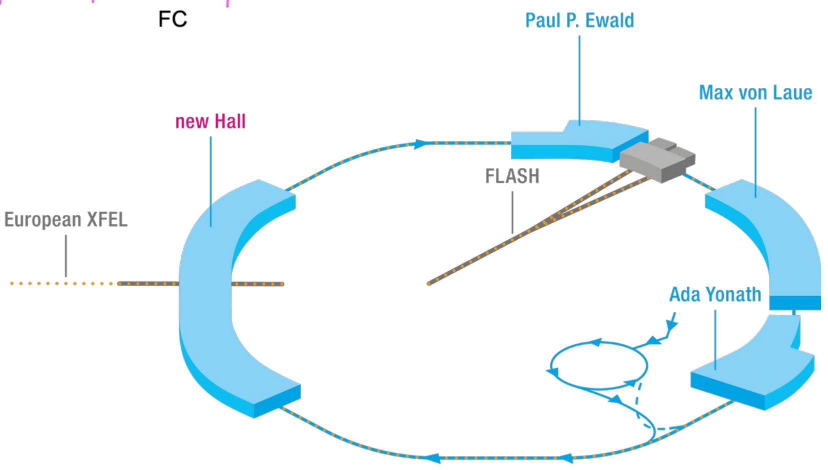
I. Agapov

- Upgrade of PETRA III
- 6 bend achromat optics

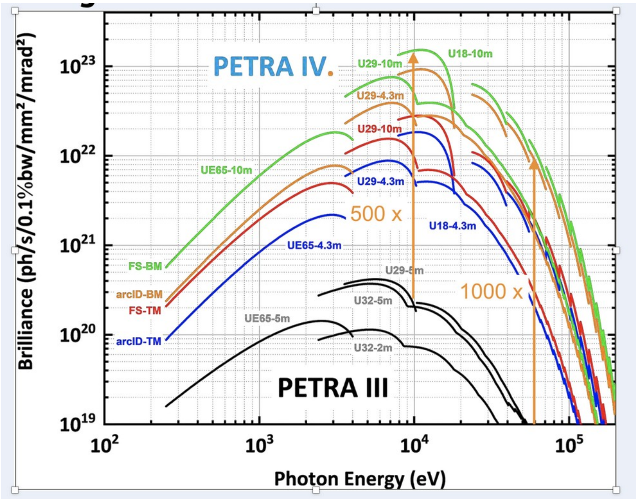




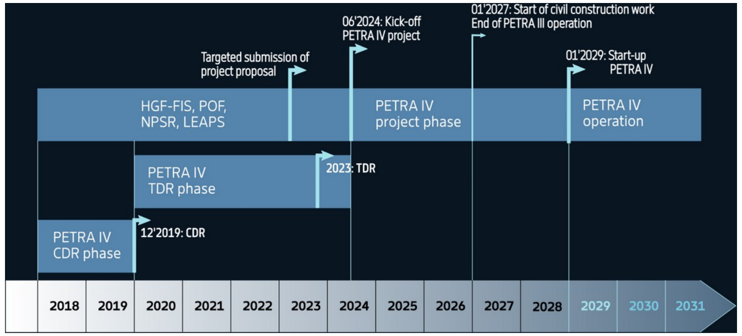




Higher brillance than PETRA III



	H6BA Lattice		PETRA III	
Parameter	brightness mode	timing mode	continuous	timing mode
Number of Bunches	1600 - 1920	80 (40)	480 - 960	40
Total current / mA Bunch current / mA	200 0.125	80 (80) 1.0 (2.0)	120 0.25 - 0.125	100 2.5
Arc ID β_x/β_y / m long ID β_x/β_y / m	2.2 / 2.2 4.0 / 4.0		high β: 20.0 / 4.0 low β: 1.4 / 4.0	
Hor. Emittance ε_x / pmrad Vert. Emittance ε_y / pmrad	20 5	35 (38) 7 (8)	1300 10	
Bunch length σ_z / ps Bunch separation / ns	30 4	65 (75) 96 (192)	40 16 - 8	43 192
Energy spread σ_p / 10^{-3} Touschek lifetime τ / h	0.9 > 10	1.2 (1.5) > 5	1.3 9 - 13	1.3 1.5
Number of beamlines	33 — 35 + 1 VUV		26 + 1 VUV	



I. Agapov, T. Charles, R. Tomas

FCC-ee and PETRA

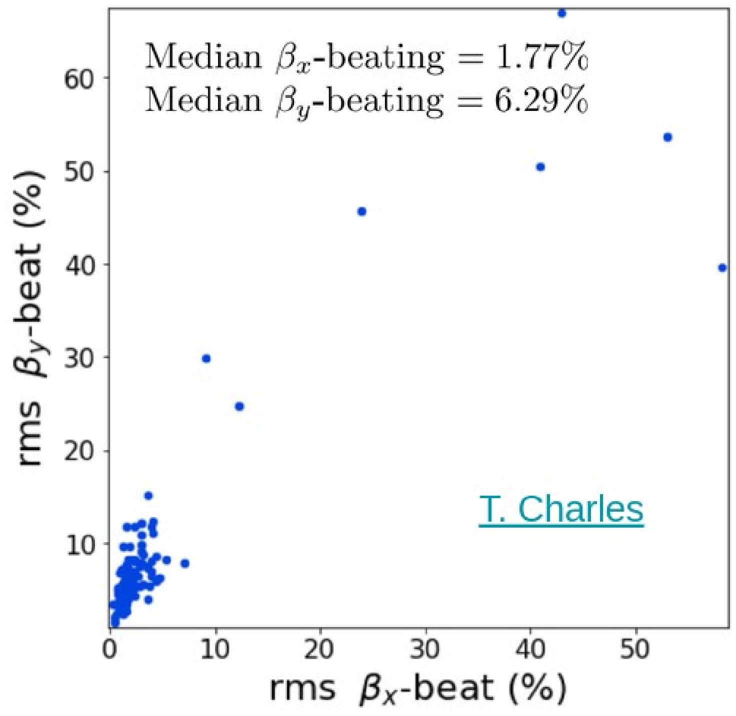
- FCC-ee and PETRA III (IV) have **comparable vertical emittance of < 10 (3) pm**
- Very tight alignment tolerances for girders and elements
- Understand vertical emittance growth from not corrected misalignments

PETRA IV tolerances

- Magnet errors
  - Dipole offset = 50 µm
  - Other magnets offset = 30 µm
  - Girder offset = 50 µm
  - Girder roll = 200 µrad
  - Magnet roll = 200 µrad
  - Magnet calibration = 1E-3

Type	ΔX (µm)	ΔY (µm)
Arc quadrupole*	50	50
Arc sextupoles*	10	10
Dipoles	1000	1000
Girders	150	150
IR quadrupole	100	100
IR sextupoles	10	10

Assuming beam-based alignment possibly with movers+BPMs+displacement sensors (design concept needed to reach 10 µm).



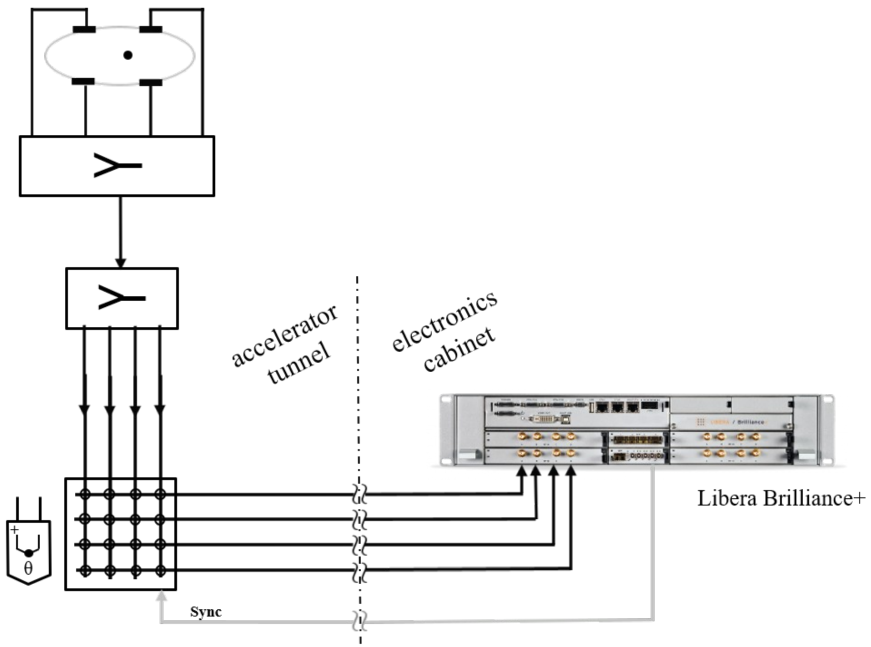
BPM System for PETRA IV

long term stabilization scheme including cable paths

F. Schmidt-Föhre *et al.*, Proc. IBIC 2021, Pohang (Korea) MOPP36.

- pilot tone compensation
- external crossbar switching

performance studies at PETRA III



long-term drift study

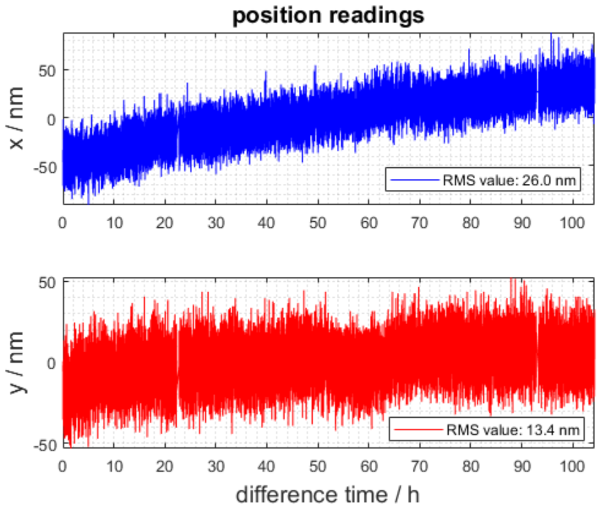
G. Kube *et al.*, Proc. IBIC 2022, Krakow (Poland) WEP08.

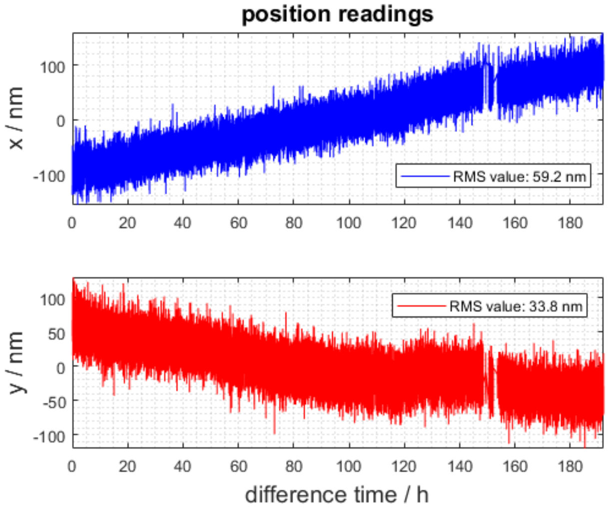
continuous mode

- 480 bunches @ 120 mA

timing mode

- 40 bunches @ 100 mA



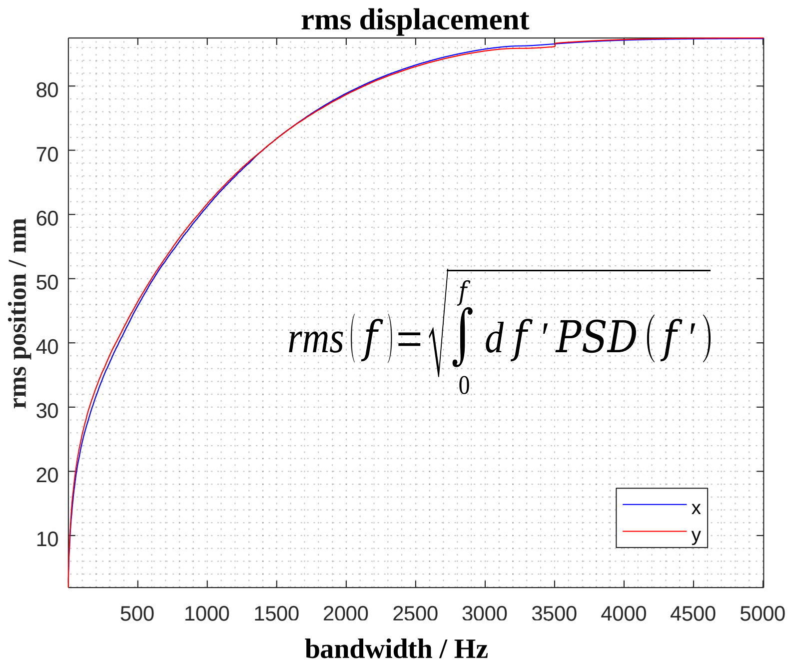


→ well within specifications < 1μm

BPM Tests at PETRA III

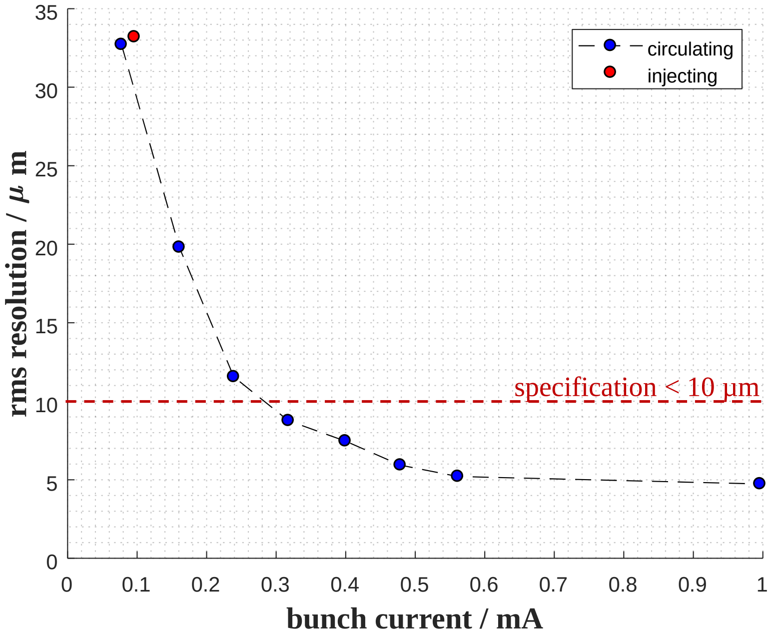
Additional Measurements

Closed Orbit Resolution



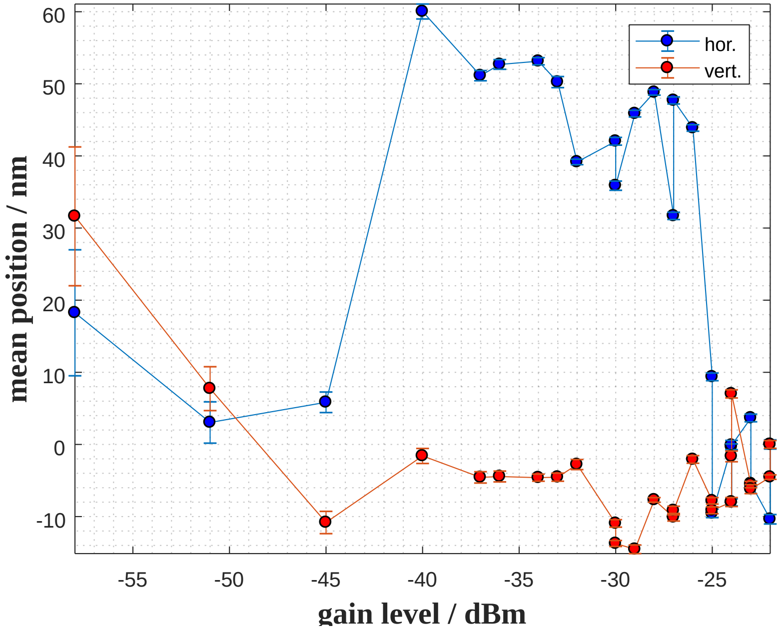
< 100 nm (rms)
@ 1 kHz BW

Single Bunch (Single Turn) Resolution



< 10 µm
0.5 mA bunch current

Beam Current Dependency (SA)



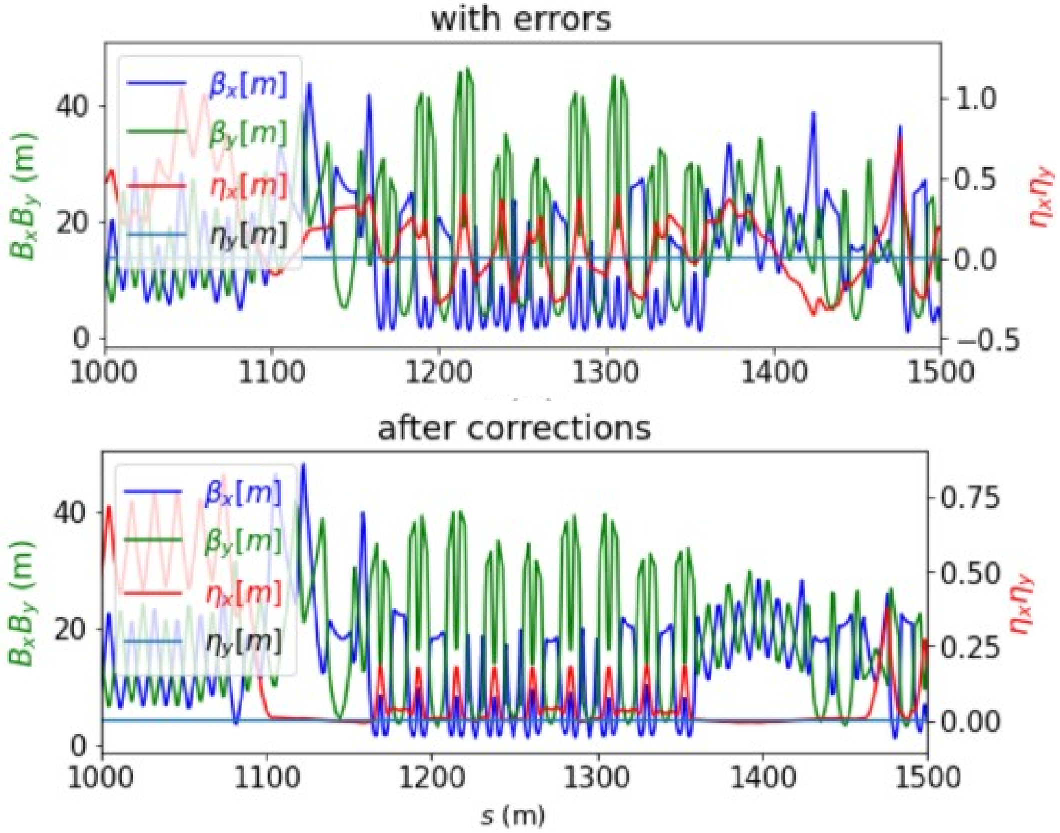
± 2 µm
60 dB range, centered beam

→ well within specifications

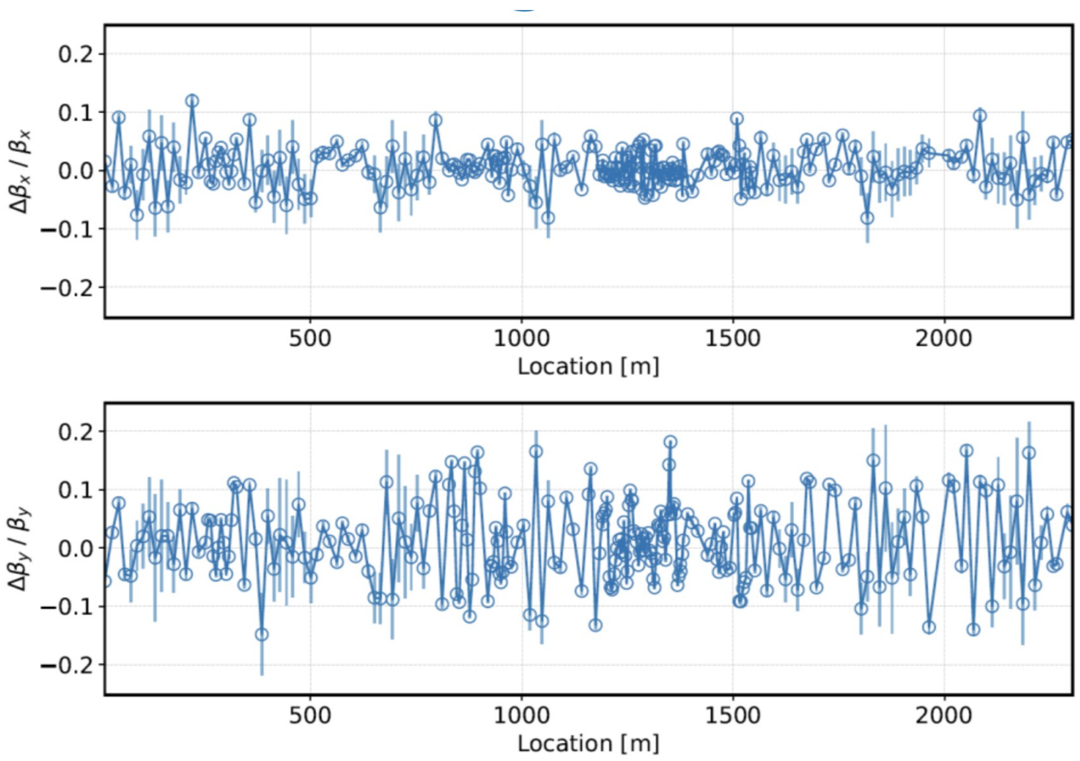
L. Malina, E. Musa

Optics Measurements

- Errors applied to PETRA III lattice
- LOCO successfully applied
- Presently also being explored for FCC-ee



- Optics measurements with AC-dipole
- Aim for faster optics measurements and corrections compared to ORM



Thank you!

I. Agapov, Jacqueline Keintzel, and Rogelio Tomás

On behalf of

The FCC-ee collaboration

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FCC-IS Workshop 2022

WP2: Accelerator

8th December 2022

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Amplitude Detuning

- No SR, with sextupoles