Prospects for Optics Measurements in FCC-ee

Jacqueline Keintzel, Rogelio Tomás and Frank Zimmermann

Acknowledgements:

FCC-ee collaboration, FCC-ee tuning group, CERN accelerator and beam physics group, SuperKEKB accelerator and operation groups

LEL 2022 – Workshop on Low Emittance Lattices

Session on Errors, Alignment and Correction

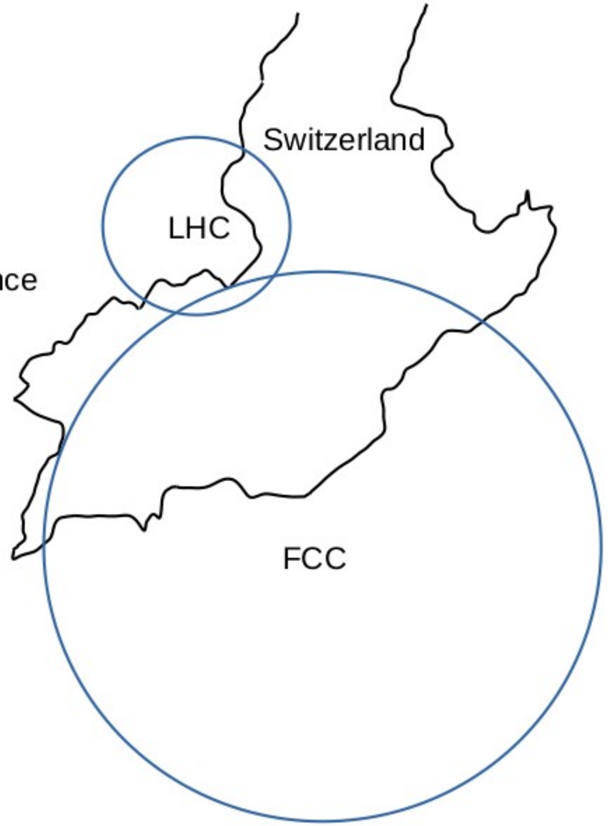
28th June 2022

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.

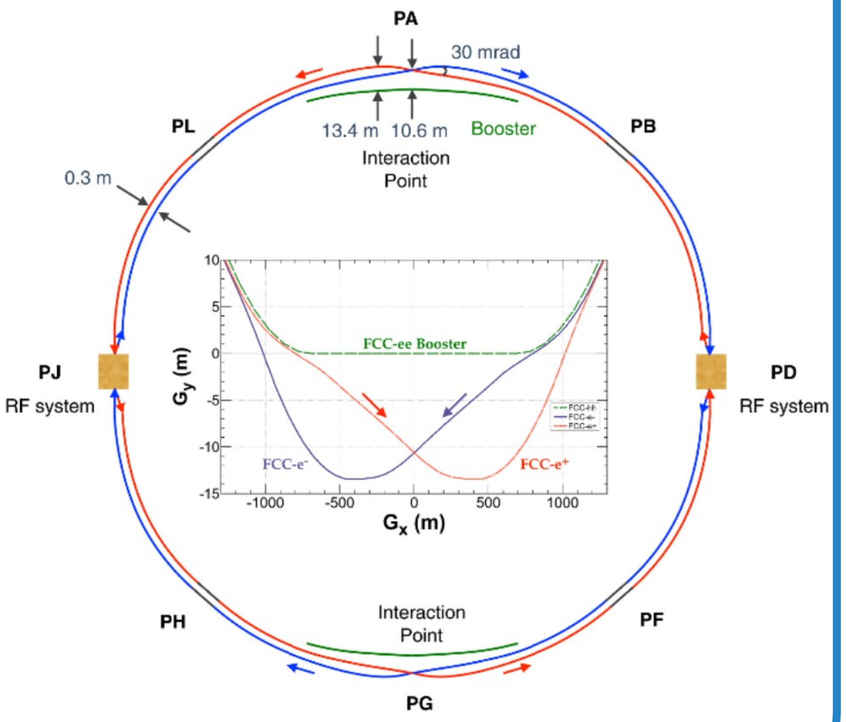
Future Circular Colliders

Inspired by LEP-LHC programm

Re-using CERN infrastructure

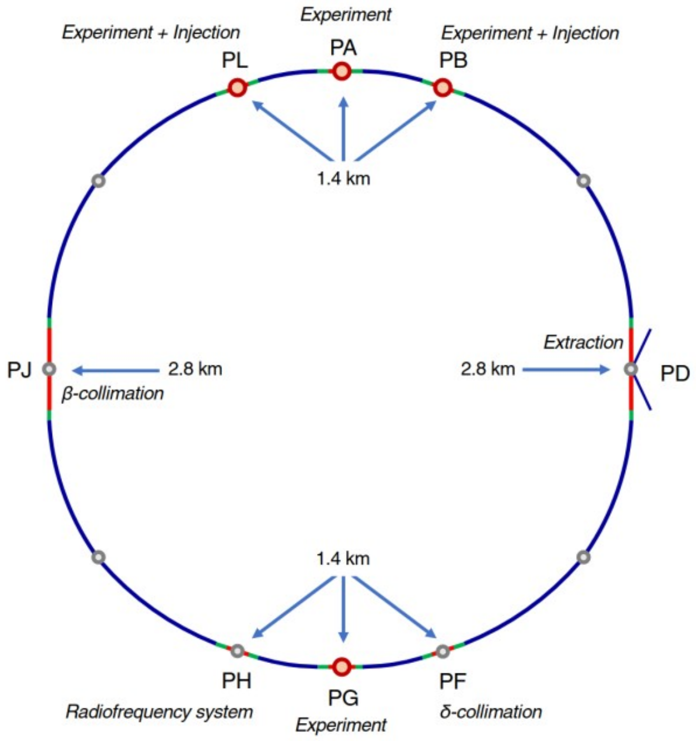


FCC-ee
Electron-positron collider



M. Benedikt et al. (ed), FCC CDR, Eur. Phys. J. Spec. Top. 228, p. 261-623, 2019.

FCC-hh
Proton-proton collider

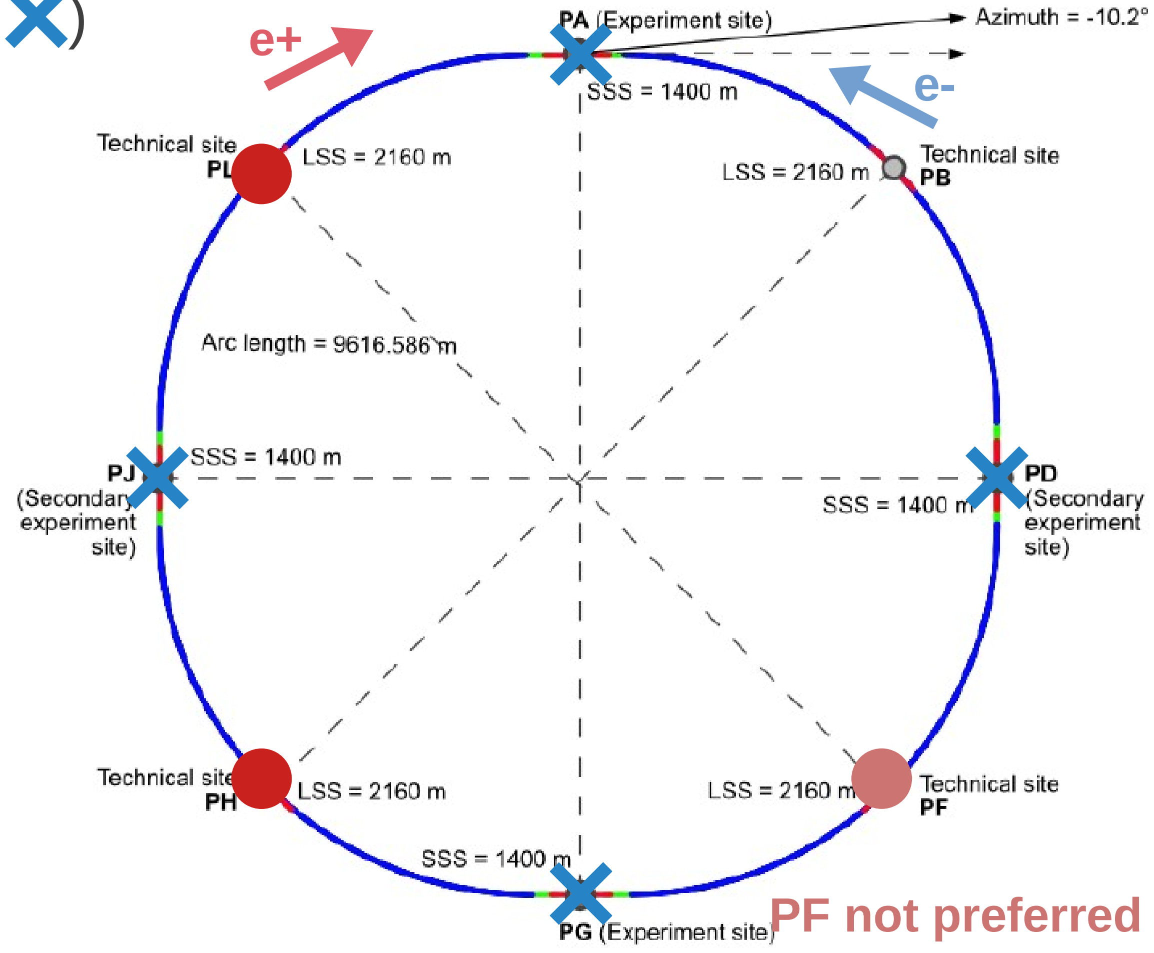


M. Benedikt et al. (ed), FCC CDR, Eur. Phys. J. Spec. Top. 228, p. 755-1107, 2019.

Introduction FCC-ee

- FCC-ee baseline with 4 Interaction Points (IPs ✕)
- Electron-positron double ring collider
- 4 different energy stages, with beam energies:
  - 45.6 GeV, at the Z-pole
  - 80 GeV, at the W-pair-threshold
  - 120 GeV, for ZH-operation
  - 182.5 GeV, above ttbar-treshold
- 1 RF-section for Z-, WW-, ZH-operation
- 2 RF-sections for highest beam energy (●)

FCC-week took place recently and progress reported on numerous topics:
https://indico.cern.ch/event/1064327/



M. Hofer and K. Oide, FCC Week 2022.

Introduction FCC-ee

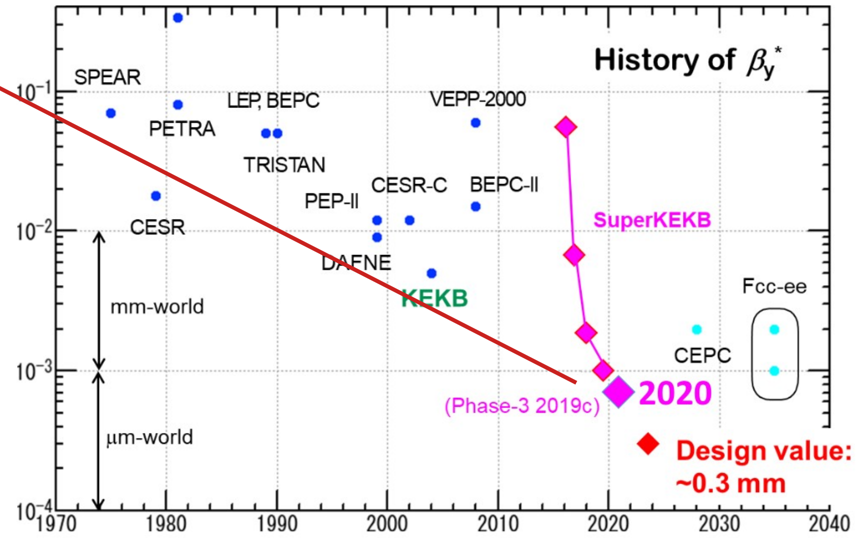
0.8 mm β_y* already achieved in SuperKEKB

Extremely low vertical β-function of 0.8 mm at the IPs

	Z 45.6 GeV	ttbar 182.5 GeV
Circumference [km]	91.17	
Hor. Emittance [nm]	0.71	1.49
Ver. Emittance [pm]	1.42	2.98
β_x* / β_y* [mm]	1000 / 0.8	1000 / 1.6
Synchrotron radiation loss/turn [GeV]	0.040	10
Luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	182	1.24

M. Hofer and K. Oide, FCC Week 2022.

Severe synchrotron radiation losses, i.e. 5 % of the beam energy per turn at highest beam energy



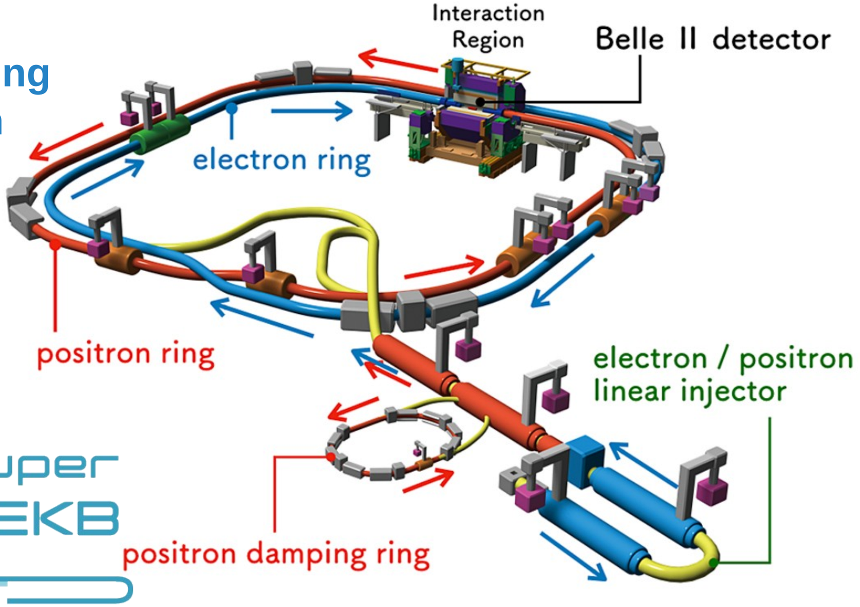
www-superkekb.kek.jp

FCC-ee designed for high precision physics experiments → demands precise optics control and thus accurate optics measurement techniques

FCC-ee: The Challenge

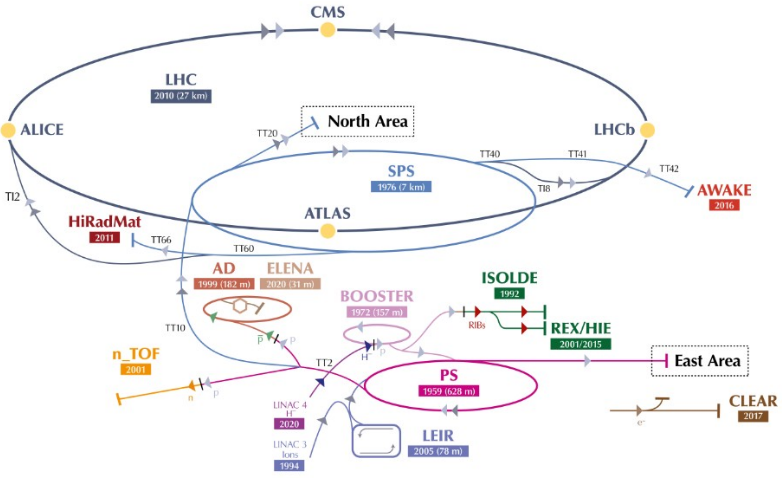
SuperKEKB:
Electron-positron double ring collider
Similar colliding scheme as FCC
Similar arc layout as FCC
Record luminosity of 4.65 x 10^{34} $cm^{-2}s^{-1}$
SuperKEKB is a small version of FCC-ee!

International Task Force formed, including dedicated optics working group to push performance of SuperKEKB further:
https://kds.kek.jp/category/2242/



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

- FCC-ee would be **commissioned around 2045**
  - Experience from existing facilities inevitable



E. Mobs, The CERN accelerator complex - 2019, 2019.

Optics Measurements and Corrections (OMC) team at CERN
Experience on LHC, PS, PSB, LEAR, SuperKEKB, IOTA, PETRA III, ESRF:
https://pylhc.github.io/

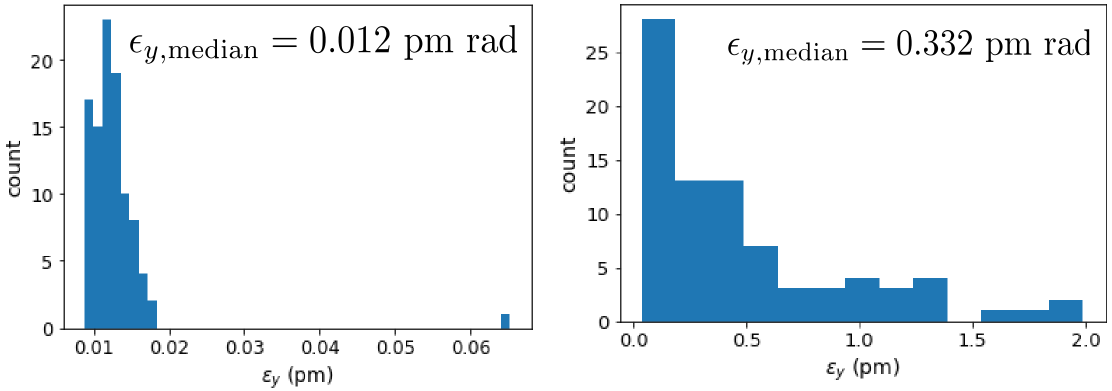
Other examples of beam tests for the FCC-ee:
J. Keintzel, Experimental beam tests for FCC-ee, 10.22323/1.398.0877, 2022.

FCC-ee: The Challenge

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔDTHETA (μrad)	ΔDPHI (μrad)	Field Errors
Arc quadrupole*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	1000	1000	300	1000	0	0	$\Delta B/B = 1 \times 10^{-4}$
Girders	150	150	-	1000	-	-	-
IR quadrupole	100	100	250	250	100	100	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	100	100	250	250	100	100	$\Delta k/k = 2 \times 10^{-4}$

T. Charles, FCC Week 2022.

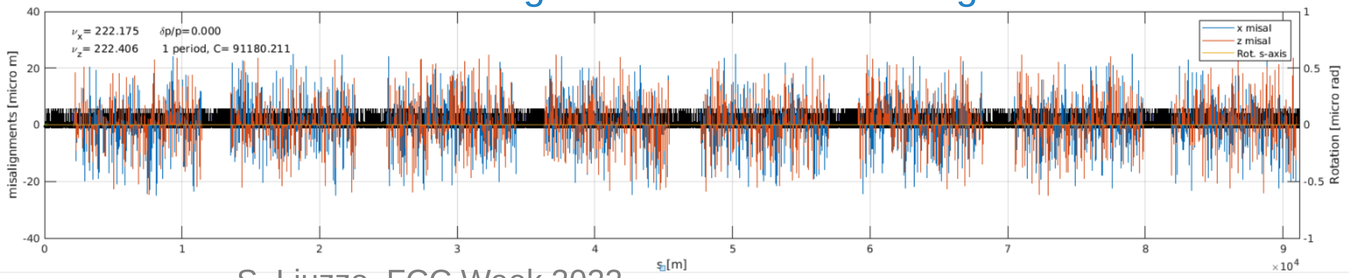
Presently considered alignement and gradient tolerances for optics tuning studies
Final emittances for 100 seeds and ttbar-lattice without (left) and with (right) chromaticity correction
Right: 8 largest emittances removed



T. Charles, FCC Week 2022.

- FCC-ee would be **commissioned around 2045**
  - Experience from existing facilities inevitable
- **Unprecedented size** of almost 100 km
  - Alignment requirements similar to light sources

Simulated effect of misalignments in FCC-ee using ESRF tools



S. Liuzzo, FCC Week 2022.

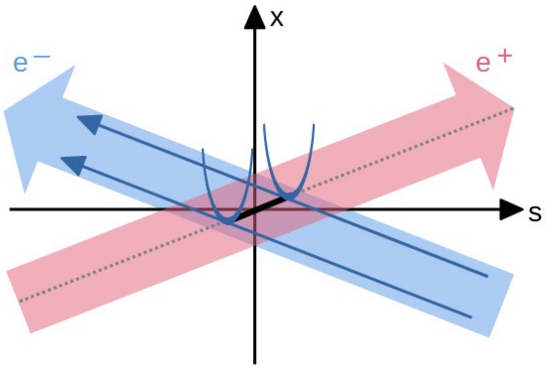
Continous progress in FCC-ee tuning working group:
https://indico.cern.ch/event/1167740/

Dedicated optics tuning and alignment workshop:
https://indico.cern.ch/event/1153631/

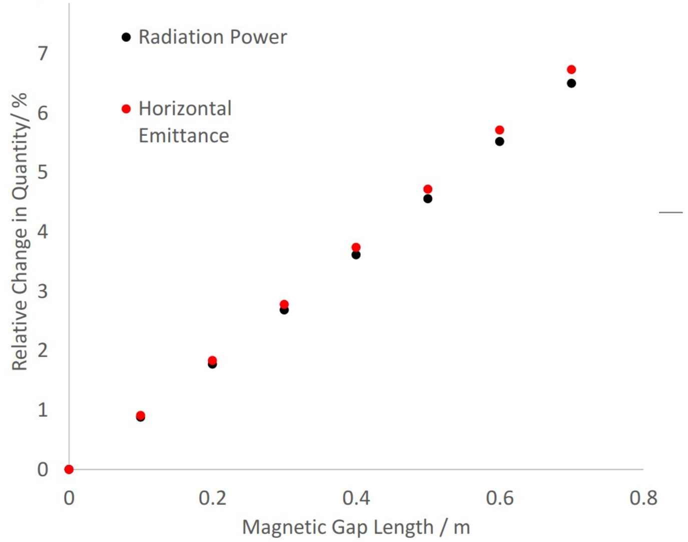
FCC-ee: The Challenge

Crab-waist collision optics
Can enhance resonances
and limit dynamic aperture

D. Shatilov, FCC Week 2022.

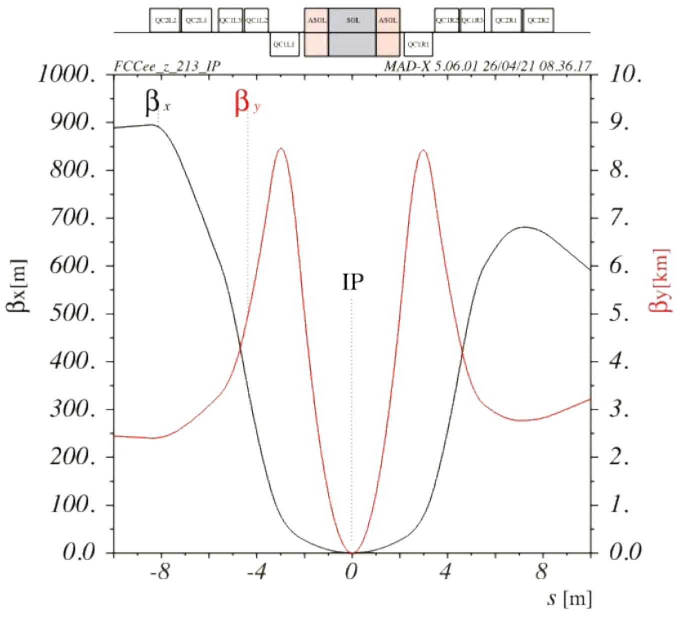


Recent study showing the emittance growth due to larger magnet gaps



L. van Riesen-Haupt, FCC Week 2022.

- FCC-ee would be **commissioned around 2045**
  - Experience from existing facilities inevitable
- **Unprecedented size** of almost 100 km
  - Alignment requirements similar to light sources
- Extremely **small β_y*** of up to 0.8 mm
  - Challenging (final focus) optics
- Demands also robust and accurate modeling



H. Burkhardt, FCC Week 2022.

Interaction region optics
β-function changes by 7 orders of magnitude
→ Alignment and tuning even more crucial in this region

FCC-ee: The Challenge

How can various beam optics measurement techniques be applied to the FCC-ee?
What are their merits and limitations?
How can the FCC-ee benefit from existing state-of-the art storage ring colliders?

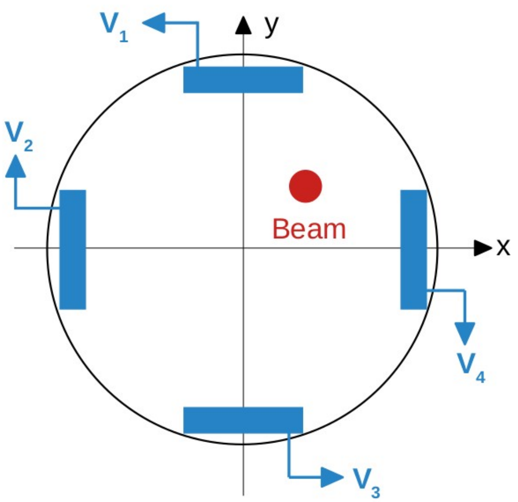
- FCC-ee would be **commissioned around 2045**
  - Experience from existing facilities inevitable
- **Unprecedented size** of almost 100 km
  - Alignment requirements similar to light sources
- Extremely **small β_y*** of up to 0.8 mm
  - Challenging (final focus) optics
- Demands also robust and accurate modeling

Needs to be considered for studies of suitable optics measurement techniques

Beam Position Monitors

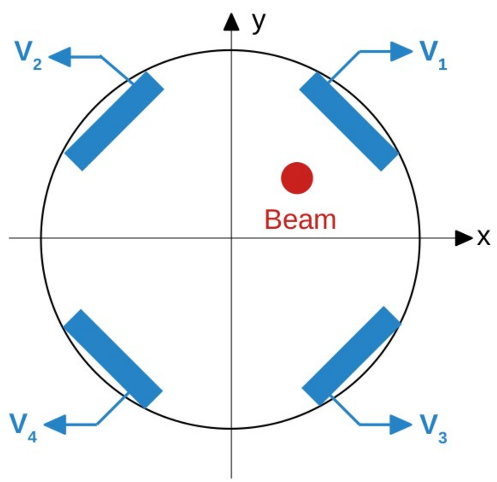
- Beam Position Monitors (BPMs) are crucial devices for beam optics measurements
- Button BPMs are the most common type, spoiled by resolution, calibration, non-linearity, ...

Hadrons:



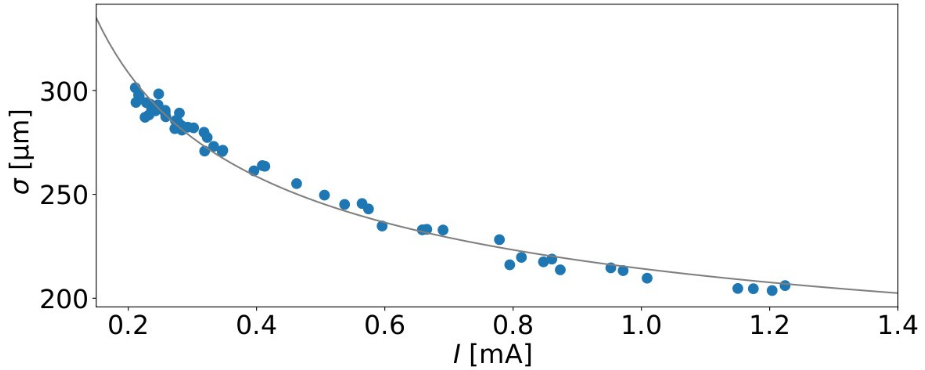
Buttons typically aligned on the transverse axes

Leptons:

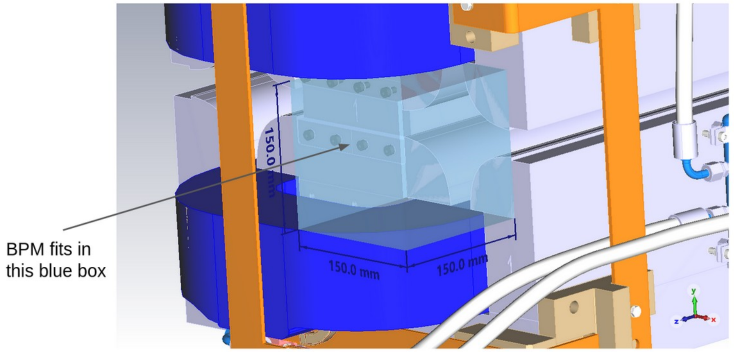


Buttons typically rotated by 45° due to strong synchrotron radiation

Single bunch measurements for SuperKEKB positron ring with 4 GeV
Estimated BPM resolution improves with bunch intensity



BPMs could be installed next to every quadrupole
Would require about 1800 BPMs
No additional space presently presumed



M. Wendt, FCC Alignment and Tuning Workshop, 2022.

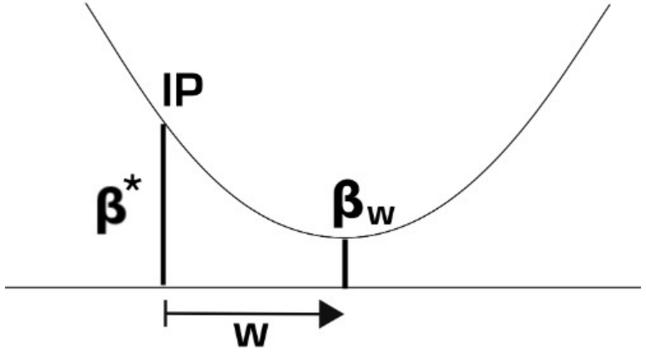
K-Modulation

- 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

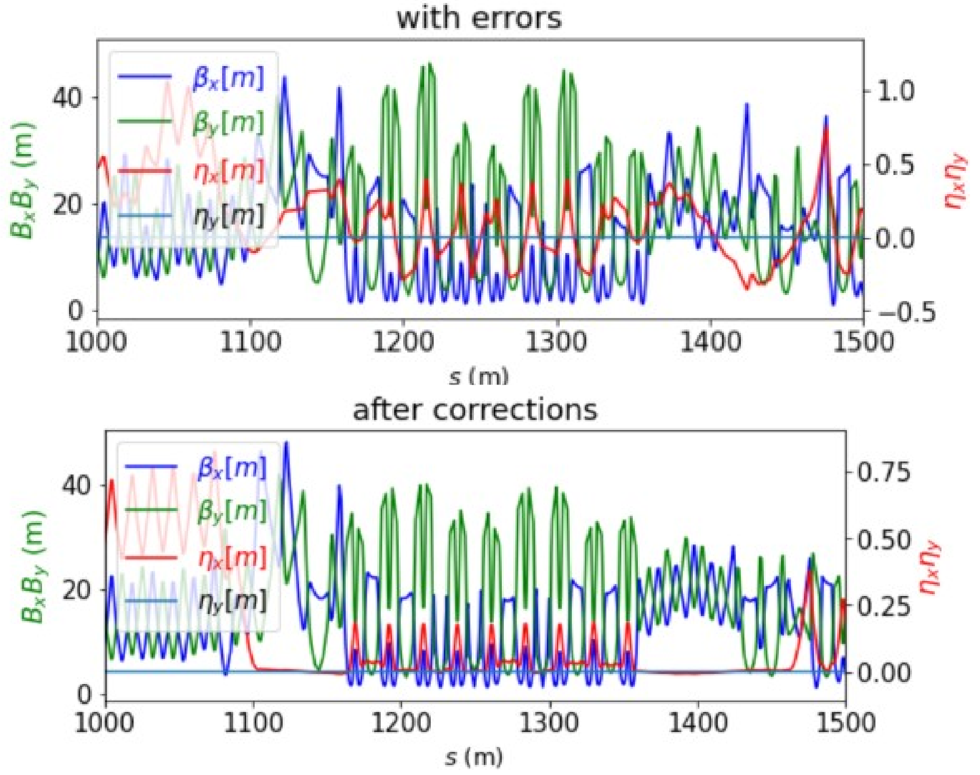
Hysteresis from magnets could disturb optics
Fewer problem with superconducting magnets

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

Orbit Response Matrix

- Orbit correctors excite the beam, average orbit recorded
- Optics then retrieved by analytical equations

In PETRA III: LOCO tested and currently explored for FCC-ee



E. Musa, FCC-ee tuning meeting, 9th June 2022.

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

H. Sugimoto, Optics Correction at SuperKEKB, presented at the 1st SKEKB ITF meeting, 2021.

Orbit Response Matrix

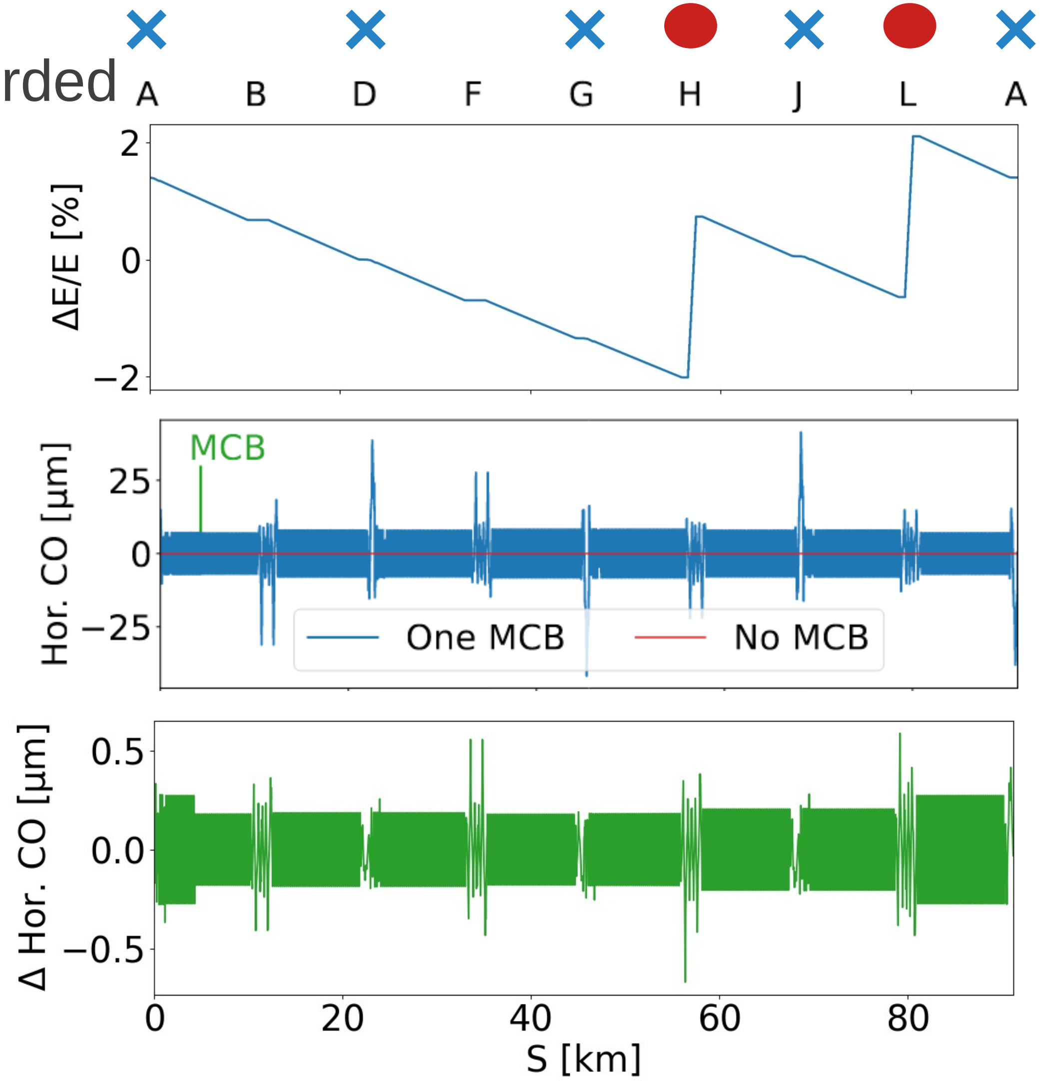
- Orbit correctors excite the beam, average orbit recorded
- Optics then retrieved by analytical equations

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

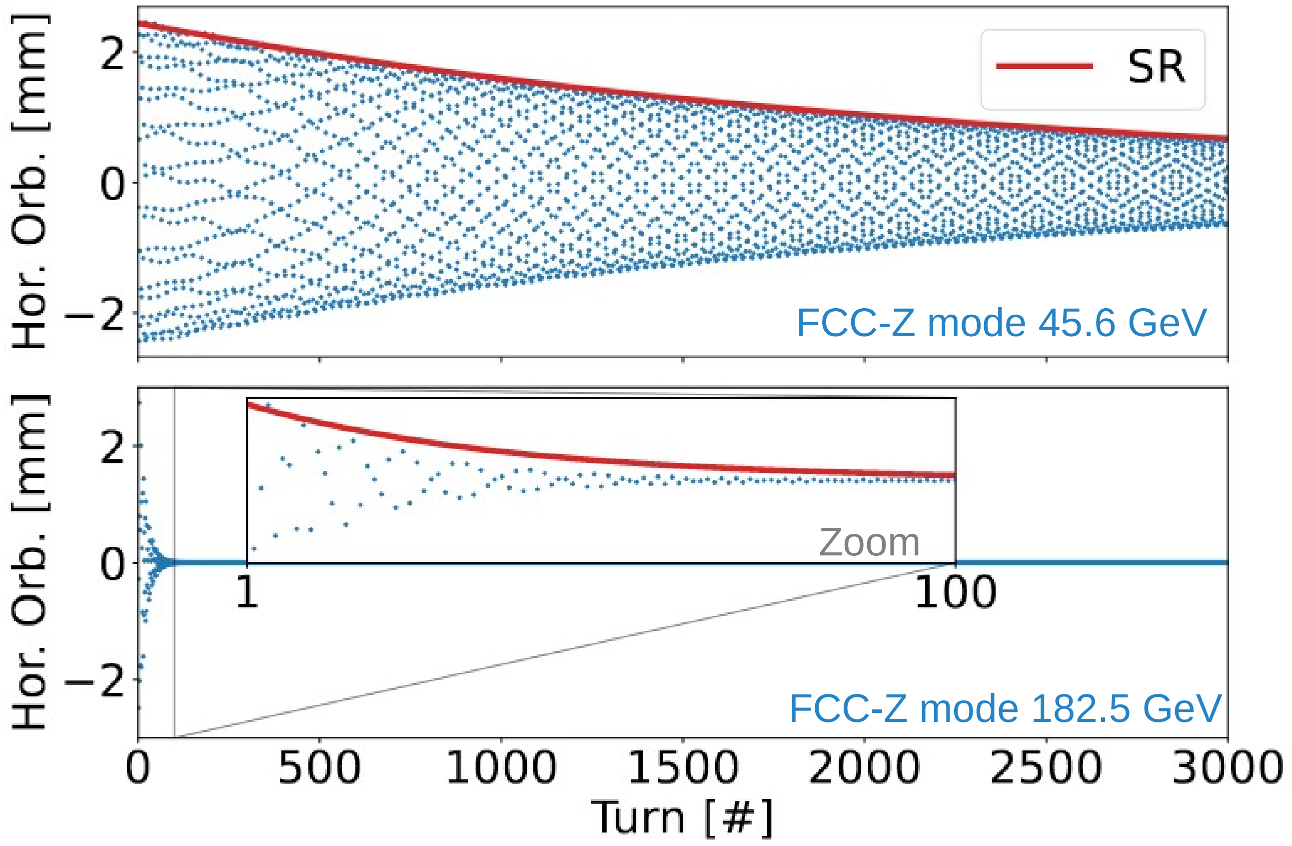


Turn-by-Turn Measurements

- 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**

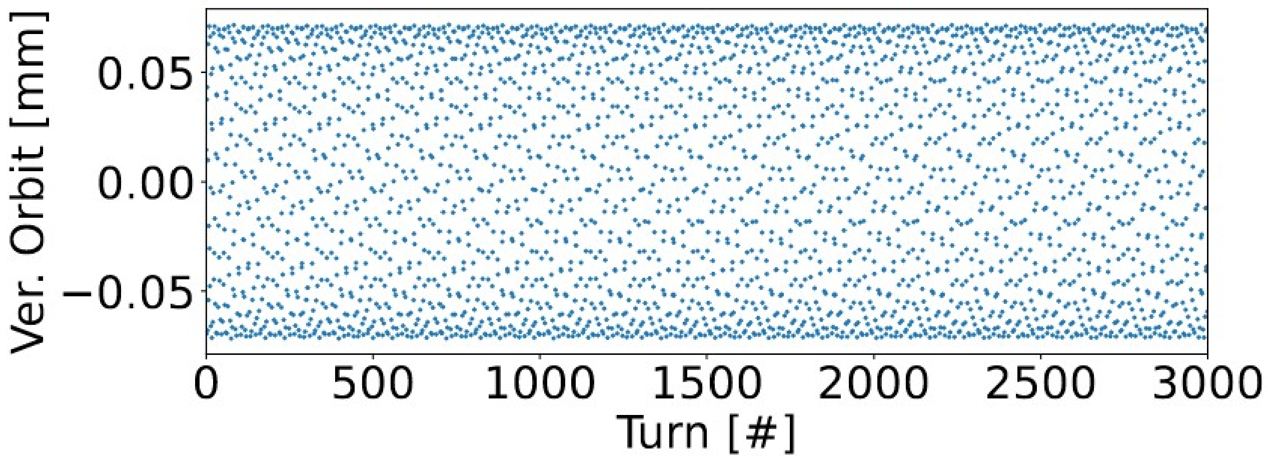
Bottom: FCC-ttbar mode 182.5 GeV beam energy
Damping of single particle tracking orbit after $10\sigma_x$, $10\sigma_y$ kick
40 turns damping time
→ **Too fast to be used for TbT measurements**

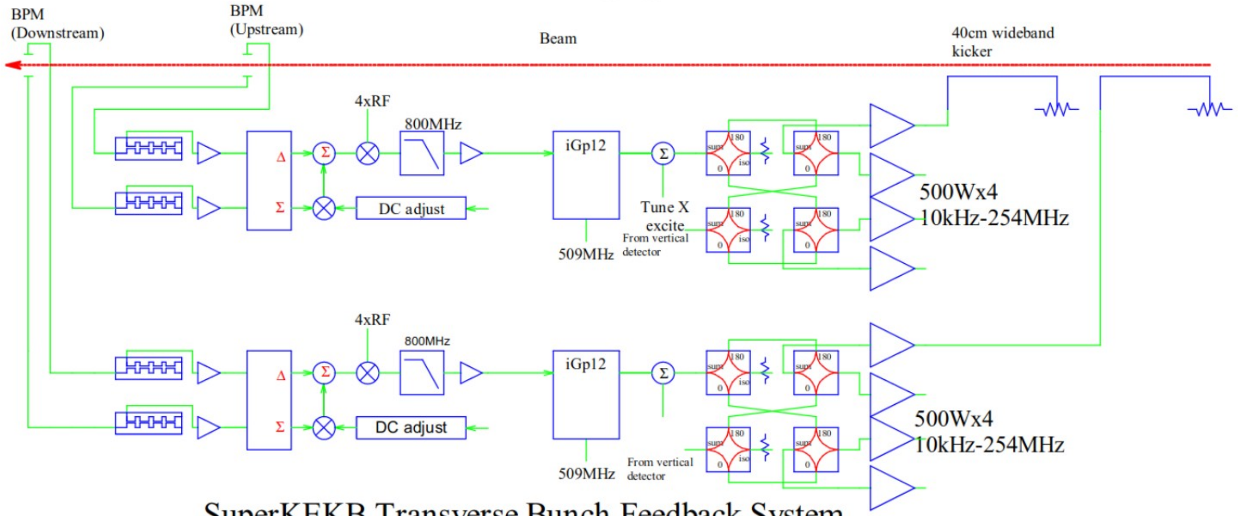


Turn-by-Turn Measurements

- 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

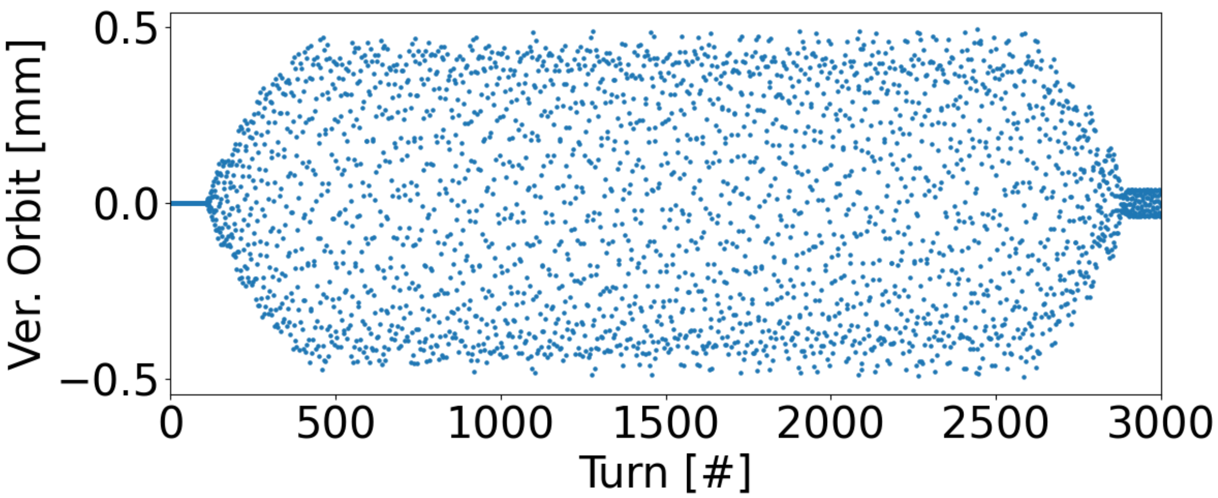
Continous excitation achieved in SuperKEKB using transverse feedback system and amplification
+ Drives the beam at the natural tune (no compensation)
- Typically limited in amplification (low excitation)

Turn-by-Turn Measurements

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

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

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

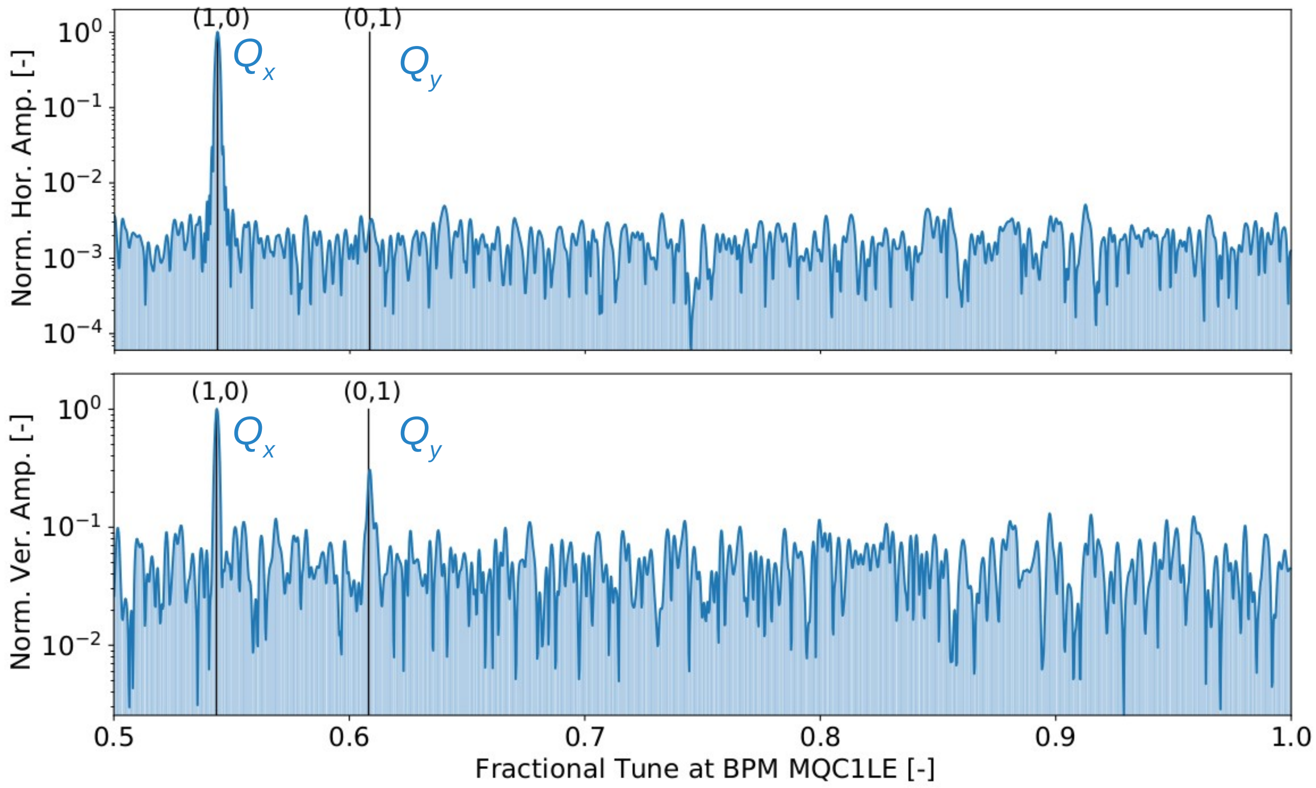


AC-dipole excitation ramps up and down adiabatically
→ ramping needs to be slow enough to avoid emittance growth
- Drives the beam close to the natural tune (dedicated compensation techniques in analysis required)
+ Typically sufficient amplitude (larger excitation)

Turn-by-Turn Measurements

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

Example of horizontal and vertical frequency spectrum, obtained by Fourier transformation of cleaned TbT orbit data



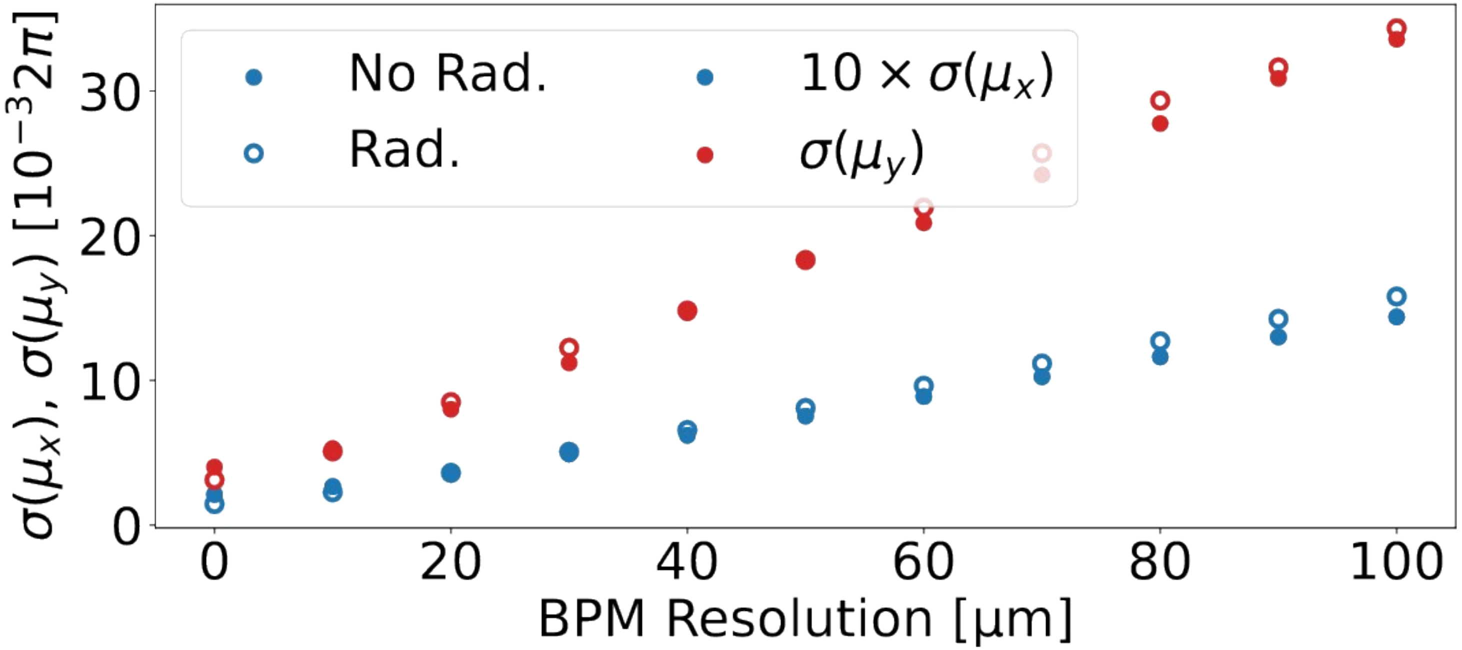
For example: β-function from phase advances

$$\beta_u^{\mathrm{ph}}(i) = \frac{\cot\left(\varphi_u(i \to j)\right) + \cot\left(\varphi_u(i \to k)\right)}{\frac{M_{11}(i \to j)}{M_{12}(i \to j)} + \frac{M_{11}(i \to k)}{M_{12}(i \to k)}}$$

BPM Errors and Phase Advance

- Relative rms phase advance error with respect to the model used for figure-of-merit for quality of TbT measurements
- First TbT tracking over 500 turns for FCC-Z mode and 360 installed BPMs
- With and without synchrotron radiation
- Kick amplitude of $6\sigma_x$, $6\sigma_y$
- Gaussian BPM noise applied

FCC-Z mode at 45.6 GeV single particle tracking



Including radiation damping has no significant impact on phase error

Phase error increases with increasing BPM noise

Effect on vertical plane 20 times more severe

Kick Strength and Phase Advance

- Relative rms phase advance error with respect to the model used for figure-of-merit for 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

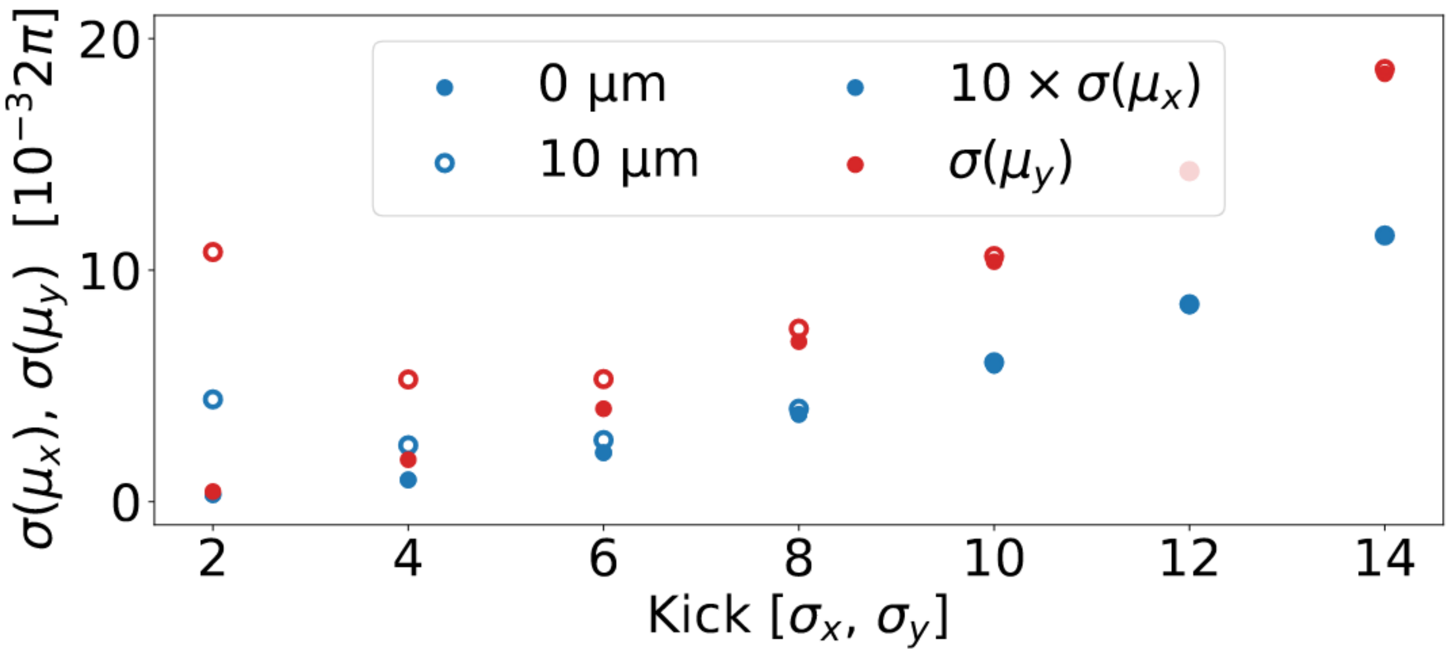
Without BPM noise phase error increases with increasing excitation strength

With BPM noise (here 10 µm) optimum kick strength found at 4 σx, 4σy

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



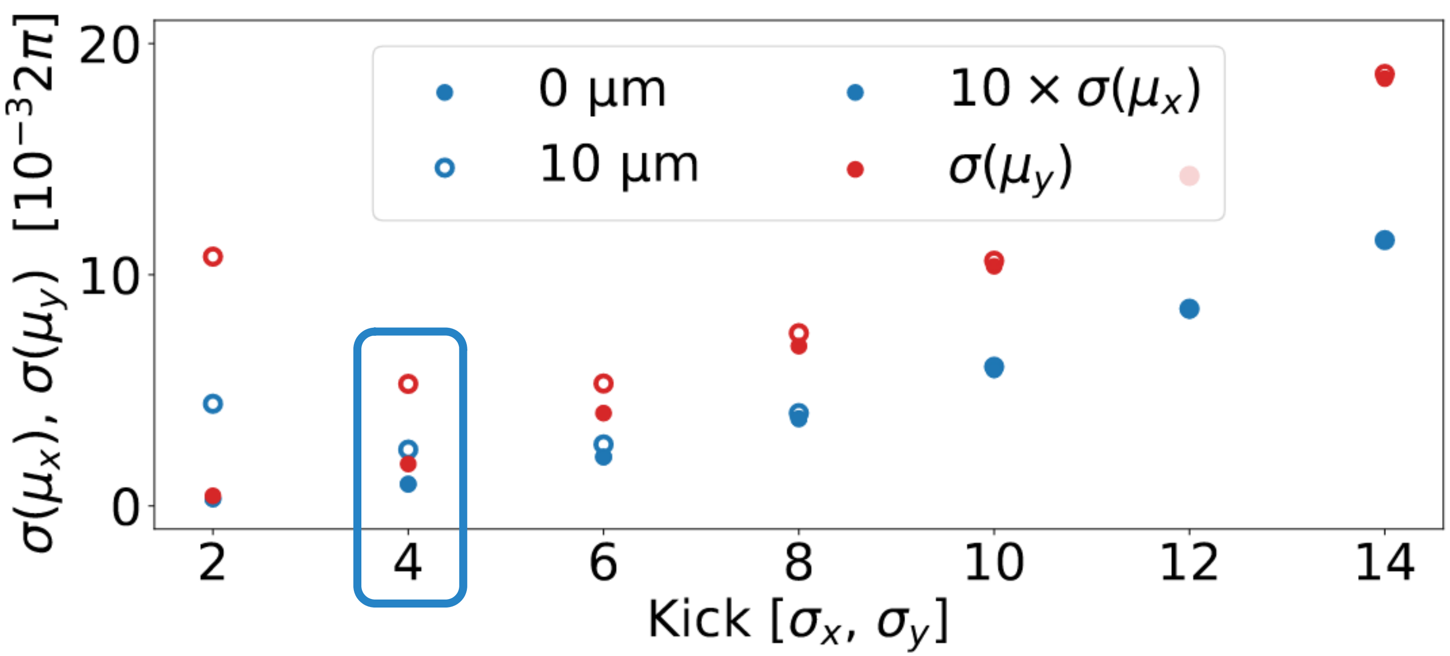
Kick Strength and Phase Advance

- Relative rms phase advance error with respect to the model used for figure-of-merit for 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

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)

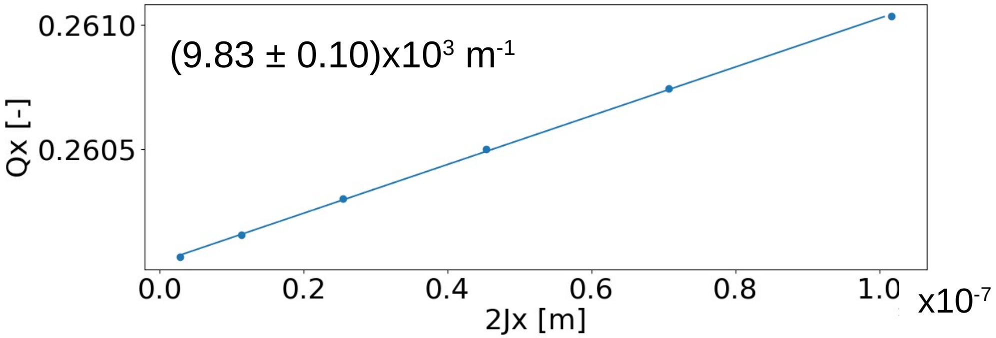
FCC-Z mode at 45.6 GeV single particle tracking



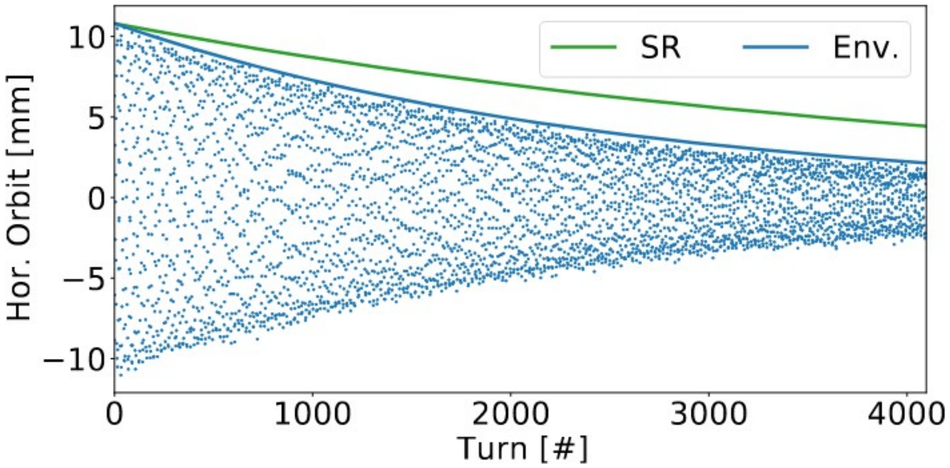
Single Kicks in Measurement

- After kick is applied, orbit is affected by
  - Synchrotron radiation
  - Decoherence from tune spread
  - Head-tail effect and impedance
- Detailed analysis of SuperKEKB TbT data

Decoherence could result from chromaticity and amplitude detuning
FCC-Z mode at 45.6 GeV amplitude detuning



Qx’ = 1.70 ± 0.04 , Qx’’ = -22 ± 18



Measurements for SuperKEKB 4 GeV positron ring
Single bunch with rather low intensity of 0.3 mA

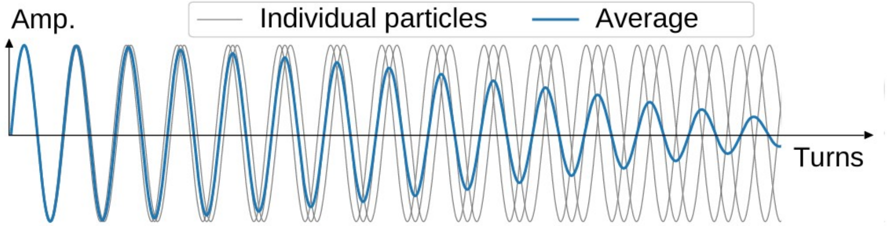
Faster damping after applying horizontal kick than predicted from synchrotron radiation

Since bunch current is low, additional damping tentatively attributed to decoherence
Impedance model presently being updated in SuperKEKB

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

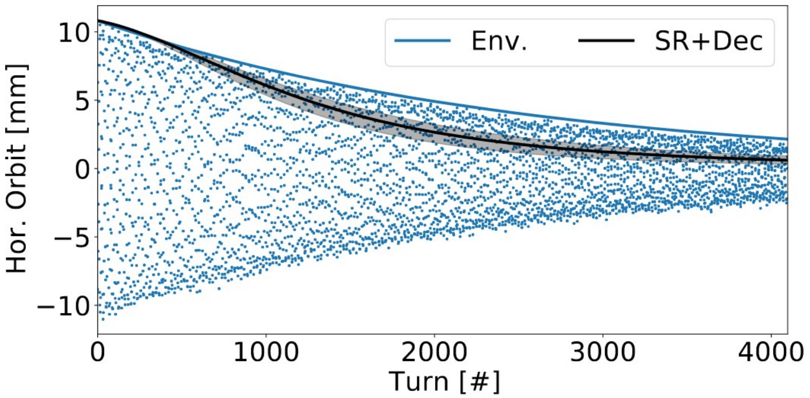
Existing theory for hadrons:

μ … Amplitude detuning   N … Turns
Z … Kick strength

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

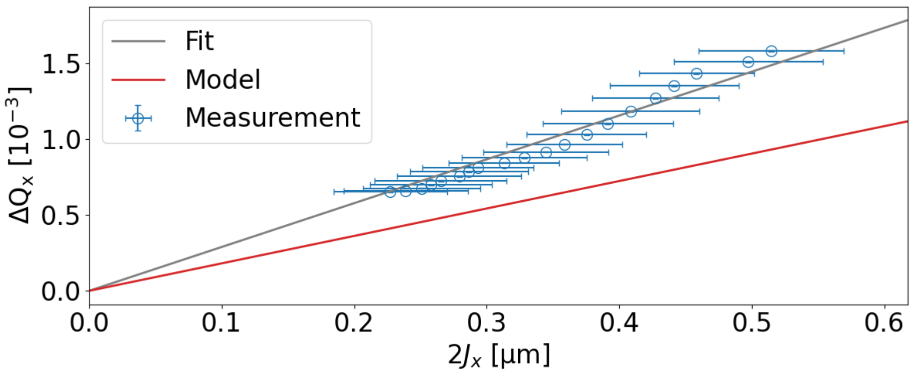
Here extended for leptons:

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



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



Summary

- Alignment, tuning, optics measurements and corrections crucial challenge for FCC-ee
  - Large combined effort from colleagues of numerous institutes

- Different optics measurement techniques presently being explored for FCC-ee
  - K-Modulation, orbit response matrix, turn-by-turn measurements

- Experience from existing facilities inevitable for further FCC-ee design study
  - E.g. novel description for lepton decoherence thanks to SuperKEKB experience

A lot of things to be explored and tested in the future!

Thank you!

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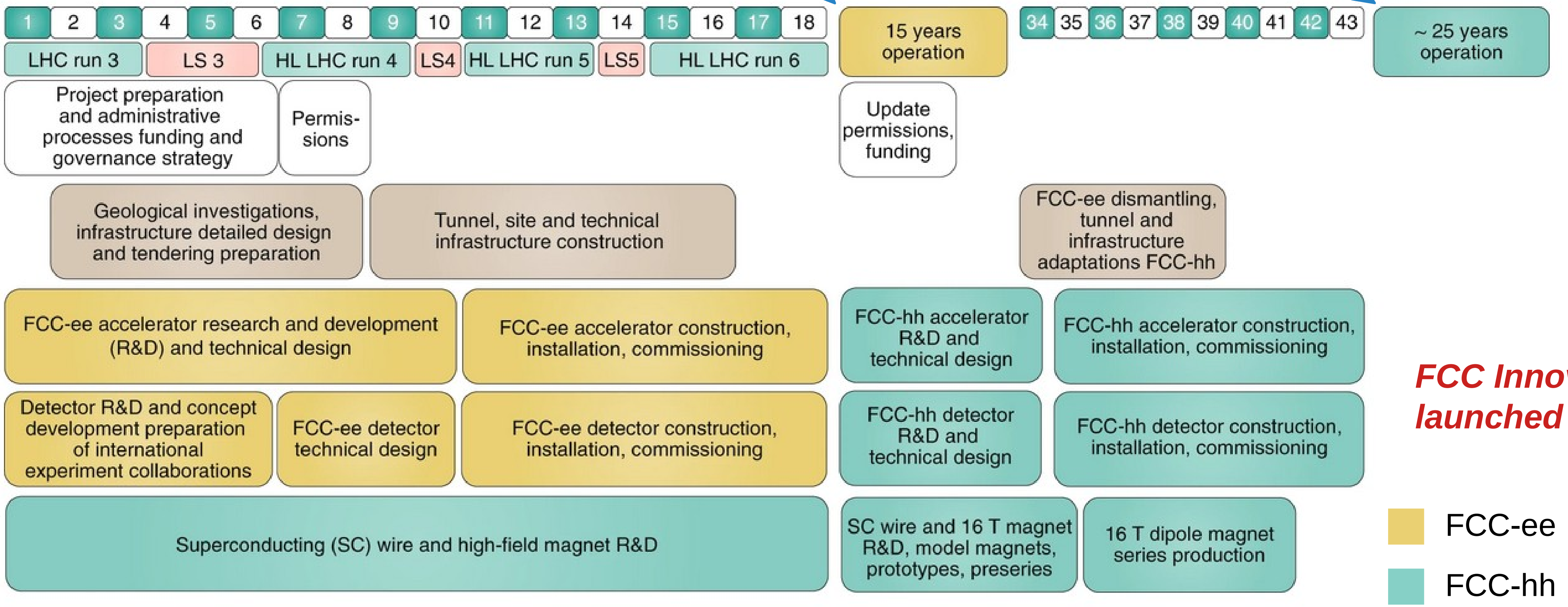
FCC Integrated Project

Lepton collider (FCC-ee) followed by hadron collider (FCC-hh)

FCC-ee commissioning around 2040

FCC-hh commissioning around 2065

Starts at 2021



FCC Innovation Study launched 2020

M. Benedikt et al., Nature Physics 16, 402-407, 2020.