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CIRCULAR  
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# Prospects for Optics Measurements in FCC-ee

Jacqueline Keintzel, Rogelio Tomás and Frank Zimmermann

Paper ID: TUOZSP1

Acknowledgements:

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

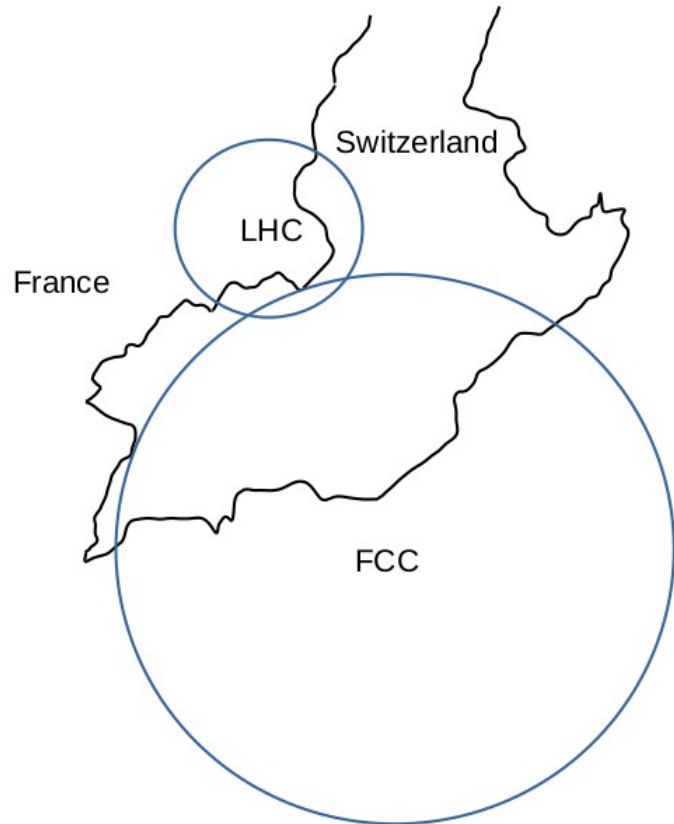
13<sup>th</sup> International Particle Accelerator Conference  
MC1 Circular and Linear Colliders  
14<sup>th</sup> June 2022



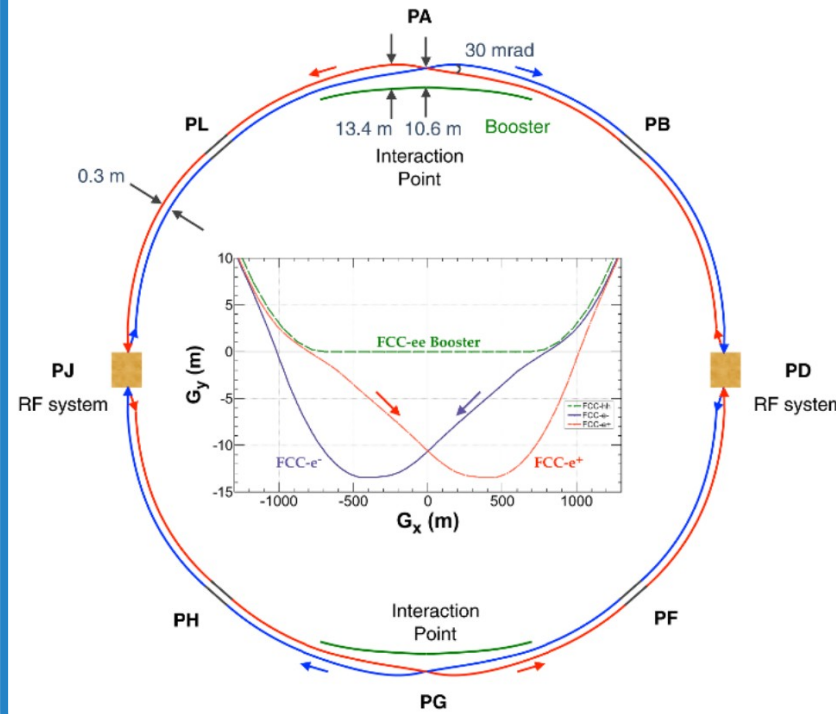
**FCCIS – The Future Circular Collider Innovation Study.**  
This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

# Future Circular Colliders

Inspired by LEP-LHC programm  
Re-using CERN infrastructure

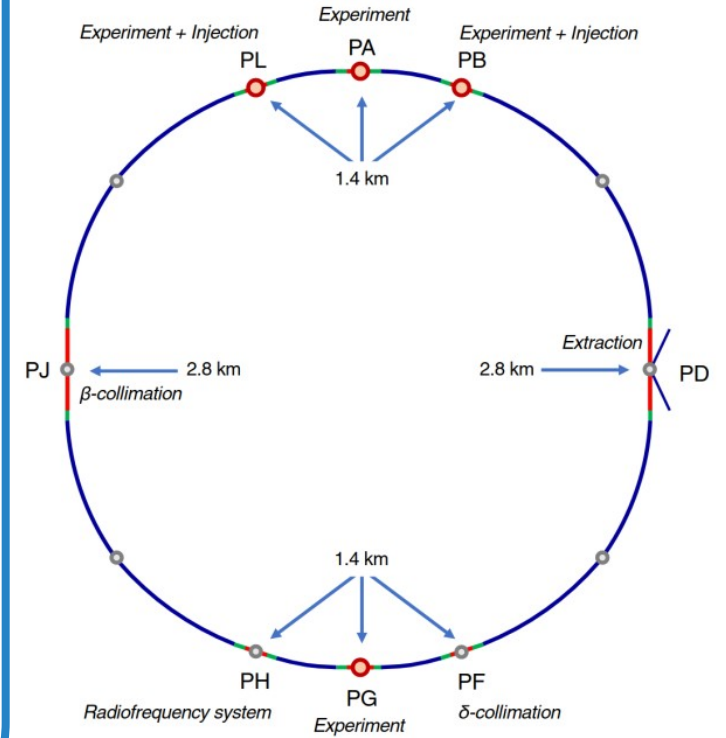


## FCC-ee Electron-positron collider



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

## FCC-hh Proton-proton collider



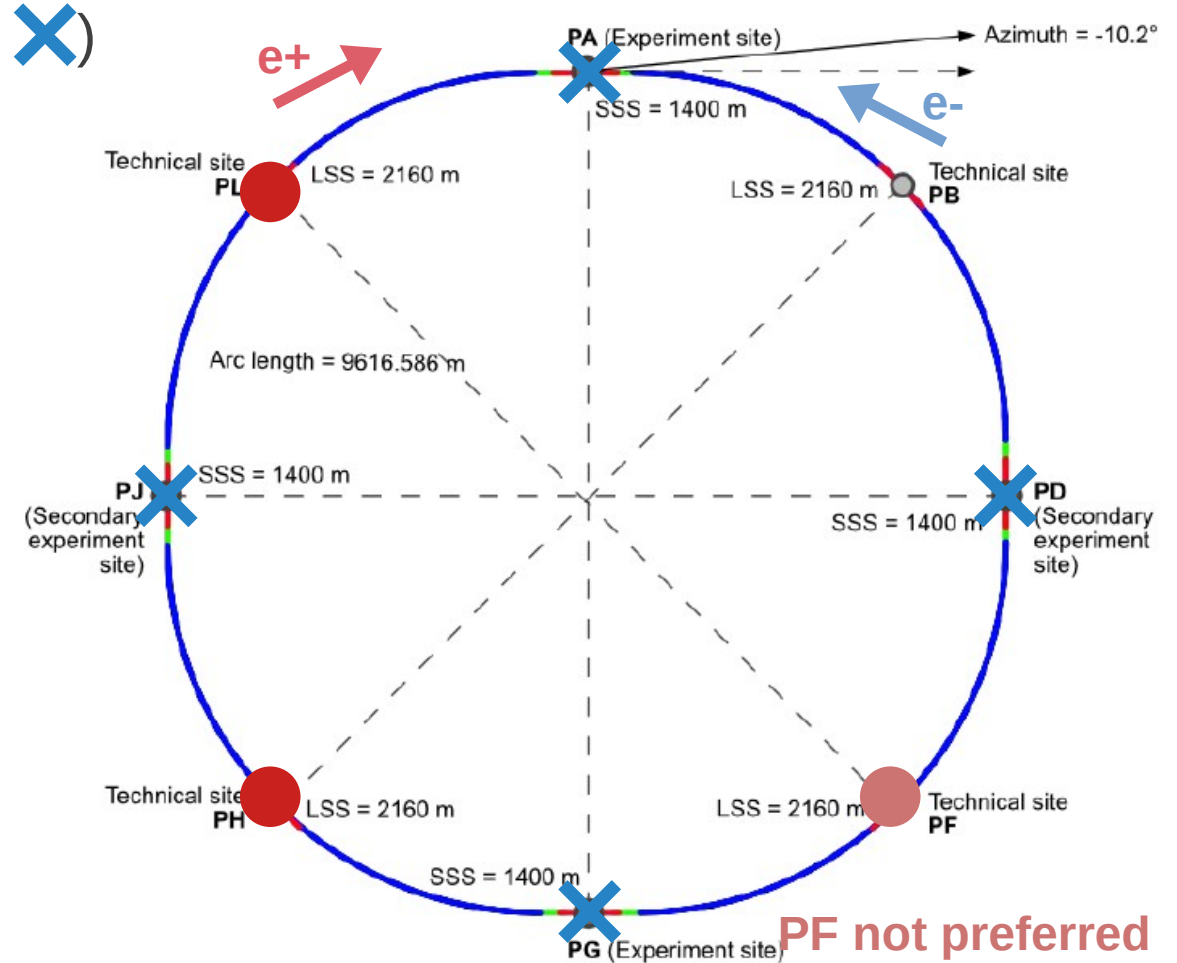
M. Benedikt et al. (ed), FCC CDR, Eur. Phys. J. Spec. Top. 228, p. 755-1107, 2019.

# Introduction FCC-ee

- FCC-ee baseline with 4 Interaction Points (IPs) **X**
- 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  $t\bar{t}$ -threshold
- 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.

**PF not preferred section**

# Introduction FCC-ee

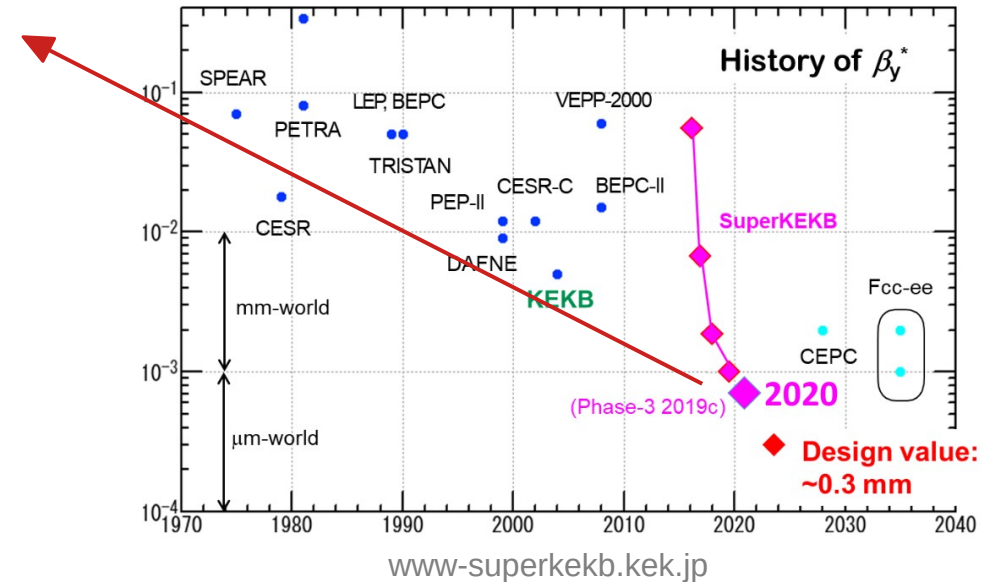
Extremely low vertical  $\beta$ -function of 0.8 mm at the IPs

0.8 mm  $\beta_y^*$  already achieved in SuperKEKB

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



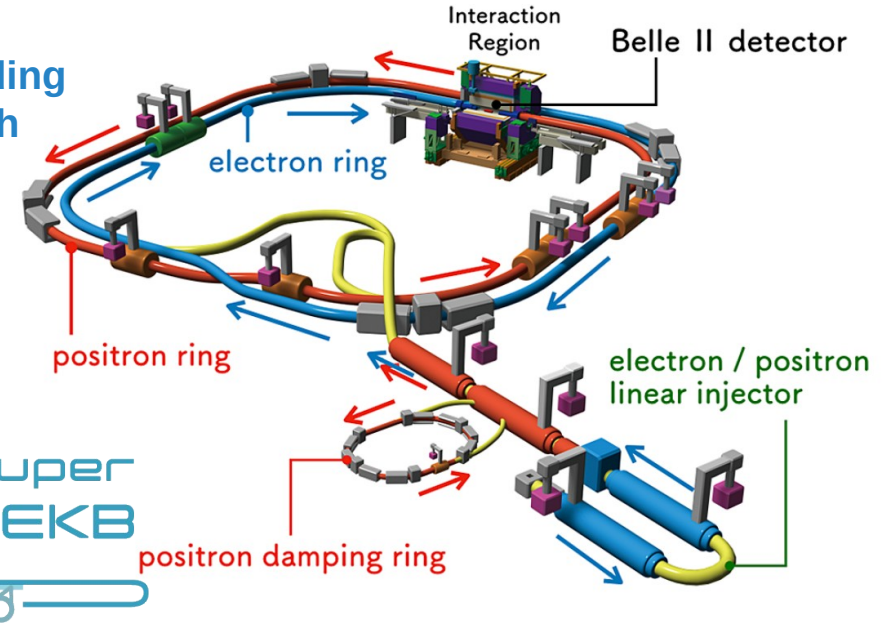
FCC-ee designed for high precision physics experiments  $\rightarrow$  demands precise optics control and thus accurate optics measurement techniques

# FCC-ee: The Challenge

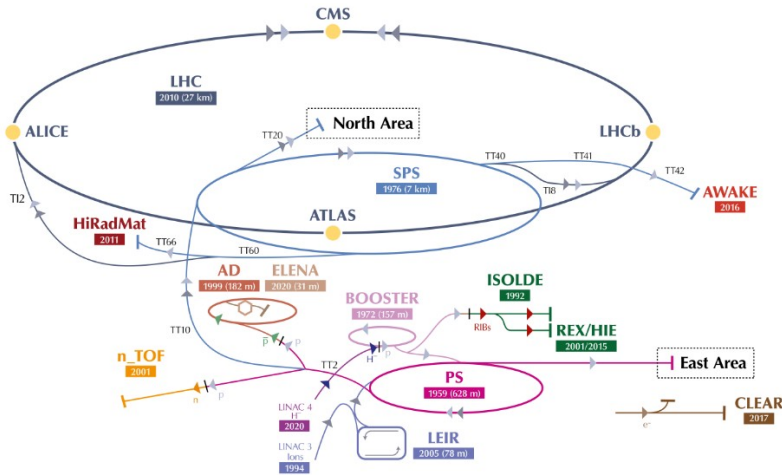
## SuperKEKB:

- Electron-positron double ring collider
- Similar colliding scheme as FCC
- Similar arc layout as FCC
- Record luminosity of  $4.65 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- 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/>



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



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



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



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

Other examples of beam tests for the FCC-ee:

J. Keintzel, Experimental beam tests for FCC-ee, 10.22323/1.398.0877, 2022.



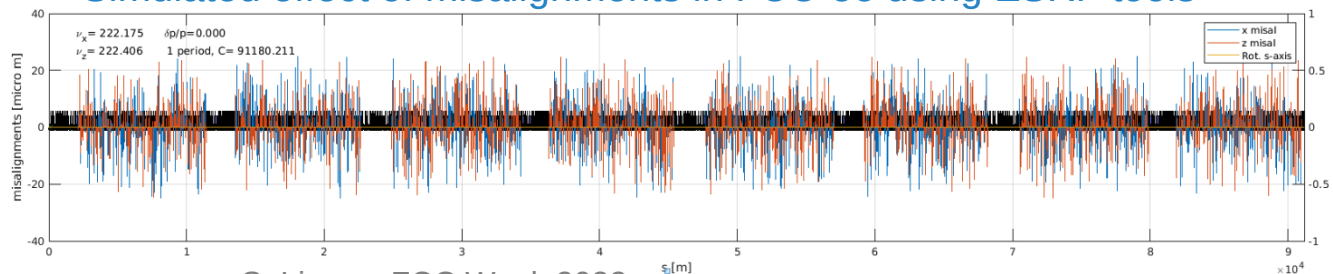
# FCC-ee: The Challenge

Type	$\Delta X$ ( $\mu\text{m}$ )	$\Delta Y$ ( $\mu\text{m}$ )	$\Delta\text{PSI}$ ( $\mu\text{rad}$ )	$\Delta S$ ( $\mu\text{m}$ )	$\Delta\text{DTHETA}$ ( $\mu\text{rad}$ )	$\Delta\text{DPHI}$ ( $\mu\text{rad}$ )	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.

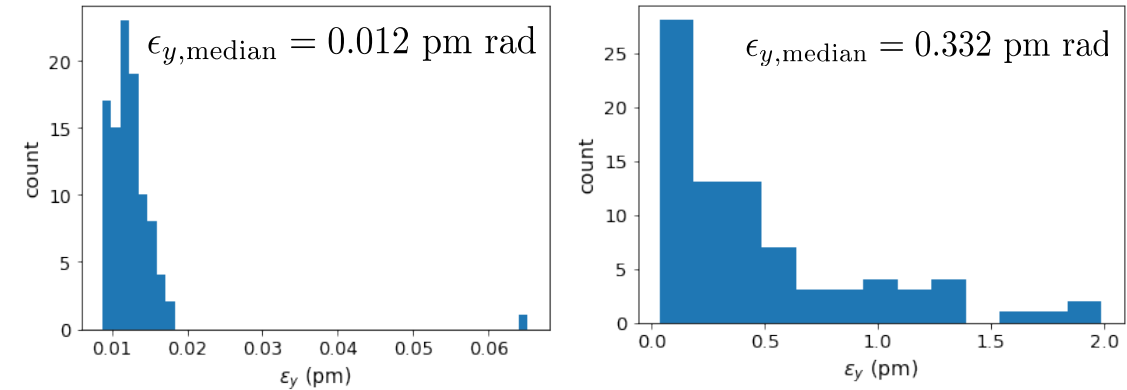
- FCC-ee would be **commissioned around 2045**
  - Experience from existing facilities inevitable
- **Unprecedented size** of almost 100 km
  - Alignment requirements similar to light sources

Simulated effect of misalignments in FCC-ee using ESRF tools



S. Liuzzo, FCC Week 2022.

Presently considered alignment 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.

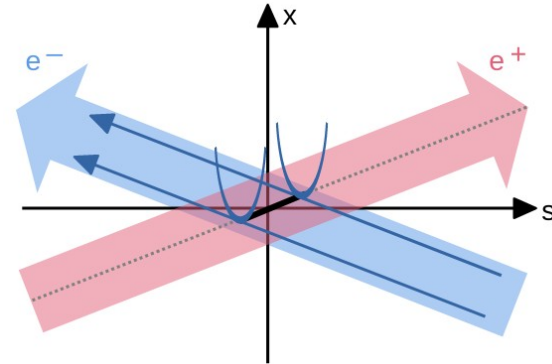
Continuous progress in FCC-ee tuning working group:  
<https://indico.cern.ch/event/1167740/>

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

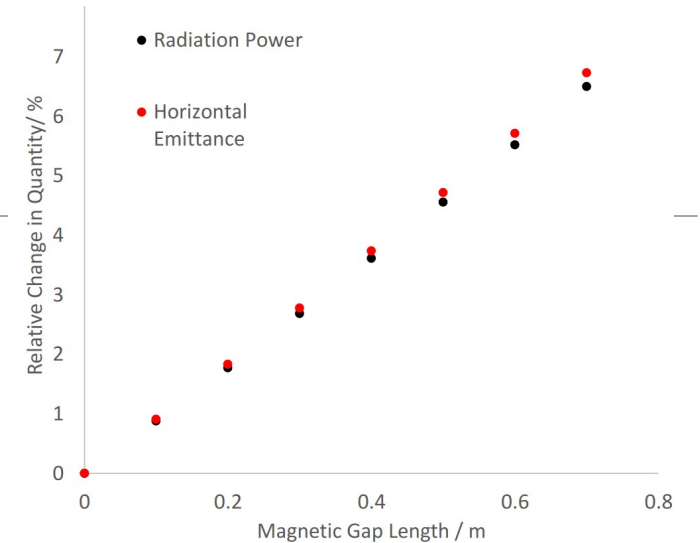
# FCC-ee: The Challenge

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

D. Shatilov, FCC Week 2022.

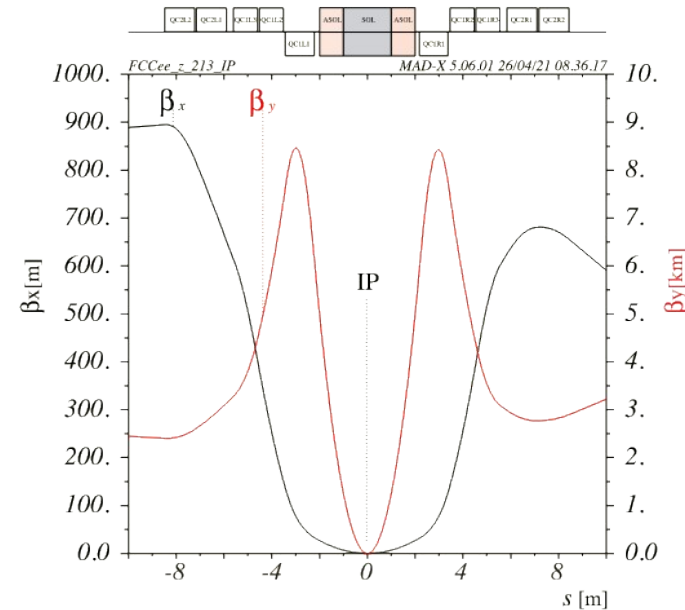


Recent study  
showing the  
emittance growth due  
to larger magnet  
gaps



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  $\beta_y^*$**  of up to 0.8 mm
  - Challenging (final focus) optics
- Demands also robust and accurate modeling



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

H. Burkhardt, FCC Week 2022.

# 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  $\beta_y^*$**  of up to 0.8 mm
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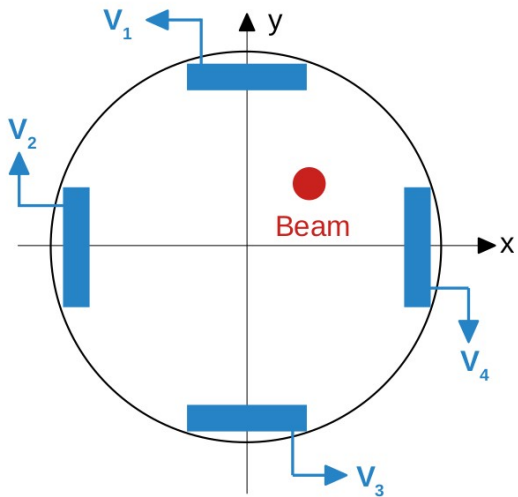
Needs to be considered for studies of suitable optics measurement techniques



# Beam Position Monitors

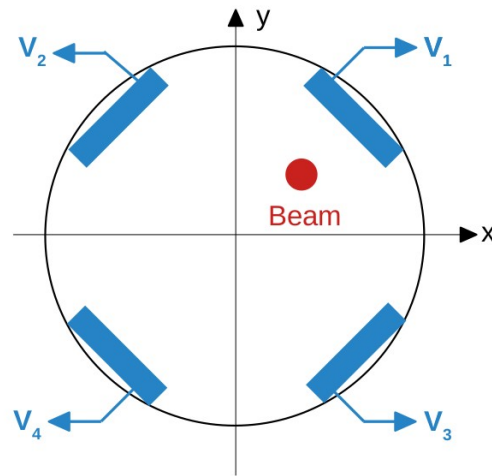
- Beam Position Monitors (BPMs) are crucial devices for beam optics measurements
- Button BPMs are the most common type, spoiled by resolution, calibration, non-linearity, ...

Hadrons:



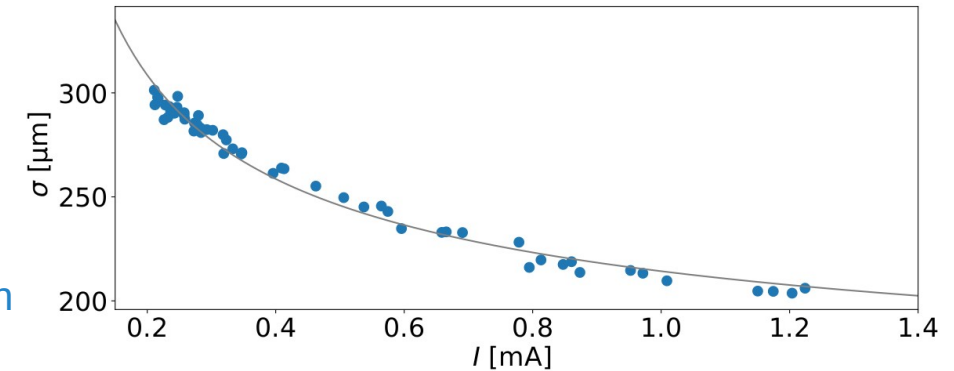
Buttons typically aligned on the transverse axes

Leptons:

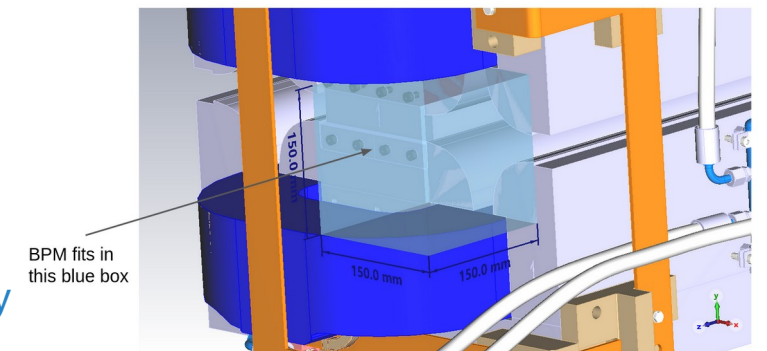


Buttons typically rotated by 45° due to strong synchrotron radiation

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  $\beta^*$  by varying quadrupole strength
- $\beta$ -function at quadrupoles estimated by tune change

$\Delta KL$  ... relative change of integrated quadrupole strength  
 $\Delta Q$  ... relative change of tune

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

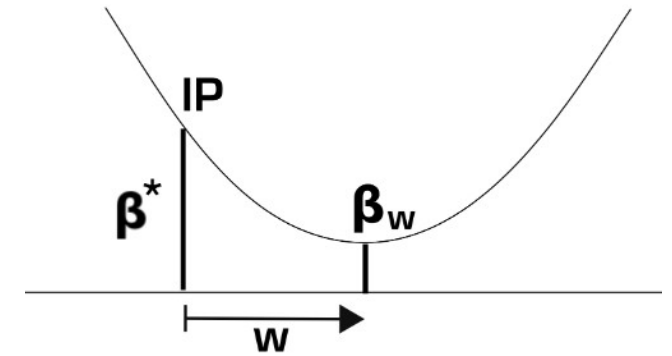
- $\beta_w$  propagated from  $\beta_0$  at the final focus quadrupoles and  $\beta^*$  given by

$L^*$  ... distance from IP to first quadrupole

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

- Main limitation is tune accuracy measurement

Minimum  $\beta$ -function not always at IP but shifted by waist  $w$



$$\beta^* = \beta_w + \frac{w^2}{\beta_w}$$

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.

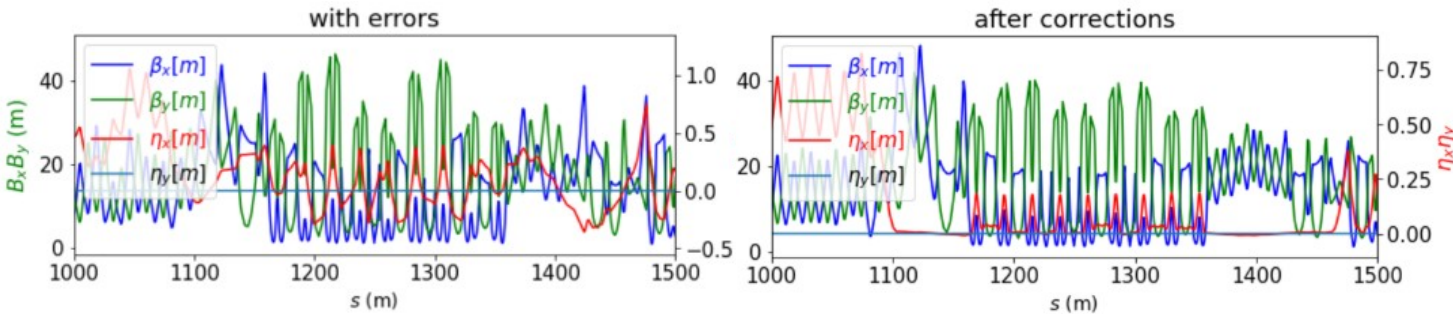
# Orbit Response Matrix

- 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

In FCC-ee  $t\bar{t}$  mode:

Beam energy 182.5 GeV and radiation losses/turn about 10 GeV → Large energy variation of about  $\pm 2\%$ , tapering applied  
Effect of energy losses on ORM to be explored



E. Musa, FCC-ee tuning meeting, 9<sup>th</sup> 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

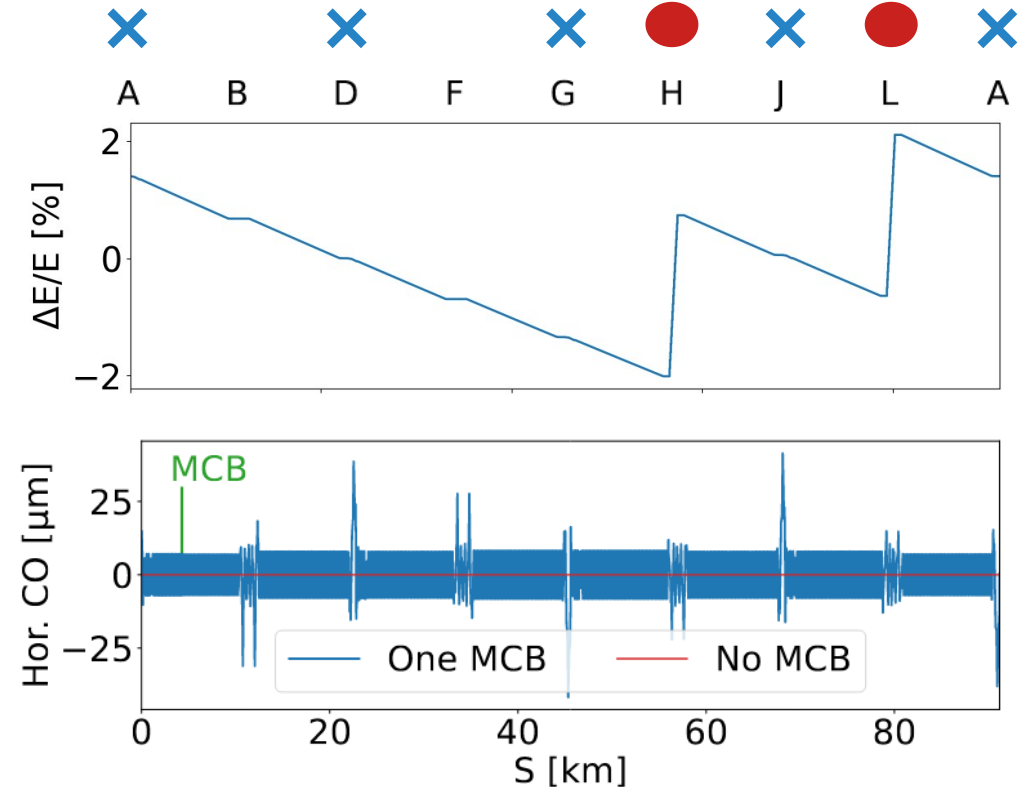
+ Very good resolution of about 5  $\mu\text{m}$

- Rather time consuming procedure

- Orbit limited to 10-20  $\mu\text{m}$  to avoid distortions from interaction

region quadrupoles and sextupoles

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

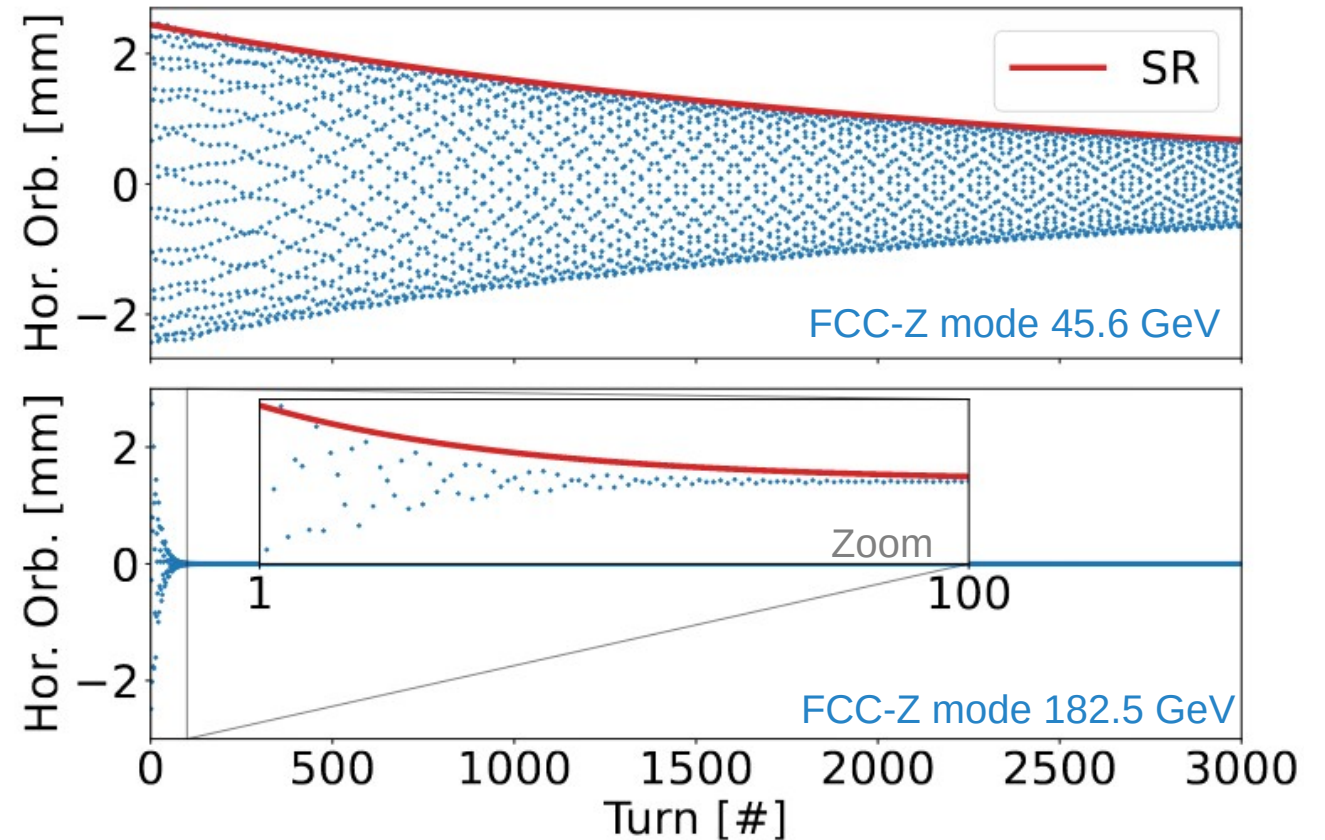


# Turn-by-Turn Measurements

- 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**

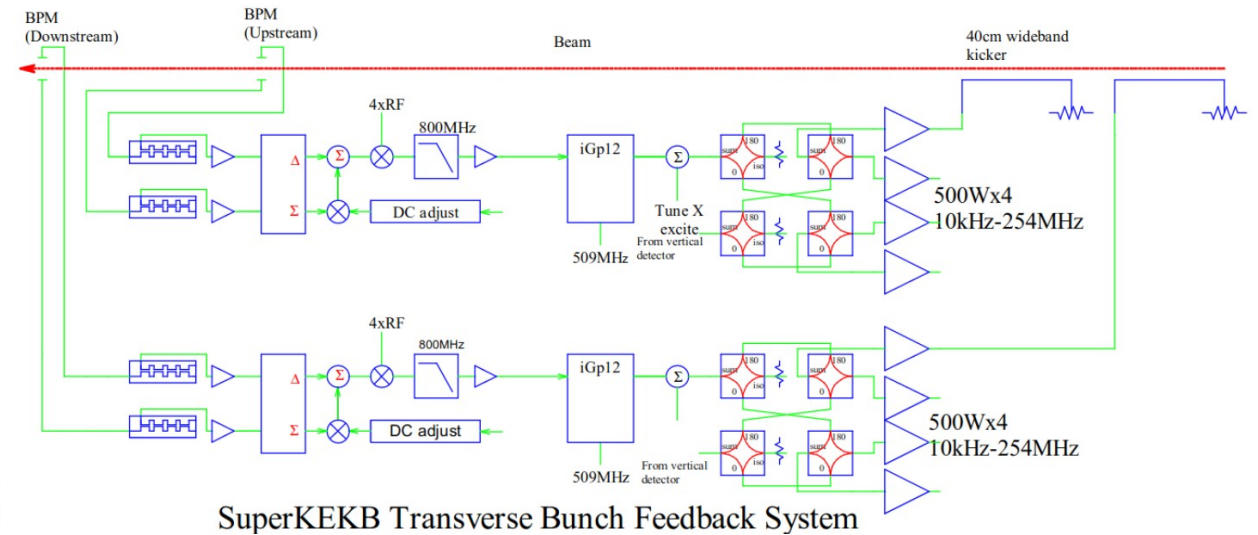
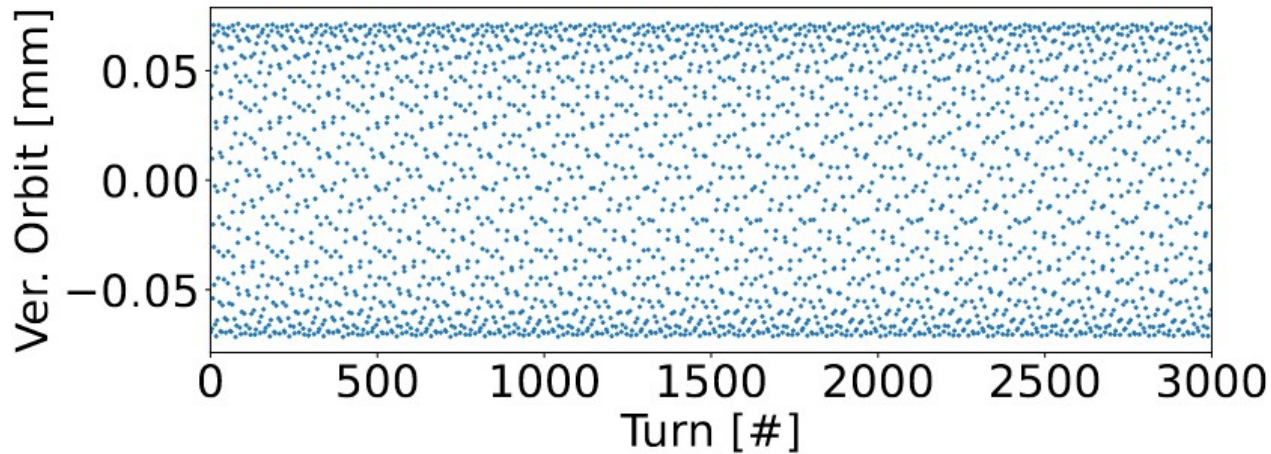




# Turn-by-Turn Measurements

- 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

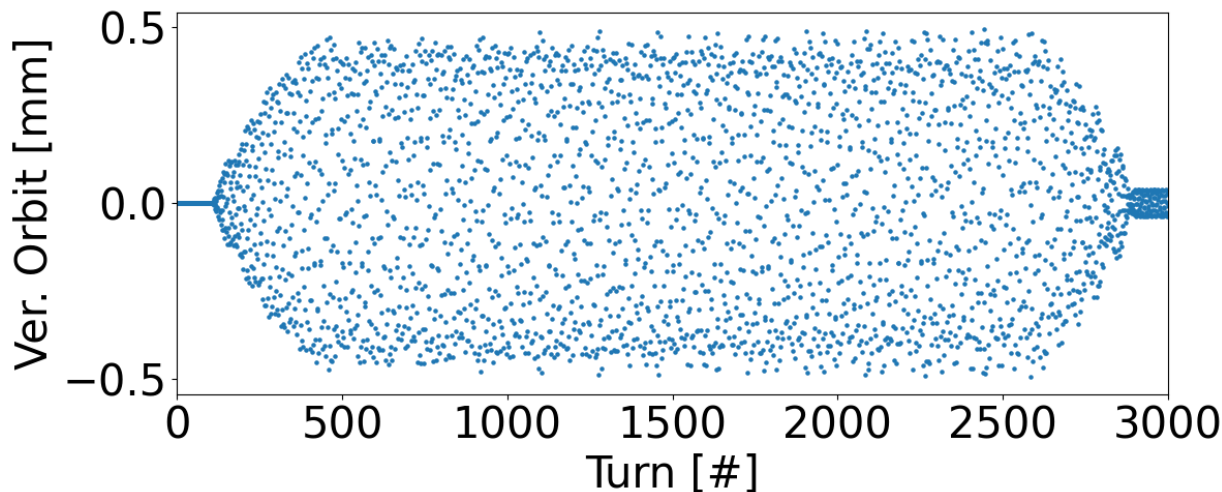


Continuous excitation achieved in SuperKEKB using transverse feedback system and amplification  
+ Drives the beam at the natural tune (no compensation)  
- Typically limited in amplification (low excitation)

# Turn-by-Turn Measurements

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

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



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

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)



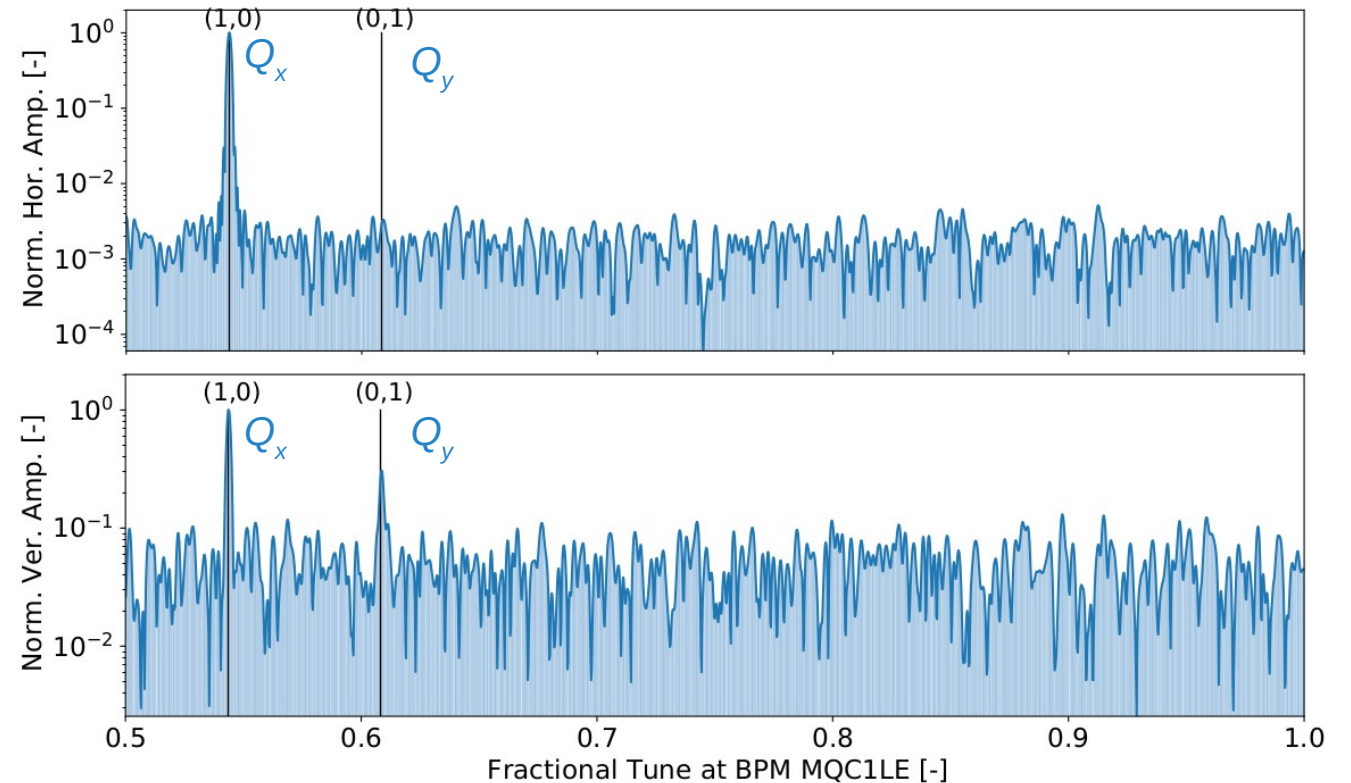
# Turn-by-Turn Measurements

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

For example:  $\beta$ -function from phase advances

$$\beta_u^{\text{ph}}(i) = \frac{\cot(\varphi_u(i \rightarrow j)) + \cot(\varphi_u(i \rightarrow k))}{\frac{M_{11}(i \rightarrow j)}{M_{12}(i \rightarrow j)} + \frac{M_{11}(i \rightarrow k)}{M_{12}(i \rightarrow k)}}$$

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



# BPM Errors and Phase Advance

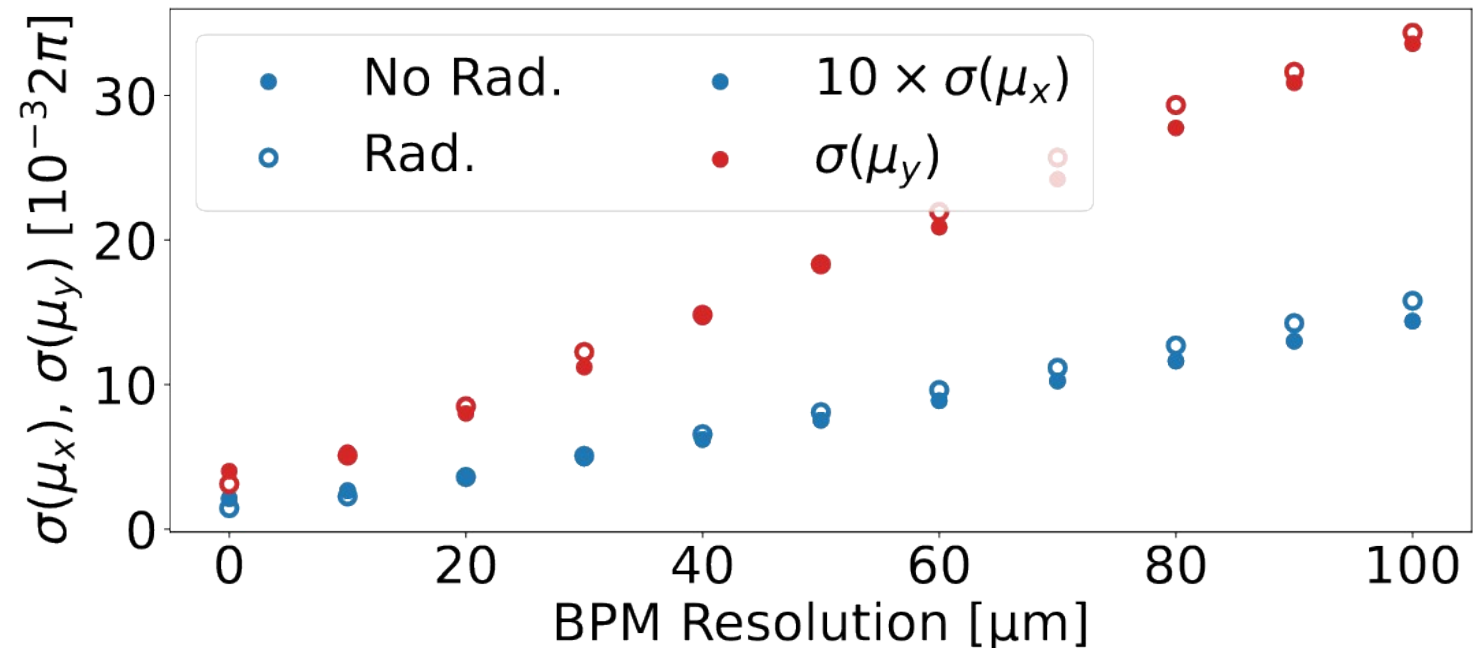
- Relative rms phase advance error with respect to the model used for figure-of-merit for quality of TbT measurements
- First TbT tracking over 500 turns for FCC-Z mode and 360 installed BPMs
- With and without synchrotron radiation
- Kick amplitude of  $6\sigma_x$ ,  $6\sigma_y$
- Gaussian BPM noise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

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

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

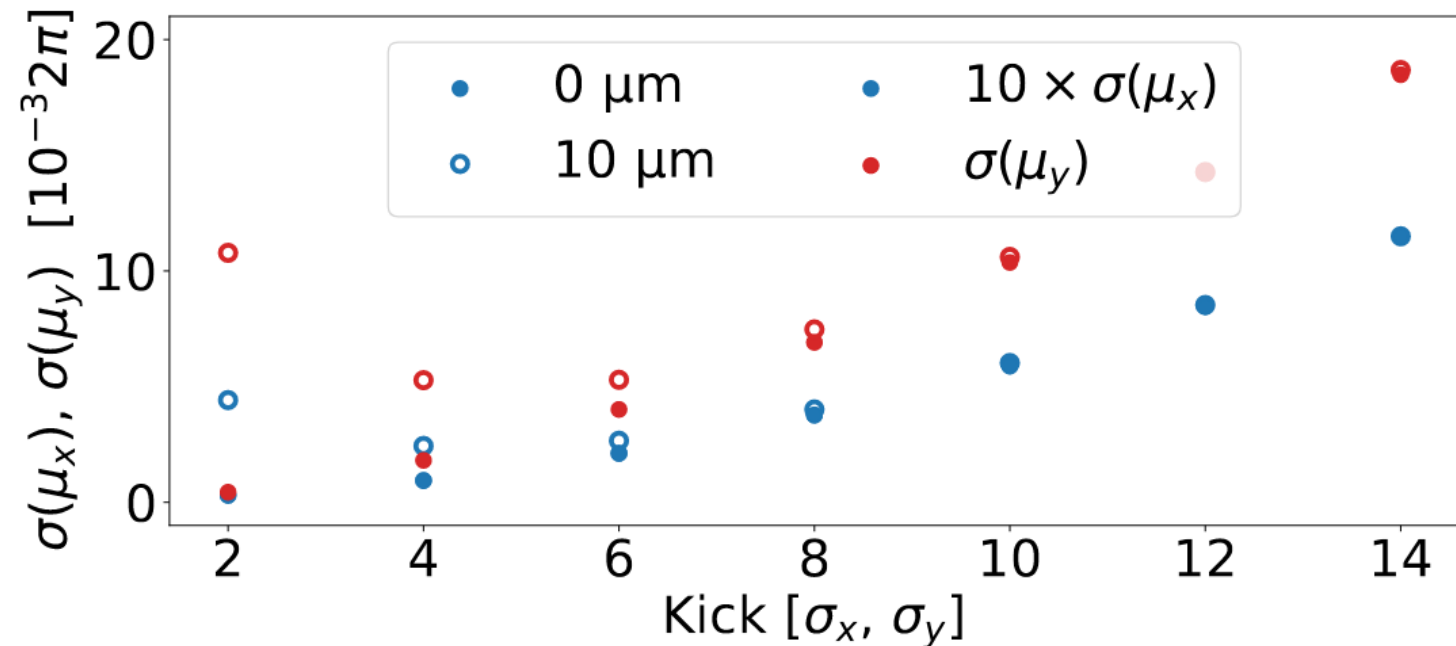
Without BPM noise phase error increases with increasing excitation strength

With BPM noise (here 10  $\mu\text{m}$ ) optimum kick strength found at 4  $\sigma_x$ , 4 $\sigma_y$

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



# 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

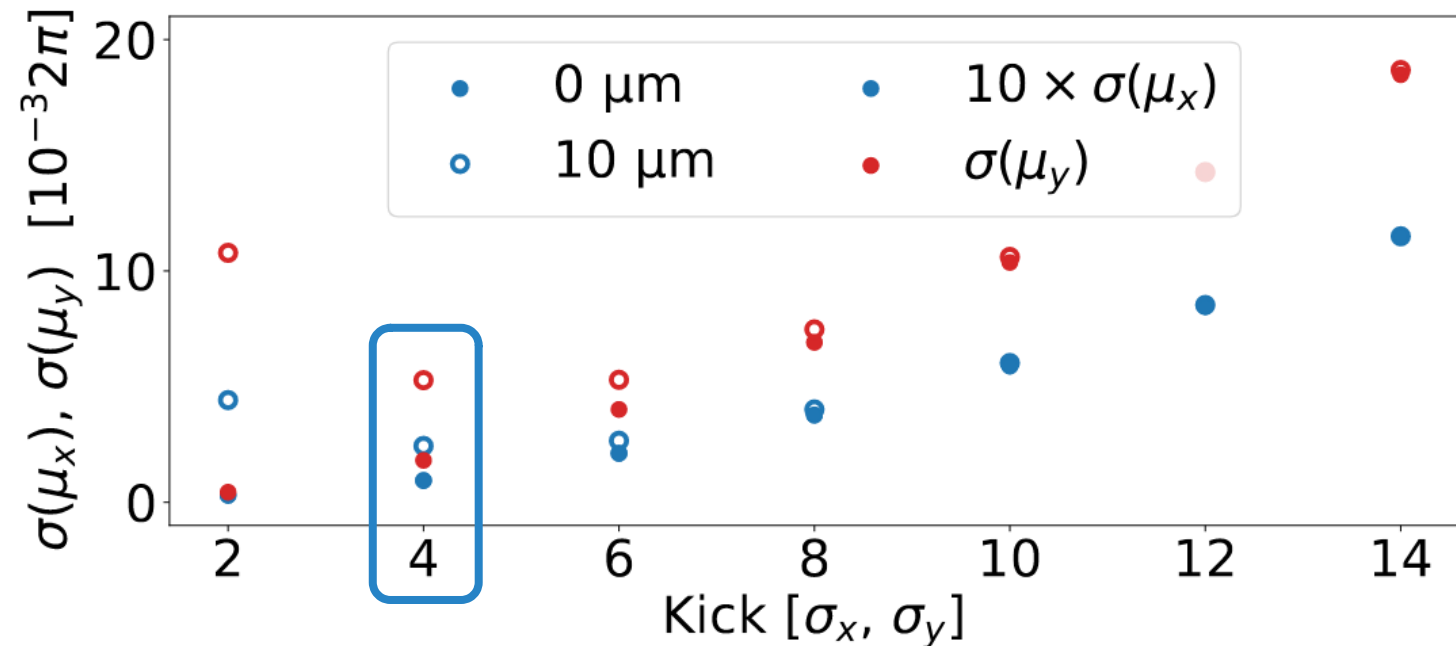
Minimum hor and ver. phase advance error with  
10  $\mu\text{m}$  BPM noise:  $0.24 \times 10^{-3} (2\pi)$  and  $5.28 \times 10^{-3} (2\pi)$

Comparison LHC

6600 turns, AC-dipole

Minimum hor and ver. phase advance error,  $\sim 100 \mu\text{m}$   
BPM noise:  $< 1 \times 10^{-3} (2\pi)$

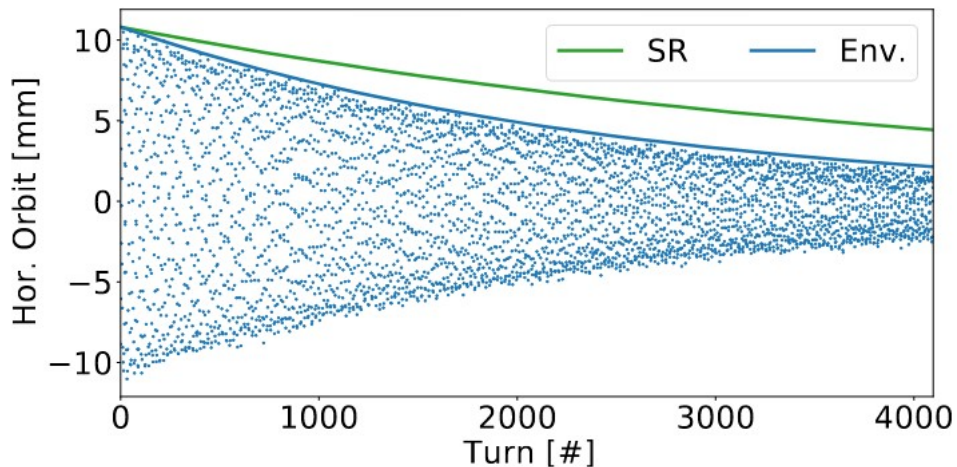
FCC-Z mode at 45.6 GeV single particle tracking



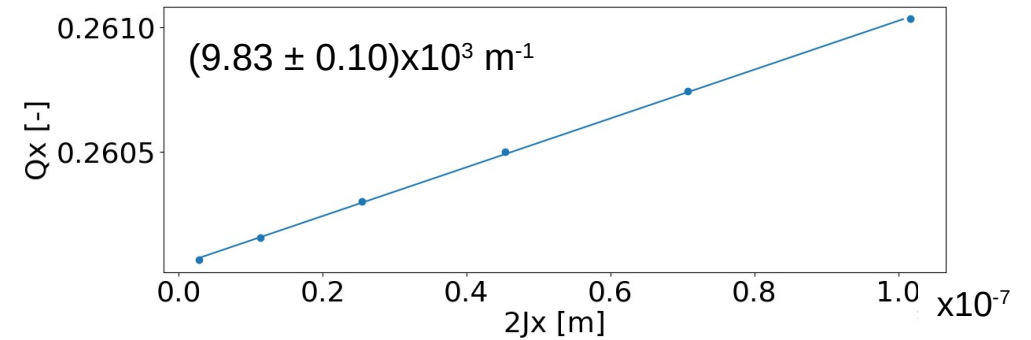
# Single Kicks in Measurement

- 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

$$Q_x' = 1.70 \pm 0.04, \quad Q_x'' = -22 \pm 18$$



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



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

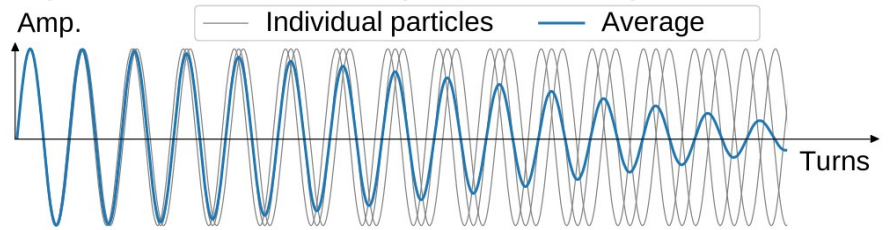
Since bunch current is low, additional damping tentatively  
attributed to decoherence  
Impedance model presently being updated in SuperKEKB

# 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

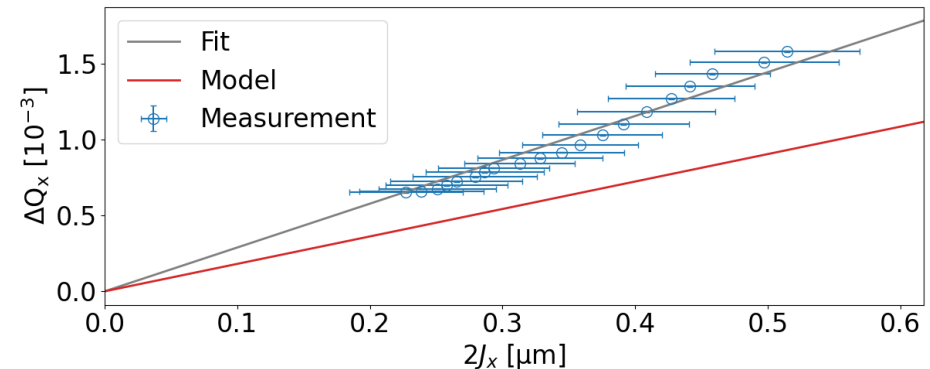
Existing theory for hadrons:  $\mu$  ... Amplitude detuning  $N$  ... Turns  
 $Z$  ... Kick strength

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

Here extended for leptons:

$$\theta = 2\pi\mu \tau_{\text{SR}} (1 - e^{-2N/\tau_{\text{SR}}})$$

SuperKEKB LER amplitude detuning measurement

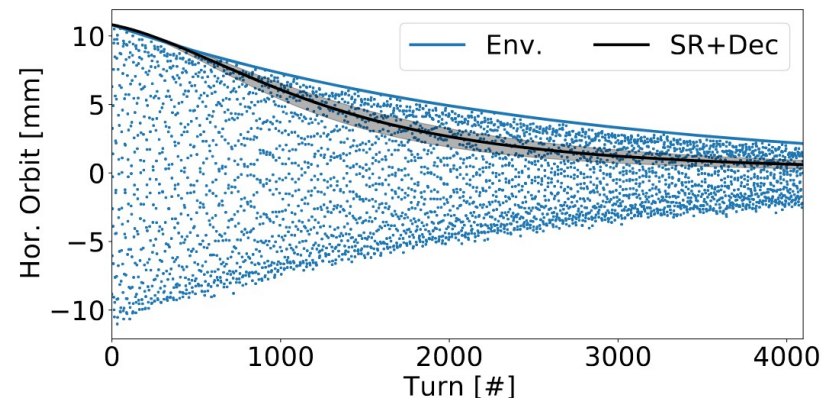


Damping explained by synchrotron radiation and decoherence

→ 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





# Summary

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- 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!



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# Thank you!

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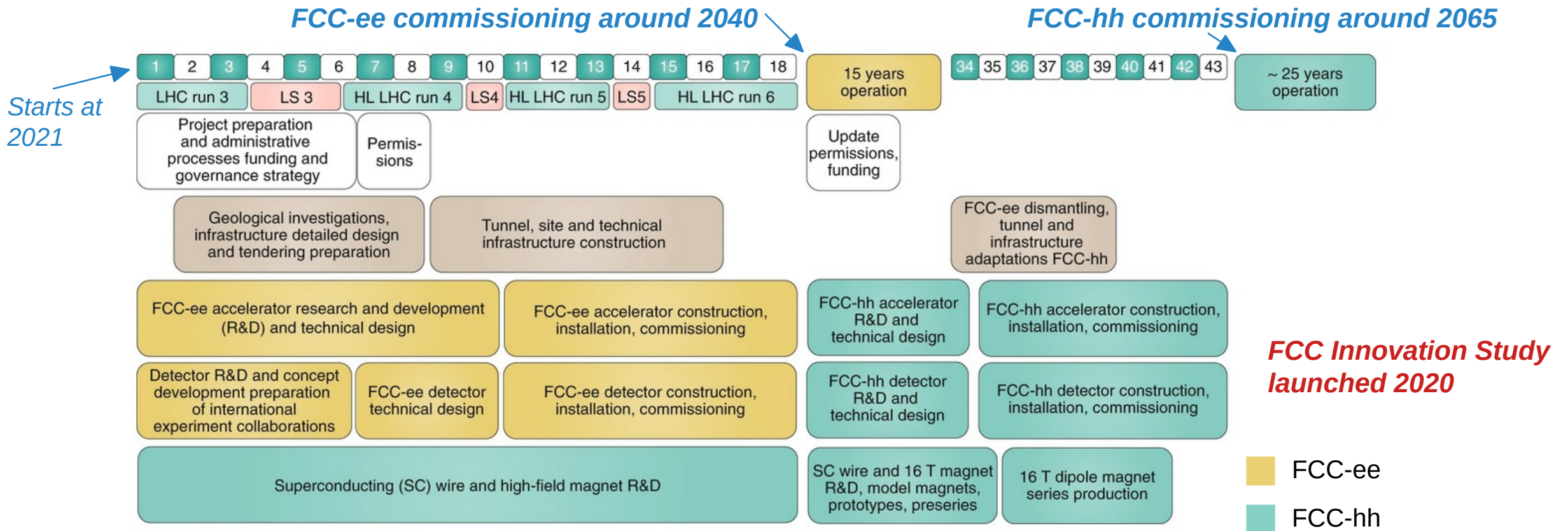
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# FCC Integrated Project

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



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