FCC-ee Lattice Design

Michael Benedikt, Michael Hofer, Jacqueline Keintzel, Katsunobu Oide, Tor Raubenheimer, Rogelio Tomás and Frank Zimmermann

On behalf of

The FCC-ee collaboration and the FCC IS DS team

65th ICFA Advanced Beam Dynamics Workshop
on High Luminosity Circular e+e- Colliders (eeFACT2022)
13th September 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.

ESPP Update 2020

In 2020 the European strategy upgrade of particle physics (ESPP) expressed the long-term plan for particle colliders

Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a center-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.

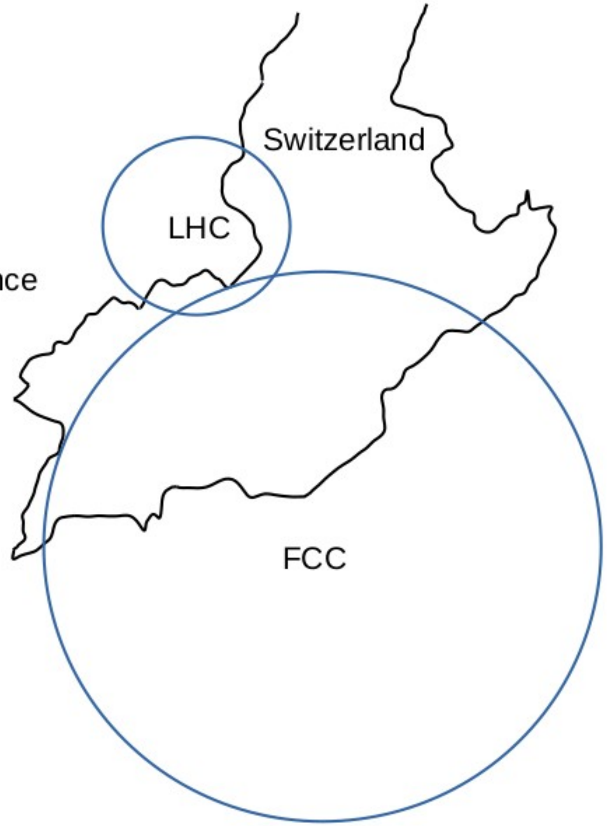
Lepton Future Circular Collider, FCC-ee
Hadron Future Circular Collider, FCC-hh
} FCC Integrated Project

Future Circular Colliders

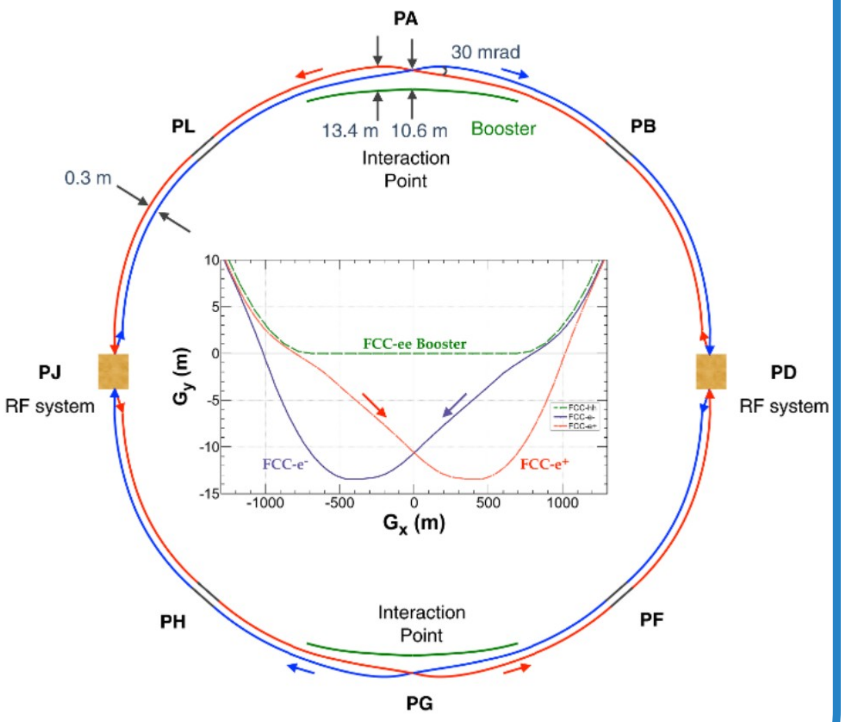
Compatible lattice designs

Inspired by LEP-LHC programm

Re-using CERN infrastructure

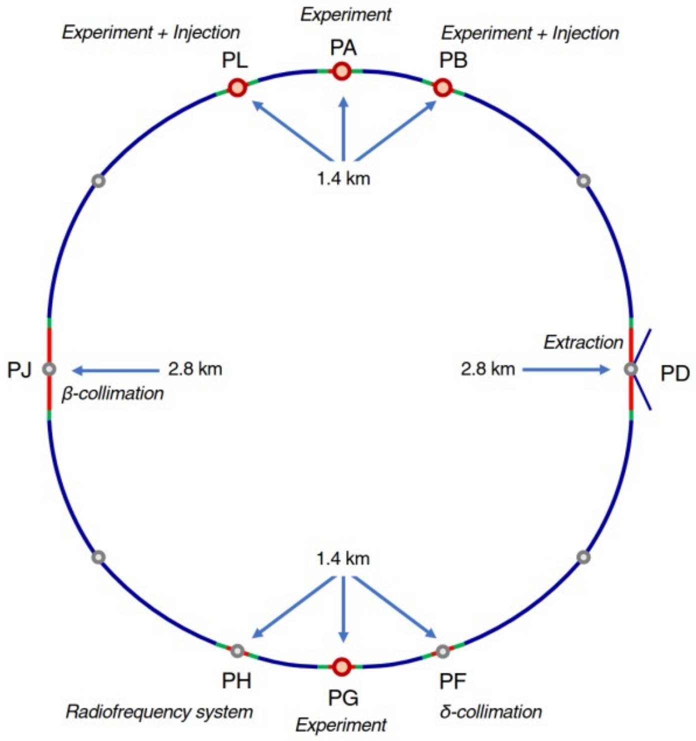


FCC-ee
Electron-positron collider



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.

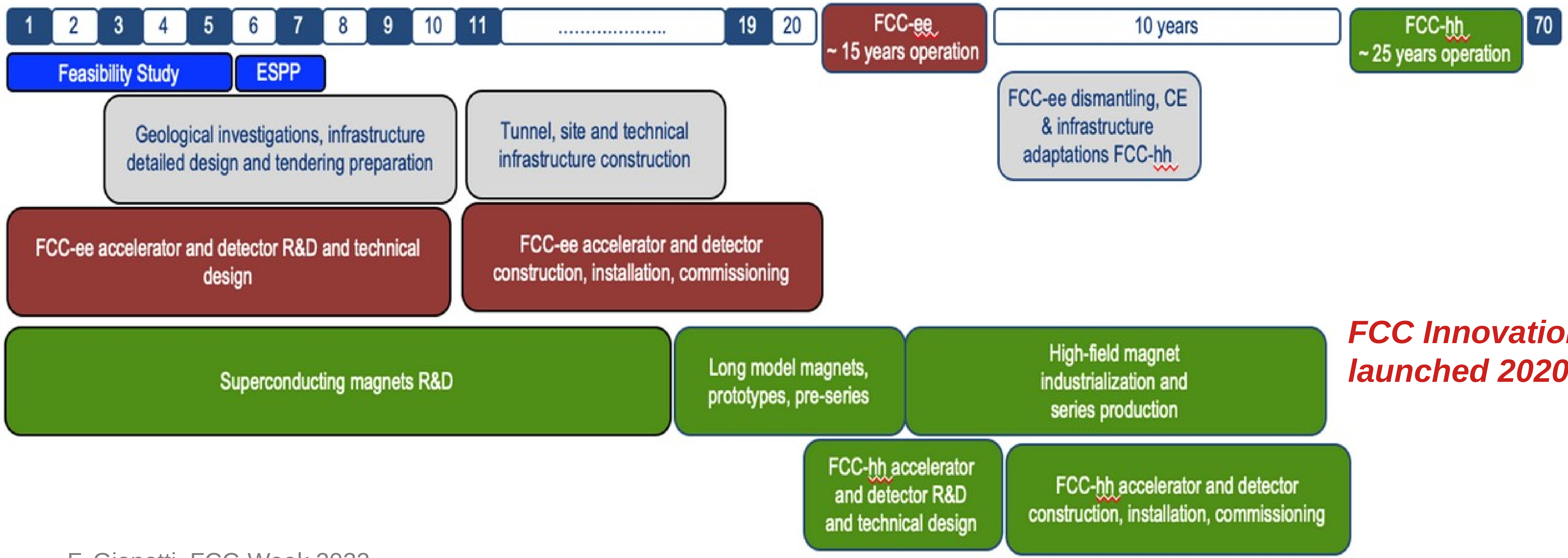
FCC Integrated Project

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

FCC-ee commissioning second half of the 2040s

FCC-hh commissioning around 2070

Starts at 2021



FCC Innovation Study launched 2020

F. Gianotti, FCC-Week 2022.

J. Gutleber, V. Mertens

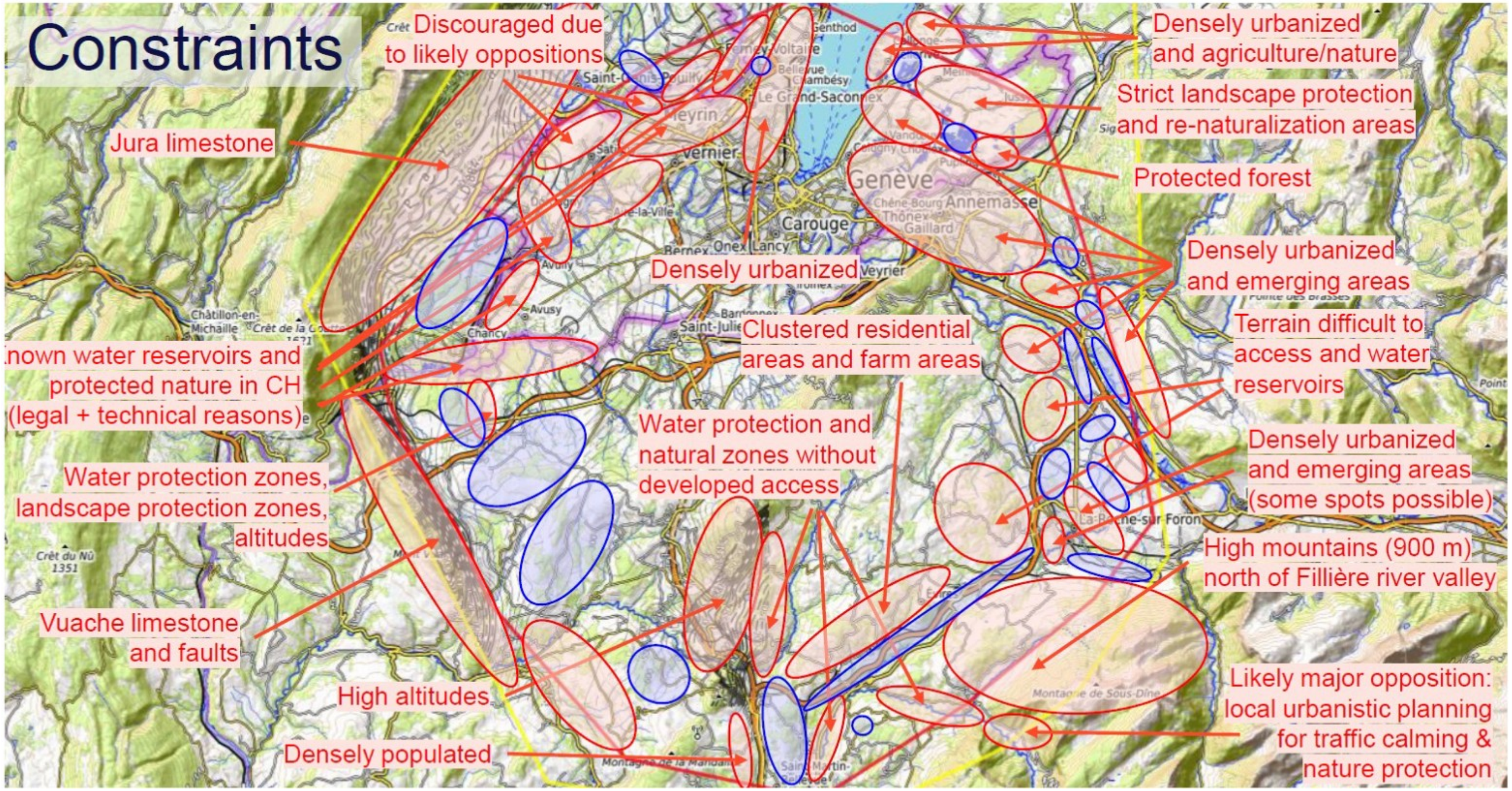
Placement Studies

Constraints:

- 8 or 12 surface sites
- Topography
- Geology
- Infrastructure
- …

Result:

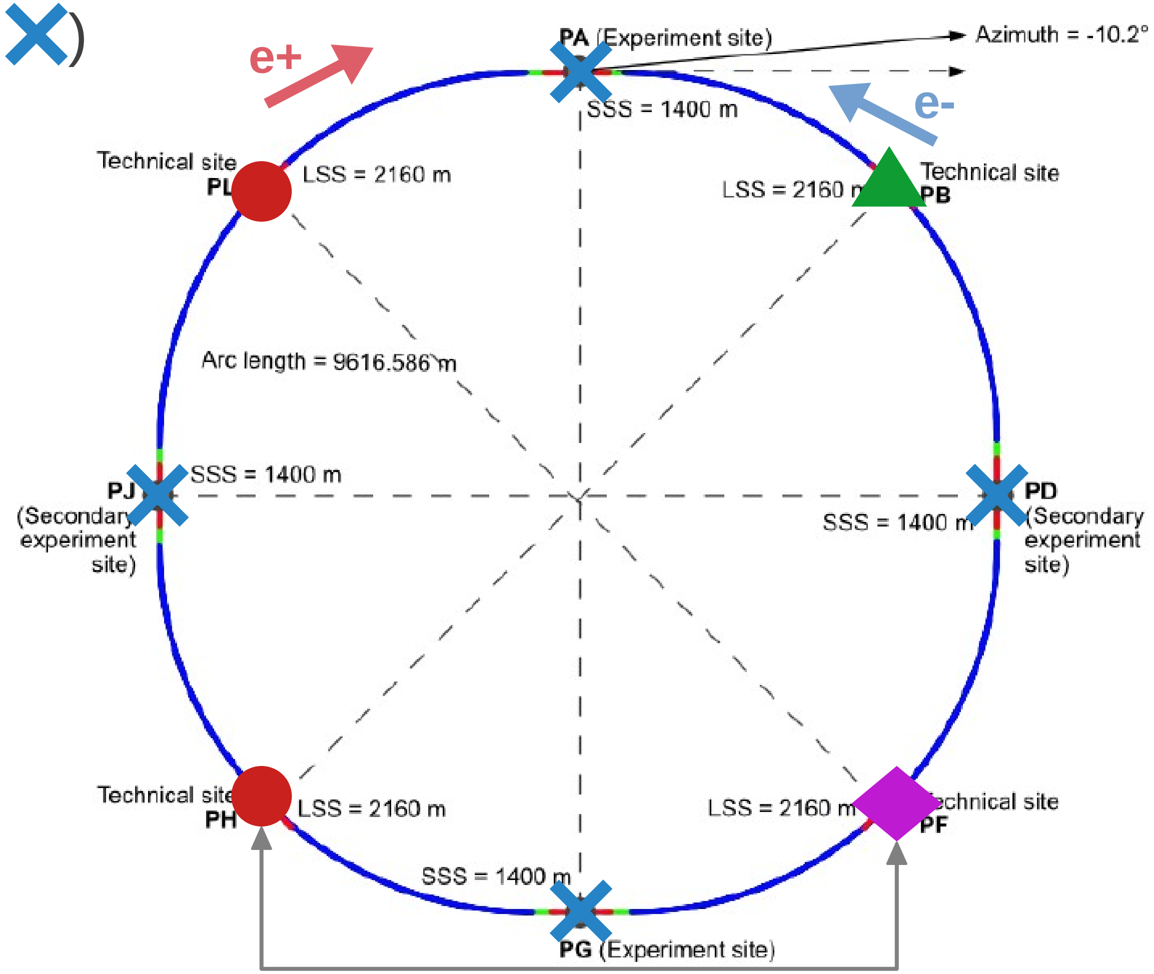
89 km to 91 km best geolical and territorial fits



P. Boillon: indico.cern.ch/event/995850

Introduction FCC-ee

- FCC-ee baseline with 4 Interaction Points (IPs ✕)
- Designed for precision physics experiments
- 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 (Z, WW, ZH) to 2 (ttbar) RF-sections (●)
- Top-up injection and beam dump system (▲)
- Collimation system (◆)



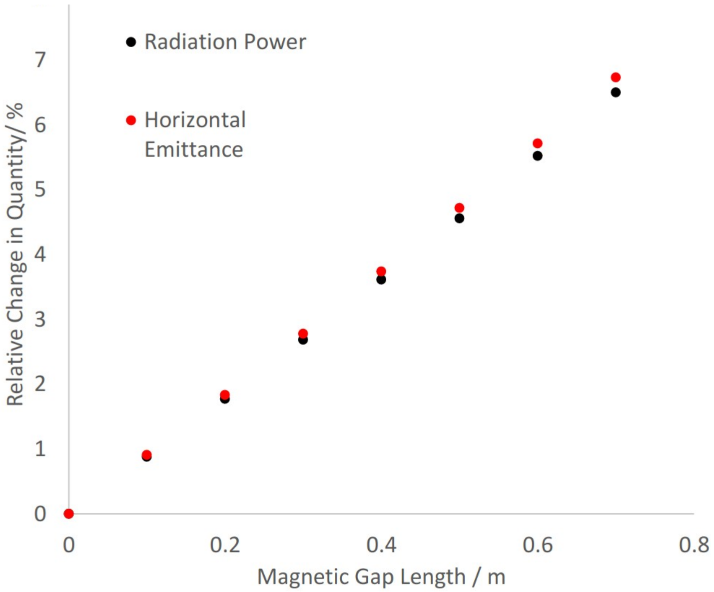
FCC-week in May – June, progress reported on numerous topics:
https://indico.cern.ch/event/1064327/

RF in PH and collimation in PF could also be switched

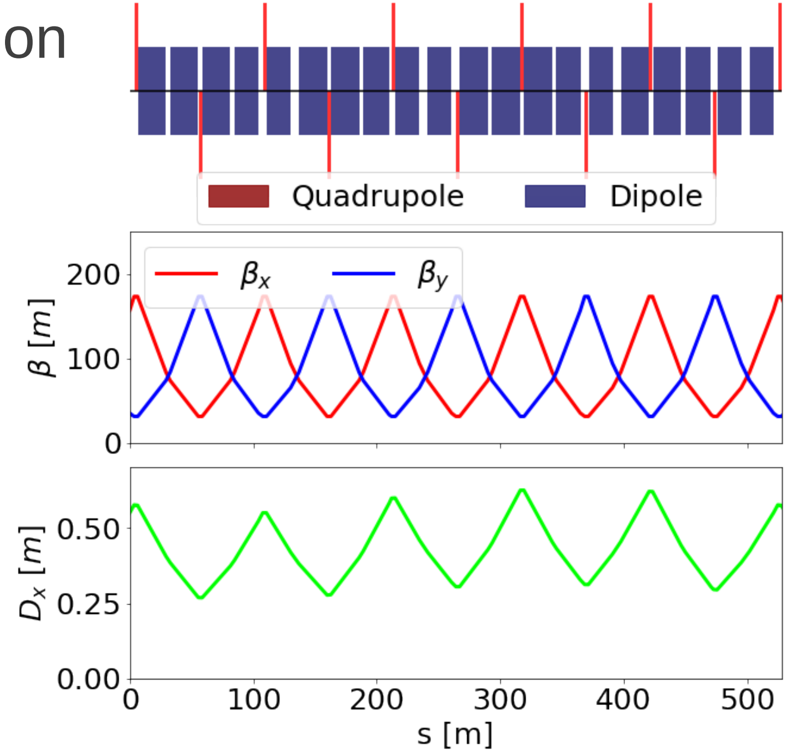
M. Hofer, K. Oide, L. van Riesen-Haupt

Arc Design

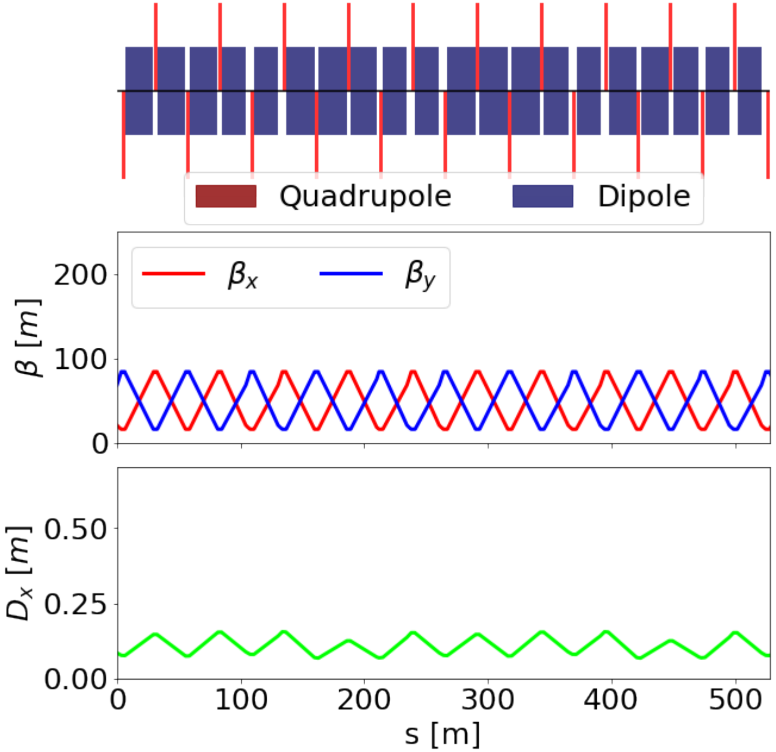
- 8 arcs with FODO cell design
- Recent studies to include BPMs, correctors ongoing
- Impact of magnet length gap on reached emittance



Z-operation
WW-operation
Arc FODO cell length 100 m
90° transverse phase advance



ZH-operation
ttbar-operation
Arc FODO cell length 50 m
90° transverse phase advance

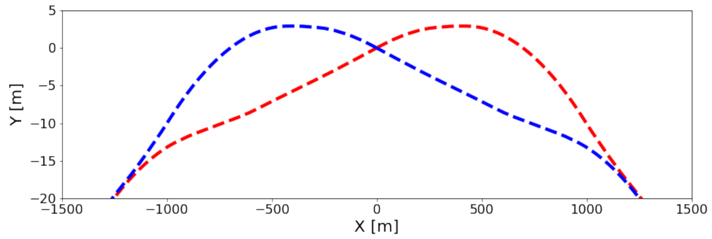


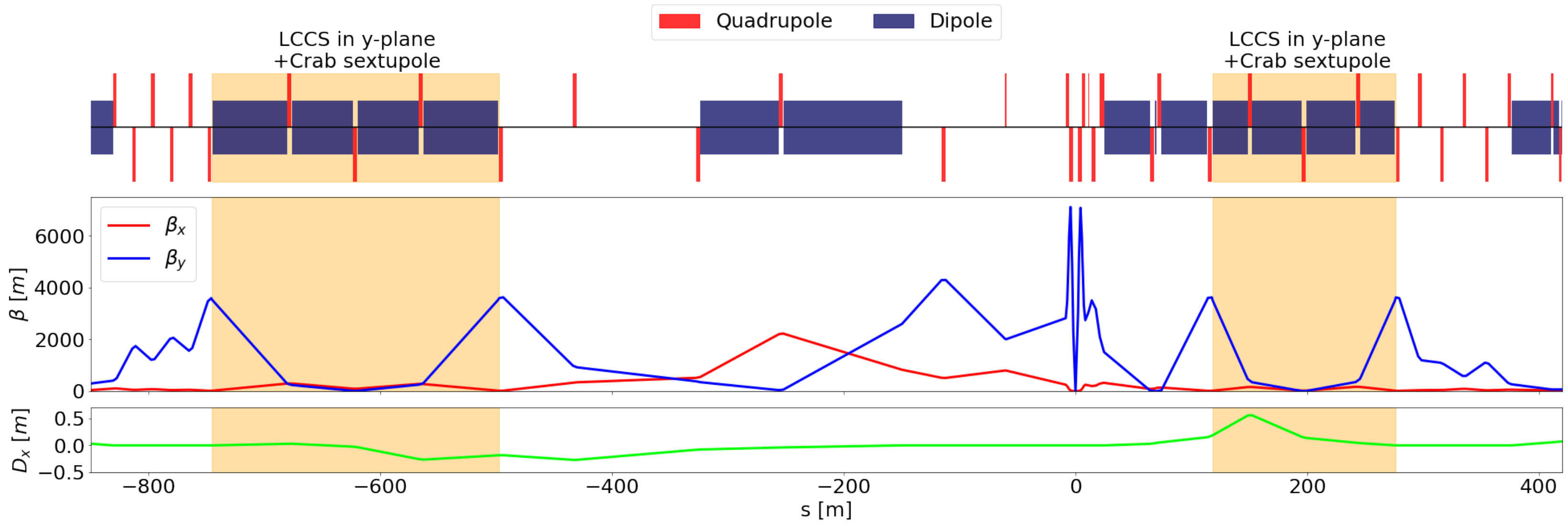
H. Burkhardt, M. Hofer, K. Oide

Experimental Insertions

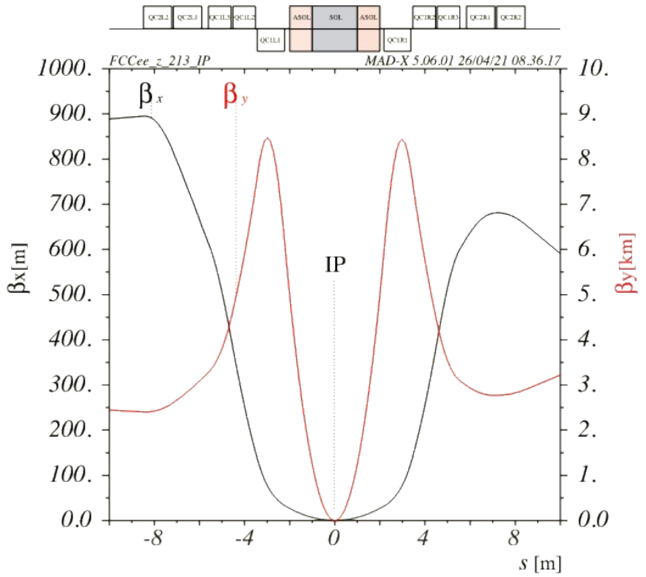
- Highly complex interaction region design for the FCC-ee
- Overlap of final focus and solenoid → challenging model
- Crab-waist transformation with local chromaticity correction

Beam collide while always crossing outwards due reduce radiation at IP





β-function variation over 7 orders of magnitudes

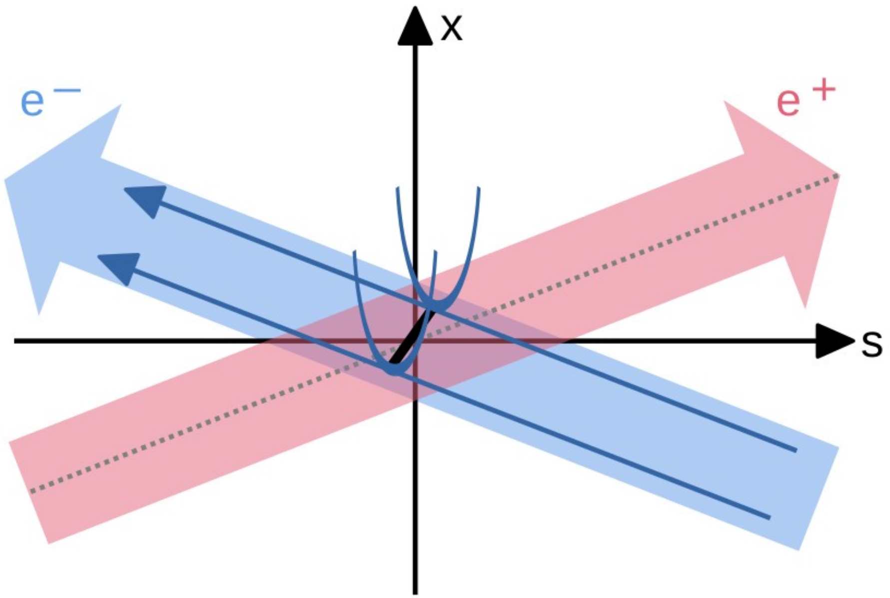


Crab-Waist Collision Scheme

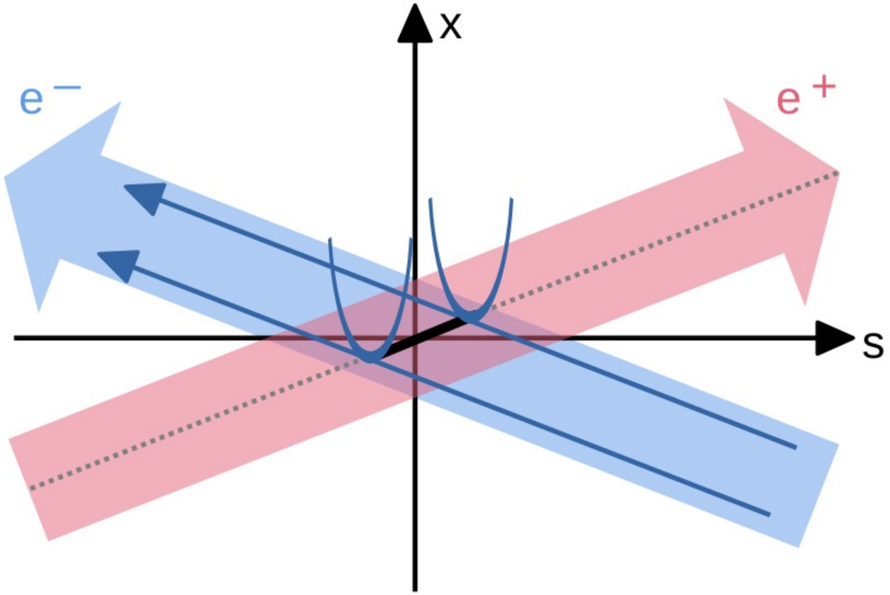
- Original crab-waist scheme used at DAFNE, INFN, Italy P. Raimondi et al., arXiv:physics/0702033, 2007. M. Zobov et al., arXiv:1608.06150, 2016.
- Virtual crab-waist scheme used in SuperKEKB Y. Ohnishi et al., Progr. of Theoretical and Experimental Physics, 2013 (3), 2013
- Virtual crab-waist scheme foreseen for FCC-ee K. Oide et al., Phys. Rev. Accel. Beams 19, p. 111005, 2016.

Powering sextupoles rotates the vertical β-function and aligns the minimum on the longitudinal axis on the other beam

Without crab-waist transformation



With crab-waist transformation



M. Hofer, K. Oide

RF-Insertions

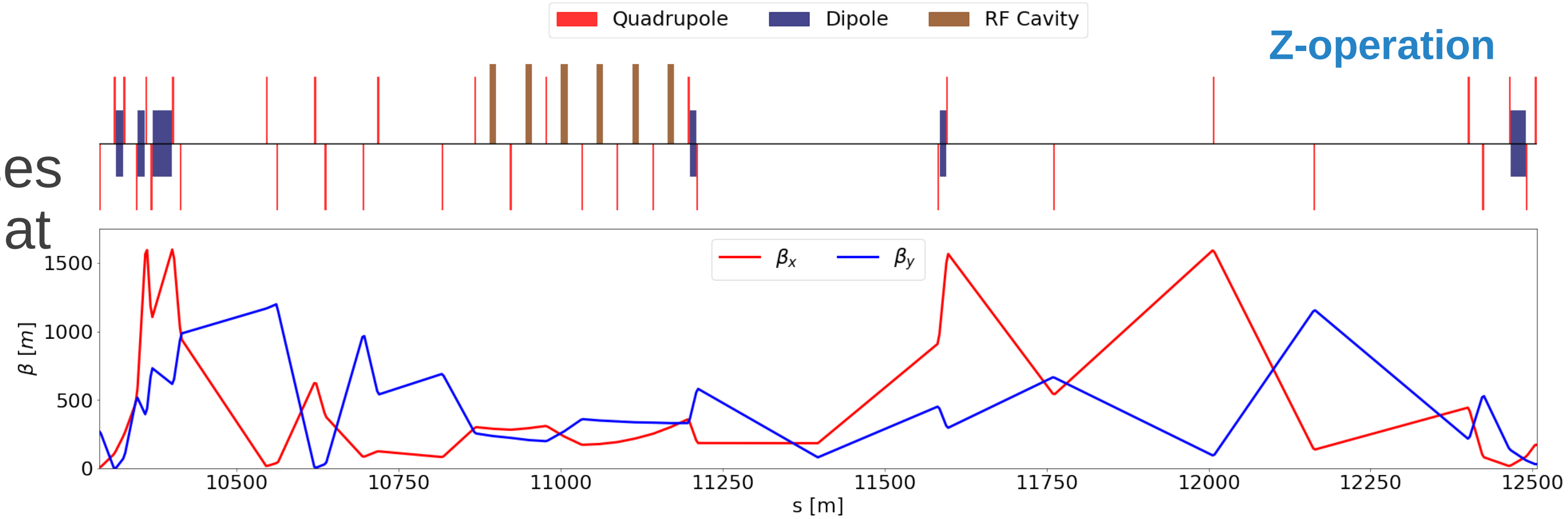
- Beam crossing in middle of IR
- Compensate for radiation losses (Up to 5% of the beam energy at highest beam energy)
- 400 MHz and 800 MHz considered

Two reviews will take place in October:

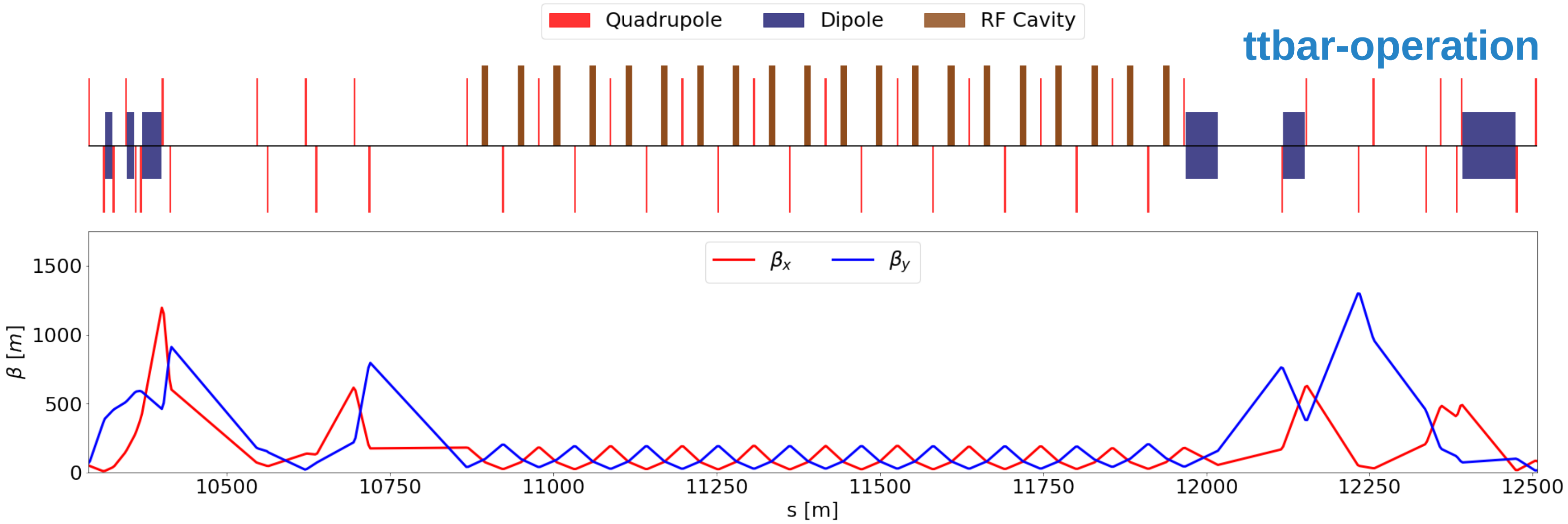
Civil Engineering (CE) and Technical (TI) Infrastructure Requirements for FCC Experimental Sites

FCC-ee SRF Systems Layout with Associated CE and TI Concepts

Z-operation



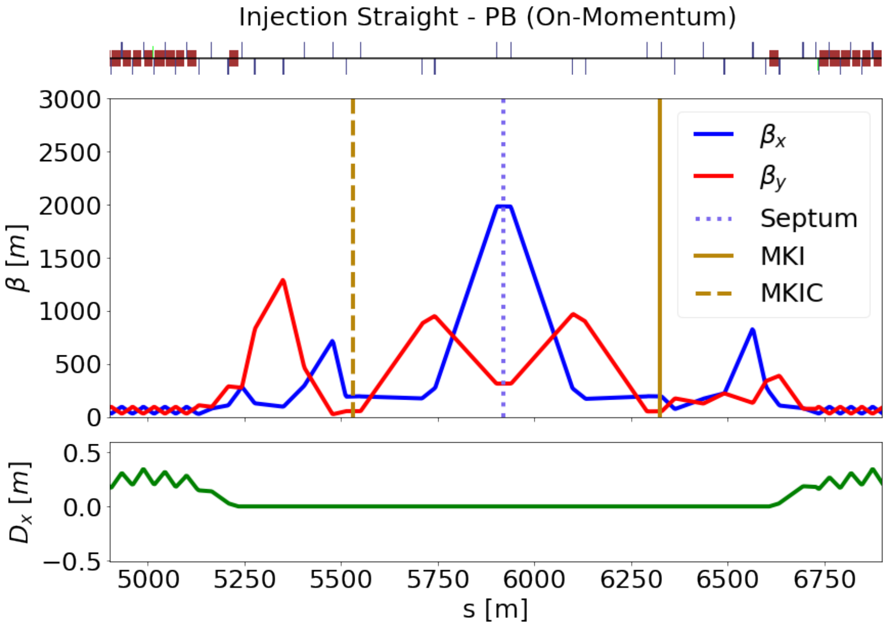
ttbar-operation

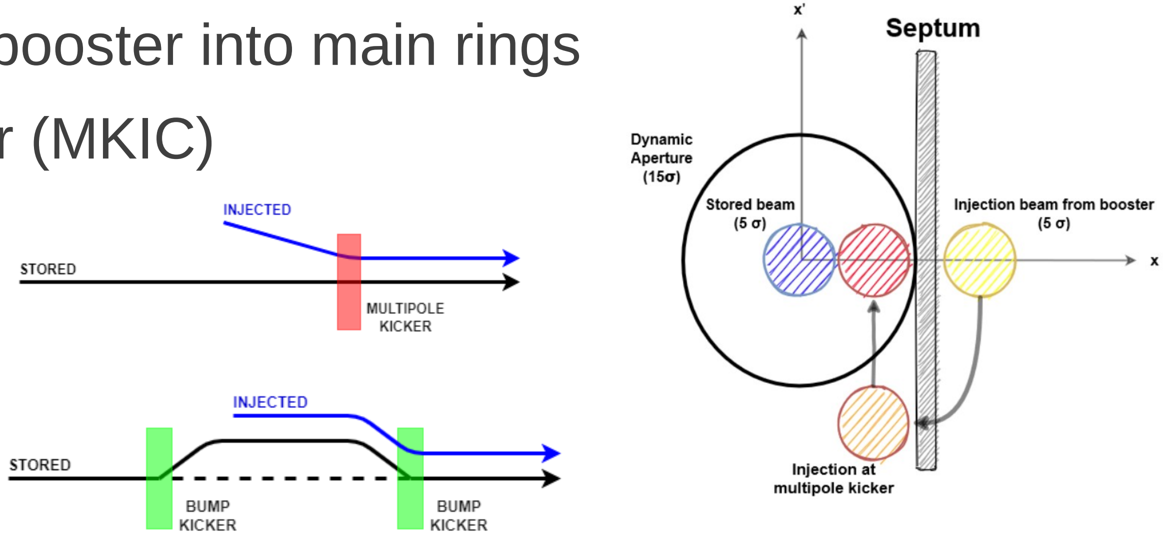


M. Hofer, P. Hunchak, R. Ramjiawan

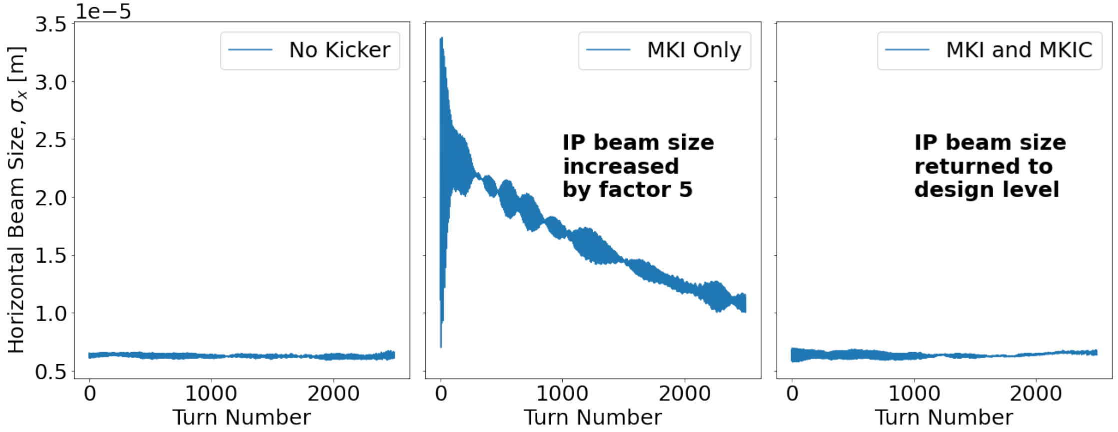
Top-Up Injection

- Continous beam injection from high energy booster into main rings
- Multipole kicker injection (MKI) and corrector (MKIC)
- 180° phase advance between kickers
- Large horizontal optics at injection point





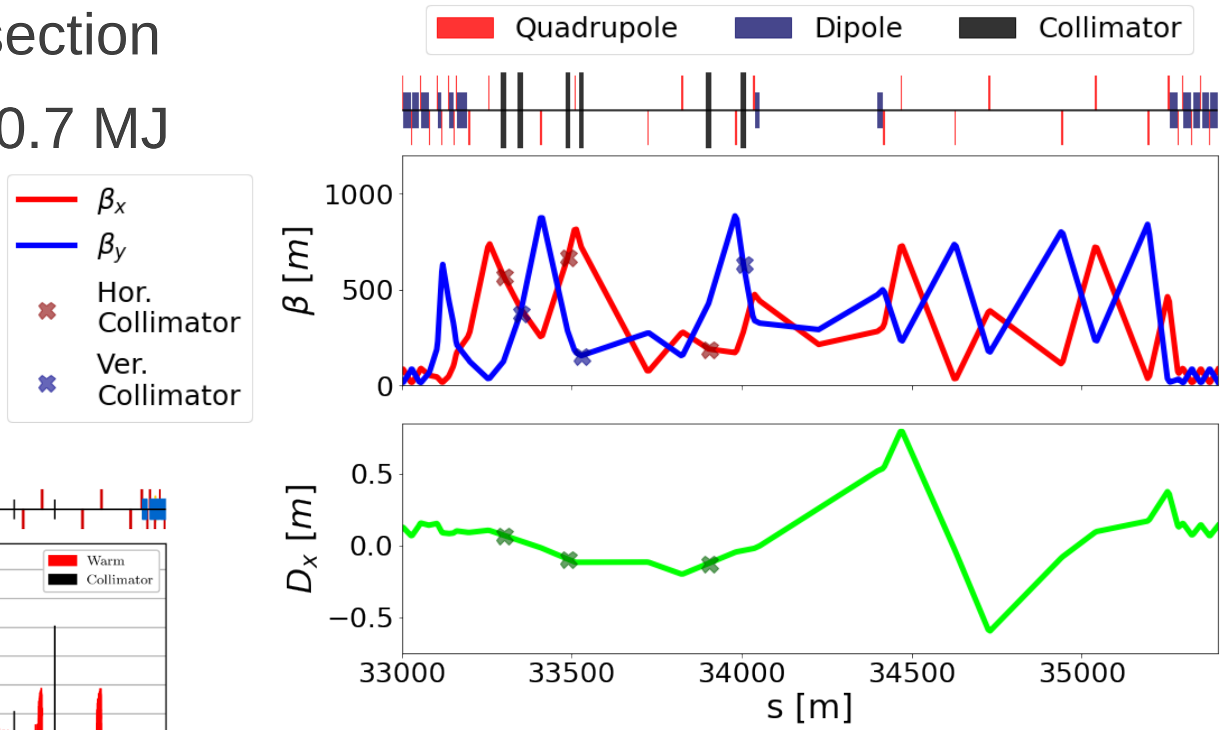
Using MKI with correction magent restores beam at IP to desired size

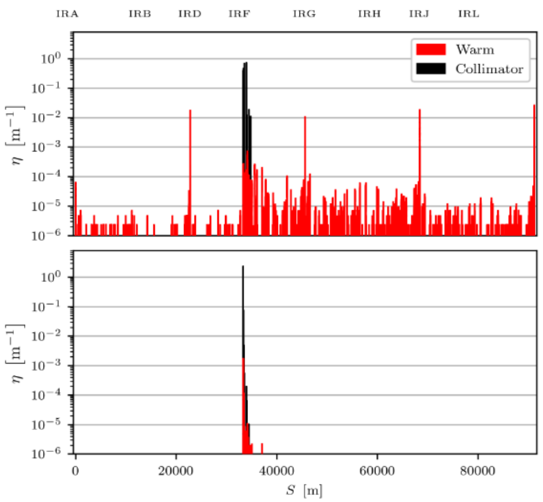


A. Abramov, M. Hofer

Collimation Insertion

- Beam crossing at the center of the straight section
- Stored beam in the FCC-ee reaches up to 20.7 MJ
- One combined collimation insertion for
  - Betatron collimation (upstream)
  - Off-momentum collimation (downstream)



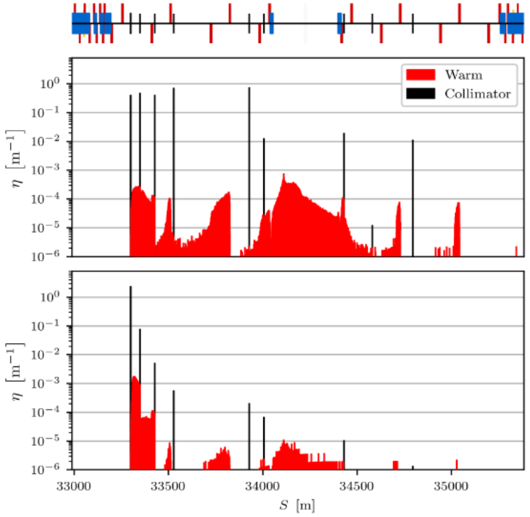


PRELIMINARY

Molybdenum-Graphite primary collimator

Tungsten primary collimator

for comparison only, likely not feasible with with multi-MJ beams



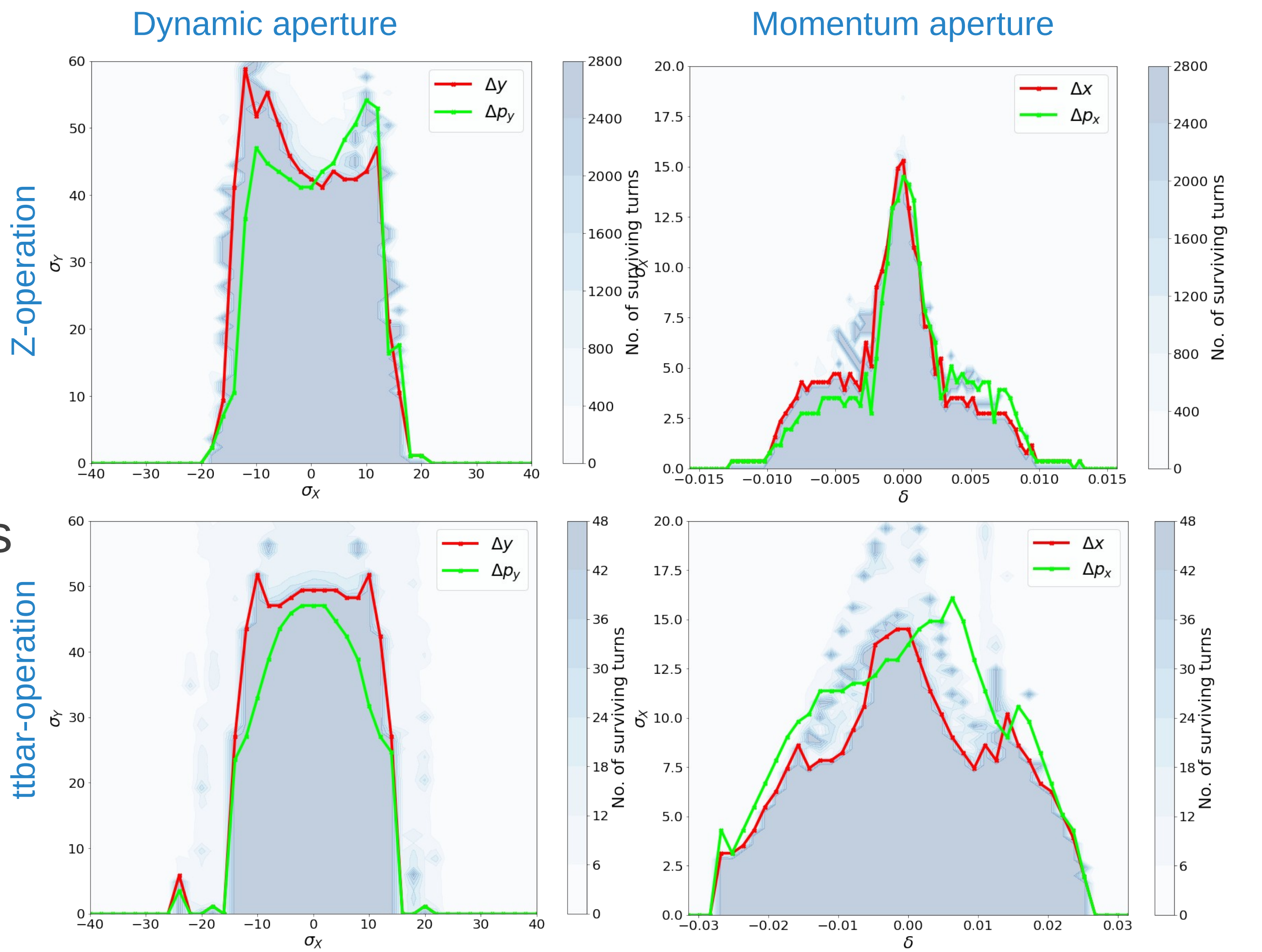
Betatron collimation study

182.5 GeV, no radiation or tapering, 5x10^6 primary positrons, 700 turns

M. Hofer

Dynamic and Momentum Aperture

- Non-interleaved sextupole scheme with pseudo -I transformation
- Large momentum acceptance
  - 1.3 % for Z-mode
  - -2.8 % to 2.4 % for ttbar-mode
- No errors or corrections
- Performance with errors and corrections to be studied
- All sextupole pairs used independently
- Possibility of reducing number of sextupoles ongoing

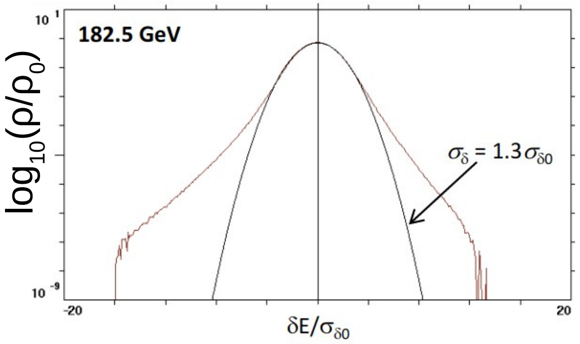


D. Shatilov, J. Wenninger

Determining the ECM

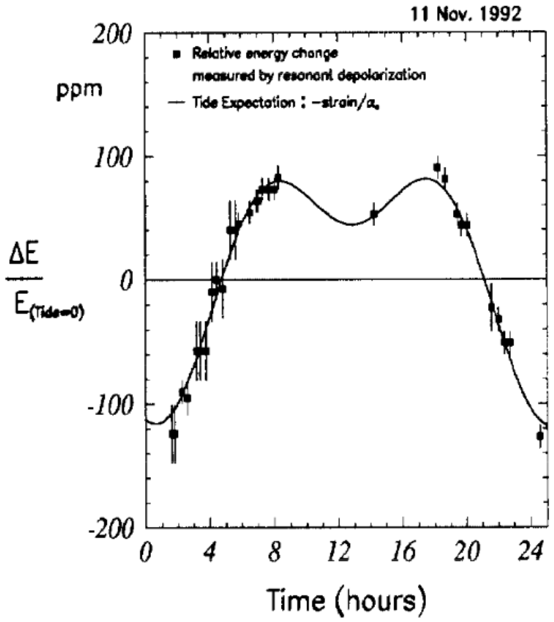
- Predicting center of mass energy (ECM) and boosts not trivial

Beamstrahlung
Crossing bunches interact with force field created by other bunch, which increases the energy spread



Optics errors
Tuning and measurement techniques essential

Earth tides
Machine circumference changes compensation by RF, as done in LEP

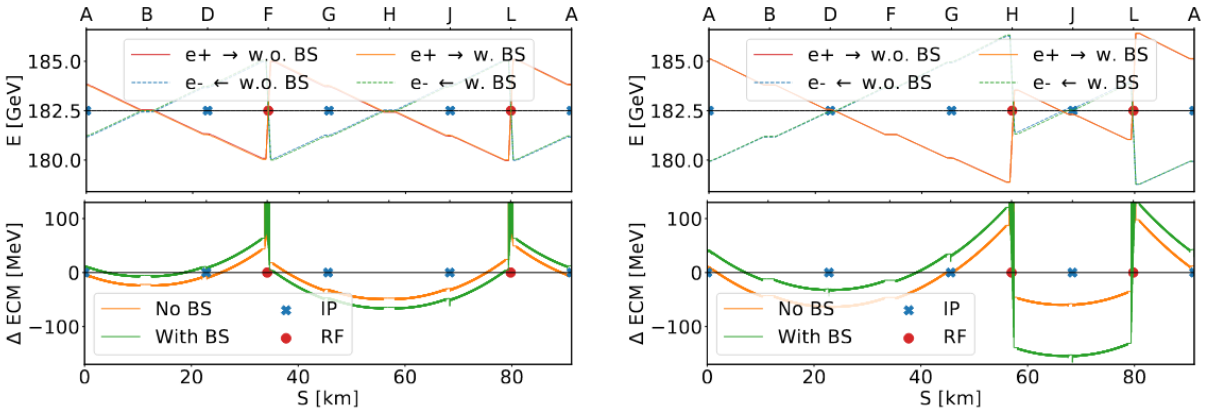


Dispersion at IP

$$\Delta\sqrt{s} = -2u_0 \frac{\sigma_E^2 (D_{u1} - D_{u2})}{E_0(\sigma_{B1}^2 + \sigma_{B2}^2)}$$

U_0 … nominal ECM
$D_{u1,2}$ … dispersion at the IP
E_0… nominal energy
$\sigma_{B1,2}$ … beam size at the IP

Placement, number and exact configuration of RF-cavities
Example: ttbar-lattice with 2 RF section either in PF+PL or PH+PL



Energy Polarization, Calibration and Monochromatization Workshop in September:

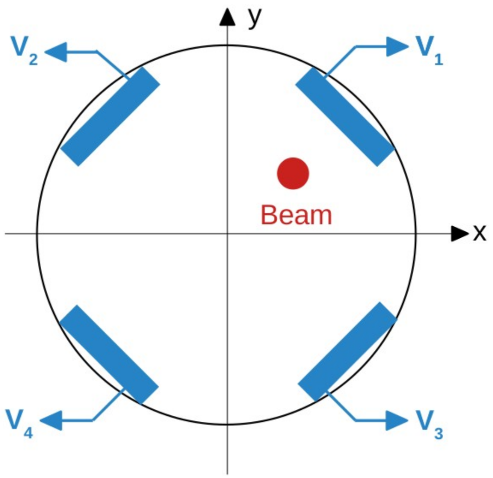
https://indico.cern.ch/e/EPOL2022

M. Wendt

Beam Position Monitors

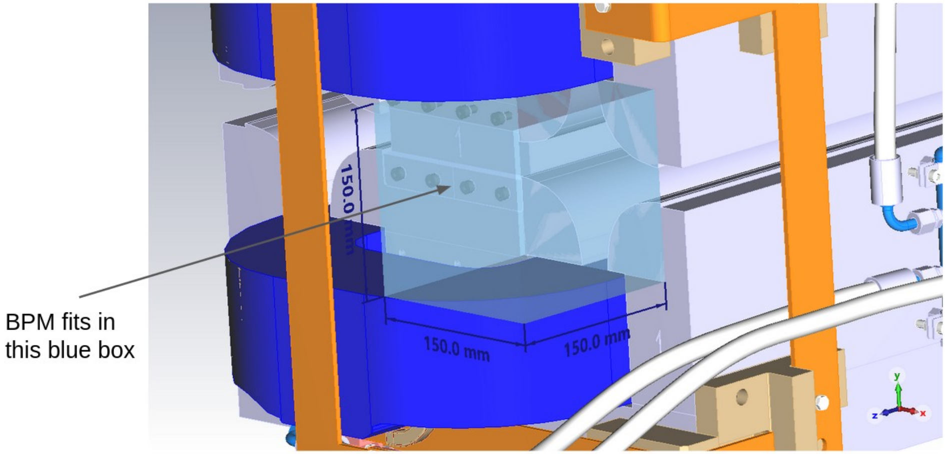
- Beam Position Monitors (BPMs) are crucial devices for beam optics measurements
- Button BPMs are the most common type, spoiled by resolution, calibration, non-linearity, ...

Schematic possible button BPM for FCC-ee

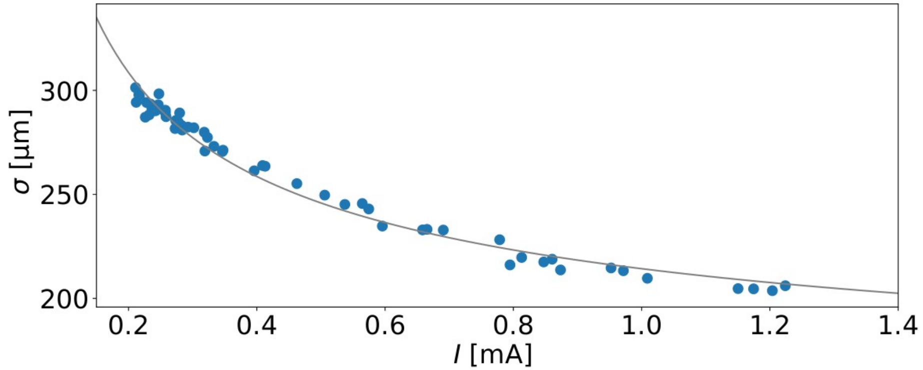


Buttons typically rotated by 45° due to strong synchrotron radiation

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



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



BPMs could be installed either next to
- every quadrupole
- every sextupole
- interleaved quadrupole-sextupole element
- ...

Tuning studies will show preferred solution

T. Charles, Y. Wang

Misalignments and Field Errors

- Aim to build and correct realistic lattice with misalignment and field errors

FCC-ee, T. Charles

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	$\Delta k/k = 2 \times 10^{-4}$

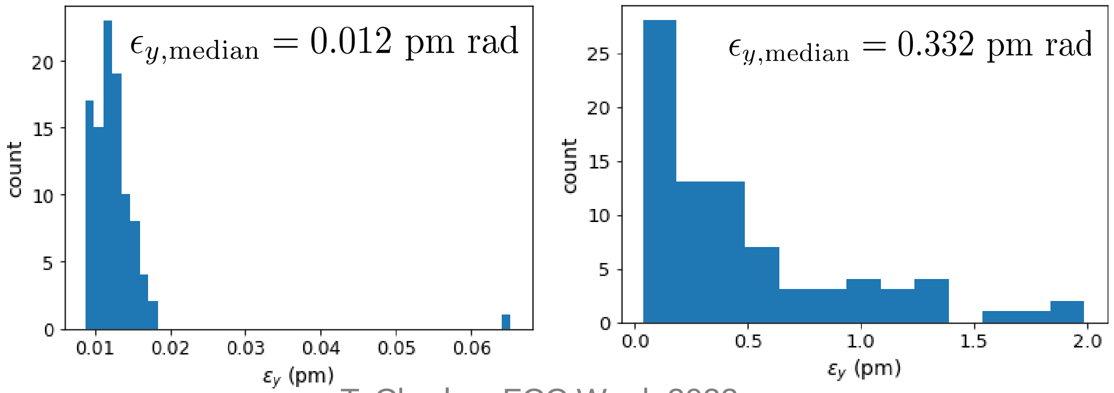
CEPC, Y. Wang

CEPC RMS misalignment and field errors tolerances (tentative)

Component	Δx (um)	Δy (um)	$\Delta\theta_z$ (urad)	Field error
Arc Quadrupole	100	100	100	0.02%
Arc Sextupole	100*	100*	100	
Dipole	100	100	100	0.01%
IR Quadrupole	100	100	100	
IR Sextupole	100*	100*	100	

*reduced to 10 um with movers
w/o misalignment of the girder
w/o main field errors of the sextupole and IR quadruple

Final emittances for 100 seeds and ttbar-lattice without (left) and with (right) chromaticity correction



T. Charles, FCC Week 2022.

Controlling sextupole errors crucial to achieve required FCC-ee and CEPC collider performance

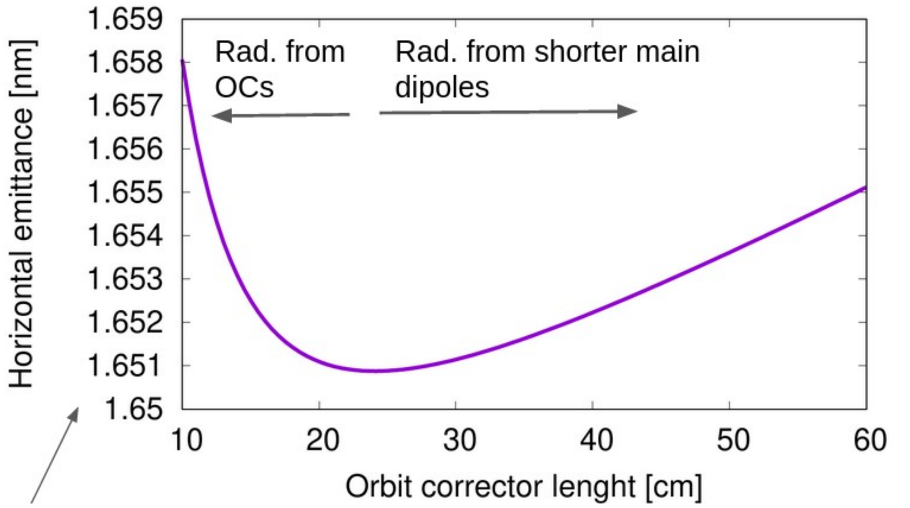
Techniques to achieve an effective sextupole misalignment of 10 μm being explored

C. Garcia, R. Tomás

Tuning Studies

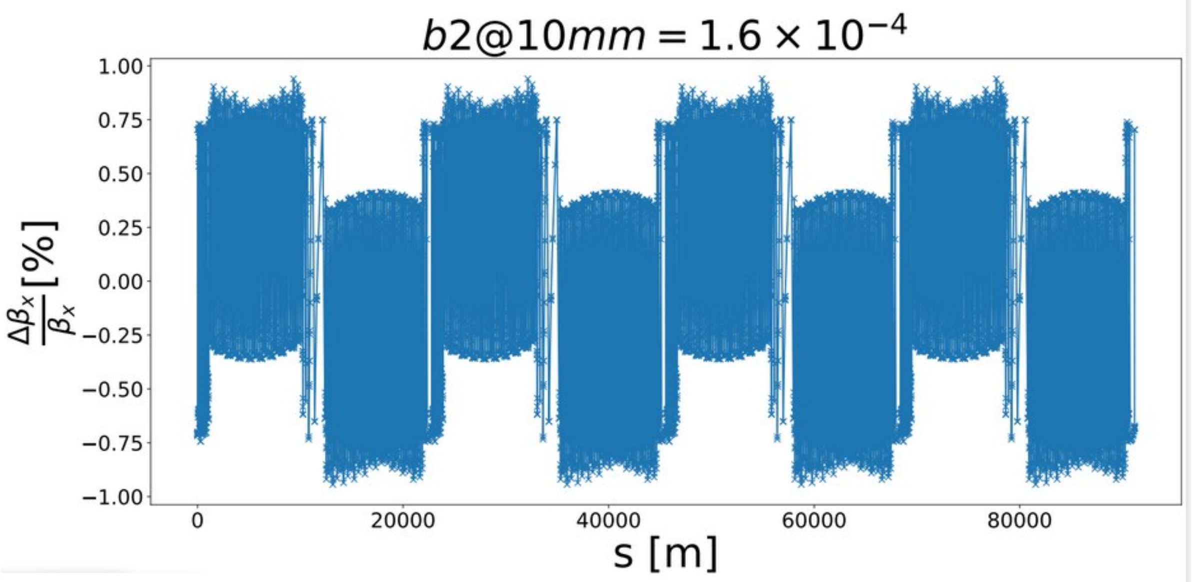
- Numerous tuning studies ongoing

Ideal orbit corrector length found to be about 25 cm to reach minimum horizontal emittance
Different corrector length has also direct impact on rest of the lattice



Quadrupole errors (b_2) in main dipoles up to 1.6 units limit β-beating to 1%

Should systematic quadrupole errors in the main dipoles already be included in the design?



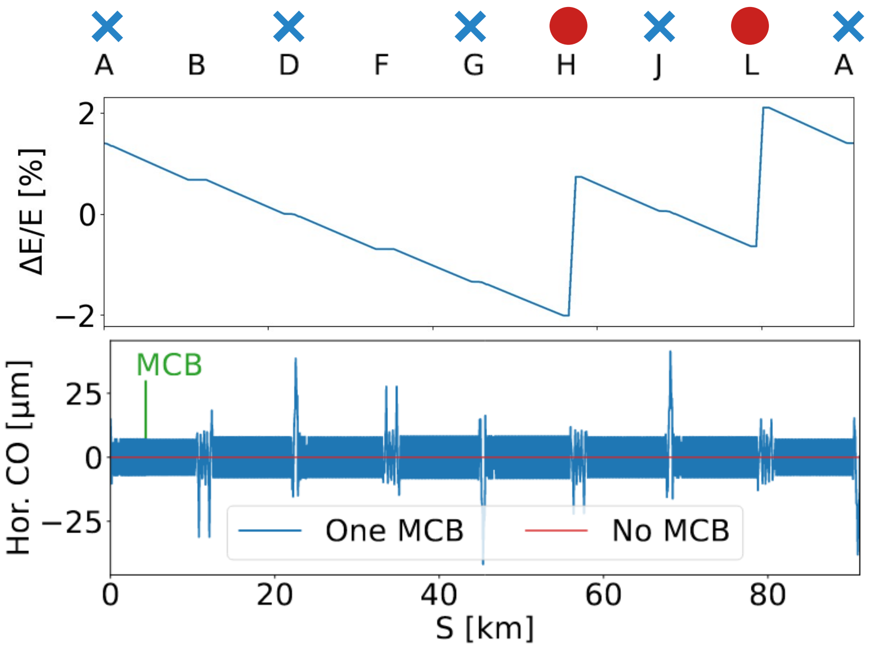
Continous progress in FCC-ee tuning working group:
https://indico.cern.ch/event/1167740/
Dedicated optics tuning and alignment workshop:
https://indico.cern.ch/event/1153631/

Results of tuning studies will help shaping the final design of the FCC-ee!

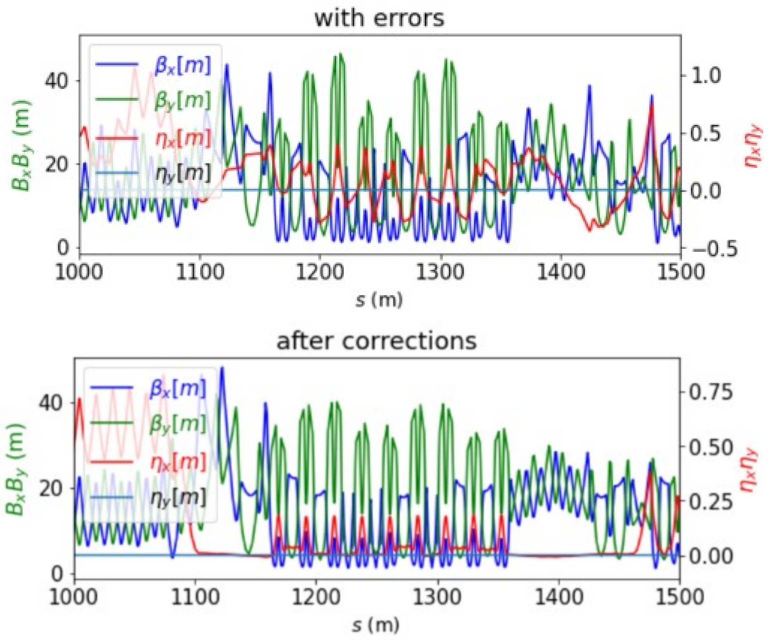
Optics Measurement

- Various techniques presently explored for the FCC-ee

Orbit response matrix
At beam energy 182.5 GeV and radiation losses/turn about 10 GeV → Large energy variation of about ± 2 %, tapering applied
Effect of SR losses on ORM to be explored



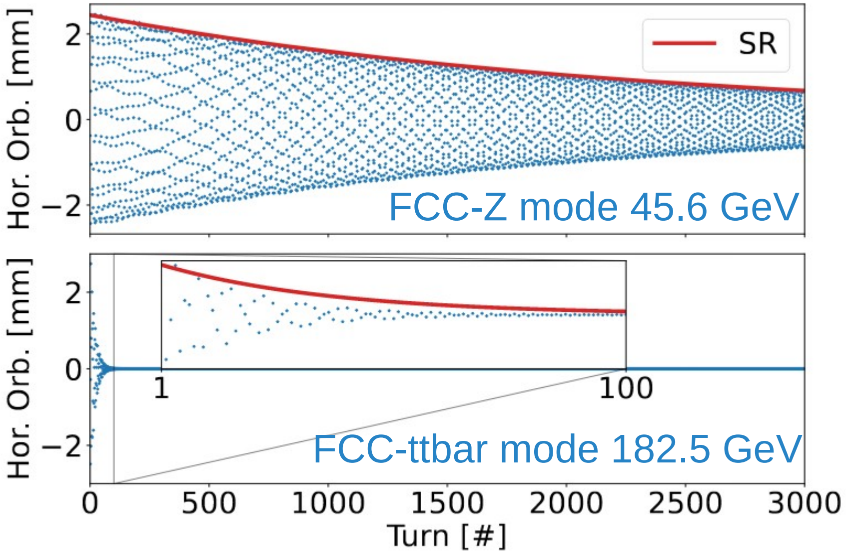
LOCO
Simulated for PETRA III and currently being explored for the FCC-ee



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

Turn-by-Turn Measurements
Procedure: Beam excitation → harmonics analysis (Fourier Transform) → optics analysis

Z-mode: 2300 damping time is slow enough to use single kicks for TbT measurements
ttbar mode: 40 turns damping time and thus single kicks too fast for TbT measurements (use e.g. AC-dipole as in LHC, or transverse feedback with amplification as in SKEKB)



Kick Strength and Phase Advance

- Relative rms phase advance error with respect to the model used for defining/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

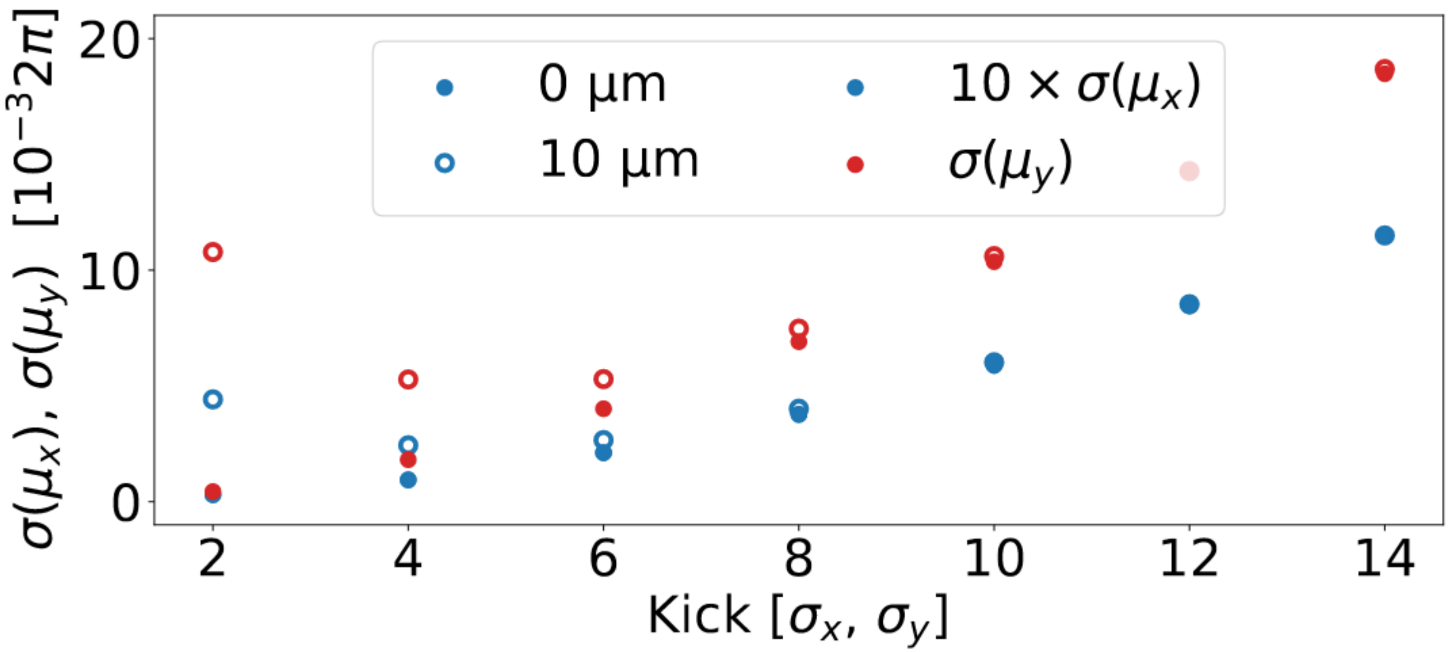
Without BPM noise phase error increases with increasing excitation strength

With BPM noise (here 10 μm) optimum kick strength found at 4 σ_x, 4 σ_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
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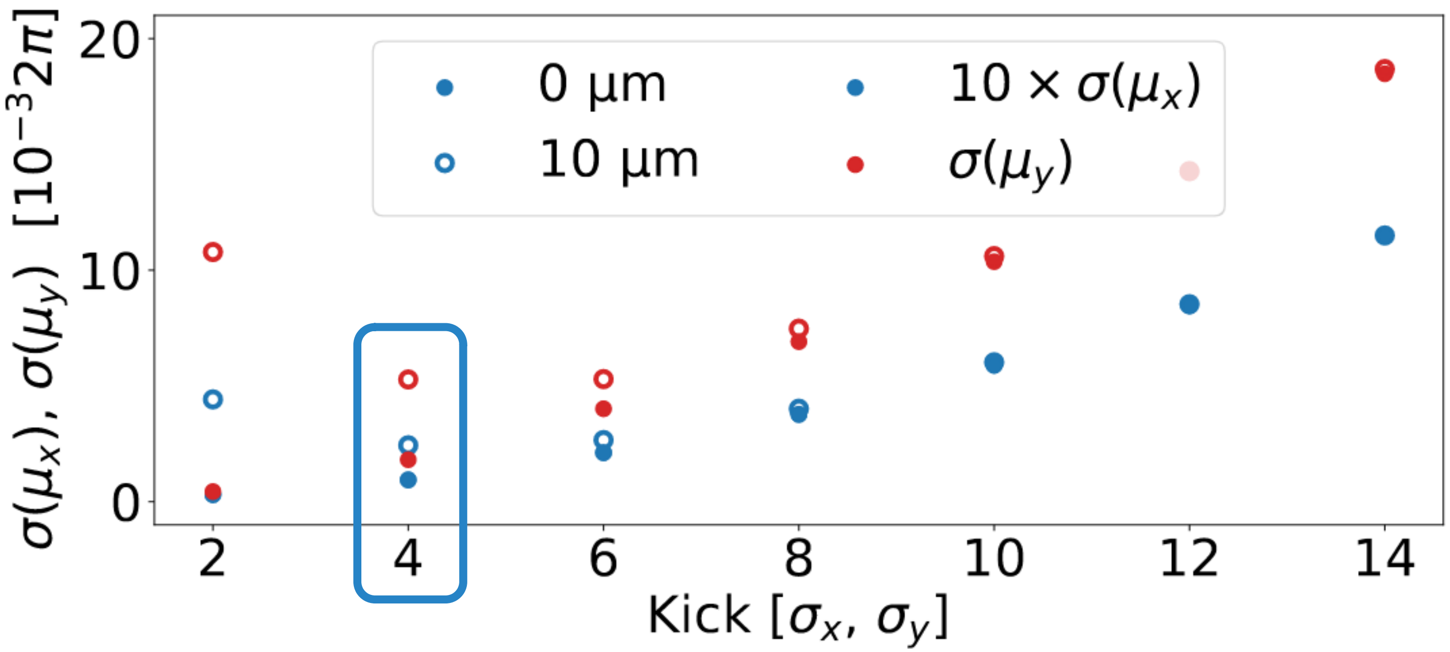
FCC-Z mode
500 turns, no synchrotron radiation
Minimum hor and ver. phase advance error with
10 µm BPM noise: 0.24 x 10^{-3} (2π) and 5.28 x 10^{-3} (2π)

Comparison LHC
6600 turns, AC-dipole
Minimum hor and ver. phase advance error, ~100 µm
BPM noise: < 1 x 10^{-3} (2π)

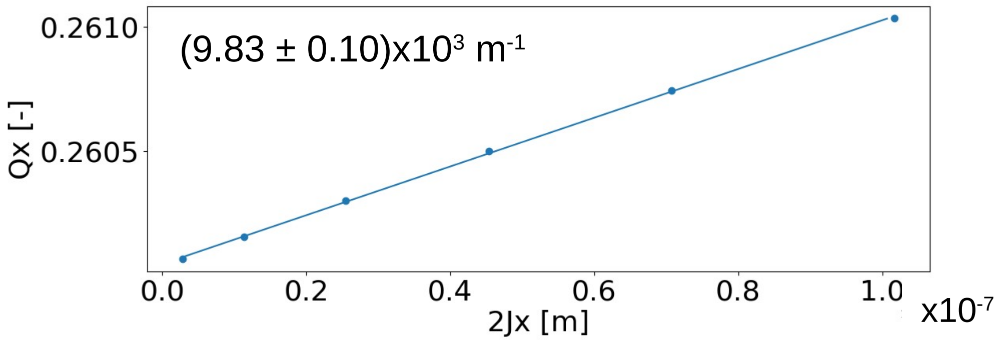
FCC-Z mode at 45.6 GeV single particle tracking



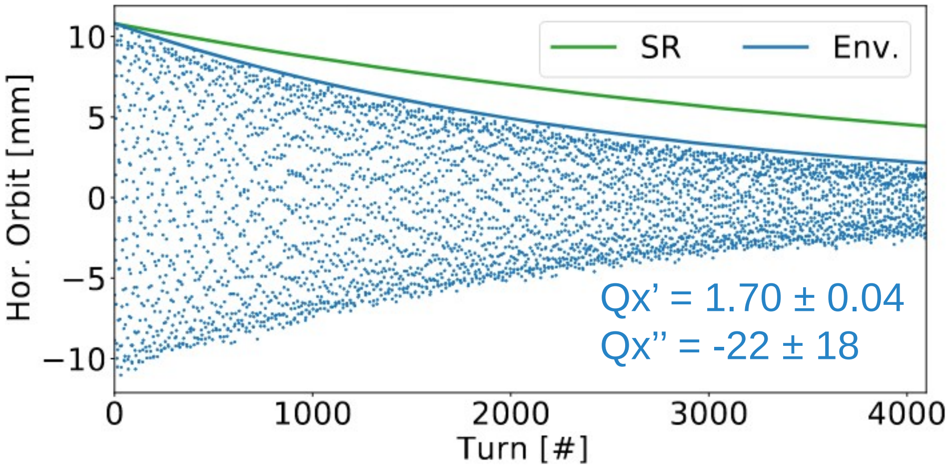
Single Kicks in Measurements

- Experience from existing machines such as LHC and SuperKEKB essential for FCC-ee
- After kick is applied, orbit is affected by
  - Synchrotron radiation
  - Decoherence from tune spread
  - Head-tail effect and impedance

FCC could experience decoherence from chromaticity and amplitude detuning
FCC-Z mode at 45.6 GeV amplitude detuning



SuperKEKB 4 GeV positron ring (LER) TbT measurements



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

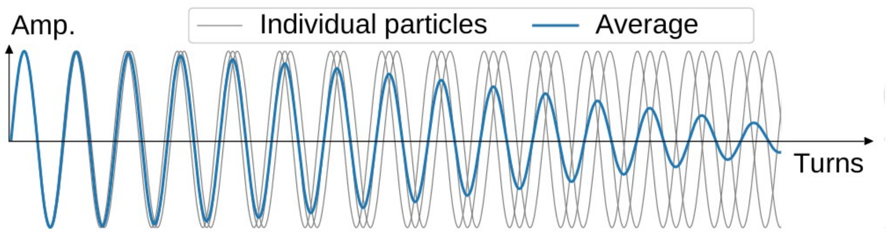
Faster damping after applying horizontal kick than predicted from synchrotron radiation

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



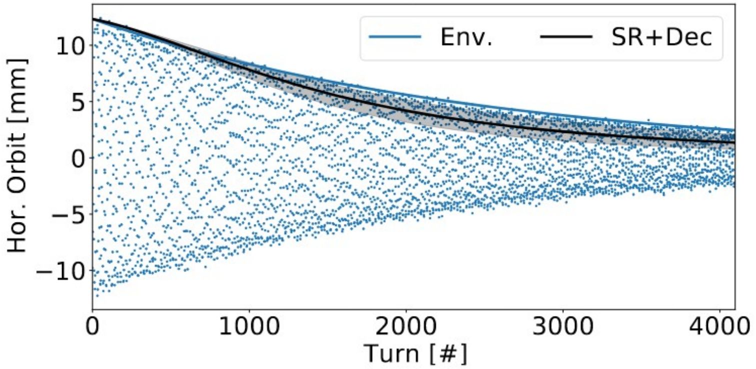
Existing theory for hadrons:

μ … Amplitude detuning N … Turns
Z … Kick strength

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

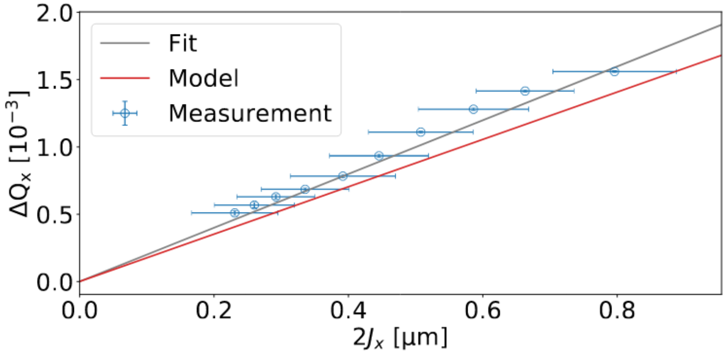
Here extended for leptons:

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



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, 10 % larger than model



Summary

- Integrated FCC project would be compatible with ESPP 2020
  - FCC-ee (Higgs and electro-weak factory) followed by FCC-hh (up to 100 TeV E_{com})

- Numerous challenges for FCC-ee (optics design, dynamic aperture, alignment, tuning, optics measurements, ECM prediction, etc.)
  - Great international effort to provide a self-consistent and feasible baseline design

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

Continous progress and lots of fun still ahead of us!

Thank you!

FCC-ee Lattice Design

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On behalf of

The FCC-ee collaboration and the FCC IS DS team

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