OPTICS TUNING SIMULATIONS FOR FCC-EE USING PYTHON ACCELERATOR TOOLBOX

Elaf Musa (DESY)

With thanks to: K. Oide, F. Zimmermann, R. Tomas, S. Liuzzo, S. White and the entire FCC-ee optics team

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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.

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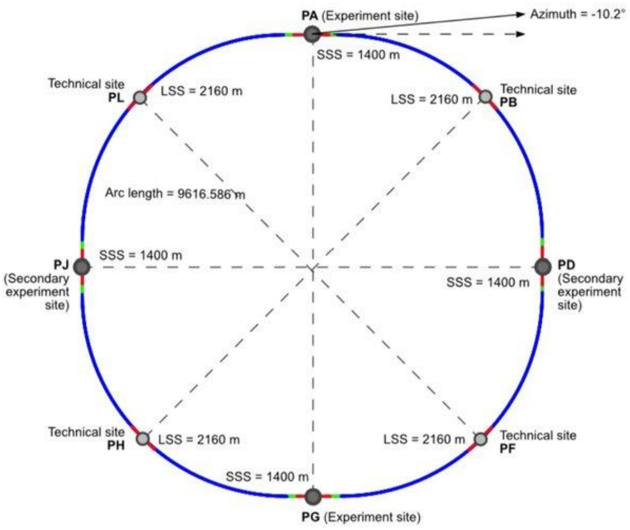
- # The e+/e- Future Circular Collider

  - Ultra-low emittance storage rings, with a circumference of about 90 km, aims to achieve unprecedented luminosity and beam size.

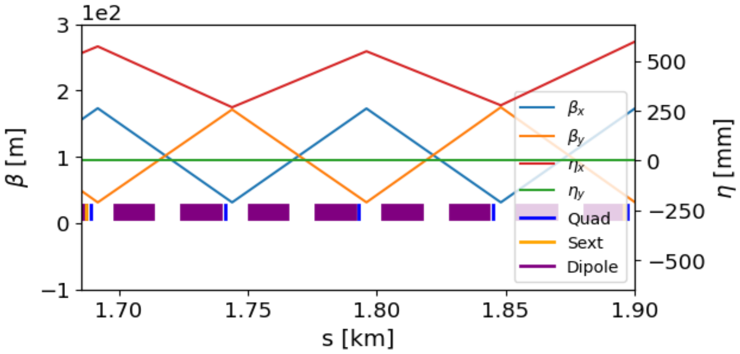


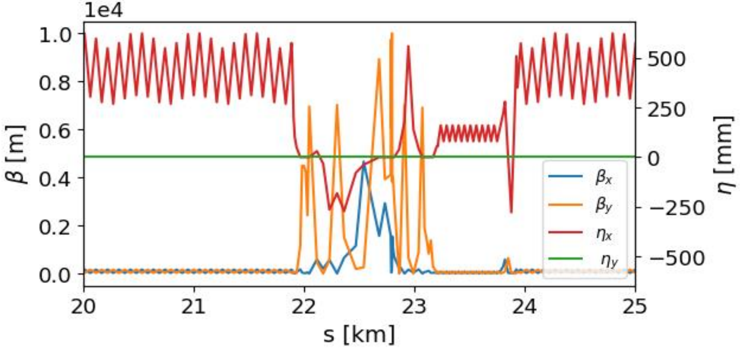
Lattice parameter	Z	tt
Energy (GeV)	45.60	182.50
Horizontal tune Q_x	218.16	398.15
Vertical tune Q_y	222.20	398.22
Horizontal emittance (nm)	0.71	1.57
Vertical emittance (pm)	1.90	1.60
$\beta*$ at IP x/y (mm)	110 / 0.7	800 /1.5
Luminosity / IP (×10^34cm^2s)	141	1.38

- Unique precision instrument to study the heaviest known particles (Z, W, H bosons and the top quark), offering great insights into new physics.

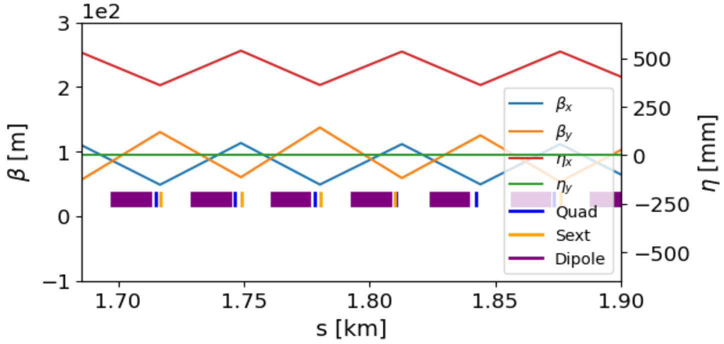
- **Two proposed optics design for FCC-ee**

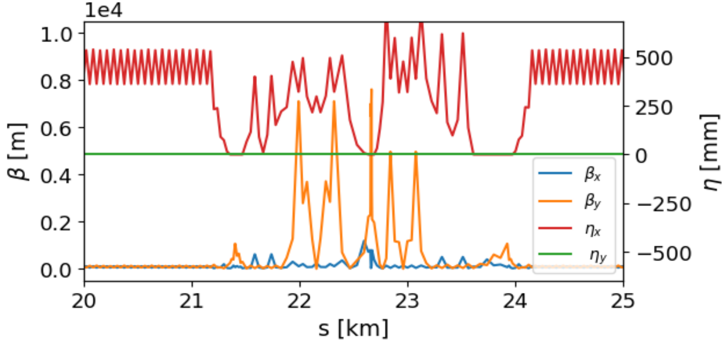
Baseline optics (K. Oide)





LCC optics (P. Raimondi)



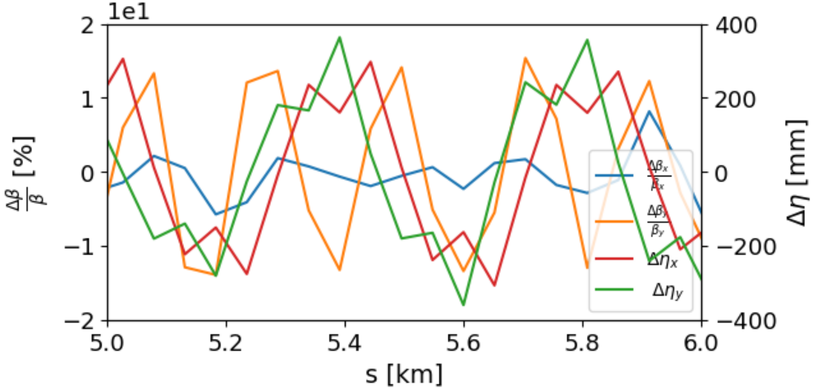


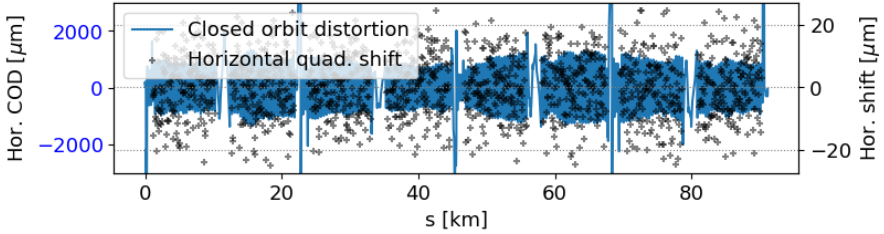
Beam dynamics challenges

- Aiming for such ultra-low vertical emittance highlights the necessity for a comprehensive understanding of tolerance requirements of magnet field imperfections and misalignments which can significantly impact the machine performance.

- Large optics tuning simulation campaigns are needed to achieve this.

Impact of 10 μm alignments and errors of arc magnets on optics and orbit





Correction algorithms

- The aim of orbit and optics correction algorithms is to minimize impact of lattice errors by adjusting magnet strengths.

SVD orbit correction

$$M_{i,j} = \frac{\sqrt{\beta_i(s)\beta_j(s_0)}}{2\sin(\pi Q)}\cos\left(\pi Q - \psi_i(s) + \psi_j(s_0)\right) + \frac{\eta_i(s)\eta_j(s_0)}{\alpha_c L_o}, \qquad \Delta x + M\Delta\theta = 0,$$

Phase advance + η_x correction

$$\begin{pmatrix} \alpha_1 \Delta\psi_x \\ \alpha_1 \Delta\psi_y \\ \alpha_2 \eta_x \end{pmatrix}_{\text{meas}} = -C_{model}\delta K,$$

LOCO for optics correction

$$\chi^2 = \sum_{i,j} \frac{(M_{model,i,j} - \hat{M}_{i,j})^2}{\sigma_i^2} \qquad W = \frac{1}{\sigma^2}$$

$$\delta h_{\text{GN}} = \left[J^\top W J\right]^{-1} J^\top W(M - M_{model}),$$

Coupling RDTs + η_y correction

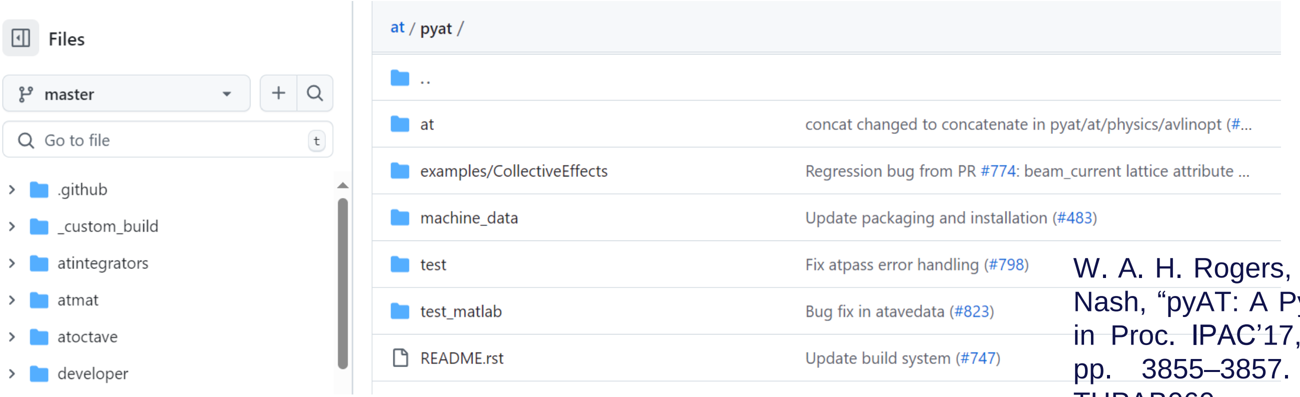
$$f_{\substack{1001\\1010}}(s) = -\frac{1}{4\left(1 - e^{2\pi i(Q_x \mp Q_y)}\right)} \sum_l K^{sl}(s)\sqrt{\beta_x^l(s)\beta_y^l(s)} \times e^{i\left(\Delta\psi_x^{sl}(s) + \Delta\psi_y^{sl}(s)\right)},$$

$$\begin{pmatrix} \alpha_1 f_{1001} \\ \alpha_1 f_{1010} \\ \alpha_2 \eta_y \end{pmatrix}_{\text{meas}} = -N_{model}\delta K_s.$$

Python Accelerator Toolbox (PyAT)

- **Accelerator Toolbox (AT)** is a collection of tools that model storage rings and beam transport lines, Track particles through the lattice, choosing the correct integrator to represent the applicable physics and determine properties of the beam.

- We used the Python interface of AT;
  User friendly tool that leverages open-source scientific libraries in Python and provides needed support for users.



W. A. H. Rogers, N. Carmignani, L. Farvacque, andB. Nash, “pyAT: A Python Build of Accelerator Tool-box,” in Proc. IPAC’17, Copenhagen, Denmark, May2017, pp. 3855–3857. doi: 10.18429/JACoW-IPAC2017-THPAB060.

Optics correction with PyAT

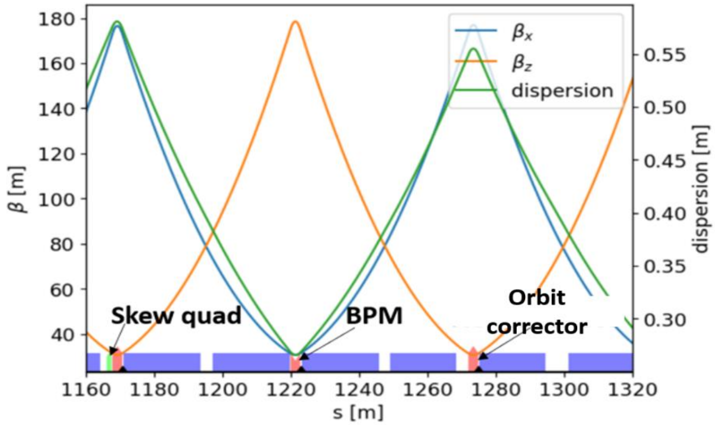
- We have developed an optics tuning code based on PyAT, which includes the following:

  - Numerical calculations for Orbit Response Matrices (ORMs) and Jacobians
  - Implementation of number of optics and orbit correction algorithms
  - Dynamic aperture (DA) and emittance calculations
  - Parallel processing in clusters

- The code, along with various examples, is available in our GitHub repository: elafmusa/Optics-corrections-with-PyAT.

FCC-ee tuning studies

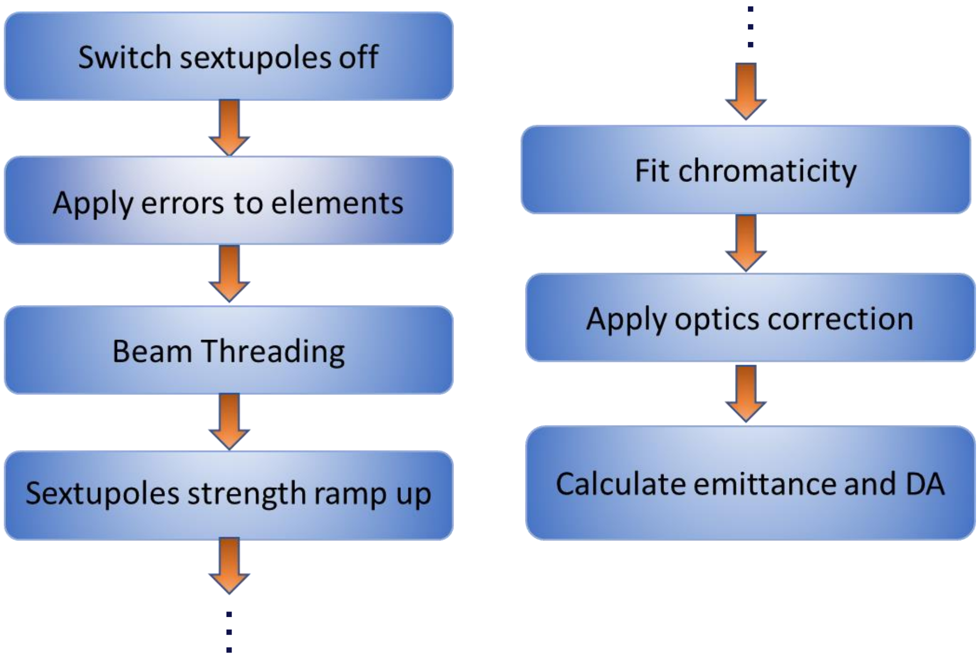
Used correctors



Number of correctors

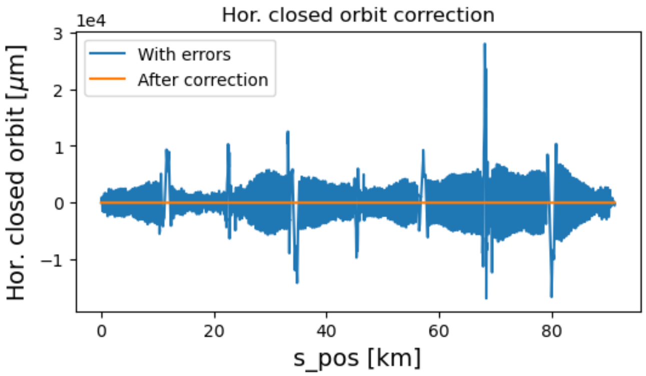
Corrector type	Baseline	LCCO
Hor. Orbit	1856	2700
Ver. Orbit	1856	2700
Skew Quads	632	2000
BPMs	1856	2700

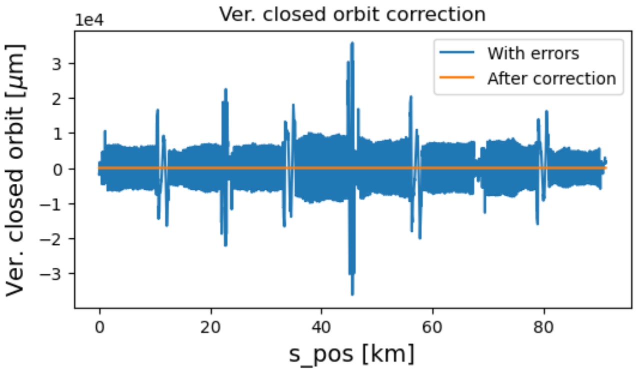
Followed correction procedure



- # FCC-ee tuning studies

  - ## SVD Orbit correction

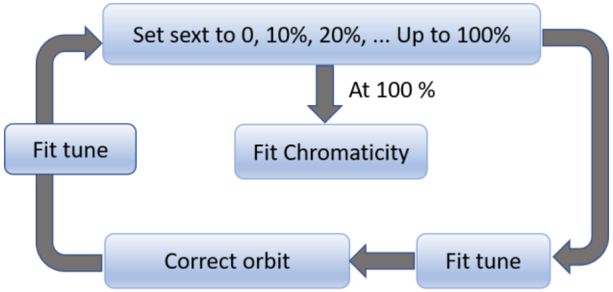




  - ## Tune & chromaticity fitting

Choosing proper knops:
- All **arc** focusing and defocusing quadrupoles
- All **arc** focusing and defocusing sextupoles

  - ## Sextupole ramping



• Implemented Python-based numerical code for LOCO correction

Input

- Model Orbit response matrix.
  Jacobian: $J = \sum_k \frac{\partial C_{i,j}}{\partial g_k}$

  - Three dim matrix (# fit parameters, # cors, # bpms)
  - Each column of the Jacobian matrix is the derivative of the response matrix over one fitting Parameter.
  - Parallel processing in DESY maxwell cluster.
  - Analytical option:
    A.Franchi S. Liuzzo and Z. Marti, Analytic formulas
    https://arxiv.org/abs/1711.06589

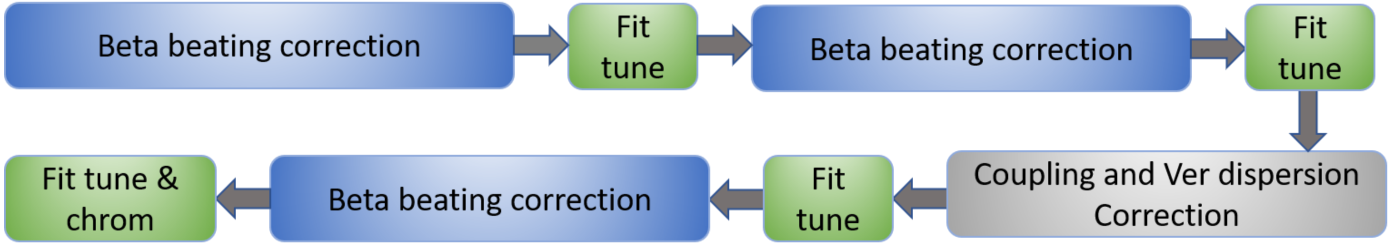
- Other inputs.
  Initial guess
  Included fit parameters
  …

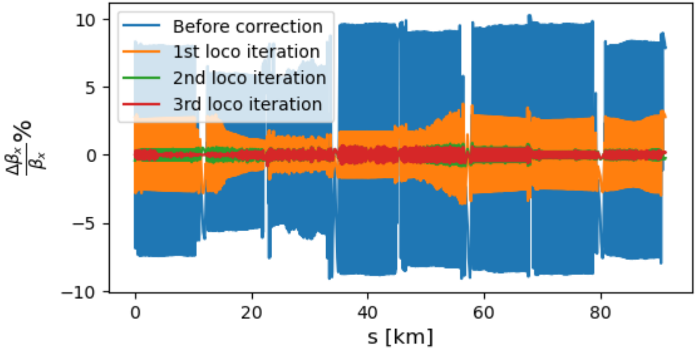
LOCO iterations

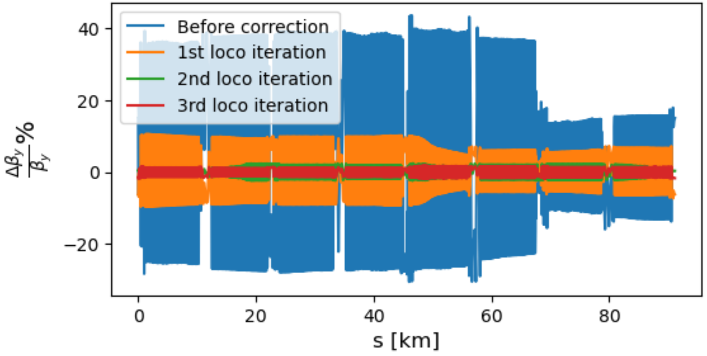
- Measured orbit response matrix.
- Minimization
  (Newton-Gauss or Levenberg-Marquardt)
- Apply the fitting results to the lattice.
- Convergence of optics parameters.

The implemented code is integrated into the Python version of the Simulated Commissioning toolkit for Synchrotrons (PySC) for PETRA at DESY.
E. Musa, I. Agapov and L. Malina, pysc/correction/loco.py at master · lmalina/pysc, 2024, LOCO module in PySC,

Implementation of LOCO for FCC-ee

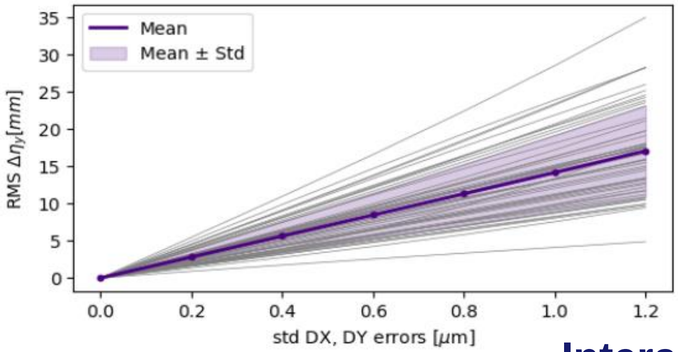


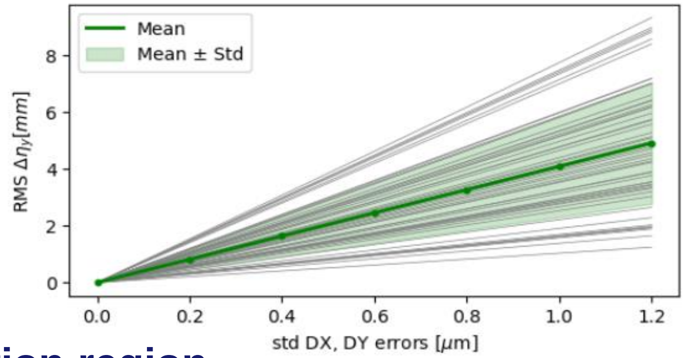




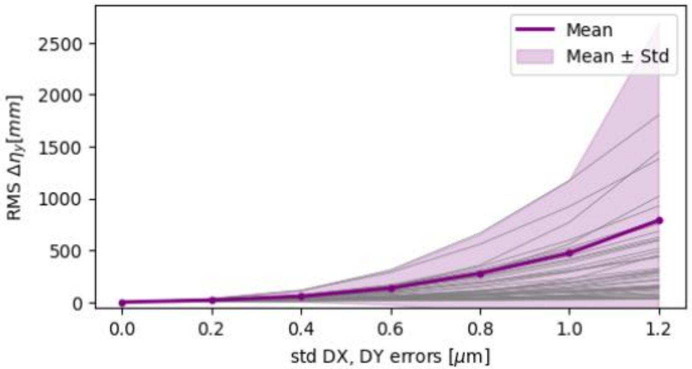
• Optics sensitivity to magnet alignment errors study (Z energy)

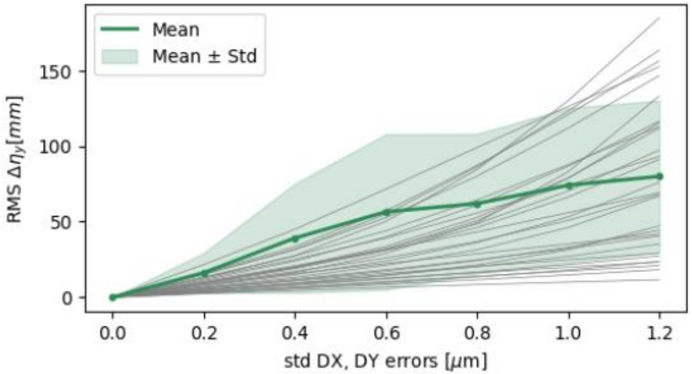
Baseline optics **Arc region** **LCC optics**





Interaction region





Optics tuning results

- Horizontal and vertical random displacement errors distributed via a Gaussian distribution with a standard deviation of 100 μm in arc magnets

50 Seeds (Mean values)	rms orbit x (μm)	rms orbit y (μm)	$\Delta\beta x/\beta x$ %	$\Delta\beta y/\beta y$ %	$\Delta\ \eta x$ (mm)	$\Delta\ \eta y$ (mm)	ε_h (nm)	ε_v (pm)
With err	5727.4	7304.3	9.35e-7	2.07e-4	10560	70773	-	-
After sext ramping	8.49	8.40	5.98	10.40	44.27	43.72	0.71	10.29
Beta beat cor.	10.76	14.90	2.50	3.69	41.52	44.11	0.721	327.05
Coupling cor.	12.62	18.09	4.92	13.38	2.37	4.17	0.73	636.65
Final cor. results	12.81	17.74	3.10	6.28	10.19	3.88	0.73	537.30

- Emittance growth was mitigated vie interleave LOCO with orbit correction

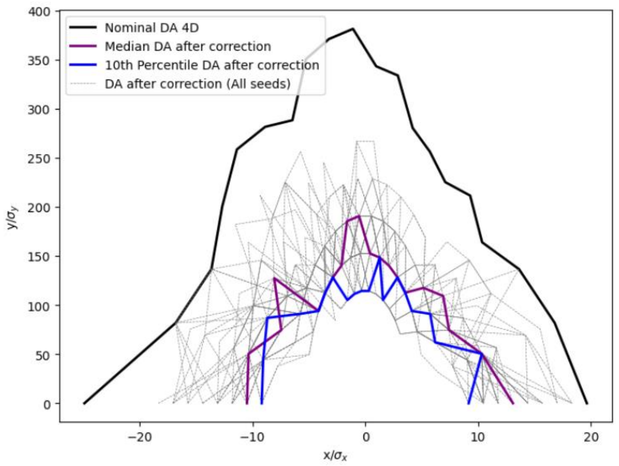
50 seeds (mean values)	rms orbit x (μm)	rms orbit y (μm)	$\Delta\beta x/\beta x$ %	$\Delta\beta y/\beta y$ %	$\Delta\ \eta x$ (mm)	$\Delta\ \eta y$ (mm)	ε_h (nm)	ε_v (pm)
Final cor. results	8.56	8.35	1.93	3.23	4.95	2.92	0.70	5.99

- # Optimizing LOCO results

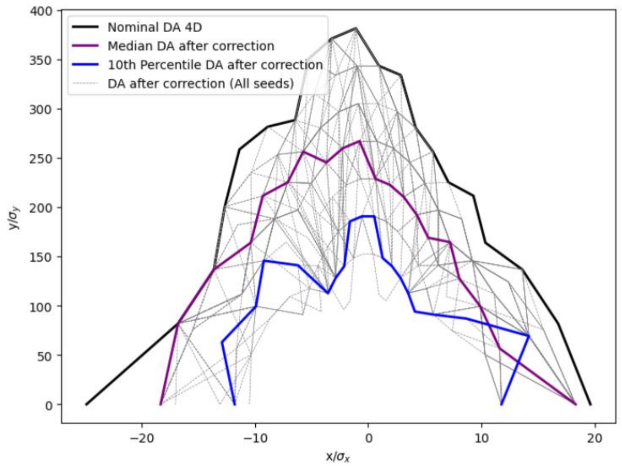
  - **Following LOCO correction with coupling RDTs/η_y**
    Helped in reducing the achived vertical emittance **5.99 pm** ➡ **0.75 pm**

  - **Different corrector locations**

LOCO with all normal quadruples

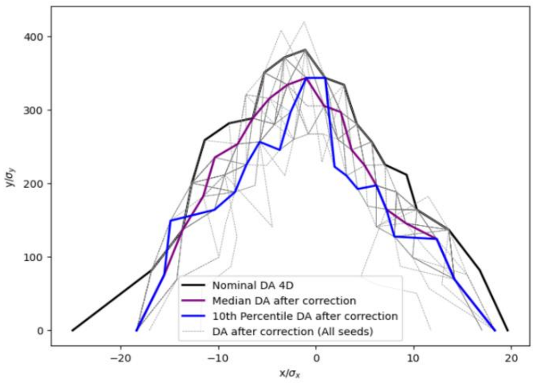


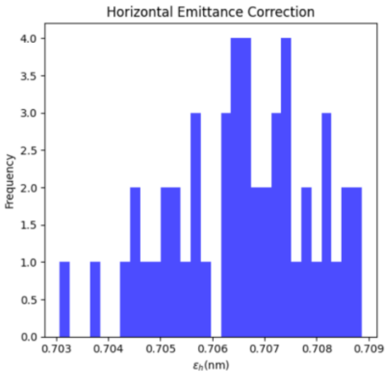
LOCO with normal trim quadruples at sextupoles

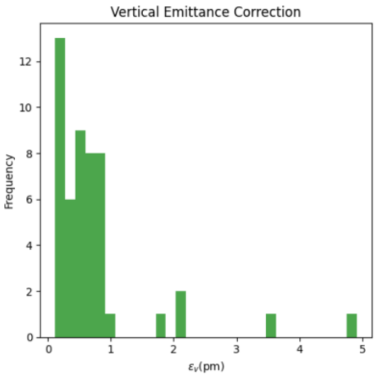


- **Alternative optics correction methods Phase advance/η_x and RDTs/η_y correction**

50 Seeds (Mean values)	rms orbit x (μm)	rms orbit y (μm)	Δβx/βx %	Δβy/βy %	Δ ηx (mm)	Δ ηy (mm)	ε_h (nm)	ε_v (pm)
With err	6224.8	7276.7	1e-6	1e-4	11985	73458	-	-
After sext ramping	8.55	8.35	5.98	9.91	45.23	45.96	0.71	9.61
RDTs & ηy correction	8.58	8.42	6.01	9.94	45.09	4.49	0.71	2.32
Phase cor.	8.55	8.35	0.35	0.79	2.94	4.36	0.70	0.88
Final cor. results	8.55	8.35	0.35	0.89	2.94	4.37	0.70	0.73







- # More realistic scenarios

Including Synchrotron radiation

<table>
<tr><th colspan="2">Elements</th><th>Hor. & Ver. displacement</th><th>Tilt θ</th></tr>
<tr><td colspan="2">Arc quads and sext</td><td>50 μm</td><td>50 μrad</td></tr>
<tr><td colspan="2">All dipoles</td><td>1000 μm</td><td>1000 μrad</td></tr>
<tr><td colspan="2">Girders</td><td>150 μm</td><td>150 μrad</td></tr>
<tr><td rowspan="2">BPMs</td><td>To quads</td><td>10 μm</td><td rowspan="2"></td></tr>
<tr><td>To sext</td><td>20 μm</td></tr>
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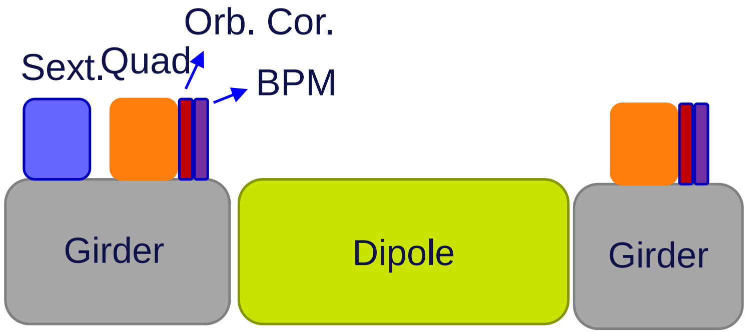
Numbers from BBA obtained by Xiaobiao Huang simulations

Case 1



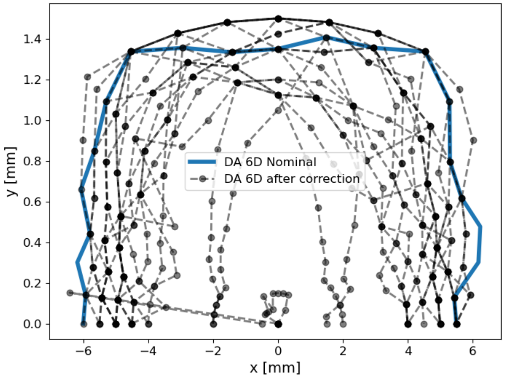
Case 2

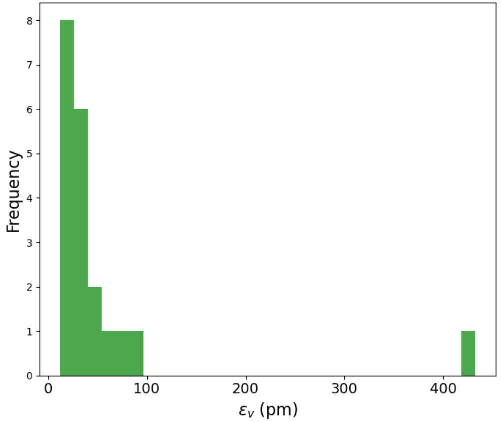
- **Ballistic optics** **(Cristobal Garcia <u>FCC-ee optics tuning WG meeting, Sep. 13, 3034.</u>)**

BPMs aligned to Quadrupoles

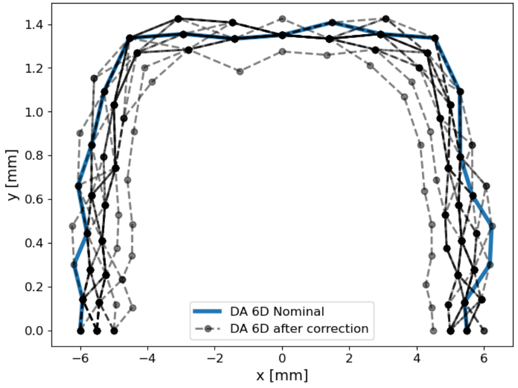
Parameter	Prior optics Cor.	Final Cor.
rms hor. orbit (μm)	130.23	130.36
rms ver. orbit (μm)	144.76	144.75
rms Δβx/βx%	9.72	1.02
rms Δβy/βy%	27.37	0.63
rms Δ ηx (mm)	73.73	0.66
rms Δ ηy (mm)	54.82	1.68
ε_y (nm)	31.57	0.23

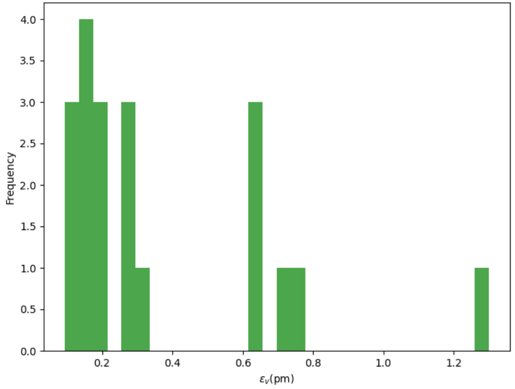
Prior to linear optics correction





Final correction





- **Outcome:**

  - Feasibility of the developed tuning procedure in achieving design parameters for the FCC-ee @ Z energy lattice.

  - **Error tolerances:** accounts for:

    Random displacement and tilt errors with standard deviations of:

    - 50 μm on arc quadrupoles and sextupoles
    - 1000 μm on all dipoles
    - 150 μm on girders
    - BPMs alignments

- **Future outlook:**
- **Aim to refine these correction procedures under more realistic conditions:**
  - Multipolar errors, Long-range alignment errors.
  - Interaction region's magnets misalignments.
  - Address Beam-Beam effect.
- **Advanced algorithms and computational methods will continue to be explored.**

Thank you for your attention!

Elaf.musa@desy.de