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Optics Tuning For the Electron Positron Future Circular Collider (FCC-ee)

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Acknowledgment: K. Oide, F. Zimmermann, R. Tomas, T.Charles, S. Liuzzo

and the entire FCC-ee optics tuning group.

3ed March 2025

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- Optics design for FCC-ee (nominal and ballistic lattices)
- Optics tuning challenges of FCC-ee
- Tuning algorithms and developed correction procedure
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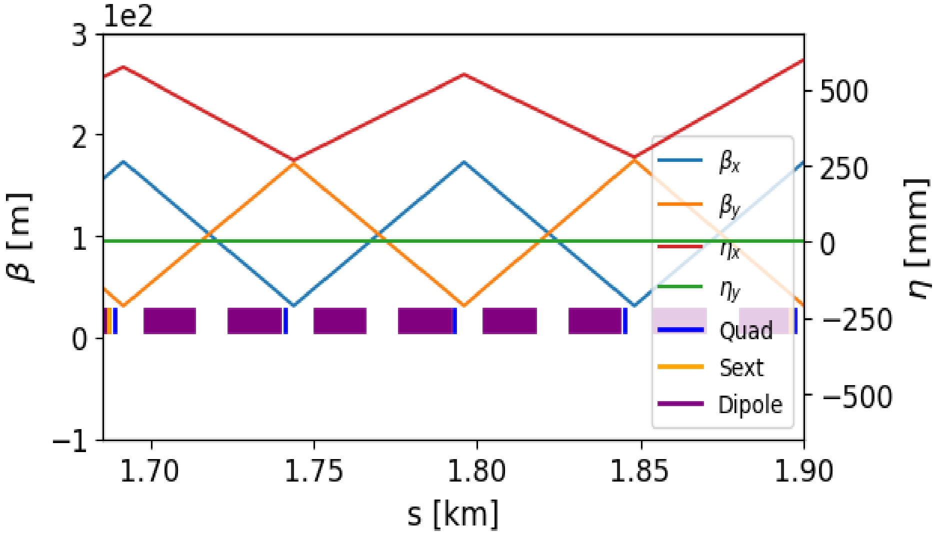
Baseline optics for FCC-ee

Optics of the arc region



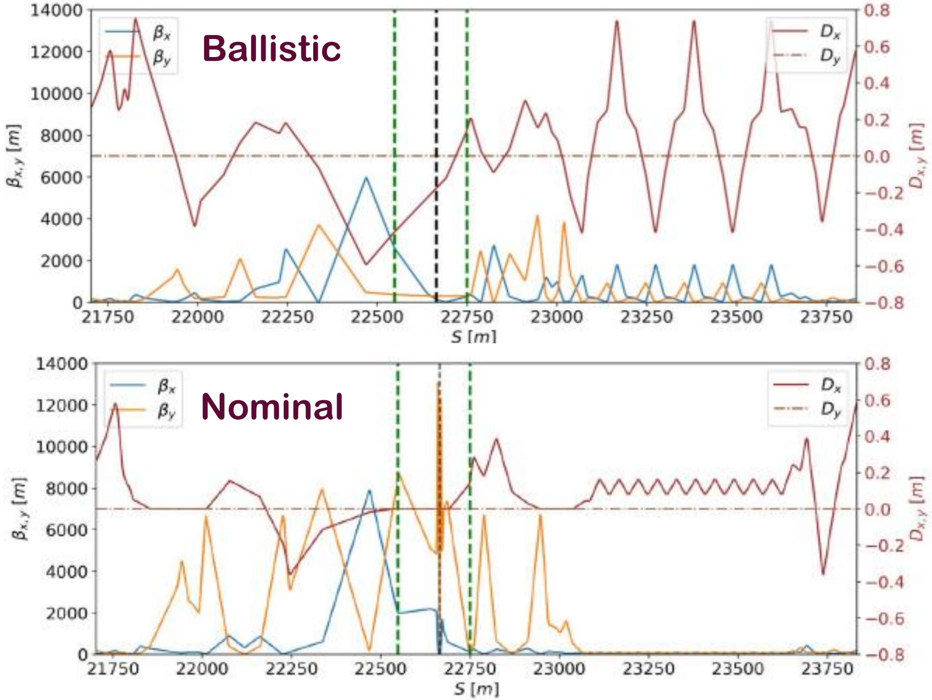
- The optics of the arc region of the lattice rely on FODO cell structure.

Optics parameters at Z energy

Lattice Parameter	Value
Beam Energy (GeV)	45.6
Horizontal tune Q_x	218.16
Vertical tune Q_y	222.20
Horizontal emittance (nm)	0.71
Vertical emittance (pm)	1.90
$\beta*$ at IP x/y (mm)	110/0.7
Luminosity / IP (×10^{34} cm^2s)	141

Ballistic optics for FCC-ee

Cristobal Garcia FCC-ee optics tuning WG meeting, Sep. 13



Optics parameters at Z energy

Parameter	Ballistic	Nominal
Max betax [m]	5969.65	7884.28
Max betay [m]	4153.92	13076.04
Max Dx [m]	0.75	0.75
Chroma	0.00/ -0.03	0.29/ 4.28
Tune	217.77/ 220.37	218.15/ 222.19
Emittance [nm]	0.70	0.85

- **The ballistic commissioning optics involves turning off all IR sextupoles, and quadrupoles 200 m around the IP (used in the first commissioning phases).**

Beam dynamics challenges of FCC-ee

- The target collider performance is defined by the luminosity:

$$\mathcal{L} = \frac{1}{4\pi}\frac{f_{\mathrm{rev}}N_1N_2}{\sigma_x\sigma_y}\frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\frac{\theta}{2}\right)^2}}$$

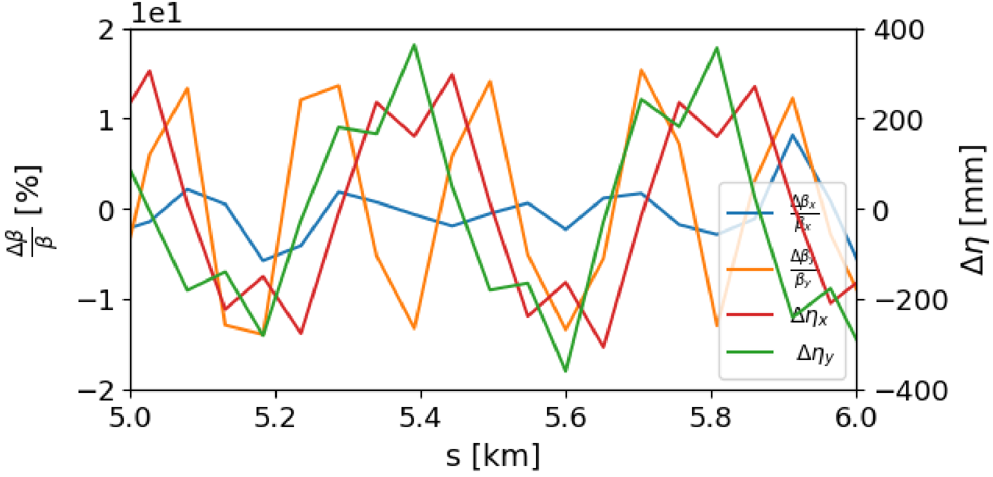
- Increasing the luminosity requires:
  - High beam current (will excite multi-particle effects).
  - A very small beta function β at the IPs which requires strong FF magnets, which in turn need strong sextupoles for local chromaticity correction in the Interaction Region (IR) (very sensitive to even small imperfections).

- Beam-Beam effect.

Optics tuning challenges

- Magnets field imperfections and misalignments have several impacts on the beam dynamics (Orbit distortion, coupling, beta-beating, tune shift .. etc.).

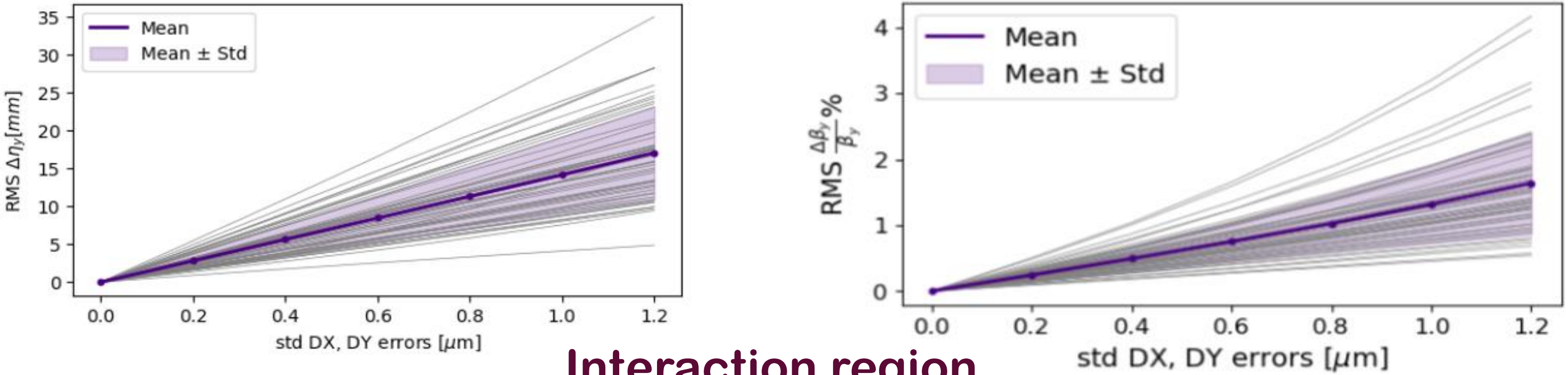
- The beam emittances, the Dynamic Aperture (DA), the beam life time and the overall machine performance are strongly dominated by these imperfections.



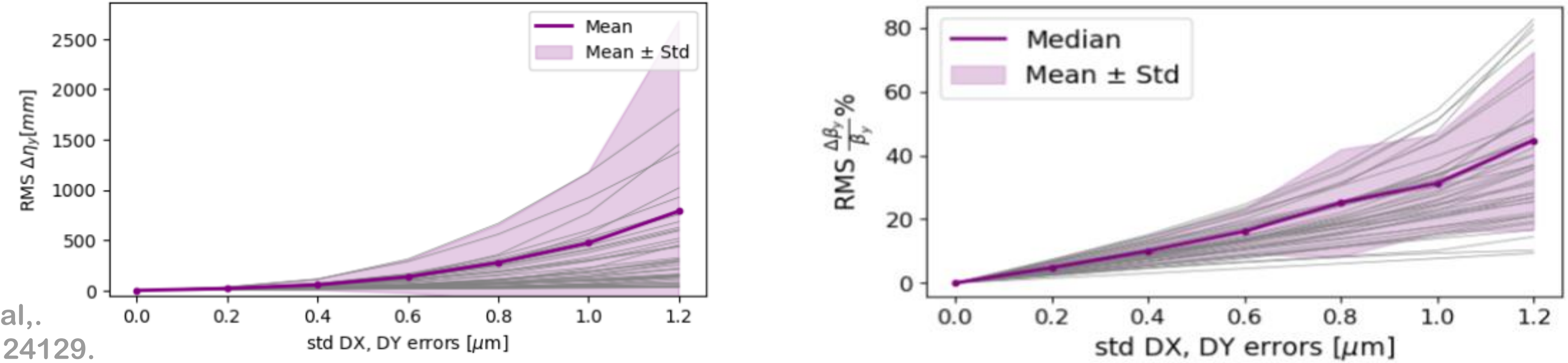
Impact of 10 μm alignments errors of arc magnets on optics parameters

Optics sensitivity to magnet alignment errors

Arc region

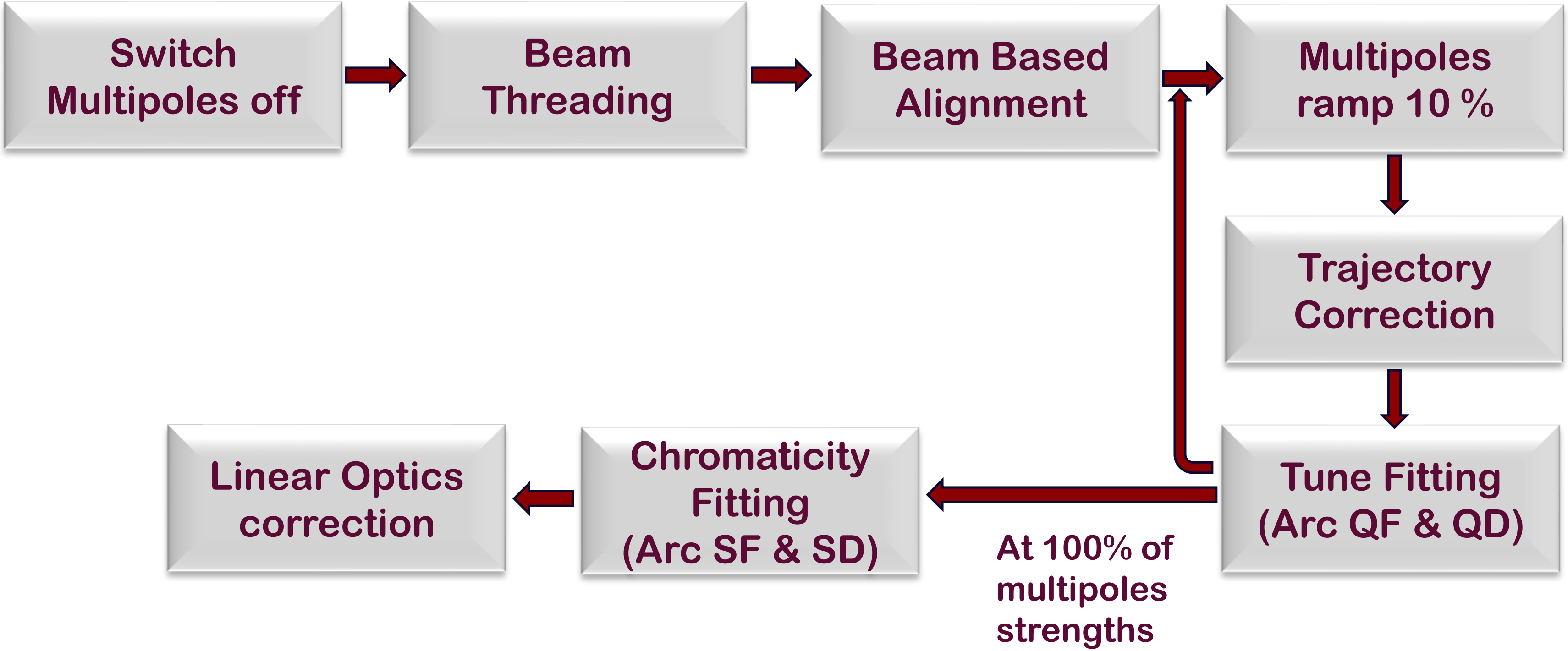


Interaction region



E.Musa, et.al,.
arXiv:2410.24129.

Correction procedure



Switch Multipoles off

Beam Threading

Beam Based Alignment

Multipoles ramp 10 %

Trajectory Correction

Tune Fitting (Arc QF & QD)

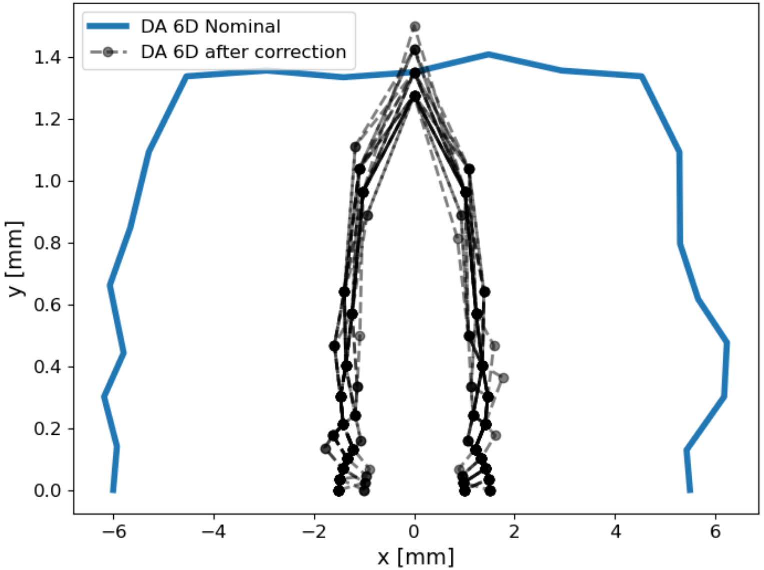
Chromaticity Fitting (Arc SF & SD)

Linear Optics correction

At 100% of multipoles strengths

Correction procedure

- For the ballistic optics with nominal errors Dispersion Free Steering (DFS) was found to be essential to proceed to BBA and optics correction.



rms	DFS	W/O DFS
Ver. Orbit (μm)	255	222
$\Delta\ \eta_x$ (mm)	70	446
$\Delta\ \eta_y$ (mm)	39	416
ε_y (pm)	4	659

- DA after beam threading Including initial BPM-to-Quad alignment of 100 μm. Sextupoles Off

Correction algorithms

The aim of orbit and optics correction algorithms is to minimize the impact of lattice errors by adjusting magnets (correctors) strengths.

1. Orbit correction involves generating Orbit Response Matrix (ORM)

- **For the i^{th} BPM and the j^{th} corrector the ORM element is:**

$$M_{i,j} = \frac{\sqrt{\beta_i(s)\beta_j(s_0)}}{2\sin(\pi Q)}\cos\left(\pi Q - \psi_i(s) + \psi_j(s_0)\right) + \frac{\eta_i(s)\eta_j(s_0)}{\alpha_c L_o}, \qquad \Delta\theta = -M^{-1}\Delta x.$$

2. Linear Optics from Closed Orbit (LOCO) uses the ORM for optics correction

$$\chi^2 = \sum_{i,j}\frac{\left(M_{\text{model},i,j} - \hat{M}_{i,j}\right)^2}{\sigma_i^2}, \sigma_i \text{ is the BPMs noise}$$

- **Weighted least square problem that can be solved by minimization algorithms e.g, Gauss-Newton (GN) or Levenberg-Marquardt (LM).**
- **Parameters like the relative quadrupole strengths are adjusted in iterations.**

Correction algorithms

In the Turn by Turn (TbT) measurements the beam is excited and beam position data is recorded over one or multiple turns to determine optics parameters.

3. **Phase advance + η_x correction**

$$\Delta\varphi(s_0,s)=\int_{s_0}^{s}\frac{\mathrm{d}s'}{\beta_{(\mathrm{theo})}}\left(\frac{1}{1+\frac{\Delta\beta}{\beta}}-1\right).\qquad\begin{pmatrix}\alpha_1\Delta\varphi_x\\ \alpha_1\Delta\varphi_y\\ \alpha_2\Delta\eta_x\end{pmatrix}_{\mathrm{measured}}=-C_{\mathrm{model}}\,\delta K.$$

4. **Coupling RDTs + η_y correction**

$$f_{\substack{1001\\1010}}(s)=-\frac{1}{4\left(1-e^{2\pi i\left(Q_x\mp Q_y\right)}\right)}\sum k_s(s)\sqrt{\beta_x(s)\beta_y(s)}\,e^{i\left(\Delta\psi_x^s+\Delta\psi_y^s\right)}.\qquad\begin{pmatrix}\alpha_1 f_{1001}\\ \alpha_1 f_{1010}\\ \alpha_2\eta_y\end{pmatrix}_{\mathrm{measured}}=-N_{\mathrm{model}}\,\delta K_s.$$

Optics tuning tools

- Using the Python interface of Accelerator Toolbox (PyAT) we have developed an optics tuning code/tools. https://github.com/elafmusa/Optics-corrections-with-PyAT

  Tuning simulations for FCC-ee at Z energy:

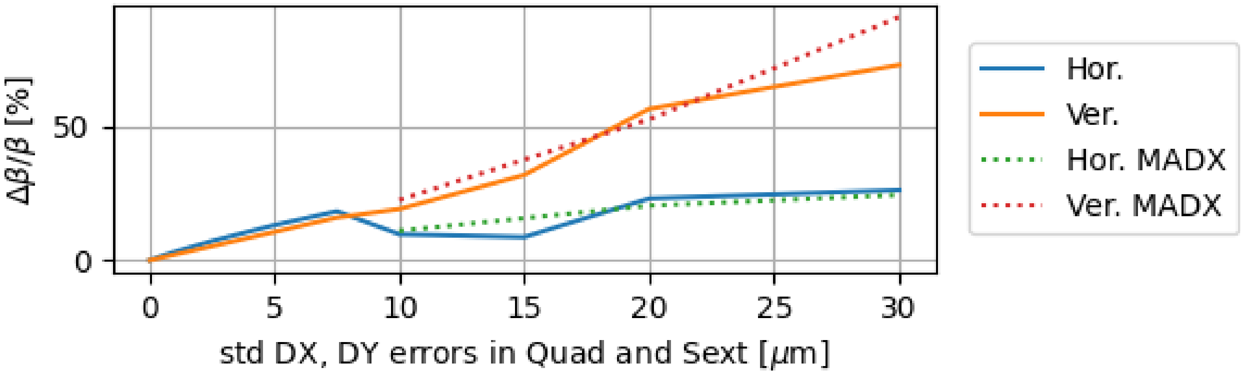
  - A correction procedure was developed.
  - Proper tuning sequence including the number of iterations was defined.
  - Proper parameters and weight values for each step were defined.

- Some functions were imported from the commissioning simulations tools on AT by S. Luizzo - ESRF.

- We started to merge the code with the Python version of the Simulated Commissioning toolkit for Synchrotrons (PySC) that offers a wider and more expanded implementations (Girders misalignment, BBA simulation, BPMs reading function, tracking modes .. etc.)

Benchmark of commissioning simulations with errors and corrections: AT vs. MAD-X

- The benchmarking study were performed by applying the same errors and following the same correction steps.
- The study demonstrated good agreement between the two codes.

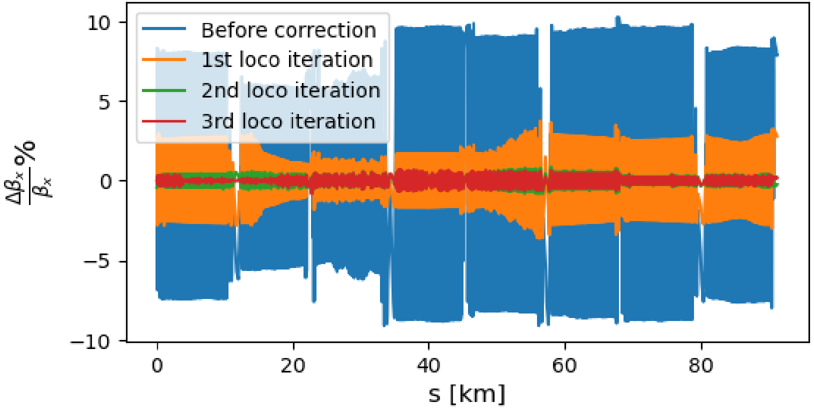


S. Luizzo, T. Charles, R. Tomas, I. Agapov and E. Musa, Benchmark of commissioning simulations with errors and corrections: AT vs MADX vs MADX PTC, FCC-ee optics tuning WG meeting.

Implemented Python-based numerical code for LOCO

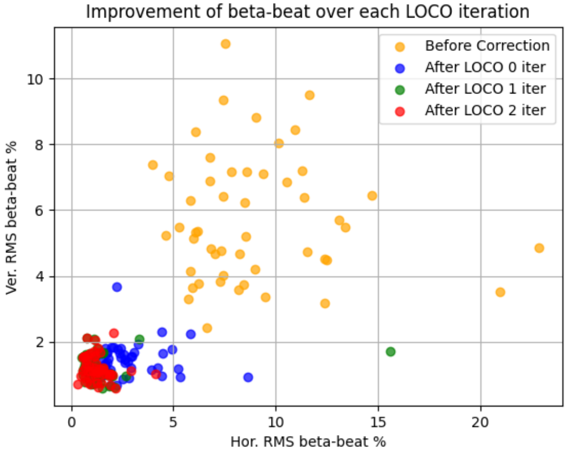
- The validity of the implemented code is demonstrated, where random relative field errors, were applied to all quadrupoles.
- The figure shows the reduction in vertical beta beating over each LOCO iteration until convergence.

FCC-ee



E. Musa, I. Agapov, T. Charles., "Orbit-response based optics corrections for FCC-ee", presented at IPAC'23, Venice, Italy, May 2023, paper WEPL017.

PETRA IV



E. Musa, PETRAIV beam physics meeting 26 Jan 2024.

Tuning simulations (using LOCO for optics correction)

- **Random horizontal and vertical displacement errors with standard deviation of 100 μm in the arc components of the baseline**

50 Seeds (Mean rms values)	hor. orbit (μm)	ver. orbit (μm)	$\Delta\beta_x/\beta_x$ %	$\Delta\beta_y/\beta_y$ %	$\Delta\ \eta_x$ (mm)	η_y (mm)	ε_h (nm)	ε_v (pm)
With err (sext.off)	5896.03	7735.96	7.8×10^{-7}	2.1×10^{-4}	10513.98	80846.25	-	-
After sext ramping	8.54	8.34	5.64	10.46	43.94	45.45	0.71	9.18
Beta beat cor.	8.55	8.35	2.22	3.43	40.50	45.43	0.71	9.01
Coupling cor.	8.55	8.36	2.12	3.48	1.78	3.09	0.70	6.45
Final cor. results	8.56	8.35	1.93	3.23	4.95	2.93	0.70	5.99

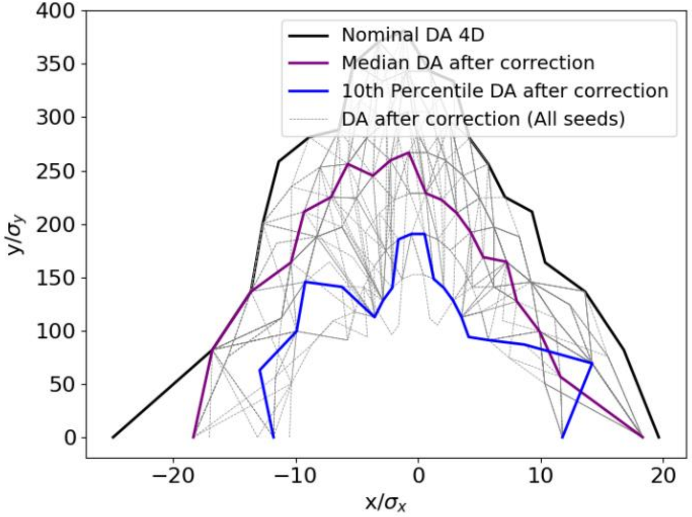
Alternative optics correction methods: Phase advance/η_x and RDTs/η_y correction

σ=100 μm	hor. orbit (μm)	ver. orbit (μm)	$\Delta\beta_x/\beta_x$ %	$\Delta\beta_y/\beta_y$ %	$\Delta\ \eta_x$ (mm)	η_y (mm)	ε_h (nm)	ε_v (pm)
With err	6224.8	7276.7	1×10^{-6}	1×10^{-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

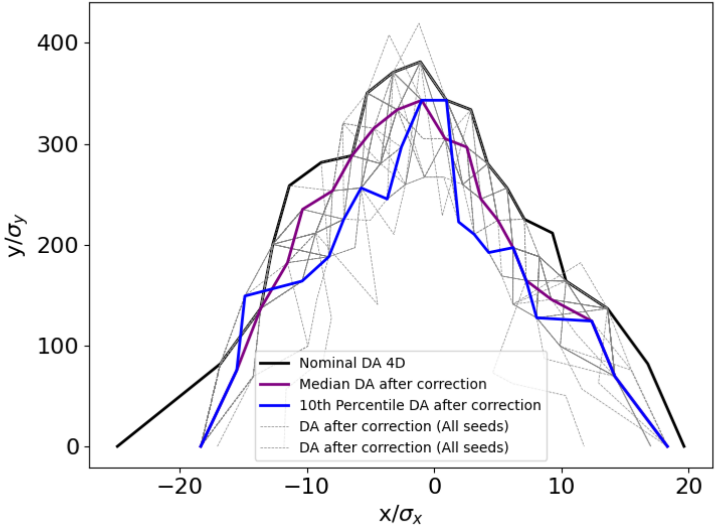
LOCO Vs. Phase advance/η_x and RDTs/η_y correction

- **The large median DA for 50 seeds after correction demonstrate a better performance for the TbT compared to LOCO.**

LOCO



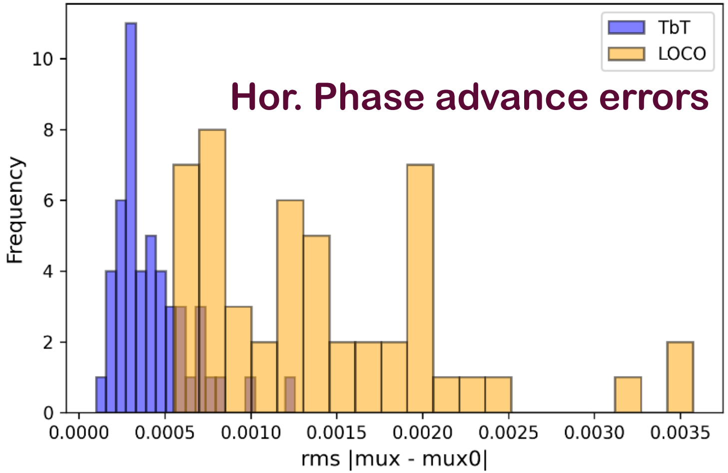
TbT

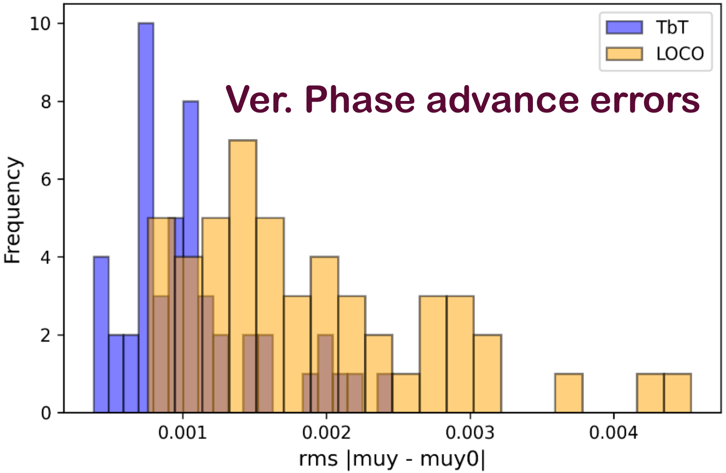


σ_x= 8.84 $\times10^{-6}$m, σ_y = 3.12$\times10^{-6}$m, Rad off.

Phase advance between sextupoles

- The cancellation scheme of the nonlinear effects by the sextupoles relies on the phase advances between the sextupoles.
- Distorting the phase advances increases the nonlinear effects and reduce the DA.

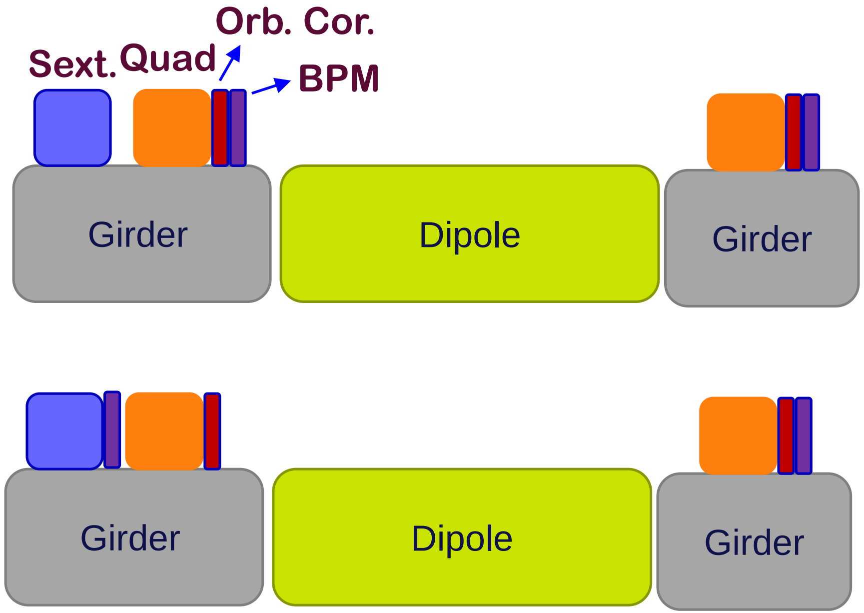




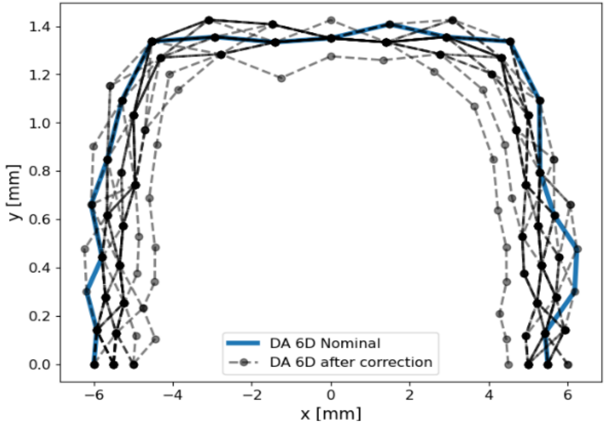
LOCO Mean RMS hor. $\Delta\varphi$ = 1.27$\times 10^{-3}$
TbT Mean RMS hor. $\Delta\varphi$ =3.6 $\times 10^{-4}$

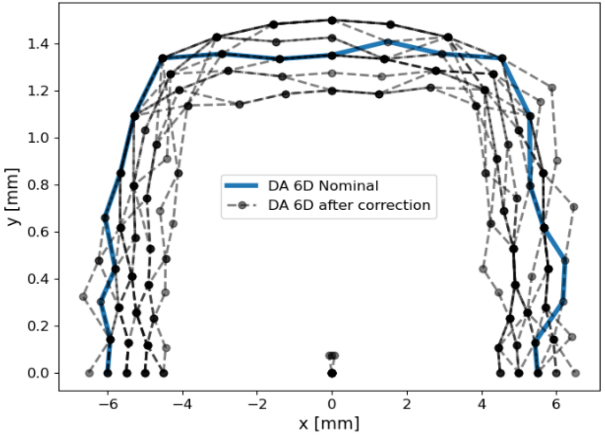
LOCO Mean RMS ver. $\Delta\varphi$ = 1.67$\times 10^{-3}$
TbT Mean RMS ver. $\Delta\varphi$ = 9.9 $\times 10^{-4}$

Girders configurations & BPMS locations



- **Results of correction showed a preference to have the BPMS attached to the quadrupoles.**





5 failed seeds

Applied magnets misalignments and strength errors

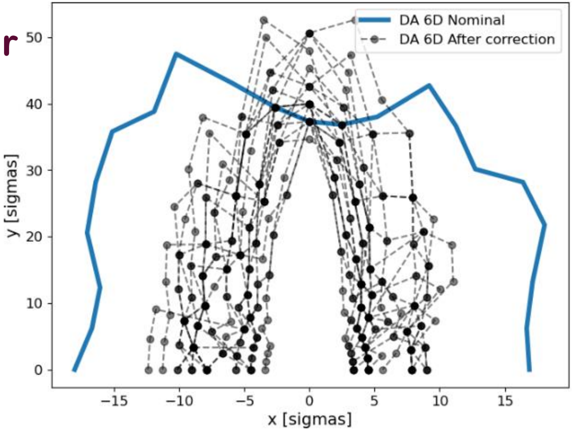
Elements	Hor. & Ver. Displacement (µm)	Rotations (µrad)
Arc quads and sext.	50	50
All dipoles	1000	1000
Girders	150	150
BPMs-quads.	10	10

Elements	Strength errors $\frac{\Delta K}{K}$
Arc quads and sext.	2×10^{-4}
All dipoles	2×10^{-4}

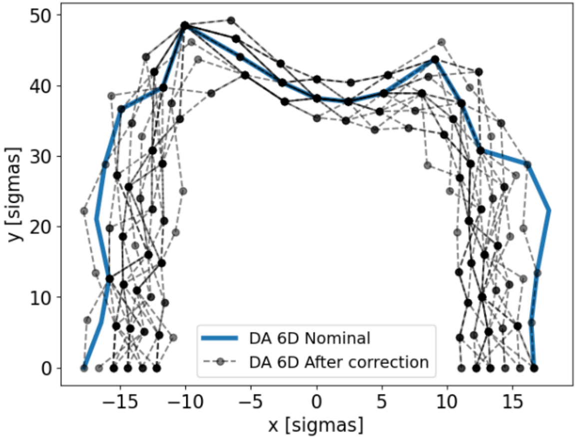
- These values correspond to one sigma Gaussian distribution truncated at 2.5 sigma.

Tuning results (nominal lattice)

Before linear optics cor

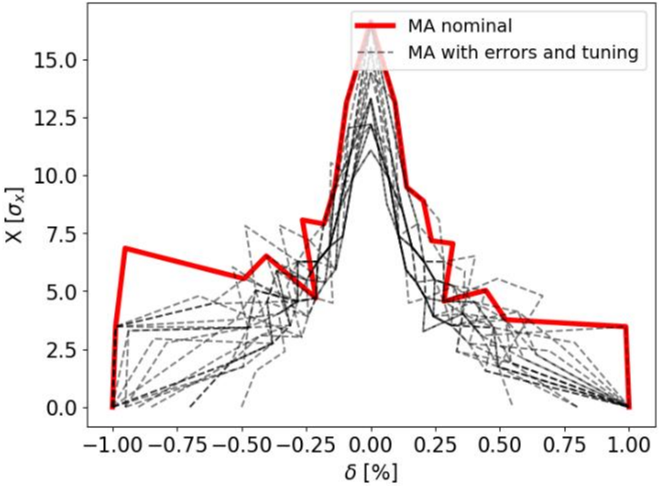


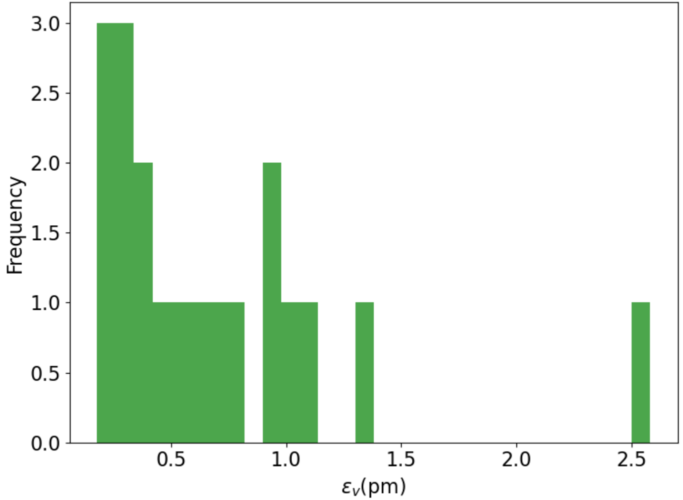
Final correction



Parameter	Prior optics cor.	Final cor.
hor. orbi(μm)	120.25	120.46
ver. orbit(μm)	217.53	217.56
$\Delta\beta_x/\beta_x\%$	7.41	0.29
$\Delta\beta_y/\beta_y\%$	15.79	2.81
$\Delta\ \eta_x$ (mm)	57.79	0.28
$\Delta\ \eta_y$ (mm)	62.24	2.80
ε_y (pm)	26.01	0.57
ε_x(pm)	0.72	0.71
hor. $\Delta\varphi$ [2π]	1.13×10^{-2}	2.91×10^{-4}
ver. $\Delta\varphi$ [2π]	1.93×10^{-2}	2.29×10^{-3}

Tuning results (nominal lattice)



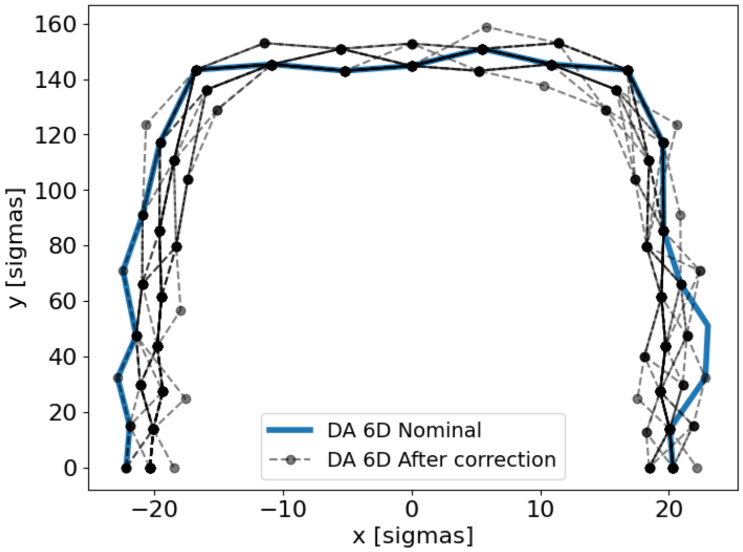


- **Parameters after correction (at IP)**

$\Delta\beta_x/\beta_x$ %	$\Delta\beta_y/\beta_y$ %	$\Delta\eta_x$ (mm)	$\Delta\eta_y$ (mm)	Re F1001	Im F1001	Re F1010	Im F1010
0.34	3.08	0.003	0.001	6.49×10^{-6}	1.72×10^{-5}	1.59×10^{-5}	2.23×10^{-5}

Tuning results (Ballistic optics)

- **The simulation included IR alignment errors of 50 μm in addition to the arc errors.**



Parameter	Prior optics cor.	Final cor.
hor.orbit (μm)	120.45	120.44
ver.orbit (μm)	212.29	212.25
$\Delta\beta_x/\beta_x$%	8.39	0.85
$\Delta\beta_y/\beta_y$%	18.97	0.50
$\Delta\ \eta_x$ (mm)	73.14	0.45
$\Delta\ \eta_y$ (mm)	65.73	0.39
ε_y (pm)	30.37	0.26
ε_x (pm)	0.89	0.85
hor. $\Delta\varphi$ [2π]	0.012	8×10^{-4}
ver. $\Delta\varphi$ [2π]	0.023	6×10^{-4}

Conclusion

- The developed correction procedure managed to achieve a median vertical and horizontal emittance within the target (**0.57pm** and **0.71 pm** respectively) , and optics parameters $\frac{\Delta\beta_y}{\beta_y}$ of **2.81% and** $\Delta\ \eta_y$ of **0.28 mm** with normal errors.
- Tuning simulations to the ballistic optics allows to include 50 μm alignment errors in the IR.
- Looking ahead, we plan to incorporate IR magnet errors for the nominal lattice, and conducting tuning simulations for the other energy modes.

Selected References

[1] Future Circular Collider Conceptual Design Report CDR, 2019, FCC CDR on CERN Website.

[2] K. Oide, June 1, 2023@168th FCC-ee Optics Design Meeting&39th FCCISWP2.

[3] J. Safranek, "Experimental determination of storage ring optics using orbit response measurements,“ Nucl. Inst. And Meth. A388, pp. 27-36, 1997.

[4] T. Charles, et al., "Alignment and Stability Challenges for FCC-ee," EPJ Techniques and Instrumentation, vol. 10, no. 8, 2023.

[5] M. G. Minty and F. Zimmermann, Measurement and Control of Charged Particle Beams (Springer, 2011), Springer Link.

[6] R. Tom´as, M. Aiba, A. Franchi, et.al, Review of Linear Optics Measurement and Correction for Charged Particle Accelerators), 10.1103/PhysRevAccelBeams.20.054801.

[7] C. Garcia, et al., “Ballistic optics for FCC-ee,” FCC-ee optics tuning WG meeting, Sept. 13, 2024.

[8] atcollab/at: Accelerator Toolbox

Thank you for your attention

ご清聴ありがとうございました

Backups

Improving the correction procedure

- Adjusting the **number of singular values** used for orbit and optics corrections.

- **Sextupoles ramping** in steps of 10%, with further orbit and tune correction performed at every stage. Once at 100% of the design value, the sextupole strengths are varied to perform chromaticity correction.

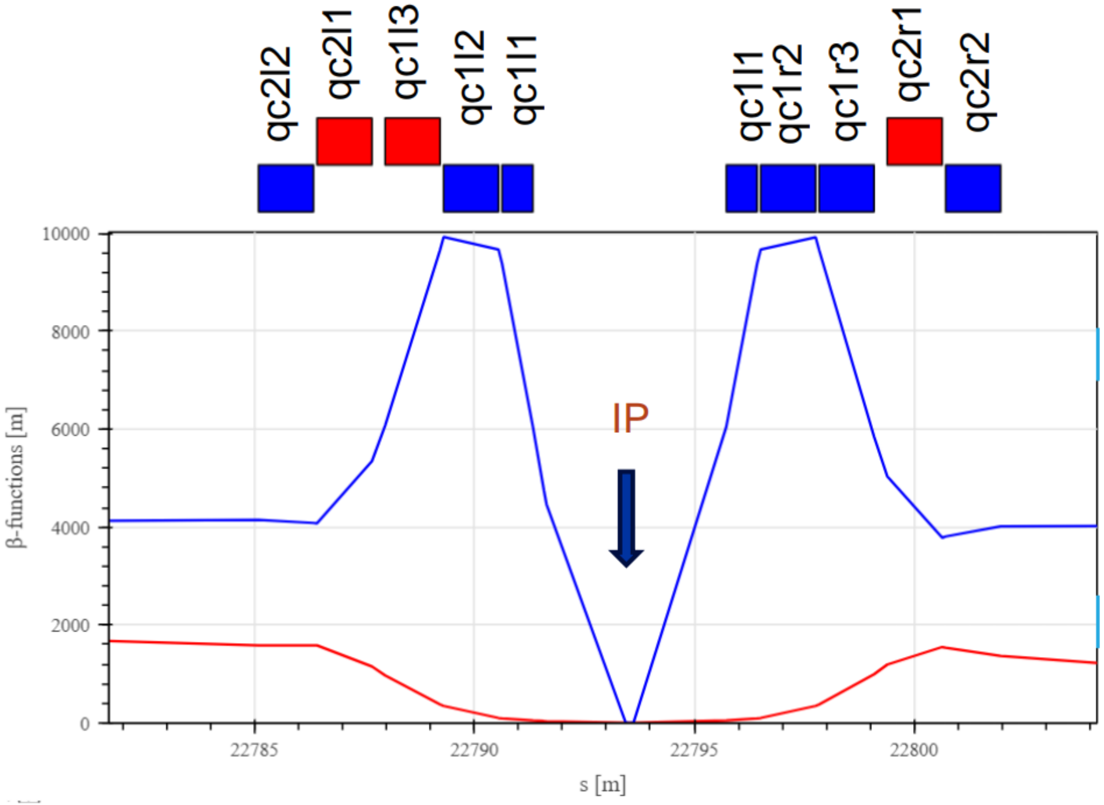
  - This improvement managed to increase the manageable alignment tolerances in the arc magnets to 30 μm standard deviation.

- **Additional orbit correction** steps along the scheme.
  - Interleaved with LOCO to control emittance growth.
  - Example: For 100 μm alignment errors in the arc, the mean vertical emittance was reduced from:
    - **Baseline:** 537.30 pm to 5.99 pm
    - **LCCO:** 444 pm to 2.52 pm

FCC-ee elements

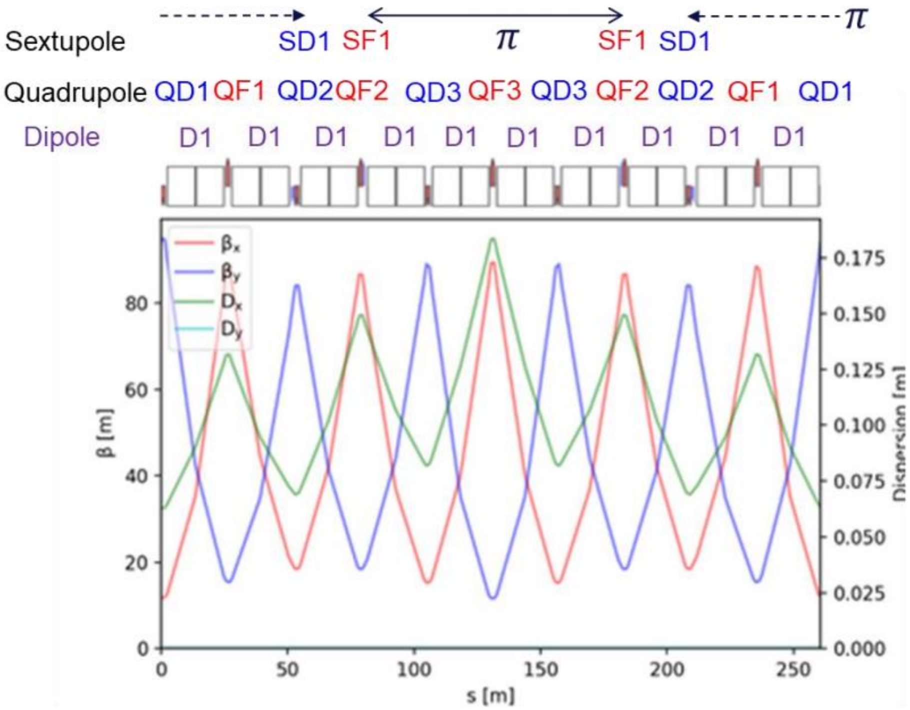
- Dipole lengths: 100 m – 1.7 m
- Quadrupole lengths: 0.7 m – 3.5 m

Elements	Z Baseline	$t\bar{t}$ Baseline	Z LCC
IR quads.	436	488	532
IR sext.	64	96	136
Arc quads.	1420	3324	2168
Arc sext.	568	2368	1728
Dipoles	3056	3056	2412



S.Jagabathuni

Non-interleaved sextupole scheme



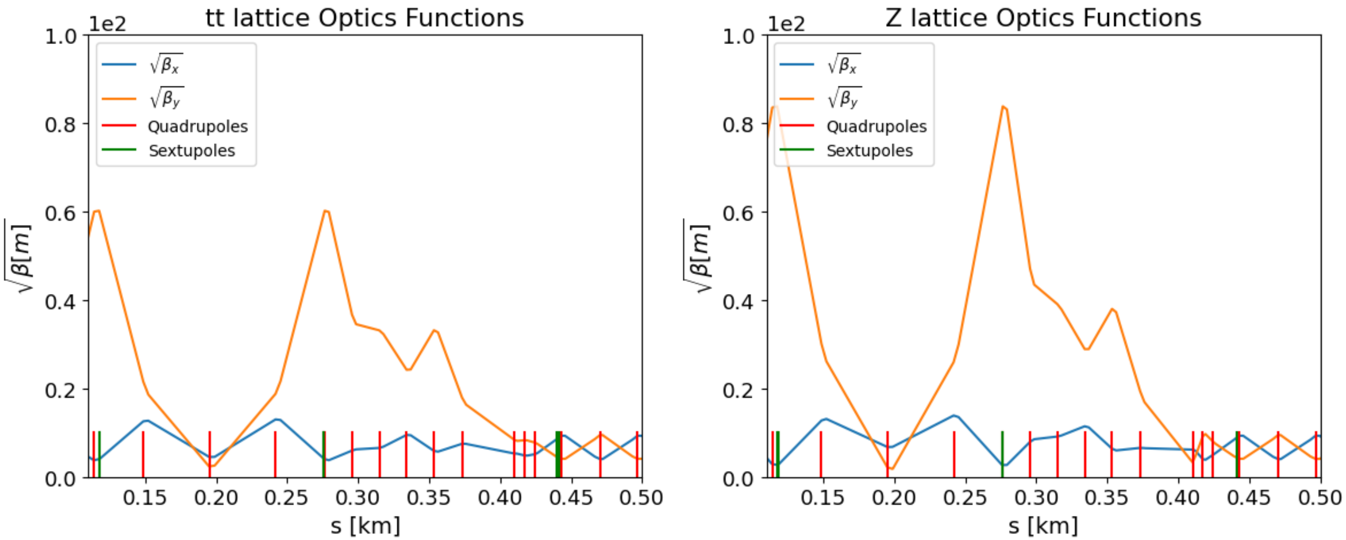
Phase advance of π in both planes of between the sextupoles to maximize the geometric aberration cancellation.

FCC-ee lattices

Z & $t\bar{t}$ lattices

Lattice sensitivity to errors: comparison between: z and $t\bar{t}$ lattices

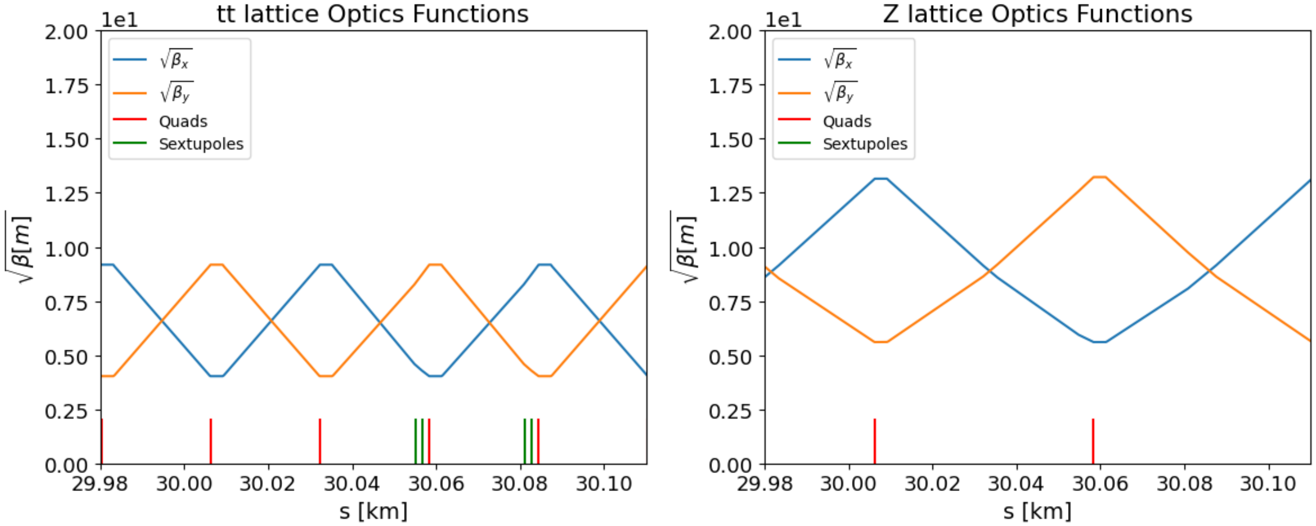
Interaction region



E. Musa, “Tuning studies with pyAT”, FCC-ee optics tuning WG meeting, 23th Jul 2024.
https://indico.cern.ch/event/1439019/

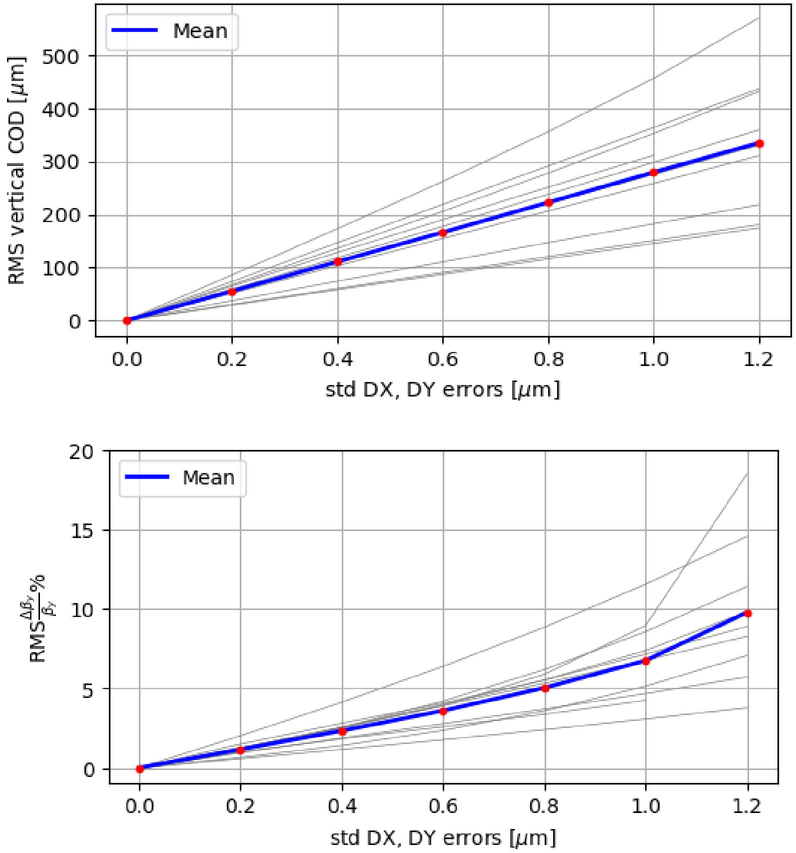
Lattice sensitivity to errors: comparison between: Z and $t\bar{t}$ lattices

Arc region

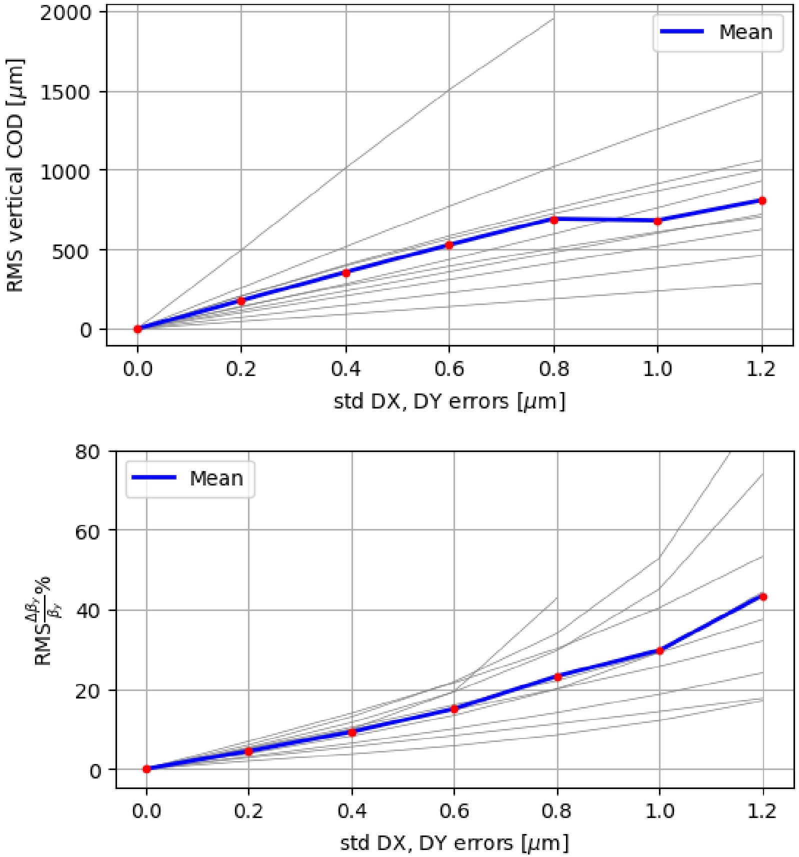


E. Musa, “Tuning studies with pyAT”, FCC-ee optics tuning WG meeting, 23th Jul 2024.
https://indico.cern.ch/event/1439019/

$t\bar{t}$


Mean
RMS vertical COD [μm]
0
100
200
300
400
500
0.0
0.2
0.4
0.6
0.8
1.0
1.2
std DX, DY errors [μm]
Mean
RMS$\frac{\Delta\beta_y}{\beta_y}$%
0
5
10
15
20
0.0
0.2
0.4
0.6
0.8
1.0
1.2
std DX, DY errors [μm]

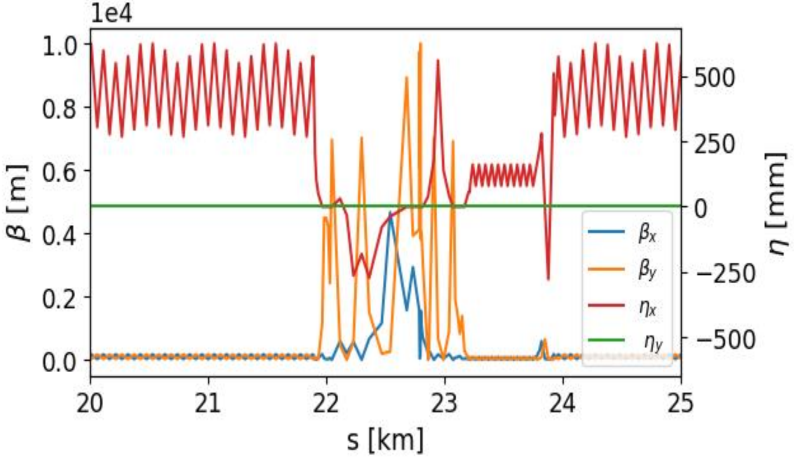
Z


Mean
RMS vertical COD [μm]
0
500
1000
1500
2000
0.0
0.2
0.4
0.6
0.8
1.0
1.2
std DX, DY errors [μm]
Mean
RMS$\frac{\Delta\beta_y}{\beta_y}$%
0
20
40
60
80
0.0
0.2
0.4
0.6
0.8
1.0
1.2
std DX, DY errors [μm]

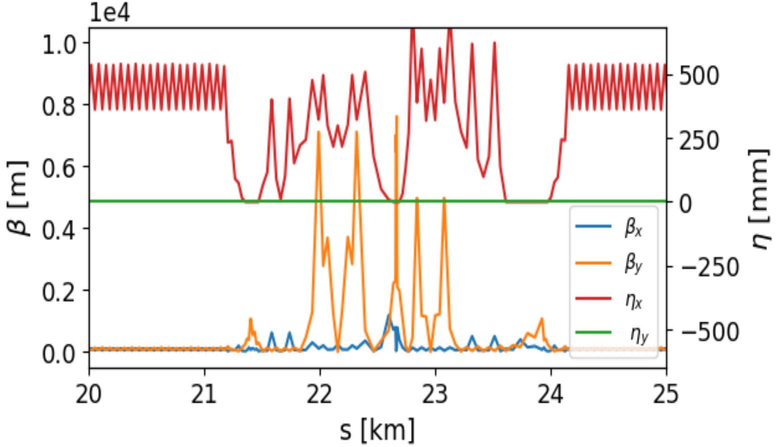
Baseline & LCC

Two proposed optics design for FCC-ee

Baseline optics



HFD optics



- In the baseline lattice, the IR has a Local Chromaticity Correction System (LCCS) only in the vertical plane at each side of the IP.
- The LCCO final focusing system based in correcting the chromaticity in both planes.

Tuning simulations with Phase advance/η_x and RDTs/η_y correction

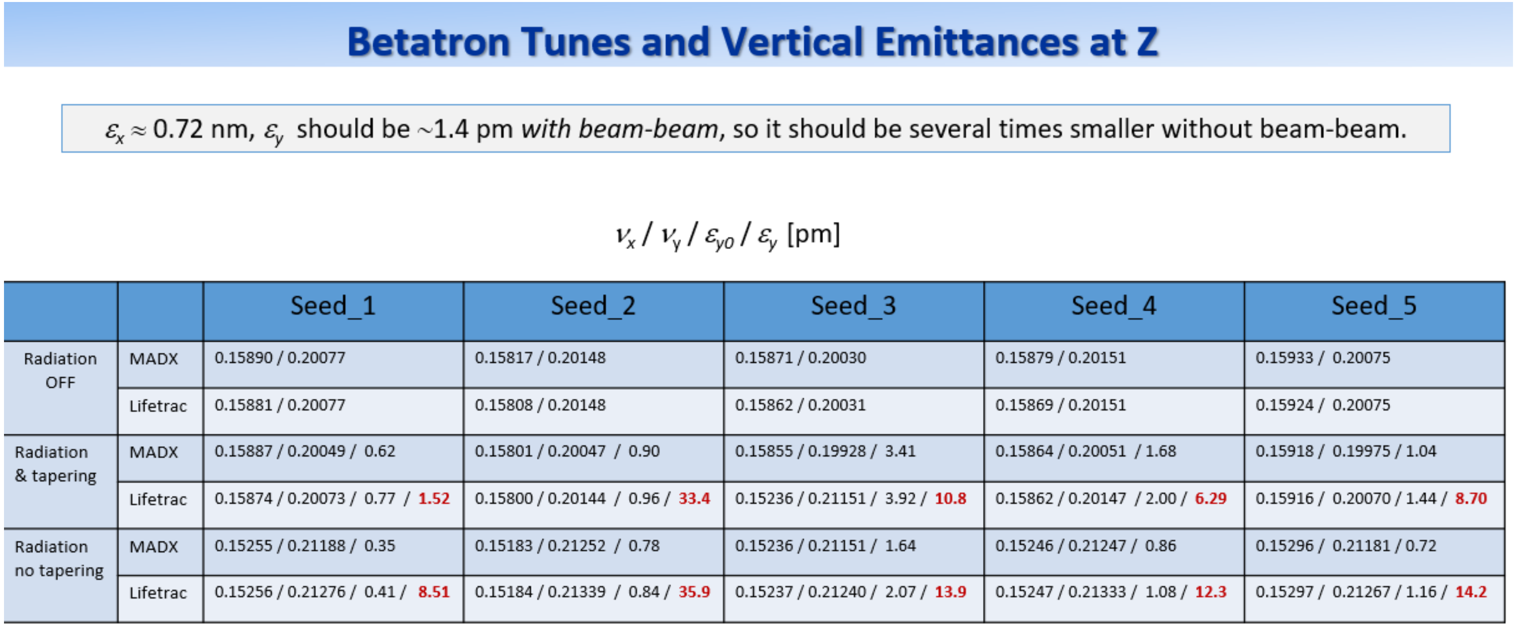
- Correction of random horizontal and vertical displacement errors with standard deviation of 100 μm in the arc quadrupoles and sextupoles. (using Phase advance for optics correction).
    - Baseline

hor. orbit (μm)	ver. orbit (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)
8.55	8.35	0.35	0.89	2.94	4.37	0.70	0.73

- LCCO

hor. orbit (μm)	ver. orbit (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)
6.50	5.62	0.09	0.38	0.37	0.89	0.70	0.43

Beam-Beam studies in lifetrack



Betatron Tunes and Vertical Emittances at Z

$\varepsilon_x \approx$ 0.72 nm, ε_y should be ~1.4 pm *with beam-beam*, so it should be several times smaller without beam-beam.

ν_x / ν_y / ε_{y0} / ε_y [pm]

		Seed_1	Seed_2	Seed_3	Seed_4	Seed_5
Radiation OFF	MADX	0.15890 / 0.20077	0.15817 / 0.20148	0.15871 / 0.20030	0.15879 / 0.20151	0.15933 / 0.20075
	Lifetrac	0.15881 / 0.20077	0.15808 / 0.20148	0.15862 / 0.20031	0.15869 / 0.20151	0.15924 / 0.20075
Radiation & tapering	MADX	0.15887 / 0.20049 / 0.62	0.15801 / 0.20047 / 0.90	0.15855 / 0.19928 / 3.41	0.15864 / 0.20051 / 1.68	0.15918 / 0.19975 / 1.04
	Lifetrac	0.15874 / 0.20073 / 0.77 / **1.52**	0.15800 / 0.20144 / 0.96 / **33.4**	0.15236 / 0.21151 / 3.92 / **10.8**	0.15862 / 0.20147 / 2.00 / **6.29**	0.15916 / 0.20070 / 1.44 / **8.70**
Radiation no tapering	MADX	0.15255 / 0.21188 / 0.35	0.15183 / 0.21252 / 0.78	0.15236 / 0.21151 / 1.64	0.15246 / 0.21247 / 0.86	0.15296 / 0.21181 / 0.72
	Lifetrac	0.15256 / 0.21276 / 0.41 / **8.51**	0.15184 / 0.21339 / 0.84 / **35.9**	0.15237 / 0.21240 / 2.07 / **13.9**	0.15247 / 0.21333 / 1.08 / **12.3**	0.15297 / 0.21267 / 1.16 / **14.2**

Dmitry Shatilov, Private communication, Oct. 2023

Correction procedure

Implemented Python-based numerical code for LOCO

Input

- Model orbit response matrix.
- Jacobian:
  - 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, et.al, arXiv:1711.06589
- Other inputs (Initial guess, Included fit parameters, etc.)

LOCO iterations

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

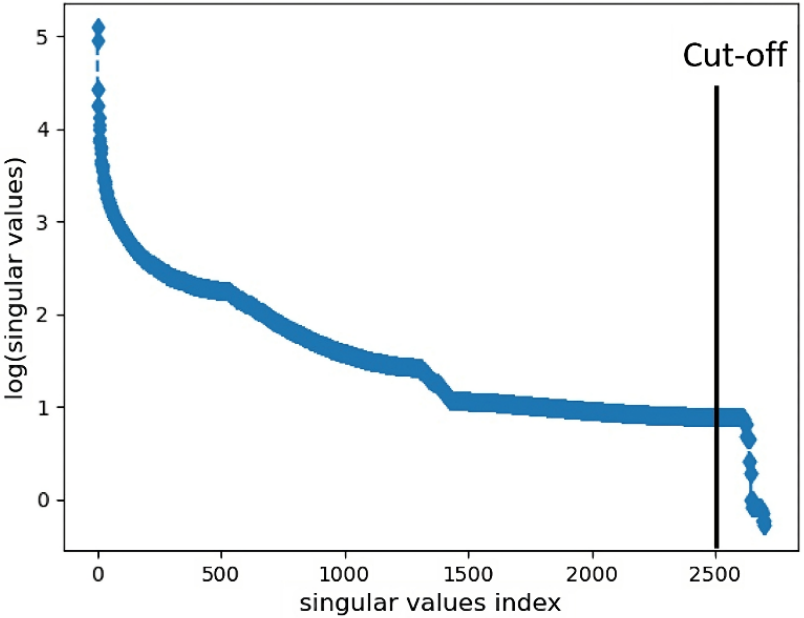
Parameters update formula

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

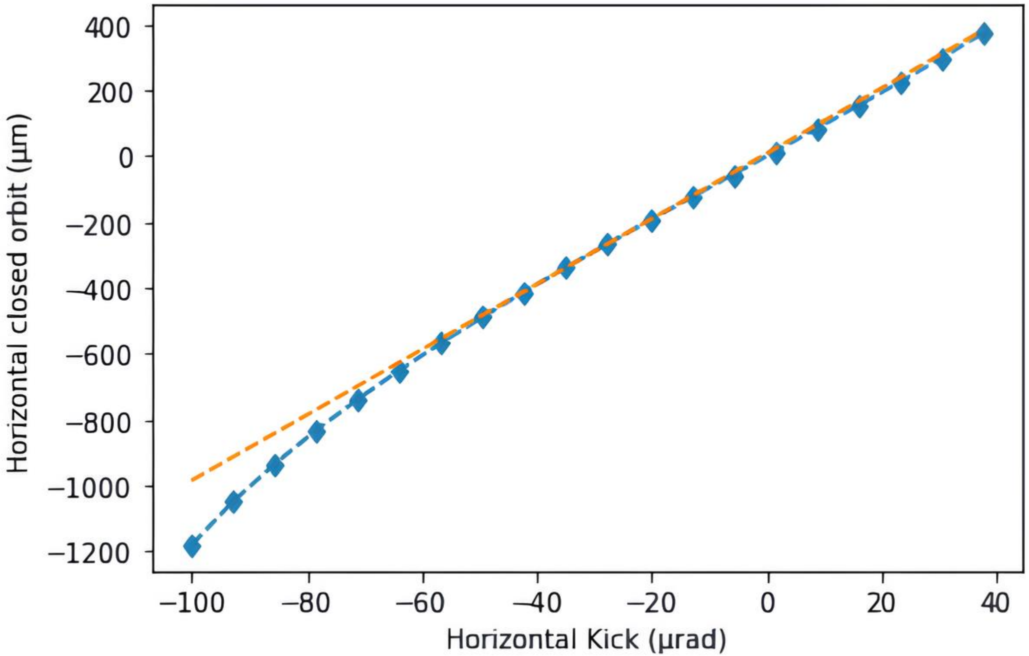
Improving the correction procedure

- Adjusting the number of singular values

No of singular values	rms hor. orbit (µm)	rms ver. orbit (µm)	$\Delta\eta_x$ (mm)	$\Delta\eta_y$ (mm)
500	14.29	12.02	1.67	48.96
1000	4.29	4.27	1.18	18.02
1500	3.41	2.01	1.15	9.61
2500	3.09	1.52	1.13	9.11



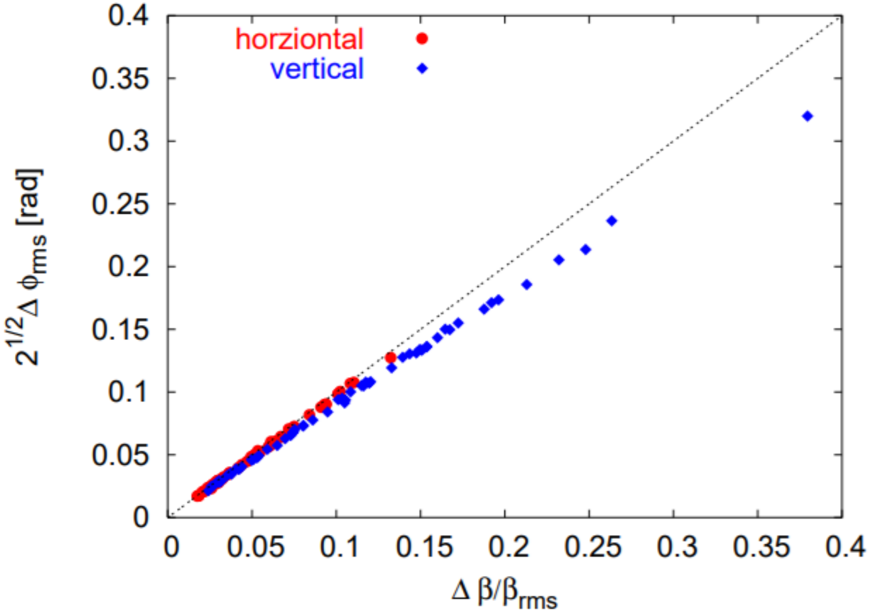
Sextupoles nonlinear effect on the ORMs



E. Musa, “Orbit-response based optics correction studies for FCC-ee,” presented at the FCCee Tuning Workshop, 27 June 2023, (CERN), Geneva, Switzerland

Phase advance matching

$$\Delta\phi(s_0,s)=\int_{s_0}^{s}\frac{\mathrm{d}s'}{\beta_{(\mathrm{theo})}}\left(\frac{1}{1+\frac{\Delta\beta}{\beta}}-1\right).$$



R. Tom´as, et. Al, „PROCEDURES AND ACCURACY ESTIMATES FOR BETA-BEAT CORRECTION IN THE LHC”, WEPCH047

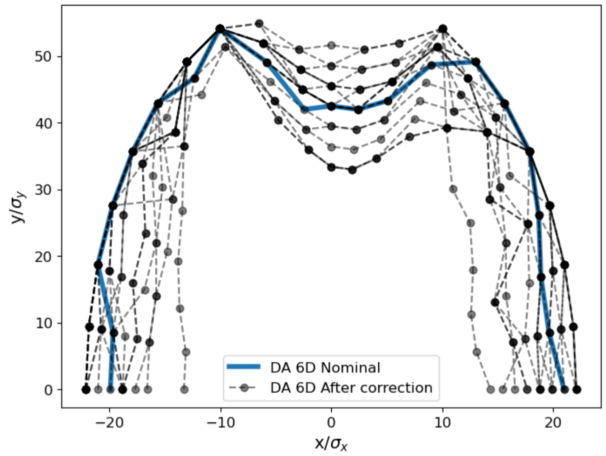
Tuning simulation studies for the baseline

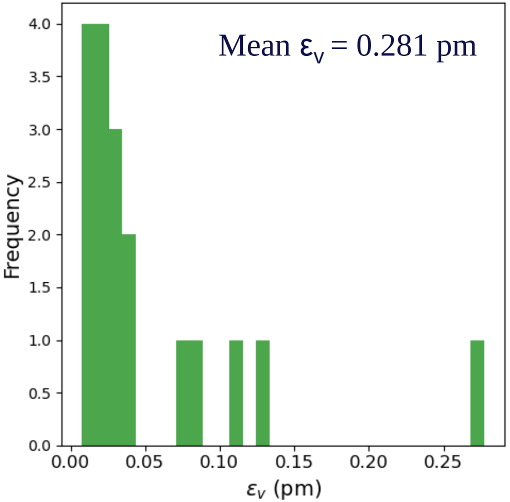
Following LOCO with coupling RDTs correction

	Rms hor. orbit (μm)	rms ver. orbit (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	5896.03	7735.96	7.8e-7	2.1e-4	10513.98	80846.25	-	-
After sext ramping	8.54	8.34	5.64	10.46	43.94	45.45	0.71	9.18
Beta beat cor.	8.55	8.35	2.22	3.43	40.50	45.43	0.71	9.01
Coupling cor.	8.55	8.36	2.12	3.48	1.78	3.09	0.70	6.45
Beta beat cor.	8.56	8.35	1.93	3.23	4.95	2.93	0.70	5.99
RDTs cor.	8.56	8.35	1.77	2.95	4.97	0.37	0.70	0.66

Including of BPMs alignment

- A transverse ”Offset” field was introduced for each BPM and set to equal the assigned offset errors of the corresponding quadrupole.





Elements	Hor. & Ver. Displacement & tilt
Arc quads and sext	100 μm
All dipoles	150 μm
BPMs	Same as quads.

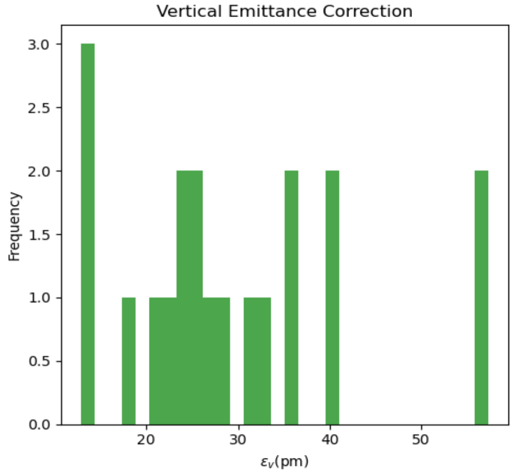
E. Musa, “Tuning studies with pyAT”, FCC-ee optics tuning WG meeting, 23th Jul 2024. https://indico.cern.ch/event/1439019/

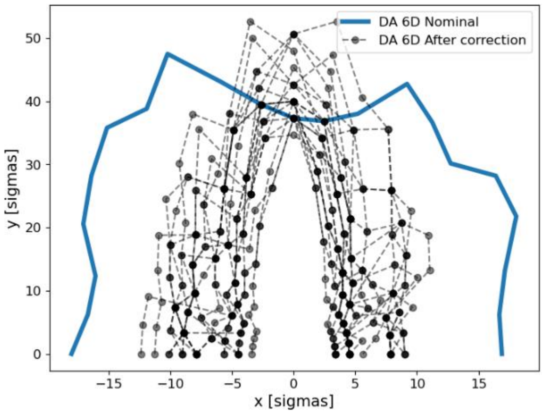
Tuning simulations for the baseline lattice

- Results include girders tilt and strength errors of value 0.02% to arc quadrupole, sextupoles and to all dipoles.
- 10 μm BPM-to-quadrupole after BBA.

Before linear optics correction

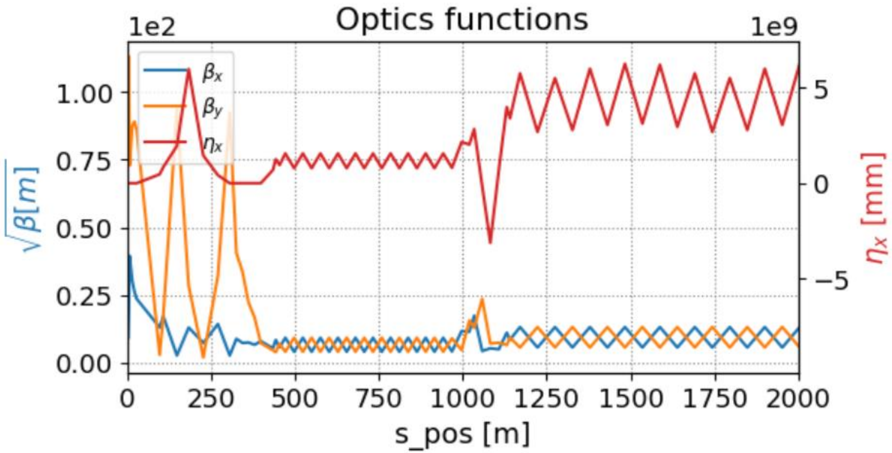
rms hor. orbit (μm)	rms ver. orbit (μm)	rms Δβx/βx %	rms Δβy/βy %	rms Δ ηx (mm)	rms Δ ηy (mm)	ε_h (nm)	ε_v (pm)
120.25	217.53	7.41	15.79	57.79	62.24	0.72	26.01





Interaction Region

Tuning studies with field errors



Errors Applied

Type	**Field Errors**
Arc quadrupole	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles	$\Delta k/k = 2 \times 10^{-4}$
IR quadrupole	$\Delta k/k = 1 \times 10^{-4}$
IR sextupoles	$\Delta k/k = 2 \times 10^{-4}$

enable_6d()
Setting the cavity parameters
Tapering

lattice optics with errors (1 seed):

$\Delta\beta_x/\beta_x$: 9.2141%
$\Delta\beta_y/\beta_y$: 38.2045%
$\Delta\eta_x$: 12.3859
$\Delta\eta_y$: 2.6723e-12 mm
Tune: [218.162, 222.209, 0.0288]
Chromaticity: [0.1294, 5.2607, -0.0246]

E. Musa, “pyAT for FCC-ee optics corrections,” presented at the AT Workshop, Accelerator Toolbox Workshop, 2-3 October 2023, ESRF, Grenoble, France.

Tuning studies with field errors

E. Musa, “pyAT for FCC-ee optics corrections,” presented at the AT Workshop, Accelerator Toolbox Workshop, 2-3 October 2023, ESRF, Grenoble, France.

LOCO 1st iteration:

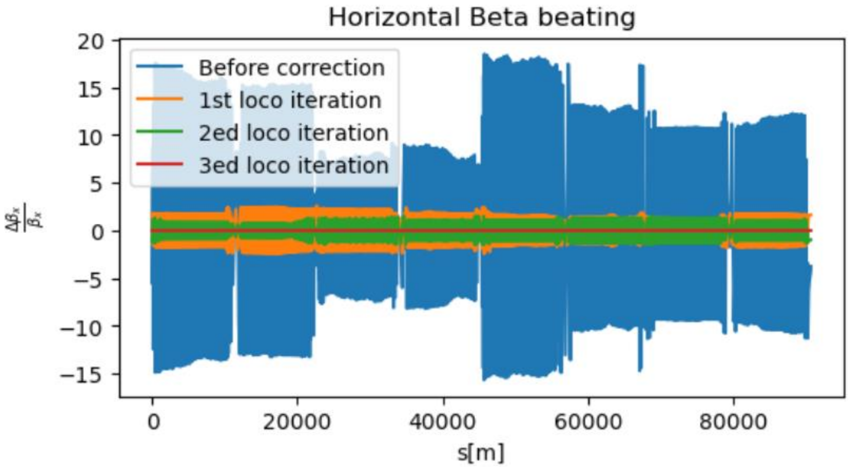
$\Delta\beta_x/\beta_x$: 1.4666%
$\Delta\beta_y/\beta_y$: 7.4342%
$\Delta\eta_x$: 3.4701
$\Delta\eta_y$: 8.0814e-12 mm
Tune: [218.1584, 222.1786]
Chromaticity: [0.03895, 5.0126]

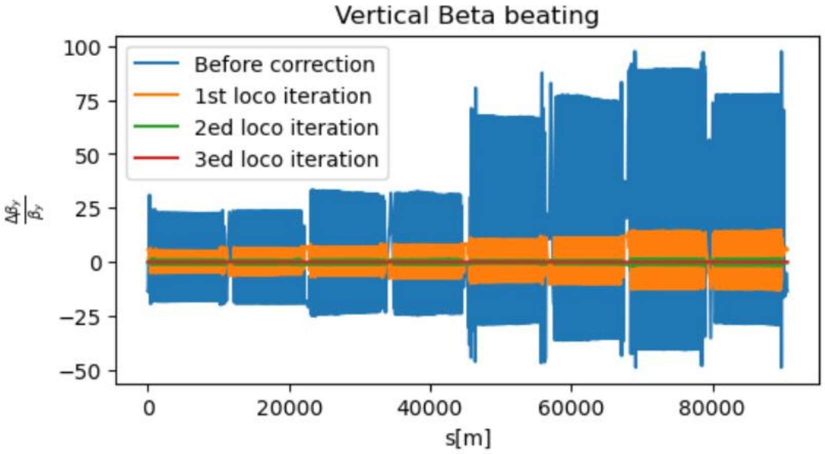
LOCO 2ed iteration:

$\Delta\beta_x/\beta_x$: 0.9190%
$\Delta\beta_y/\beta_y$: 0.8944%
$\Delta\eta_x$: 2.8573
$\Delta\eta_y$: 3.4580e-12 mm
Tune: [218.1569, 222.2036]
Chromaticity: [-0.0257, 5.2638]

LOCO 3ed iteration:

$\Delta\beta_x/\beta_x$: 0.6136%
$\Delta\beta_y/\beta_y$: 0.2899%
$\Delta\eta_x$: 3.1049
$\Delta\eta_y$: 3.2505e-12 mm
Tune: [218.1574, 222.2000]
Chromaticity: [0.0268, 5.2584]



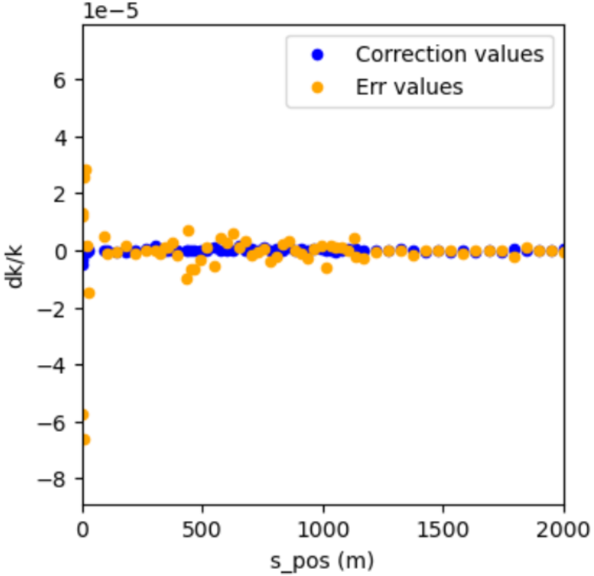


Tuning studies with field errors

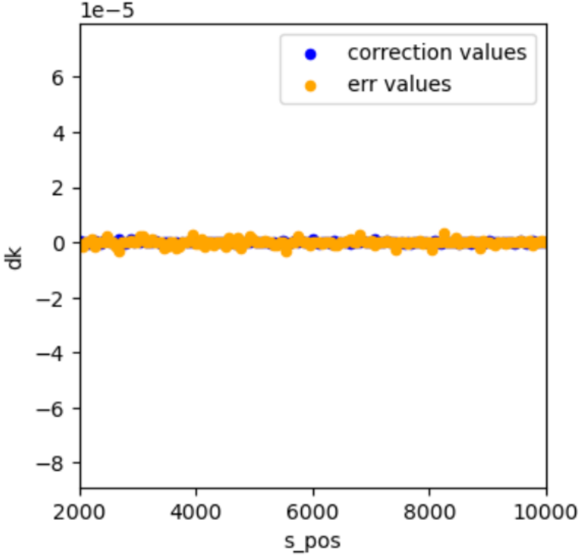
Type	**Field Errors**
Arc quadrupole	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	$\Delta B/B = 1 \times 10^{-4}$
IR quadrupole	$\Delta k/k = 1 \times 10^{-4}$
IR sextupoles	$\Delta k/k = 2 \times 10^{-4}$

<5 seeds>	$\Delta\beta_x/\beta_x$ %	$\Delta\beta_x/\beta_x$ %
With Error	6.4694	18.3786
Correction	2.261	3.724

IR



Arc



E. Musa, “pyAT for FCC-ee optics corrections,” presented at the AT Workshop, Accelerator Toolbox Workshop, 2-3 October 2023, ESRF, Grenoble, France.

Correction results including IR magnets alignment errors

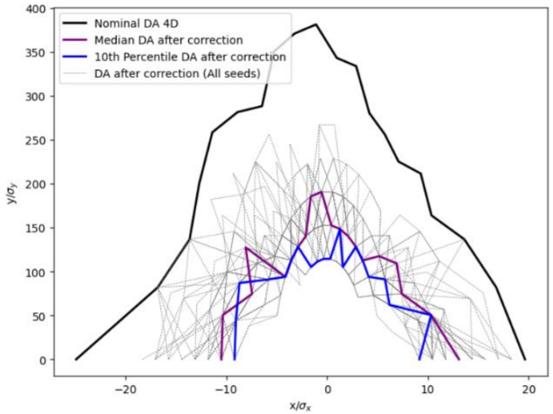
100 μm in the arc magnets and 5 μm in the IR

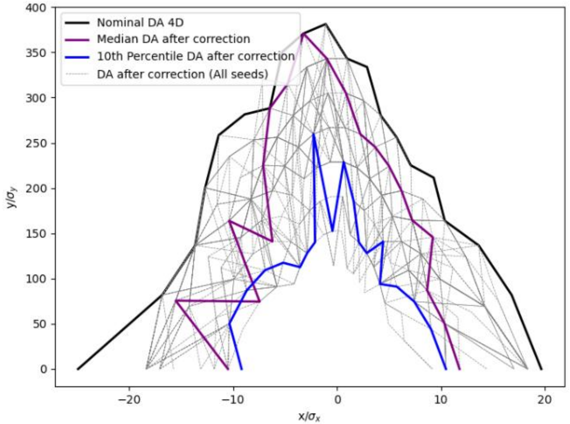
- Initial correction results

	hor. orbit (μm)	ver. orbit (μm)	$\Delta\beta_x/\beta_x$ %	$\Delta\beta_y/\beta_y$ %	$\Delta \eta_x$ (mm)	$\Delta \eta_y$ (mm)
mean	15.60	13.87	0.59	3.47	4.47	7.80
std	49.51	38.81	0.46	2.78	8.99	5.22

- Results after Improvement

	hor. orbit (μm)	ver. orbit (μm)	$\Delta\beta_x/\beta_x$ %	$\Delta\beta_y/\beta_y$ %	$\Delta \eta_x$ (mm)	$\Delta \eta_y$ (mm)
mean	8.510	8.310	0.056	0.086	0.125	0.242
std	0.590	0.520	0.089	0.088	0.050	0.247

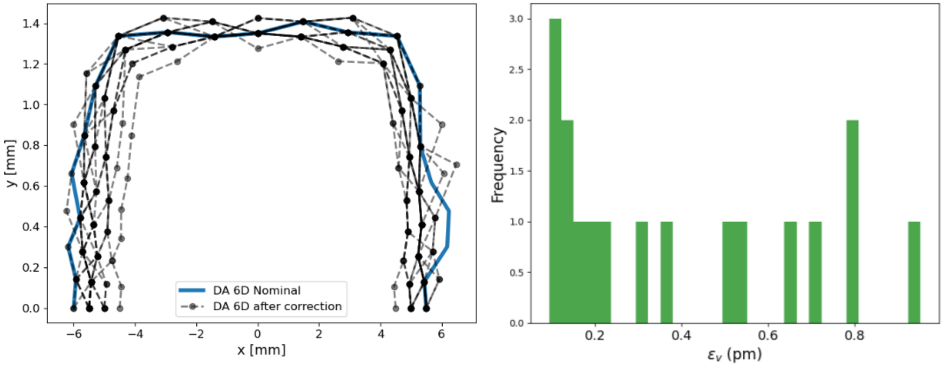




Adding errors to IR (Ballistic optics)

E. Musa, “Tuning studies for ballistic optics”, FCC-ee optics tuning WG meeting, 6th Nov 2024.

Elements	Hor. & Ver. displacement	Tilt θ
Arc quads and sext	50 µm	50 µrad
IR quads and sext	50 µm	50 µrad
All dipoles	1000 µm	1000 µrad
Girders	150 µm	150 µrad
BPMs to quads	10 µm	-



rms hor. orbit (µm)	rms ver. orbit (µm)	rms Δβx/βx %	rms Δβy/βy %	rms Δ ηx (mm)	rms Δ ηy (mm)	ε_h (nm)	ε_v (pm)	rms Hor. Δφ	rms Ver. Δφ
131.18	144.79	1.58	1.00	0.86	1.71	0.85	0.31	1.90×10^{-3}	1.80×10^{-3}

Synchrotron Radiation

Tuning simulations with synchrotron radiation

- Correction of random horizontal and vertical displacement errors with standard deviation of 100 μm in the arc quadrupoles and sextupoles and 150 μm to the dipoles. **without SR**

hor. orbit (μm)	ver. orbit (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)
8.55	8.35	0.35	0.89	2.94	4.37	0.70	0.73

- Correction of random horizontal and vertical displacement errors with standard deviation of 100 μm in the arc quadrupoles and sextupoles and 150 μm to the dipoles.

hor. orbit (μm)	ver. orbit (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)
9.91	8.56	1.17	11.38	13.36	0.46	0.71	0.28

Tuning simulations with synchrotron radiation

- Correction of random horizontal and vertical displacement errors with standard deviation of 100 μm in the arc quadrupoles and sextupoles and 150 μm to the dipoles.

	hor. orbit (μm)	ver. orbit (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)
mean	9.9120	8.5602	1.1666	11.3845	13.3624	0.4630	0.7066	0.2813
std	1.3112	0.6557	0.7179	7.1324	5.7058	0.5455	0.0024	0.4129

- Adding horizontal and vertical **rotation** errors with standard deviation of 100 μm in the arc quadrupoles and sextupoles and 150 μm to the dipoles.

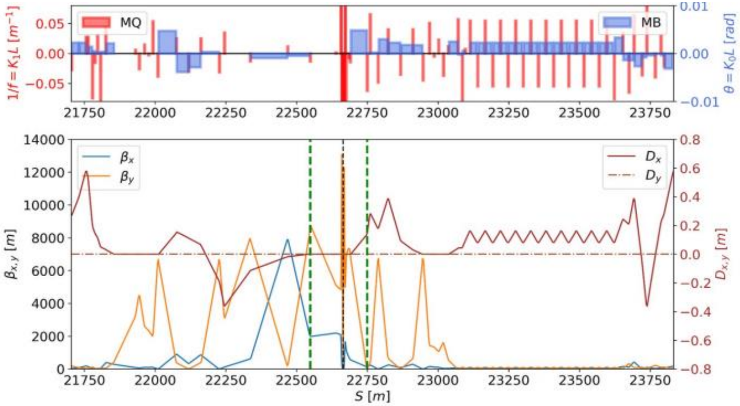
	hor. orbit (μm)	ver. orbit (μm)	$\Delta\beta_x/\beta_x$ %	$\Delta\beta_y/\beta_y$ %	$\Delta \eta_x$ (mm)	$\Delta \eta_y$ (mm)	ε_h (nm)	ε_v (pm)
mean	9.3580	8.4064	0.9423	9.2066	8.4097	0.7843	0.7070	0.1811
std	0.8505	0.3993	0.5410	5.3534	4.7790	0.6588	0.0024	0.1814

Ballistic Optics

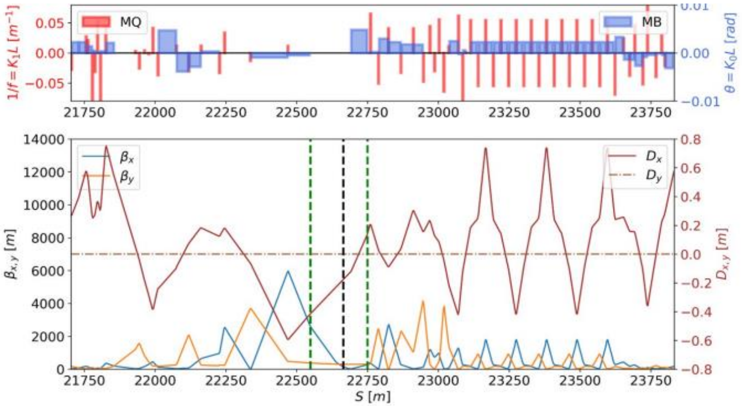
Tuning simulation results for FCC-ee ballistic optics

- Ballistic commissioning optics involves turning off certain IR magnets (200m) around the IP
- Reduce chromaticity, peak beta functions, IR aberrations, remove Synchrotron Radiation from Final Doublet, mitigate instabilities with reduced sextupole strength and establish a straight line reference trajectory around the IP. →Ideal for the first commissioning phases
- It will allow for a smoother start to the machine commissioning process.

Baseline lattice

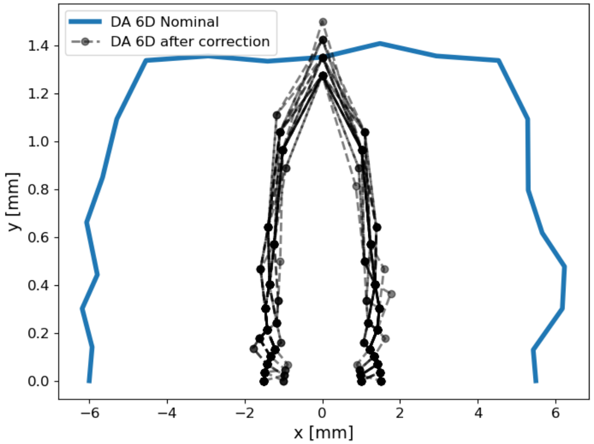


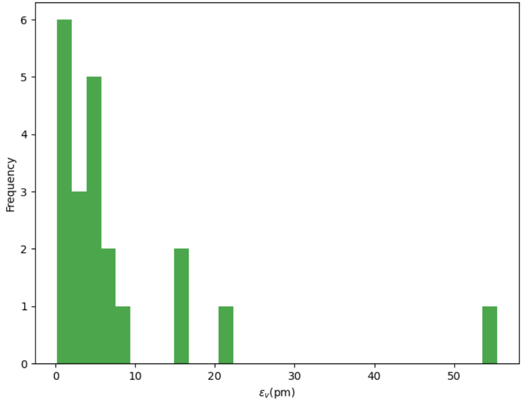
Ballistic lattice



Adding Dispersion Free Steering
(After beam threading, H&V dispersion correction using orbit correctors)

Parameter	w/o DFS	w DFS
hor.orbit (μm)	204.83	151.57
ver. orbit (μm)	255.57	222.34
$\Delta\beta_x/\beta_x\%$	1.32	1.16
$\Delta\beta_y/\beta_y\%$	0.81	0.70
$\Delta\ \eta_x$ (mm)	446.47	69.73
$\Delta\ \eta_y$ (mm)	416.40	34.12
ε_y (pm)	659.44	4.38

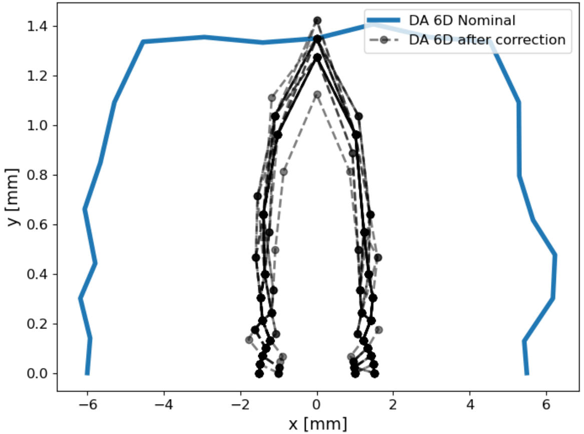


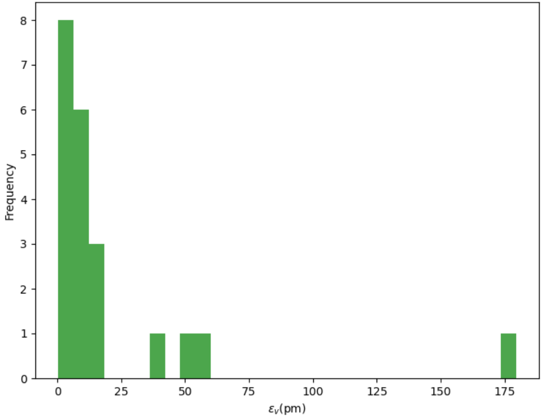


E. Musa, “Tuning studies for ballistic optics”, FCC-ee optics tuning WG meeting, 6th Nov 2024.

Ballistic optics: Right after 1^{st} beam threading

150 µm BPM-to-quadrupole

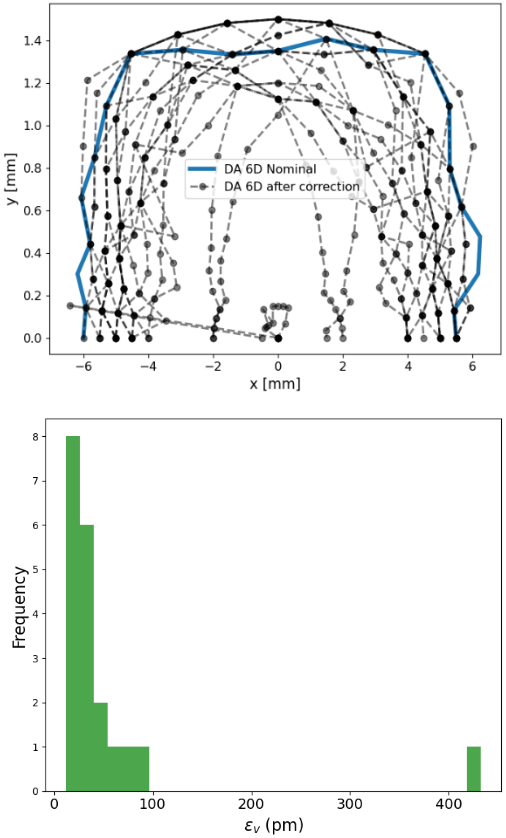




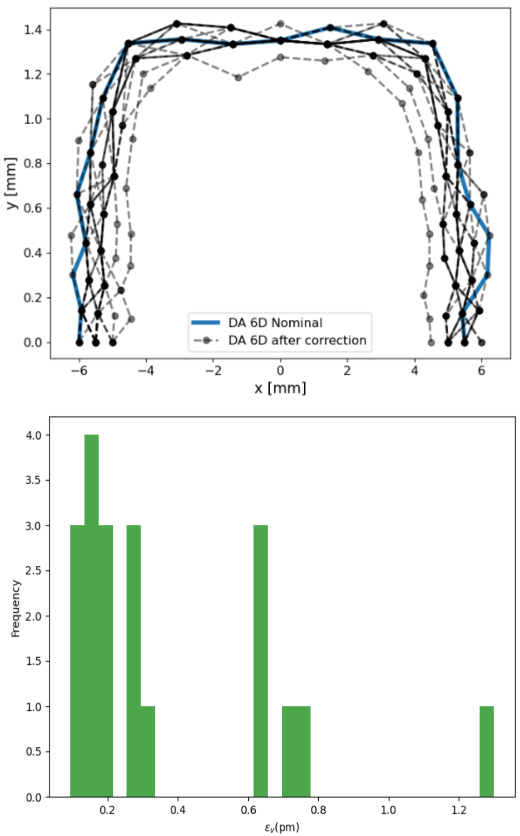
rms hor. orbit (µm)	rms ver. orbit (µm)	$\Delta\beta_x/\beta_x$ %	$\Delta\beta_y/\beta_y$ %	$\Delta\ \eta_x$ (mm)	$\Delta\ \eta_y$ (mm)	ε_h (nm)	ε_v (pm)
186.72	264.25	1.48	0.84	93.91	51.24	0.86	9.21

BPMs attached to quadrupoles (10 μm)

Parameter	Prior optics Cor.	Final Cor.
hor.orbit (μm)	130.23	130.36
ver. orbit (μm)	144.76	144.75
$\Delta\beta_x/\beta_x\%$	9.72	1.02
$\Delta\beta_y/\beta_y\%$	27.37	0.63
$\Delta\ \eta_x$ (mm)	73.73	0.66
$\Delta\ \eta_y$ (mm)	54.82	1.68
ε_y (pm)	31.57	0.23



Prior to linear optics correction



Final correction

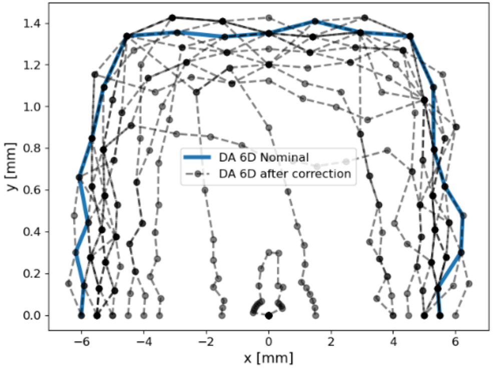
E. Musa, "Tuning studies for ballistic optics", FCC-ee optics tuning WG meeting, 2ed Oct 2024.

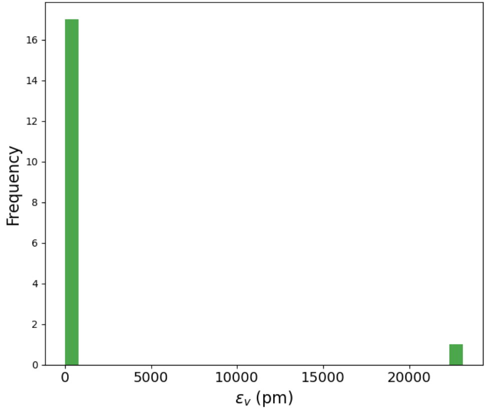
BPMs attached to sextupoles (20 μm)

Parameter	Prior optics Cor.	Final Cor.
hor.orbit (μm)	144.40	144.49
ver. orbit (μm)	160.96	160.96
$\Delta\beta_x/\beta_x$%	7.42	1.92
$\Delta\beta_y/\beta_y$%	10.67	1.14
$\Delta\ \eta_x$ (mm)	55.17	1.97
$\Delta\ \eta_y$ (mm)	1.93	2.00
ε_y (pm)	3.61	3.0

E. Musa, "Tuning studies for ballistic optics", FCC-ee optics tuning WG meeting, 2ed Oct 2024.

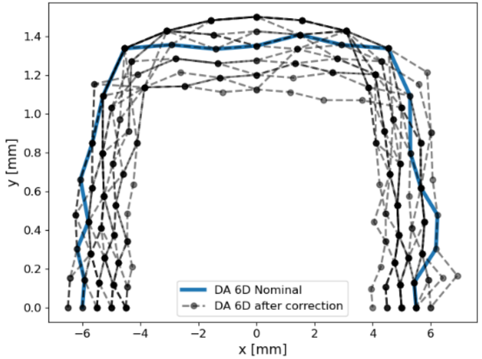
Prior to linear optic correction

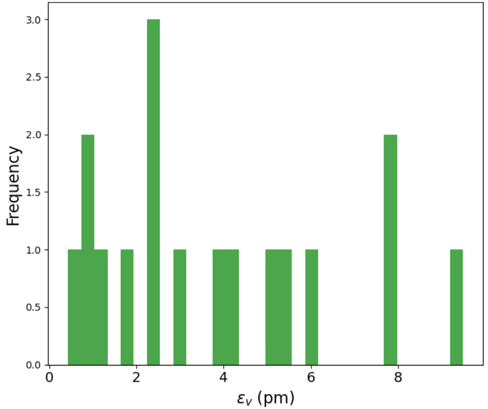




Final correction

3 failed seeds



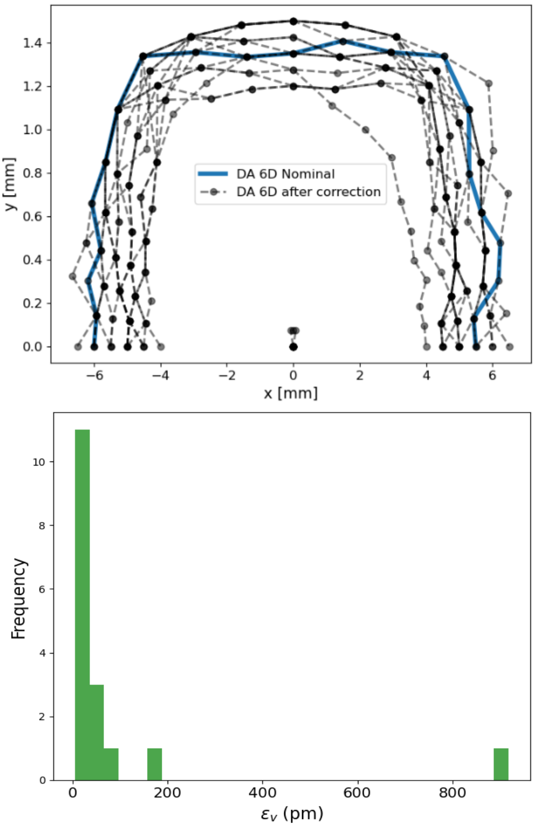


BPMs attached to sextupoles (10 μm)

Parameter	Prior optics Cor.	Final Cor.
hor.orbit (μm)	144.51	144.51
ver. orbit (μm)	160.75	160.75
$\Delta\beta_x/\beta_x$%	7.69	1.92
$\Delta\beta_y/\beta_y$%	10.74	1.12
$\Delta\ \eta_x$ (mm)	53.51	1.96
$\Delta\ \eta_y$ (mm)	1.77	1.84
ε_y (pm)	2.25	2.39

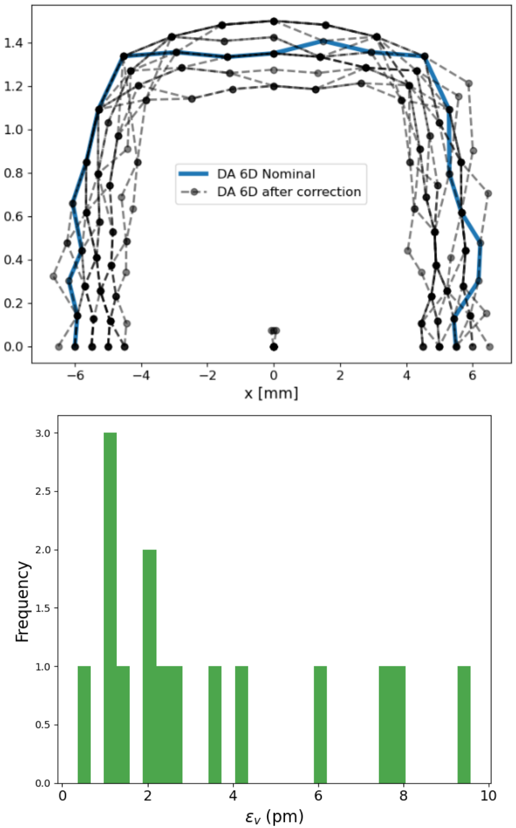
E. Musa, "Tuning studies for ballistic optics", FCC-ee optics tuning WG meeting, 18th Oct 2024.

Prior to linear optic correction



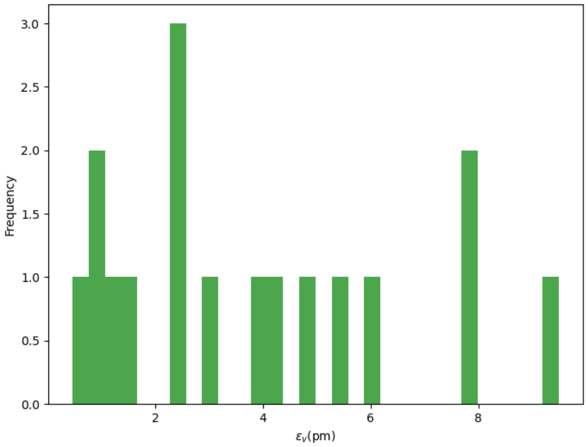
Final correction

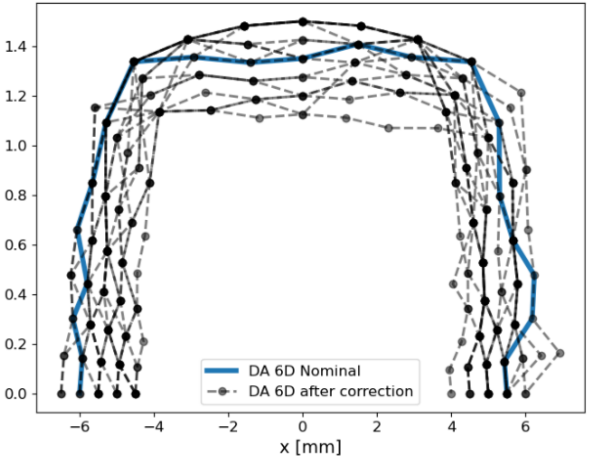
5 failed seeds



Ballistic optics: Final correction results

10 μm BPM-to-quadrupole after BBA



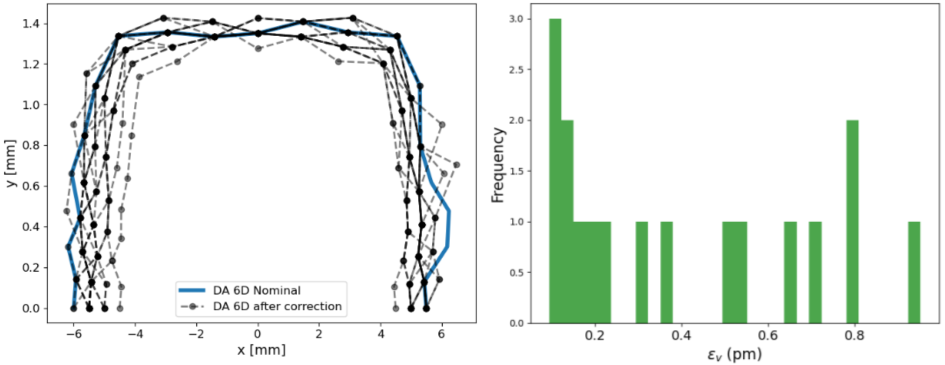


	rms hor. orbit (μm)	rms ver. orbit (μm)	$\Delta\beta_x/\beta_x$ %	$\Delta\beta_y/\beta_y$ %	$\Delta\,\eta_x$ (mm)	$\Delta\,\eta_y$ (mm)	ε_h (nm)	ε_v (pm)
mean	24.786	24.395	1.122	10.821	14.523	1.159	0.706	0.054
std	1.577	1.113	0.826	8.126	7.819	0.971	0.002	0.065

Adding errors to IR (Ballistic optics)

E. Musa, "Tuning studies for ballistic optics", FCC-ee optics tuning WG meeting, 6th Nov 2024.

Elements	Hor. & Ver. displacement	Rotation θ
Arc quads and sext	50 μm	50 μrad
IR quads and sext	50 μm	50 μrad
All dipoles	1000 μm	1000 μrad
Girders	150 μm	150 μrad
BPMs to quads	10 μm	10 μm



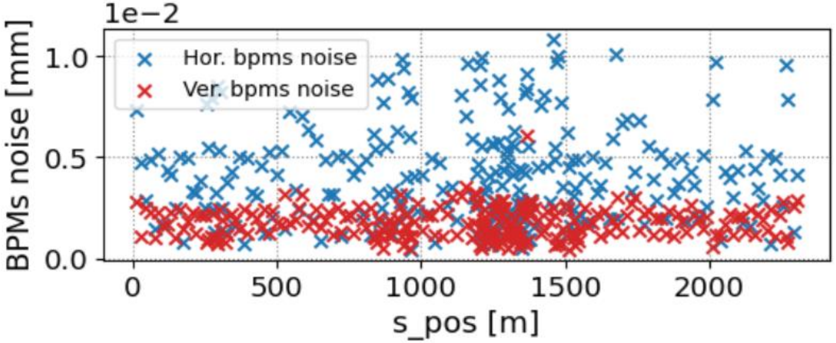
rms hor. orbit (μm)	rms ver. orbit (μm)	rms $\Delta\beta x/\beta x$ %	rms $\Delta\beta y/\beta y$ %	rms $\Delta\ \eta x$ (mm)	rms $\Delta\ \eta y$ (mm)	ε_h (nm)	ε_v (pm)	rms Hor. $\Delta\varphi$	rms Ver. $\Delta\varphi$
131.18	144.79	1.58	1.00	0.86	1.71	0.85	0.31	1.90×10^{-3}	1.80×10^{-3}

PETRA III and PETRA IV

Optics correction at PETRA III

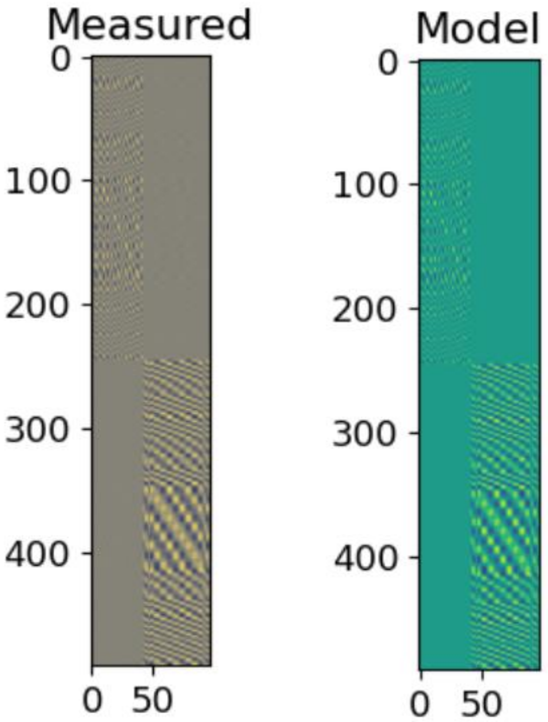
(PETRA III-High-Beta Optics p3x_v24)

- The lattice has **246 BPMs, 620 Correctors**, and **417 quadrupoles**.
- Measurement was with all corrector magnets of type **PKH (41)** and **PKV(55)**.
- Optics errors were introduced by changing some **quadrupoles. BPMs noise** included.



Orbit response matrices

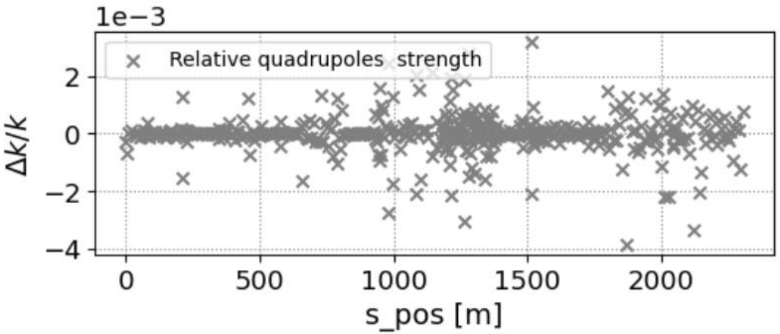
Multiplied by 10



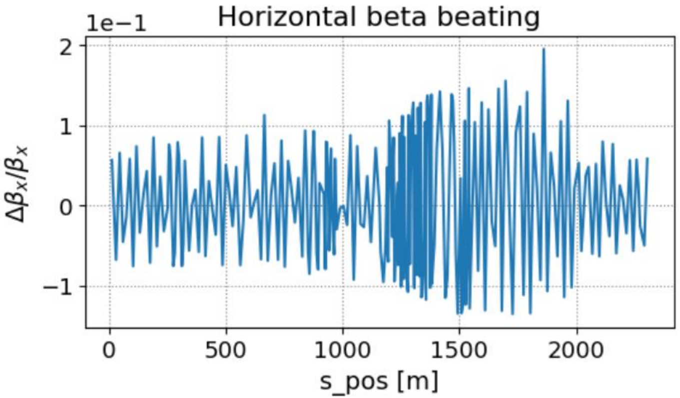
PETRA III measurements test

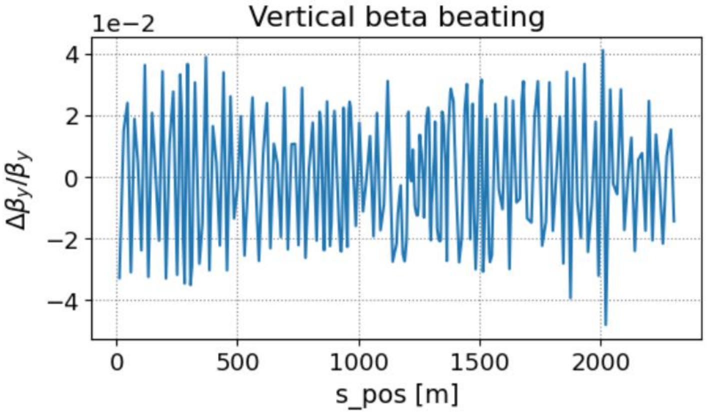
(PETRA III-High-Beta Optics p3x_v24)

- The implemented LOCO was utilized.
- The results were applied to the model lattice.
- Including the BPMs and correctors calibration errors in the fit.



- Δβx/βx : 7.768%
- Δβy/βy : 2.032%





- The correction has not been implemented in the machine; another measurement will be conducted.

PETRAIV error tolerances

BPM Errors:

- BPM offsets = 500 µm
- BPM noise (TBT) = 50 µm
- BPM noise (CO) = 0.1 µm
- BPM roll = 400 µrad
- BPM calibration = 5%

Magnet Errors:

- Magnet offsets = 30 µm
- Magnet roll = 200 µrad
- Magnet calibration = 0.1%
- Quadrupole calibration = 0.05%

Corrector Errors:

- Corrector roll = 200 µrad
- Corrector calibration = 2%

Girder Errors:

- Girder offsets = 150 µm
- Girder roll = 200 µrad

RF errors:

- RF phase is random
- RF frequency = 100 Hz
- RF Voltage = 1 kV
- Relative ring circumference = 10^{-6}