

Optics Tuning Simulations For the Electron Positron Future Circular Collider lattices

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Acknowledgment: R. Tomas, F. Zimmermann, T. Charles, K. Oide, S. Liuzzo, S. White
and the entire FCC-ee optics tuning group

FCC Week 19 – 25 May 2025

Vienna, Austria



PhD Thesis June 2021-Dec 2024

Optics measurement and correction for future electron circular colliders

Dissertation
zur Erlangung des Doktorgrades
an der Fakultät für Mathematik, Informatik und
Naturwissenschaften
Fachbereich Physik
der Universität Hamburg

vorgelegt von
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Hamburg
2024

Contributions

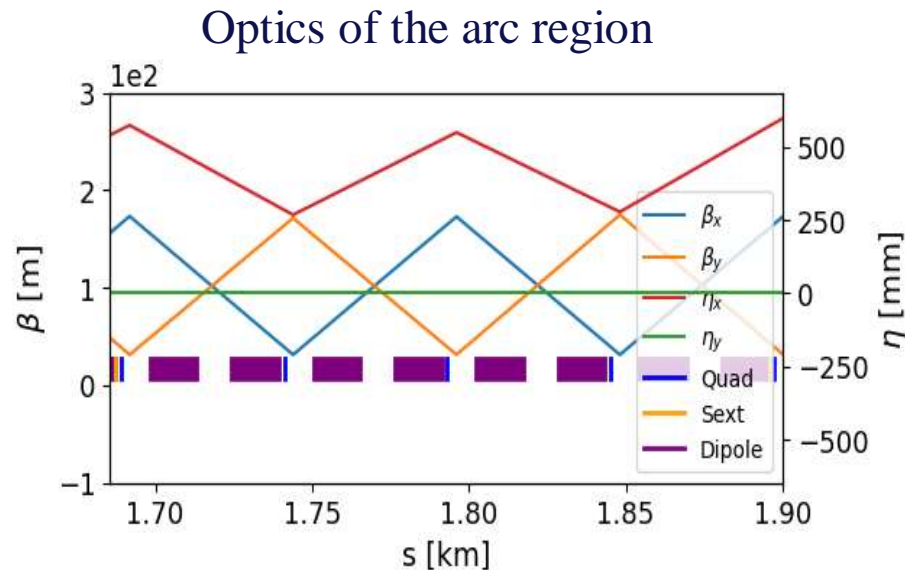
E. Musa, I. Agapov, and T. Charles, “Orbit-response based optics corrections for FCC-ee” presented at IPAC’23, WEPL017. Venice, Italy, May 2023.

E. Musa, I. Agapov, T. Charles, “Optics tuning simulations for FCC-ee using Python Accelerator Toolbox”, arXiv:2410.24129 [physics.acc-ph], 2024, <https://arxiv.org/abs/2410.24129>.

E. Musa, I. Agapov, T. Charles “Optics correction for the electron positron future circular collider: nominal and ballistic optics. eeFACT 2025 - 70th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders, Tsukuba, Japan.

Baseline optics for FCC-ee

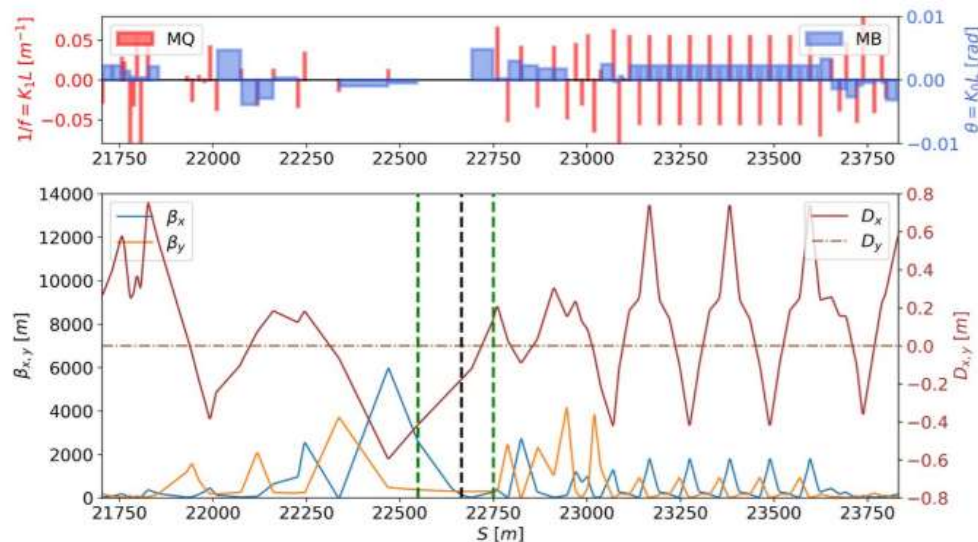
Optics parameters at Z energy



The optics of the arc region for the baseline lattice rely on a FODO cell structure.

Lattice Parameters	Nominal
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
β^* at IP x/y (mm)	110/0.7
Luminosity / IP ($\times 10^{34} \text{ cm}^{-2} \text{ s}$)	141

Ballistic optics for FCC-ee



Cristobal Garcia **FCC-ee optics tuning WG meeting, Sep. 13, 3034.**

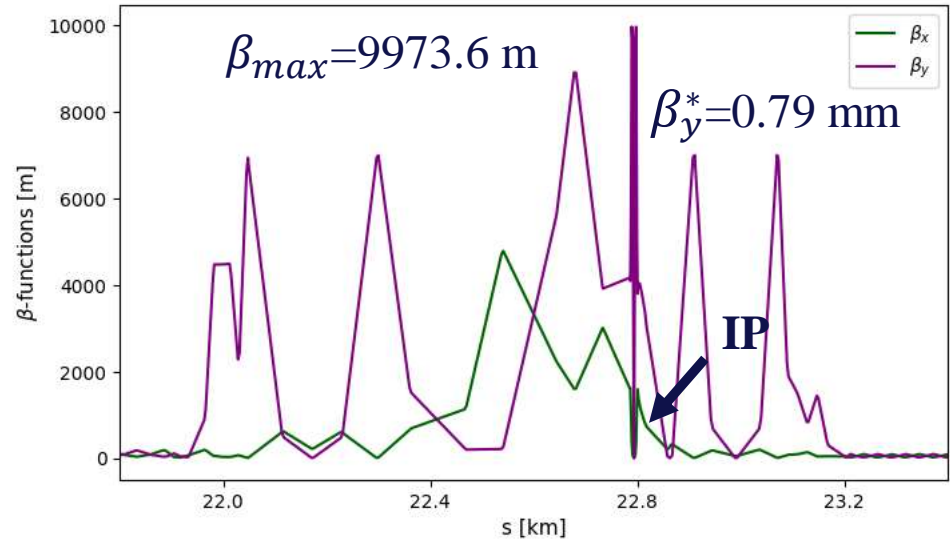
Optics parameters at Z energy

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/ -0.176	0.29/ 4.28
Tune	217.77/ 220.37	218.15/ 222.19

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

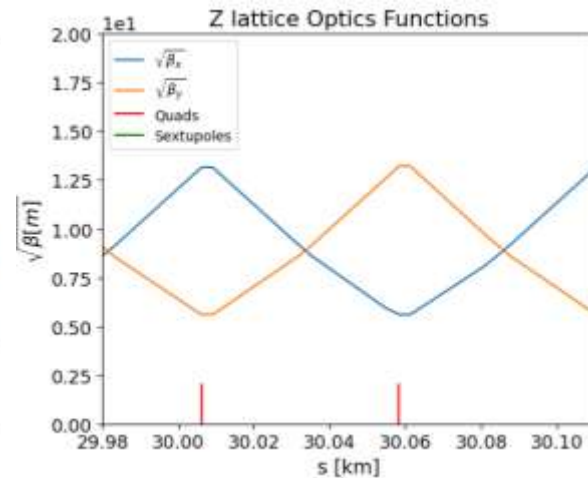
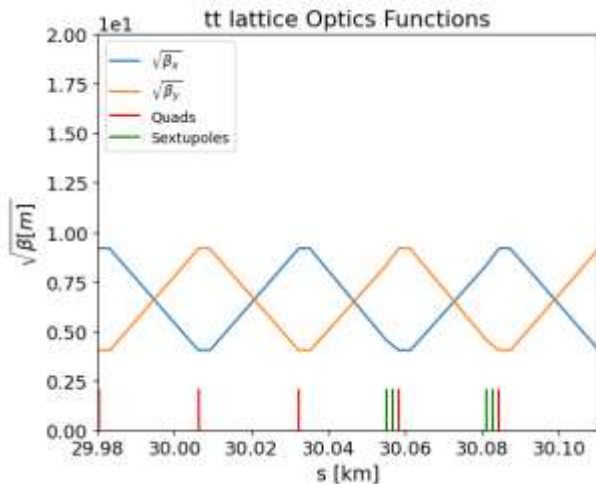
Optics tuning challenges

- The overall machine performance is strongly dominated by magnet field imperfections and misalignments.
- The very small beta function β at the Interaction Point (IP) requires strong FF magnets, which in turn need strong sextupoles for local chromaticity correction (very sensitive to even small imperfections).
- Small emittance ratio makes the lattice sensitive to any coupling between the horizontal and vertical motion.



Tuning simulations studies

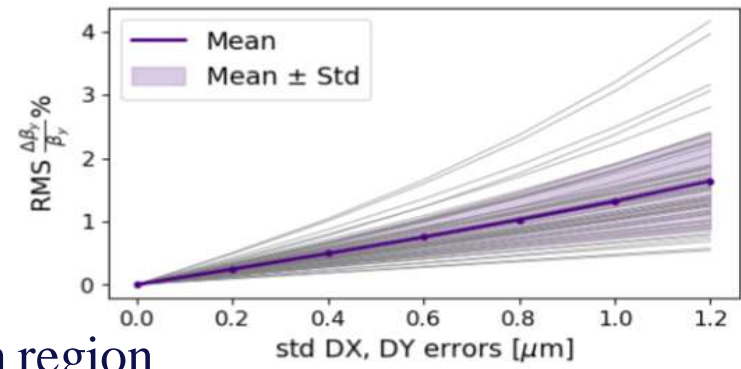
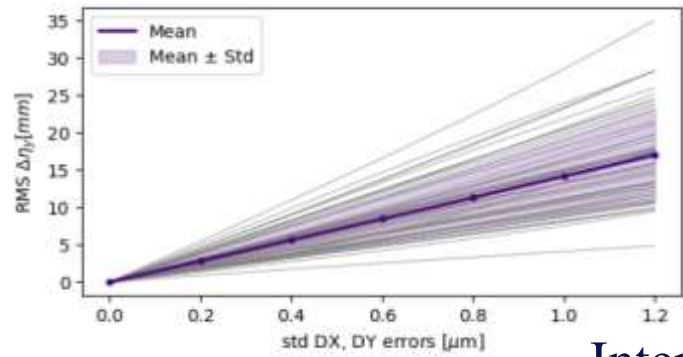
- Tuning simulations for the FCC-ee lattice at $t\bar{t}$ energy were performed using (MAD-X) T. Charles, et al., "Alignment & Stability Challenges for FCC-ee," EPJ Techniques and Instrumentation, vol. 10,no. 8, 2023.
- The larger beta functions at the magnet locations in the Z lattice indicate a higher sensitivity compared to the $t\bar{t}$ lattice.
- We focused on the Z energy mode, and work is ongoing toward having a first look at the tuning of the W lattice.



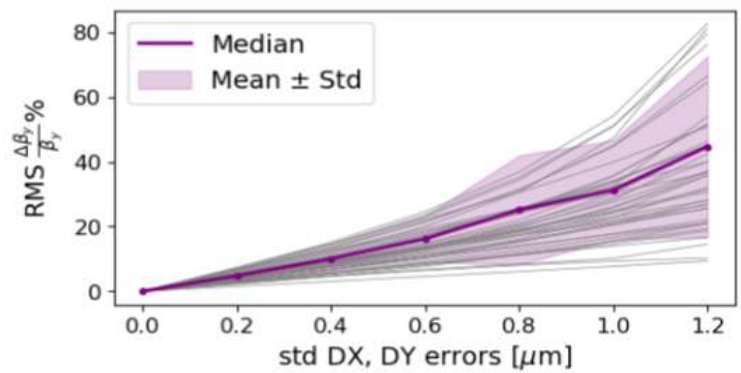
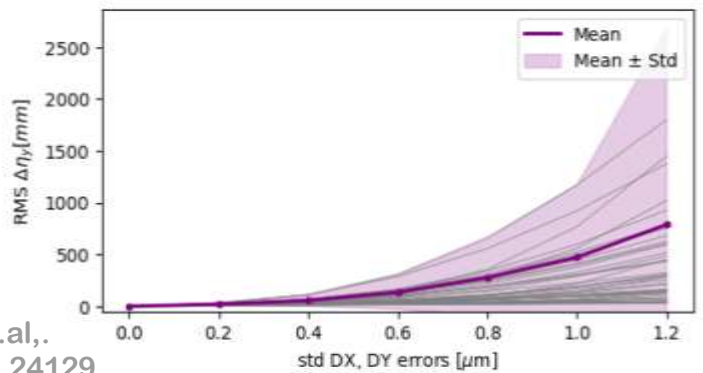
E. Musa, "Tuning studies with pyAT", FCC-ee optics tuning WG meeting, 23th Jul 2024.

Optics sensitivity to magnet alignment errors (Z lattice)

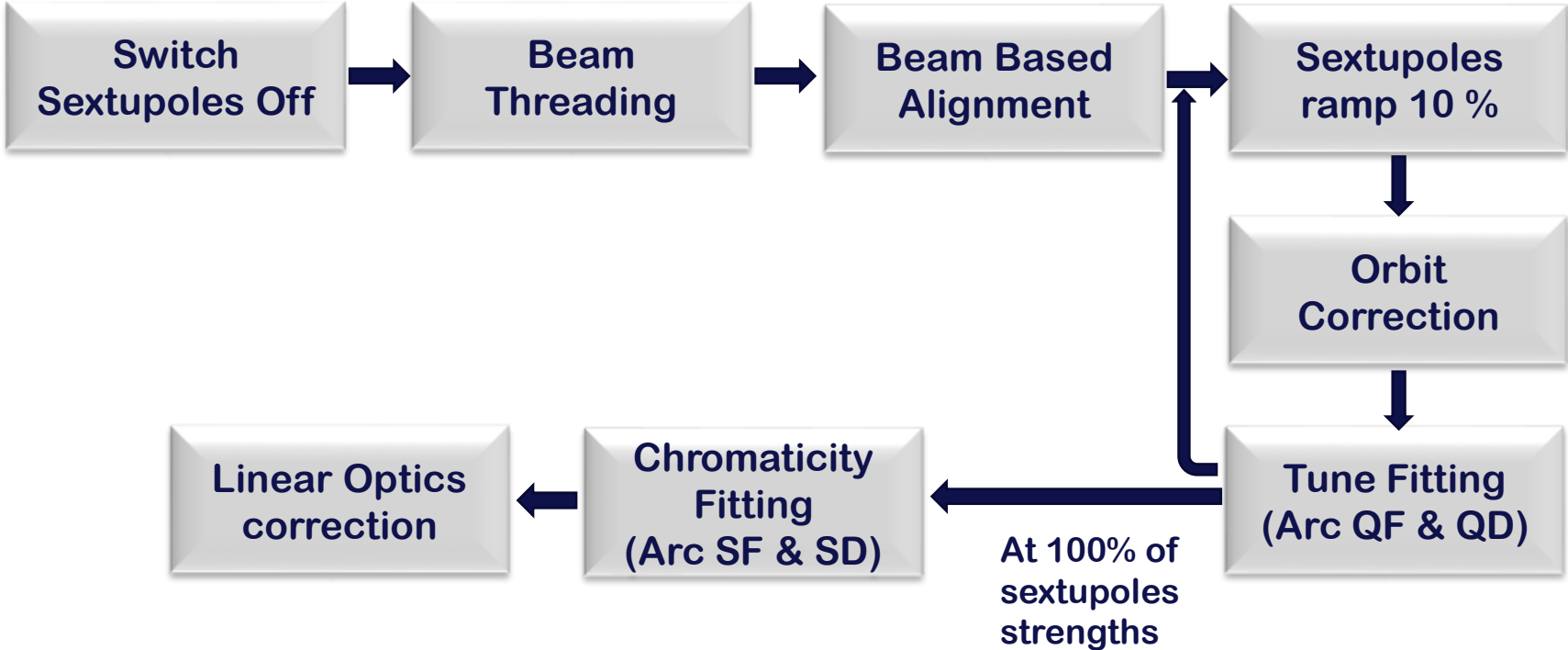
Arc region



Interaction region

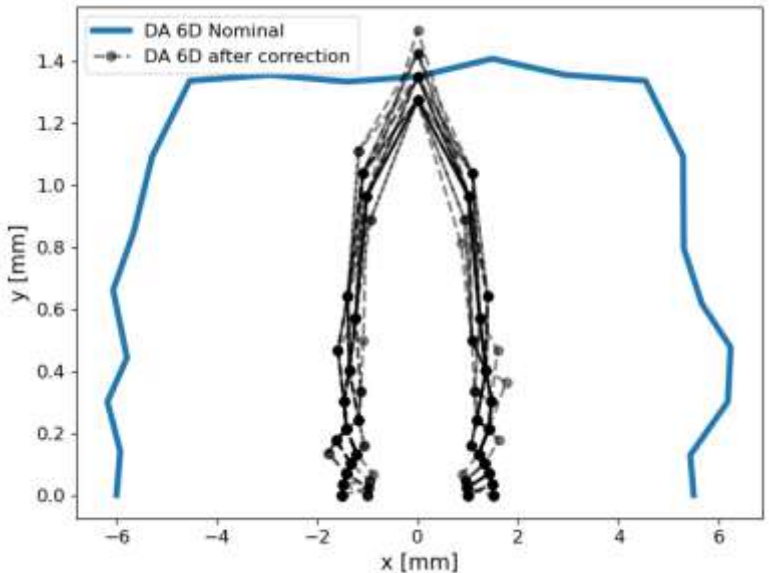


Correction procedure



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.



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

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

Correction algorithms

Orbit correction

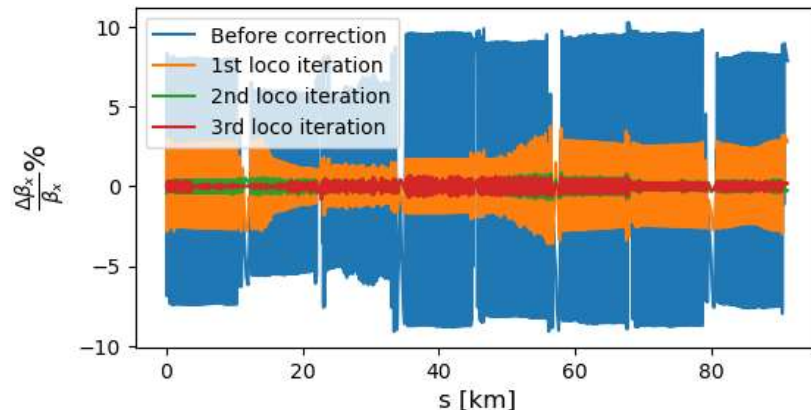
- Singular value decomposition

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

Linear Optics from Closed Orbit (LOCO)

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

- We studied the validity of the orbit response based optics correction for FCC-ee.
- Implemented Python-based numerical code for LOCO.



Correction algorithms

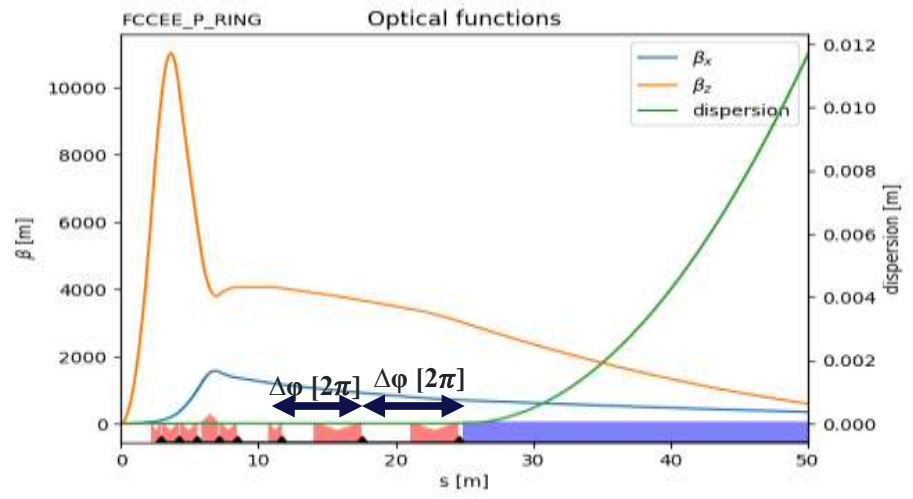
Beta beating and coupling correction

- Phase advance + η_x correction

$$\begin{pmatrix} \alpha_1 \Delta \varphi_x \\ \alpha_1 \Delta \varphi_y \\ \alpha_2 \Delta \eta_x \end{pmatrix}_{\text{measured}} = -C_{\text{model}} \delta K.$$

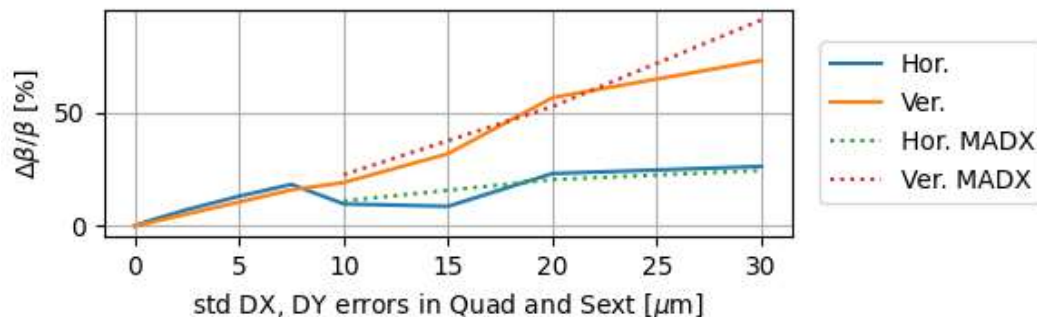
- Coupling RDTs + η_y correction

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



Optics tuning tools

- We developed optics tuning tools using the Python interface of the Accelerator Toolbox (**PyAT**) [GitHub Repository](#)

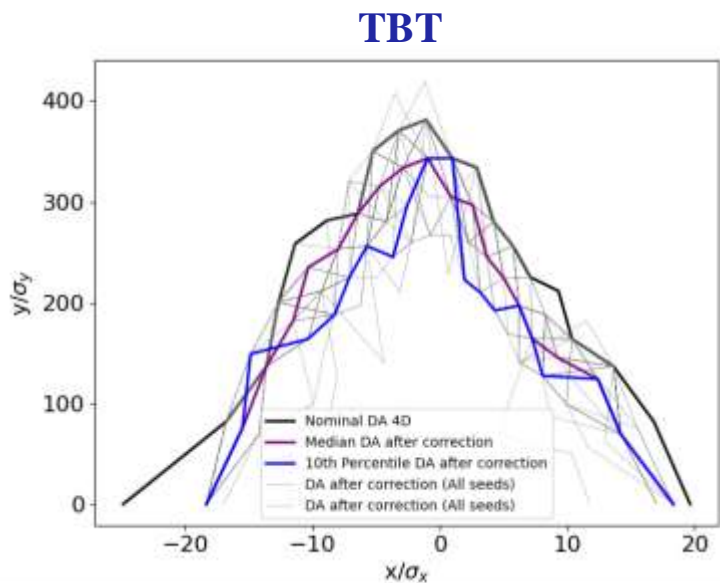
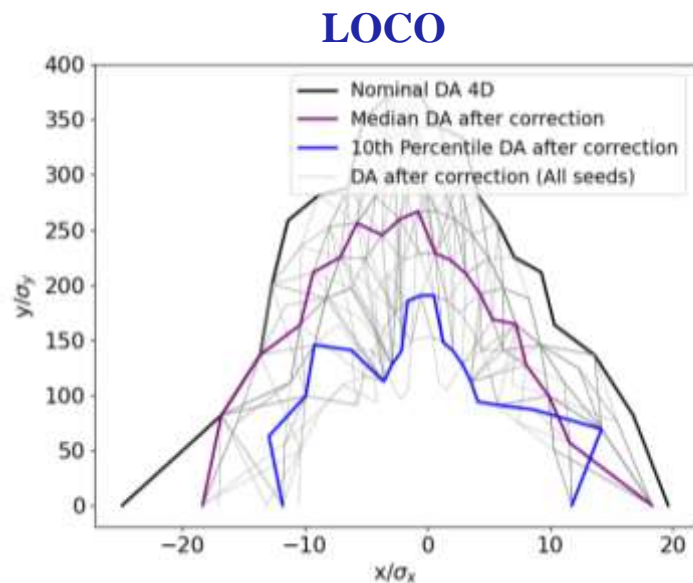


S. Luizzo, et.al, Benchmark of commissioning simulations with errors and corrections: AT vs MADX vs MADX PTC.

- The tools were integrated into the Python version of the Simulated Commissioning toolkit for Synchrotrons (PySC) which is being used in the commissioning simulations of PETRAIV at DESY,
 - ✓ highlighting the synergies between light sources and FCC.
- The simulated commissioning tools can be integrated with other frameworks (e.g., **Xsuite**).

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.



$$\sigma_x = 8.84 e^{-6} \text{ m}, \sigma_y = 3.12 e^{-8} \text{ m}, \text{Rad off.}$$

Applied magnets misalignments and strength errors

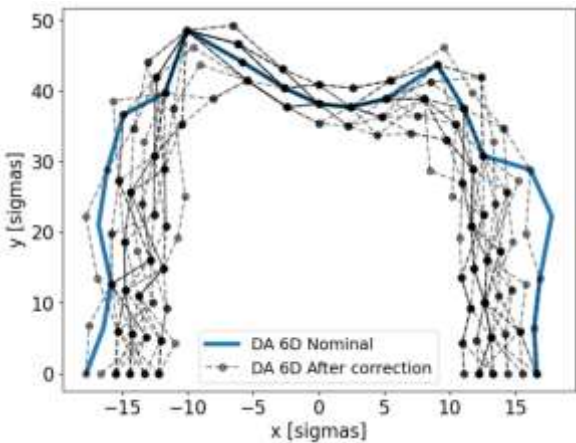
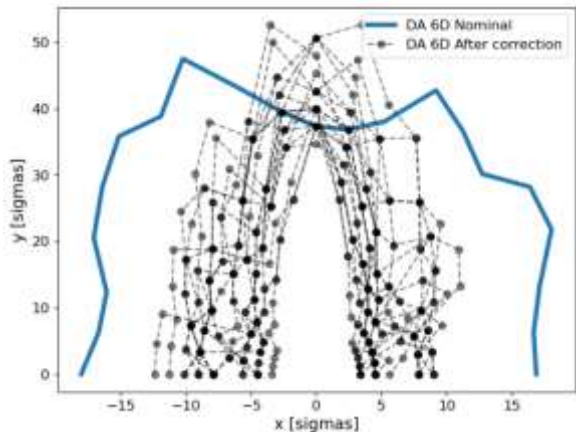
Elements	Hor. & Ver. displacement	Tilt θ
Arc quads and sext.	50 μm	50 μrad
All dipoles	1000 μm	1000 μrad
Girders	150 μm	150 μrad
BPMs-quads.	100 \rightarrow 10 μm	-

Elements	Field Errors
Arc quads and sext.	$\frac{\Delta K}{K} = 2 \times 10^{-4}$
All dipoles	$\frac{\Delta K}{K} = 2 \times 10^{-4}$

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

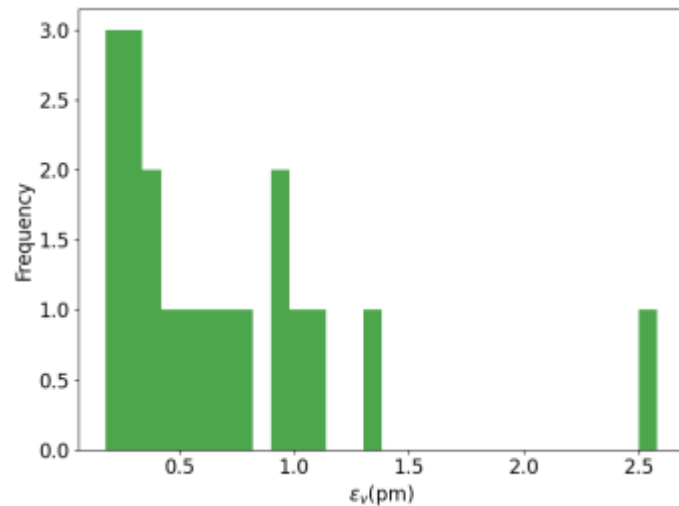
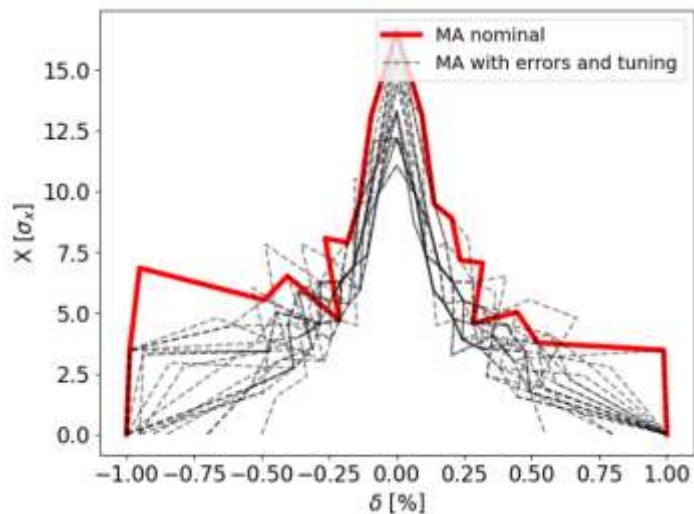
Tuning simulation results (nominal lattice)

Before linear optics cor.



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_x (pm)	0.72	0.71
ϵ_y (pm)	26.01	0.57
hor. $\Delta\phi$ [2π]	1.13×10^{-2}	2.91×10^{-4}
ver. $\Delta\phi$ [2π]	1.93×10^{-2}	2.29×10^{-3}

Tuning simulation results (nominal lattice)

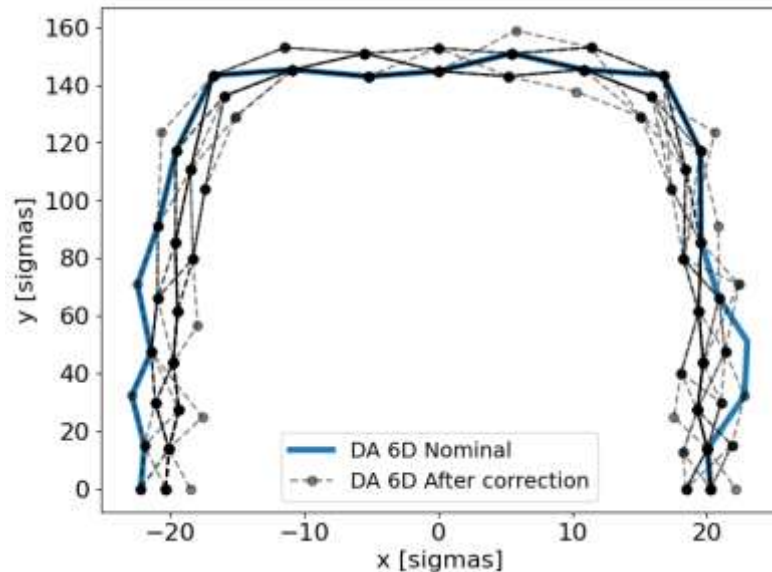


Parameters after correction (at IP)

$\Delta\beta_x/\beta_x$ %	$\Delta\beta_y/\beta_y$ %	$\Delta\eta_x$ (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 simulation results (Ballistic optics)

- The simulation included IR alignment errors of $50 \mu\text{m}$ in addition to the arc errors.



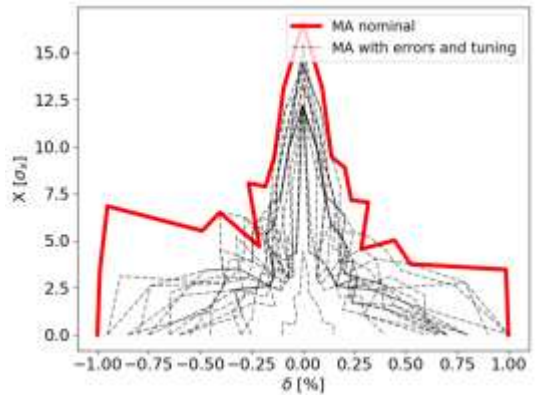
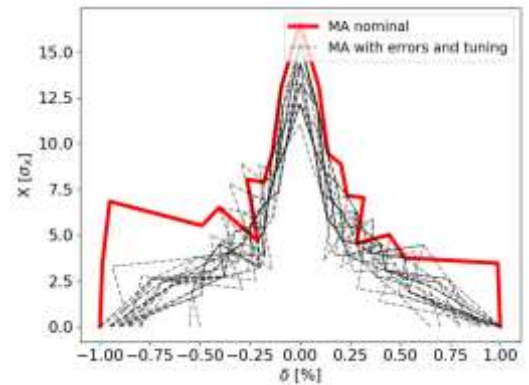
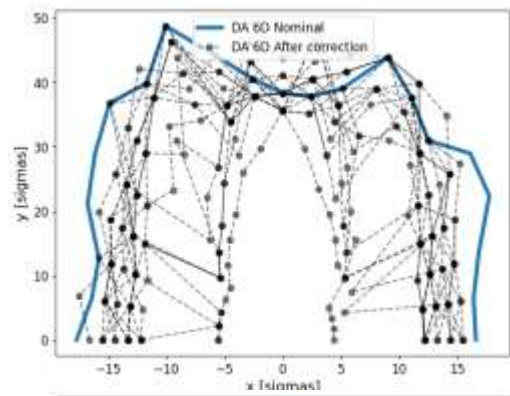
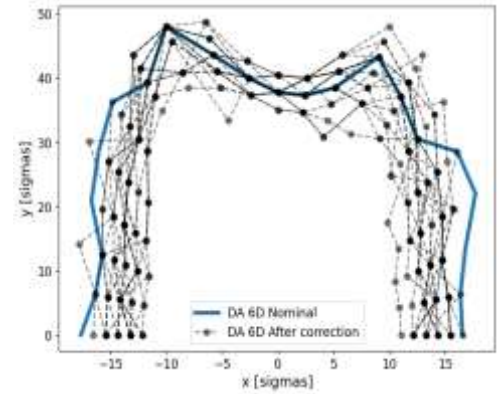
Parameter	Prior optics Cor.	Final Cor.
hor.orbi(μm)	130.23	130.36
ver. orbit(μm)	144.76	144.75
$\Delta\beta_x/\beta_x\%$	9.72	1.02
$\Delta\beta_y/\beta_y\%$	27.37	0.63
$\Delta\eta_x$ (mm)	73.73	0.66
$\Delta\eta_y$ (mm)	54.82	1.68
ε_y (pm)	31.57	0.23

Ongoing studies:

Using different correctors for beta beating correction.

Normal trim quads at sextupoles

Normal quadrupoles



Parameter	All sext.	All quads.
$\Delta\beta_x/\beta_x\%$	0.29	0.29
$\Delta\beta_y/\beta_y\%$	2.67	2.46
$\Delta\eta_x$ (mm)	0.22	0.08
$\Delta\eta_y$ (mm)	0.27	0.28
ϵ_y (pm)	0.48	0.35

Ongoing studies:

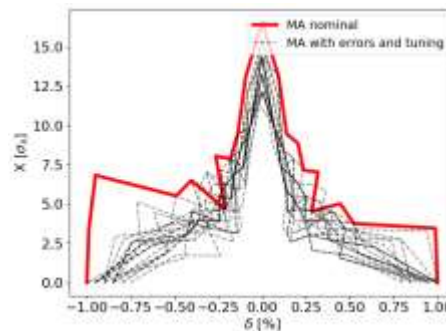
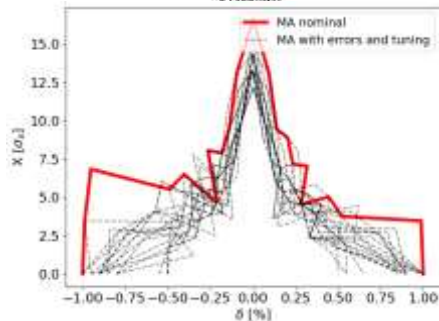
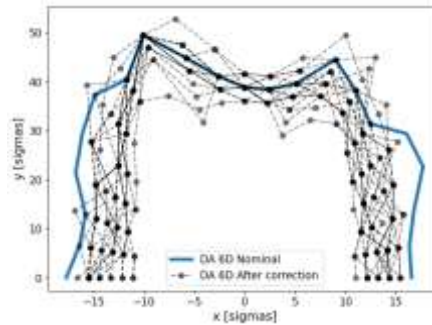
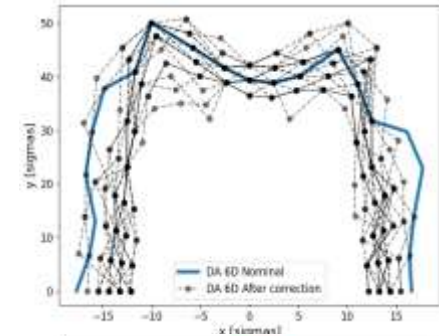
Adding measurement noise to the TbT approach.

Measurement noise are added to phase advance and coupling RDTs.

The standard deviation σ of the noise was scanned.

$$\sigma = 1 \times 10^{-5}$$

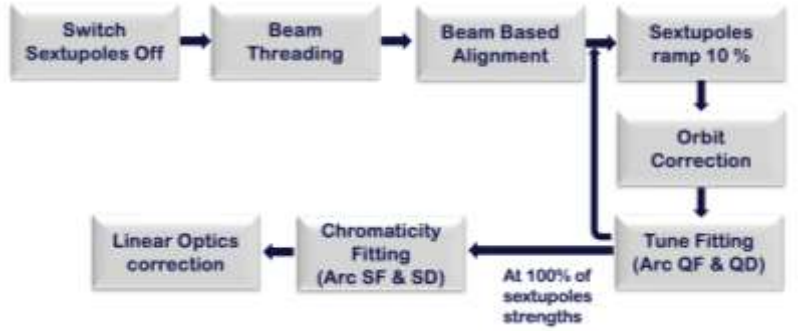
$$\sigma = 2 \times 10^{-3}$$



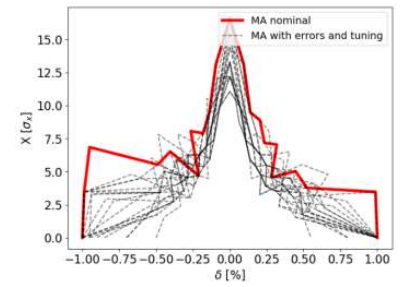
Parameter	$\sigma = 1 \times 10^{-5}$	$\sigma = 2 \times 10^{-3}$
$\Delta\beta_x/\beta_x\%$	0.33	0.27
$\Delta\beta_y/\beta_y\%$	3.12	2.46
$\Delta\eta_x$ (mm)	0.24	0.24
$\Delta\eta_y$ (mm)	0.29	0.78
ε_y (pm)	0.75	1.09

Conclusion

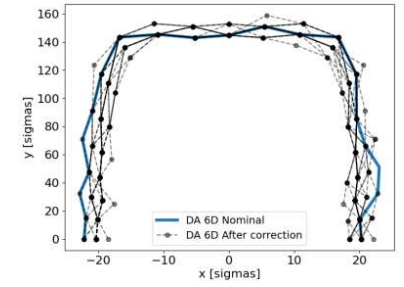
Developed correction procedure



Baseline tuning simulations



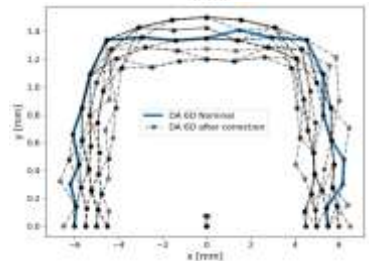
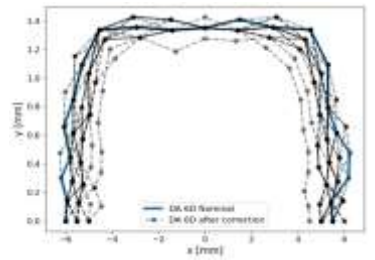
Ballistic lattice tuning



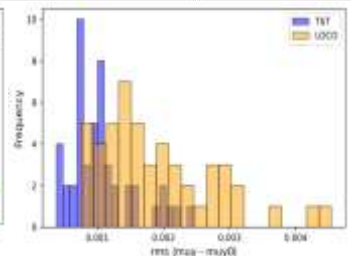
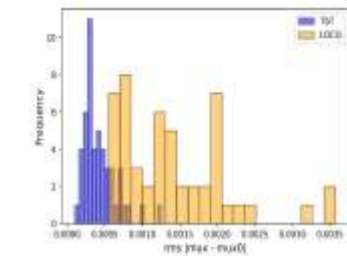
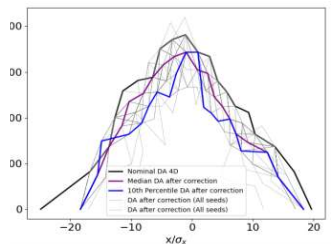
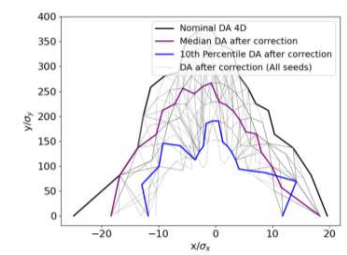
Defining alignment and field tolerances

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

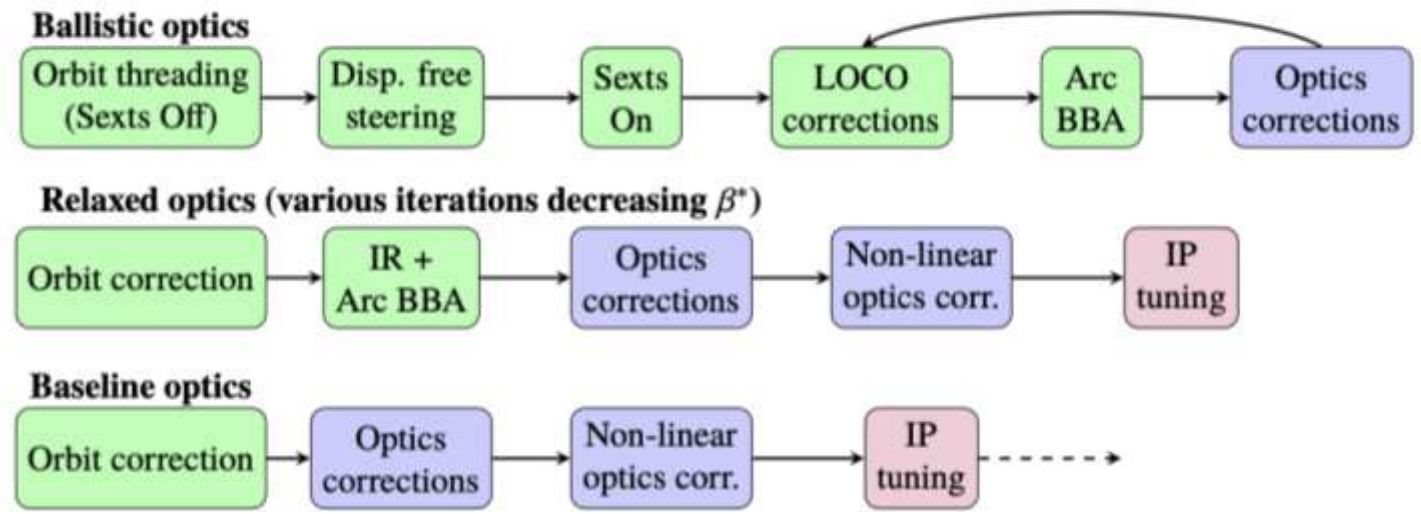
Preference to attach BPMs to quads



LOCO vs. phase advance performance





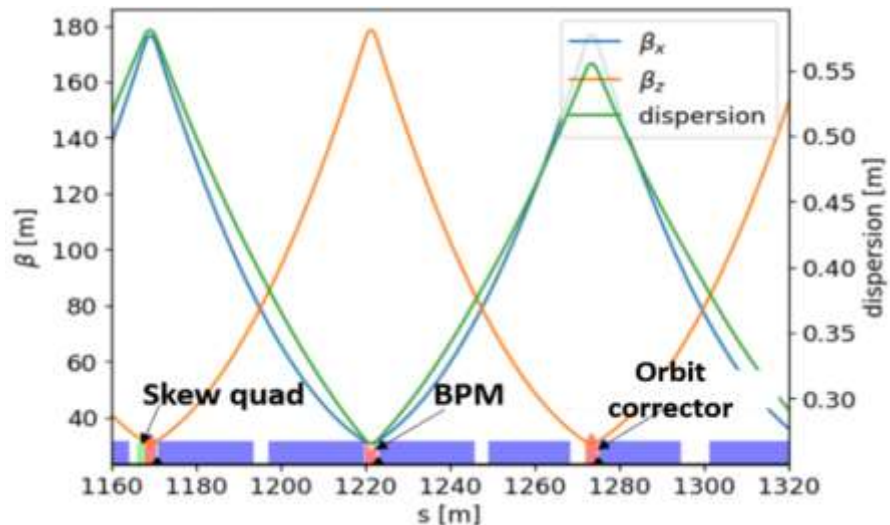


R. Tomas

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

Used Correctors



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

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}