Orbit-response based optics correction studies for Fcc-ee

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Introduction

- The FCC-ee lattice components are subject to different types of errors: randomly distributed misalignments and field errors
- The primary aim is to achieve a well focused beam by minimizing the beta function at the IPs, increasing the dynamic aperture to increase the life time and achieving the desired momentum acceptance. this will lead to achieving high machine luminosity and hence increase the machine efficiency.
- Over the past few years, many algorithms for correcting the optics have been developed using MAD-X and Python.
- To achieve better optics and DA, further improvements to the correction algorithms are required.

Orbit and optics error Corrections

Optics with m-BPMS and n-correctors produces an m x n dimensional response matrix:

$$\chi^2 = \sum_{ij} (\Delta C^{ij} - \sum_k \frac{\partial C^{ij}}{\partial g_k} \Delta g_k)^2$$

$$C_{mn} = \frac{\sqrt{\beta_m \beta_n}}{2 \sin(\pi\nu)} \cos(\pi\nu - \phi(s) + \phi(s_0)) + \frac{\eta_i \eta_j}{\alpha_c L_o}$$

$$\Delta g_k = (\frac{\partial C^{ij^T}}{\partial g_k} \frac{\partial C^{ij}}{\partial g_k})^{-1} (\frac{\partial C^{ij^T}}{\partial g_k} \Delta C^{ij})$$

- In LOCO (Linear Optics from Closed Orbit) the measured orbit response matrix ORM is fitted to the lattice model by varying parameters in the used model to minimize the deviation between the model and measured orbit response matrices

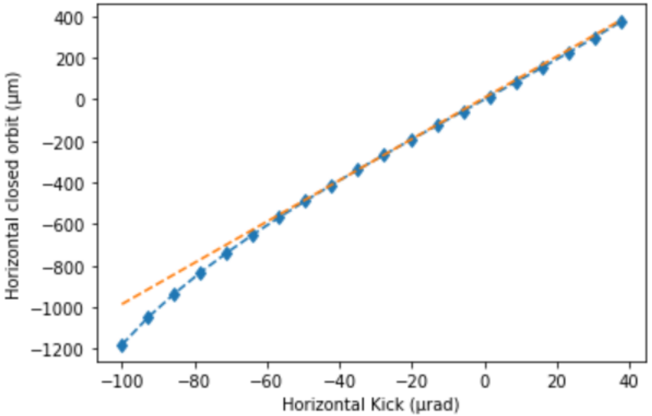
- Orbit correction aims to invert the response matrix to find the proper orbit correctors kicks θ that satisfy the relation $\Delta x + C\Delta\theta = 0$.

Orbit and optics error Corrections

Optics with m-BPMS and n-correctors produces an m x n dimensional response matrix:

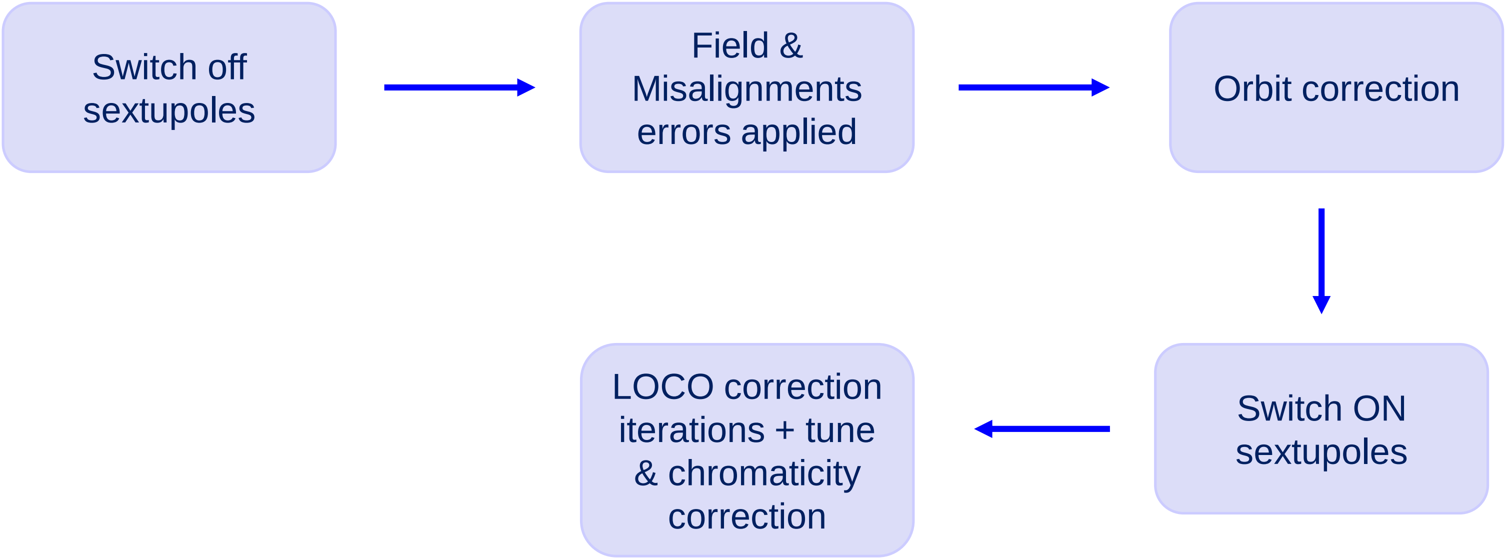
$$C_{mn} = \frac{\sqrt{\beta_m \beta_n}}{2\sin(\pi\nu)} \cos(\pi\nu - \phi(s) + \phi(s_0)) + \frac{\eta_i \eta_j}{\alpha_c L_o}$$

- The changes of correctors kick used in generating the ORMs, changes the horizontal and vertical tune as a result due to the sextupoles effect.



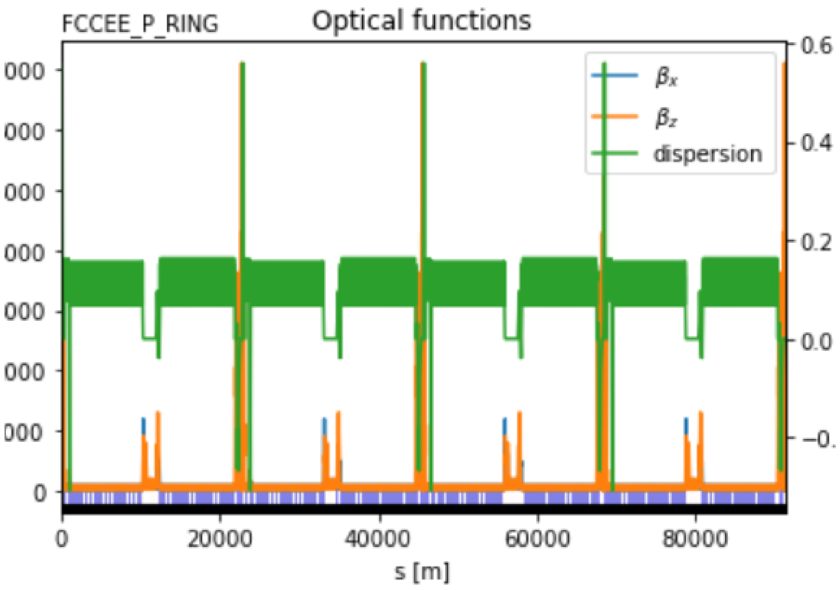
- An acceptable range for the horizontal correctors kick within the FCCee-t-v22 lattice is between -10.e-5 and 3.75e-5 radiance.

Correction procedure



LOCO PyAT based implementation

- To investigate the possibility of using LOCO for FCC-ee lattices we used the Python accelerator toolbox (PyAT) to implement the code and utilised it to produce preliminary results.
  - BPMs noise = 0.0
  - Radiation off
  - Girders are not included
  - BPMS & Correctors added next to each quadrpole



FCCee-t-v22 lattice optics

LOCO PyAT based implementation

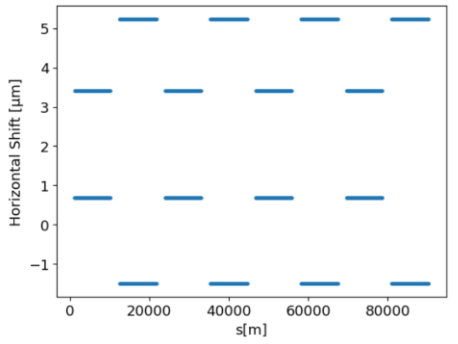
- Closed orbit response is directly simulated.
- Choosing few orbit correctors equally distributed around the lattice.
- Calculating the quadrupoles response matrices (Jacobian) while sext OFF.

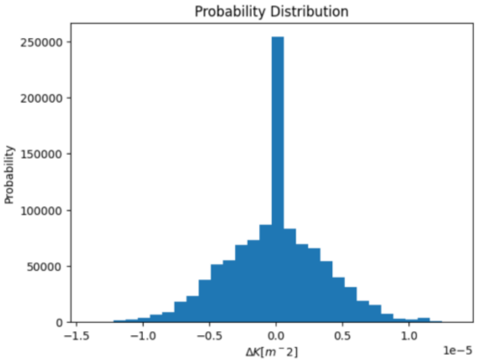
```
def quadsSensitivityMatrices(ring,correctrs_kick,used_cor_indexes,  quad_index, dk):
    strength_before = ring[quad_index].K
    ring[quad_index].K = strength_before + dk
    qxx, qxy, qyy, qyx = ORMs(correctrs_kick, ring,used_cor_indexes)
    ring[quad_index].K = strength_before
    return  qxx, qxy, qyy, qyx
```

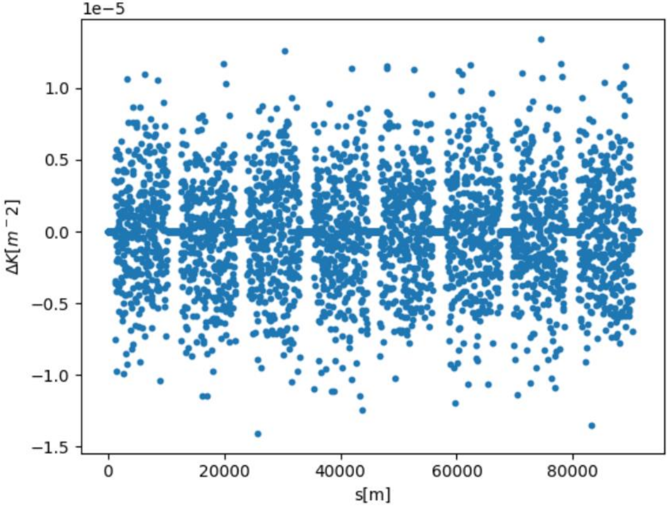
```
def generatingQuadsResponse(ring, C0x, C0y, C0xy, C0yx, correctrs_kick,used_cor_indexes, quads_indexes, dk, debug=False):
    dCx = []
    dCy = []
    dCxy = []
    dCyx = []
    for quad_index in quads_indexes:
        if debug == True :
           print('generating response to quad of index', quad_index)
        C1x, C1xy, C1y, C1yx = quadsSensitivityMatrices(ring,correctrs_kick,used_cor_indexes,  quad_index, dk)
        dCx.append((C1x - C0x) / dk)
        dCy.append((C1y - C0y) / dk)
        dCxy.append((C1xy - C0xy) / dk)
        dCyx.append((C1yx - C0yx) / dk)
    return dCx, dCy, dCxy, dCyx
```

Error Correction For The $t\bar{t}$ Lattice V22

- Applying horizontal and vertical random alignment errors of **10 μm** and **20 μm** truncated at 2.5 σ and random relative field errors of value **2.e-04** to the lattice **arc quadrupoles** resulted in a notable reduction in the calculated dynamic aperture (DA)







Error Correction For The $t\bar{t}$ Lattice

- After performing the orbit and tune correction, the implemented LOCO code was utilized to correct the beta beating, 3 loops of LOCO correction, the tune was recorded and corrected in between

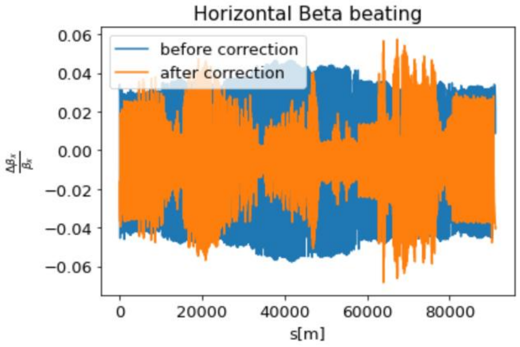
Correction	None	Orbit	LOCO
rms orbit x (μm).	31.97	15.61	15.63
rms orbit y (μm).	34.73	2.05	3.5
rms $\Delta\beta_x/\beta_x$.	16.66	3.49	1.18
ms $\Delta\beta_y/\beta_y$	17.04	11.42	1.39

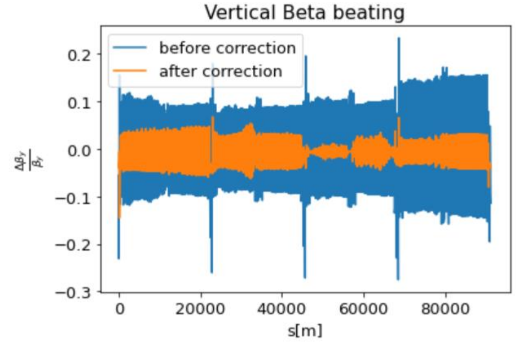
Table 2: Arc quads subjected to 10 μm alignment errors

Correction	None	Orbit	LOCO
rms orbit x (μm).	57.64	26.83	26.84
rms orbit y (μm).	106.57	6.27	8.38
rms $\Delta\beta_x/\beta_x$.	63.45	4.95	1.56
ms $\Delta\beta_y/\beta_y$	31.26	18.5	2.54

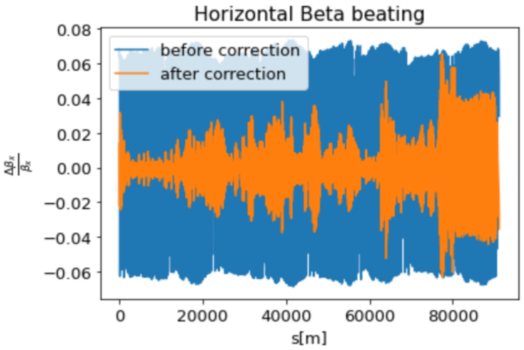
Table 3: Arc quads subjected to 20 μm alignment errors

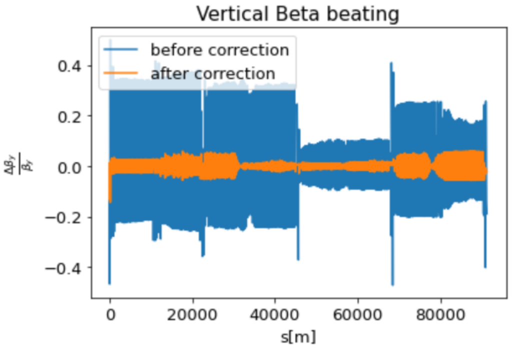
10 µm alignment errors



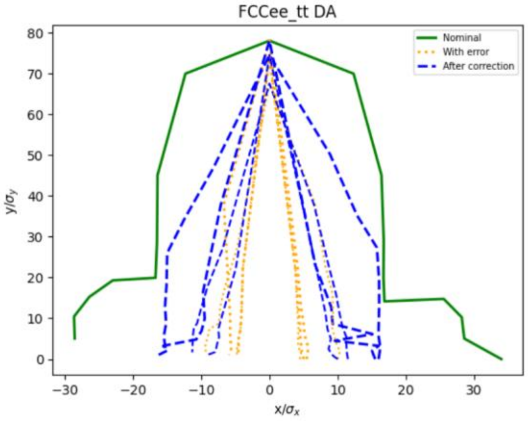


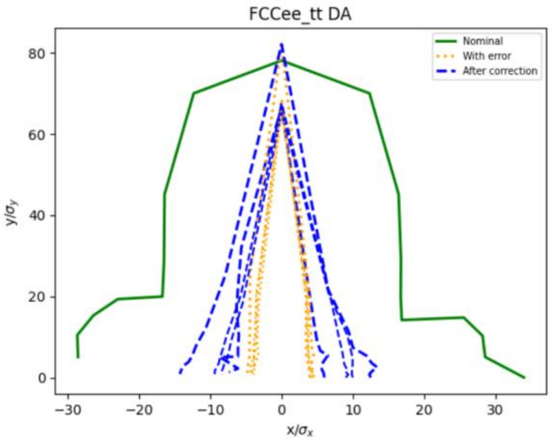
20 µm alignment errors

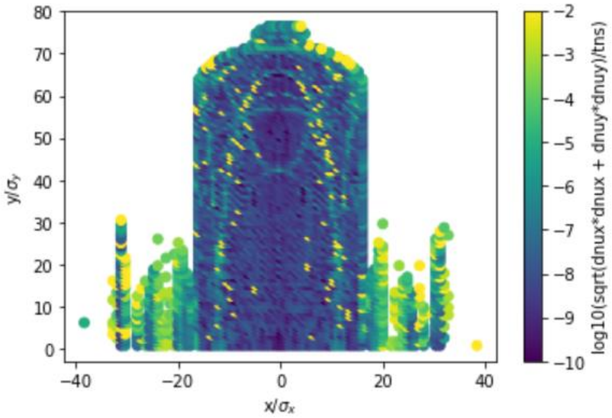




Error Correction For The $t\bar{t}$ Lattice V22







10 µm alignment errors

20 µm alignment errors

Frequency map analysis (FMA) plots shows that the resonance structure is compatible with the resulted DA after the correction chain. This provides evidence that our correction was sufficiently effective

FCCee-t-v22 DA before and after corrections for several seeds

Error Correction For The Z Lattice (FCCee_z_566_nosol_4_bb)

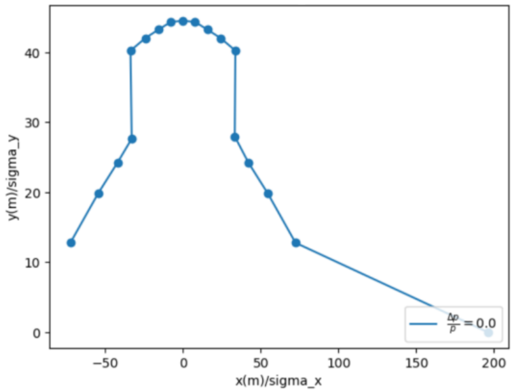
K. Oide, June 1, 2023 @ 168th FCC-ee Optics Design Meeting & 39th FCCIS WP2.2 Meeting

Parameter	Value
Beam energy [Gev]	45.6
Hor. emittance(nm)	0.71
Vert. emittance(pm)	1.4
Horizontal Tune	218.158
Vertical Tune	222.2
Chromaticities x/y	0 / +5
β_*at IP x/y (mm)	110 / 0.7

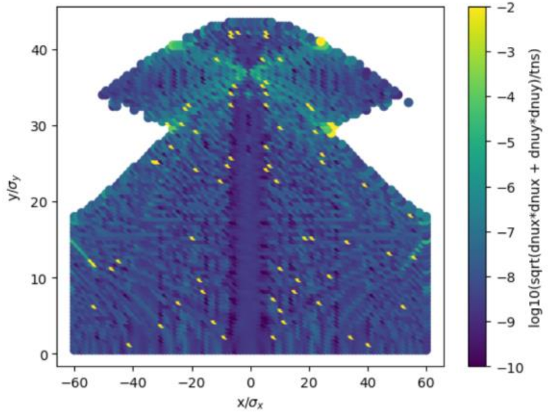
Sigma x = 8.83701052e-06

Sigma y = 3.12271638e-08

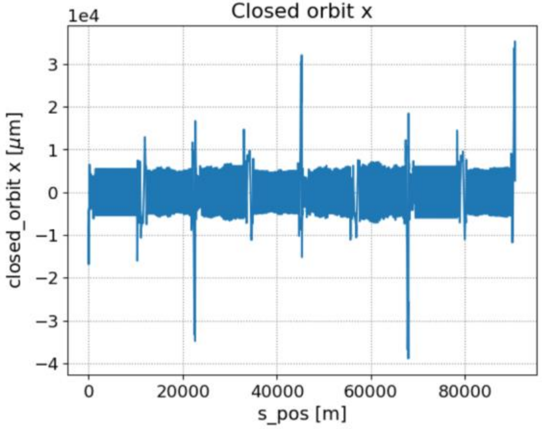
Nominal DA



FMA

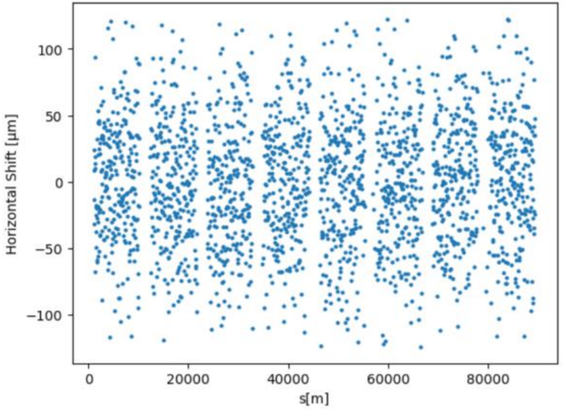


Error Correction For The *Z* Lattice (FCCee_z_566_nosol_4_bb)



Errors applied

Misaligned elements	Hor. And Ver. Shift (μm)	Rotation (μrad)
Arc Quads	50	100
Arc Sextupoles	50	100

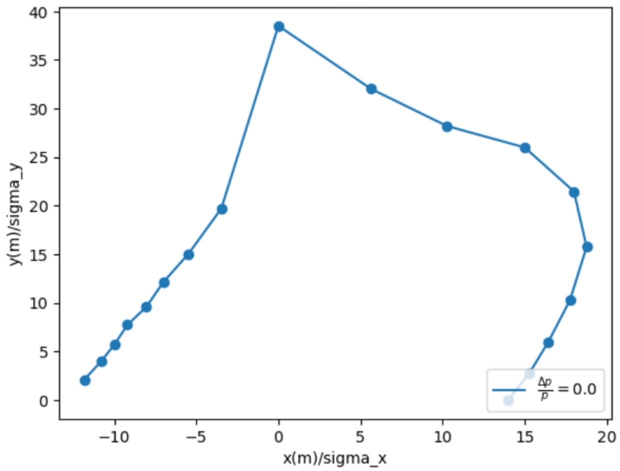


Correction	None
rms orbit x (μm)	1431.87
rms orbit y (μm)	4255.674
$\Delta\beta_x/\beta_x$	0.4132
$\Delta\beta_y/\beta_y$	0.413

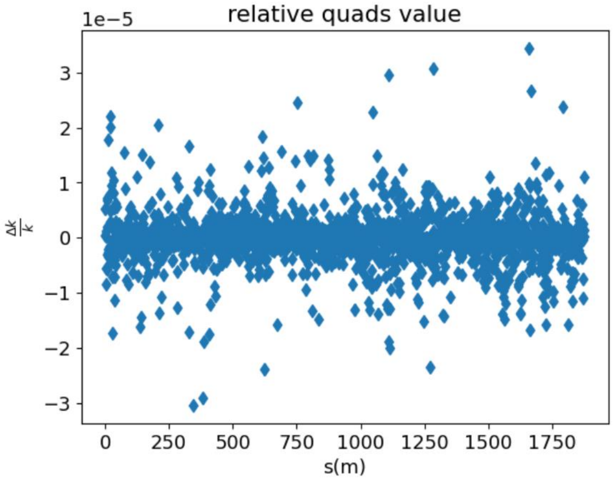
Error Correction For The Z Lattice (FCCee_z_566_nosol_4_bb)

- Orbit correction
- Switch Sextupoles ON

Correction	None	Orbit (Sext on)
rms orbit x (μm)	1431.87	38.11
rms orbit y (μm)	4255.674	24.379
$\Delta\beta_x/\beta_x$	0.4132	1.64
$\Delta\beta_y/\beta_y$	0.413	3.405

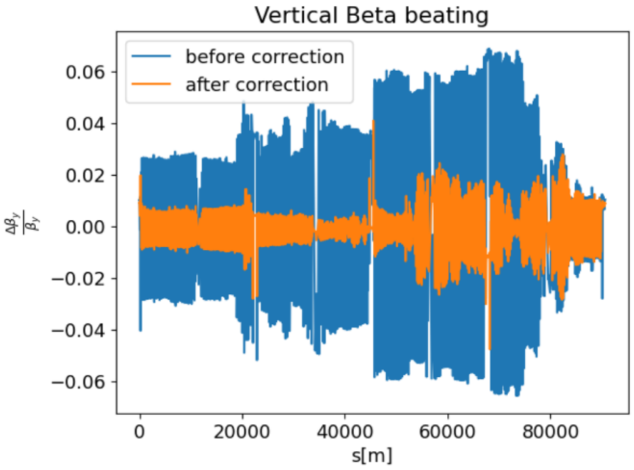


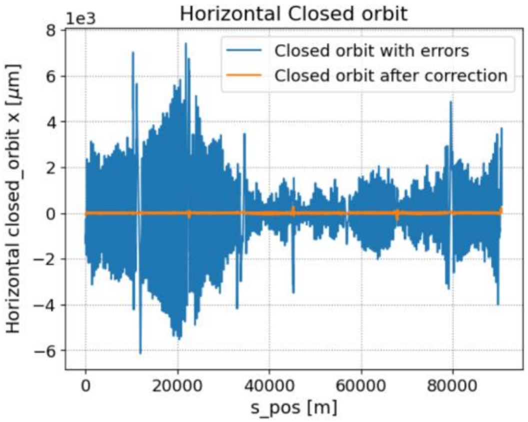
- Tune & chromaticity correction + LOCO

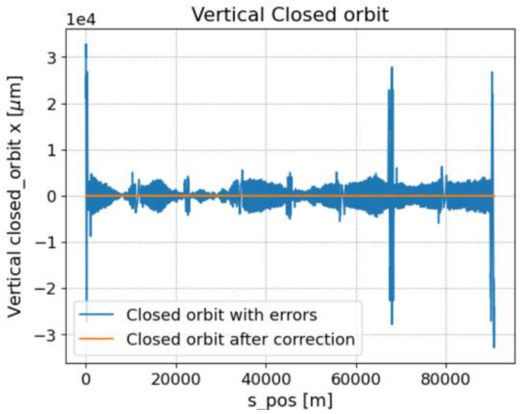


Error Correction For The *Z* Lattice (FCCee_z_566_nosol_4_bb)

Correction	None	Orbit (Sext on)	LOCO
rms orbit x (μm)	1431.87	38.11	40.18
rms orbit y (μm)	4255.674	24.379	24.19
$\Delta\beta_x/\beta_x$	0.4132	1.64	1.78
$\Delta\beta_y/\beta_y$	0.413	3.405	0.869



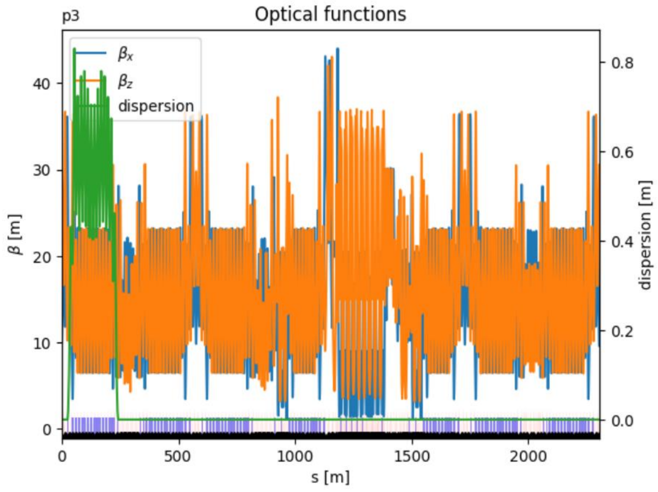




PETRA III measurements test

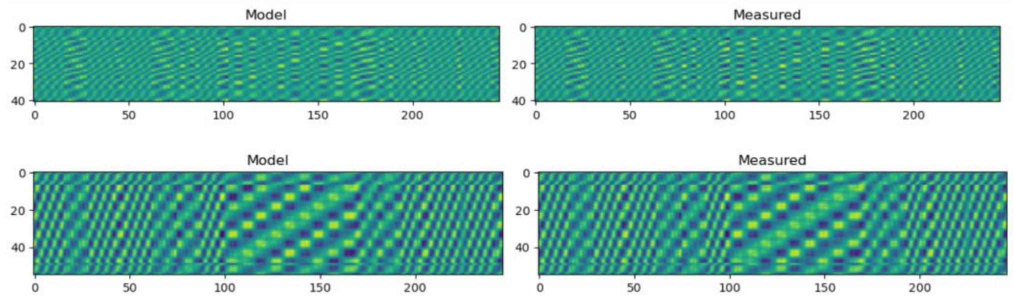
(PETRA III-High-Beta Optics p3x_v24)

- Optics errors applied to the machine quadrpoles.
- BPMs noise included
- Measurement with 41 (HCM) & 55 (VCM) correctors.
- The implemented LOCO code was utilized to generate the proper quadrpoles strengths.



Model Hor ORM of dimensions (41, 246), (55,246)

Gradient errors applied

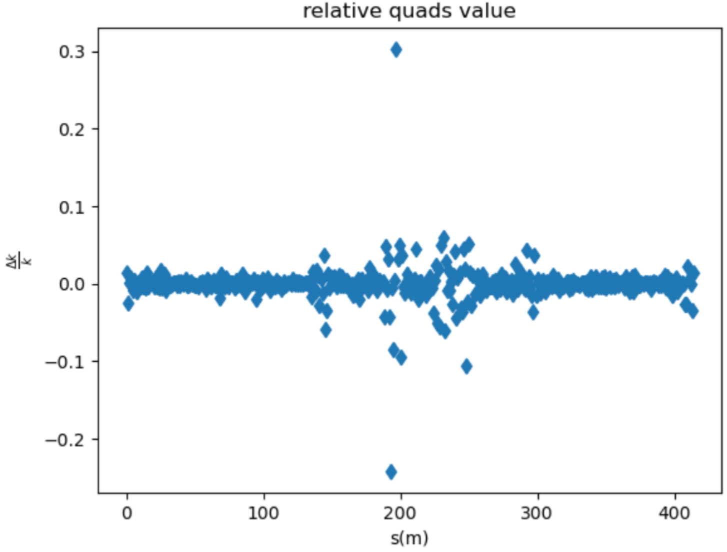


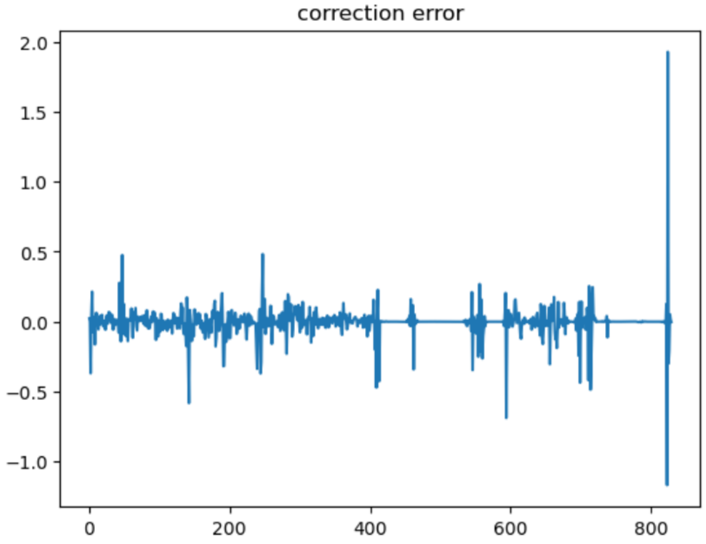
PETRA III measurements test (PETRA III-High-Beta Optics p3x_v24)

- The implemented LOCO code was utilized to generate the proper quadrpoles strengths.
- Checking the correction result (on going)

ΔK values

	0
0	0.013276
1	-0.024967
2	0.000276
3	0.008011
4	0.001428
5	-0.009158
6	0.004826
7	-0.009566
8	-0.002195
9	0.003400
10	-0.004079
11	0.007003
12	-0.004089
13	-0.003592
14	-0.004819
15	0.013691
16	-0.003835
17	0.005050
18	0.000272





Summary

- We investigated the impact of the FCCee-t-v22 and FCCee_z_566_nosol_4_bb optics arc quadruples alignment errors on the beam optics.
- The application of closed orbit-based optics correction LOCO for FCC-ee lattices is demonstrate using the Python accelerator toolbox (PyAT).
- Examples are available on :

  https://github.com/elafmusa/PyAT_LOCO_fccee/tree/main/Examples

- Reduction in the rms orbit, a decrease in beta beating, and an increase in the dynamic aperture (DA) were achieved.
- Experimental validation of the developed methods at PETRA III.

Outlook

- Including IR elements errors.
- Demonstrating the full correction chain.(on going)
- We aim to Improve the PyAT-based LOCO code to reduce the simulation consumed time, ie. reduced size LOCO, study of the required BPMs, correctors and quadruples.
- Fcc-ee performance (e.g. achievable luminosity) and the required alignment and field error tolerances will be defined in close collaboration with CERN.
- Novel approaches for optics correction such as **Bayesian** based correction will be investigated in the next.
- Experimental validation of the developed methods at PETRA III

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Thank you
for your attention.