FCC OPTICS CORRECTION STUDIES AND POSSIBLE VERIFICATION AT PETRA

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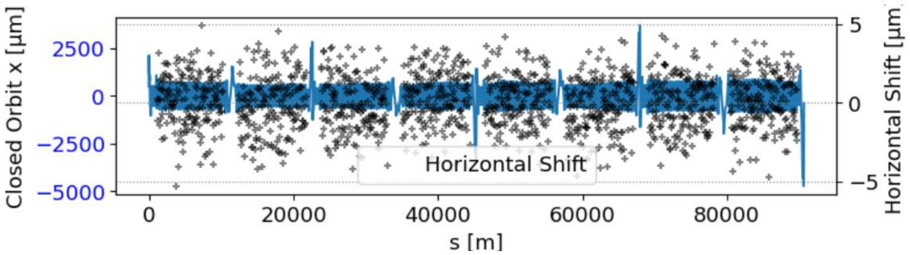
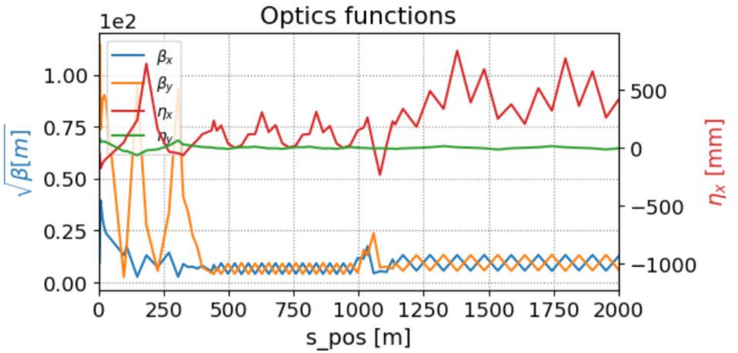
Orbit and optics corrections

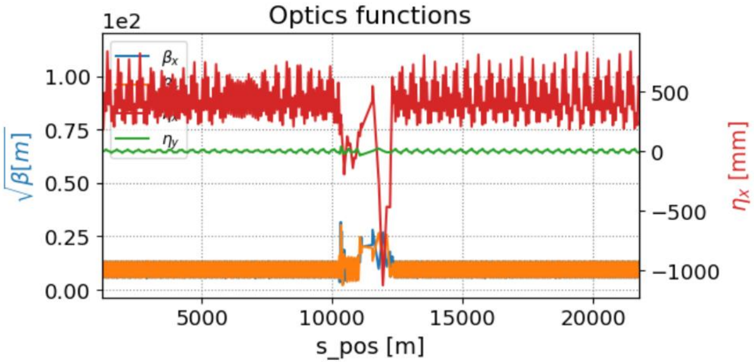
- Several corrections steps are required to achieve a well focused beam at the IPs, increasing the dynamic aperture and achieving high machine luminosity.
- Orbit and optics corrections algorithms aim to minimize the lattice errors by correcting the magnet's strength and finding the proper orbit corrector strength values.

Distortion of the horizontal closed orbit due to of 1 µm alignments of arc magnets



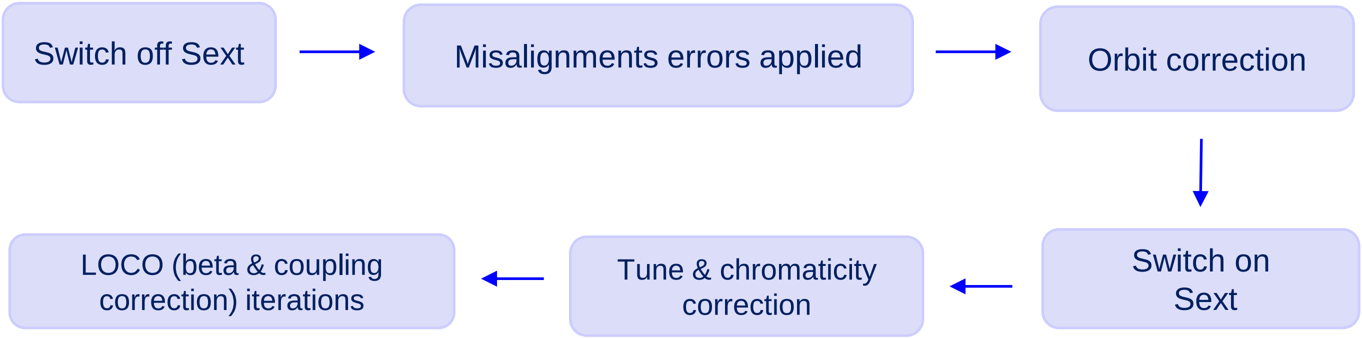
Impact of 1 µm alignments and errors of arc magnets on the IR and arc regions (sext on)





Correction procedure

- To simulate the FCC-ee optics and corrections we used the Python accelerator toolbox (PyAT)
- **Assumptions**:
  - BPMs noise = 0.0
  - Radiation off
  - Girders are not included



- One orbit corrector and one bpm added next to each quadrupole.
- One skew quadrupole added at each sextuple. (on going).

Correction procedure

Switch off Sext → Field & Misalignments errors applied → Orbit correction → Switch on Sext → Tune & chromaticity correction → LOCO (beta & coupling) iterations

- SVD used to invert the response matrix to find the proper orbit correctors kicks θ that satisfy the relation $\Delta x + C\Delta\theta = 0$. Choosing the proper cut of the singular values.

- Fitting tune and chromaticity

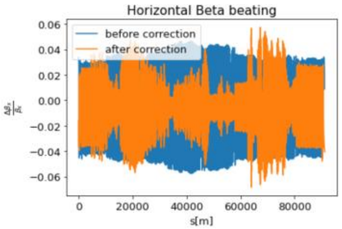
```
fit_tune(ring, QF, QD,nominal_tune )
fit_chrom(ring, DF, SD,nominal_crom)
```

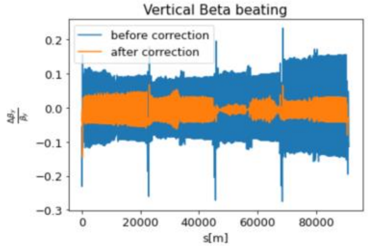
- **LOCO** $$\chi^2 = \sum_{i,j} \frac{(C_{\text{measure},i,j} - \hat{C}_{i,j})^2}{\sigma_i^2}$$
  - Calculating the Jacobian matrix: Each column of the Jacobian $J = \sum_k \frac{\partial C_{i,j}}{\partial g_k}$ matrix is the derivative of the residual vector over one Fitting Parameter.
  - 20 correctors where used.
  - Parallel processing in DESY maxwell cluster
    J (1876, 20, 1876) ~ 15 min
  - Non linear least square minimization.

Previous study on V22 $t\bar{t}$ lattice

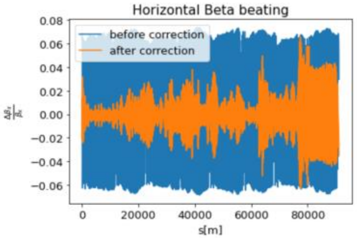
- Applying horizontal and vertical random alignment errors of **10 µm** and **20 µm** truncated at 2.5 σ and random relative field errors of value **2.e-04** to the lattice **arc quadrupoles**
- 3 Iteration of LOCO correction, the tune was recorded and corrected in between

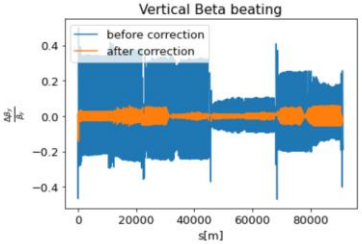
10 µm alignment errors



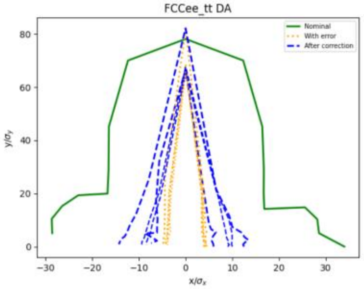


20 µm alignment errors

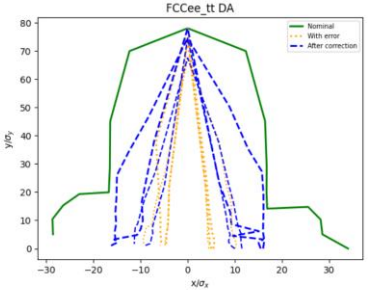




20 µm alignment errors



10 µm alignment errors



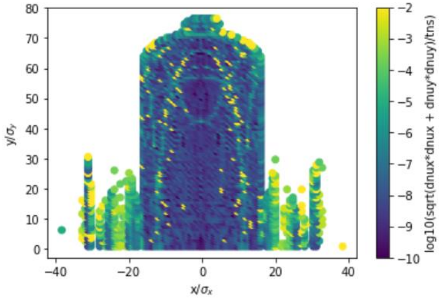
FCCee-t-v22 DA before and after corrections for several seeds

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



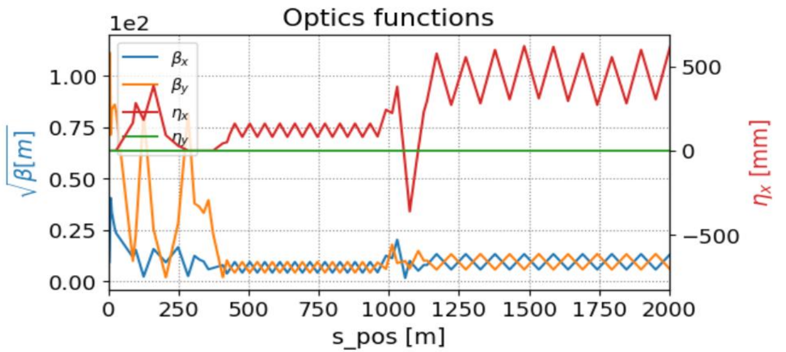
Frequency map for the ideal lattice

Used lattice Fcc-ee V22 Z FODO arc lattice

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

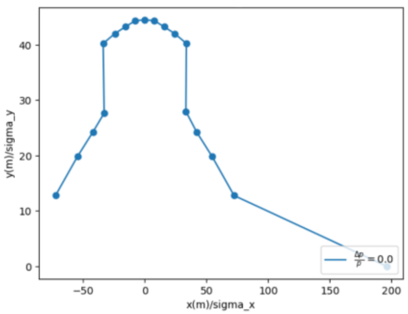
Parameter (unit)	E [Gev]	εh (nm)	εv (pm)	Q_x	Q_y	ξx/y	β_*at IP x/y (mm)
Value	45.6	0.71	1.4	218.16	222.2	0 / +5	110/0.7

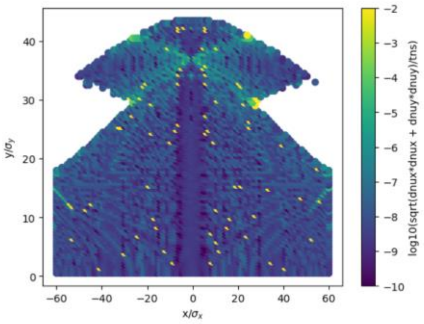
(456) IR quadrbols and (64) IR sextupoles.



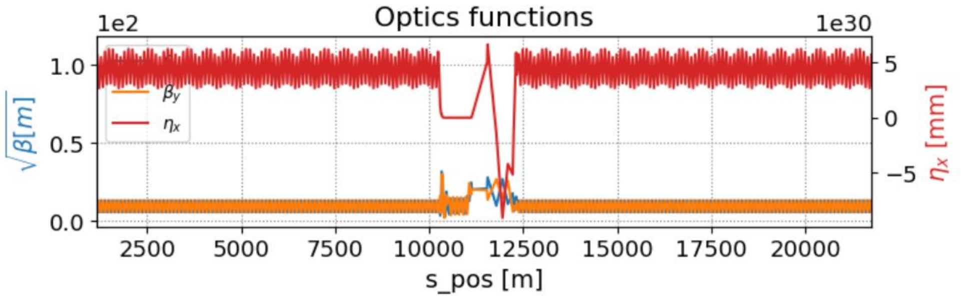
DA of Fcc-ee V22 Z lattice at the IP

Sigma x = 8.84e-06 Sigma y = 3.12e-08





(1420) arcs quadrbols and (568) arcs sextupoles.



Impact of alignments errors on arc components

- Appling hor & ver displacement and 3 angles rotations randomly distributed via a Gaussian distribution, truncated at 2.5 sigma to **arc quadrupoles, sextuples**

Misaligned elements	Hor. And Ver. Shift (μm) tilt (μrad)
Quads	**10,20**
Sextuples	**10,20**

Errors (μm) & (μrad)	rms orbit x (μm)	rms orbit y (μm)	$\Delta\beta x/\beta x$ % (sext on)	$\Delta\beta y/\beta y$ % (sext on)	$\Delta\ \eta x$ (mm)	$\Delta\ \eta y$ (mm)
10 (seed1)	1787.184	646.373	0.436	0.626	4388.37	41892.71
20 (seed1)	1404.5	4018.9	0.863	0.826	5997	127571
20 (seed2)	1221.6	3502.25	1.168	1.414	3247	121153
20 (seed3)	2194.0	1422.3	1.12	0.614	5160.	45696
20 (seed4)	602.86	2090.51	1.7318	1.3597	919.5	65640

Correction result with beam beam simulation Lifetrac by Dmitry Shatilov

Errors (μm) & (μrad)	rms orbit x (μm)	rms orbit y (μm)	Δβx/βx % (sext on)	Δβy/βy % (sext on)	Δ ηx (mm)	Δ ηy (mm)	Eh (nm)	Ev (pm)	**(lifetrac) Ev (pm) Without Beam Beam**	**(lifetrac) Ev (pm) Beam Beam**
10 (seed1)	2.69	2.55	0.155	0.325	60.47	7.44	0.721	1.065	0.77	1.52
20 (seed1)	5.8178	4.917	0.335	0.348	55.71	32.18	0.7177	0.901	0.96	33.4
20 (seed2)	5.4903	5.663	0.774	1.094	61.08	3.143	0.7172	5.196	3.92	10.8
20 (seed3)	5.6538	7.205	0.583	1.406	56.26	5.304	0.717	2.0243	2.00	6.29
20 (seed4)	5.987	4.903	0.323	0.893	61.07	16.59	0.720	1.661	1.44	8.70

With Radiation and tapering

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

Larger maslignments on arc magnets

- Without radiation.
- Appling hor & ver displacement errors and 3 angles rotations randomly distributed via a Gaussian distribution, truncated at 2.5 sigma to **arc quadrupoles, sextupoles, and to the lattice dipoles.**

- Up to **60** (µm) Hor. & Ver shift errors and Rotations (µrad) to **arc magnet** while the **sextupoles OFF.**

- Up to **1** (µm) Hor. & Ver shift errors and Rotations (µrad) to **arc magnet** while the **sextupoles 100% ON.**

Misaligned elements	Hor. And Ver. Shift (µm)	Rotation (µrad) (Roll/Pitch/Yaw)
Quadrupoles	10,20,,..60	10,20,,..60
Sextuples	10,20,,..60	10,20,,..60
Dipoles	10,20,,..60	10,20,,..60 (Only Roll)

Impact of alignments errors on arc components and dipoles

- coupling and dispersion were not corrected

<20 seeds> Errors (μm) & (μrad)	rms orbit x (μm)	rms orbit y (μm)	Δβx/βx % (sext on)	Δβy/βy % (sext on)	Δ ηx (mm)	Δ ηy (mm)	Eh (nm)	Ev (pm)
10	1660.64	1852.96	2.868	1.1769	8372.5	95190.9	-	-
Corrected	0.9509	1.215	0.268	0.238	7.829	18.094	0.0026	2.0487
20	2405.49	4668.72	4.199	4.256	9491.0	184837	-	-
Corrected	8.619	11.676	1.420	1.531	21.1526	18.061	0.01497	11.033
30	4499.84	4449.24	7.7149	7.1481	33826.24	348549	-	-
Corrected	17.02	19.53	4.855	4.913	46.799	24.719	0.1341	39.398

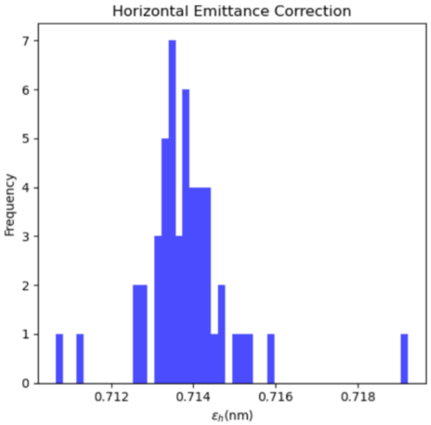
Impact of alignments errors on arc components and dipoles

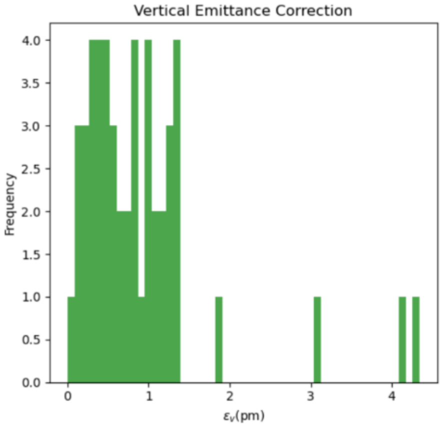
- coupling and dispersion were not corrected

<20 seeds> Errors (μm) & (μrad)	rms orbit x (μm)	rms orbit y (μm)	Δβx/βx % (sext on)	Δβy/βy % (sext on)	Δ ηx (mm)	Δ ηy (mm)	Eh (nm)	Ev (pm)
40	4558.61	9721.86	8.90295	8.38948	32810.6	374301.8	-	-
Corrected	26.984	37.89	5.1846	5.333	60.51	36.53	0.165	50.1196
50	5898.9	9059.81	9.90	9.358	41165.948	709196.7	-	-
Corrected	26.984	41.305	5.606	5.62	163.11	42.28	2.071	127.69
60	8446.4	15690.1	11.533	11.318	66069.7	864452	-	-

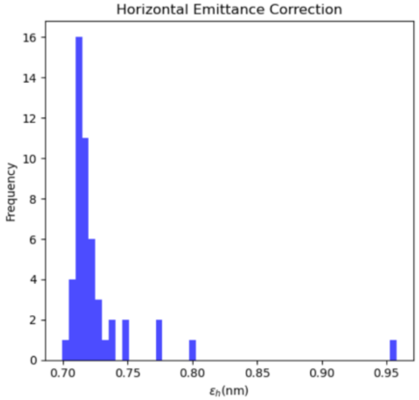
Emittances after correction

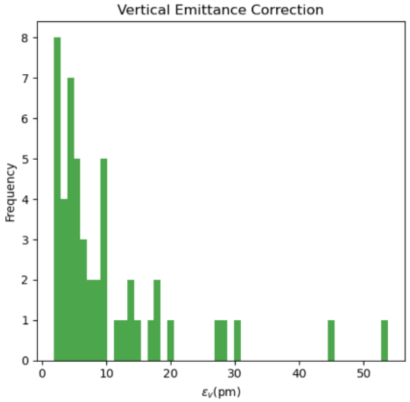
Correction of 20 hor and ver **shift errors**





Correction of 20 hor and ver **shift errors** & **rotations**



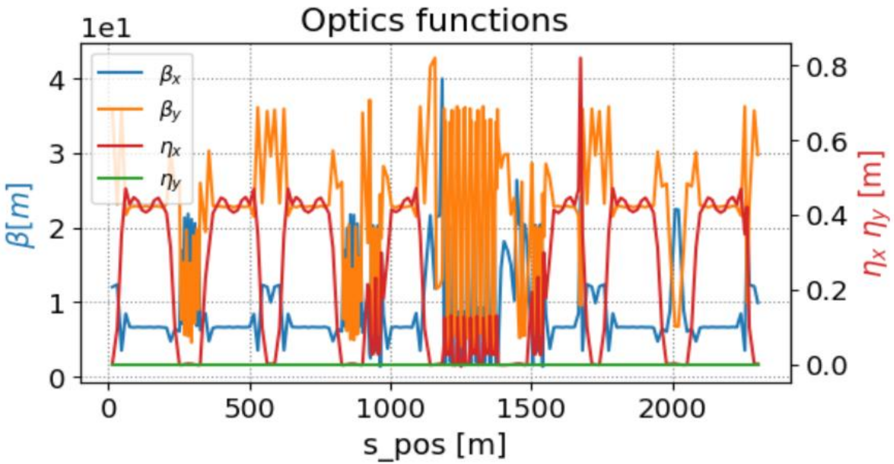


Possible verification at PETRA

PETRA III at DESY

PETRA history :

- 1979 – 1986: e+e-collider (up to 23.3 GeV / beam)
- 1988 – 2007: pre-accelerator for HERA (p @ 40 GeV, e @12 GeV)
- Since 2009: Dedicated 3rd generation light source PRTA III one of the brightest storage ring X-ray sources in the world

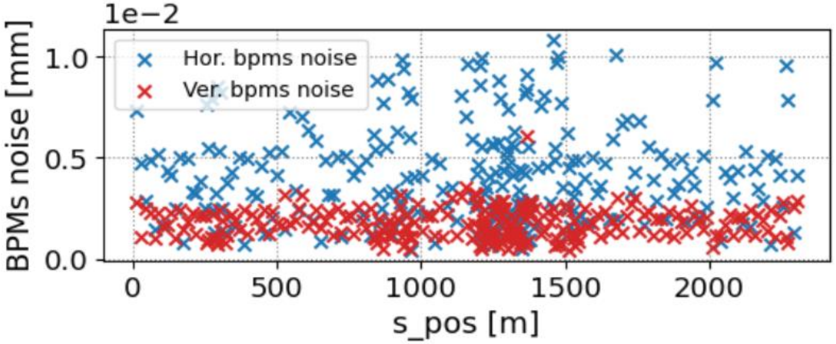


Parameter	Value
Beam energy [Gev]	6.0
Circumference (m)	2304
Eh (nmrad)	1.2
Ev (pmrad)	12
Current (mA)	100
Qx/Qy	37.128/30.27

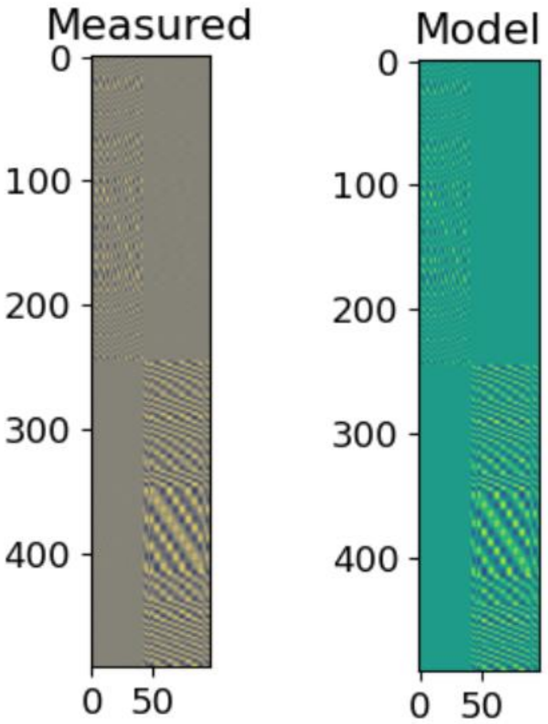
Optics correction at PETRA III

(PETRA III-High-Beta Optics p3x_v24)

- The lattice has **246 BPMs, 620 Correctors**, **4446 Dipoles**, and **417 quadrupoles**.
- Measurement was with all corrector magnets of type **PKH (41)** and **PKV(55)**.
- Optics errors were introduced by changing **4 quadrupoles. BPMs noise** included



Orbit response matrices

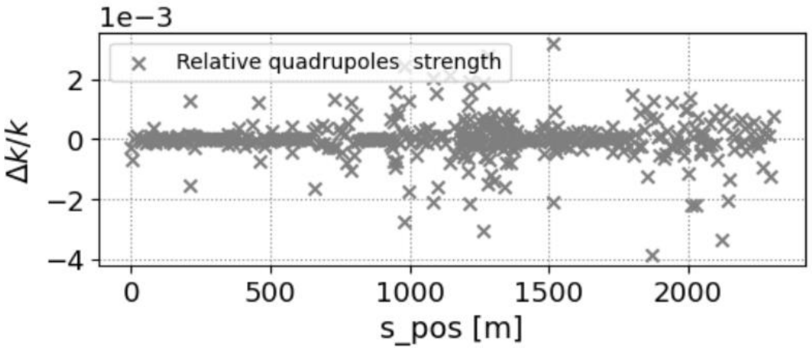


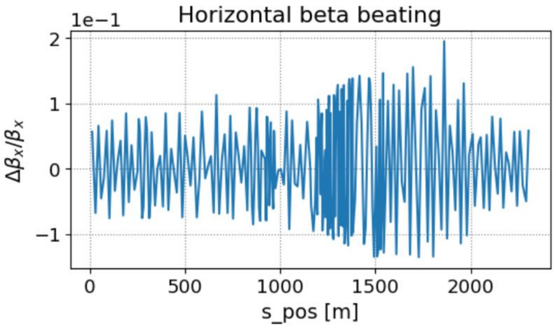
PETRA III measurements test

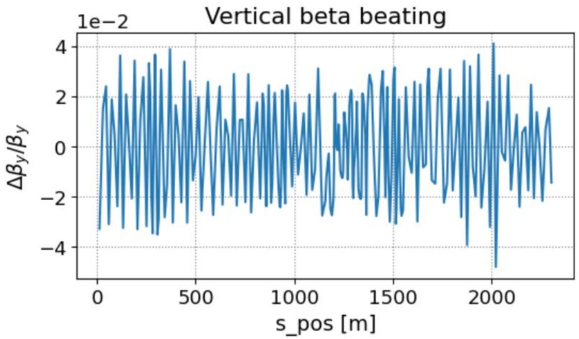
(PETRA III-High-Beta Optics p3x_v24)

- 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.

Summary

- Analysis of the Fcc-ee V22 Z Lattice correction has been performed.
- Common code based on PyAT for Fcc-ee and PETRA has been developed.

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

- Results have been integrated with beam-beam interactions, highlighting the need for further studies.
- IR misalignments to be further implemented.
- First test at PETRA.

Work ongoing

- Coupling and dispersion correction.
- Larger misalignments, possible additional correction steps.
- HFD lattice

References

[1] J. Safranek, "Experimental determination of storage ring optics using orbit response measurements," Nucl. Inst. And Meth. A388, pp. 27-36, 1997.
[2] atcollab/at: Accelerator Toolbox (github.com)
[3] K.Oide,June1,2023@168th FCC-ee Optics Design Meeting&39th FCCISWP2.
[4] https://github.com/fscarlier/xsequence
[5] K. Balewski, “Commissioning of PETRA III”, IPAC’10.

THANK YOU FOR YOUR ATTENTION

BACK UP SLIDES

Linear Optics from Closed Orbits (LOCO)

Established at NSLS by J.
Safranek, 1996

The response matrix is the shift in orbit at each BPM for a change in strength of each steering magnet.

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

The measured data are fitted to a lattice model by adjusting parameters P in iterations

$$\chi^2 = \sum_{i,j} \frac{(C_{\mathrm{measure},i,j} - \hat{C}_{i,j})^2}{\sigma_i^2}$$

$$\mathbf{\Delta}\mathrm{C} = \frac{d\Delta C}{dK_j}\Delta K_j + \frac{d\Delta C}{d\theta_j}\Delta\theta_j + \frac{d\Delta C}{dG_j}\Delta G_j + \frac{d\Delta C}{d(\Delta p/p)_j}\Delta(\Delta p/p)_j$$

$$\boldsymbol{\delta h}_{\mathrm{gn}} = [[\boldsymbol{J}^\top \boldsymbol{W} \boldsymbol{J}]]^{-}1 \boldsymbol{J}^\top \boldsymbol{W}(\boldsymbol{C} - \hat{\boldsymbol{C}})$$

Correction procedure

Switch off Sext → Field & Misalignments errors applied → Orbit correction → Switch on Sext → Tune & chromaticity correction + LOCO iterations including coupling

LOCO

- Calculating the Jacobian matrix: $J = \sum_k \frac{\partial C_{i,j}}{\partial g_k}$ Each column of the Jacobian matrix is the derivative of the residual vector over one Fitting Parameter.

Reducing Processing Time

- Limiting the number of steering magnets in the response matrix.
  20 Cor used out of 1876
- Parallel processing in DESY maxwell cluster
  J (1876, 20, 1876) ~ 15 min

- Code profiling and optimisation.

$$\Delta g_k = \left(\sum_{ij}\sum_k \frac{\partial C_{i,j}}{\partial g_k}^T W \frac{\partial C_{i,j}}{\partial g_k}\right)^{-1}$$

```
a = np.sum(dcx[i], axis=0)
b = np.sum(dcx[j], axis=0)
Ax[i, j] = np.dot(a, b)
```

- A.Franchi S. Liuzzo and Z. Marti, Analytic formulas for the rapid evaluation of the orbit response matrix and chromatic functions from lattice parameters in circular accelerators, https://arxiv.org/abs/1711.06589

Beam Beam studies with 5 seeds

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.

$\nu_x / \nu_y / \varepsilon_{y0} / \varepsilon_y$ [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**