PYAT FOR FCC-EE OPTICS CORRECTIONS

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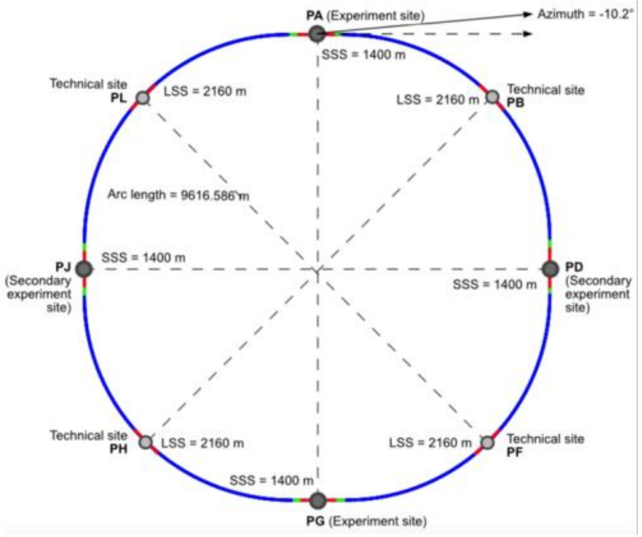
- The Future Circular Collider (FCC), with a circumference of 90 km, is one of the next planned high-performance particles colliders. aims to push the limits of the luminosity and the size of the electrons beam that can be achieved.

3064 dipoles, and 1876 quadrupoles and 632 sextupoles and other elements.



Schematic diagram of the FCC-ee [CDR 2022]

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

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	9.936			
Energy loss / turn	[GeV]	0.0394	0.374	1.89	10.42
SR power / beam	[MW]	50			
Beam current	[mA]	1270	137	26.7	4.9
Colliding bunches / beam		15880	1780	440	60
Colliding bunch population	$[10^{11}]$	1.51	1.45	1.15	1.55
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.71	1.59
Ver. emittance at collision ε_y	[pm]	1.4	2.2	1.4	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.75	1.25	0.85	0.9
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	$[10^{-6}]$	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	1000 / 1.6
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.358	398.148 / 398.182
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.089	0.070 / 0.109	0.104 / 0.143	0.160 / 0.192
Bunch length (SR/BS) σ_z	[mm]	5.60 / 12.7	3.47 / 5.41	3.40 / 4.70	1.81 / 2.17
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.091
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	2.9
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP	[mrad]	±15			
Crab waist ratio	[%]	70	55	50	40
Beam-beam $\xi_x/\xi_y{}^a$		0.0023 / 0.096	0.013 / 0.128	0.010 / 0.088	0.073 / 0.134
Lifetime (q + BS + lattice)	[sec]	15000	4000	6000	6000
Lifetime (lum)^b	[sec]	1340	970	840	730
Luminosity / IP	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	140	20	5.0	1.25
Luminosity / IP (CDR, 2IP)	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	230	28	8.5	1.8

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 in iterations

$$C_{model,i,j} = \hat{C_{i,j}} + \sum_k \frac{\partial \hat{C_{i,j}}}{\partial g_k} \Delta g_k + \hat{C_{i,j}} \Delta x^i - \hat{C_{i,j}} \Delta y^j + \sum_l \frac{\partial \hat{C_{i,j}}}{\partial p_l} \Delta p_l$$

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

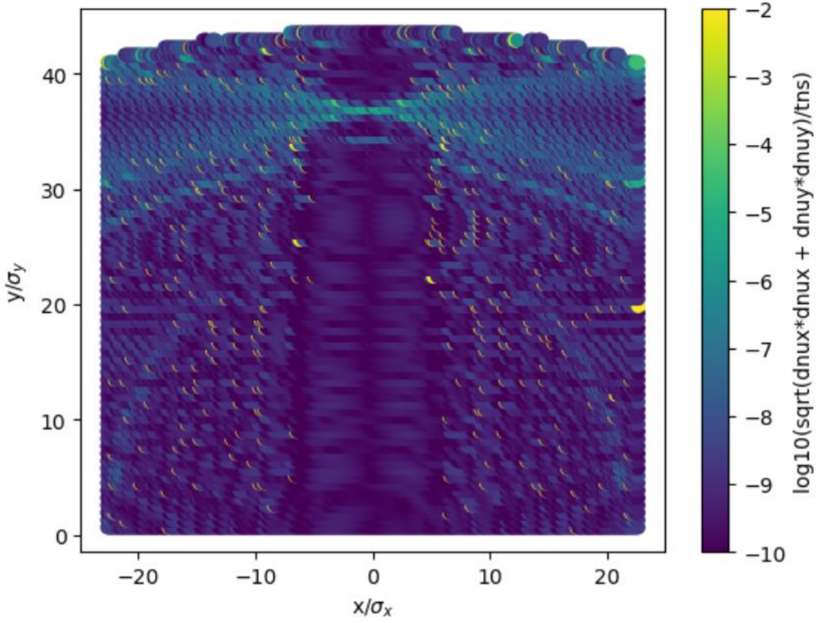
LOCO PyAT passed implementation

- To investigate the possibility of using LOCO for FCC-ee lattices we used the Python accelerator toolbox (PyAT) to implement the code and utilized it to produce preliminary results.

- **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	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



Correction procedure

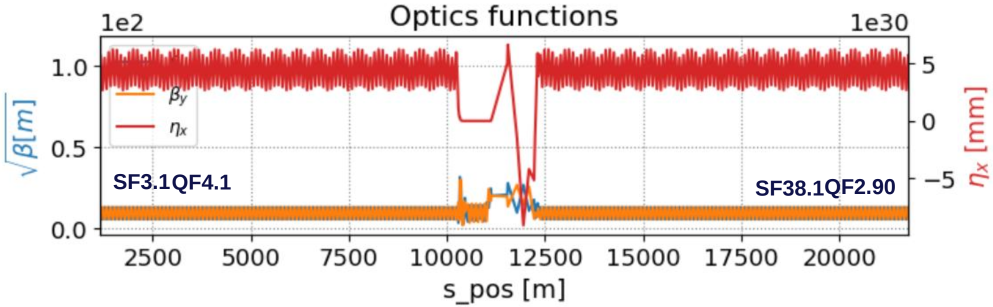
BPMS & Correctors added next to each quadrpole
BPMs noise = 0.0
Radiation off
Girders are not included

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

- Appling hor & ver displacement errors randomly distributed via a Gaussian distribution, truncated at 2.5 sigma.

```
at.shift_elem(elem: Element, deltax: float = 0.0, deltaz: float = 0.0,
relative: Optional[bool] = False)
```

- Erros applied to the lattice (1420) arcs quadrbols and (586) arcs sextupoles.



Correction procedure

BPMS & Correctors added next to each quadrpole
BPMs noise = 0.0
Radiation off
Girders are not included

Switch off Sext → Field & Misalignments errors applied → Orbit correction → Switch on Sext → Tune & chromaticity correction + LOCO and coupling correction in 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 the tune and chromaticity

```
fit_tune(ring, get_refpts(ring, 'QF*’), get_refpts(ring, 'QD*'),nominal_tune )
fit_chrom(ring, get_refpts(ring, 'SF*’), get_refpts(ring, 'SD*'),nominal_crom)
```

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 response matrix 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

Results

<5 seeds>	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)	$\varepsilon_h/\ \varepsilon_v$
Error **10** (μm)	418.931	544.047	0.12211	0.1789	1970.62	20753.3	
Correction	0.1682	0.0602	0.011	0.0516	1.601	3.3234	3329.4
Error **30** (μm)	1153.82	2978.86	0.255	0.6494	2178.39	6048.73	
Correction	0.7433	0.490	0.1291	0.355	6.77	14.79	426.098
Error **50** (μm)	2173.02	5174.996	0.400	0.7294	11039.5	187679	
Correction	3.066	3.481	0.154	0.4273	7.576	15.813	213.262

LOCO in the Python library for simulated commissioning of synchrotrons

- Work on fully Integration of LOCO on the Python library for simulated commissioning is ongoing.
- LOCO has been tested using test lattice and the Fcc-ee V22 Z lattice.
- LOCO modules will be available in the Python Simulation Commissioning correction package

  pySC.correction.loco_modules

LOCO in the Python library for simulated commissioning of synchrotrons

Generating Jacobian

```
generatingJacobian(SC, C_model, CMstep, CorOrds, SC.ORD.BPM, concatenate(quadsOrds),
Individuals=True,  dk, debug=True, trackMode='ORB', useIdealRing=False,skewness = False,
order=1, method='add', includeDispersion=False, rf_step=RFstep, cav_ords=CAVords)
```

Measured ORM

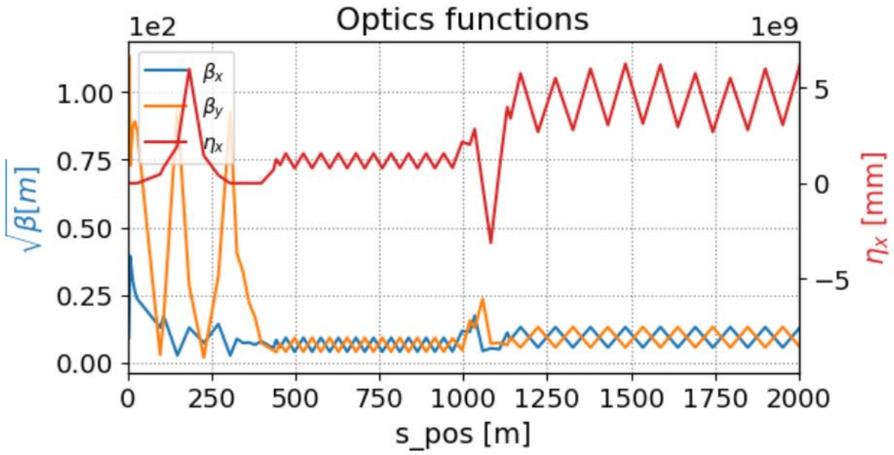
```
SCgetMeasurRM(SC, BPMords, CMords, trackMode, dkick) ➡ bpm_reading
```

Minimization problem & obtaining the fit parameters $\chi^2 = \sum_{i,j} \frac{(C_{model,i,j} - \hat{C_{i,j}})^2}{\sigma_i^2}$

Setting correction

```
SC.set_magnet_setpoints(SC, quadOrds, -r, skewness = False, order, method)
```

(Fcc-ee V22 Z lattice example)



enable_6d()
Setting the cavity parameters
Tapering

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	$\Delta k/k = 2 \times 10^{-4}$

lattice optics with errors (1 seed):

Δβx/βx: 9.2141%
Δβy/βy: 38.2045%
Δηx: 12.3859
Δηy: 2.6723e-12 mm
Tune: [218.162, 222.209, 0.0288]
Chromaticity: [0.1294, 5.2607, -0.0246]

(Fcc-ee V22 Z lattice example)

LOCO 1st iteration:

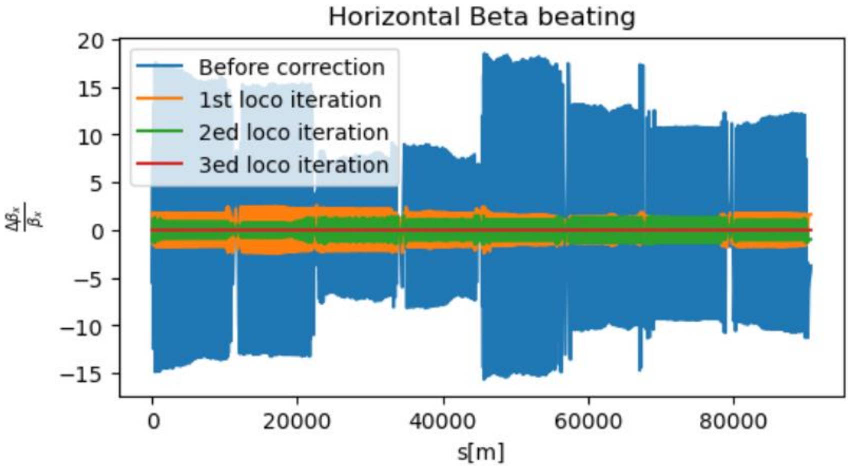
Δβx/βx: 1.4666%
Δβy/βy: 7.4342%
Δηx: 3.4701
Δηy: 8.0814e-12 mm
Tune: [218.1584, 222.1786]
Chromaticity: [0.03895, 5.0126]

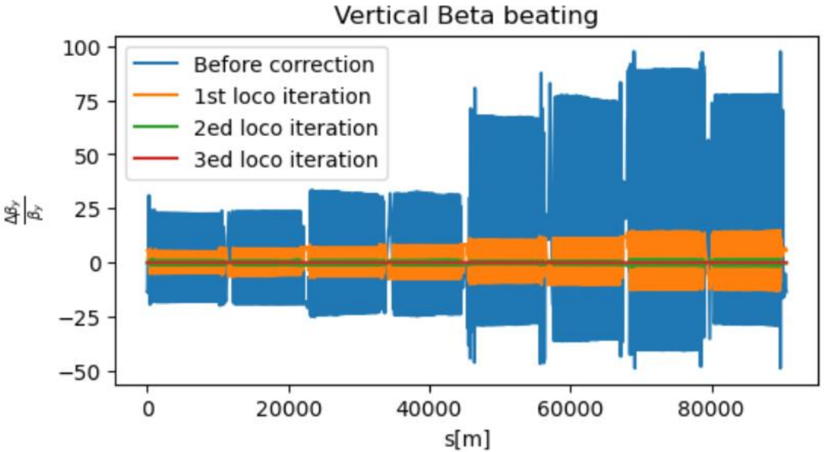
LOCO 2ed iteration:

Δβx/βx: 0.9190%
Δβy/βy: 0.8944%
Δηx: 2.8573
Δηy: 3.4580e-12 mm
Tune: [218.1569, 222.2036]
Chromaticity: [-0.0257, 5.2638]

LOCO 3ed iteration:

Δβx/βx: 0.6136%
Δβy/βy: 0.2899%
Δηx: 3.1049
Δηy: 3.2505e-12 mm
Tune: [218.1574, 222.2000]
Chromaticity: [0.0268, 5.2584]



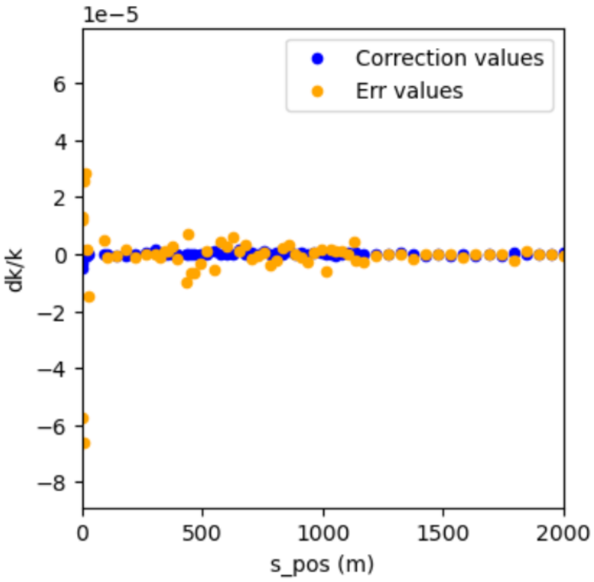


(Fcc-ee V22 Z lattice example)

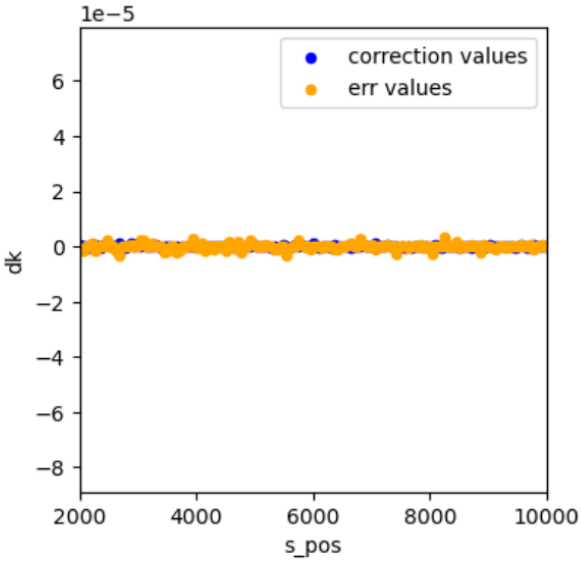
Type	Field Errors
Arc quadrupole	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	$\Delta B/B = 1 \times 10^{-4}$
IR quadrupole	$\Delta k/k = 1 \times 10^{-4}$
IR sextupoles	$\Delta k/k = 2 \times 10^{-4}$

<5 seeds>	Δβx/βx %	Δβx/βx %
With Error	**6.4694**	**18.3786**
Correction	**2.261**	**3.724**

IP



Arc



Summery

- The impacts of the arc elements alignment errors on the beam optics of the Fcc-ee V22 Z Lattice were investigated.
- The application of closed orbit-based optics correction LOCO for FCC-ee lattice was implemented using the Python accelerator toolbox (PyAT).
- LOCO in the Python Simulation Commissioning with test results.

Outlook

BPMs noise = 0.0
Radiation off or On with field errors
Girders are not included

→

Including BPMs noise
Radiation ON with misalignment & field errors (demonstrating the full correction chain)
Girders included
Complete table of errors

- Including the BPM gains and steering magnet calibrations

$$C_{model,i,j} = \hat{C_{i,j}} + \sum_k \frac{\partial \hat{C_{i,j}}}{\partial g_k} \Delta g_k + \hat{C_{i,j}} \Delta x^i - \hat{C_{i,j}} \Delta y^j + \sum_l \frac{\partial \hat{C_{i,j}}}{\partial p_l} \Delta p_l$$

- Novel approaches for optics correction such as Bayesian based correction will be investigated in the next.

THANK YOU FOR YOUR ATTENTION