

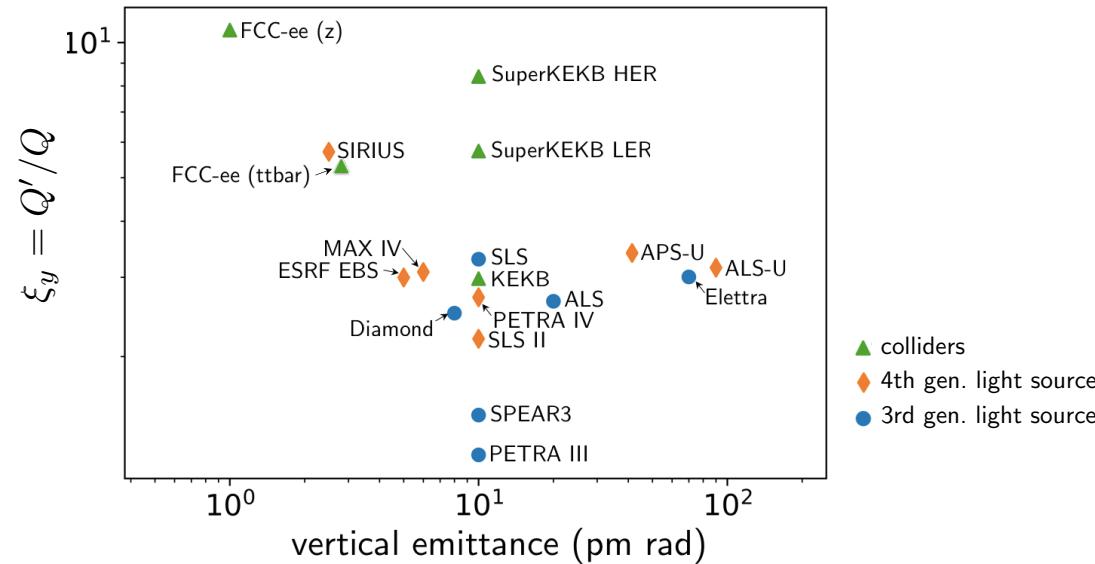
OPTICS CORRECTION

Tessa Charles ^{1,2}, Bernhard Holzer ³, Katsunobu Oide ³, Dmirty Shatilov, Frank Zimmermann ³
Rogelio Garcia ³, Leon Van Riesen-Haupt ³ and the FCC-ee optics team

1. University of Liverpool,
2. Cockcroft Institute
3. CERN



Natural chromaticities for a range of low emittance storage rings



Many thanks to:

Rohan Dowd (AS), Masamitsu Aiba (PSI), Katsunobu Oide (KEK), Thorsten Hellert (ALS), Ilya Agapov (DESY), Pedro Fernandes Tavares (MAX IV), Kent Wootton (APS), Bastian Häger (KIT), Liu Lin (LNLS), Simone Di Mitri (Elettra), Jeff Corbett (SLAC), Bernhard Holzer (CERN), Ian Martin (Diamond), David Amorim (SOLEIL)

Correction tools

Orbit correction:

- MICADO & SVD from MAD-X
 - Hor. corrector at each QF, Vert. corrector at each QD
1598 vertical correctors / 1590 horizontal correctors
 - BPM at each quadrupole
1598 BPMs vertical / 1590 BPMs horizontal

Vertical dispersion and orbit:

- Orbit Dispersion Free Steering (DFS)

$$\begin{pmatrix} (1-\alpha)\vec{y} \\ \alpha\vec{D}_y \end{pmatrix} = \begin{pmatrix} (1-\alpha)\mathbf{A} \\ \alpha\mathbf{B} \end{pmatrix} \vec{\theta}$$

Linear coupling:

- Coupling resonant driving terms (RDT)
 - 1 skew at each sextupole

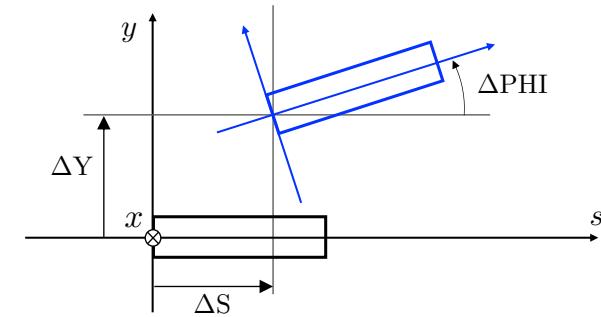
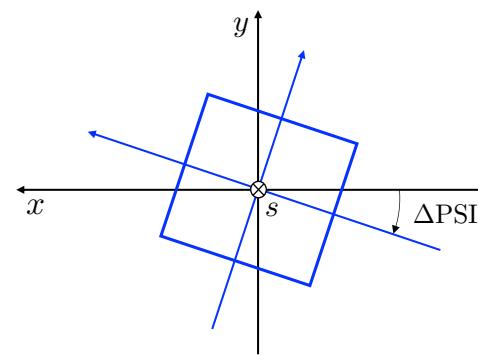
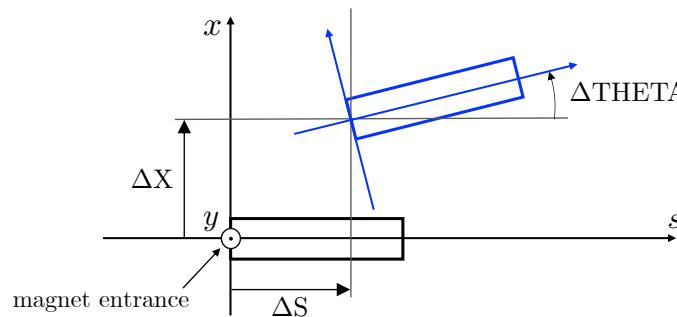
$$\begin{pmatrix} \vec{f}_{1001} \\ \vec{f}_{1010} \\ D_y \end{pmatrix} = -\mathbf{M} \vec{\mathbf{J}}$$

Beta beating correction & Horizontal dispersion via Response Matrix:

- Rematching of the phase advance at the BPMs
 - 1 trim quadrupole at each sextupole

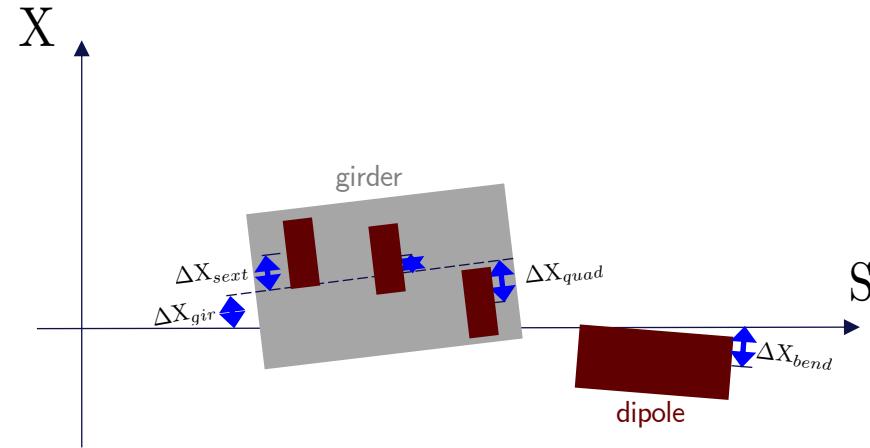
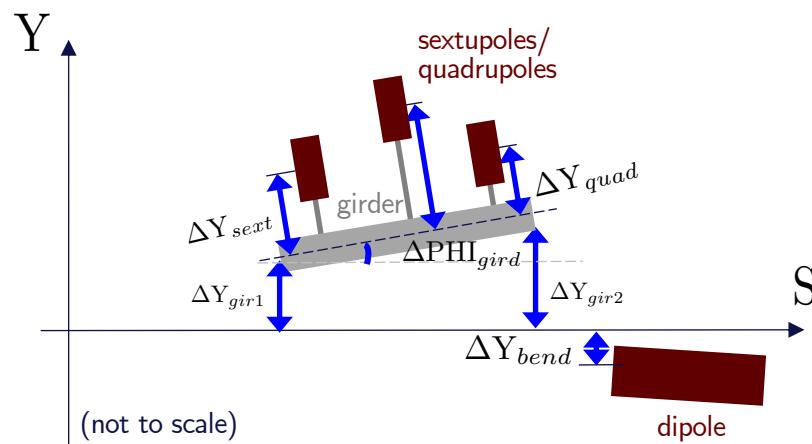
$$\begin{pmatrix} f_1 \left(\frac{\beta_1 - \beta_{y0}}{\beta_{y0}} \right) \\ f_2 \left(\frac{\beta_2 - \beta_{y0}}{\beta_{y0}} \right) \\ \dots \\ f_m \left(\frac{\beta_m - \beta_{y0}}{\beta_{y0}} \right) \end{pmatrix}_{meas} = \begin{pmatrix} f_1 (R_{11}, R_{12}, R_{13}, \dots, R_{1n}) \\ f_2 (R_{21}, R_{22}, R_{23}, \dots, R_{1n}) \\ \dots \\ f_m (R_{m1}, R_{m2}, R_{m3}, \dots, R_{mn}) \end{pmatrix} * \begin{pmatrix} k_1 \\ k_2 \\ \dots \\ k_n \end{pmatrix}$$

Assigning misalignments



- Misalignments are randomly distributed via a Gaussian distribution, truncated at 2.5 sigma.

Assigning girder misalignments



- 2 independent DX and DY misalignments for each end of the girder, and which can be used to calculate DTTHETA and DPHI.

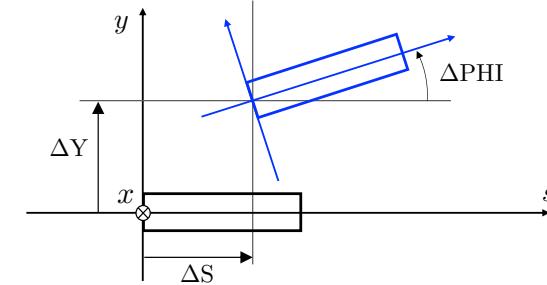
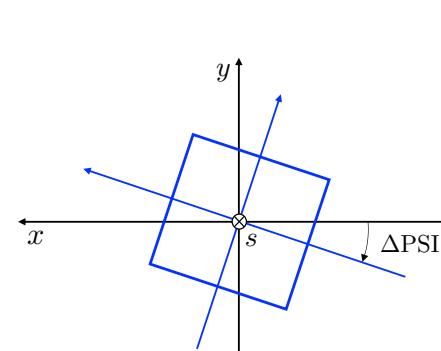
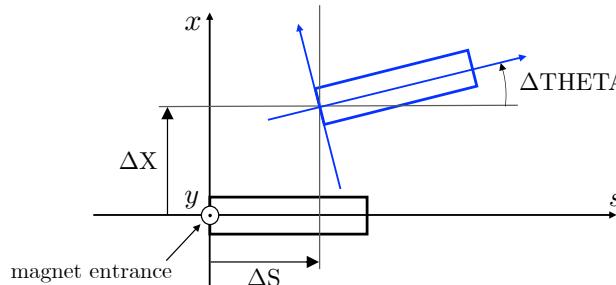
Misalignments and field errors

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)	Field Errors
Arc quadrupole*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	1000	1000	300	1000	-	-	$\Delta B/B = 1 \times 10^{-4}$
Girders	150	150	-	1000	-	-	
IR quadrupole	100	100	250	50	100	100	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	100	100	250	50	100	100	$\Delta k/k = 2 \times 10^{-4}$
BPM**	-	-	100	-	-	-	-

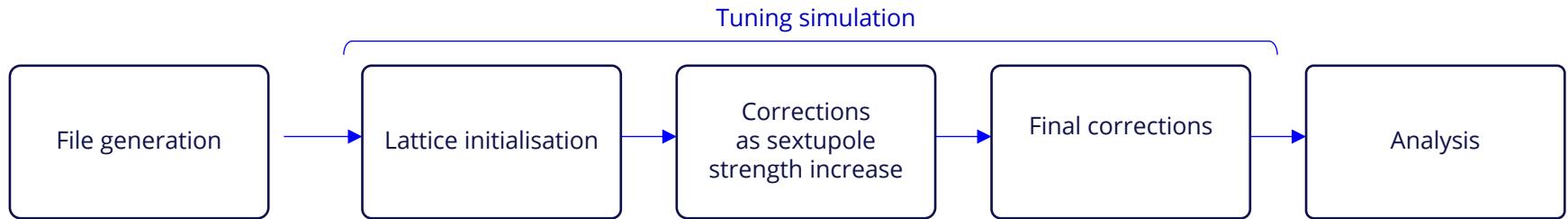
* misalignment relative to girder placement

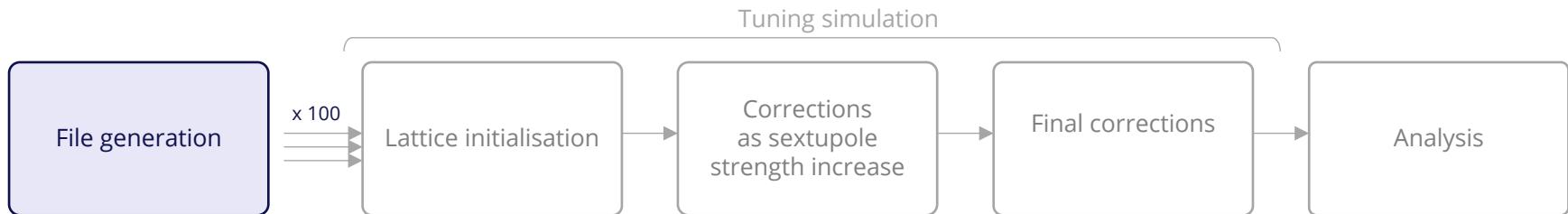
** misalignment relative to quadrupole placement

Misalignments are randomly distributed via a Gaussian distribution, truncated at 2.5 sigma.



Tuning simulations



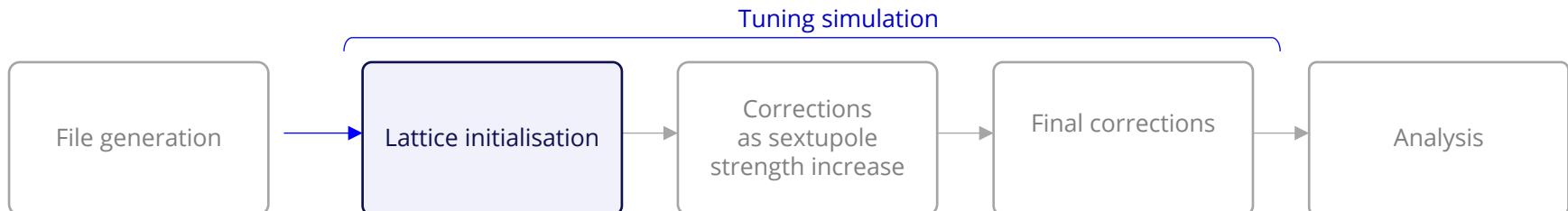
**Inputs:**

- MAD-X template file →
- Errors values (yaml file) →
- Bash template
(for HT condor submission) →

Python simulation configuration
(specify number of seeds [default 100])

**generates**

- 100 madx files,
- 100 bash files, and,
- 1 HT condor submission file



File generation

Correction macros defined
Insert bpms, correctors, skew quads, trim quads.

VOLTCA1 = 0.0; VOLTCA2 = 0.0;
Sextupoles turned off

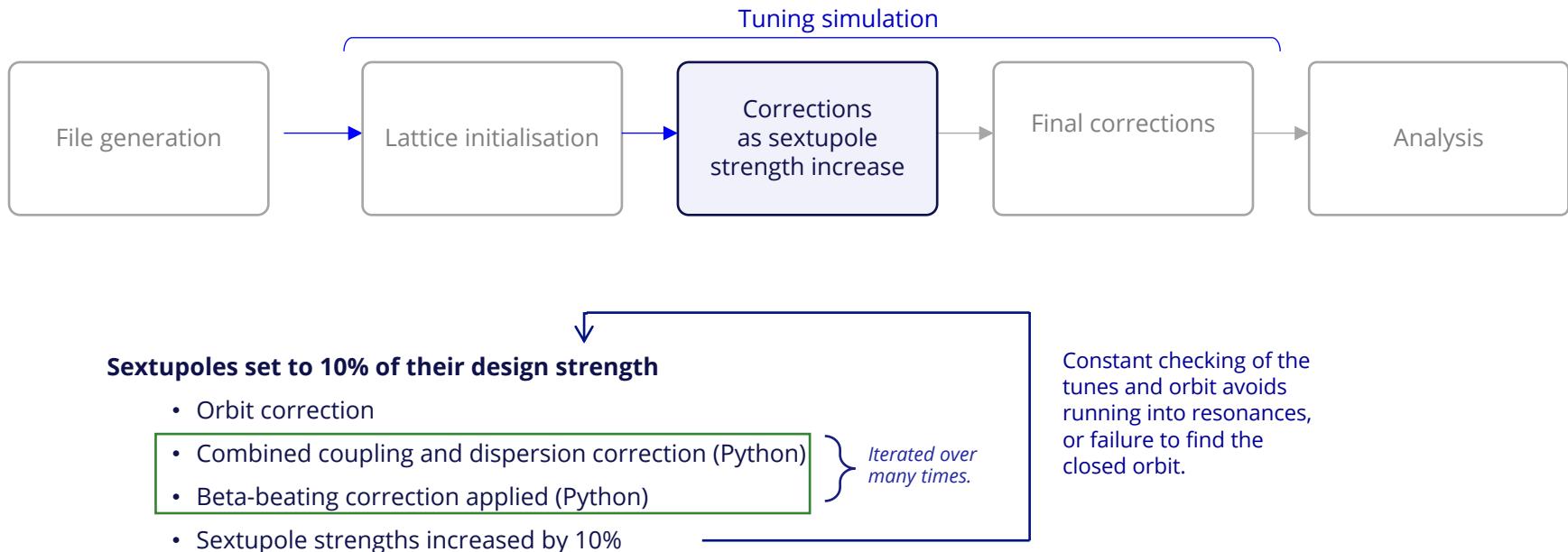
Introduce field errors
Beta beating correction (Python)

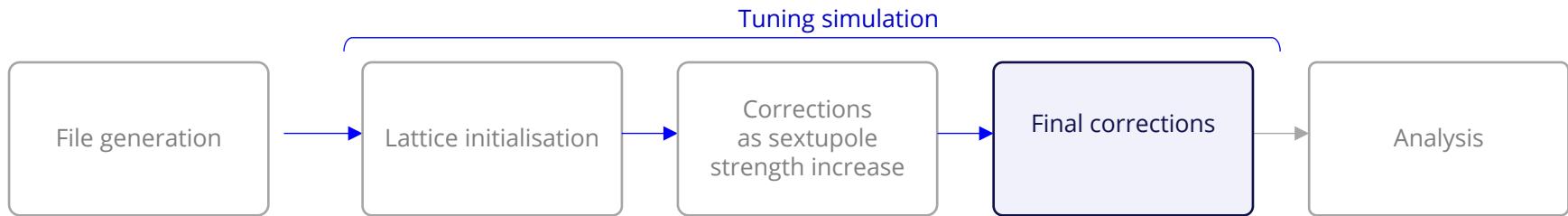
Introduce arc misalignments
Girder misalignments (Python)
Add BPM roll angle (rotation of coordinate system before and after BPM) (Python)

Corrections applied:
tune re-matched
orbit correction
beta-beat correction (Python)
coupling correction (Python)

Introduce IR misalignments

Further correction:
tune re-matched, orbit correction, beta-beat correction, and coupling and dispersion correction





Final correction (at 100% design sextupole strength)

- Additional coupling, dispersion and beta-beating correction applied.
- Step through corrections until beta beating threshold is reached.
- Vary SV cut off values
- Chromaticity correction

Lattice sequence saved.

Lattice sequence file, error tfs file, copied to eos.

FCC-ee emittance tuning results

RMS misalignment and field errors tolerances:

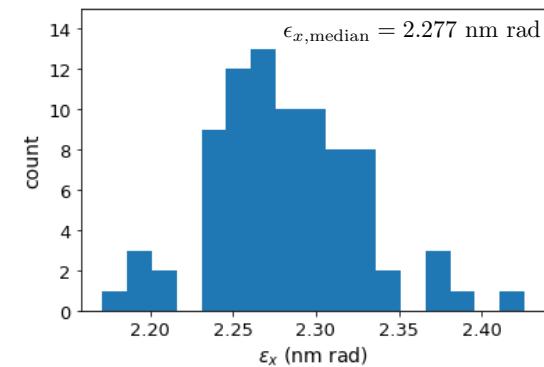
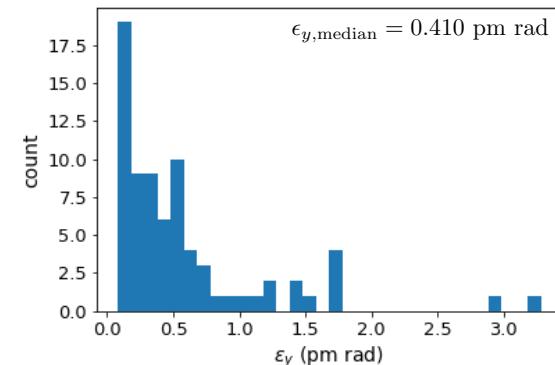
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Arc quadrupole*	50	50	300	150	100	100
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Dipoles	1000	1000	300	1000	-	-
Girders	150	150	-	1000	-	-
IR quadrupole	100	100	250	50	100	100
IR sextupoles	100	100	250	50	100	100
BPM**	-	-	100	-	-	-

* misalignment relative to girder placement

** misalignment relative to quadrupole placement

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

ttbar (182.5 GeV) 4IP lattice,
after correction strategy:



FCC-ee emittance tuning results

RMS misalignment and field errors tolerances:

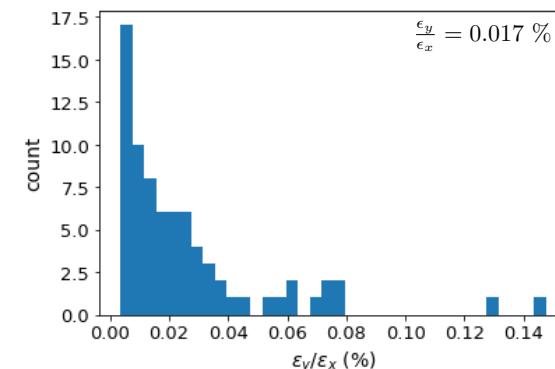
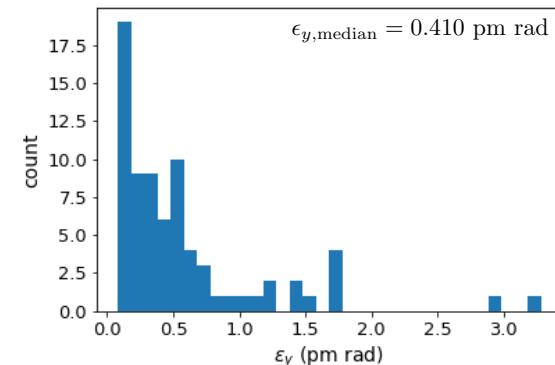
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BPM**	-	-	100	-	-	-

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ttbar (182.5 GeV) 4IP lattice,
after correction strategy:



FCC-ee emittance tuning results

RMS misalignment and field errors tolerances:

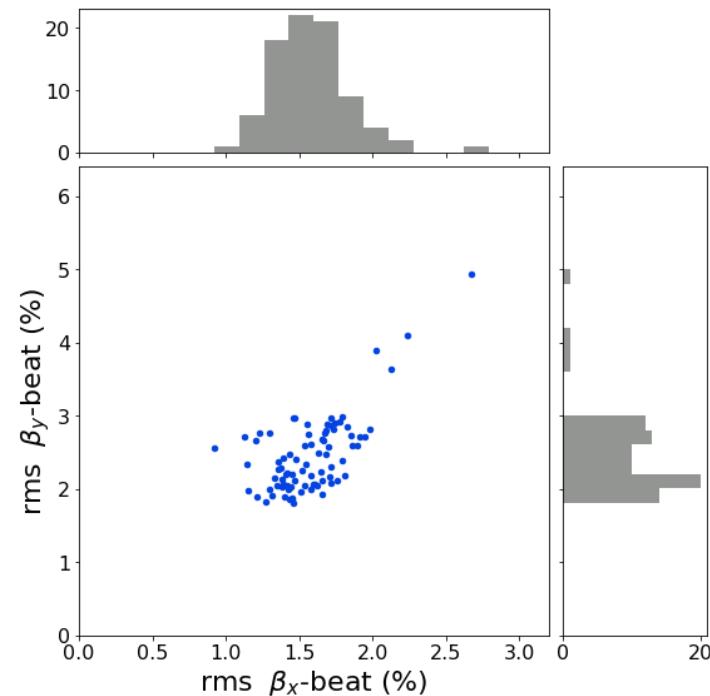
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Girders	150	150	-	1000	-	-
IR quadrupole	100	100	250	50	100	100
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BPM**	-	-	100	-	-	-

* misalignment relative to girder placement

** misalignment relative to quadrupole placement

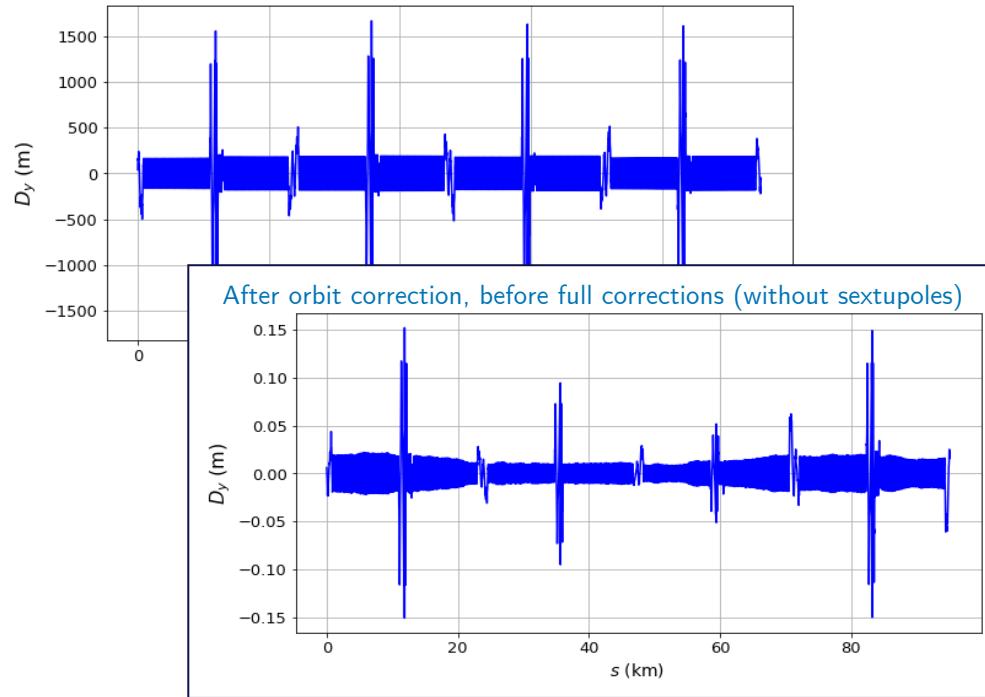
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Dipoles	$\Delta B/B = 1 \times 10^{-4}$
Girders	
IR quadrupole	$\Delta k/k = 2 \times 10^{-4}$
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ttbar (182.5 GeV) 4IP lattice,
after correction strategy:

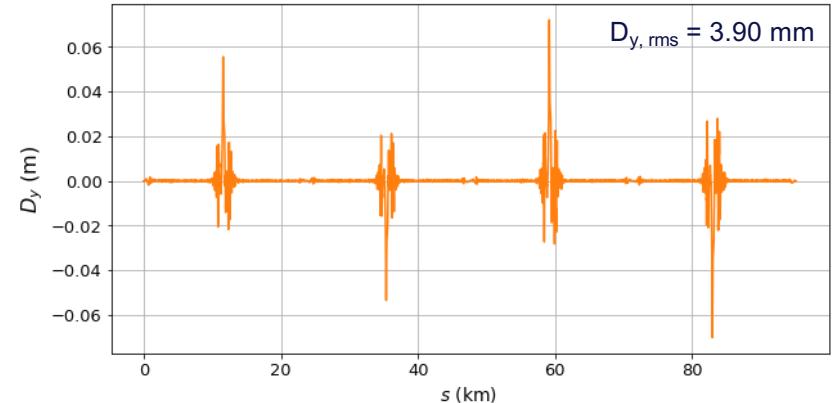


Vertical dispersion

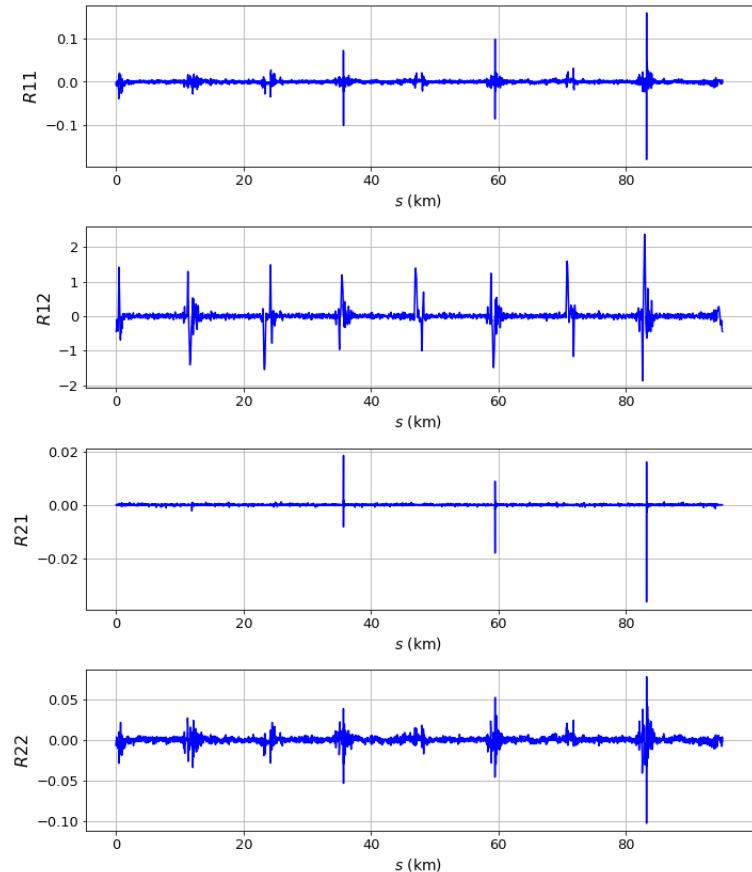
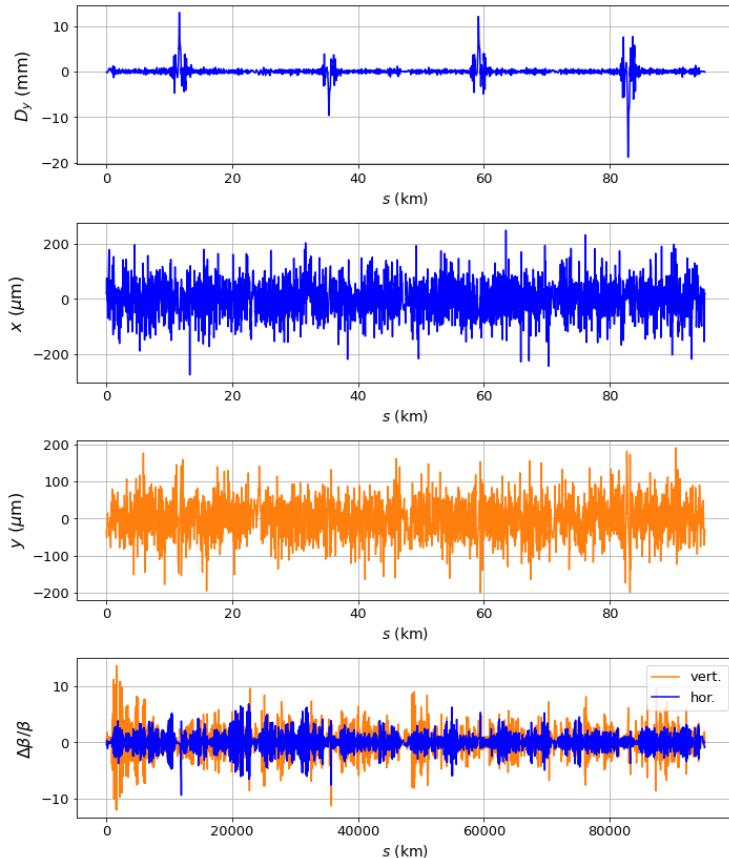
Before correction
(without sextupoles)



After full global correction
(with sextupoles)



After corrections, ttbar 4 IP lattice:



Still to do... (there are many things)

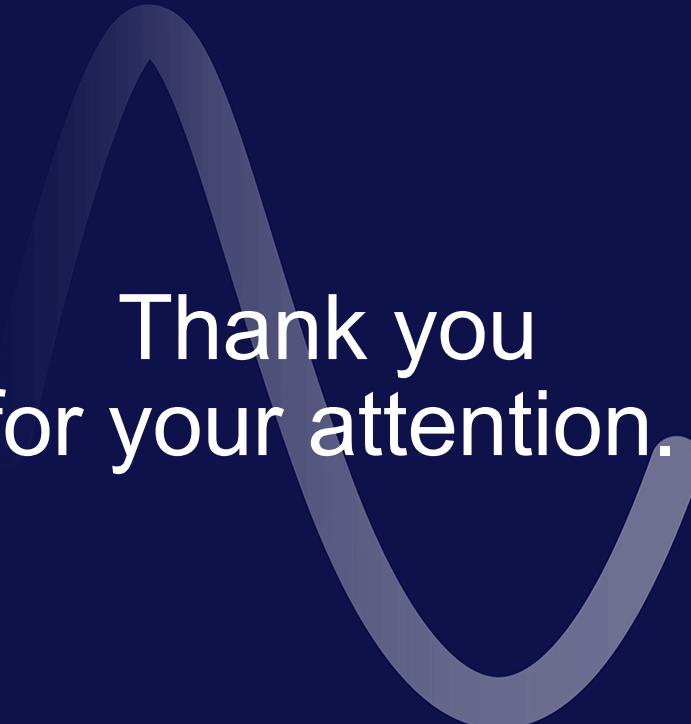
- Establish the most realistic modelling for BPM errors and resolution (e.g. non-linear responses, calibration measures for rotated BPMs, non-Gaussian BPM offset distributions, BPM orthogonality)
- DA calculation with chromaticity correction
- Solenoid imperfections to be considered
- Tapering imperfections
- IP local corrections and elsewhere (e.g. SY sextupoles)
- Non-linear corrections: lifetime, DA, chromatic aberrations, amplitude detuning, RDTs, etc.
- Design of global knobs for control of fundamental parameters e.g.: Tunes, chromas, coupling, chromatic coupling, amp. det., etc.
- Profiling simulation and look towards speeding up algorithm
- Simulate optics measurements
- BPM resolution to be included
- Apply correction technique to low energy, Z lattice
- Determine how to apply measure optics quickly
 - LOCO could be too slow on such a large machine
 - AC dipole method may run into problems due to strong damping
- Simulation of commissioning process

Summary

In a simulation campaign, we systematically studied a wide combination of magnet tolerances for field errors, alignment of individual magnets as well as girders.

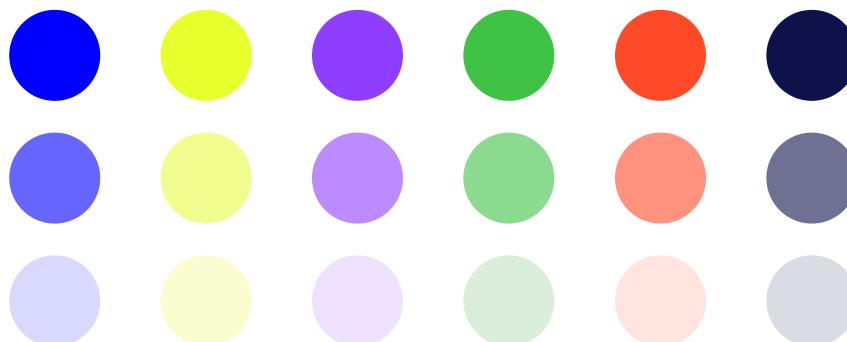
The correction algorithms developed in this context represent a powerful correction tools and lead to successful convergence for a large majority of the applied errors seeds. And, most importantly, the lead to values of coupling and emittances that lie within the requirements of the machine design. For a standard set of misalignments, the final median vertical emittance achieved is 0.410 pm rad and horizontal emittance of 2.277 nm rad.

This work is ongoing.



Thank you
for your attention.

COLORS



Radiant Blue

Flash

Energy

Green

Red

Deep Blue

BACKGROUNDS

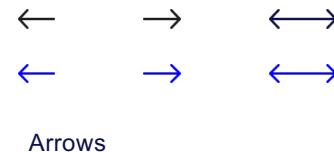


Use for Layout

GRAPHICAL ELEMENTS



Separation lines 1.5
pt

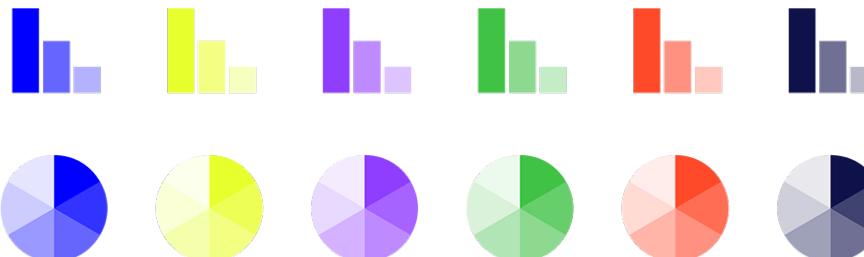


BADGES



Use blue badges on light backgrounds

INFOGRAPHICS



Use light badges on dark backgrounds