OPTICS TUNING AND ORBIT CORRECTION STUDIES FOR FCC-EE

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Rogelio Tomas [3], Leon Van Riesen-Haupt [5], **and the entire FCC-ee optics team**

1. University of Liverpool; 2. Cockcroft Institute; 3. CERN; 4. KEK; 5. EPFL

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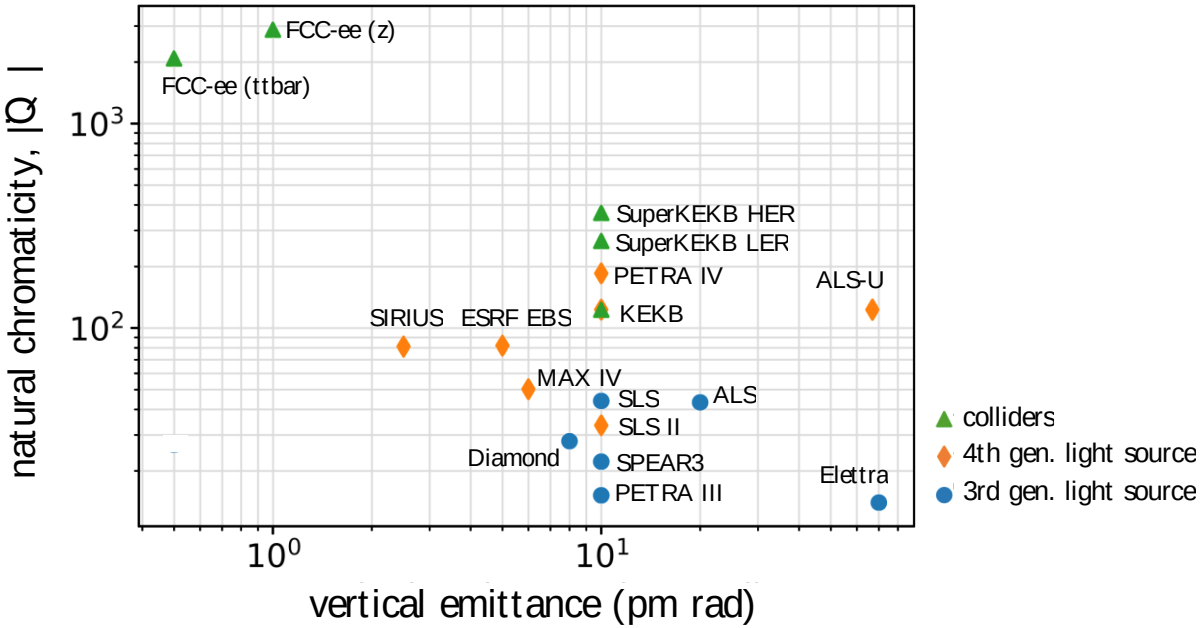
Natural chromaticities for a range of low emittance storage rings



Many thanks to:

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

Context

“Given the size of the FCC-ee, we will not be able to perform standard alignment and to use standard techniques in such a machine: we will need alignment sensors at least for the girders of the arcs quadrupoles and sextupoles. So ***applying a factor 2 on tolerances should not increase the cost by two.”*** - H. Mainaud Durand

“[Increasing the alignment tolerances will ...] increase the cost of the positioning system, but it must be compared with the total cost of the collider. If the total cost increases by a few percent, and the luminosity by fifty, then it probably makes sense.” - D Shatilov

- FCC-ee tuning & alignment mini-workshop 11 & 12 May 2022

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

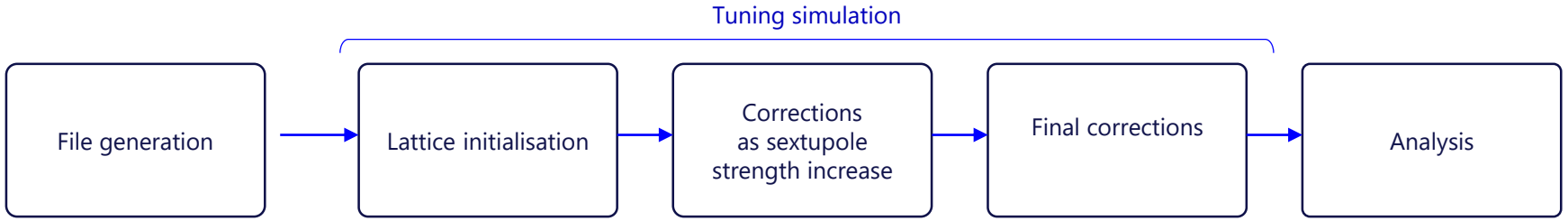
$$\begin{pmatrix} \vec{f}_{1001} \\ \vec{f}_{1010} \\ D_y \end{pmatrix} = -\mathbf{M}\,\vec{\mathbf{J}}$$

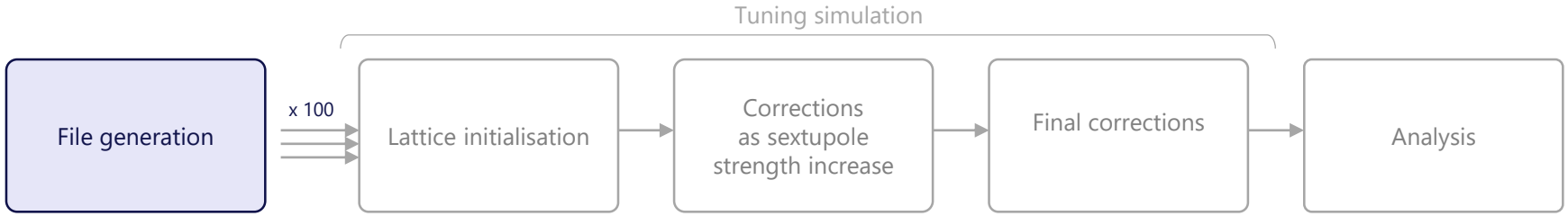
Beta beating correction & Horizontal dispersion via Response Matrix:

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

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

Tuning simulations



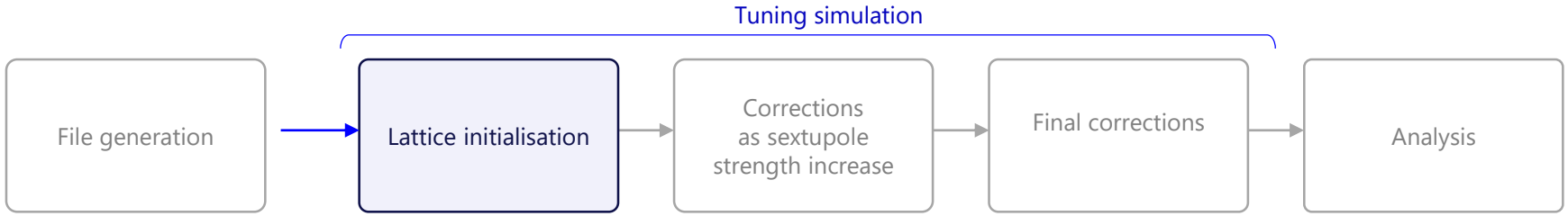


Inputs:
- MAD-X template file
- Errors values (yaml file)
- Bash template

(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



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

Beam energy = 1 GeV; radiation = off;
VOLTCA1 = 0.0; VOLTCA2 = 0.0;

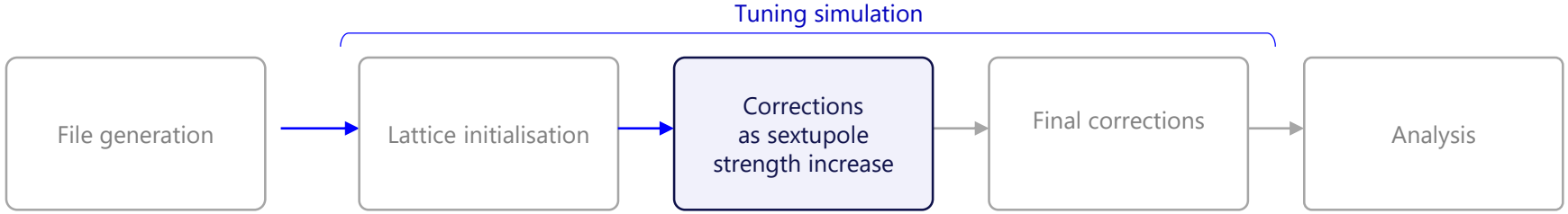
Sextupoles turned off
Introduce field errors
Beta beating correction (Python)

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



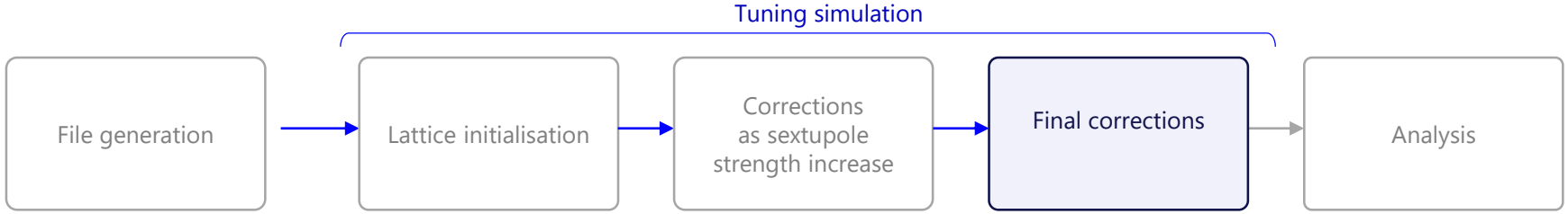
Sextupoles set to 10% of their design strength

- Orbit correction
- Combined coupling and dispersion correction (Python)
- Beta-beating correction applied (Python)

Iterated over many times.

- Sextupole strengths increased by 10%

Constant checking of the tunes and orbit avoids running into resonances, or failure to find the closed orbit.



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.

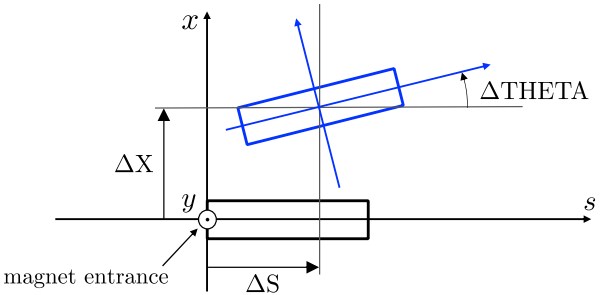
Misalignments and field errors

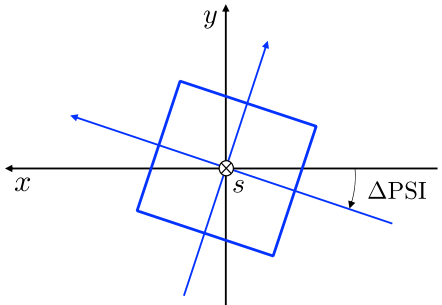
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔDTHETA (μrad)	ΔDPHI (μrad)	Field Errors
Arc quadrupole*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	1000	1000	300	1000	0	0	$\Delta B/B = 1 \times 10^{-4}$
Girders	150	150	-	1000	-	-	-
IR quadrupole	100	100	250	250	100	100	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	100	100	250	250	100	100	$\Delta k/k = 2 \times 10^{-4}$

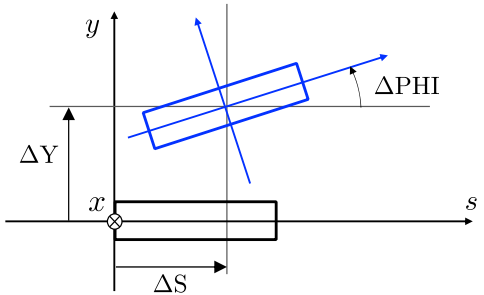
* misalignment relative to girder placement

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

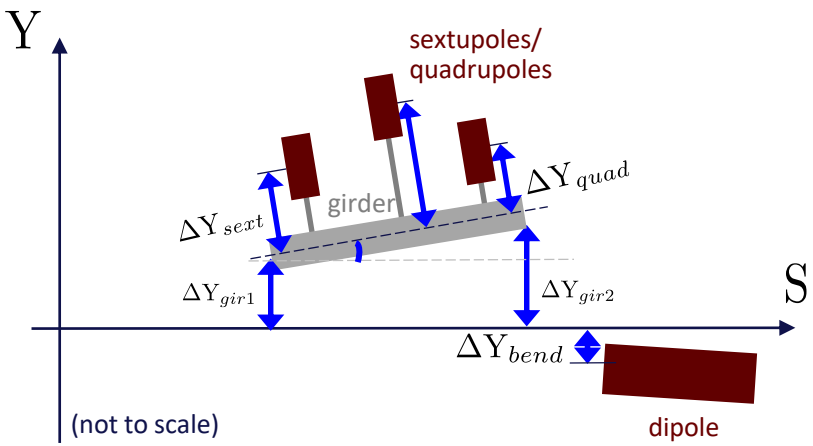
This table is not the final set of tolerances.

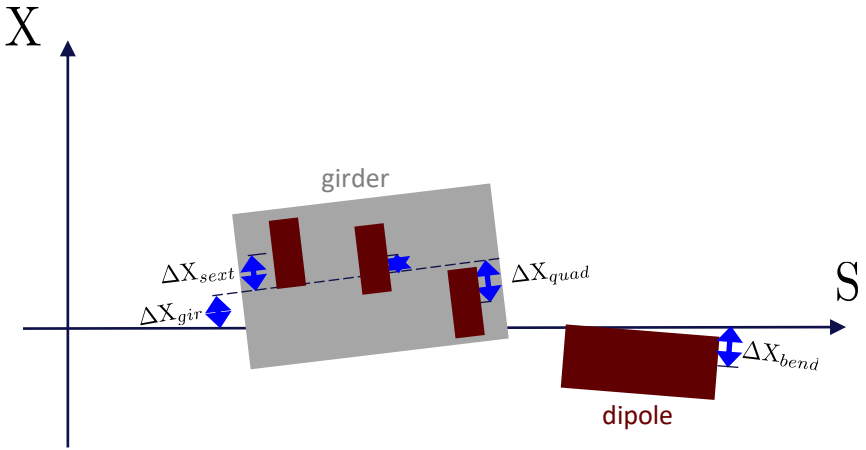






Assigning girder misalignments





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

Misalignments and field errors

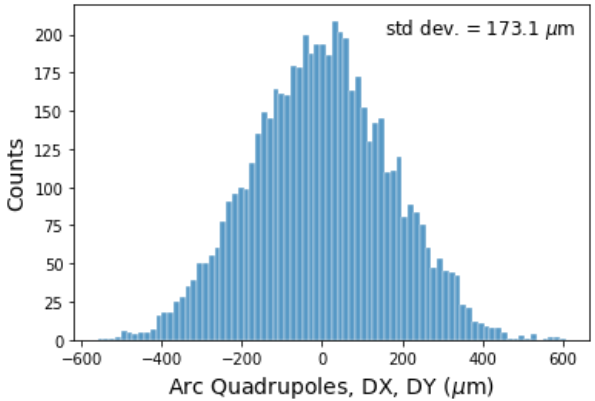
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔDTHETA (μrad)	ΔDPHI (μrad)	Field Errors
Arc quadrupole*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	1000	1000	300	1000	0	0	$\Delta B/B = 1 \times 10^{-4}$
Girders	150	150	-	1000	-	-	-
IR quadrupole	100	100	250	250	100	100	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	100	100	250	250	100	100	$\Delta k/k = 2 \times 10^{-4}$

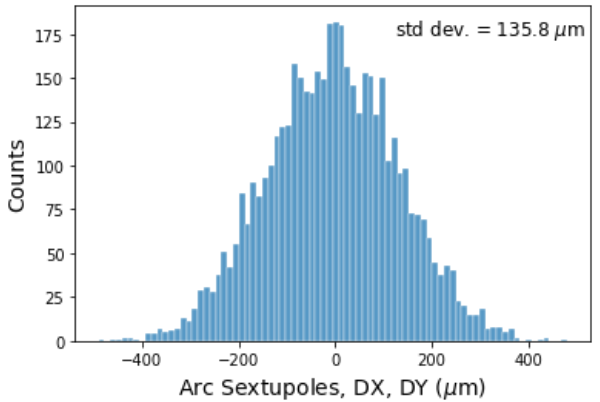
* misalignment relative to girder placement

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

This table is not the final set of tolerances.

Distributions of arc quadrupoles and sextupoles, total DX and DX misalignments:





RESULTS

FCC-ee emittance tuning results

without BPM errors and *without* chromaticity correction

RMS misalignment and field errors tolerances:

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔDTHETA (μrad)	ΔDPHI (μrad)
Arc quadrupole*	50	50	300	150	100	100
Arc sextupoles*	50	50	300	150	100	100
Dipoles	1000	1000	300	1000	-	-
Girders	150	150	-	1000	-	-
IR quadrupole	100	100	250	250	100	100
IR sextupoles	100	100	250	250	100	100

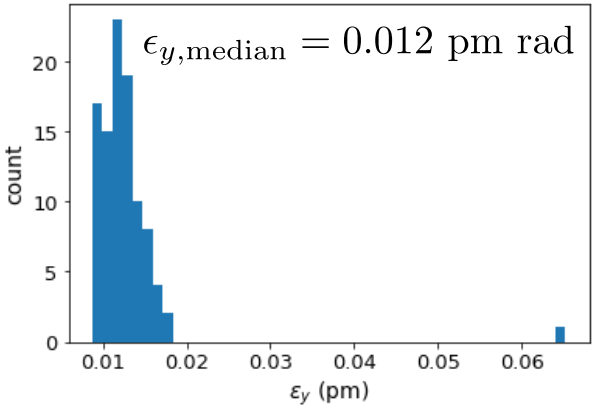
* misalignments relative to girder placement

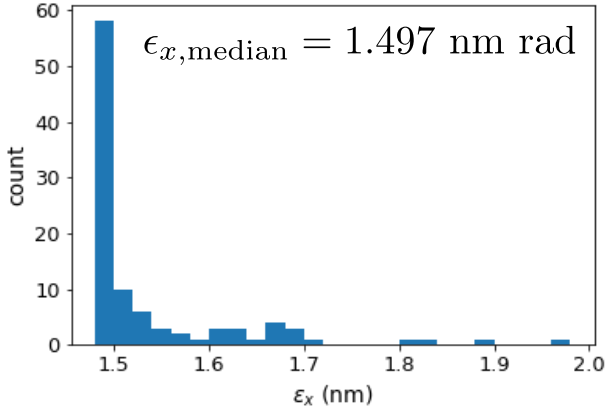
Type	Field Errors
Arc quadrupole*	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	$\Delta B/B = 1 \times 10^{-4}$
Girders	-
IR quadrupole	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	$\Delta k/k = 2 \times 10^{-4}$

Important to note:
BPM errors not included.

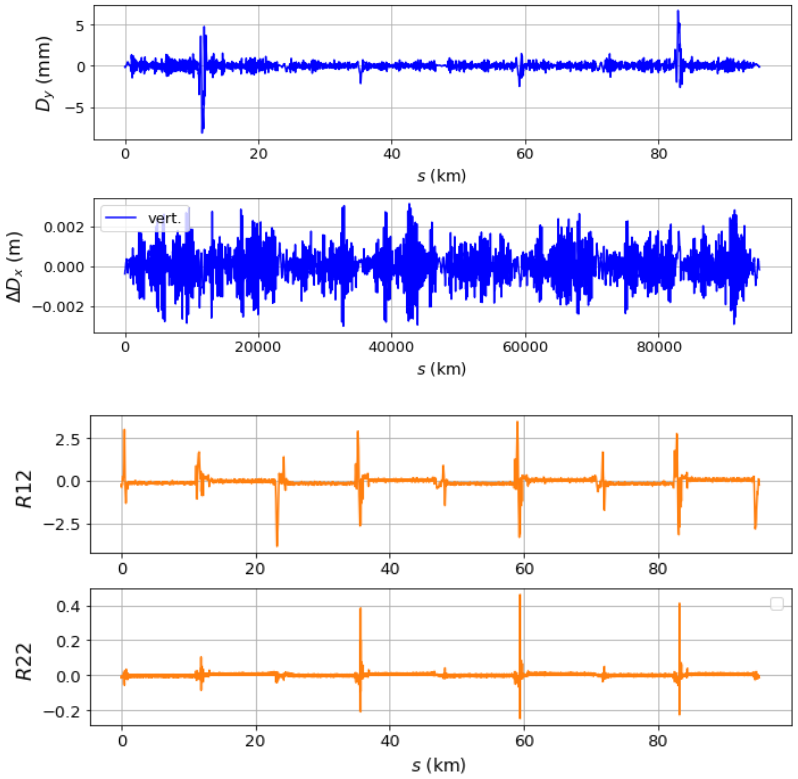
Radiation not included in correctors and trim and skew quads.

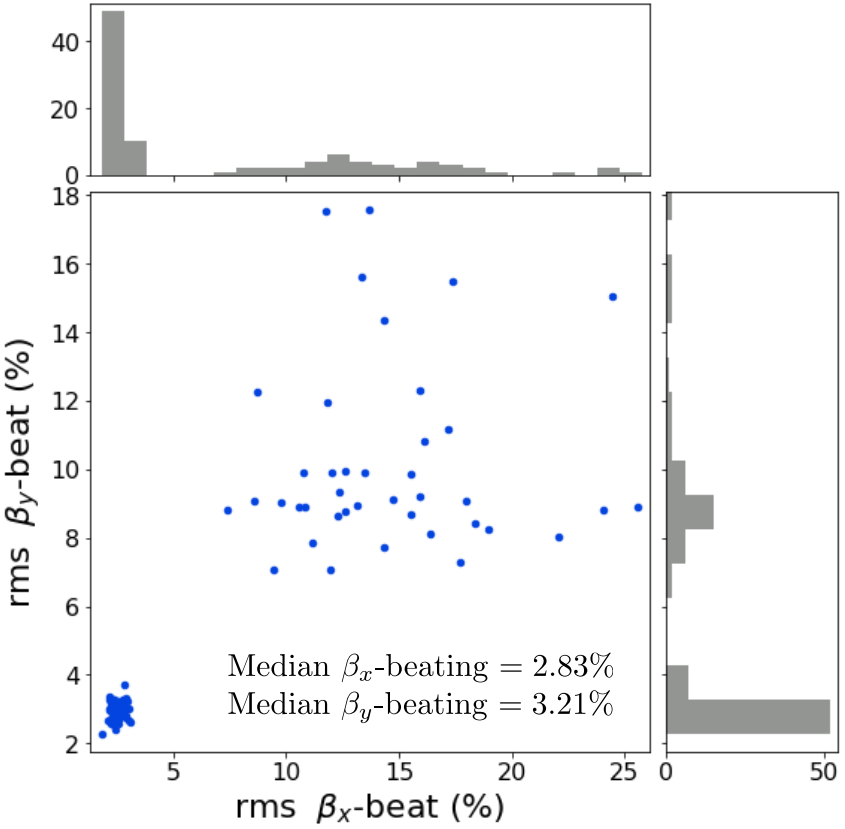
ttbar (182.5 GeV) 4IP lattice, after correction strategy:





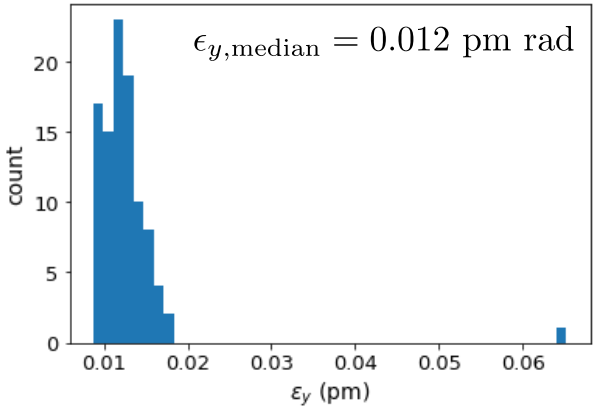
After corrections, ttbar 4 IP lattice:



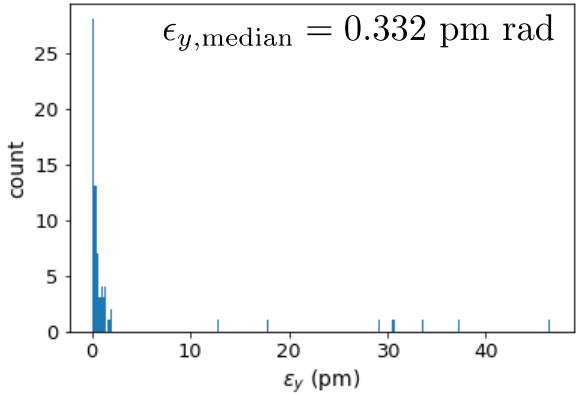


Chromaticity correction added

No chromaticity correction:



Chromaticity correction:

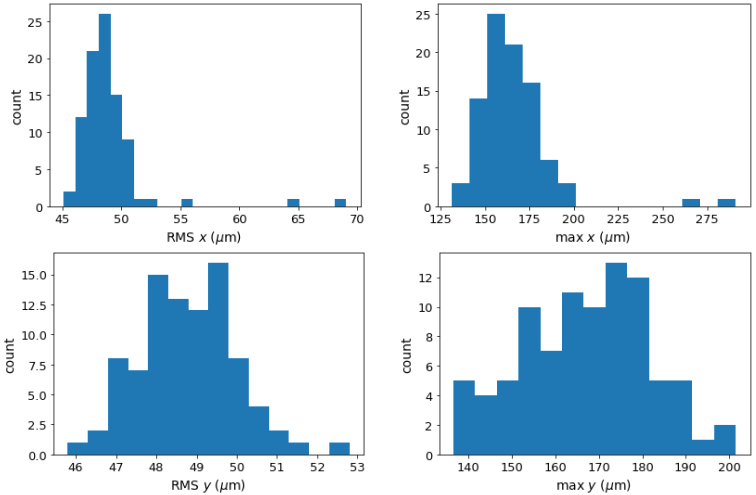


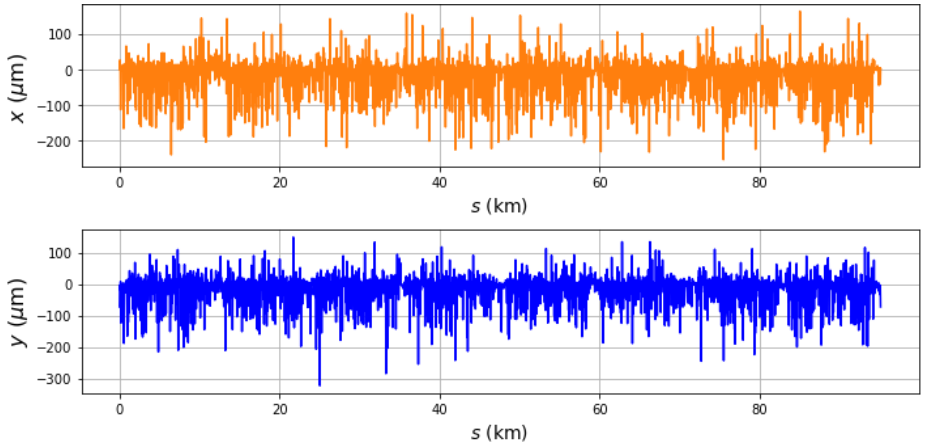
Large proportion of seeds start to fail

Adding chromaticity correction

Chromaticity correction corrects chromaticity well, but increases coupling.
Applying additional coupling correction changes the chromaticity -> An iterative procedure is necessary.

RMS horizontal orbit and max orbit distortion, after corrections (without BPM errors):





Reducing the sextupole misalignment to 10 μm

without BPM errors but *with* chromaticity correction

RMS misalignment and field errors tolerances:

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔDTHETA (μrad)	ΔDPHI (μrad)
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Arc sextupoles*	10	10	300	150	100	100
Dipoles	1000	1000	300	1000	0	0
Girders	150	150	-	1000	-	-
IR quadrupole	100	100	250	250	100	100
IR sextupoles	10	10	250	250	100	100

* misalignments relative to girder placement

Type	Field Errors
Arc quadrupole*	$\Delta k/k = 2 \times 10^{-4}$
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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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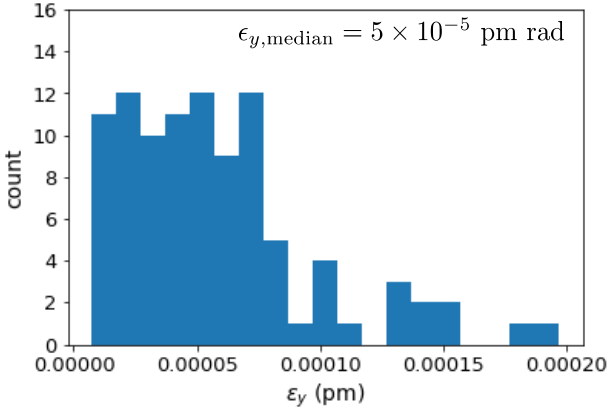
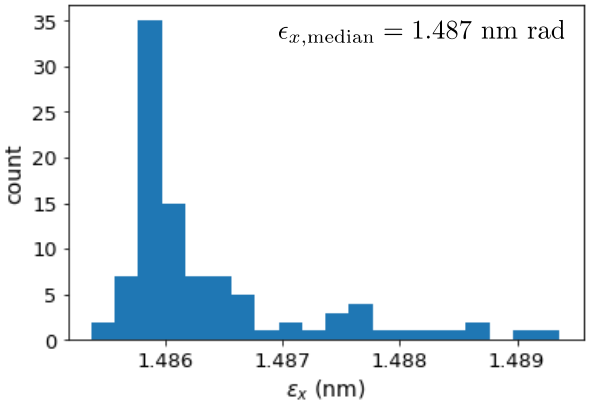
Important to note:
BPM errors not included.

Radiation not included in correctors and trim and skew quads.

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





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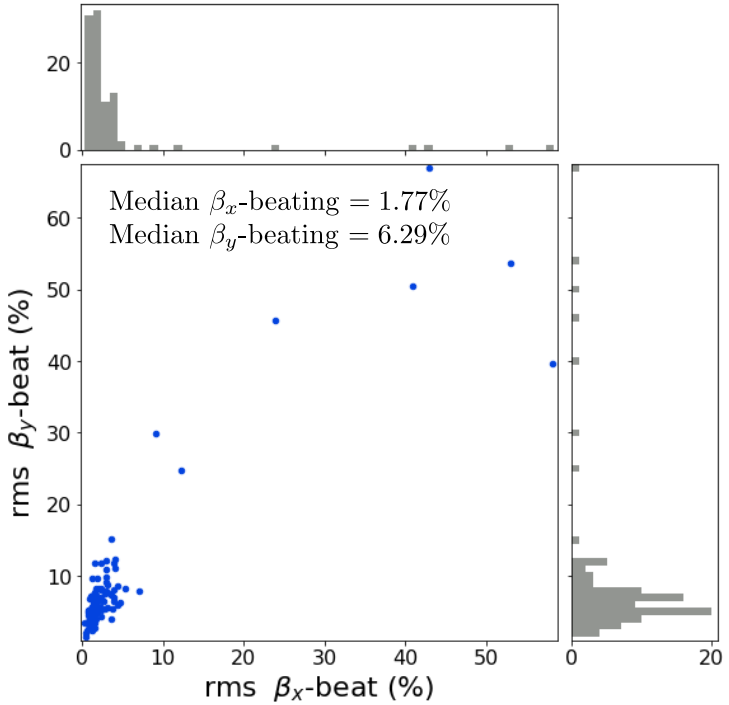


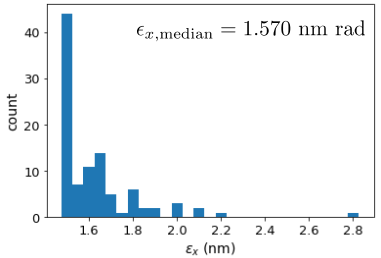
Emittance Tuning with Dipole b2 and b3 Errors

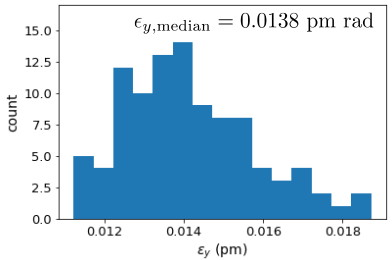
without BPM errors but *without* chromaticity correction

Systematic errors applied of: b2 = -4e-4, b3 = 2e-4.
(b2 errors change sign as beams exchange apertures.)

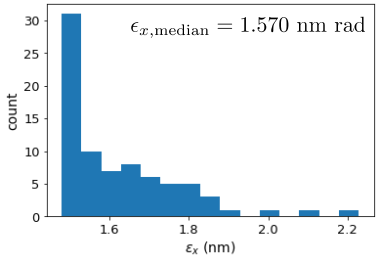
All other misalignments and field errors, as per latest first table of on slide 12.

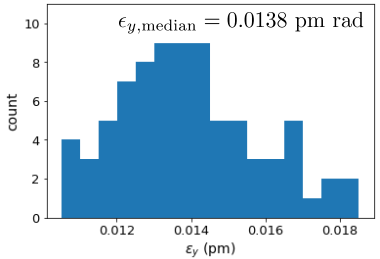
without dipole b2 & b3 errors:





with dipole b2 & b3 errors:





Conclusion: Systematic dipole b2 and b3 errors can be handled by correction algorithm.
B2 and b3 errors caused simulation to take longer and 19 seeds to exceed time limit.

Thanks to Jeremie Bauche for the values of b2 and b3 errors.
Thanks to Cristobal Garcia for identifying dipole element patter.

Summary

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 0.332 pm rad and horizontal emittance of 1.497 nm rad. *However,* the reduced DA needs dedicated investigation.

Reduction in sextupole misalignment (or rather improved orbit through sextupoles), which could be implemented through placing sextupoles on movers, presents a promising option towards restoring DA.

This work is ongoing.

FCC

Thank you
for your attention.