STATUS OF FCC-EE OPTICS TUNING SIMULATIONS

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

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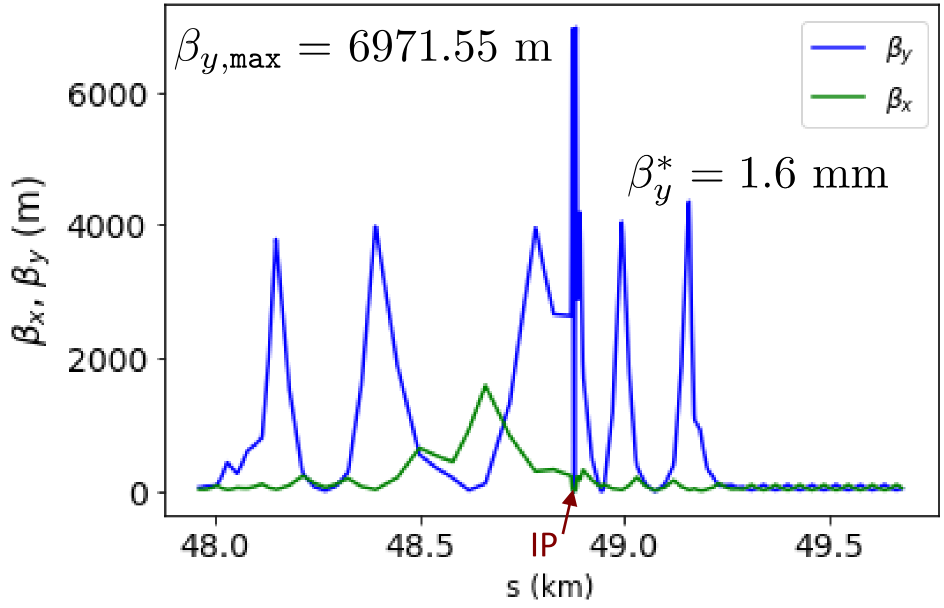
FCC-ee Emittance Tuning: Challenges & Constraints

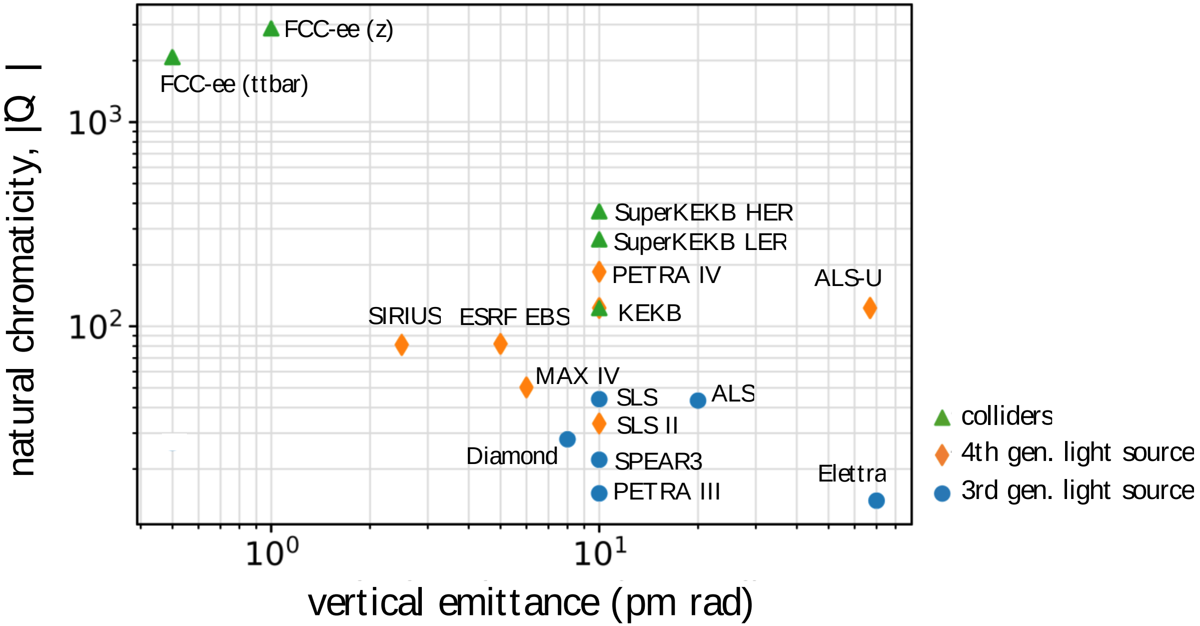


Small emittance ratio, $\frac{\epsilon_y}{\epsilon_x} < 0.2\ \%$

Challenges:

1. Large beta function values makes us sensitive to field and misalignment errors
2. Small beta* means strong FF magnets, which in turn requires strong sextupoles for local chromaticity correction.
3. Small emittance ratio makes us sensitive to any coupling between the horizontal and vertical motion.

Natural chromaticities for a range of low emittance storage rings



Many thanks to:

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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

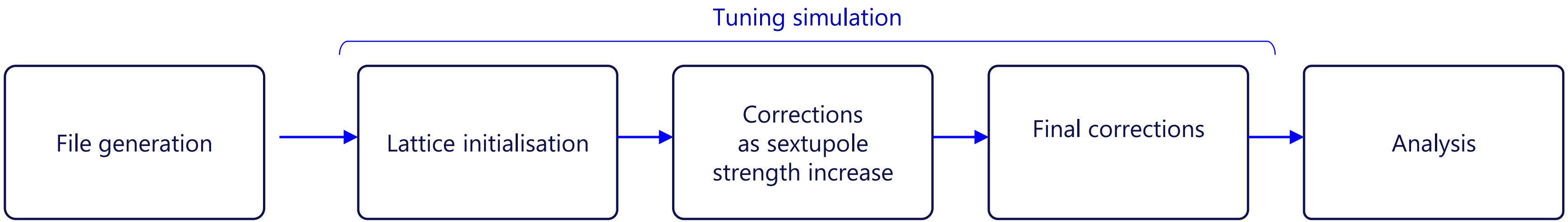
$$\begin{pmatrix}\vec{f}_{1001} \\ \vec{f}_{1010} \\ D_y\end{pmatrix} = -\mathbf{M}\,\vec{\mathbf{J}}$$

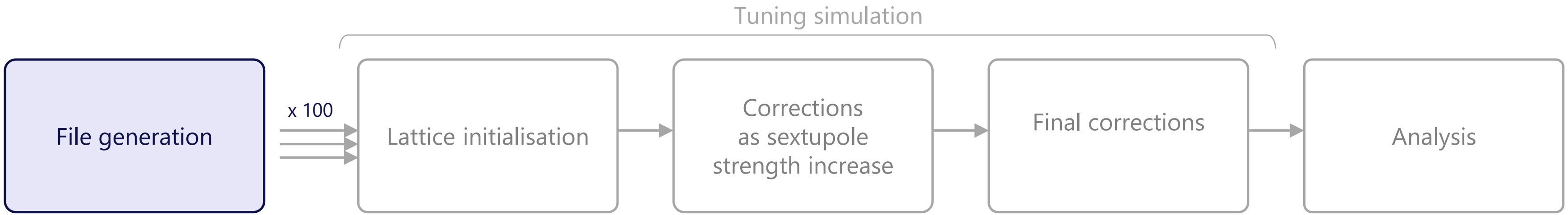
Beta beating correction & Horizontal dispersion via Response Matrix:

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

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

Tuning simulations



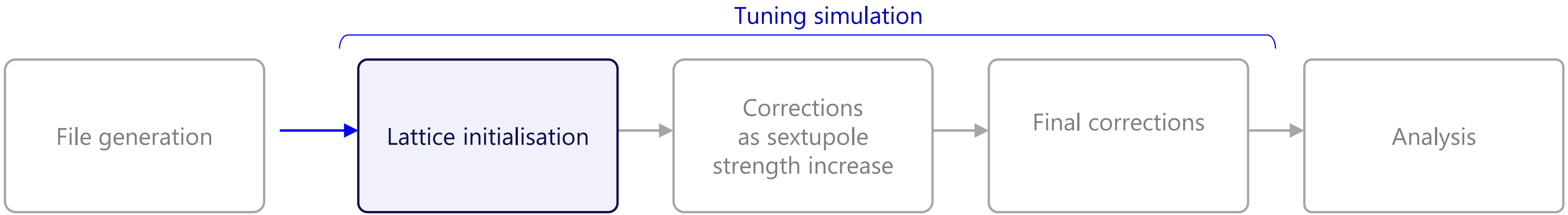


Inputs:
- MAD-X template file
- Errors values (yaml file)
- Bash template

(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.

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

Tuning simulation

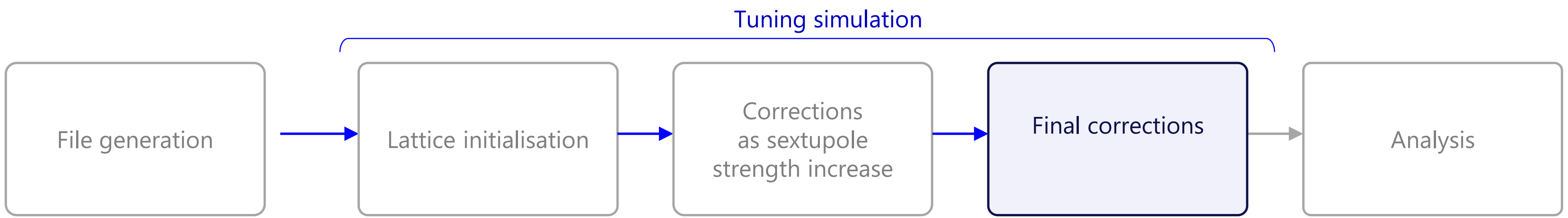
File generation → Lattice initialisation → **Corrections as sextupole strength increase** → Final corrections → Analysis

Sextupoles set to 10% of their design strength

- Orbit correction
- Combined coupling and dispersion correction (Python)
- Beta-beating correction applied (Python)
- Sextupole strengths increased by 10%

Iterated over many times.

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

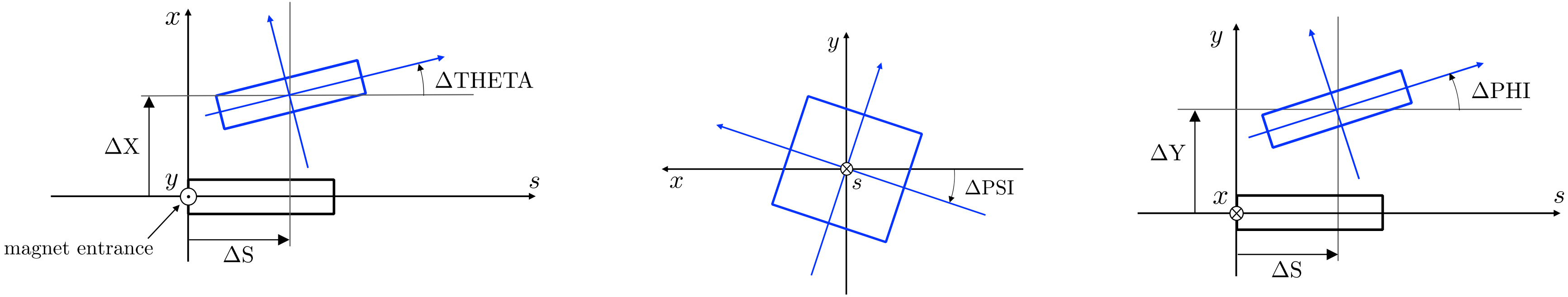
Lattice sequence saved.

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

Three sets of results

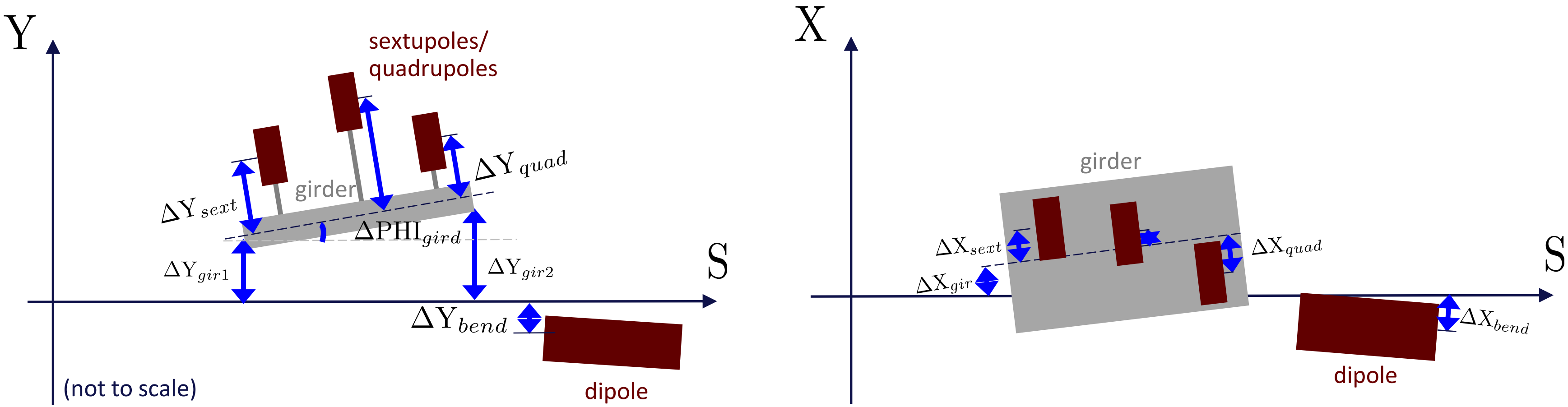
1. Corrections applied without chromaticity correction
2. Corrections applied with chromaticity correction
3. Corrections applied with chromaticity correction with half misalignment values

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 DTHETA and DPHI.

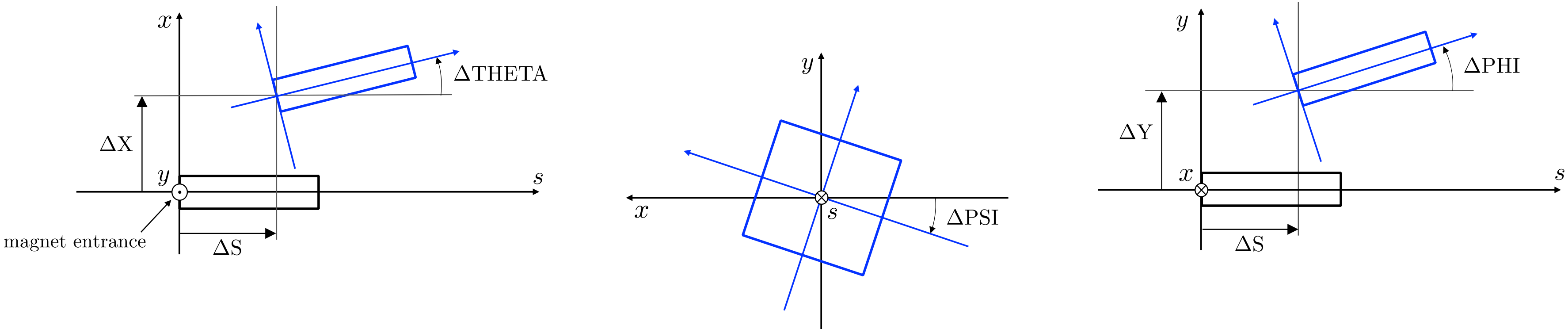
Misalignments and field errors

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.



FCC-ee emittance tuning results

without chromaticity correction & BPM errors

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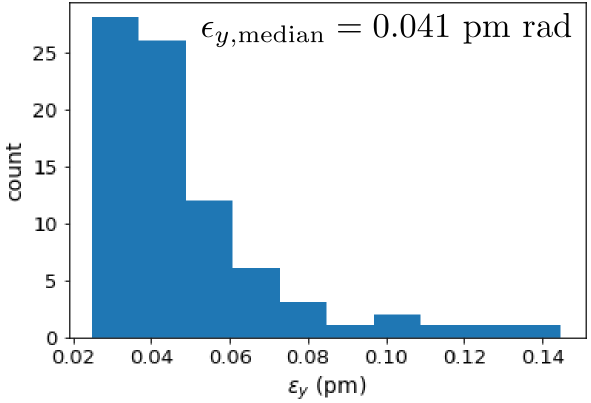
Dipoles	$\Delta B/B = 1 \times 10^{-4}$
Girders	-
IR quadrupole	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	$\Delta k/k = 2 \times 10^{-4}$

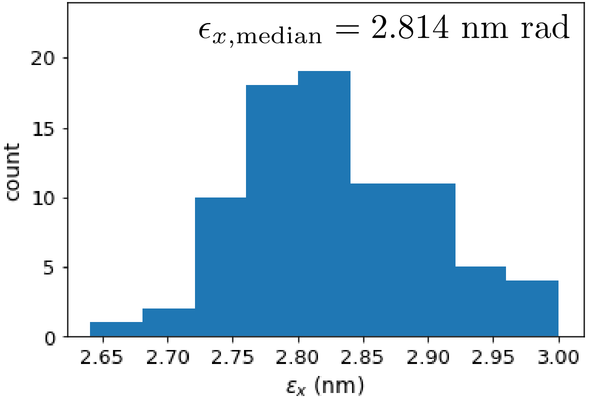
Important to note:
BPM errors not included
Chromaticity correction not included.

Radiation not included in correctors and trim and skew quads.

Also note:
Despite well corrected linear optics, the DA is still greatly reduced.

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





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Girders	150	150	-	1000	-	-
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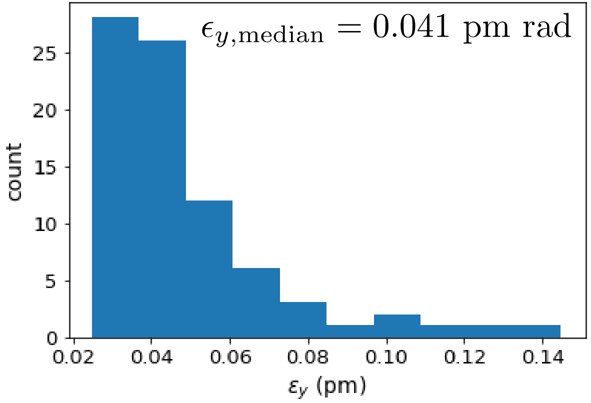

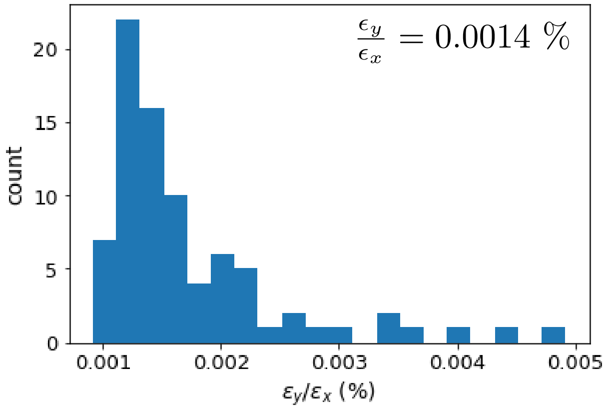

FCC-ee emittance tuning results
without chromaticity correction & BPM errors

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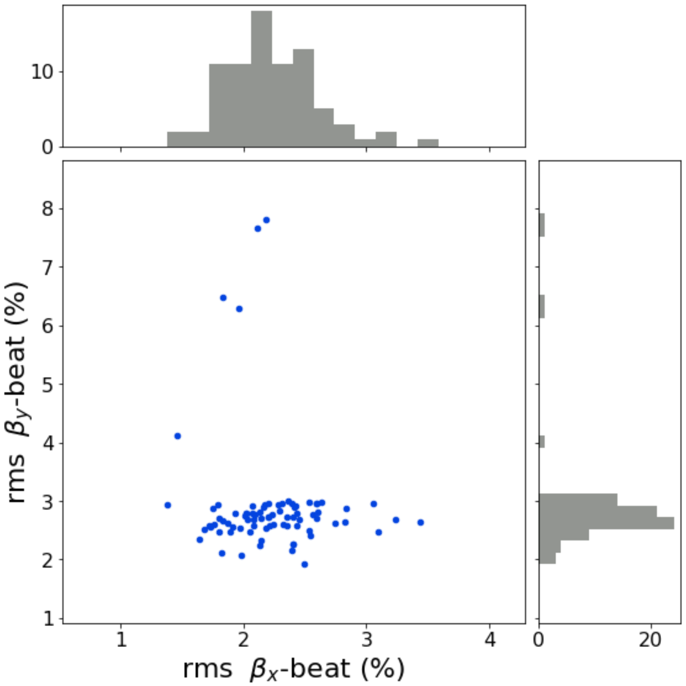

FCC-ee emittance tuning results
with chromaticity correction

RMS misalignment and field errors tolerances:

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔDTHETA (μrad)	ΔDPHI (μrad)
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Dipoles	1000	1000	300	1000	-	-
Girders	150	150	-	1000	-	-
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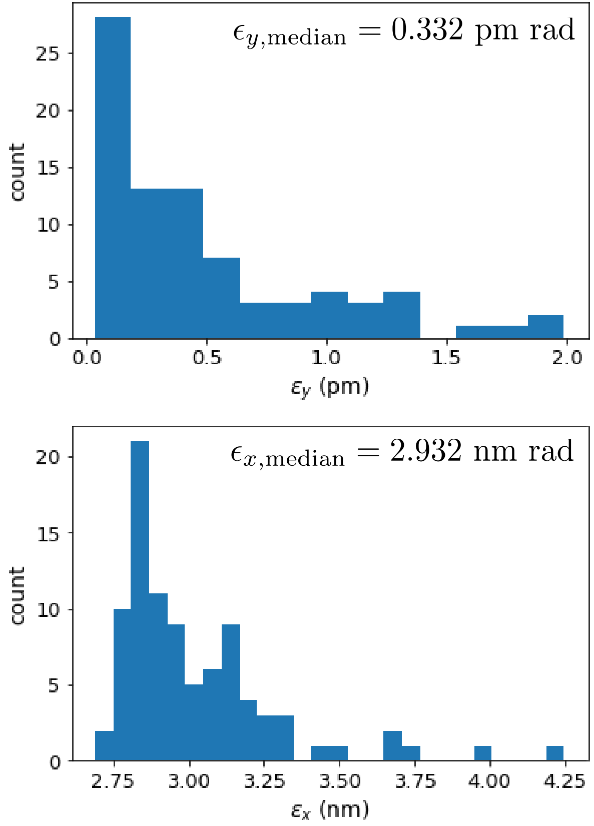

FCC-ee emittance tuning results

with chromaticity correction

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

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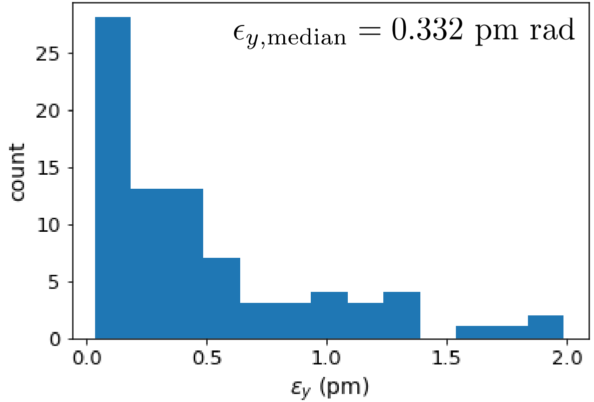

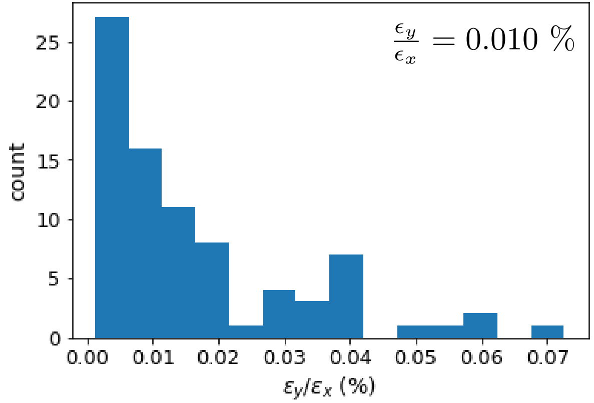

FCC-ee emittance tuning results

with chromaticity correction. **Half misalignment values**.

RMS misalignment and field errors tolerances:

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔDTHETA (μrad)	ΔDPHI (μrad)
Arc quadrupole*	25	25	150	75	50	50
Arc sextupoles*	25	25	150	75	50	50
Dipoles	500	500	150	500	0	0
Girders	75	75	-	500	-	-
IR quadrupole	50	50	125	125	50	50
IR sextupoles	50	50	125	125	50	50

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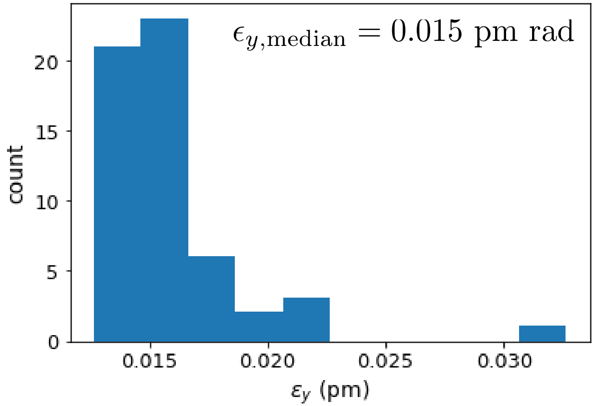
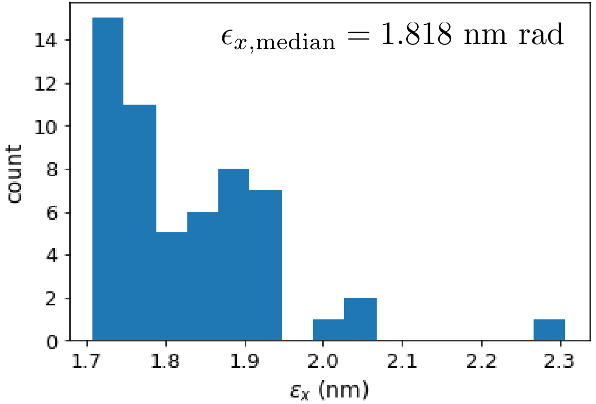
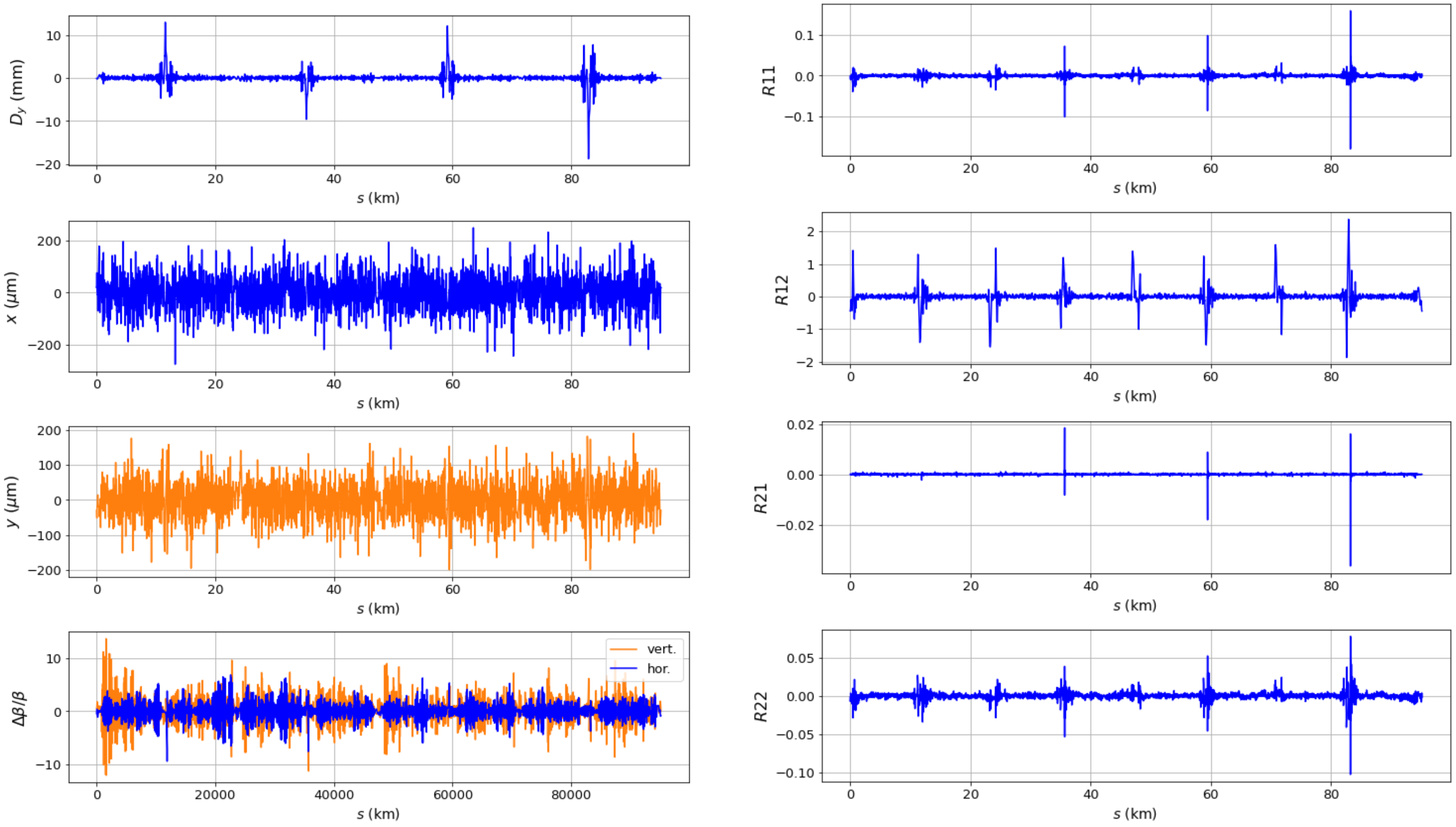




After corrections, ttbar 4 IP lattice:



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)
- Non-linear corrections: lifetime, DA, chromatic aberrations, amplitude detuning, RDTs, etc.
- Solenoid imperfections to be considered
- Tapering imperfections
- Improvements to tuning speed / efficiency (both in code and machine)
- Studies for all lattices: Z, W, H, t
- Measurements simulations (single kick, AC dipole, (AC-)ORM, Kmod, LOCO etc.)
- Local corrections of IR parameters (IP knobs, K-mod, waist-shift, etc.)
- Tolerance on multipoles / offsets with dedicated correction approaches.
- Calculation of DA and MA after tuning (and polarization eventually)
- Sextupole knobs or schemes for DA / MA optimization
- Design of global knobs for control of fundamental parameters e.g.: Tunes, chromas, coupling, chromatic coupling, amp. det., etc.
- Simulation of commissioning process

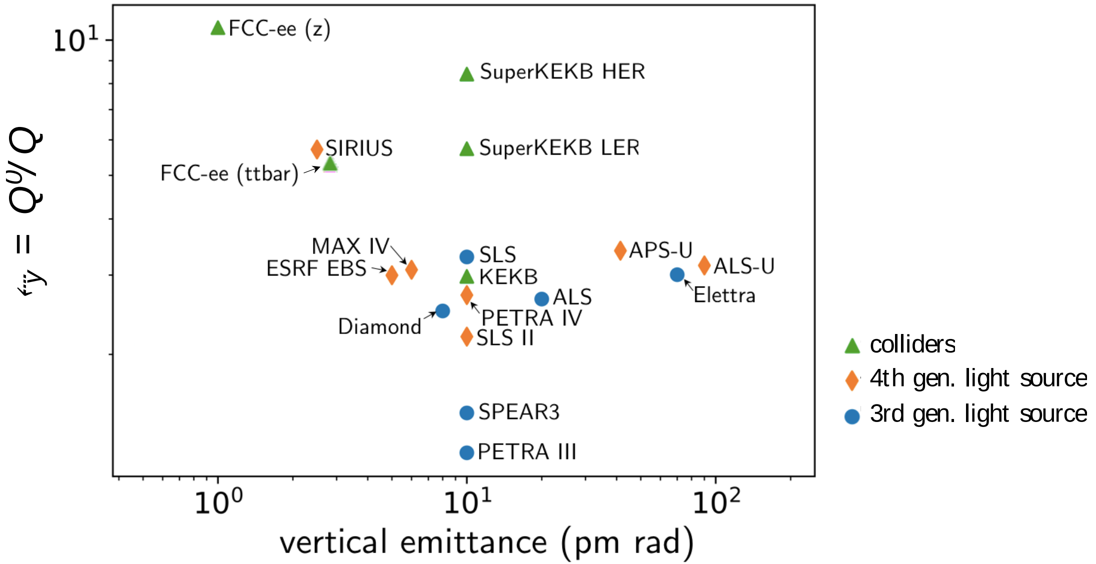
Summary

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 2.932 nm rad. The reduced DA needs dedicated investigation.

This work is ongoing.

Thank you for your attention.

Natural chromaticities for a range of low emittance storage rings



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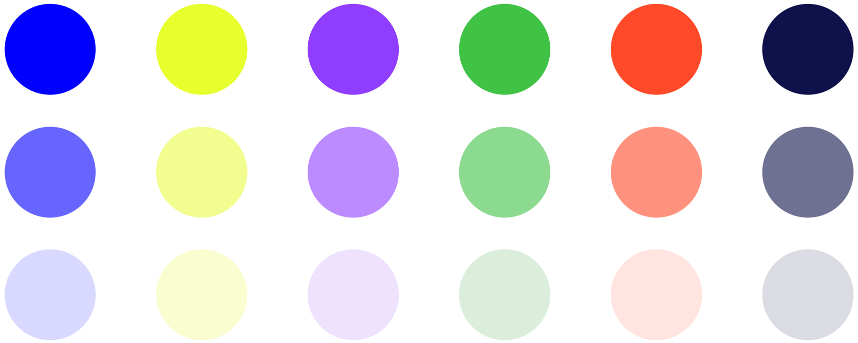
COLORS



Radiant Blue | Flash | Energy | Green | Red | Deep Blue

BACKGROUNDS

Background Blue

Background Purple

Background Yellow

Background Grey

Use for Layout

GRAPHICAL ELEMENTS

Separation lines 1.5 pt

Arrows

BADGES

This information is a badge because it is important!

This information is a badge because it is important!

Use blue badges on light backgrounds

This information is a badge because it is important!

This information is a badge because it is important!

Use light badges on dark backgrounds

INFOGRAPHICS