The Cockcroft Institute of Accelerator Science and Technology
UNIVERSITY OF LIVERPOOL

STATUS AND PLANS FOR OPTICS CORRECTIONS AND EMITTANCE PERFORMANCE

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and the FCC-ee optics team

1. University of Liverpool,
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3. CERN

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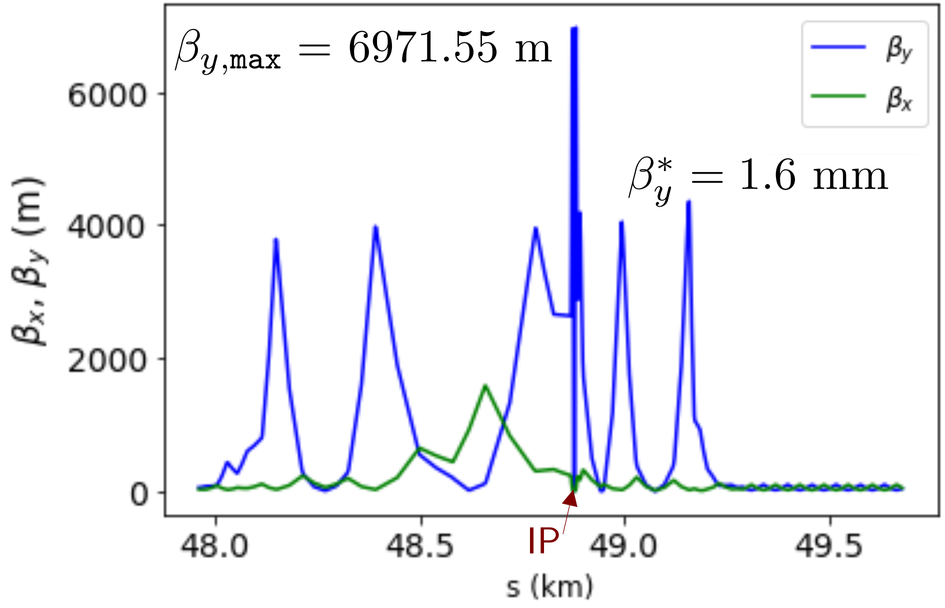
FCC-ee Emittance Tuning: Challenges & Constraints

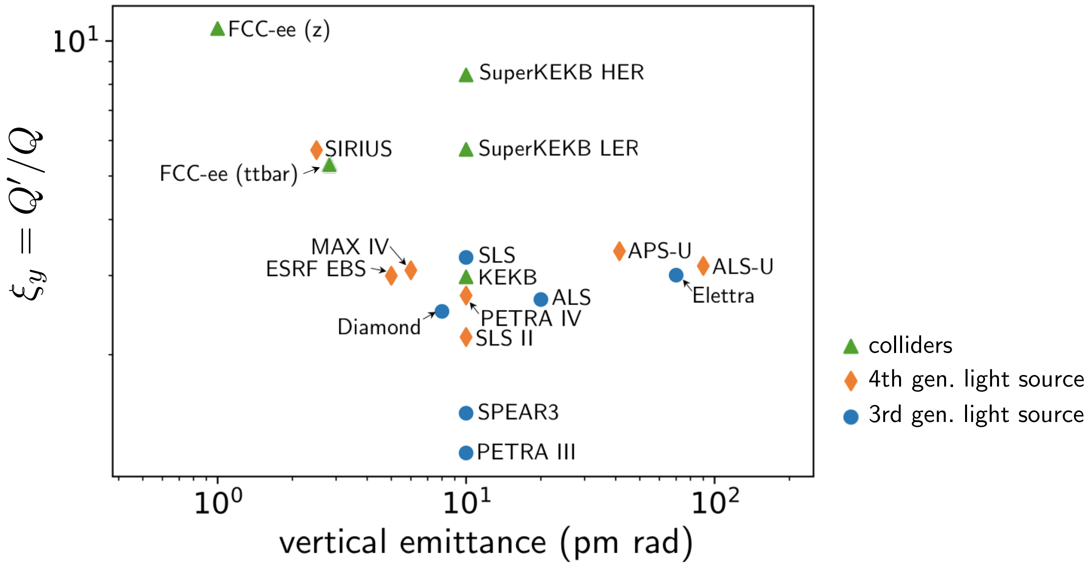


Small emittance ratio, $\frac{\epsilon_y}{\epsilon_x} < 0.2$ %

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:

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)

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

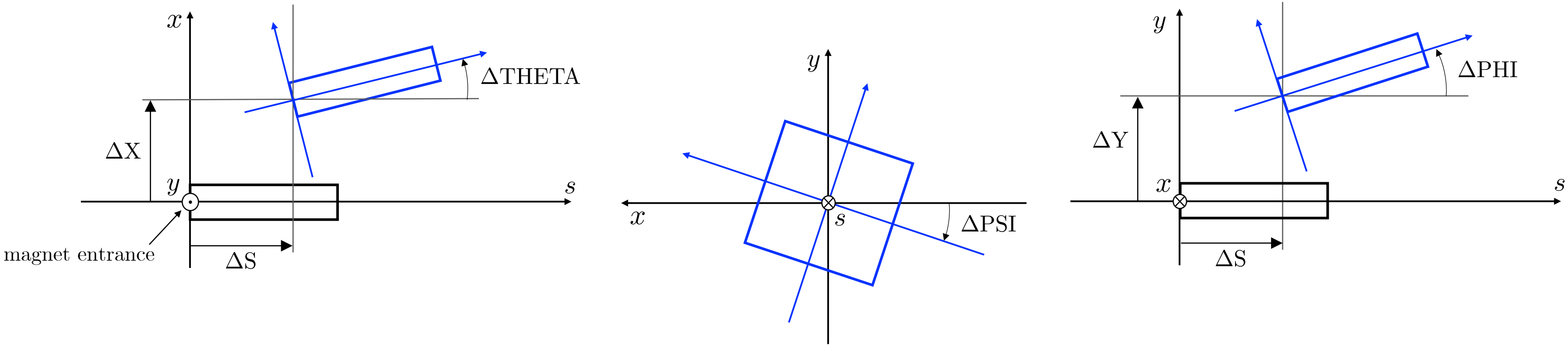
$$\begin{pmatrix}\vec{f}_{1001}\\ \vec{f}_{1010}\\ D_y\end{pmatrix} = -\mathbf{M}\,\vec{\mathbf{J}}$$

Beta beating correction & Horizontal dispersion via Response Matrix:

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

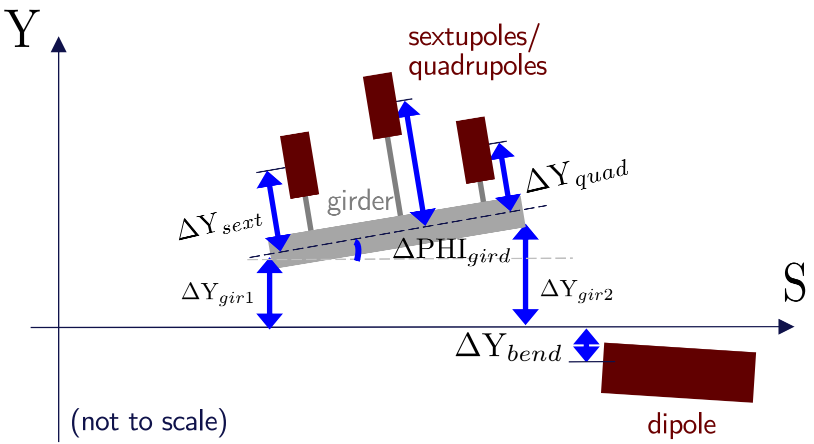
$$\begin{pmatrix} f_1\left(\frac{\beta_1-\beta_{y0}}{\beta_{y0}}\right)\\ f_2\left(\frac{\beta_2-\beta_{y0}}{\beta_{y0}}\right)\\ \dots\\ f_m\left(\frac{\beta_m-\beta_{y0}}{\beta_{y0}}\right)\end{pmatrix}_{meas} = \begin{pmatrix} f_1\ (R_{11}, R_{12}, R_{13}, \dots, R_{1n})\\ f_2\ (R_{21}, R_{22}, R_{23},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

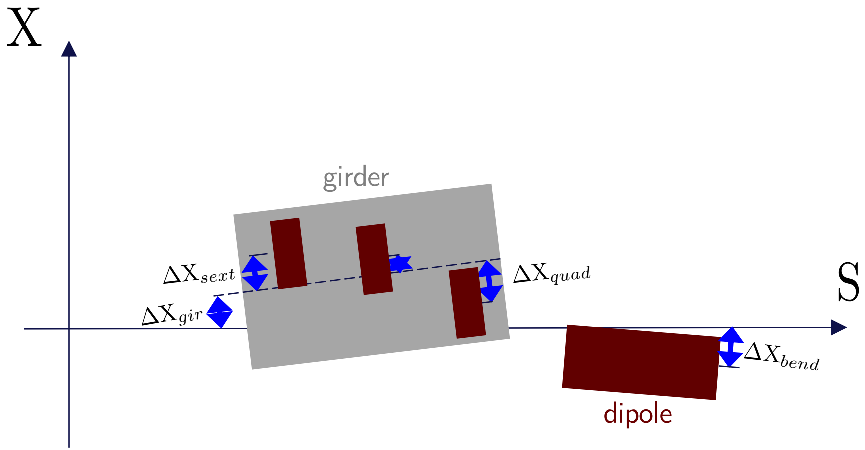
Assigning misalignments



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

Assigning girder misalignments





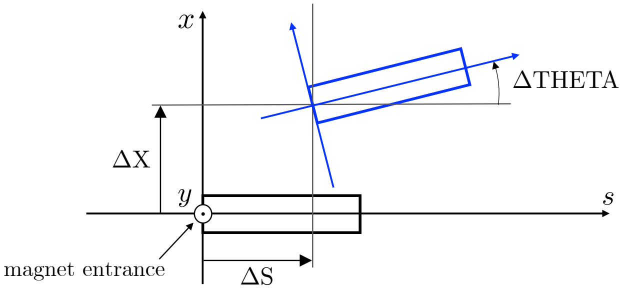
- 2 independent DX and DY misalignments for each end of the girder, and which can be used to calculate DTHETA and DPHI.

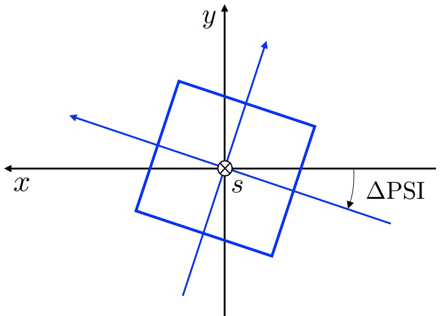
Misalignments and field errors

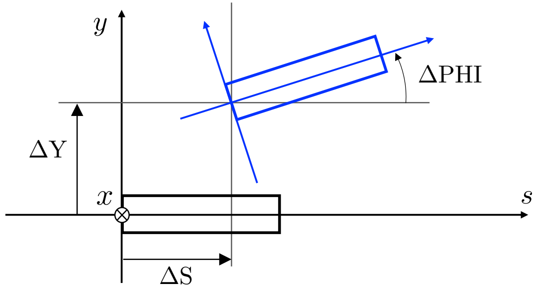
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)	Field Errors
Arc quadrupole*	50	50	200	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	50	50	200	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	1000	1000	300	1000	-	-	$\Delta B/B = 1 \times 10^{-4}$
Girders	150	150	-	1000	-	-	
IR quadrupole	100	100	250	200	100	100	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	100	100	250	200	100	100	$\Delta k/k = 2 \times 10^{-4}$
BPM**	40	40	100	-	-	-	-

* misalignments relative to girder placement
** misalignments relative to quadruple placement

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







Misalignments and field errors

FCC week 2020 = FCCIS kickoff meeting, November 2020
FCC week 2021, June 2021

	ΔX (μm)		ΔY (μm)		ΔPSI (μrad)		ΔS (μm)		ΔTHETA (μrad)		ΔPHI (μrad)	
FCC week	2020	**2021**	2020	**2021**	2020	**2021**	2020	**2021**	2020	**2021**	2020	**2021**
Arc quadrupole*	50	50	50	50	200	200	50	150	0	100	0	100
Arc sextupoles*	50	50	50	50	200	200	50	150	0	100	0	100
Dipoles	1000	1000	1000	1000	200	300	500	1000	-	-	-	-
Girders	150	150	150	150	-	-	500	1000	-	-	-	-
IR quadrupole	75	100	75	100	100	250	150	200	0	100	0	100
IR sextupoles	75	100	75	100	100	250	150	200	0	100	0	100
BPM**	40	40	40	40	100	100	-	-	-	-	-	-

* misalignments relative to girder placement
** misalignments relative to quadruple placement

Correction Strategy (1/2)

- **Sextupoles strengths set to zero.**
  - Gradient errors applied
    - Weighted beta-beat correction was performed and tune re-matched.
    - Sextupole and dipole field errors introduced.
    - Weighted beta-beat correction was performed and tune re-matched.
  - Misalignments applied to all magnets and girders.
    - Tune re-matched to the nominal tune, and orbit correction performed.
    - Beta-beat correction applied, and if needed orbit corrected and tune rematched.
    - Coupling correction, followed by beta-beat correction and coupling correction.

- **Sextupoles set to 10% of their design strength**

  (details on next slide)

- **Final correction** (at 100% sextupole strength)

  (details on next slide)

Correction Strategy (2/2)

- **Sextupoles strengths set to zero.**
  (details on previous slide)

- **Sextupoles set to 10% of their design strength**
  - Orbit correction
  - Combined coupling and dispersion correction
  - Beta-beating correction applied.
  - Sextupole strengths increased by 10%

These two steps repeated ~12 times.

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

- **Final correction** (at 100% sextupole strength)
  - Additional coupling, dispersion and beta-beating correction was applied.
  - Step through corrections until beta beating threshold is reached (trade-off between beta beating and vertical emittance can be varied).
  - Vary SV cut off values

FCC-ee emittance tuning results

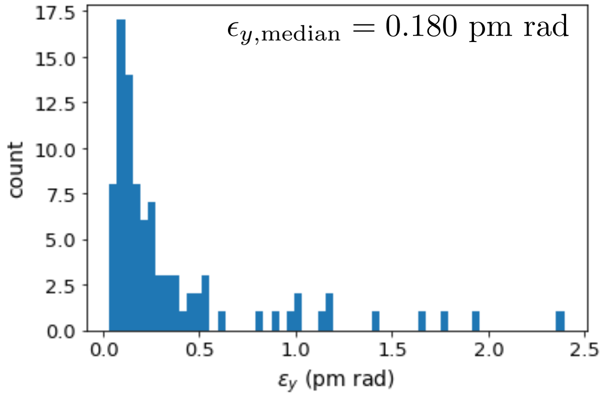
RMS misalignment and field errors tolerances:

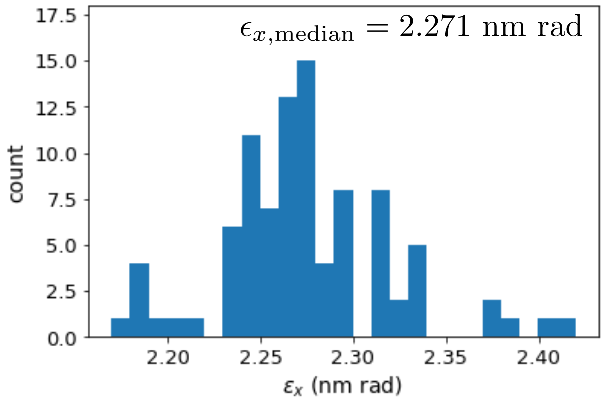
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
Arc quadrupole*	50	50	200	150	100	100
Arc sextupoles*	50	50	200	150	100	100
Dipoles	1000	1000	300	1000	-	-
Girders	150	150	-	1000	-	-
IR quadrupole	100	100	250	200	100	100
IR sextupoles	100	100	250	200	100	100
BPM**	40	40	100	-	-	-

* misalignments relative to girder placement
** misalignments relative to quadruple 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

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Dipoles	1000	1000	300	1000	-	-
Girders	150	150	-	1000	-	-
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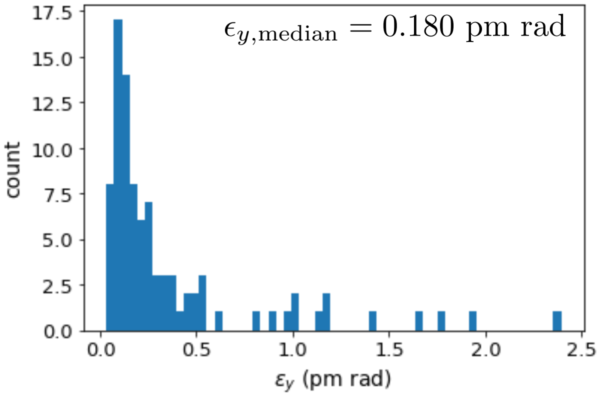

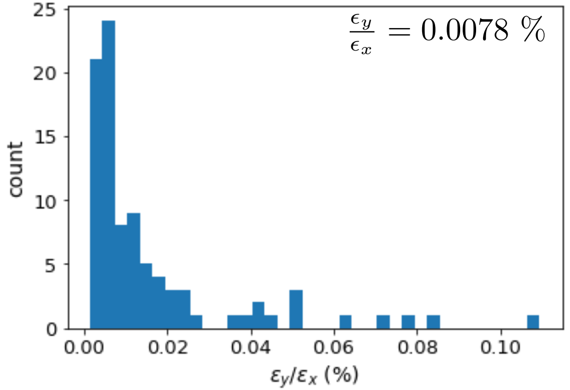

FCC-ee emittance tuning results

RMS misalignment and field errors tolerances:

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Dipoles	1000	1000	300	1000	-	-
Girders	150	150	-	1000	-	-
IR quadrupole	100	100	250	200	100	100
IR sextupoles	100	100	250	200	100	100
BPM**	40	40	100	-	-	-

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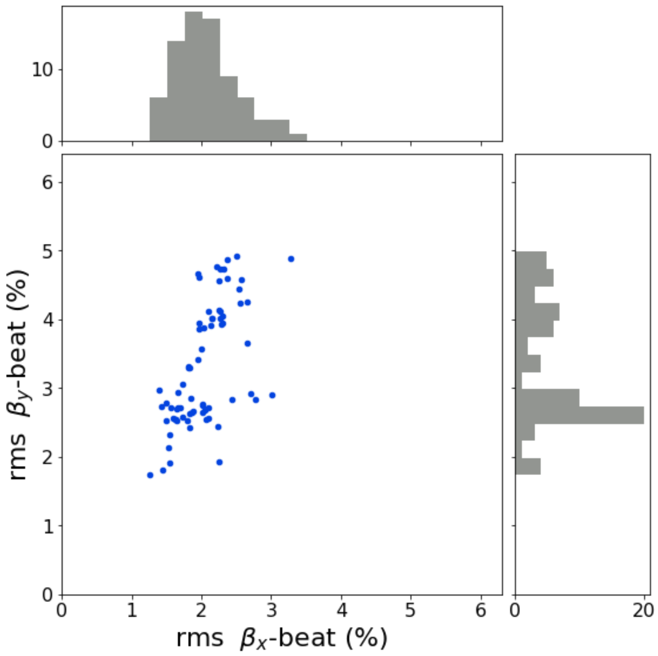
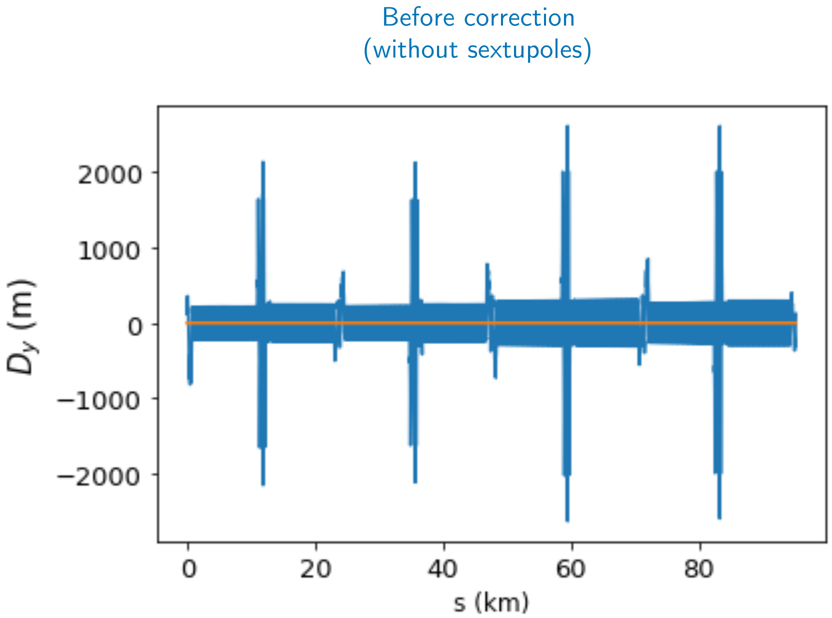
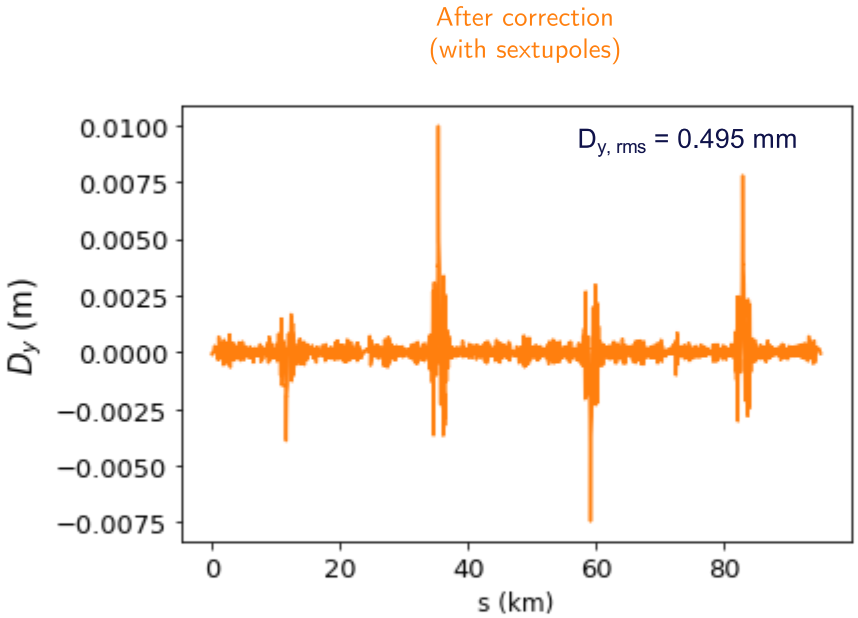


Vertical dispersion

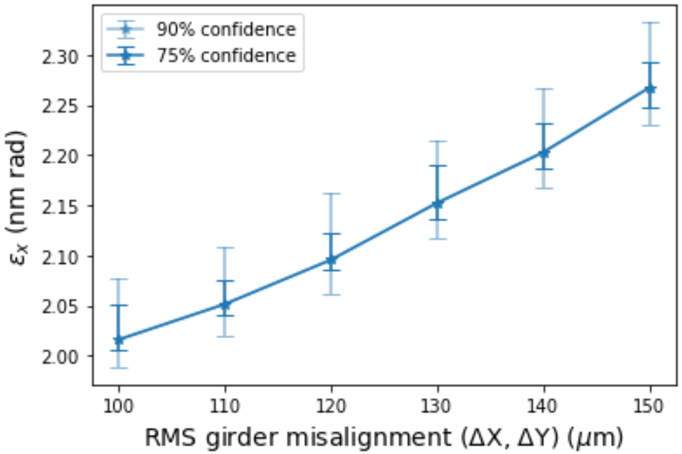


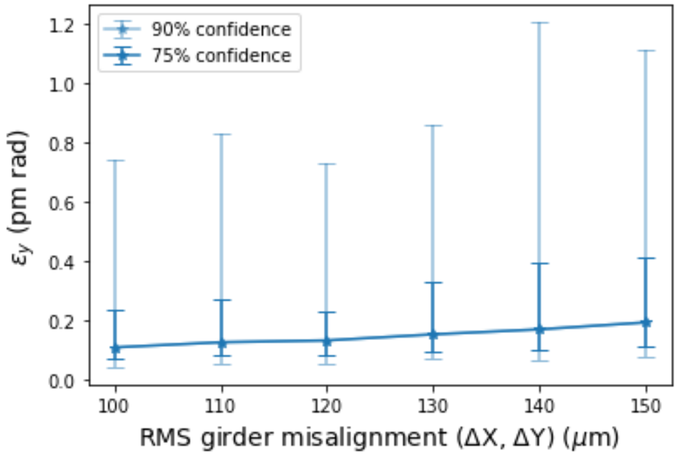


MISALIGNMENTS OF VARIOUS MAGNET TYPES

Girder misalignment

The girder misalignment has the strongest influence on horizontal emittance of all the parameters listed in the previous table.

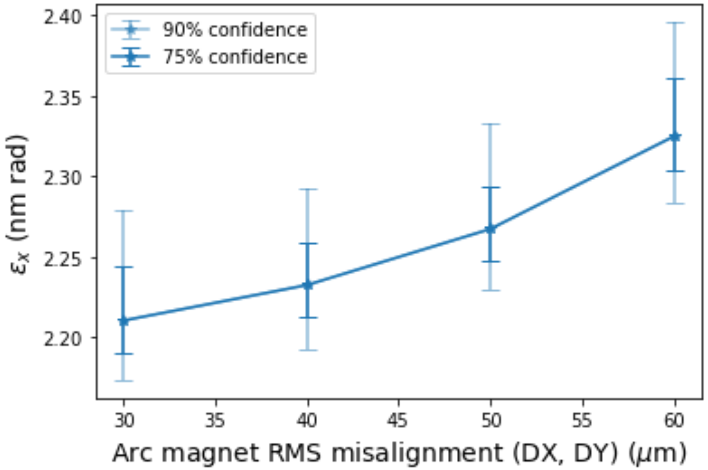


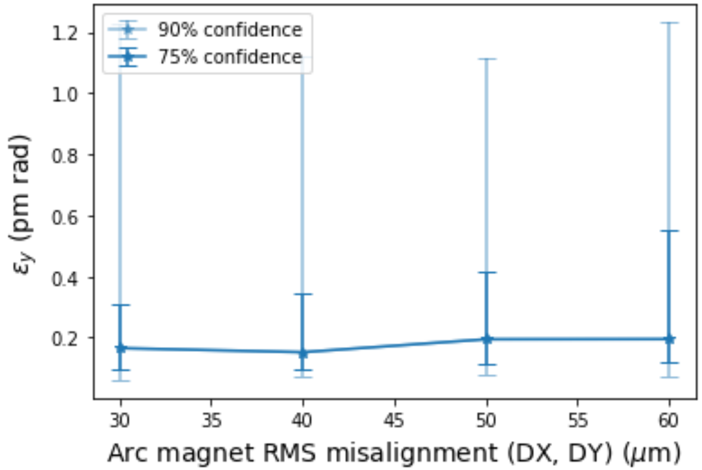


All other misalignments are as defined previously (slide 7).

Arc magnet misalignments

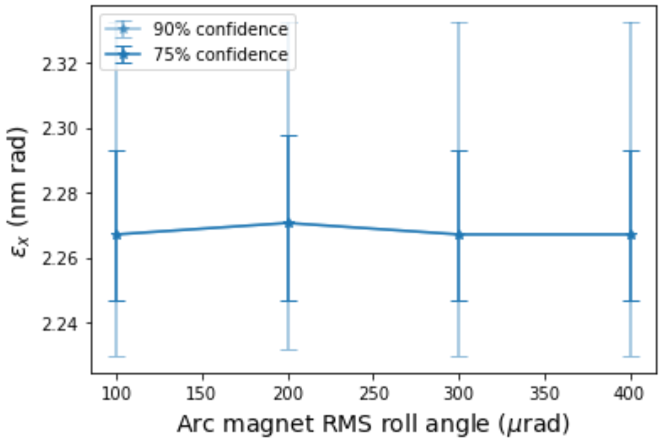
All other misalignments are as defined previously (i.e. girder DX and DY = 150 μm).

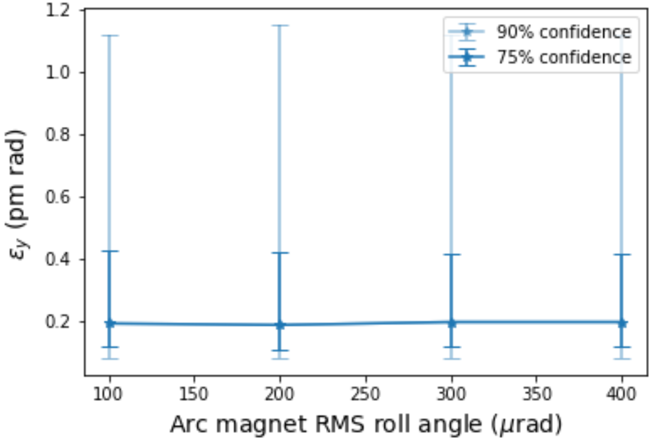




Arc magnet roll angles

Arc magnet roll angles of up 400 μrad can be handled by the correction strategy. This could be extended beyond 400 μrad if necessary.

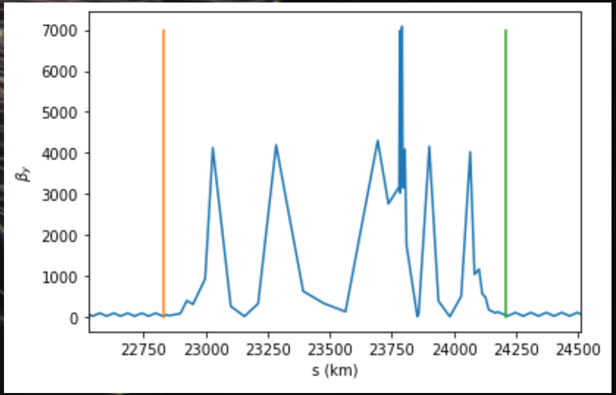




All other misalignments are as defined previously.

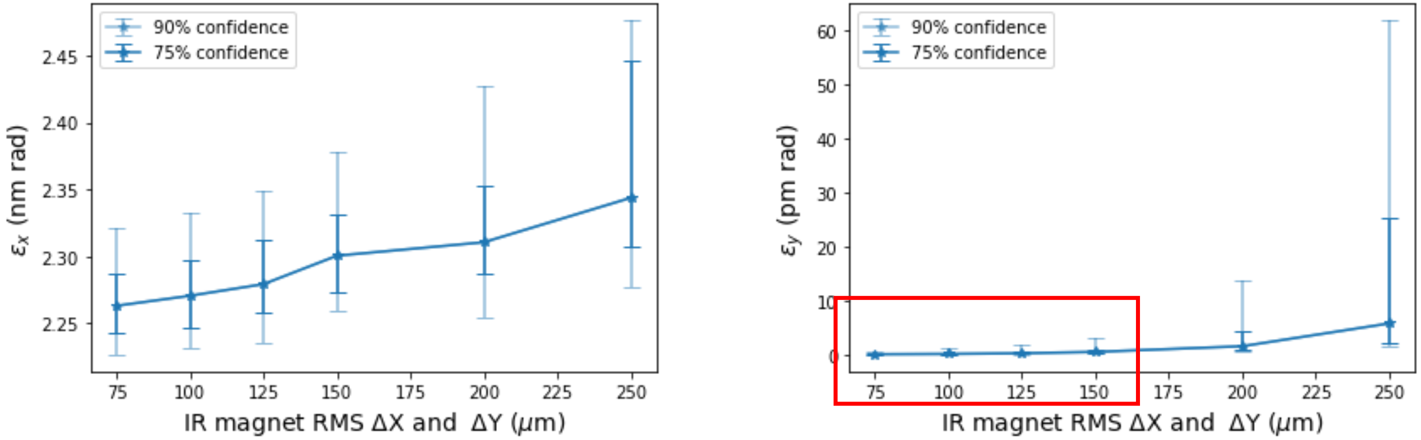
INTERACTION REGION

1. IR quads and sextupoles magnet
2. SY* sextupoles
3. QC1*, QC2* quadrupoles



IR magnets alignment - transverse misalignments (ΔX and ΔY)

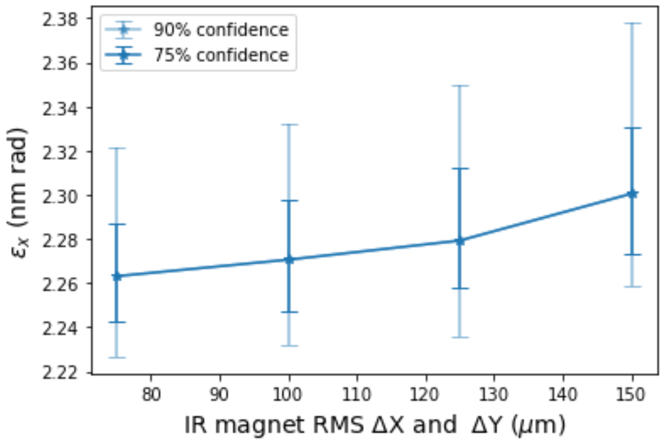
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
IR quadrupole	varied	varied	250	200	100	100
IR sextupoles	varied	varied	250	200	100	100
All other magnets	as listed in Table on slide 7					

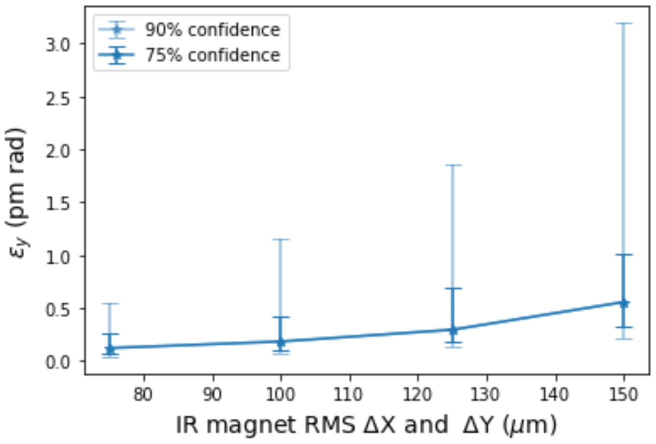


IR magnet alignment strongly influences global correction.

IR magnets alignment - transverse misalignments (ΔX and ΔY)

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
IR quadrupole	varied	varied	250	200	100	100
IR sextupoles	varied	varied	250	200	100	100
All other magnets	as listed in Table on slide 7					

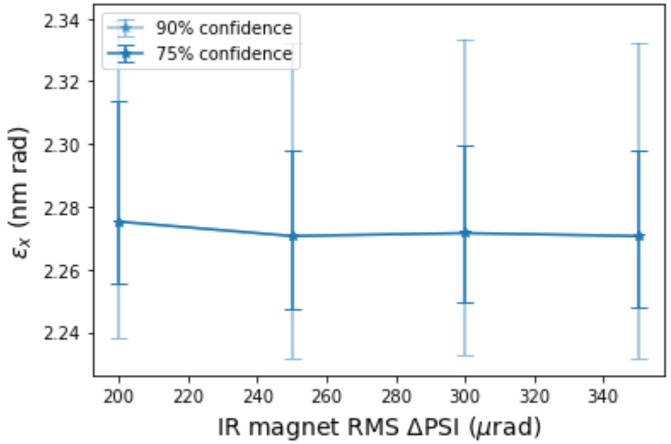


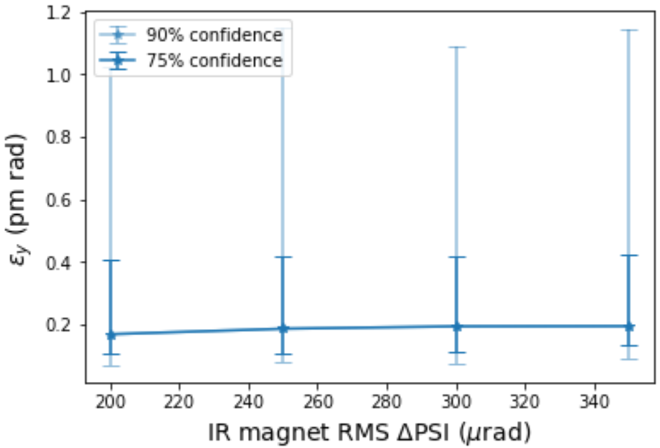


IR magnet alignment strongly influences global correction.

IR magnets alignment - roll angle (ΔPSI)

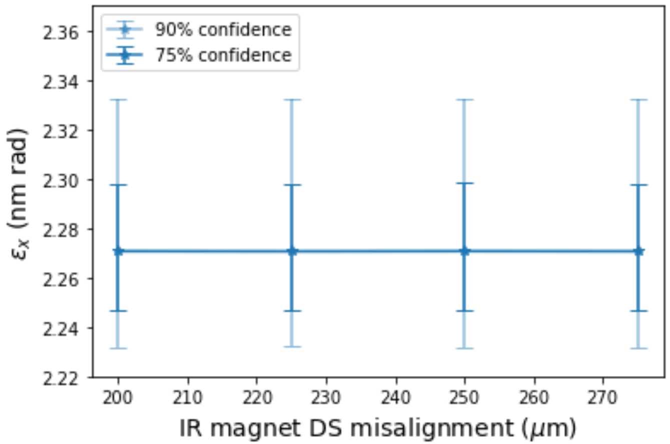
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
IR quadrupole	100	100	varied	200	100	100
IR sextupoles	100	100	varied	200	100	100
All other magnets	as listed in Table on slide 7					

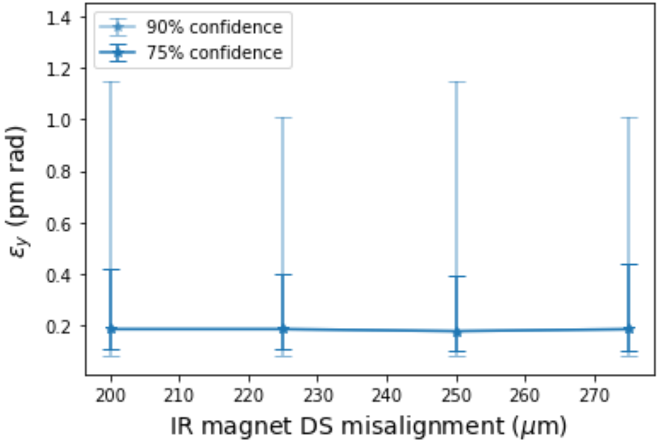




IR magnets: longitudinal alignment (ΔS)

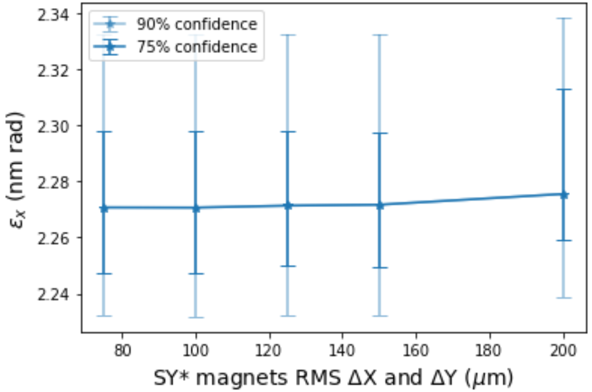
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
IR quadrupole	100	100	250	varied	100	100
IR sextupoles	100	100	250	varied	100	100
All other magnets	as listed in Table on slide 7					

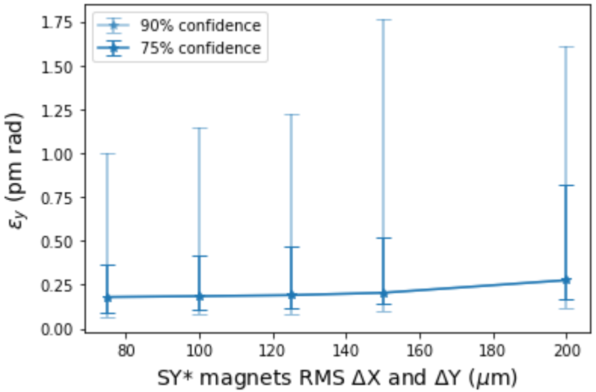




SY* sextupole alignment: ΔX and ΔY

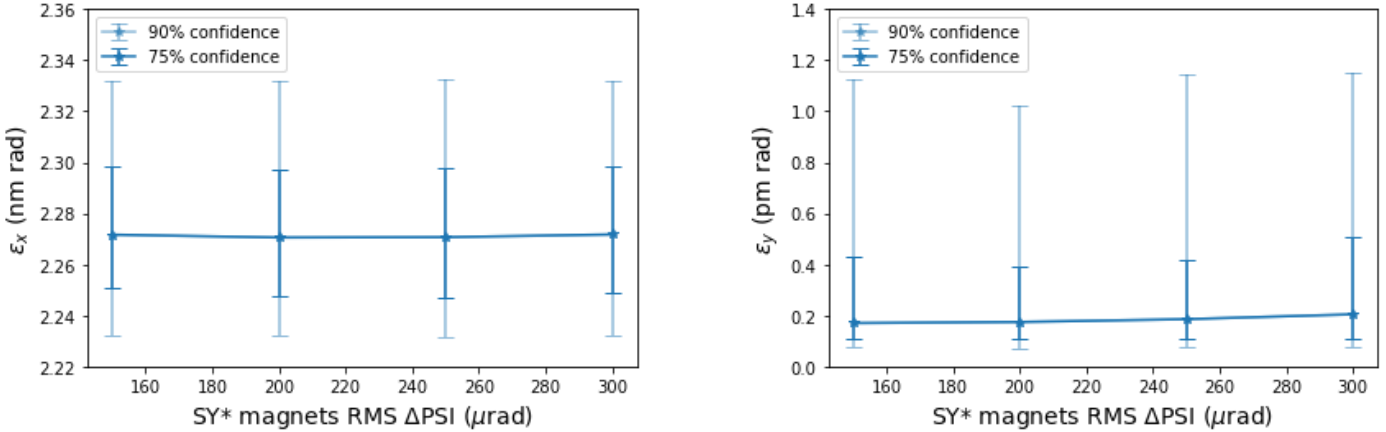
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
QC1*, QC2*	100	250	250	200	100	100
SY sextupoles	varied	varied	250	200	100	100
Other IR quads	100	100	250	200	100	100
Other IR sextupoles	100	100	250	200	100	100
All other magnets	as listed in Table on slide 7					





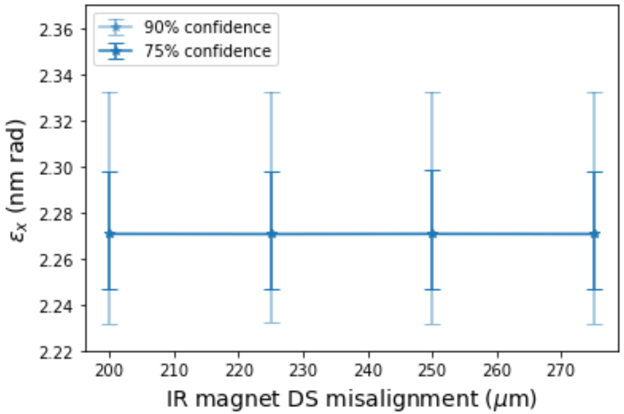
SY* sextupole roll angle: ΔPSI

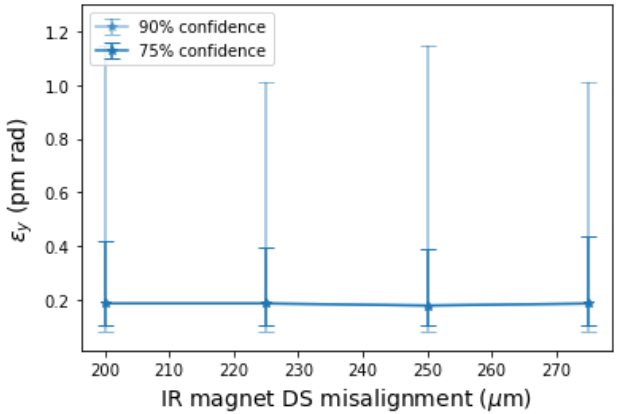
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
QC1*, QC2*	100	250	250	200	100	100
SY sextupoles	100	100	varied	200	100	100
Other IR quads	100	100	250	200	100	100
Other IR sextupoles	100	100	250	200	100	100
All other magnets	as listed in Table on slide 7					



SY* sextupole longitudinal alignment: ΔS

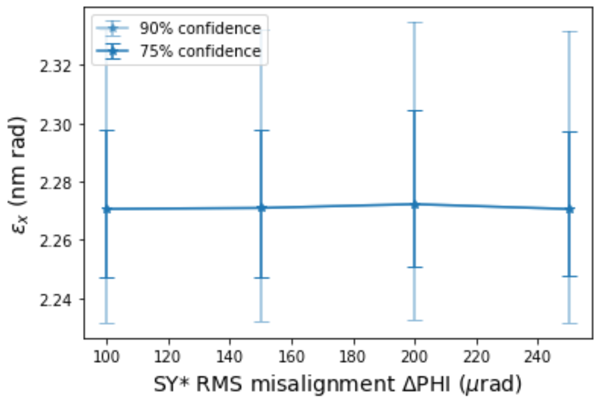
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
QC1*, QC2*	100	250	250	200	100	100
SY sextupoles	100	100	250	varied	100	100
Other IR quads	100	100	250	200	100	100
Other IR sextupoles	100	100	250	200	100	100
All other magnets	as listed in Table on slide 7					

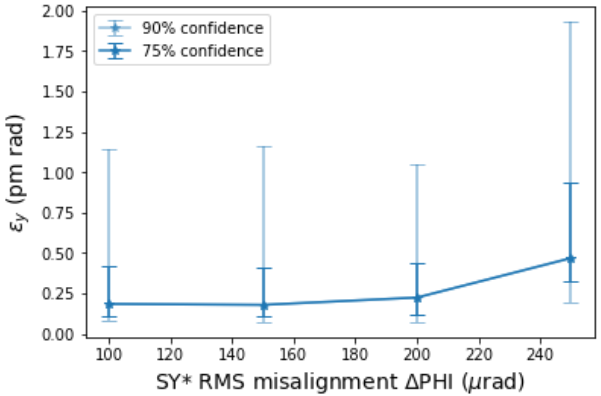




SY* sextupole alignment: ΔPHI

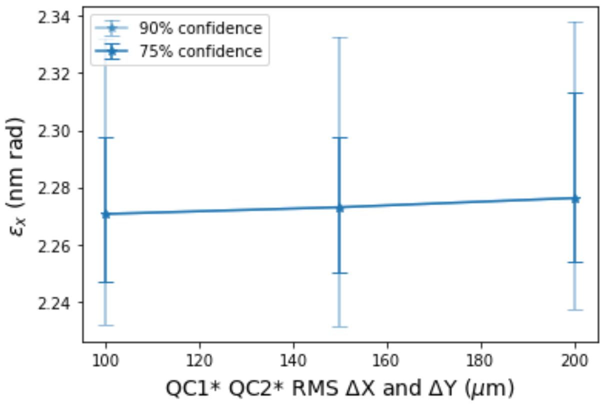
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
QC1*, QC2*	100	250	250	200	100	100
SY sextupoles	100	100	250	200	100	varied
Other IR quads	100	100	250	200	100	100
Other IR sextupoles	100	100	250	200	100	100
All other magnets	as listed in Table on slide 7					

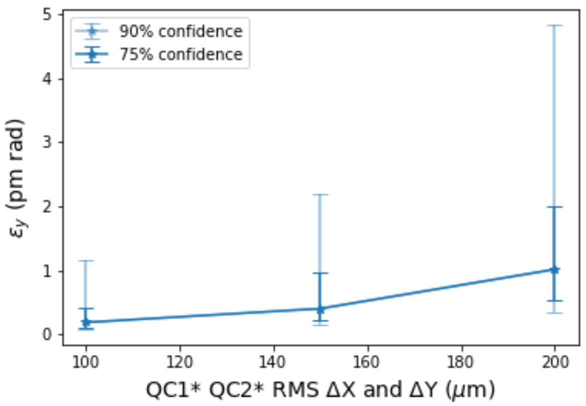




QC1* and QC2* quads alignment: ΔX and ΔY

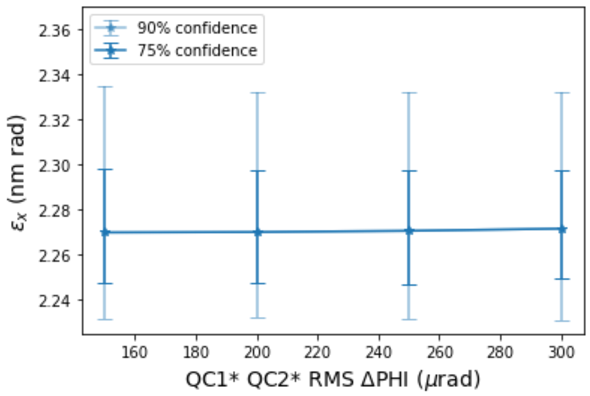
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
QC1*, QC2*	varied	varied	250	200	100	100
SY sextupoles	100	100	250	200	100	100
Other IR quads	100	100	250	200	100	100
Other IR sextupoles	100	100	250	200	100	100
All other magnets	as listed in Table on slide 7					

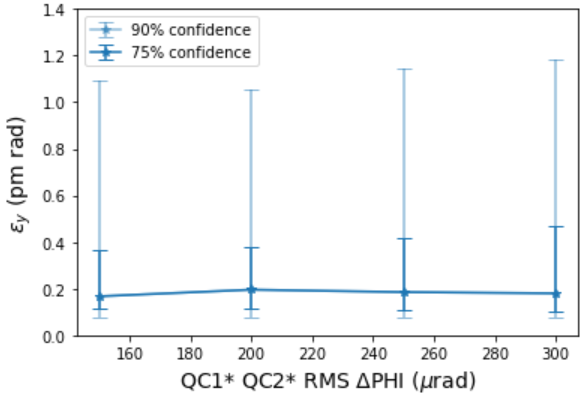




QC1* and QC2* roll angle: ΔPSI

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
QC1*, QC2*	100	100	varied	200	100	100
SY sextupoles	100	100	250	200	100	100
Other IR quads	100	100	250	200	100	100
Other IR sextupoles	100	100	250	200	100	100
All other magnets	as listed in Table on slide 7					

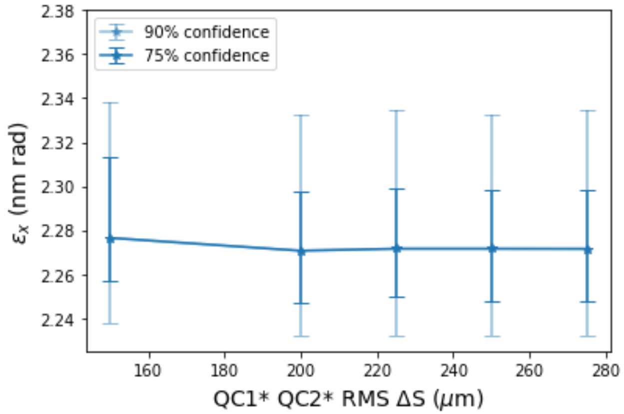


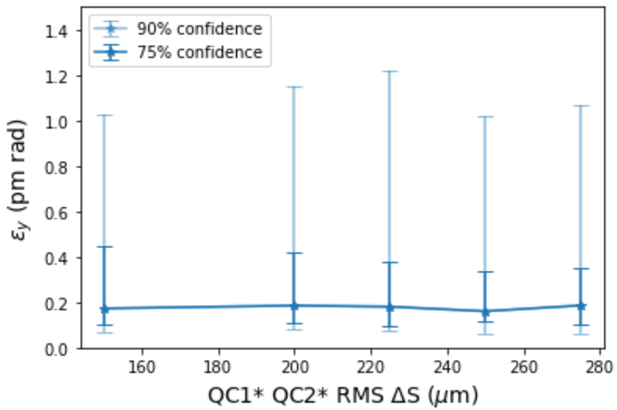


Whilst the equilibrium emittance after global correction is not strongly influenced by QC1 and QC2 misalignments, local corrections are needed which might require that these magnets are aligned to high precision.

QC1* and QC2* longitudinal alignment: ΔS

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
QC1*, QC2*	100	100	250	varied	100	100
SY sextupoles	100	100	250	200	100	100
Other IR quads	100	100	250	200	100	100
Other IR sextupoles	100	100	250	200	100	100
All other magnets	as listed in Table on slide 7					

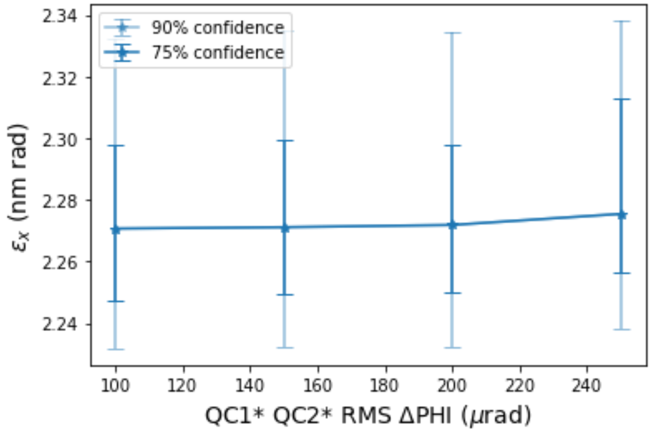


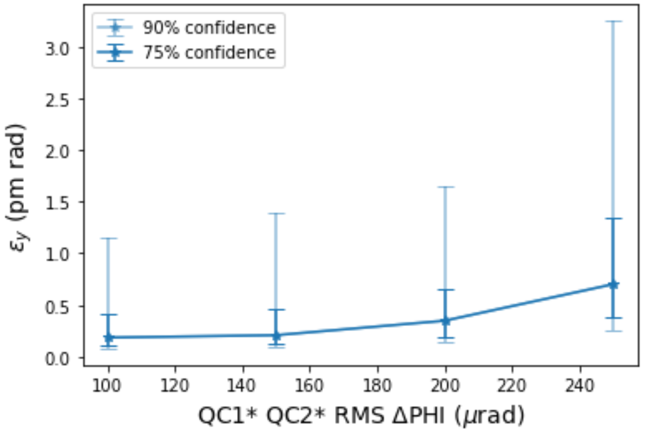


Whilst the equilibrium emittance after global correction is not strongly influenced by QC1 and QC2 misalignments, local corrections are needed which might require that these magnets are aligned to high precision.

QC1* and QC2* alignment: ΔPHI

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
QC1*, QC2*	100	100	250	200	100	varied
SY sextupoles	100	100	250	200	100	100
Other IR quads	100	100	250	200	100	100
Other IR sextupoles	100	100	250	200	100	100
All other magnets			as listed in Table on slide 7			





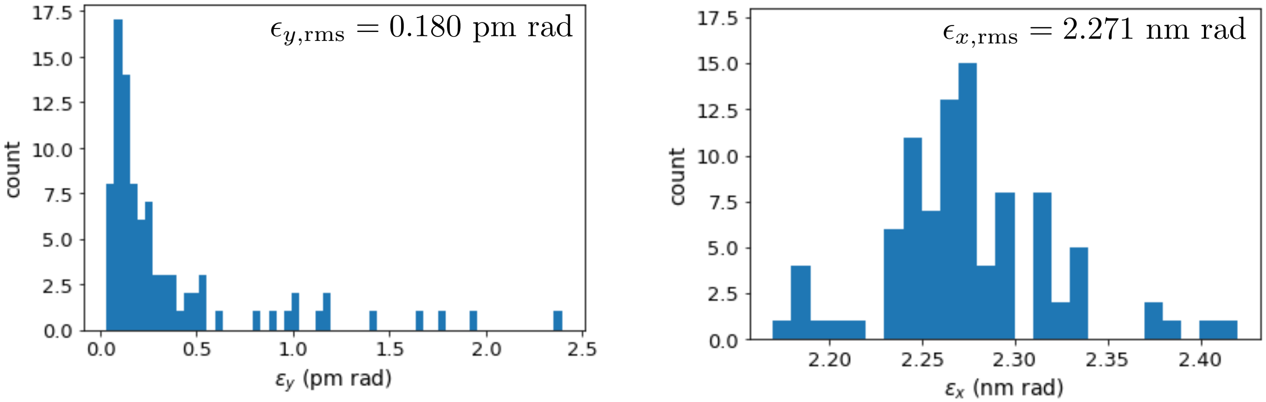
Next steps

- Include solenoid misalignment into simulations
- Establish the most realistic modelling for BPM errors (e.g. non-linear responses, calibration measures for rotated BPMs, non-Gaussian BPM offset distributions)
- Investigate the few seeds that results in vertical emittances > 2 pm rad
- Apply correction technique to low energy, Z lattice
- Local corrections for vertical dispersion at the IP
- Determine how to apply corrections quickly
  - LOCO is 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 and the settings of the BPMs.

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 0.180 pm rad and horizontal emittance of 2.271 nm rad.



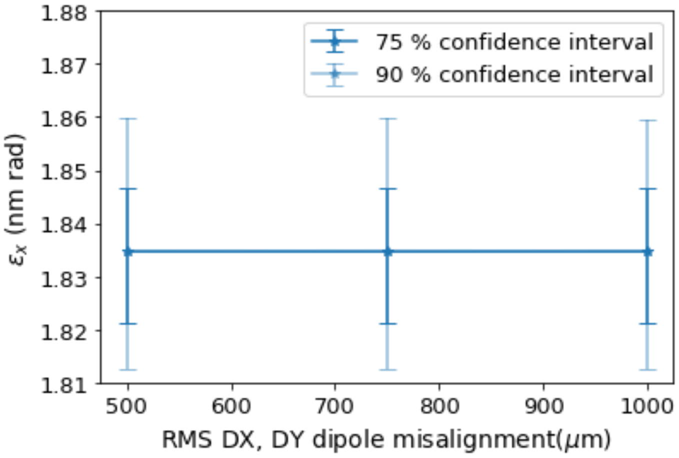
FCC

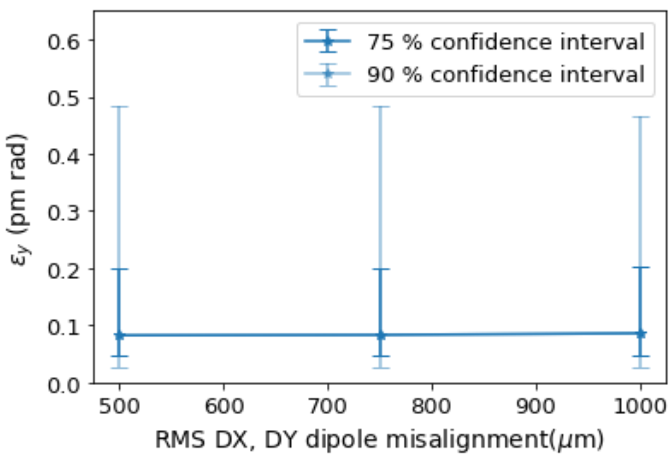
Thank you for your attention.

Dipole misalignments

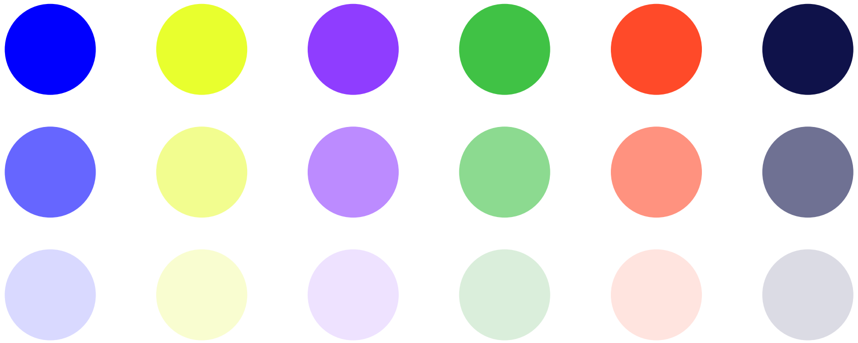
Transverse dipole misalignments have little influence on final emittances achievable.

Data from FCC week 2020.





COLORS



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

BACKGROUNDS

Background Blue

Background Purple

Background Yellow

Background Grey

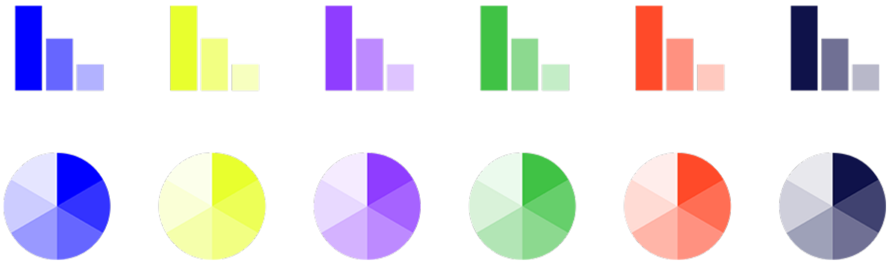
Use for Layout

GRAPHICAL ELEMENTS

Separation lines 1.5 pt

Arrows

INFOGRAPHICS



BADGES

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