Emittance tuning simulations and next steps

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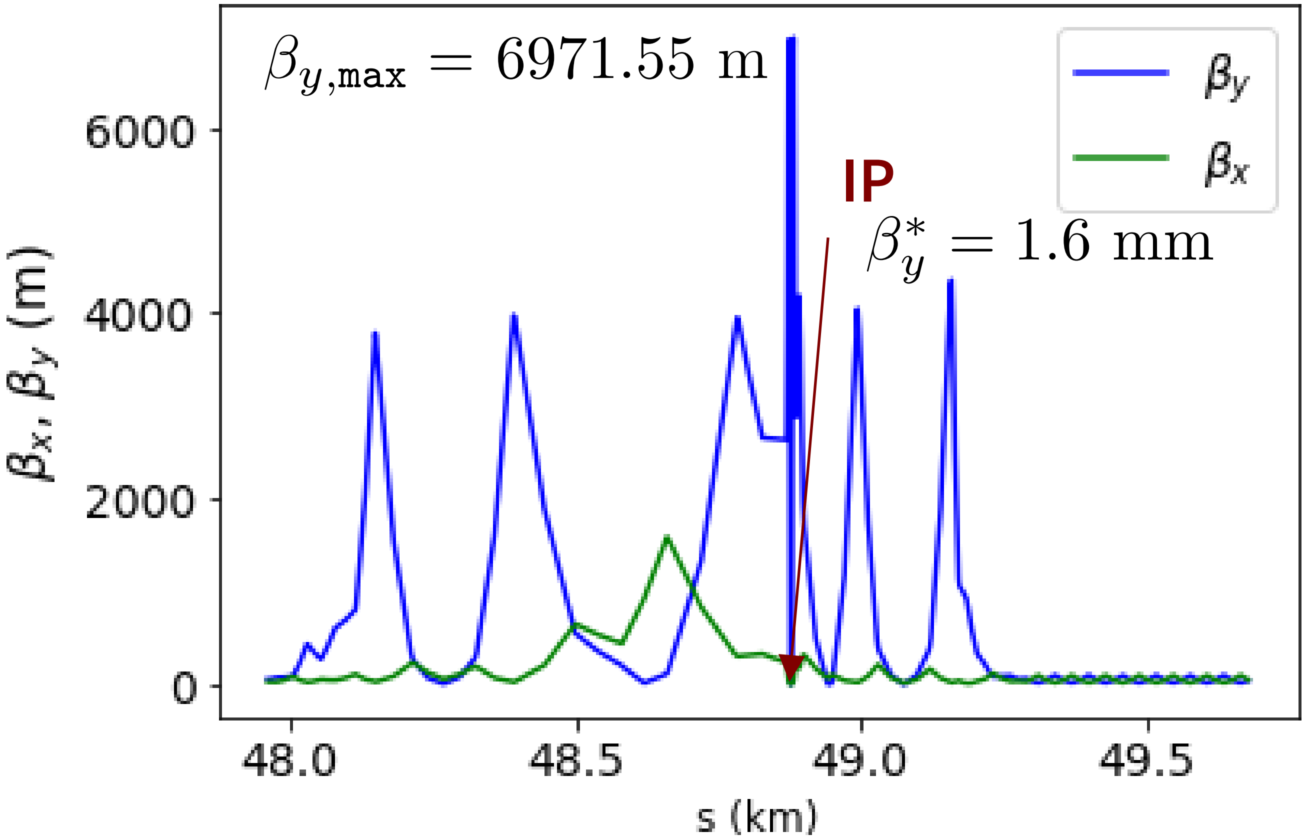
FCC-ee Emittance Tuning: Challenges & Constraints

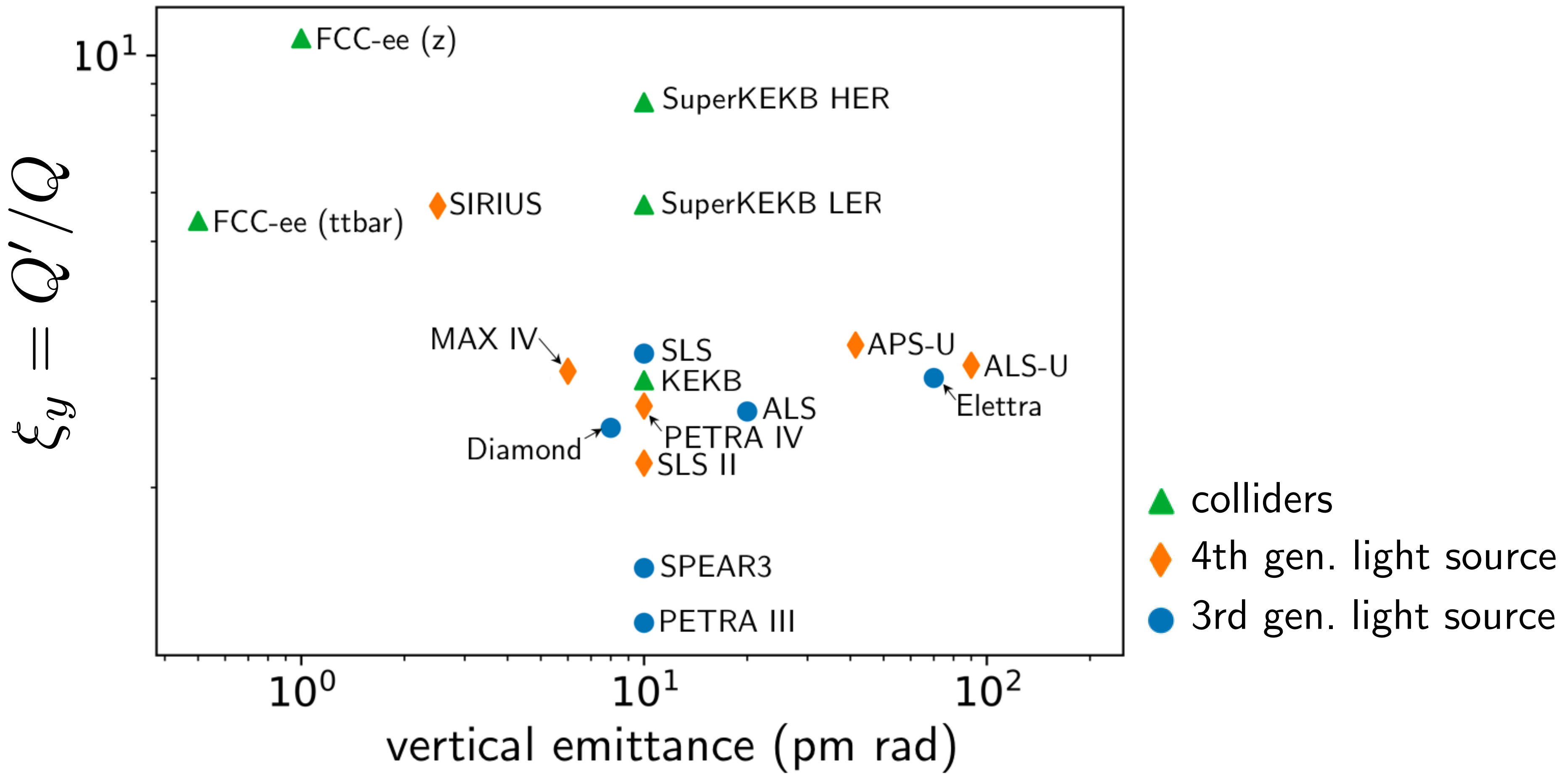


Small emittance ratio, $\frac{\epsilon_y}{\epsilon_x} < 0.2\ \%$

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 (KEK), Liu Lin (LNLS), Simone Di Mitri (Elettra), Jeff Corbett (SLAC), Bernhard Holzer (CERN), Ian Martin (Diamond)

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)

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

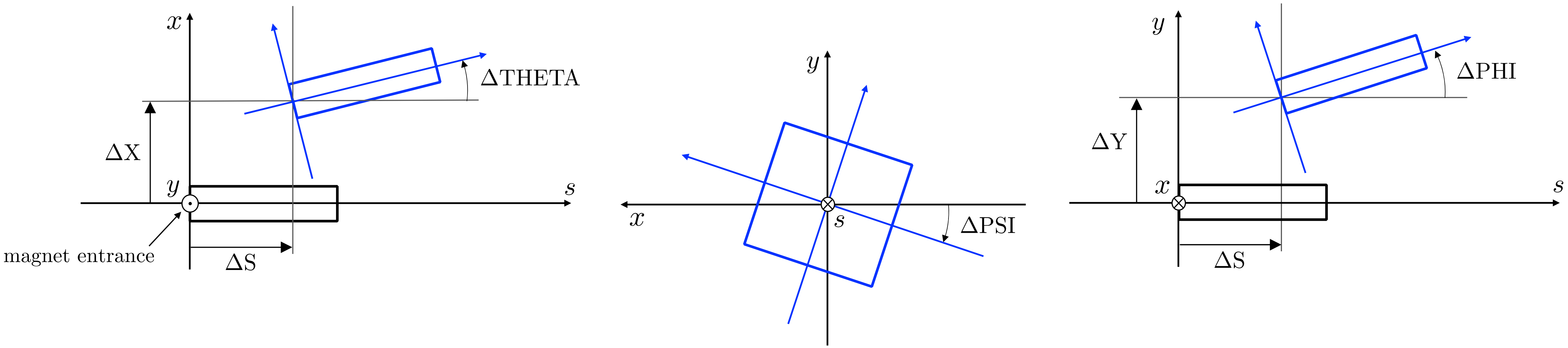
- Linear coupling:
  - Coupling resonant driving terms (RDT)
    - 1 skew at each sextupole + skews correctors at the IP

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

- Beta beating correction & Horizontal dispersion via Response Matrix:
  - Rematching of the phase advance at the BPMs
    - 1 trim quadrupole at each sextupole

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

Assigning misalignments

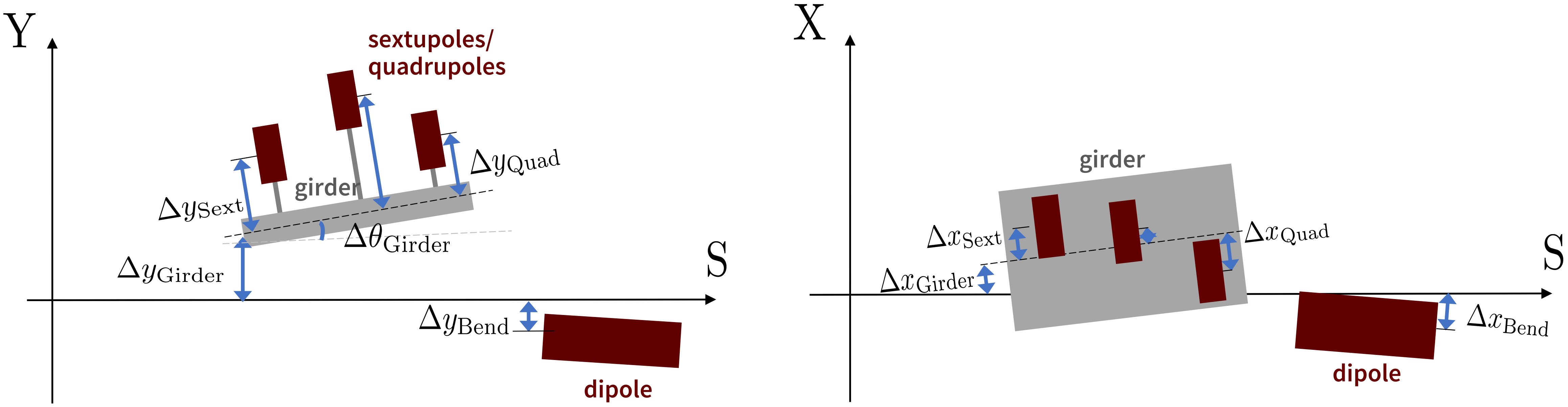


- Misalignment randomly distributed via a Gaussian, truncated at 2.5 sigma.

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

Assigning girder misalignments

Arc quadrupoles and sextupoles are misaligned relative to a girder misalignment, incorporating misalignment due to Δy_{girder} and $\Delta\theta$.



(not to scale)

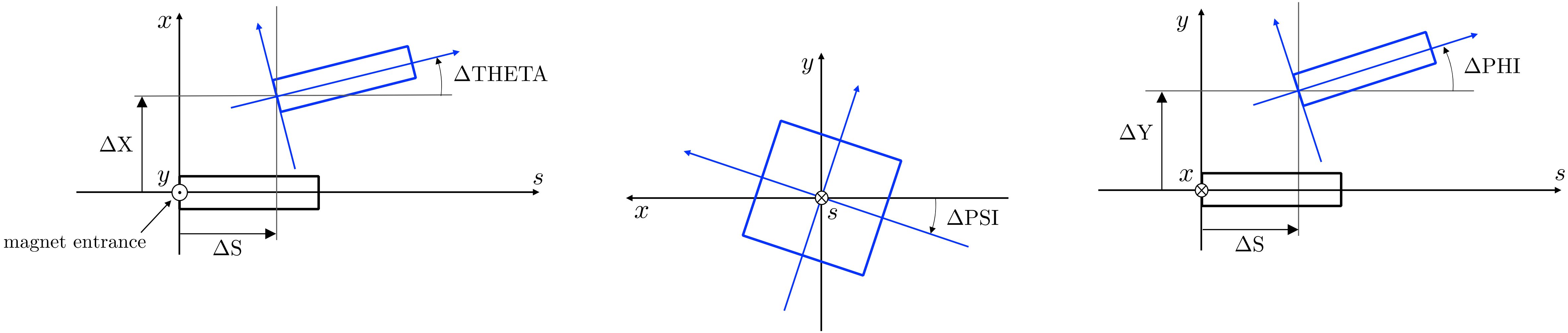
Assigning misalignments

Possibly still too tight

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	Field Errors
Arc quadrupole*	50	50	200	50	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	50	50	200	50	$\Delta k/k = 2 \times 10^{-4}$
Girders	150	150	-	500	-
Dipoles	1000	1000	200	500	$\Delta B/B = 1 \times 10^{-4}$
IR quadrupole	75	75	100	150	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	75	75	100	150	$\Delta k/k = 2 \times 10^{-4}$
BPM**	40	40	100	-	-

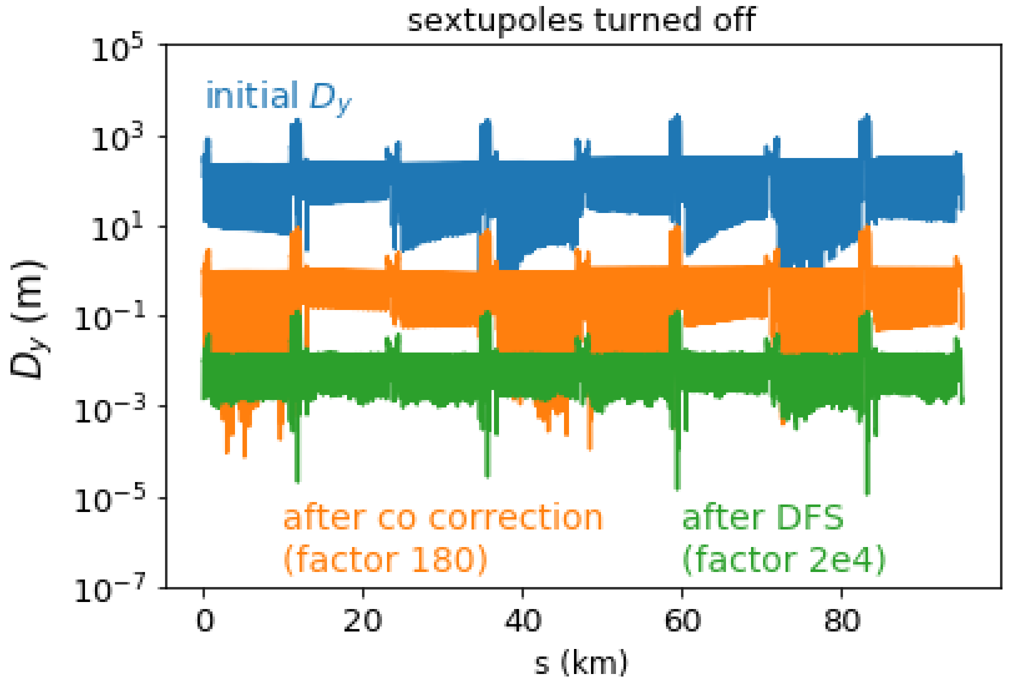
* misalignments relative to girder placement

** misalignments relative to quadruple placement



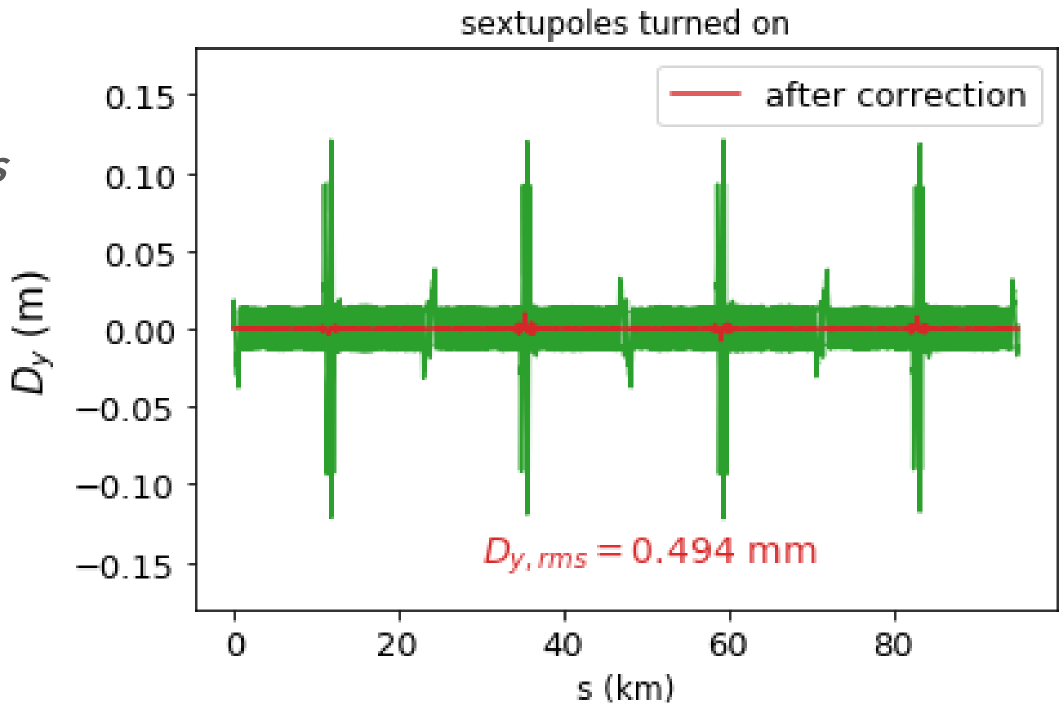
The starting situation….

Orbit correction +DFS (sextupoles off)



Switch on sextupoles

Dispersion and coupling correction (sextupoles on)



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)
Arc quadrupole*	50	50	200	50
Arc sextupoles*	50	50	200	50
Dipoles	1000	1000	200	500
Girders	150	150	-	500
IR quadrupole	75	75	200	150
IR sextupoles	75	75	200	150
BPM**	40	40	100	-

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

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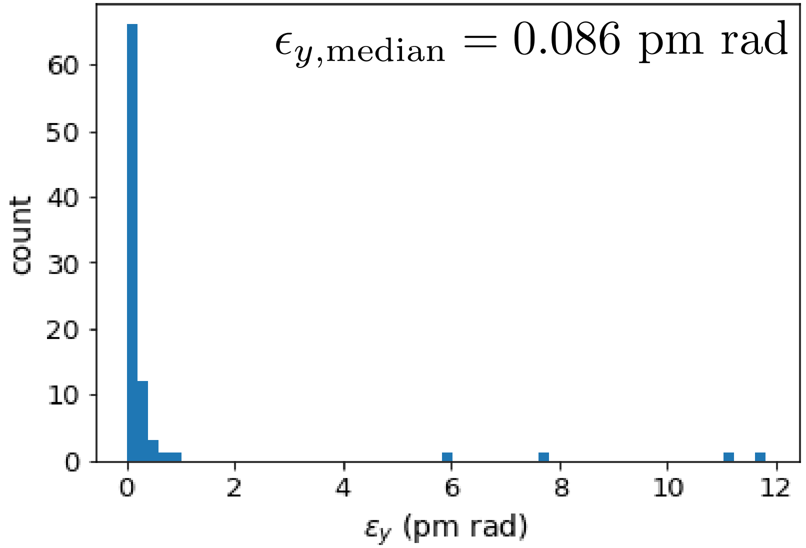
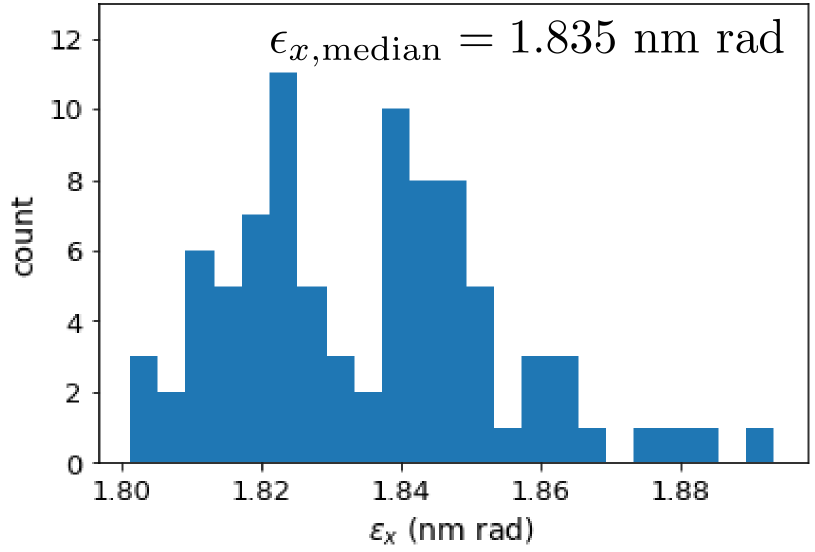
ttbar (182.5 GeV) 4IP lattice,
after correction strategy:





FCC-ee emittance tuning results

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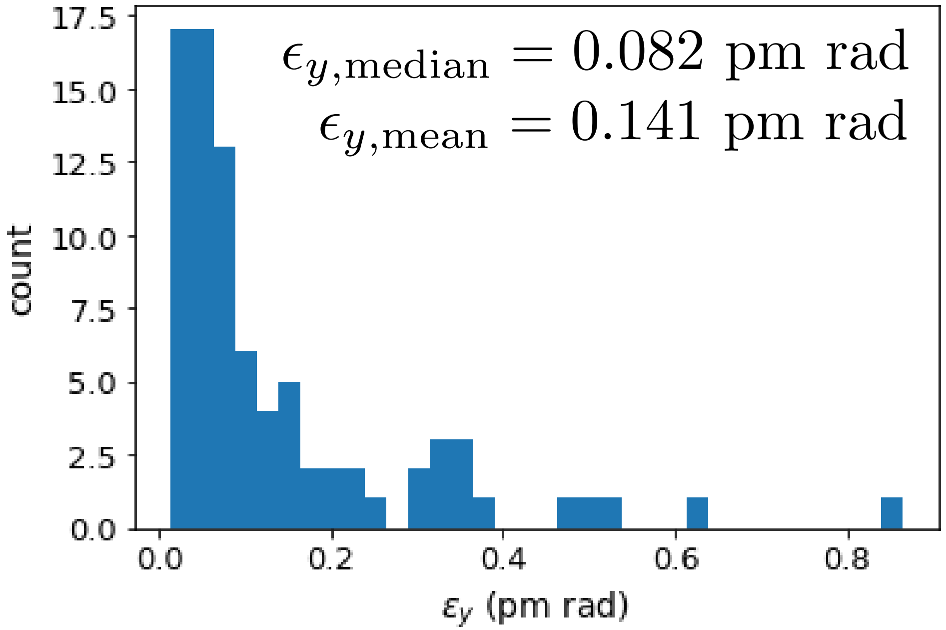
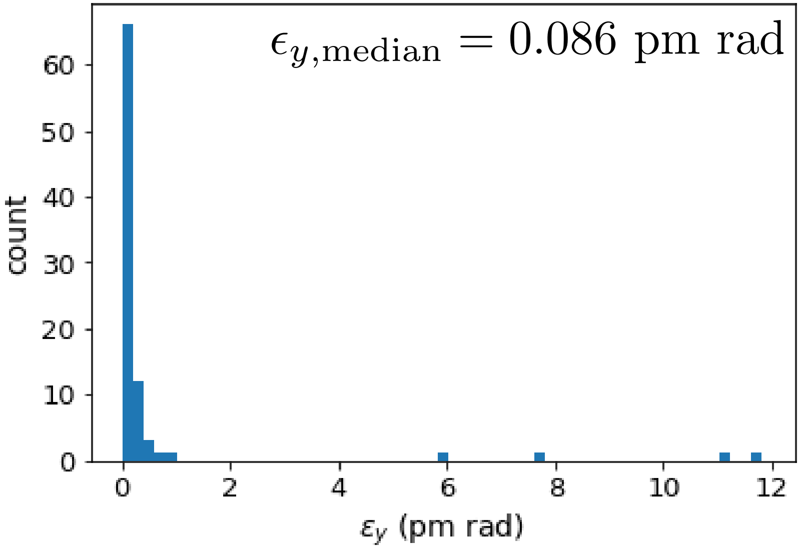
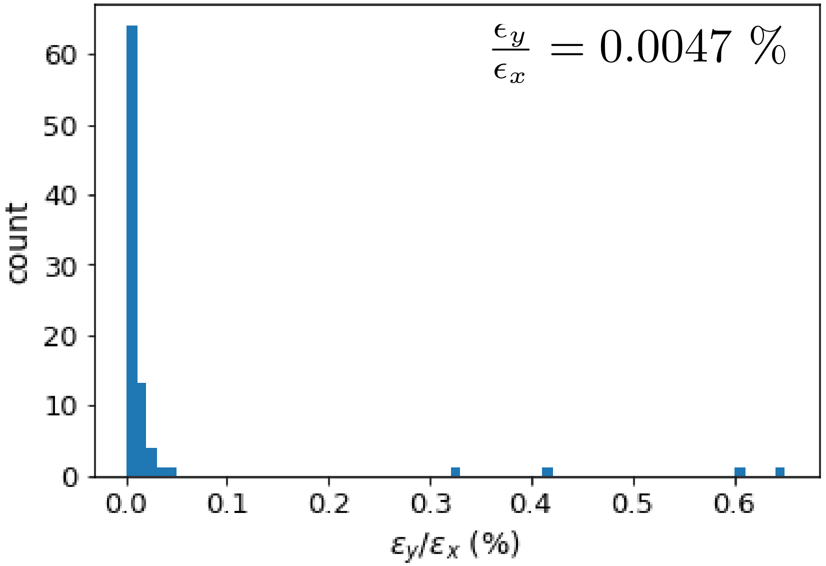


Removing 4 seeds with $\varepsilon_y > 5$ pm rad





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* misalignments relative to girder placement
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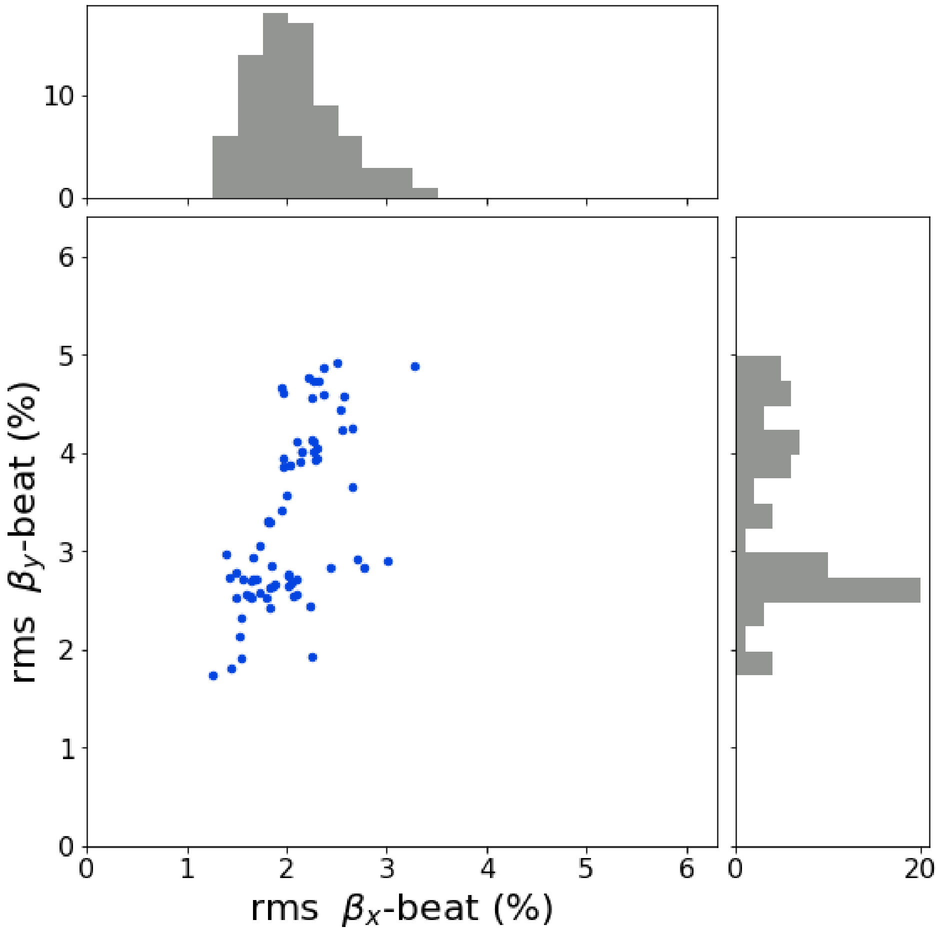
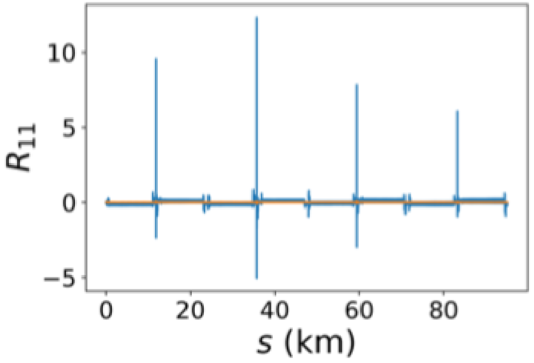
ttbar (182.5 GeV) 4IP lattice, after correction strategy:

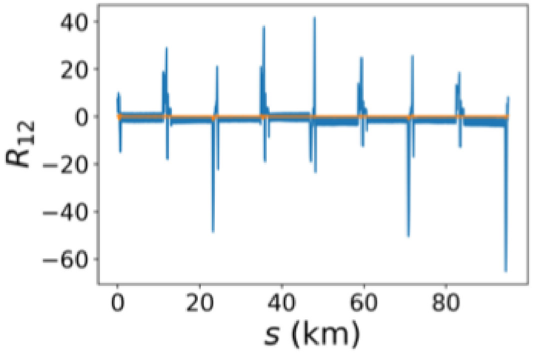


Coupling matrix elements

Before correction (without sextupoles)

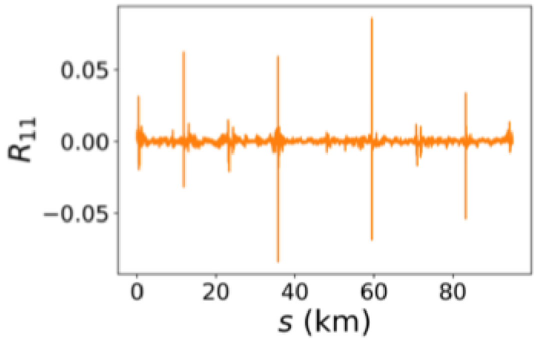


(a)

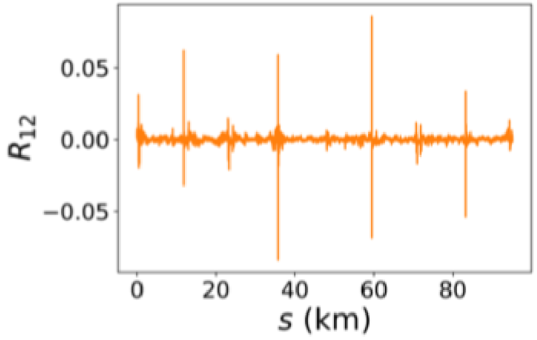


(c)

After correction (with sextupoles)

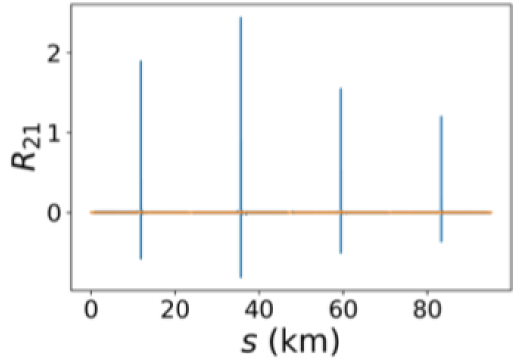


(b)

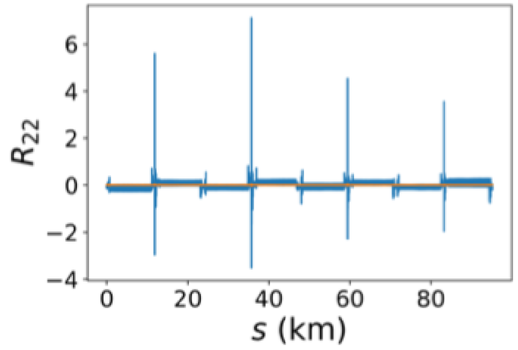


(d)

Before correction (without sextupoles)

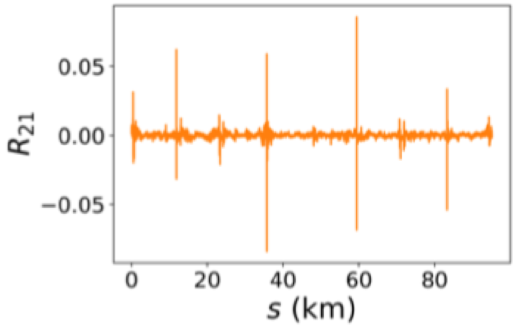


(e)

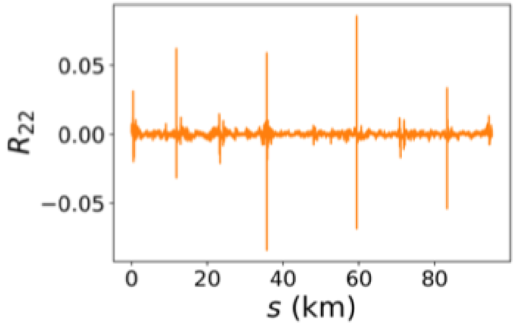


(g)

After correction (with sextupoles)



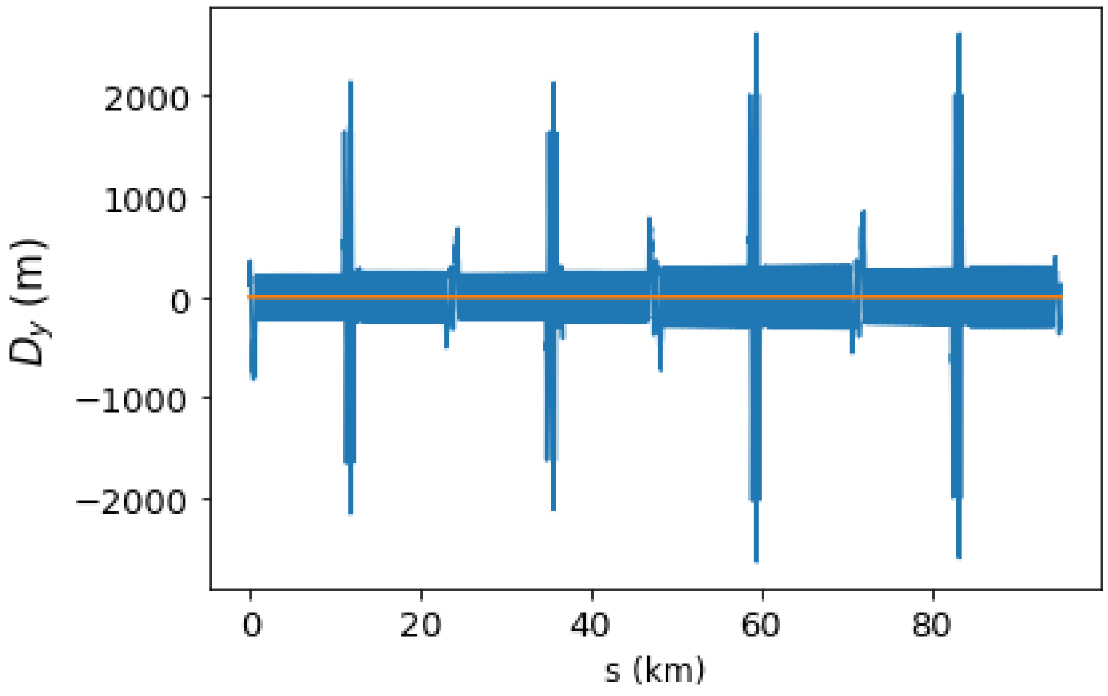
(f)



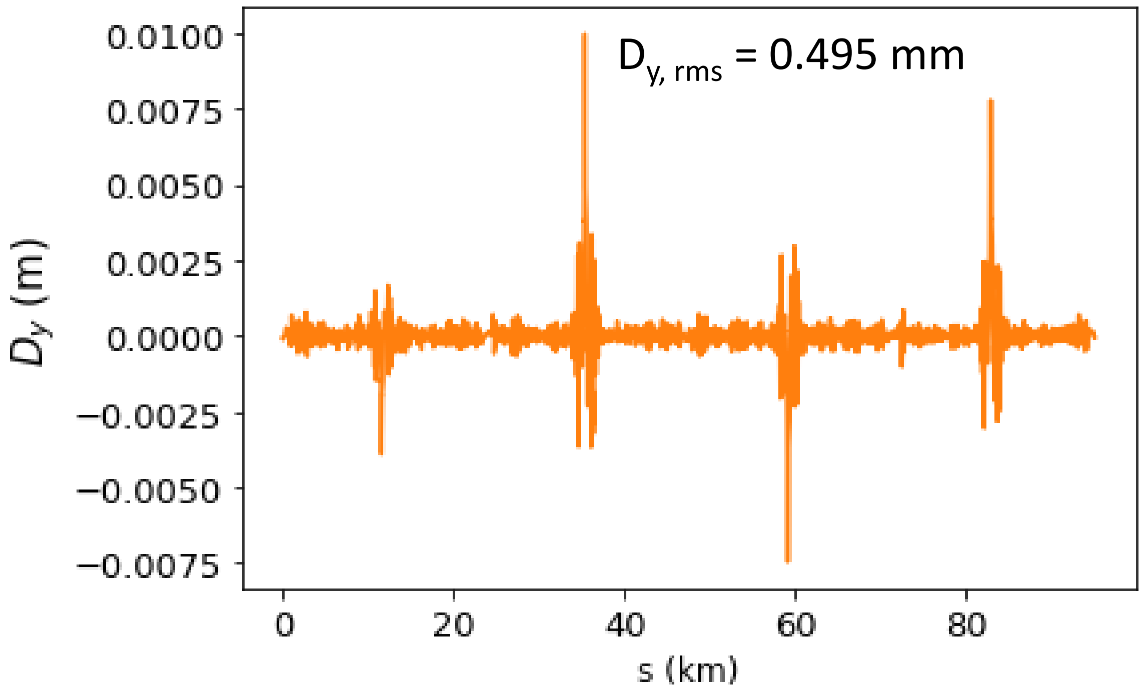
(h)

Vertical dispersion

Before correction
(without sextupoles)



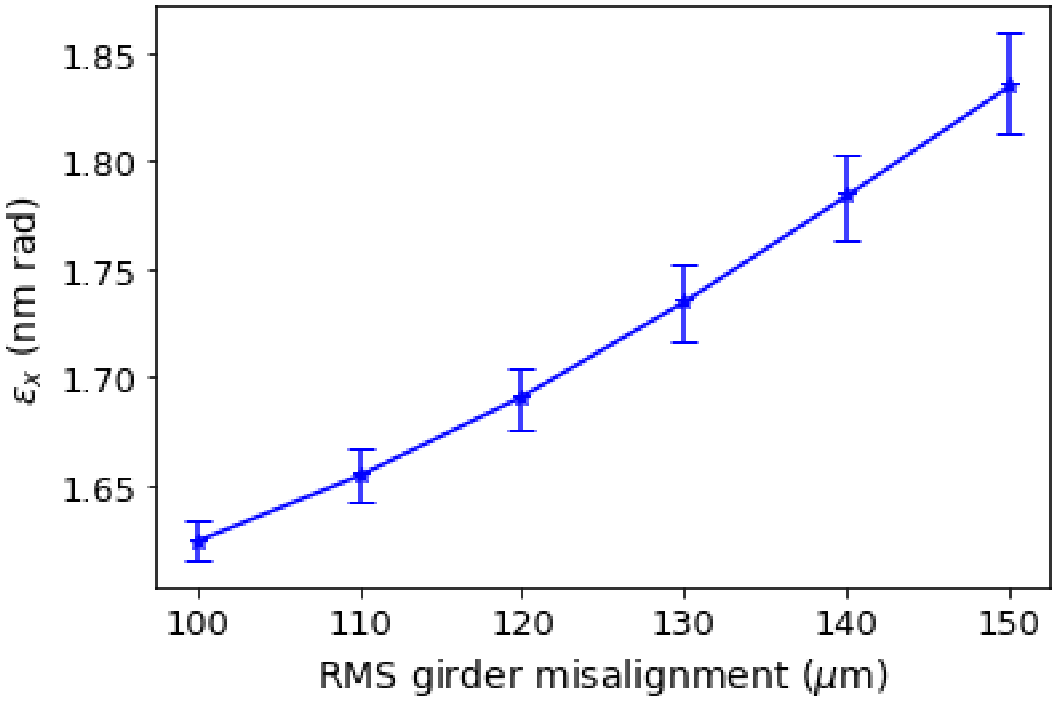
After correction
(with sextupoles)

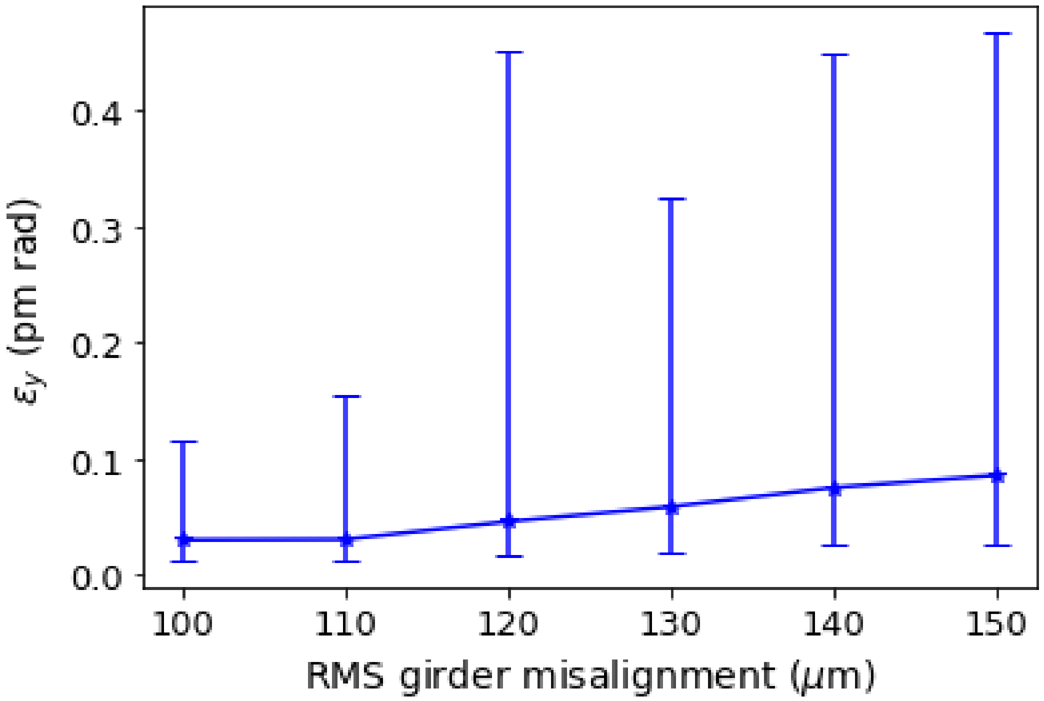


Girder misalignment

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

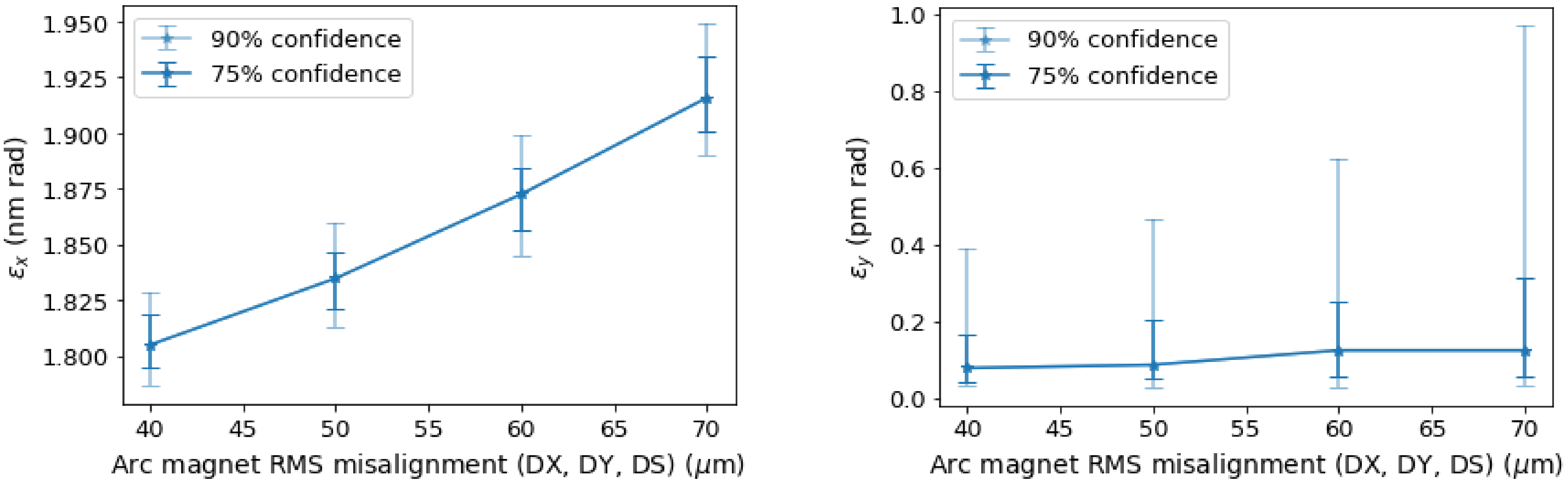
error bars = 90% confidence interval





All other misalignments are as defined previously (slide 15).

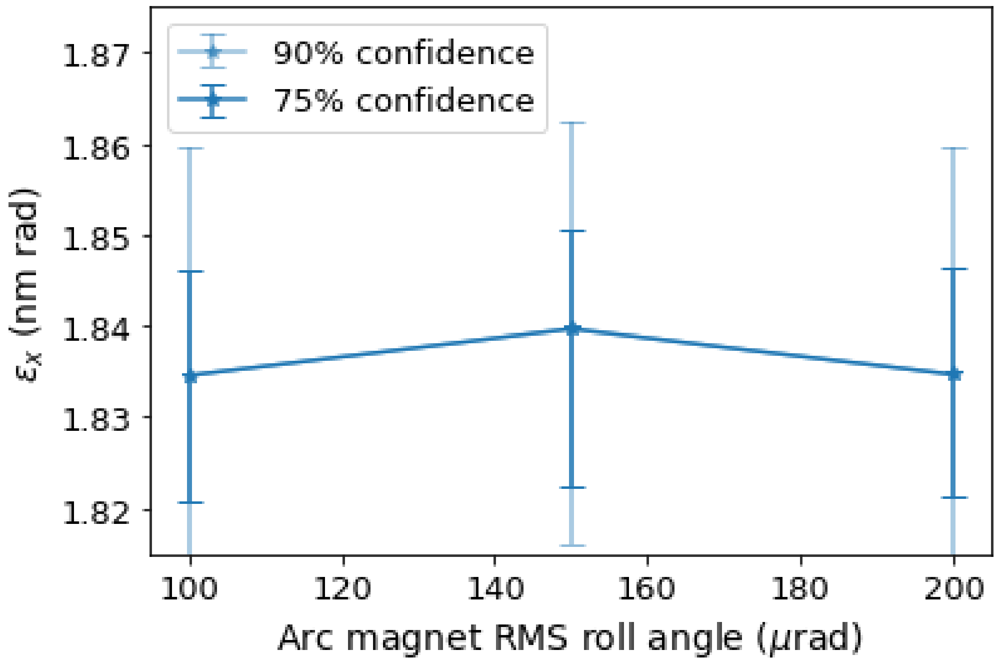
Arc magnet misalignments

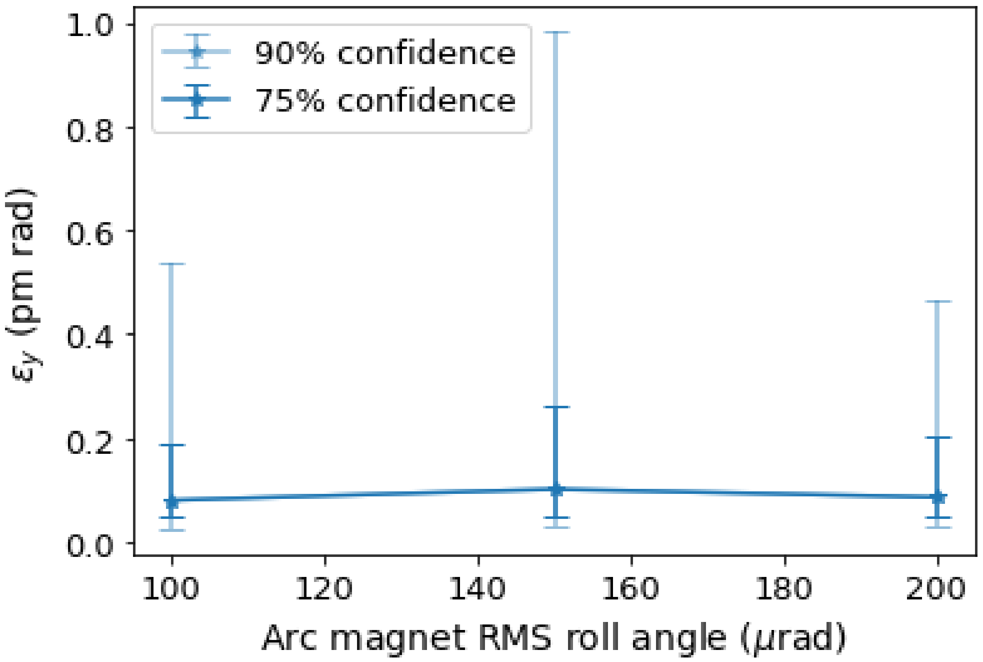


All other misalignments are as defined previously (i.e. girder DX and DY = 150 μm).

Arc magnet roll angles

Arc magnet roll angles of up 200 μrad can be handled by the correction strategy. This could be extended beyond 200 μrad if necessary.

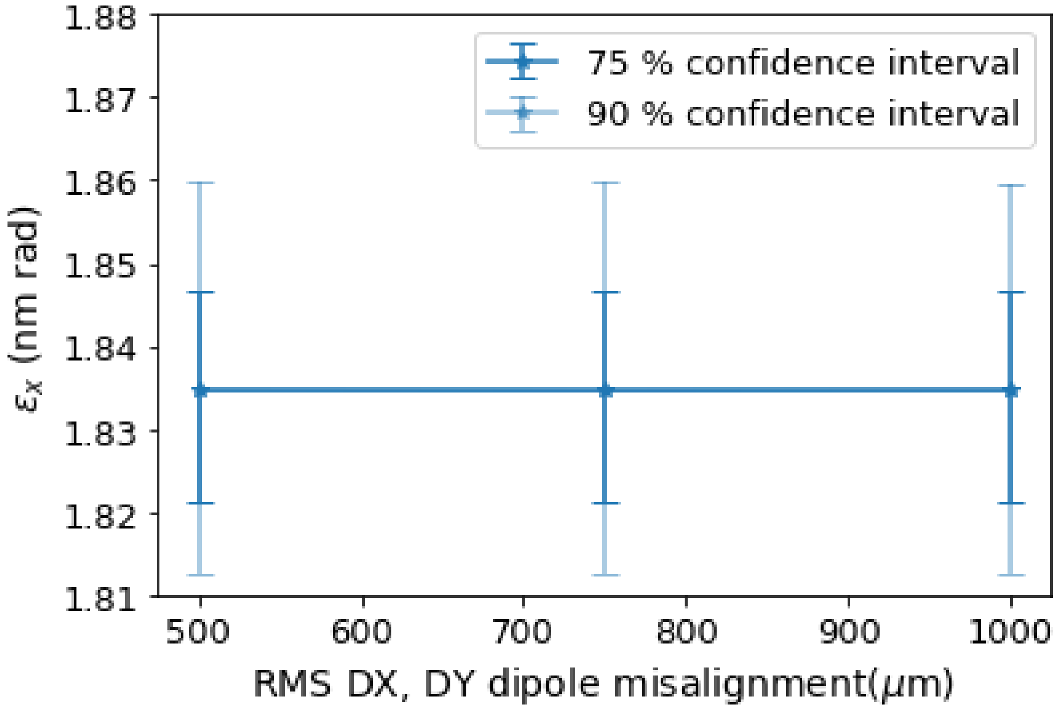


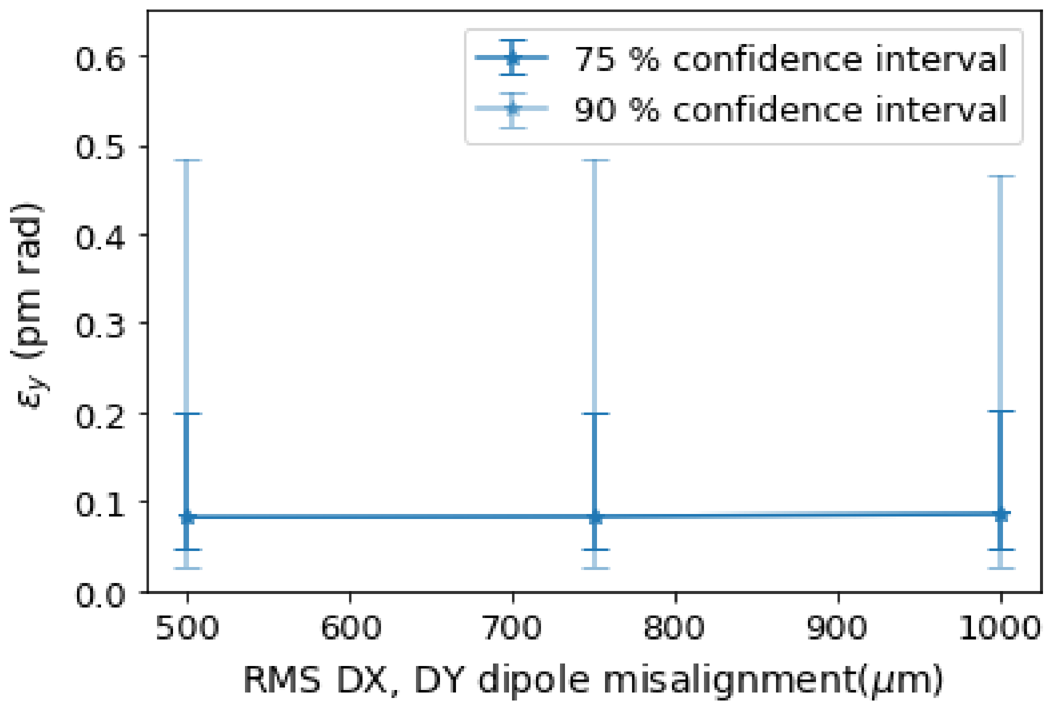


All other misalignments are as defined previously.

Dipole misalignments

Transverse dipole misalignments have little influence on final emittances achievable.



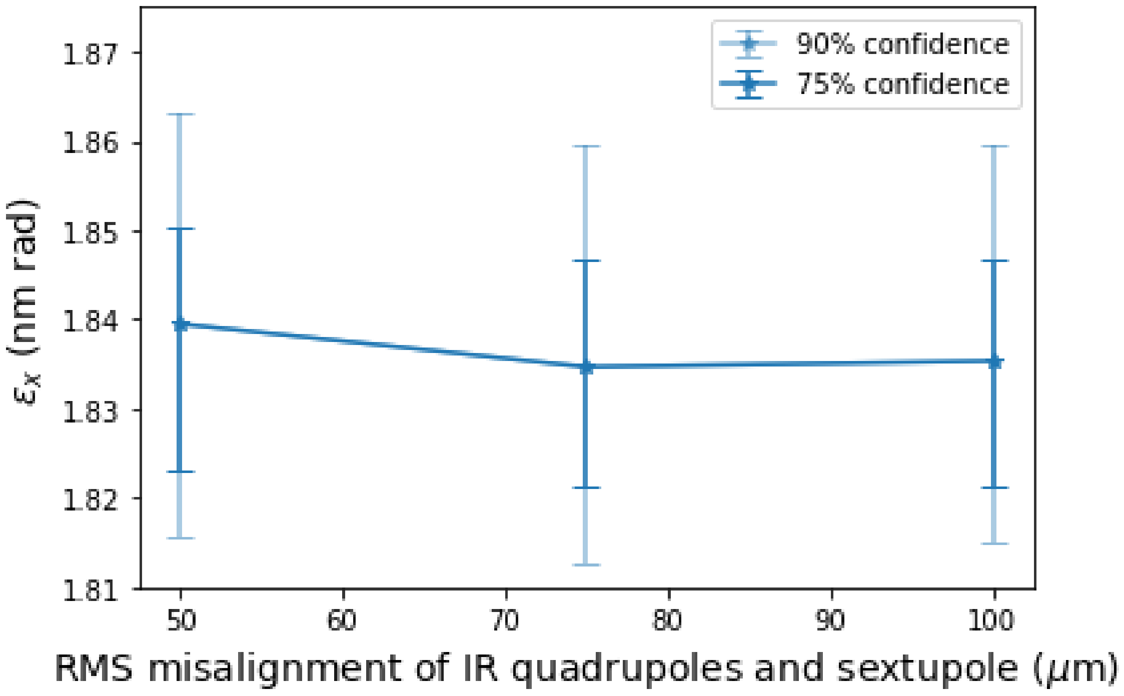


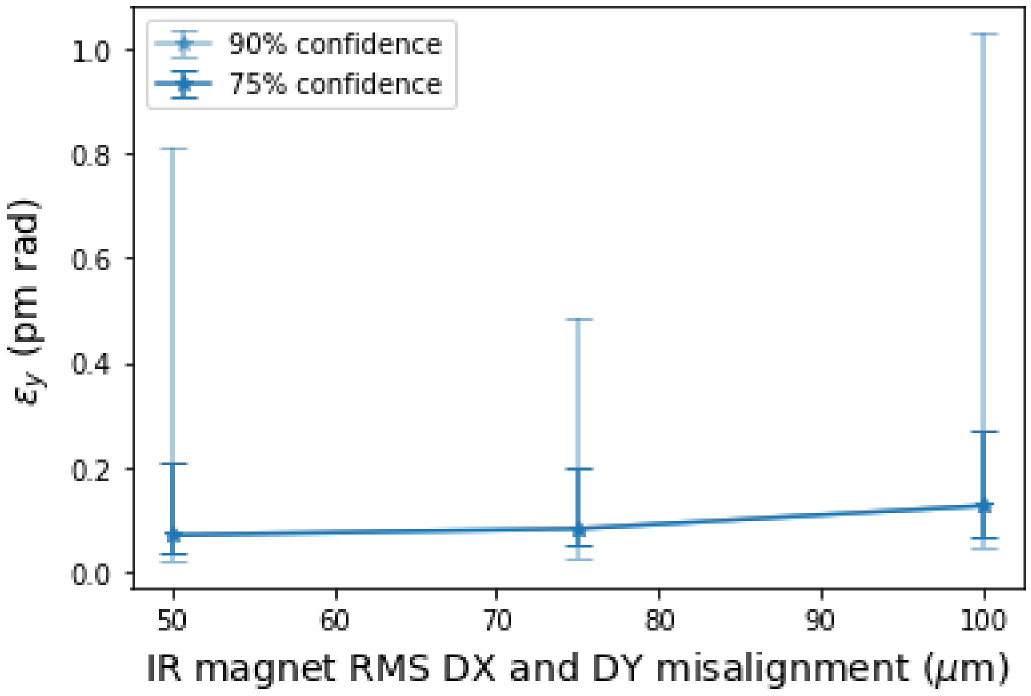
All other misalignments are as defined previously.

IR magnets alignment - transverse misalignments (ΔX and ΔY)

IR magnet misalignments as indicated in table, and all other misalignments are as defined previously (slide 11).

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)
IR quadrupole	varied	varied	200	150
IR sextupoles	varied	varied	200	150





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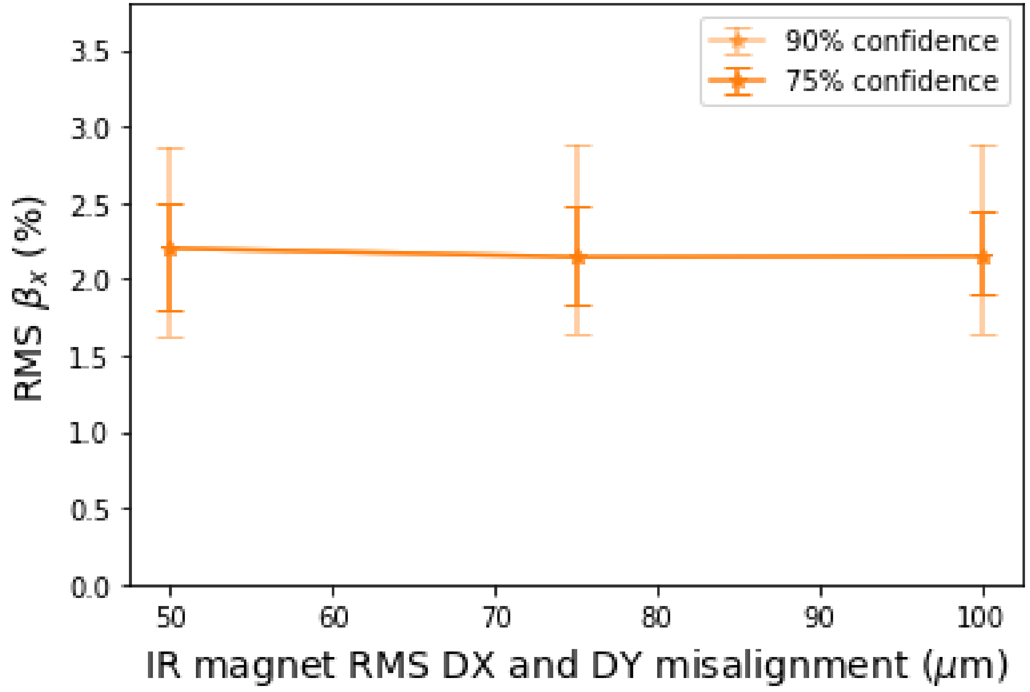
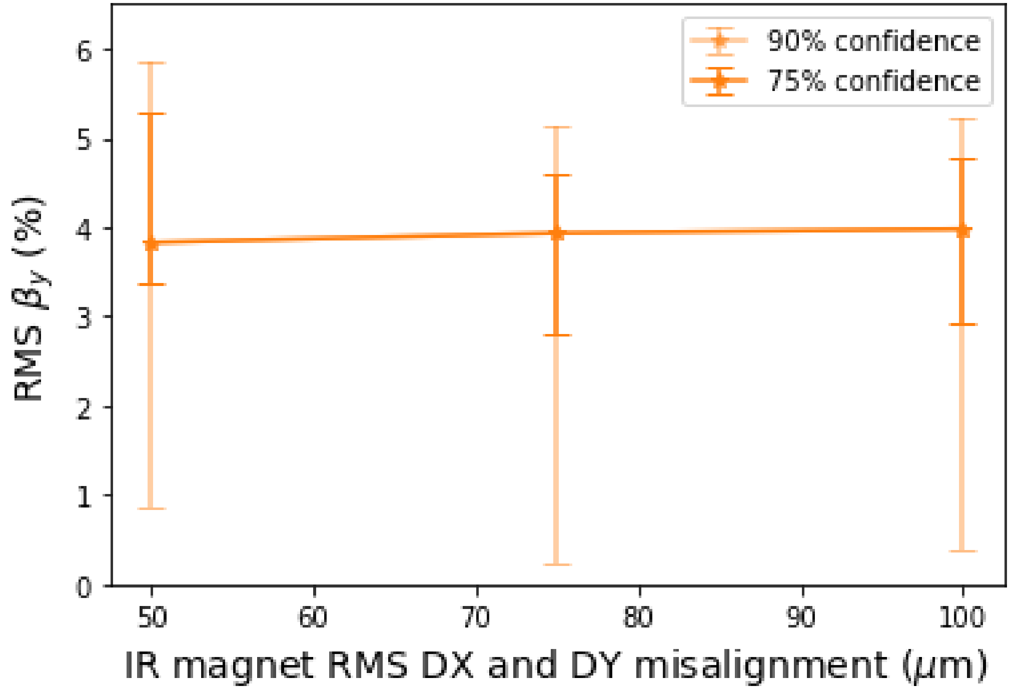
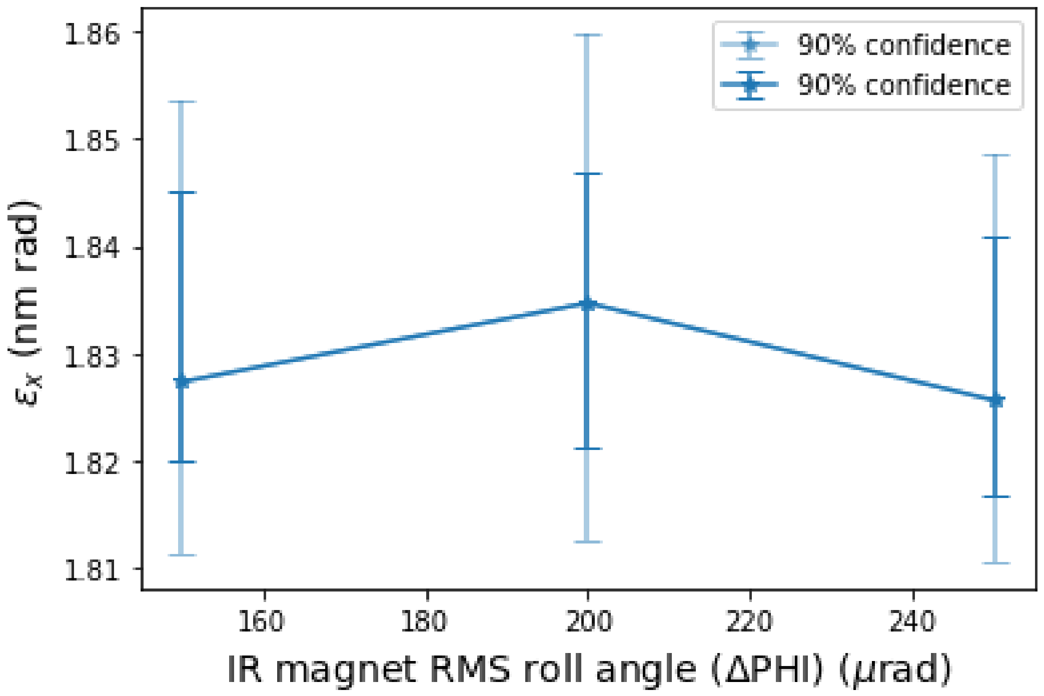


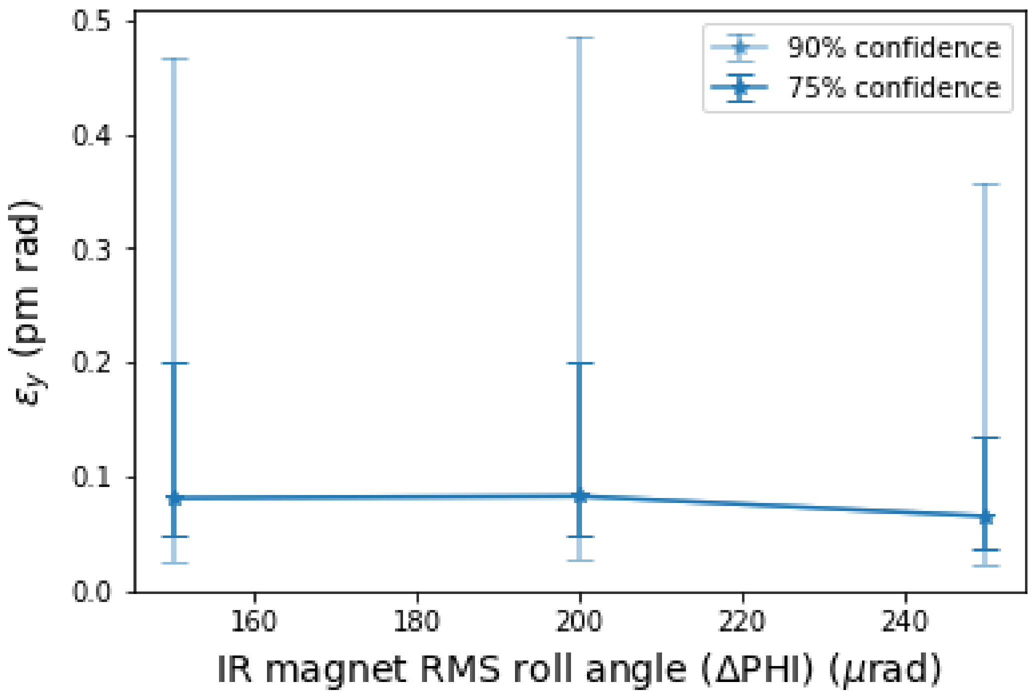


IR magnets alignment – roll angle (ΔPHI)

IR magnet misalignments as indicated in table, and all other misalignments are as defined previously (slide 11).

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)
IR quadrupole	75	75	varied	150
IR sextupoles	75	75	varied	150





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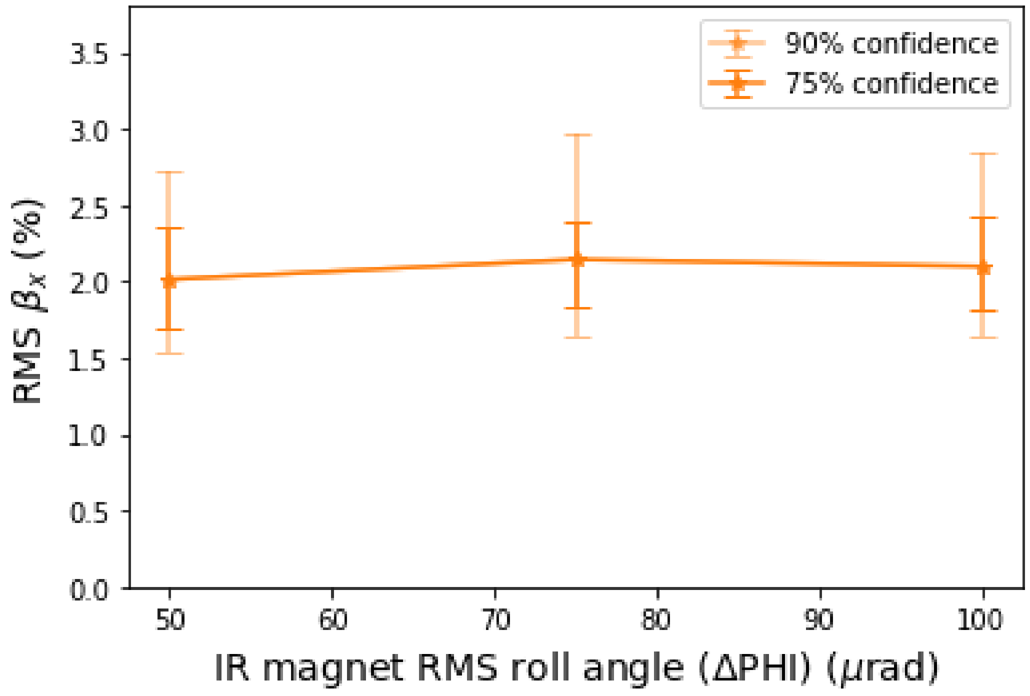
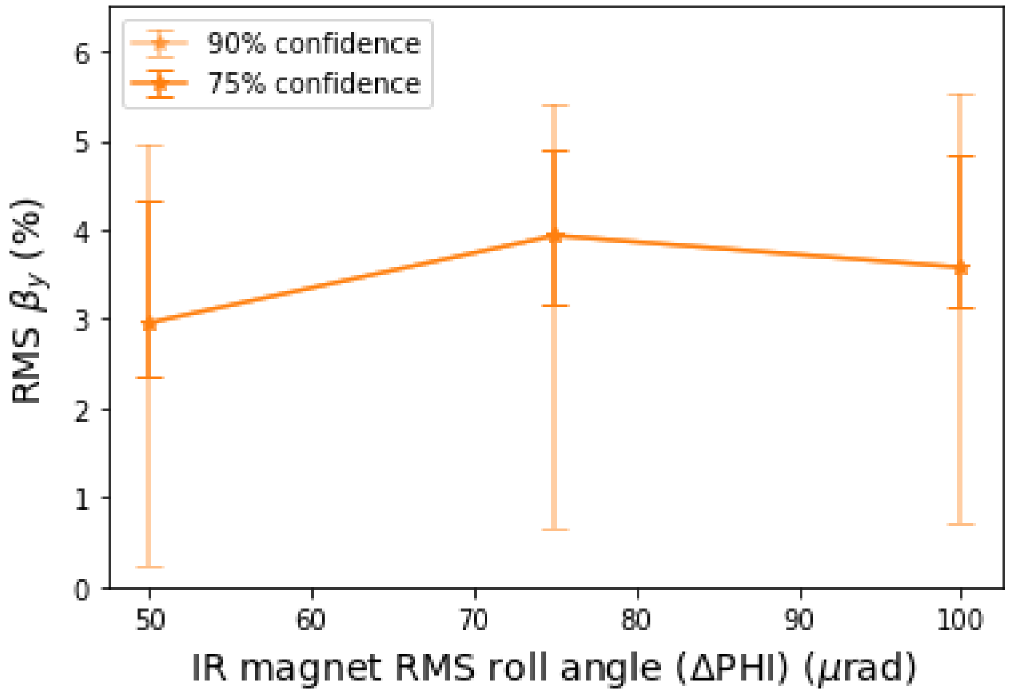


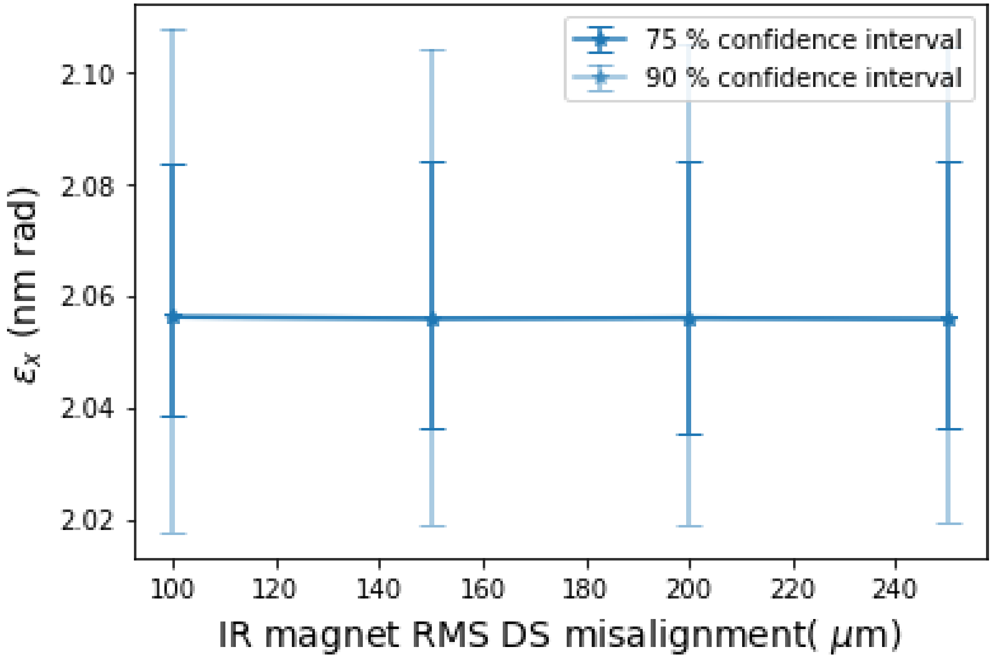


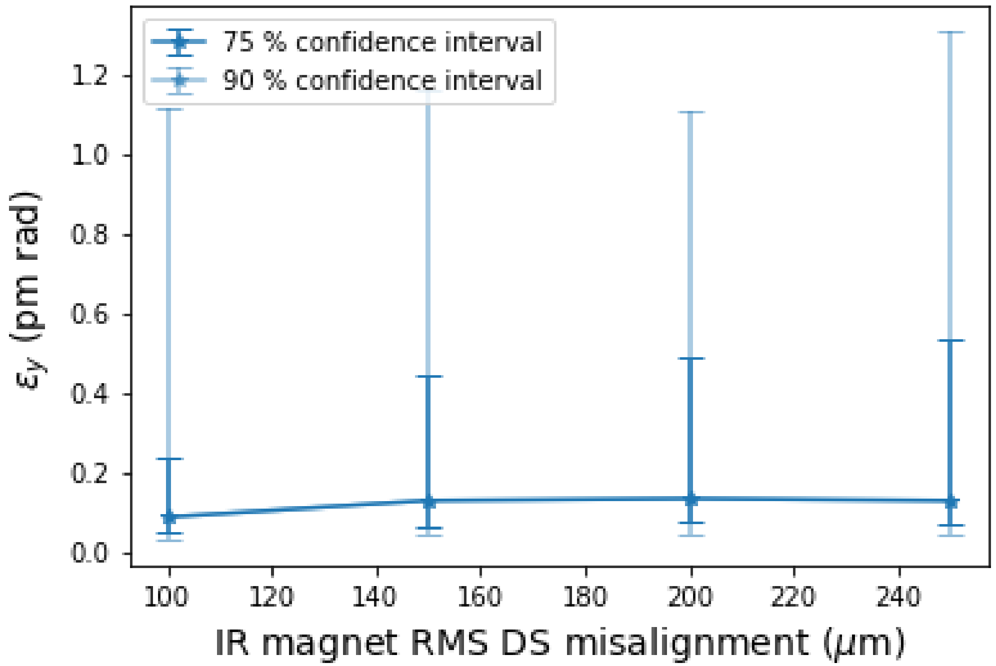
IR magnets - longitudinal alignment (ΔS)

IR magnets and girders misalignments as indicated in tables, with all other misalignments are as defined on slide 11.

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)
girder	100	100	-	500
IR quadrupole	100	100	200	varied
IR sextupoles	100	100	200	varied

This data was taken from older simulation results, with different girder misalignment. Nevertheless, these results can be used to investigate the trends.





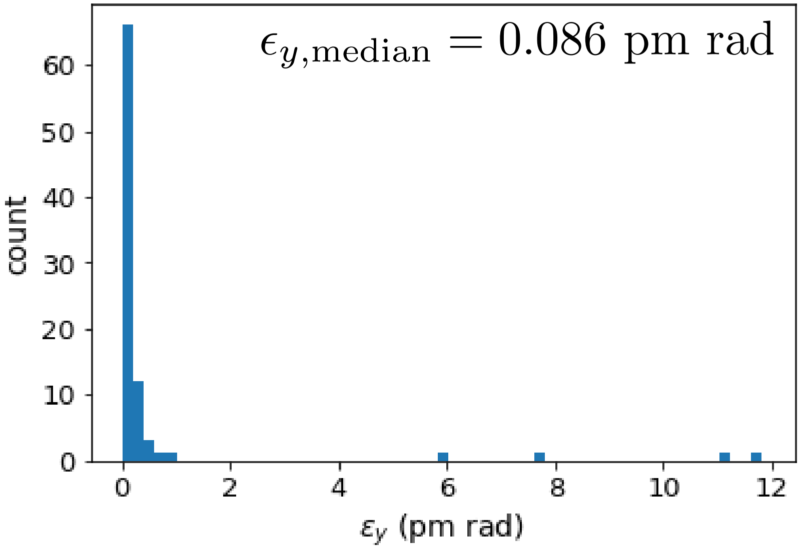
Next steps

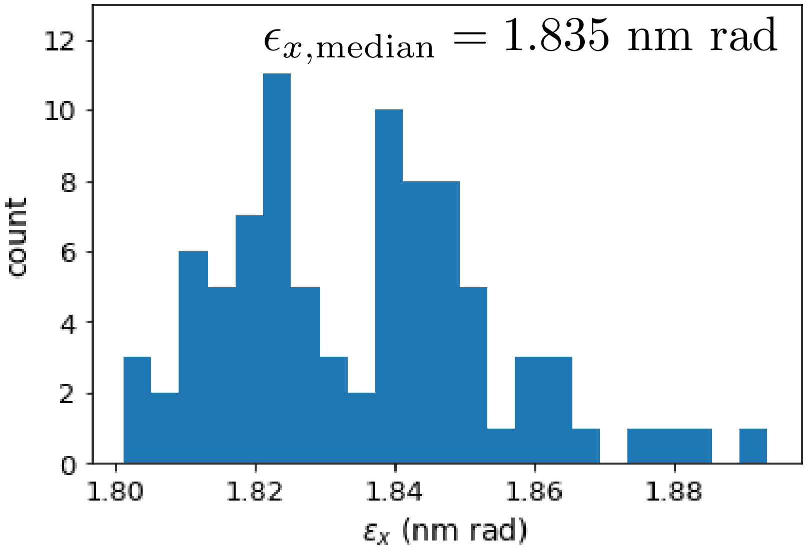
- Include solenoid misalignment into simulations
- Establish the most realistic modelling for BPM errors (e.g. non-linear responses, calibration measures for rotated BPMs, non-Gaussian BPM offset distributions)
- Investigate the few seeds that results in vertical emittances > 2 pm rad
- Apply correction 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
- Possible simulation of commissioning

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 0.086 pm rad and horizontal emittance of 1.835 nm rad (see slide 12 and 14).





Thank you

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