IMPERFECTION AND CORRECTION FOR CEPC

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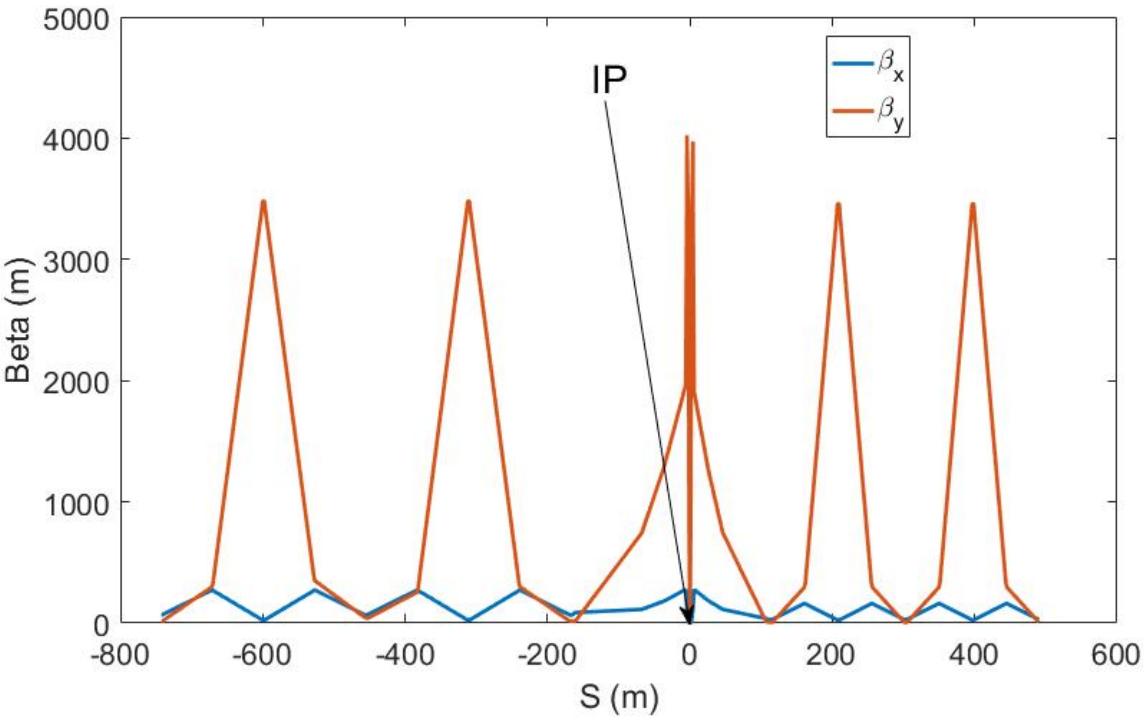
CONTENT

- Errors definition and requirements
- The correction scheme
- The correction results
- Summary and to do list

LATTICE AND REQUIREMENTS



- E=120GeV
- ν_x=363.11

  ν_y=365.22
- $\beta_x^* = 0.36$m

  $\beta_y^* = 0.0015$m

  $\beta_{x,max}$=599m

  $\beta_{y,max}$=4023m
- $\varepsilon_x = 1.21$nm

- The error correction is based on CEPC CDR lattice.
- Small emittance ration (0.2%) and small beta functions.
- Dynamics aperture (DA) requirements: $8\sigma_x \times 15\sigma_y$ & 0.0135 (on-axis injection).

ERRORS DEFINITION AND CHALLENGES

IR=50μm

Component	Δx (mm)	Δy (mm)	$\Delta\theta_z$ (mrad)	Field error
Dipole	0.10	0.10	0.1	0.01%
Arc Quadrupole	0.10	0.10	0.1	0.02%
IR Quadrupole	**0.05**	**0.05**	**0.05**	
Sextupole	0.10	0.10	0.1	

IR=100μm

Component	Δx (mm)	Δy (mm)	$\Delta\theta_z$ (mrad)	Field error
Dipole	0.10	0.10	0.1	0.01%
Arc Quadrupole	0.10	0.10	0.1	0.02%
IR Quadrupole	**0.10**	**0.10**	**0.10**	
Sextupole	0.10	0.10	0.1	

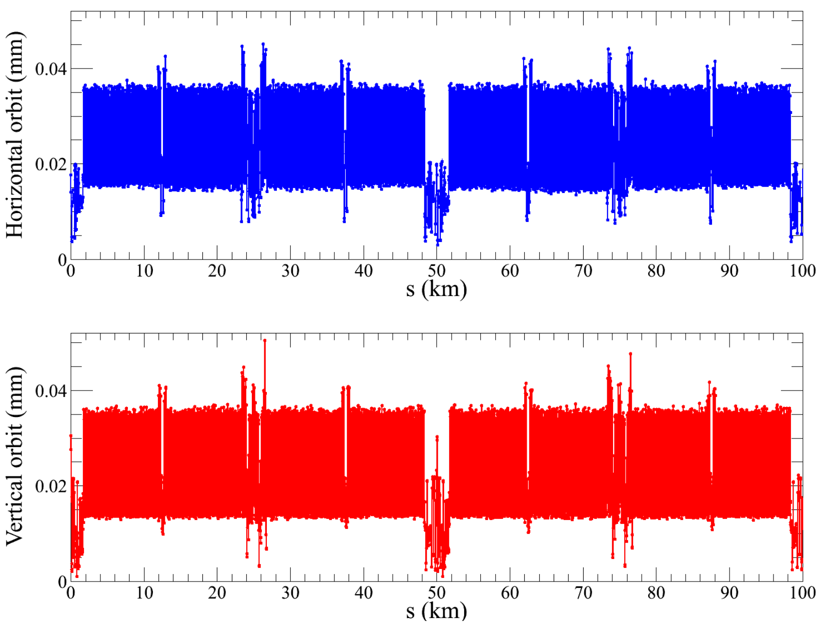
- The lattice with small beta functions is very sensitive to FF misalignments.
- The small emittance ratio requires a small vertical dispersion and the coupling correction.
- 1000 lattice seeds are generated for further correction.

THE CORRECTION SCHEME

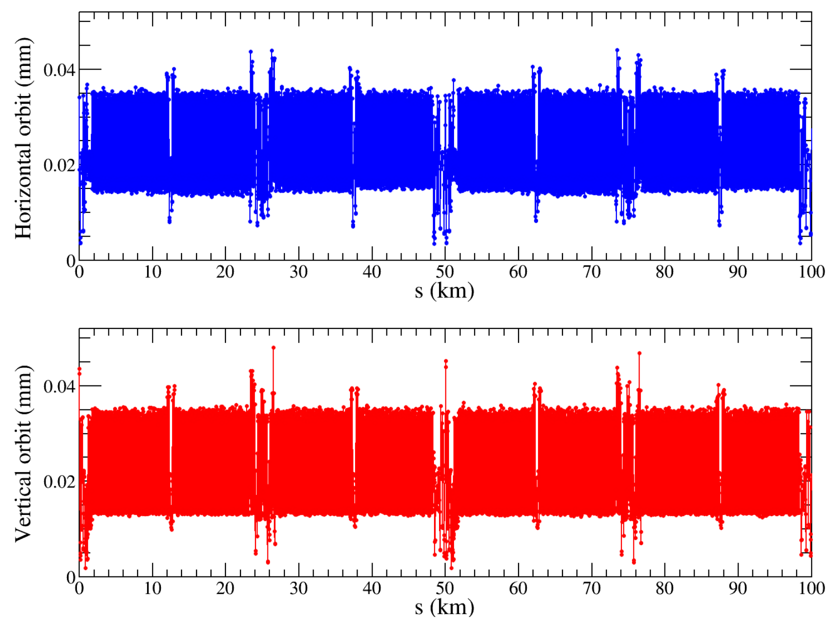
- Software: SAD and AT
- COD correction with **sextupoles off**
- **Turn on the sextupoles** and perform COD correction again.
- Dispersion correction (DFS)
- Beta beating correction (LOCO)
- Coupling and vertical dispersion correction (Local coupling parameter correction)

COD CORRECTION

- BPMs placed at quadrupoles (~1500, 4 per betatron wave) Horizontal correctors placed beside focusing quadrupoles (~1500)
- Vertical correctors placed beside defocusing quadrupoles (~1500)
- Orbit correction is applied using orbit response matrix and SVD method.



IR=50μm 981 seeds converged



IR=100μm 955 seeds converged

$$RMS_{COD} < 0.05\ mm$$

DISPERSION CORRECTION

Dispersion free steering principle (DFS): θ_c

$$\vec{d} = \begin{pmatrix} (1-\alpha)\vec{u} \\ \alpha\vec{D}_u \end{pmatrix} \quad M = \begin{pmatrix} (1-\alpha)A \\ \alpha B \end{pmatrix} \quad \vec{d} + M\vec{\theta} = 0$$

$\vec{u}$: Orbit vector

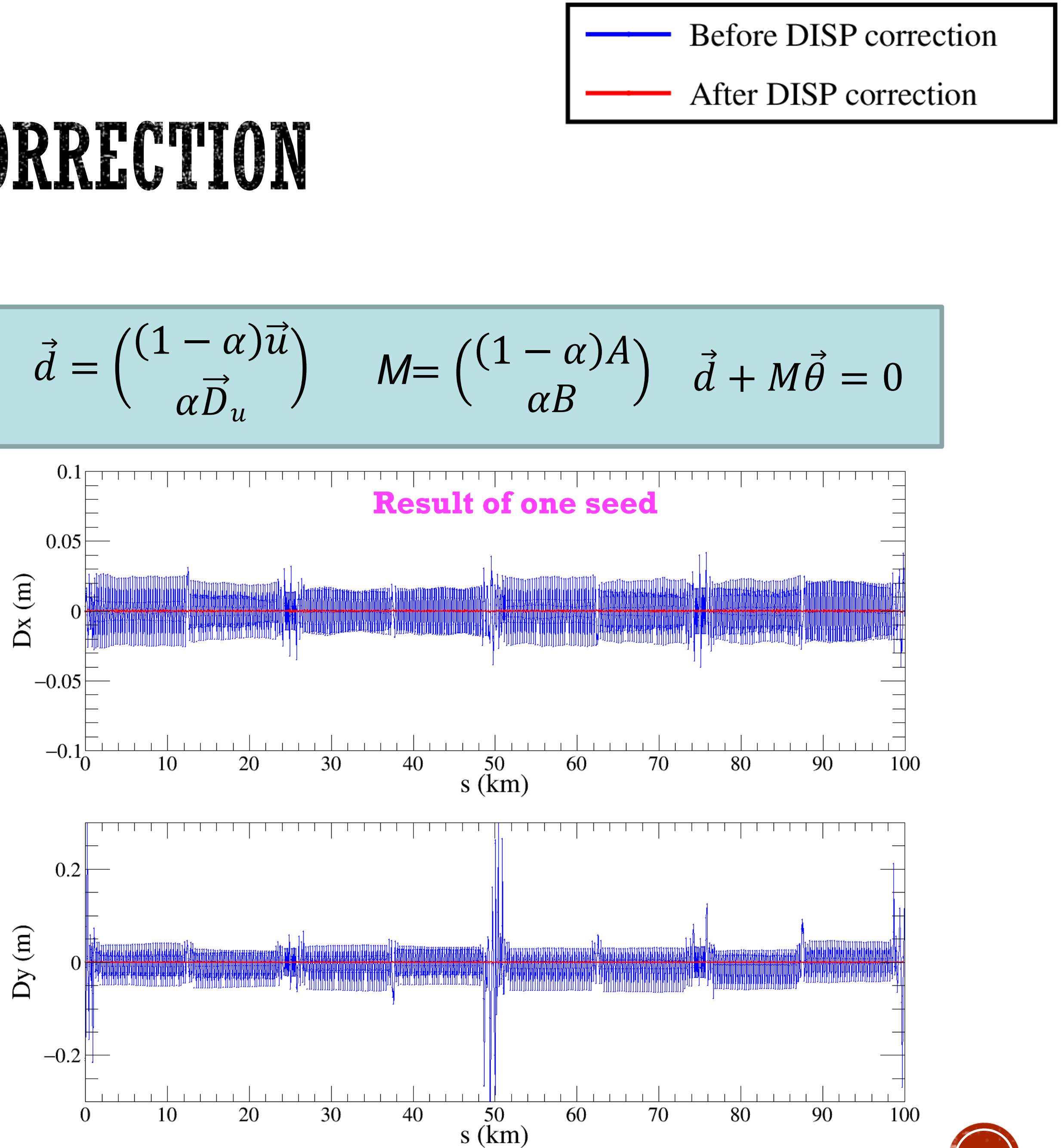
$\vec{D}_u$: Dispersion vector

$\vec{\theta}$: Corrector strengths vector

α: Weight factor

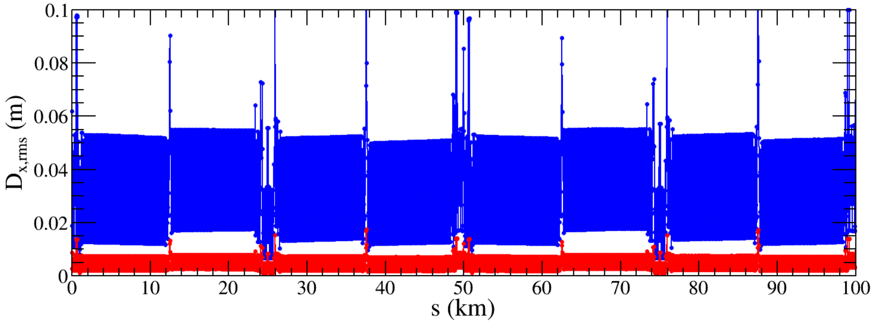
A: Orbit response matrix

B: Dispersion response matrix



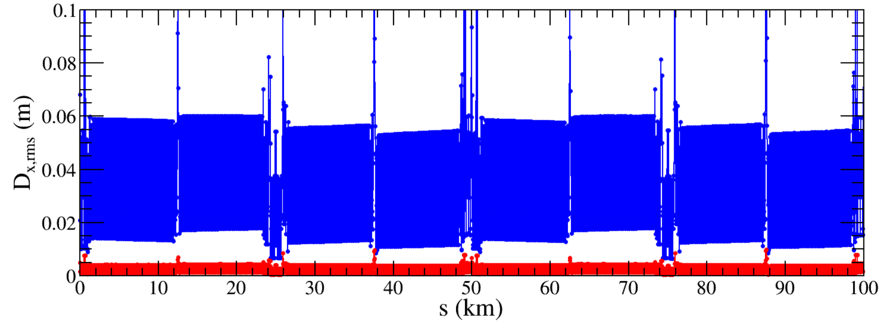
DISPERSION CORRECTION

IR=50μm 943 seeds converged

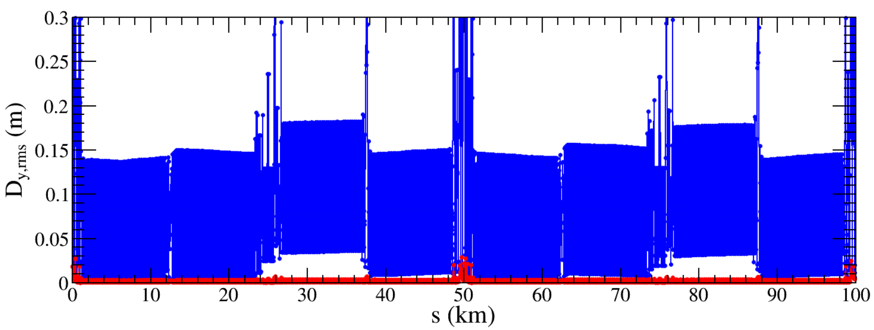


$\Delta D_{x,rms}$ decreased from 29mm to 4.3mm
Factor 7 improvement

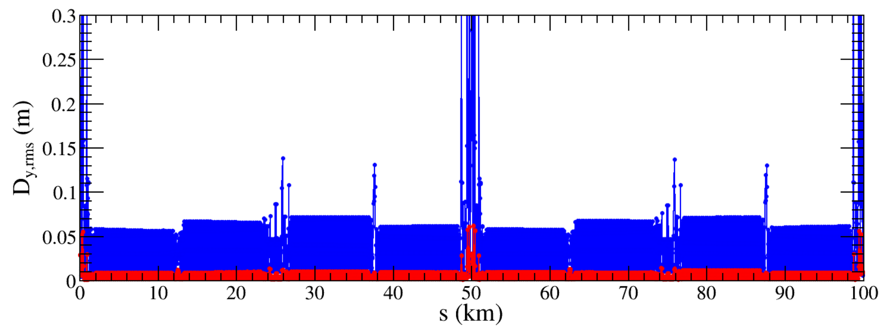
IR=100μm 736 seeds converged



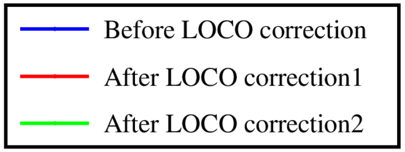
$\Delta D_{x,rms}$ decreased from 31mm to 2.2mm
Factor 14 improvement



$\Delta D_{y,rms}$ decreased from 102mm to 2.3mm
Factor 44 improvement



$\Delta D_{y,rms}$ decreased from 42.7mm to 5.9mm
Factor 7 improvement

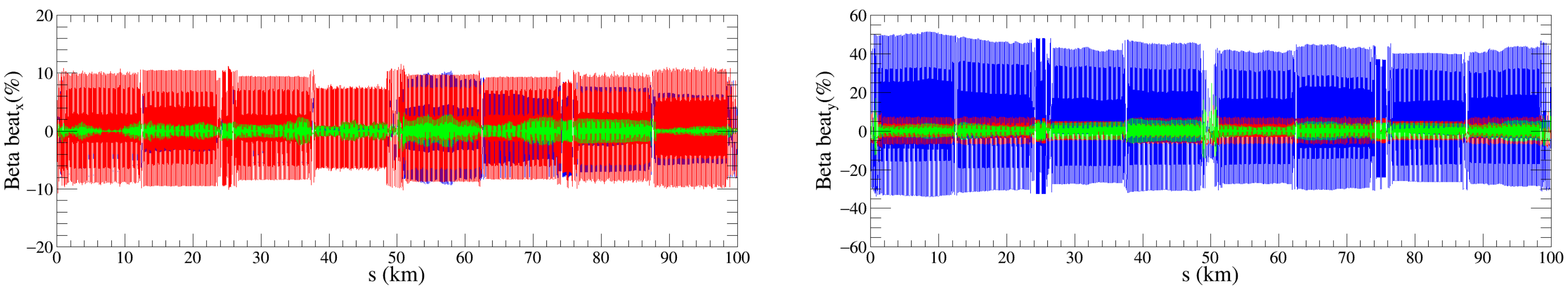


BETA-BEATING CORRECTION

- Correct the beta functions with sextupoles on.
- Based on AT LOCO: model based correction
  - Establish lattice model M_{mod}, multi-parameter fit to the orbit response matrix M_{meas} to obtain calibrated model:
  - Parameters fitted: K, KS …
  - Use calibrated model to perform correction and apply to machine.
  - Application to correct beta-beating, dispersion and coupled response matrix.

LOCO correction1

$$\chi^2 = \sum_{i,j} \frac{(M_{mod,ij} - M_{meas,ij})^2}{\sigma_i^2} \equiv \sum_{i,j} V_{ij}^2$$

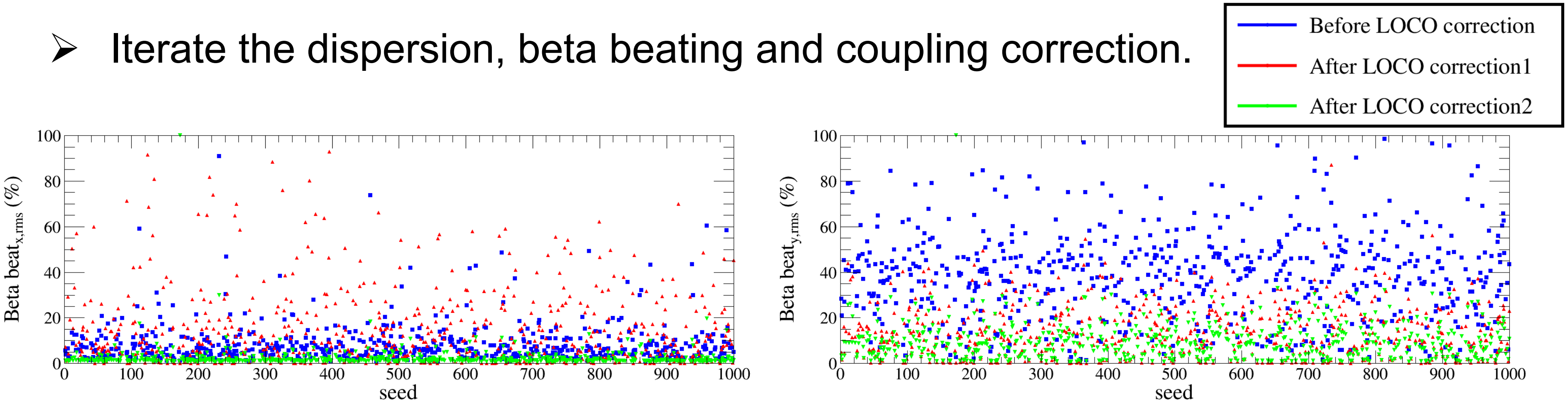


Result of one seed

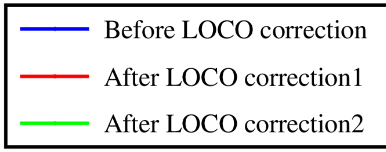
OPTIMIZATION OF BETA-BEATING CORRECTION

LOCO correction2

- More variables fitted in LOCO to improve the beta beating correction.
- Fit dispersion at the same time with beta beating correction.
- Constraint the strength of skew component in coupling correction.
- Iterate the dispersion, beta beating and coupling correction.

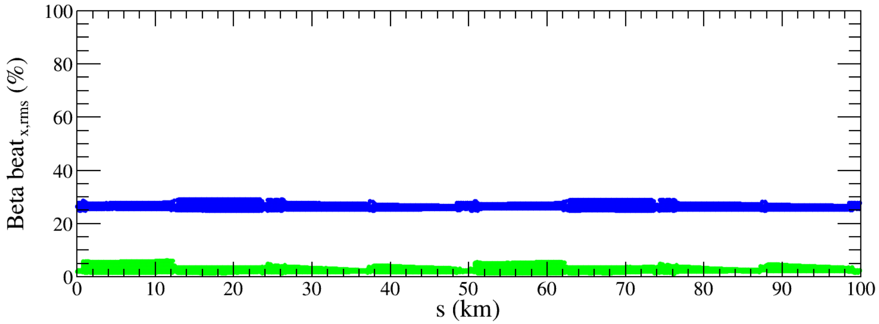


- ✓ The beta beating of the LOCO correction2 is much better than that of the correction1.
- ✓ The passing rate is dramatically decreased in the LOCO correction1, but almost not decreased in the LOCO correction2.



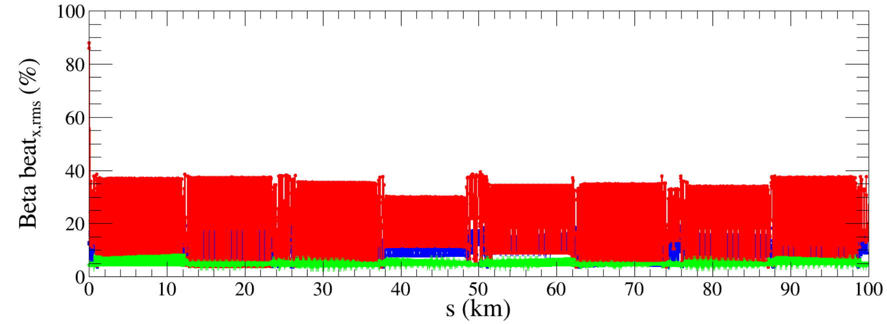
BEAT-BEATING CORRECTION

IR=50μm 891 seeds converged

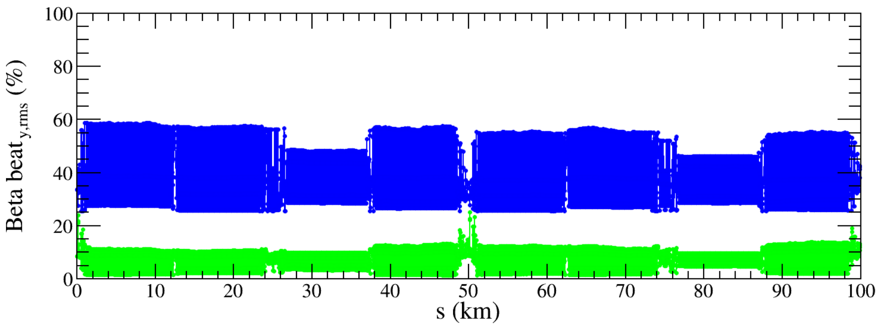


$\Delta\beta/\beta_{x,rms}$ decreased from 26.4% to 2.8%
Factor 9 improvement

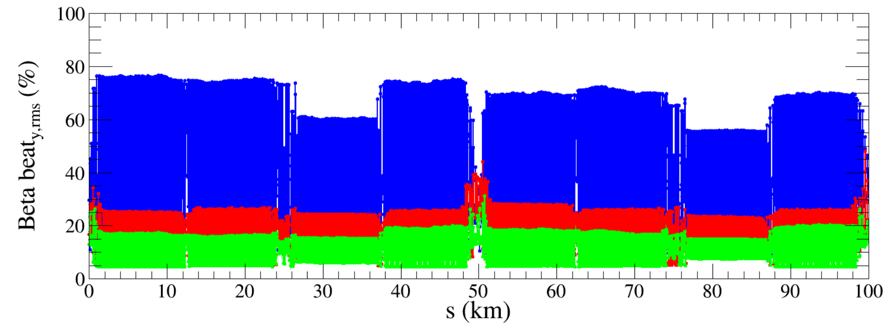
IR=100μm 724 seeds converged



$\Delta\beta/\beta_{x,rms}$ decreased from 11.7% to 5.1%
Factor 2 improvement



$\Delta\beta/\beta_{x,rms}$ decreased from 37.6% to 7.0%
Factor 5 improvement



$\Delta\beta/\beta_{x,rms}$ decreased from 37.7% to 11.2%
Factor 3 improvement

OPTIMIZATION OF BETA-BEATING CORRECTION

Component	Δx (μm)	Δy (μm)	$\Delta\theta_z$ (μrad)
Arc quadrupole	100	100	100
IR Quadrupole	50	50	50
FF Quadrupole	50	50	50
Sextupole	100	100	100

Observable	Before correction	After correction
Hori. disp.	29.0 mm	4.3 mm
Vert. disp.	102.0 mm	2.3 mm
Hori. Beta-beating	26.4%	2.8%
Vert. Beta-beating	37.6%	7.0%

Component	Δx (μm)	Δy (μm)	$\Delta\theta_z$ (μrad)
Arc quadrupole	100	100	100
IR Quadrupole	100	100	100
FF Quadrupole	100	100	100
Sextupole	100	100	100

Observable	Before correction	After correction
Hori. disp.	31 mm	2.2 mm
Vert. disp.	42.7 mm	5.9 mm
Hori. Beta-beating	11.7%	5.1%
Vert. Beta-beating	37.7%	11.2%

COUPLING CORRECTION

- Neglecting beam-beam effects $$\varepsilon_y \simeq \varepsilon_{y0} + \kappa\varepsilon_x + rE^2(D_y^{\mathrm{rms}})^2$$
- Local coupling parameter matching was developed for BEPCII.
- Both coupling and vertical dispersion are controlled.
- Using the trim coils of the sextupoles (~1000), which providing skew-quadrupole field, to perform emittance tuning for CEPC.
- The vertical orbit distortion due to a horizontal deflection at a BPM is:

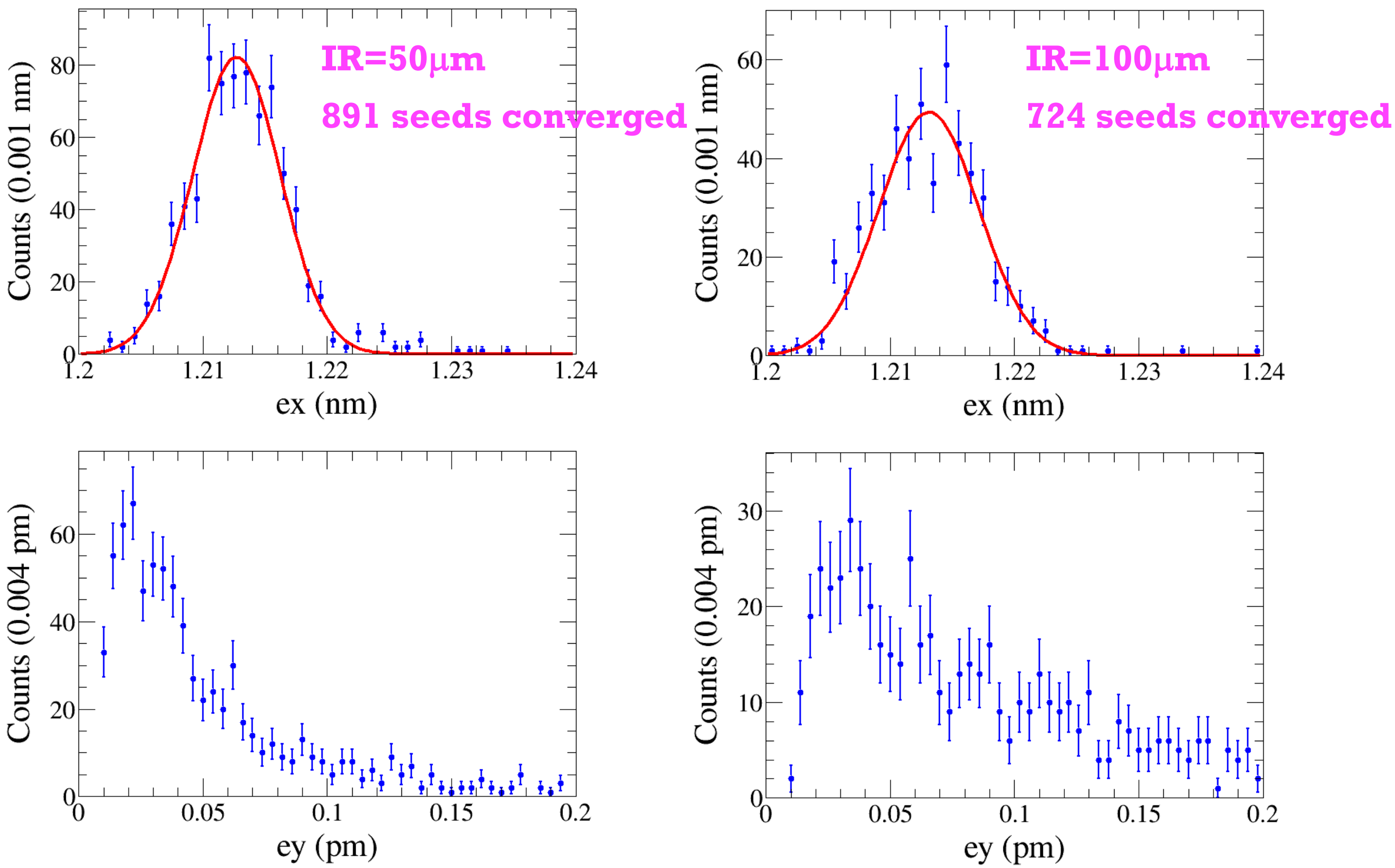
$$\frac{\Delta y_{cod}}{\Delta x_{cod}} = \bar{c}_{b,22}k_1 + \bar{c}_{b,12}k_2 + \bar{c}_{c,11}k_3 + \bar{c}_{c,12}k_4$$

k_1, k_2, k_3, k_4 : only related to the decoupled linear optics

$\bar{c}_{b,22}, \bar{c}_{b,12}, \bar{c}_{c,11}, \bar{c}_{c,12}$: local coupling parameters, $\bar{c}_{b,12} = M_c\overrightarrow{ks}$

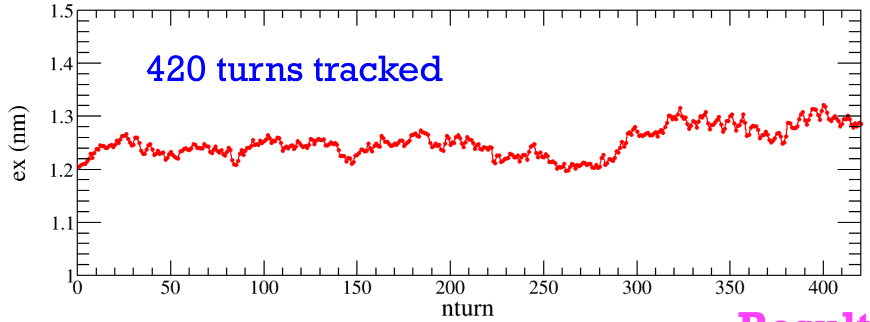
M_c: $\bar{c}_{b,12}$ response matrix $\overrightarrow{ks}$: skew-quadrupole vector

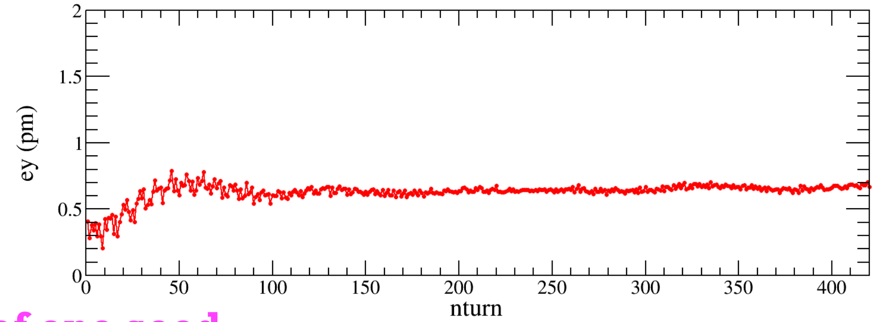
RESULTS OF EMITTANCE TUNING



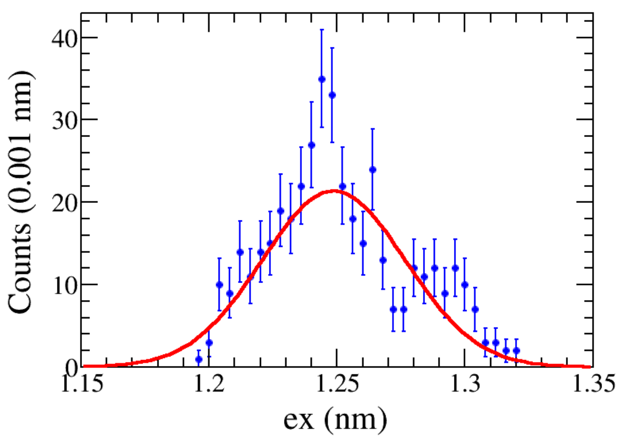
ex = 1.2127±0.0035 nm	ex = 1.2131±0.0040 nm
ey = 0.050± 0.0015 pm	ey = 0.0777± 0.0023 pm
ey/ex = (0.0041± 0.0001)%	ey/ex = (0.0064± 0.0002)%

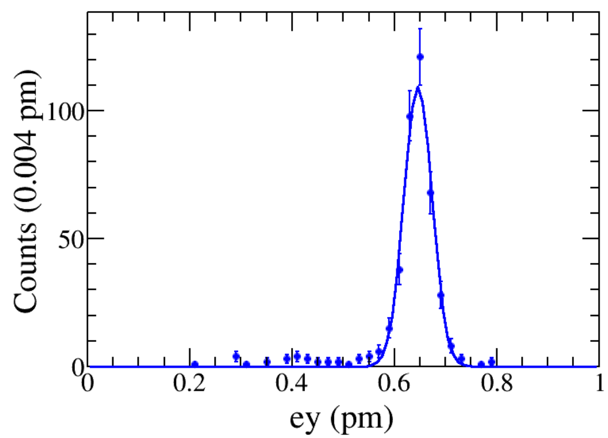
RESULTS OF EMITTANCE TRACKING





Result of one seed





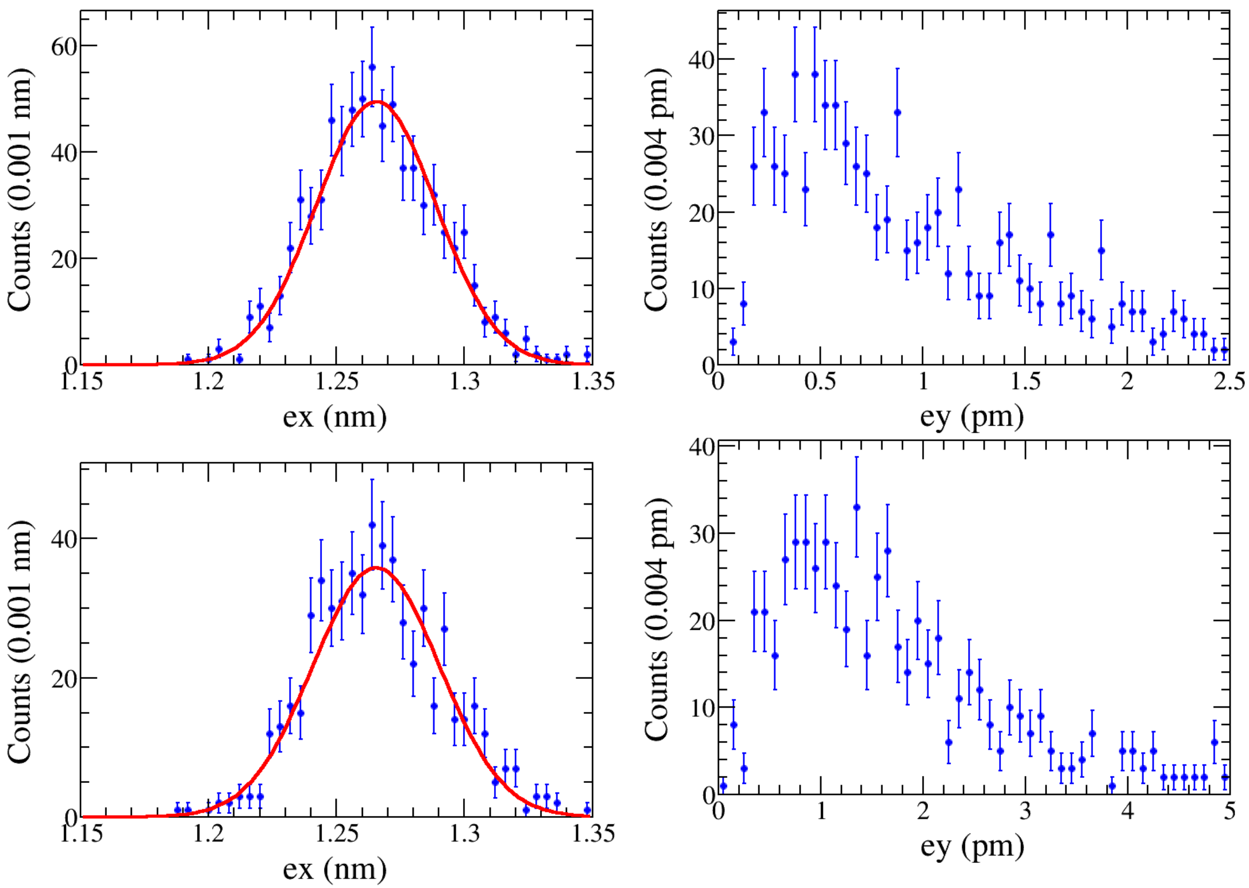
ex = 1.2488±0.0028 nm

ey = 0.6458± 0.0275 pm

ey/ex = (0.0517± 0.0022)%

- ✓ The vertical emittance from tracking result is higher than that of mapping result by 10 times.
- ✓ Both emittance results satisfy the coupling requirements.
- ✓ Further study of the emittance tracking is necessary.

RESULTS OF EMITTANCE TRACKING



IR=50μm

891 seeds converged

ex = 1.2656±0.0234 nm

ey = 0.9178± 0.3366 pm

ey/ex = (0.0725± 0.0266)%

IR=100μm

724 seeds converged

ex = 1.2656±0.0247 nm

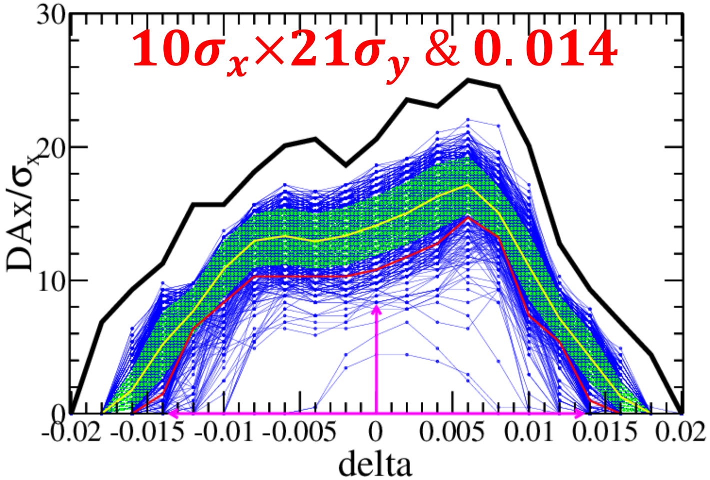
ey = 1.6927± 1.1556 pm

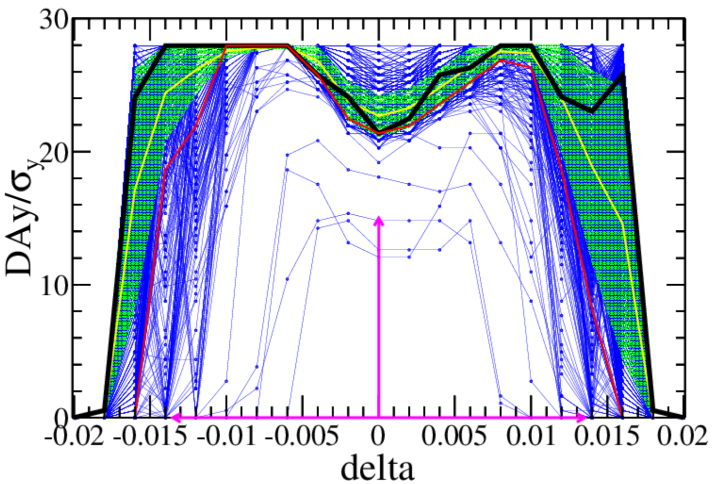
ey/ex = (0.1341± 0.0916)%

✓Further study of the effects of coupling, synchro-beta resonance and SR in each magnet are ongoing.

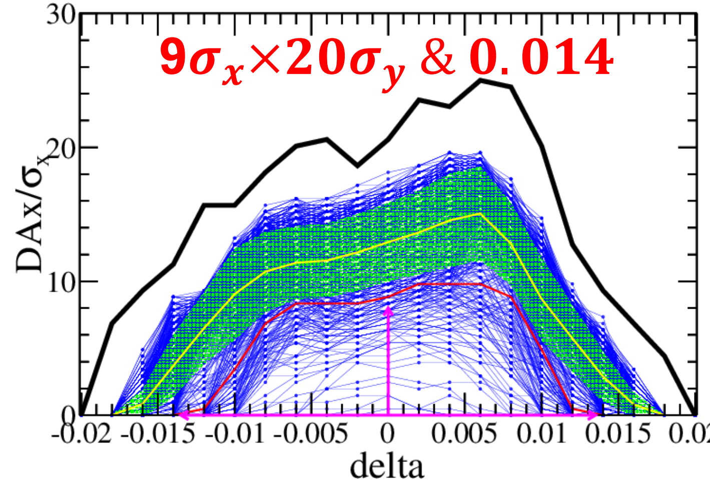
DA RESULTS

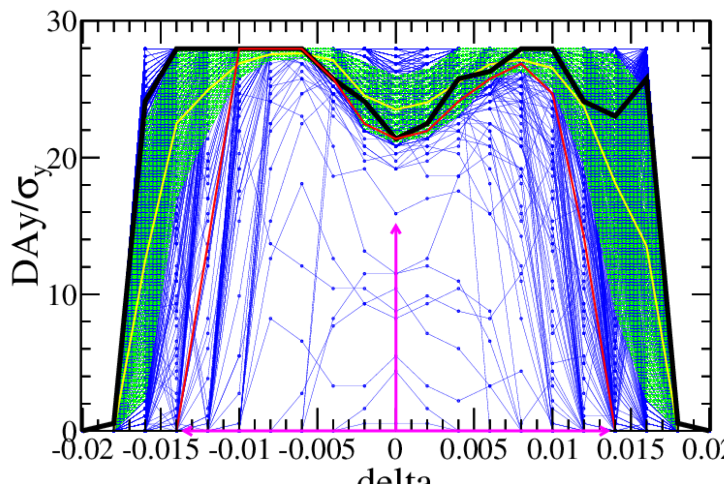
IR=50mm : 891 seeds for DA





IR=100mm : 724 seeds for DA





- ✓ The blue lines are the DA of each seed, the yellow lines and green bands are the mean value and its corresponding statistics errors, the black line is the DA of bare lattice, and the red lines show the lower limits at 90% C.L.. For the on-axis injection, $8\sigma_x \times 15\sigma_y$ & 0.0135 is required.

SUMMARY

- The optics correction is very challenging for the relaxed tolerance of the imperfections.
- The lattices with **IR=50μm** and **IR=100μm** case are corrected, the passing rates are increased to **89.1%** and **72.4%**, respectively.
- The emittance tracking is estimated, further study is ongoing.
- Optimize the DA plots which include the lower limit DA and the DA from bare lattice.

TO DO LIST

- Include more types of imperfections.
- Optimize the correction strategy to achieve finer tuning of optics.
- Study off-momentum correction.
- The development of the error correction algorithm for high luminosity lattice.

Thanks for your attention!