Error study to the collider ring

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- IARC2021 related comments and replies
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Beam parameters

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	ttbar	Higgs	W	Z
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	30			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	180	**120**	80	45.5
Energy loss per turn [GeV]	9.1	**1.8**	0.357	0.037
Piwinski angle	1.21	**5.94**	6.08	24.68
Bunch number	35	**249**	1297	11951
Bunch population [10^10]	20	**14**	13.5	14
Beam current [mA]	3.3	**16.7**	84.1	803.5
Momentum compaction [10^-5]	0.71	**0.71**	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.04/2.7	**0.33/1**	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	**0.64/1.3**	0.87/1.7	0.27/1.4
Beam size at IP (sigx/sigy) [um/nm]	39/113	**15/36**	13/42	6/35
Bunch length (SR/total) [mm]	2.2/2.9	**2.3/3.9**	2.5/4.9	2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20	**0.10/0.17**	0.07/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	2.3/2.6	**1.6/2.2**	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	0.071/0.1	**0.015/0.11**	0.012/0.113	0.004/0.127
RF voltage [GV]	10	**2.2**	0.7	0.12
RF frequency [MHz]	650	**650**	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	**1/0.4/0.2**	-/1.8/0.9	-/-/5.8
Longitudinal tune Qs	0.078	**0.049**	0.062	0.035
Beam lifetime (bhabha/beamstrahlung)[min]	81/23	**39/18**	60/717	80/182202
Beam lifetime [min]	18	**12.3**	55	80
Hour glass Factor	0.89	**0.9**	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	**5.0**	16	115

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）

Correction results of Higgs lattice

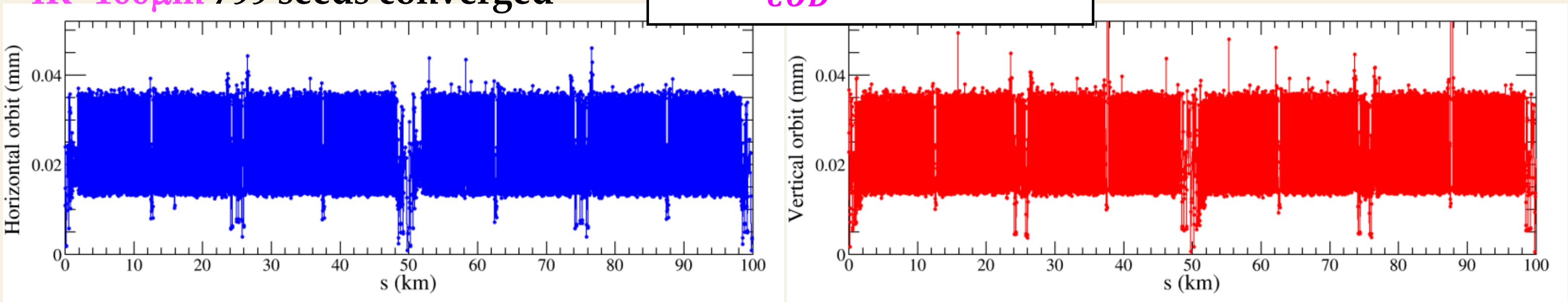
- Mainly optimization for lattice with 100 **mm** case
- Loco correction is performed
- Initial settings (corrector settings, BPM selection, iteration times, steps and so on) are adjusted for the automatic correction programme
- Manual optimization is performed for those un-converged lattice seeds

Errors definition and challenges

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

IR=100μm **799 seeds converged**

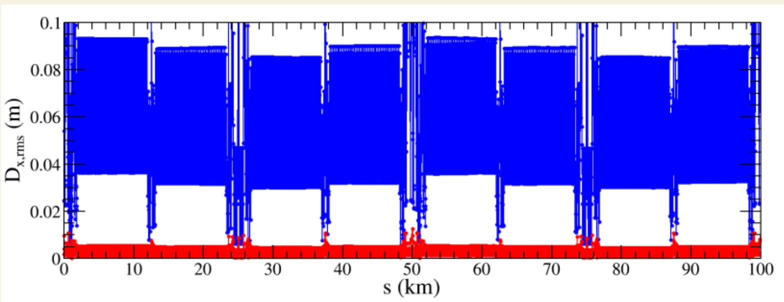
$\boldsymbol{RMS_{COD} < 0.05\ mm}$

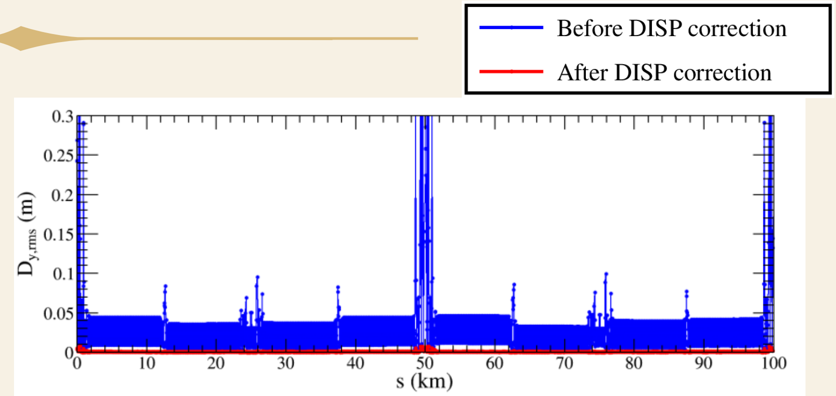


- Perform additional iteration and **manual optimization** (adjust the corrector settings according to correction result);
- The converged rate is increased from 67.8% to 79.9%;
- Due to the validation of the manual optimization for each seed and computing time limit, the remaining un-converged 201 lattice seeds are not adjusted.

Dispersion correction

IR=100μm 649 seeds converged





$\Delta D_{x,rms}$ decreased from 55.0mm to 2.7mm
Factor 20 improvement

$\Delta D_{x,rms}$ decreased from 27.9mm to 0.7mm
Factor 40 improvement

- The dispersion correction is performed for all selected 799 lattice seeds.
- According to the manual optimization, the number of converged seeds is increased from 541 to 649, the correction result is comparable with previous results and better than those results for CDR lattice.

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:

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

  - Parameters fitted: K, KS …
  - Use calibrated model to perform correction and apply to machine.
  - Fit the dispersion at the same time.
  - Application to correct beta-beating, dispersion and coupled response matrix.

- Optimizing content:
  - kernel algorithm
  - initial settings
  - the number of BPM and corrector for horizonal and vertical
  - The manual optimization is necessary

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Number of BPM:  947 horizontal 947 vertical
Number of CM:   610 horizontal 617 vertical
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  - Parameters fitted: K, KS …
  - Use calibrated model to perform correction and apply to machine.
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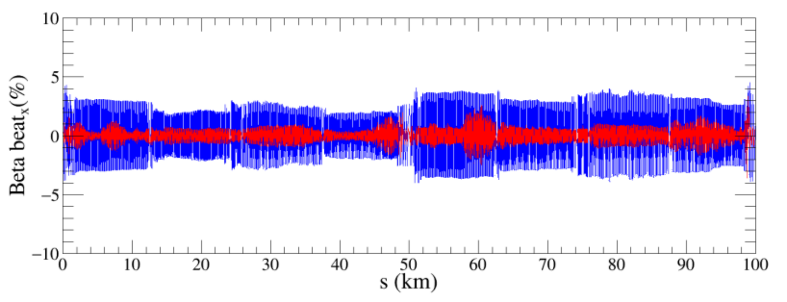
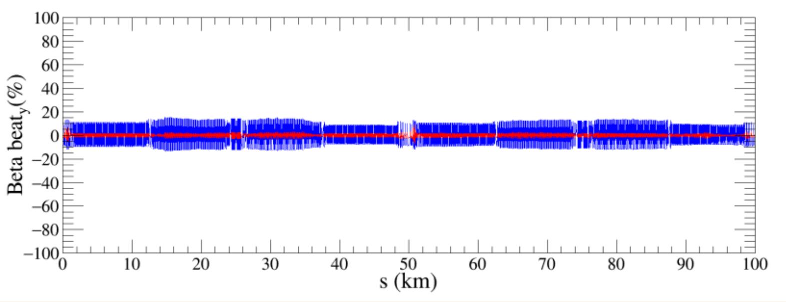
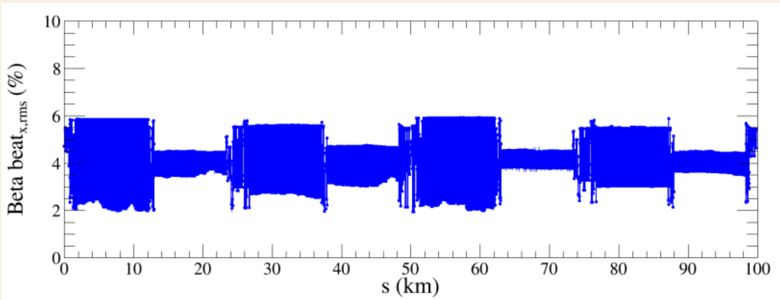
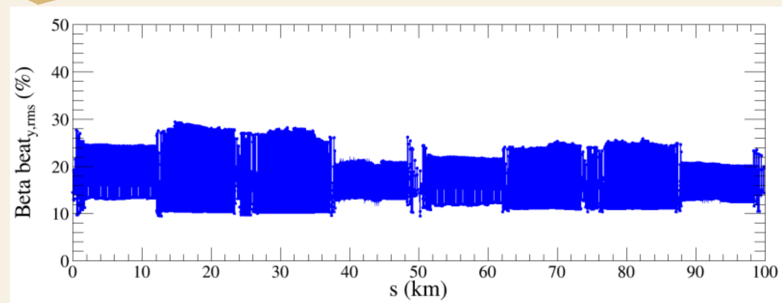
Result of one seed

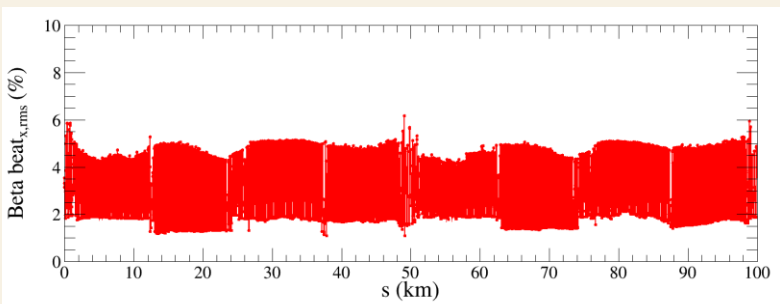


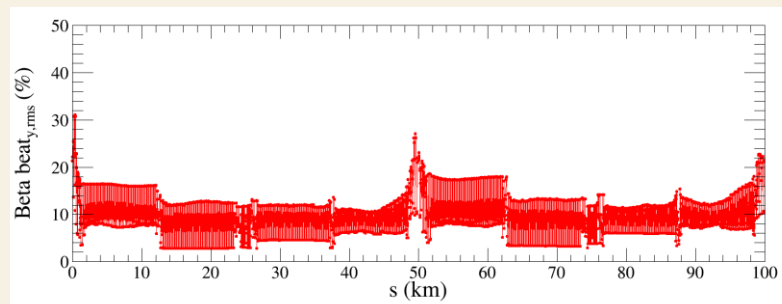


Beta-beating correction







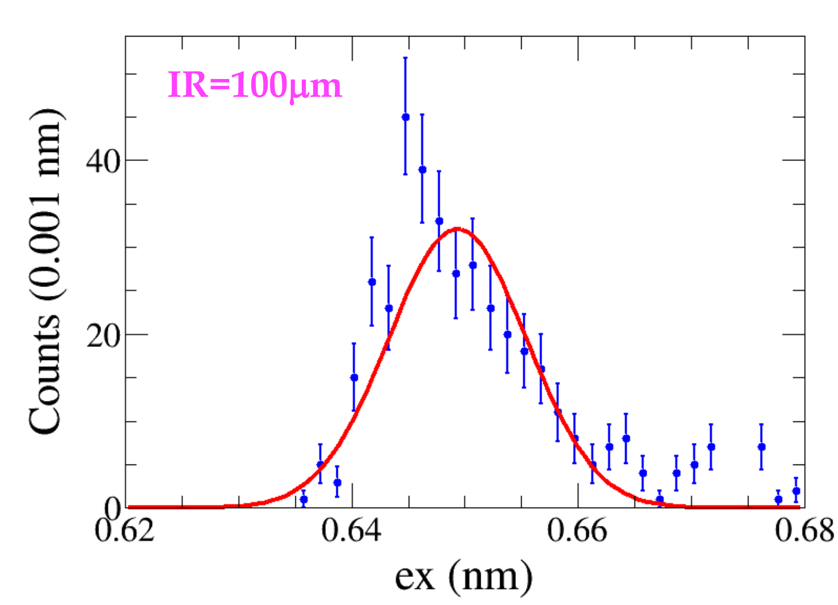


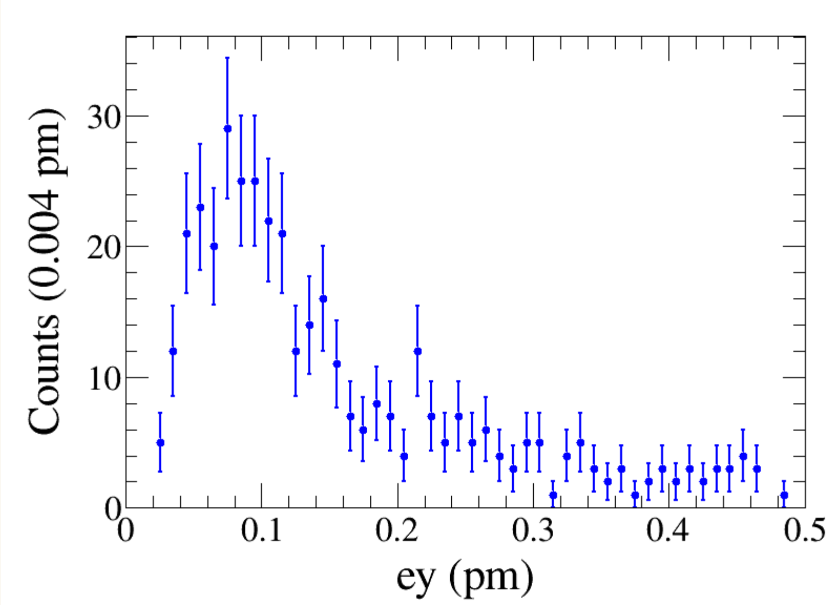
$\Delta\beta/\beta_{x,rms}$ decreased from 4.1% to 2.9%

$\Delta\beta/\beta_{y,rms}$ decreased from 17.0% to 9.8%

- During the beta beating correction, the manual adjustment is necessary for almost all lattice seeds, only 541 lattice seeds are performed for beta beating correction.
- The correction results are obvious, especially for the vertical beta beating.

Results of emittance tuning



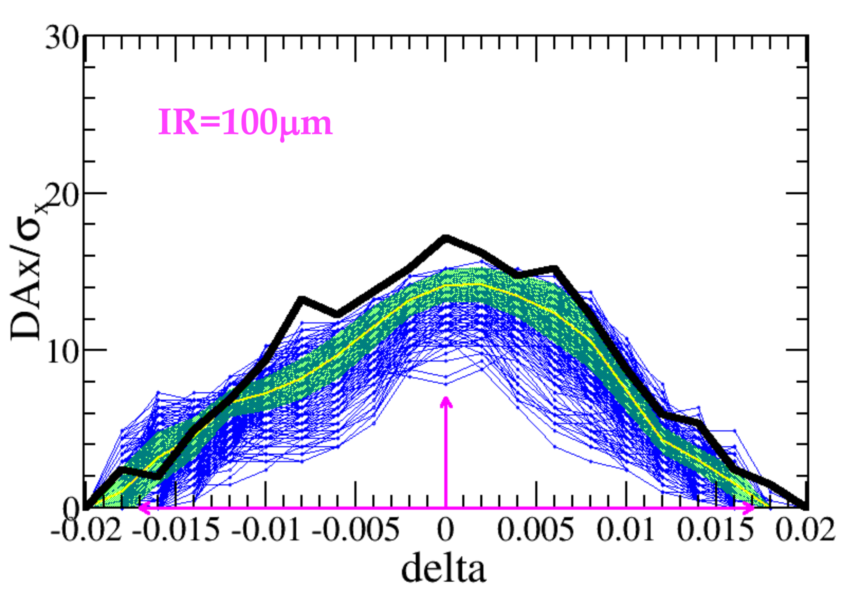


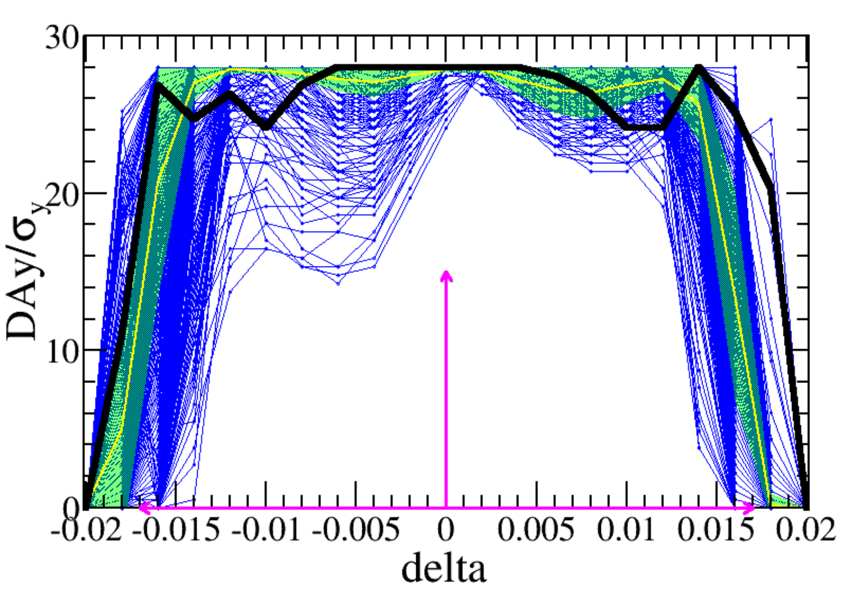
ex = 0.649 ± 0.006 nm

ey = 0.156 ± 0.012 pm

ey/ex = (0.024 ± 0.002)%

DA results





- ✓ 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 pink arrows show the DA requirement for on-axis injection, which is $7\sigma_x \times 15\sigma_y$ & 0.017. The DA of 270 error seeds (50%) with errors satisfy the on-axis injection requirements.
- ✓ 501 error seeds (93%) with errors satisfy the on-axis injection requirements $\boldsymbol{7\sigma_x \times 15\sigma_y}$ **&** $\mathbf{0.016.}$

IARC2021 comments and replies

- 1. The error-correction procedure could benefit from other tools developed for the vertical emittance correction in synchrotron-light sources, as for example the Machine Learning technique or other iterative methods as done for ESRF. Contact with the SLS community could be beneficial;

Re: We sincerely thanks for the kind suggestion of the committee! The Machine learning based error correction is essential and important for the design and optimization of the parameters of the future colliders. Currently, error corrections of traditional calculation method are valid for both CDR lattice and high luminosity lattice. We firstly plan to improve the correction results according to the typical correction method. At the same time, we also get started with the study of error correction based on machine learning.

IARC2021 comments and replies

- 2. Verify that the stability of the correction procedure complies with the 100-micron misalignment resolution in the IR quadrupoles set by the mechanical-engineering team;

Re: The error correction with 100-micron misalignment is under study. Figure 1 shows the DA results after error correction with 270 lattice seeds, where the black curves are the DA results with bare lattice, the blue curves are the DA result of each seed, the yellow and green curves are the mean value and the statistical errors of all selected seeds, the pink arrows are the DA requirements for on-axis injection. We are working on improving the correction scheme, such as beta-beating correction, to increasing the passing rate of lattices with 100-micron misalignment. This correction results are presented in the last CEPC workshop, which can be downloaded in the following link: https://indico.ihep.ac.cn/event/14938/session/8/contribution/88/material/slides/1.pptx.

IARC2021 comments and replies

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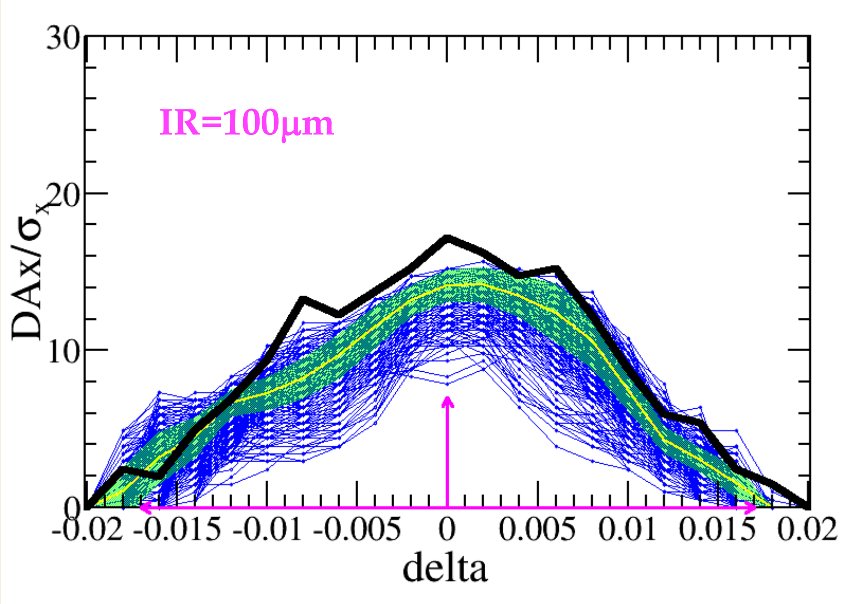
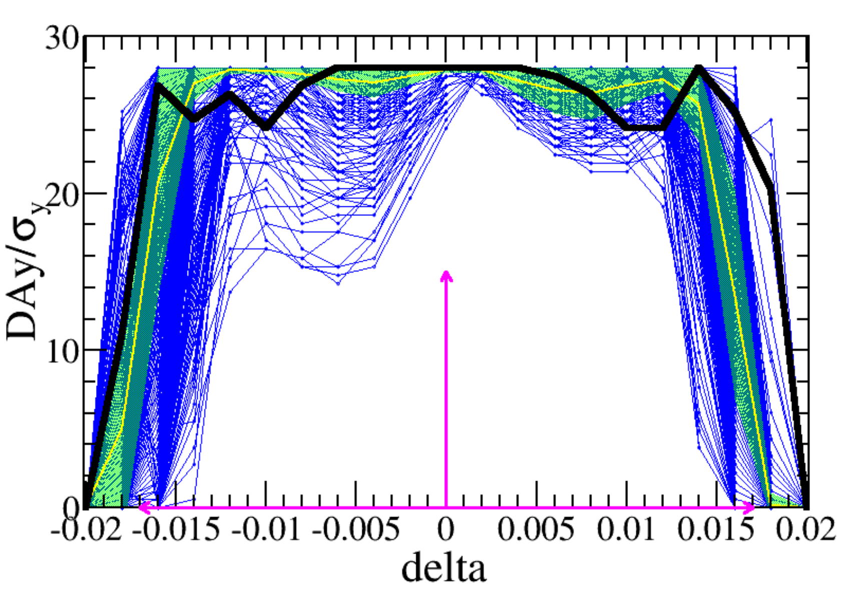




IARC2021 comments and replies

- 3. The influence of the errors on the emittance, especially for the vertical one, which is important for the luminosity, should be simulated;

Re: Figure 2 shows the results of emittance tuning for lattices with 50-micron and 100-micron misalignments. The emittance is calculated to be $\varepsilon_x = 0.6430 \pm 0.0021$ nm and $\varepsilon_y = 0.0413 \pm 0.0005$ pm for lattices with 50-micron misalignment and $\varepsilon_x = 0.6436 \pm 0.0026$ nm and $\varepsilon_y = 0.0579 \pm 0.0010$ pm for lattices with 100-micron misalignment. The emittance ratios for both lattice cases are $(0.0064 \pm 0.0001)\%$ and $(0.0090 \pm 0.0001)\%$ respectively. This emittance tuning results are also presented in the last CEPC workshop.

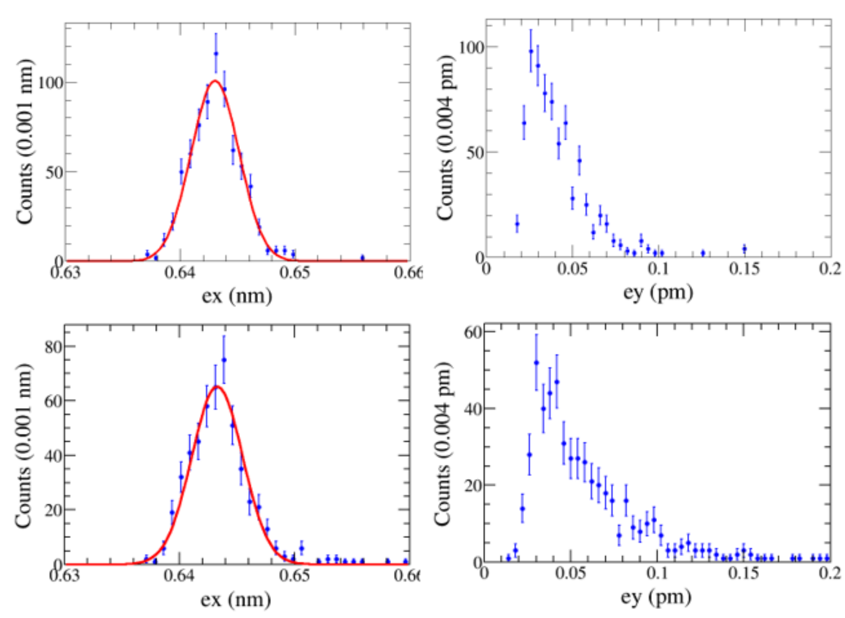
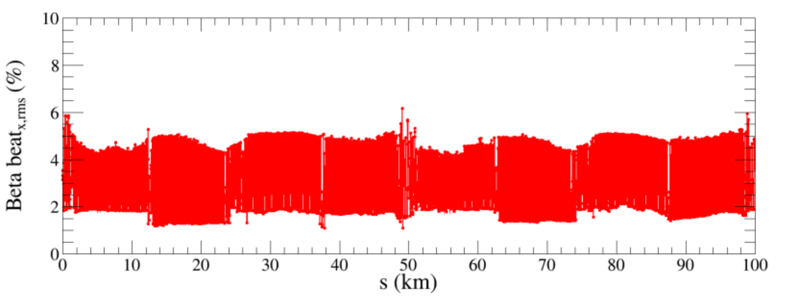


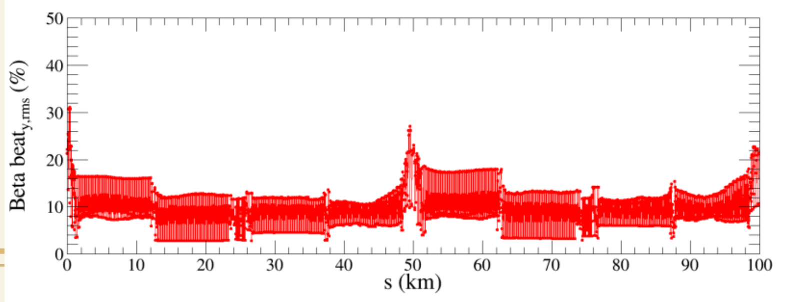
Figure 2 Results of emittance tuning for lattices with (upper) 50-micron and (lower) 100-micron misalignments.

IARC2021 comments and replies

- 4. Since on-axis injection at all energies would be preferable, further studies on the errors correction, to increase the dynamic aperture at the Higgs, where on-axis injection is preferred, would be needed. A beta-beating correction scheme should be developed and implemented, which will improve the DA.

Re: Thanks for this valuable comment, the beta-beating correction scheme is very necessary for the current error correction. The beta beating after dispersion correction is comparable with the beta beating results (with LOCO correction) of CDR lattice. The current beta beating correction needs to be optimized for smaller beta beating, such as increase the number of variables and iteration times, and so on.





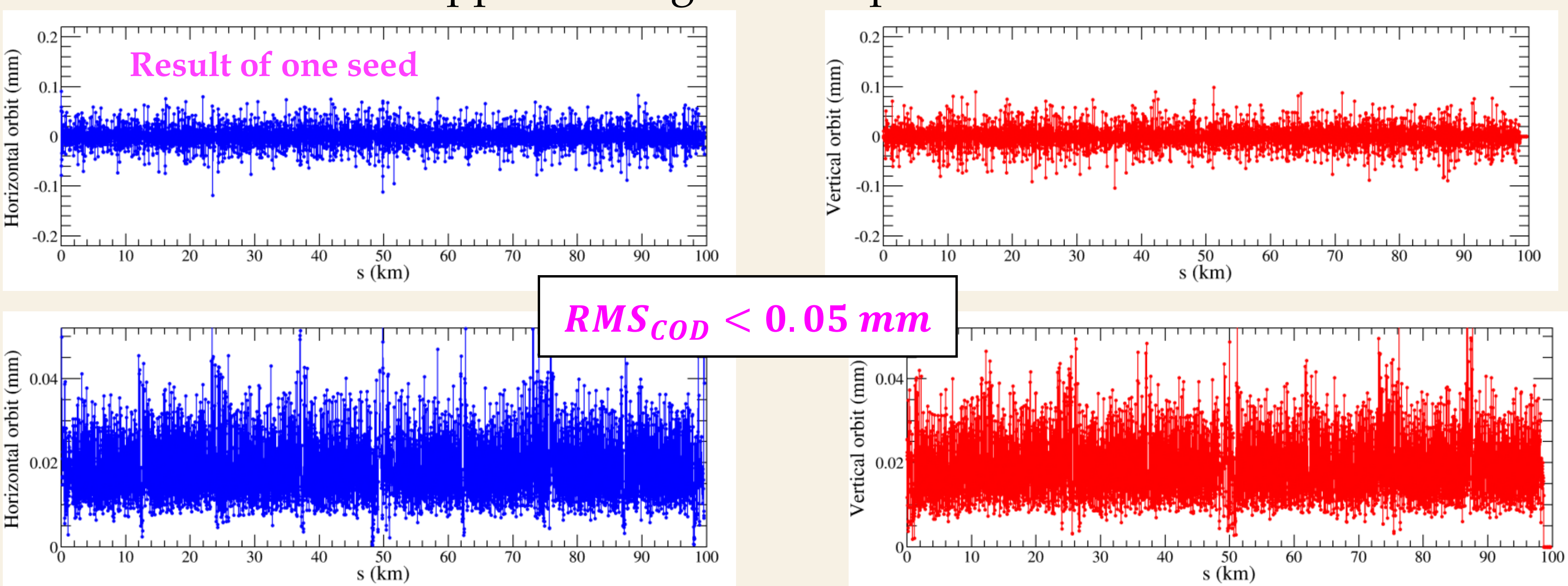
Correction scheme of Z lattice

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

- Currently, we focus on the correction performance for different errors, we only generate 100 lattice seeds of each case and try to correct all of them by automatic correction programme and manual adjustment.
- The W lattice and ttbar lattice are similar with Higgs and Z lattice, So we firstly perform the correction to Z lattice.
- The correction scheme of Z lattice is similar with that of Higgs lattice.

Correction scheme of Z lattice

- BPMs placed at quadrupoles (~3706, 4 per betatron wave)
- Horizontal correctors placed beside focusing quadrupoles（~1832）
- Vertical correctors placed beside defocusing quadrupoles（~1858）
- Orbit correction is applied using orbit response matrix and SVD method.



Dispersion correction

Dispersion free steering principle (DFS): $\boldsymbol{\theta_c}$

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

Result of one seed

$\vec{u}$: Orbit vector

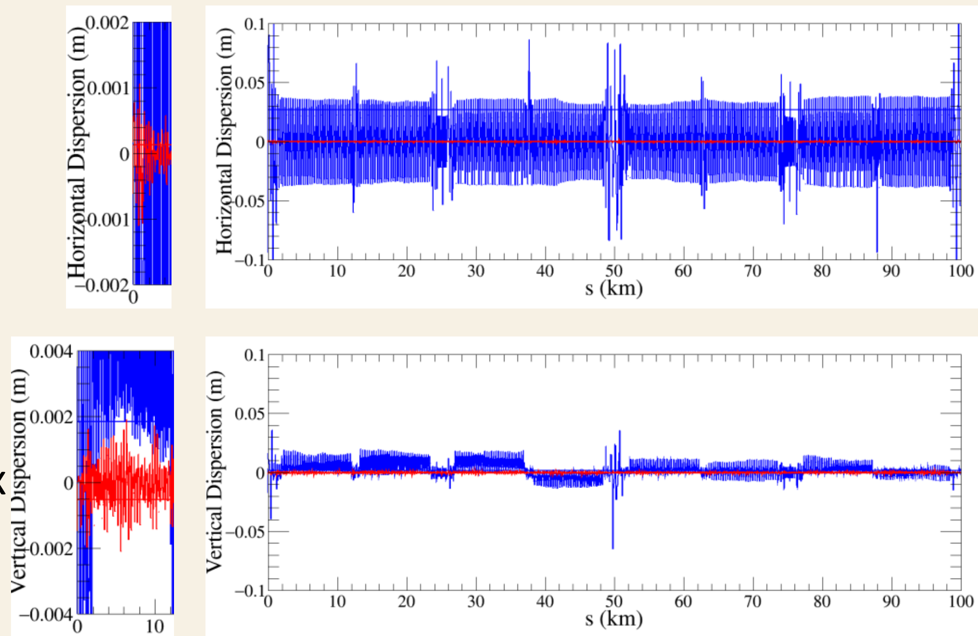
$\vec{D}_u$: Dispersion vector

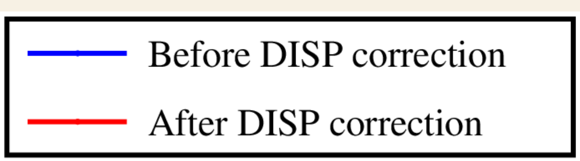
$\vec{\theta}$: Corrector strengths vector

α: Weight factor

A: Orbit response matrix

B: Dispersion response matrix





Summary

- The imperfection correction for the Higgs lattice is performed, the correction results satisfy the on-axis injection requirements.
- Comments from IARC2021 are replied.
- Part of imperfection correction for the Z lattice is performed.

- Finish the whole correction to the Z, W and ttbar lattice.
- Study the correction performance for Higgs lattice.

Thank you for your attention

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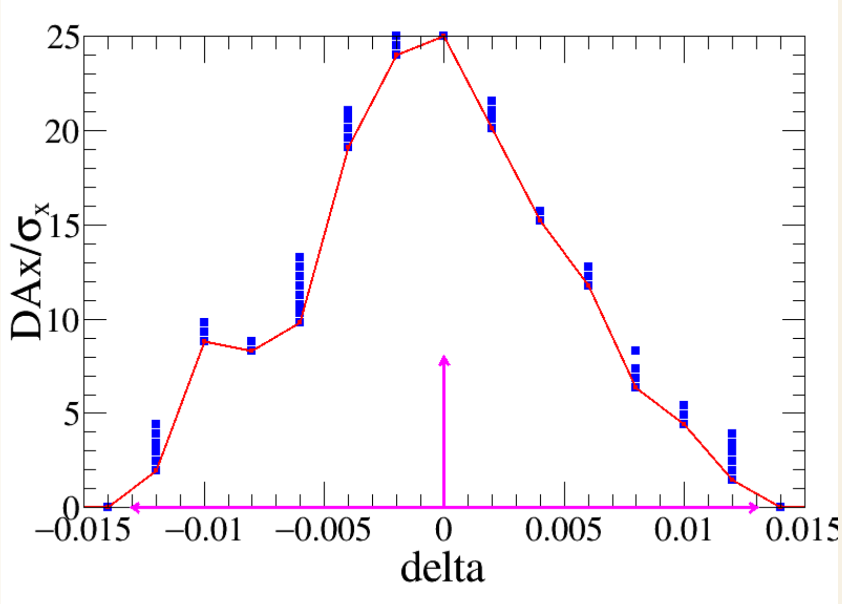
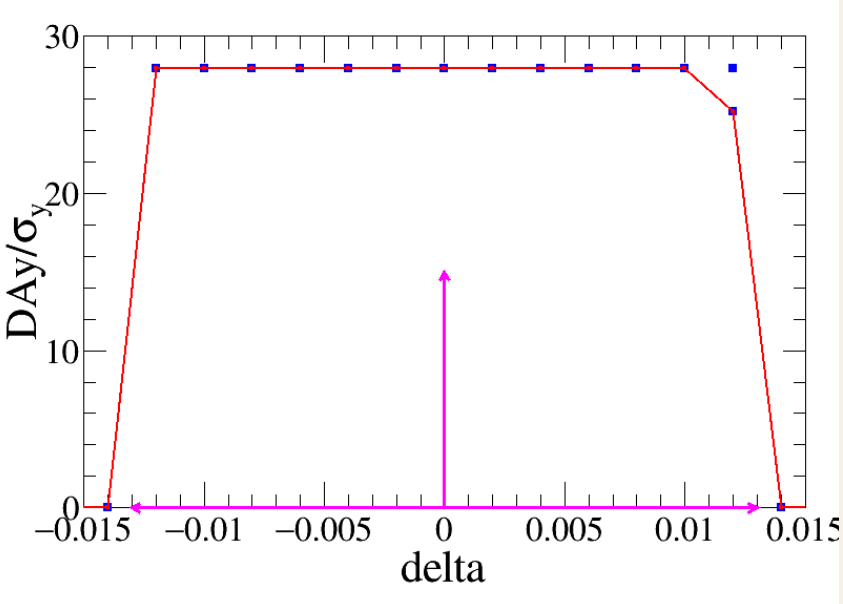
DA results





- **The DA after error correction satisfy the off-axis injection requirements, which is $11.8\sigma_x \times 9\sigma_y$ & 0.013.**