

Imperfections Model with Corrections and Beam-Beam Effects of the FCC-ee

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Many thanks to:

W. Herr, S. Jagabathuni, G. Katsanevakis

EPFL-LPAP Activity Meeting

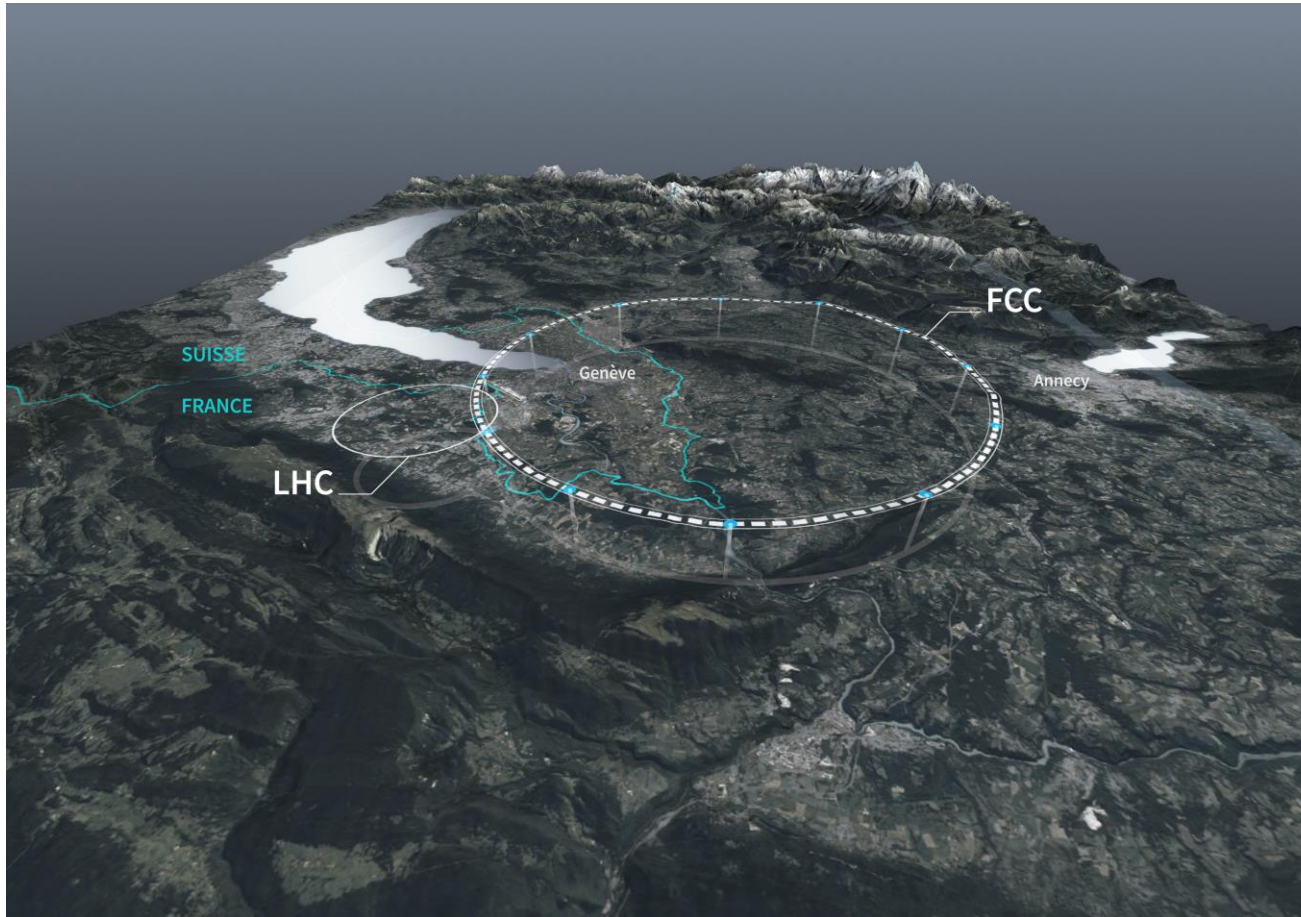
Thursday 28th May 2026

Outline

- I. Overview of FCC-ee (LCC lattice)**
- II. Imperfections model**
- III. Correction procedure**
- IV. Impact of beam-beam effects**
- V. Impact on Performance**

I. Overview of FCC-ee (LCC lattice)

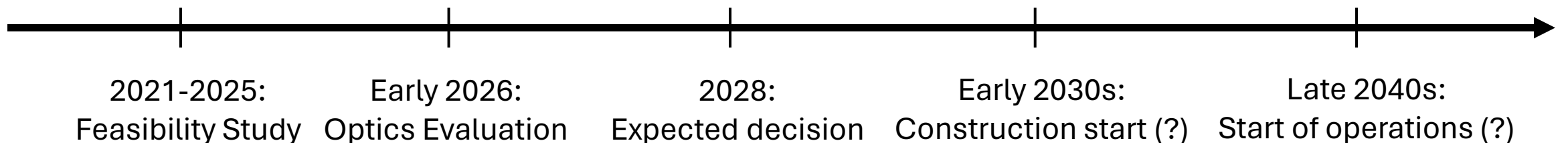
I. Overview of FCC-ee (LCC lattice)



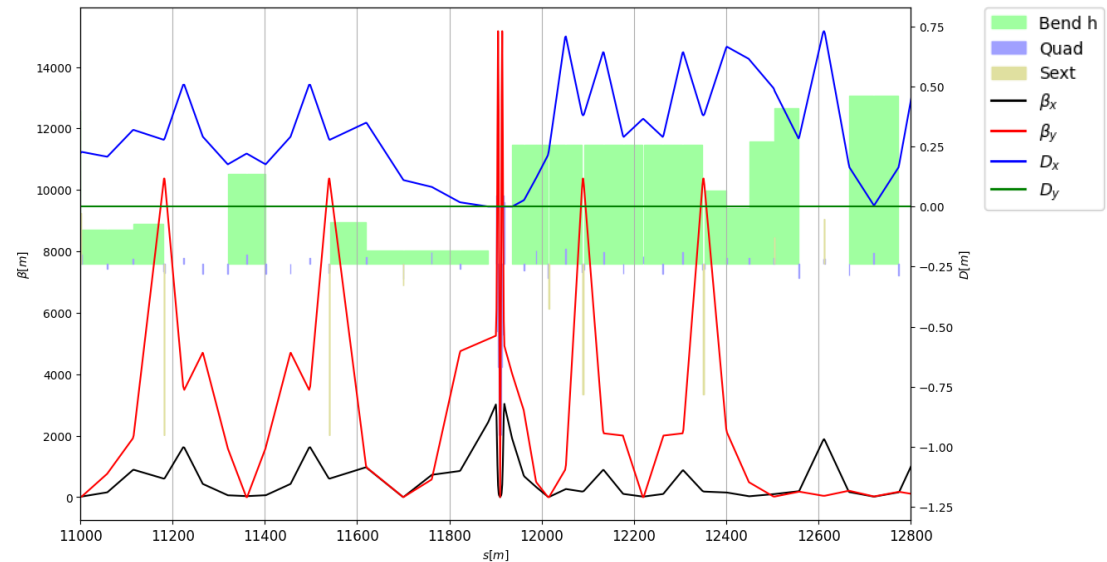
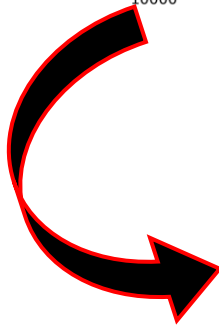
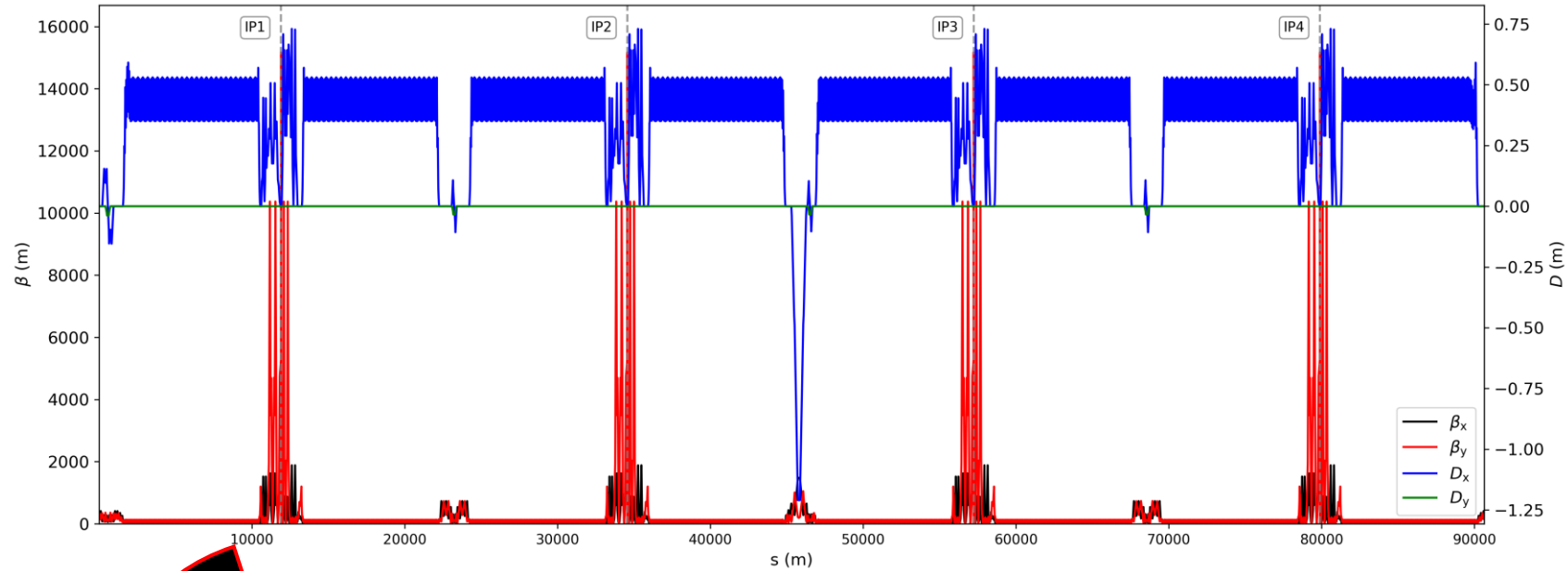
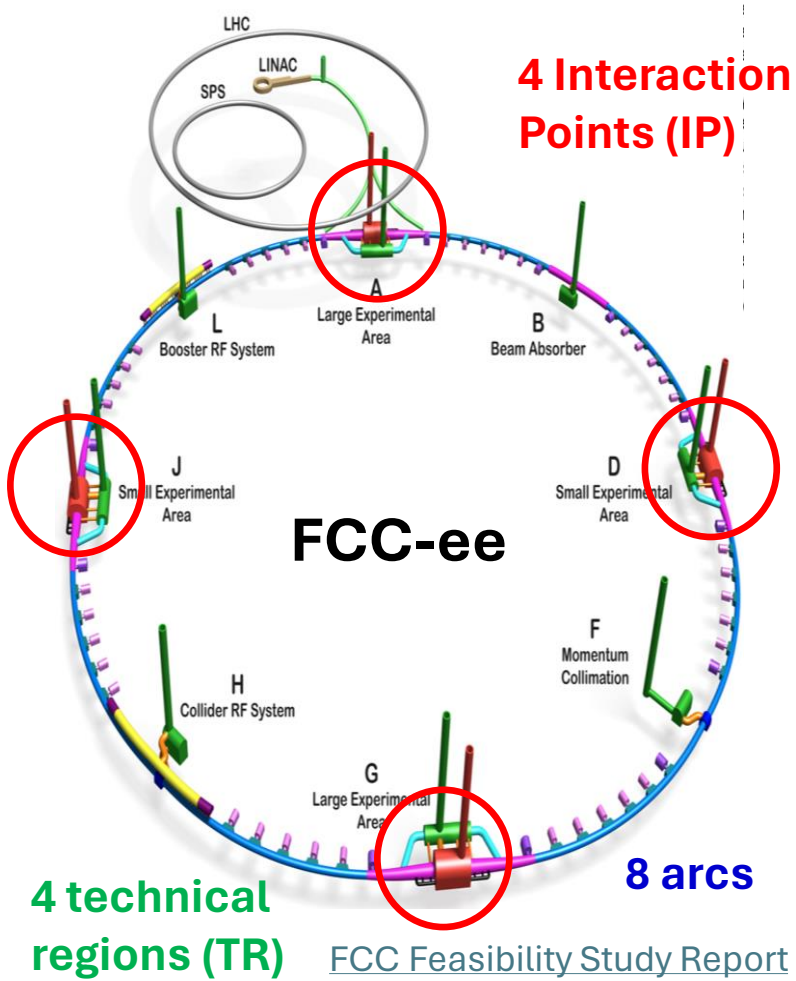
[CERN Future Circular Collider](#)

The Future Circular electron-positron Collider:

- Proposed next-generation particle accelerator of 90.7 km length
- Designed to operate at four energies: 45.6 GeV (Z), 80 GeV (WW), 120 GeV (ZH), and 182.5 GeV ($t\bar{t}$)
- Two optics options: **LCC** optics (developed since 2012 by K. Oide) and **GHC** optics (developed since 2022 by P. Raimondi)
- Spring 2026: decision on the [optics design](#) → LCC lattice chosen as the new baseline



I. Overview of FCC-ee (LCC lattice)



We study the LCC lattice @ Z pole

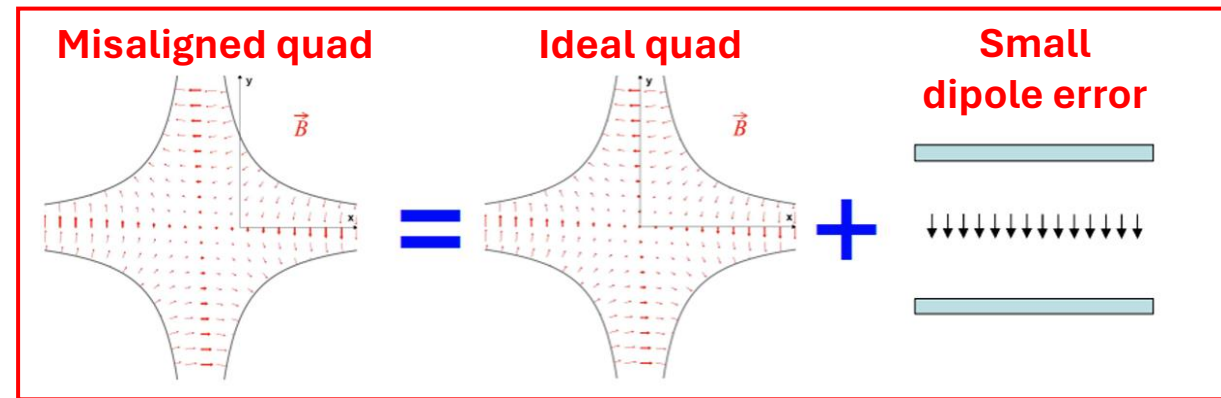
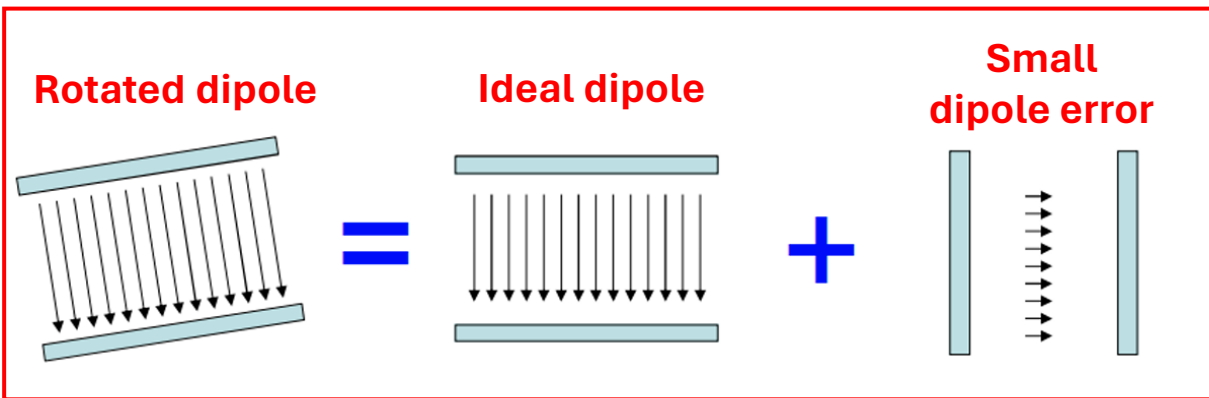
II. Imperfections Model

II. Imperfections model

Aim: Develop a model of the LCC lattice with imperfections (misalignments, rotations, and field errors) and analyse their impact

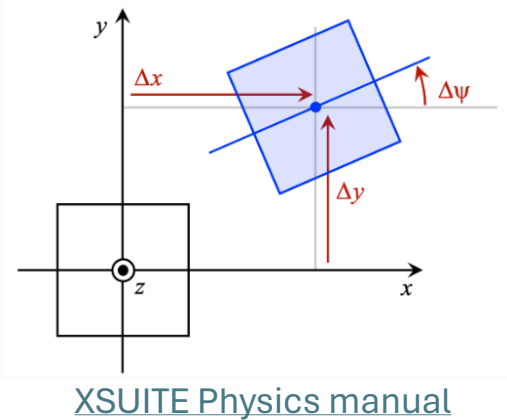
Field type	Imperfection	Error type	Impact
Dipole	Field error	Dipole	Orbit, trajectory, energy
Dipole	Roll	Dipole	Orbit, trajectory
Quadrupole	Field error	Quadrupole	Tune, optics
Quadrupole	Offset	Dipole	Orbit, trajectory
Quadrupole	Roll	Skew quadrupole	Coupling
Sextupole	Field error	Sextupole	Chromaticity
Sextupole	Horizontal offset	Quadrupole	Tune, optics
Sextupole	Vertical offset	Skew quadrupole	Coupling

J. Wenninger, “[Linear Imperfections](#)”, CAS 2018.

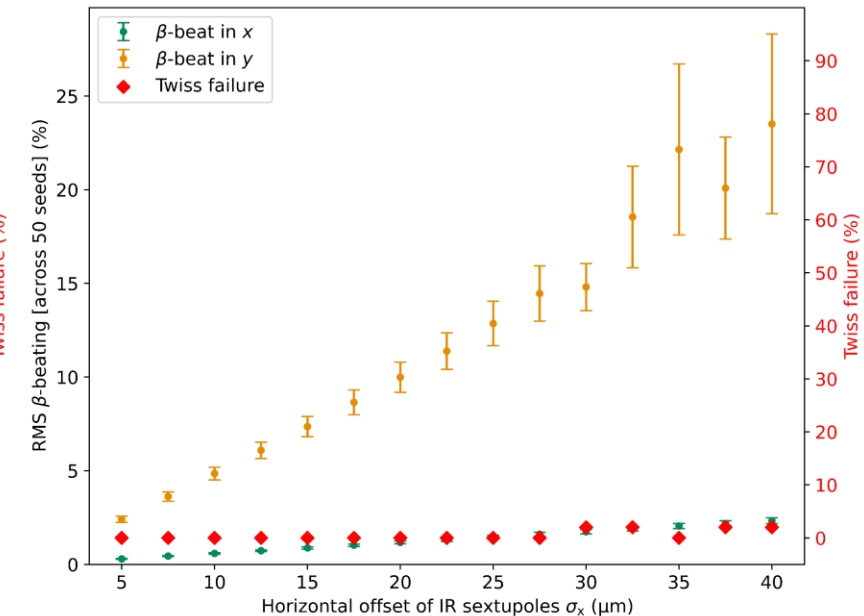
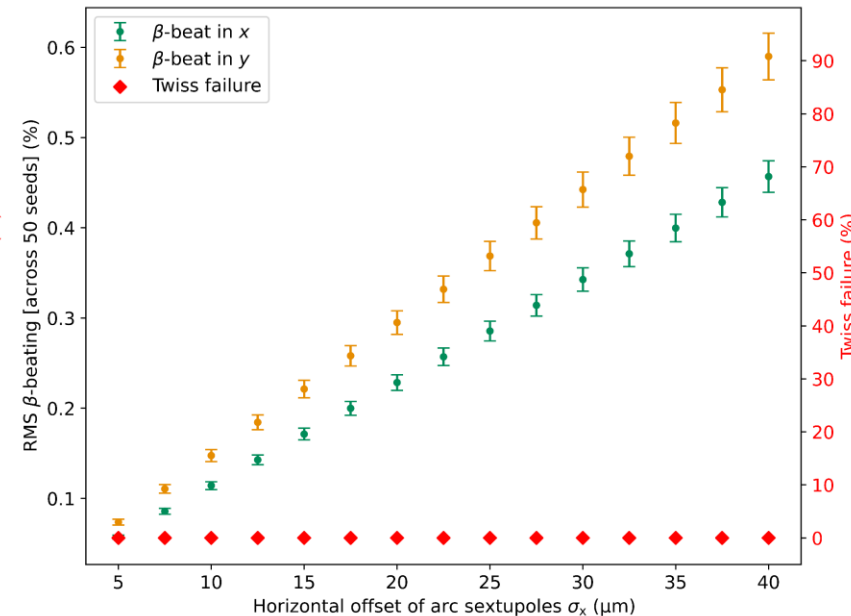
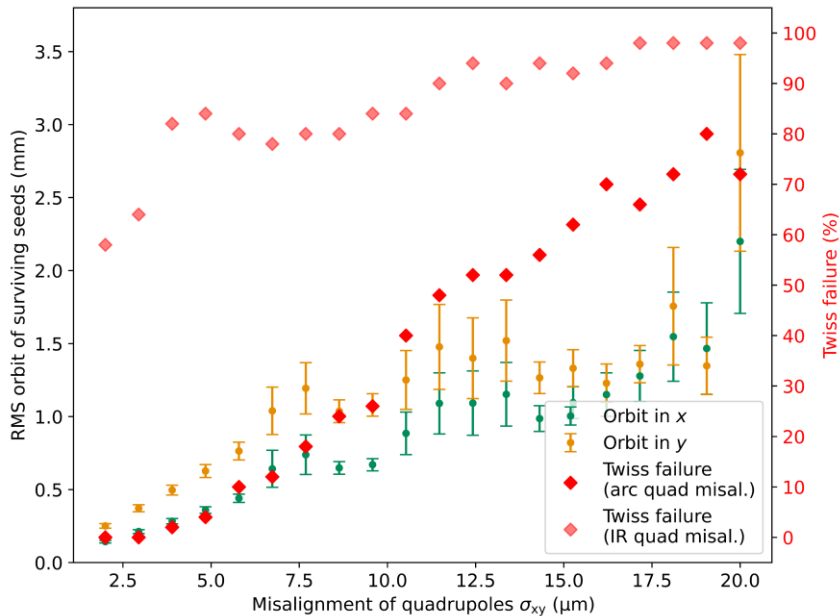


Depending on the type of imperfection, the **orbit** and/or **optics** of the lattice are affected

II. Imperfections model

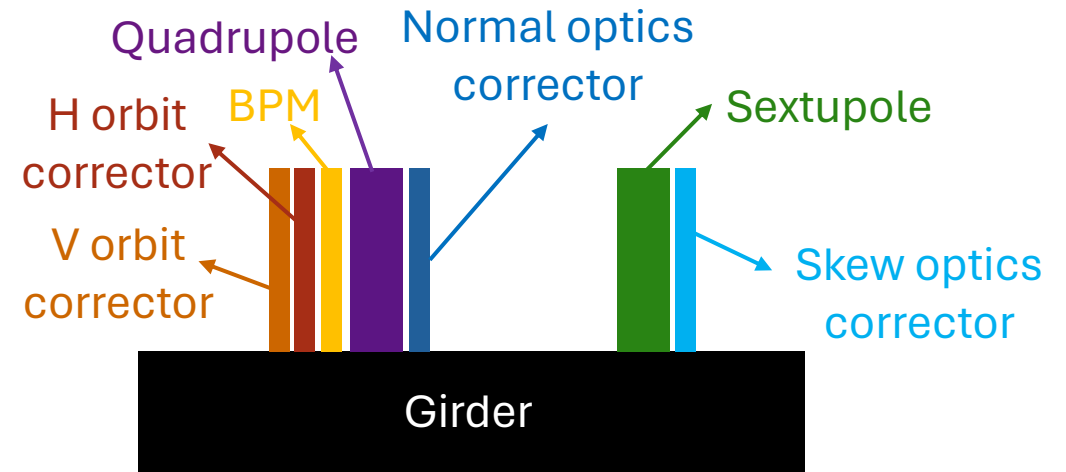


- Imperfections model includes:
 - transverse and longitudinal misalignments (x shift, y shift, s shift)
 - transverse rotations (s rotation)
 - field errors
- Errors are applied randomly based on a Gaussian distribution truncated at 2.5σ
 - ➔ different “seeds”
- Different error tolerances are to be considered for arc and straight section elements



II. Imperfections model

Element type	Number of elements
Dipole	2436
Quadrupole	2684
Sextupole	1952
BPM	2219
H orbit corrector	2259
V orbit corrector	2259
Normal optics corrector	2668
Skew optics corrector	1950

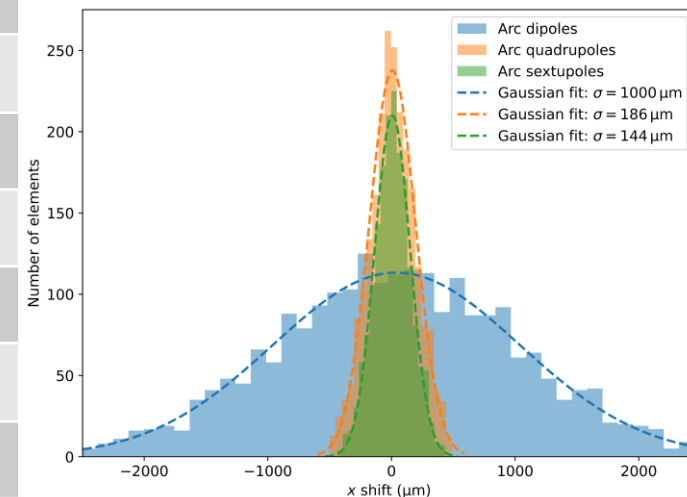
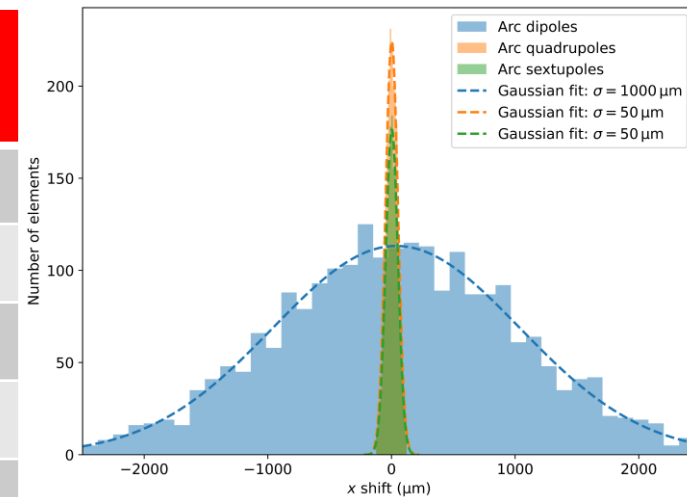


Structure of an arc section

- Misalignments and rotations are also applied to the girders in the arcs
- Elements mounted on top of a girder receive their own imperfections plus the misalignments from the girder
- BPMs inherit the misalignments from the quadrupoles to which they are attached and are assumed to have an additional position resolution error

II. Imperfections model

	Element	σ_x (μm)	σ_y (μm)	σ_s (μm)	σ_θ (μrad)	Field error (rel.)
ARC	Dipole	1000	1000	500	1000	k0: 1e-3
	Quadrupole	50	50	100	50	k1: 2e-4
	Sextupole	50	50	100	50	k2: 2e-4
	Girder	150	150	500	150	—
STRAIGHT SECTION	IP Dipole	1000	1000	100	1000	k0: 1e-3
	TR Dipole	1000	1000	500	1000	k0: 1e-3
	FD Quadrupole	10	10	100	10	k1: 1e-5
	FF Quadrupole	30	30	100	30	k1: 1e-4
	DS/TR Quadrupole	100	100	100	100	k1: 2e-4
	FF Sextupole	30	30	100	30	k2: 1e-4
OTHER	BPM	10	10	—	10	—



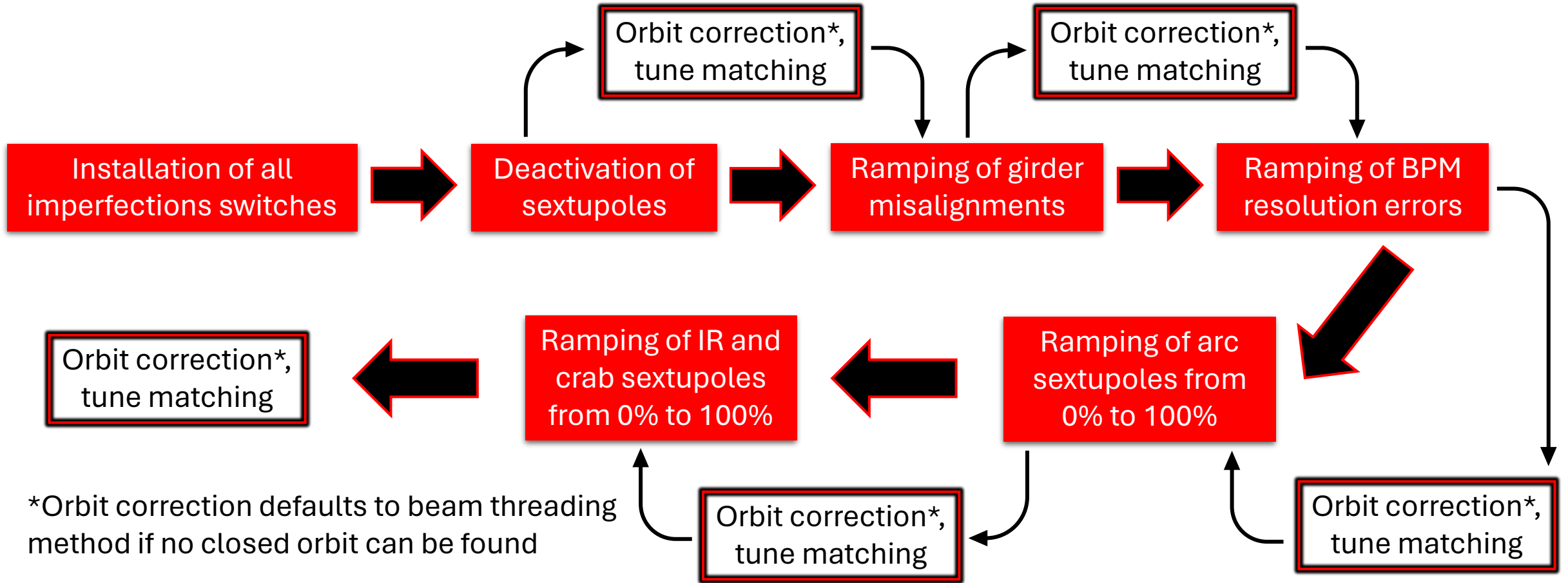
IP = Interaction Point
 TR = Technical Region
 FD = Final Doublet

FF = Final Focussing
 DS = Dispersion
 Suppression

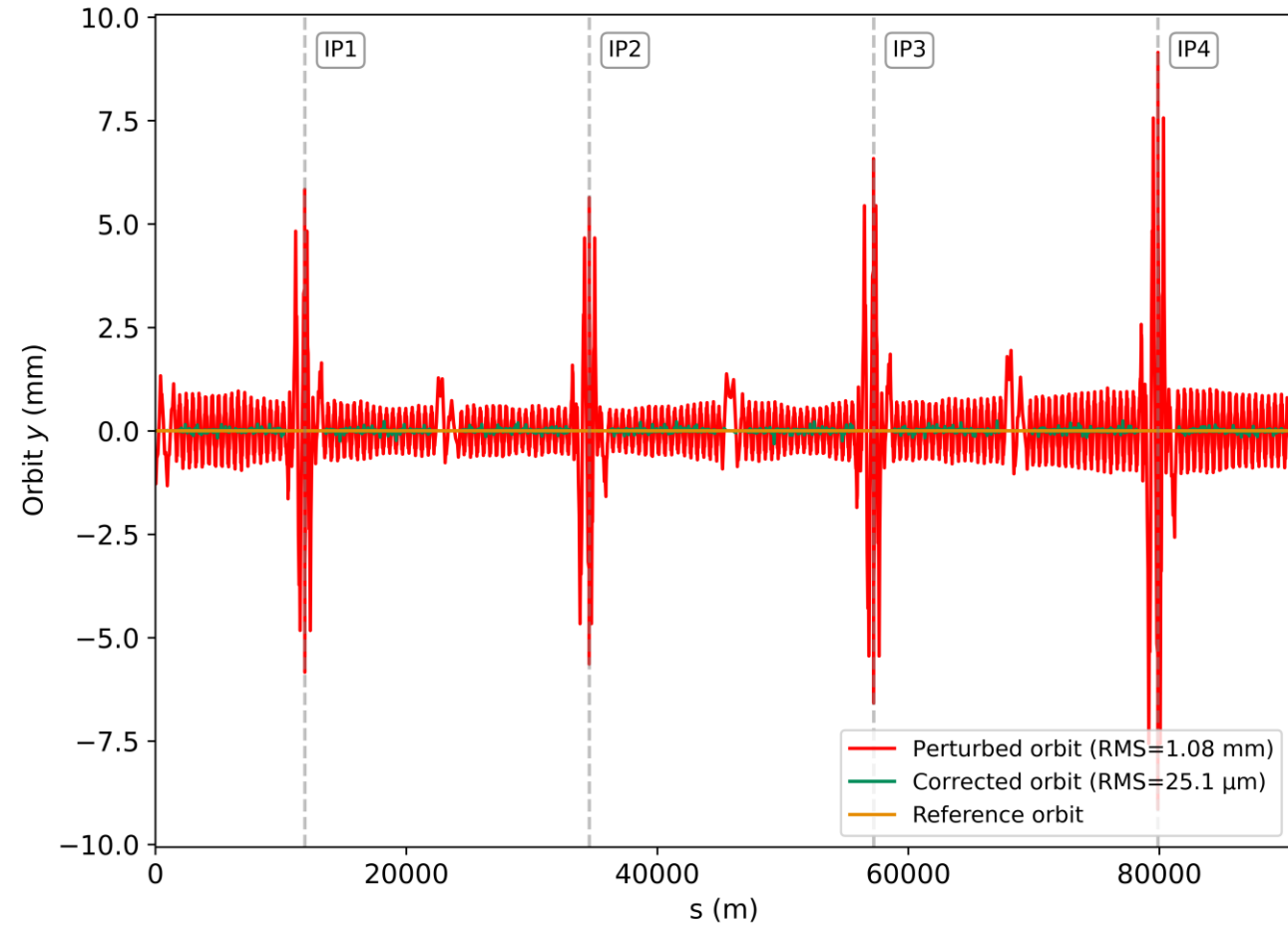
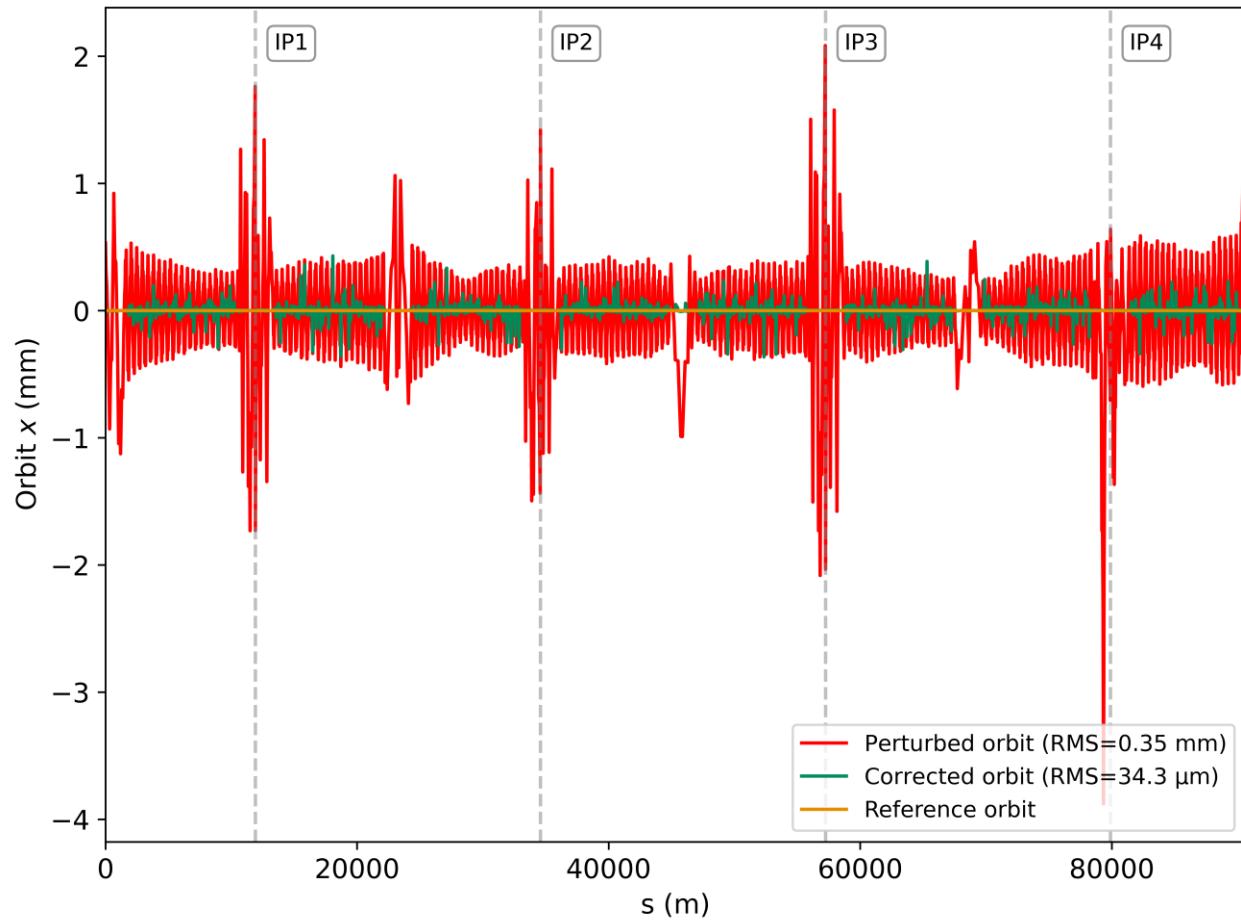
III. Correction Procedure

III. Correction Procedure

ORBIT CORRECTION



III. Correction Procedure



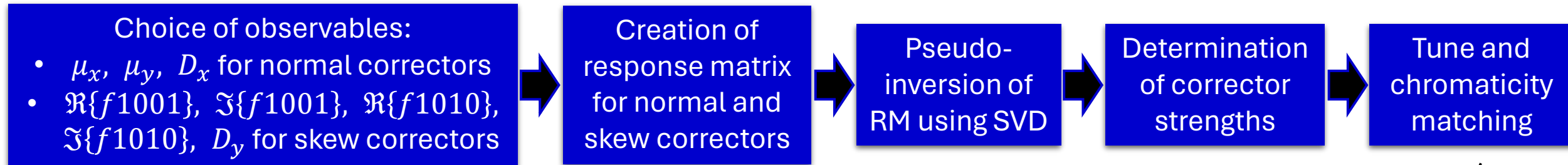
Applied imperfections: Quadrupole misalignments
@ 10 % of the chosen error tolerances

III. Correction Procedure

OPTICS CORRECTION

Optics quantities of interest:

- Beta function β
- Phase advance μ
- Dispersion D
- Coupling f_{1001}, f_{1010}



- Choice of observables:
- μ_x, μ_y, D_x for normal correctors
 - $\Re\{f_{1001}\}, \Im\{f_{1001}\}, \Re\{f_{1010}\}, \Im\{f_{1010}\}, D_y$ for skew correctors

Creation of response matrix for normal and skew correctors

Pseudo-inversion of RM using SVD

Determination of corrector strengths

Tune and chromaticity matching

Normal correctors at quadrupoles
Skew correctors at sextupoles

$$\Delta u = R \Delta c$$
$$\rightarrow \Delta c = R^{-1} \Delta u$$

R is the RM storing the “response” of the chosen observables at the observation points (BPMs)

Δc is the corrector strength variation
 Δu is the optics observable variation

Using the arc quadrupoles and arc sextupoles

III. Correction Procedure

A representative seed after global orbit and optics correction

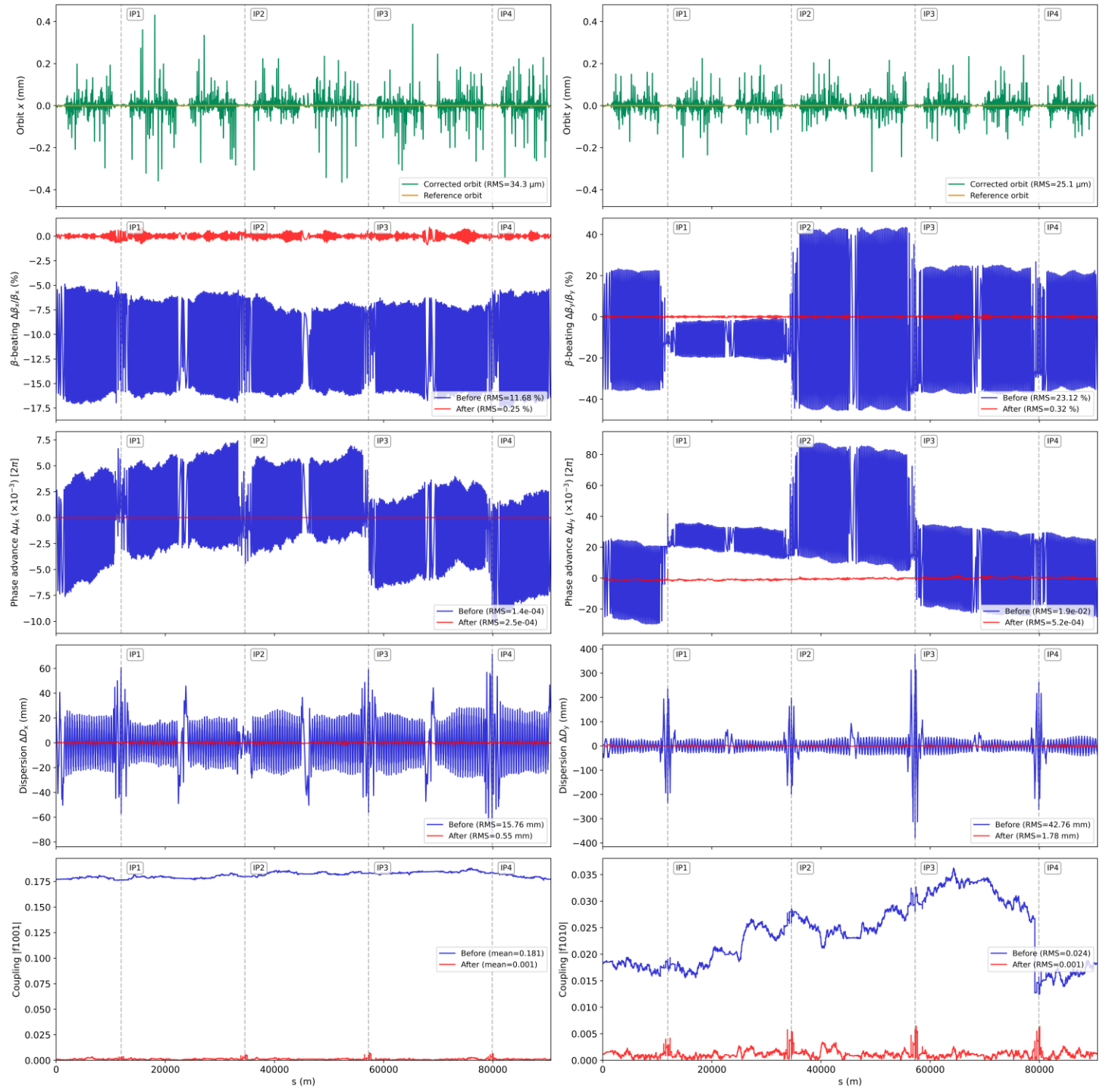
Orbit

β -beating

Phase adv.

Dispersion

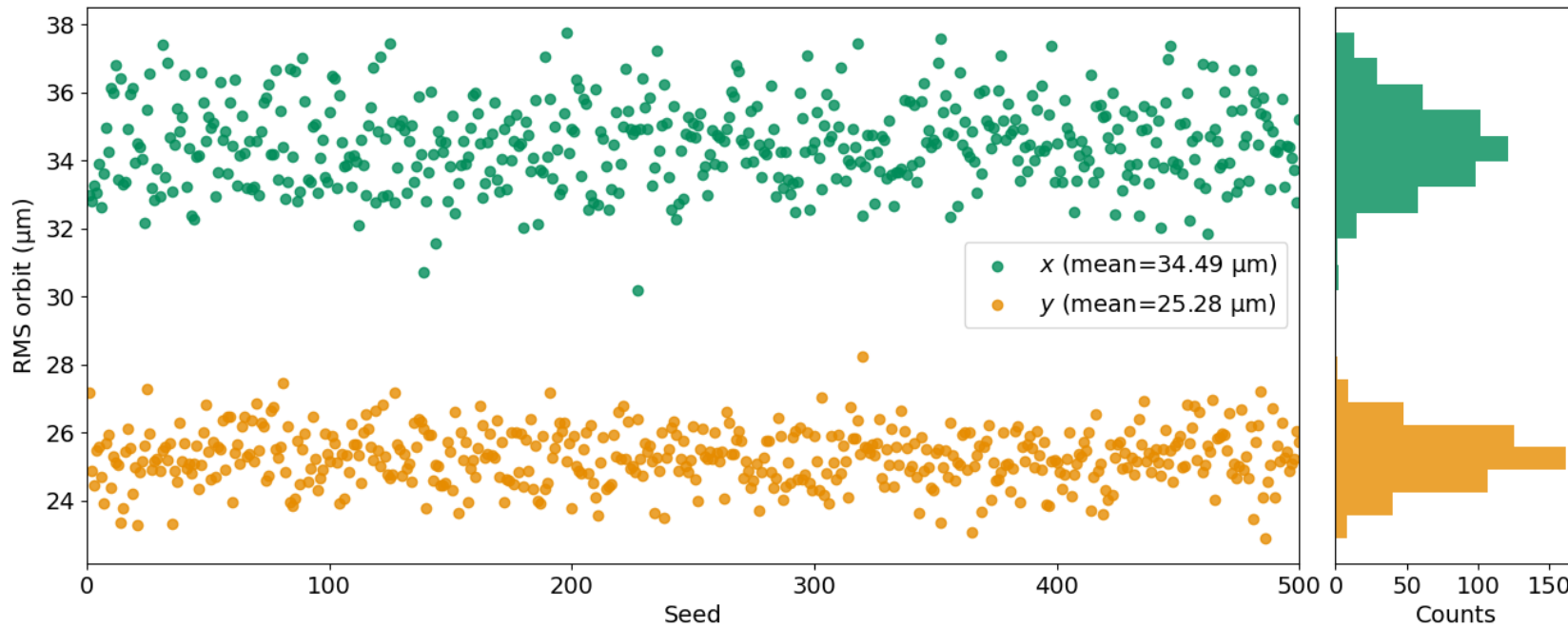
Coupling



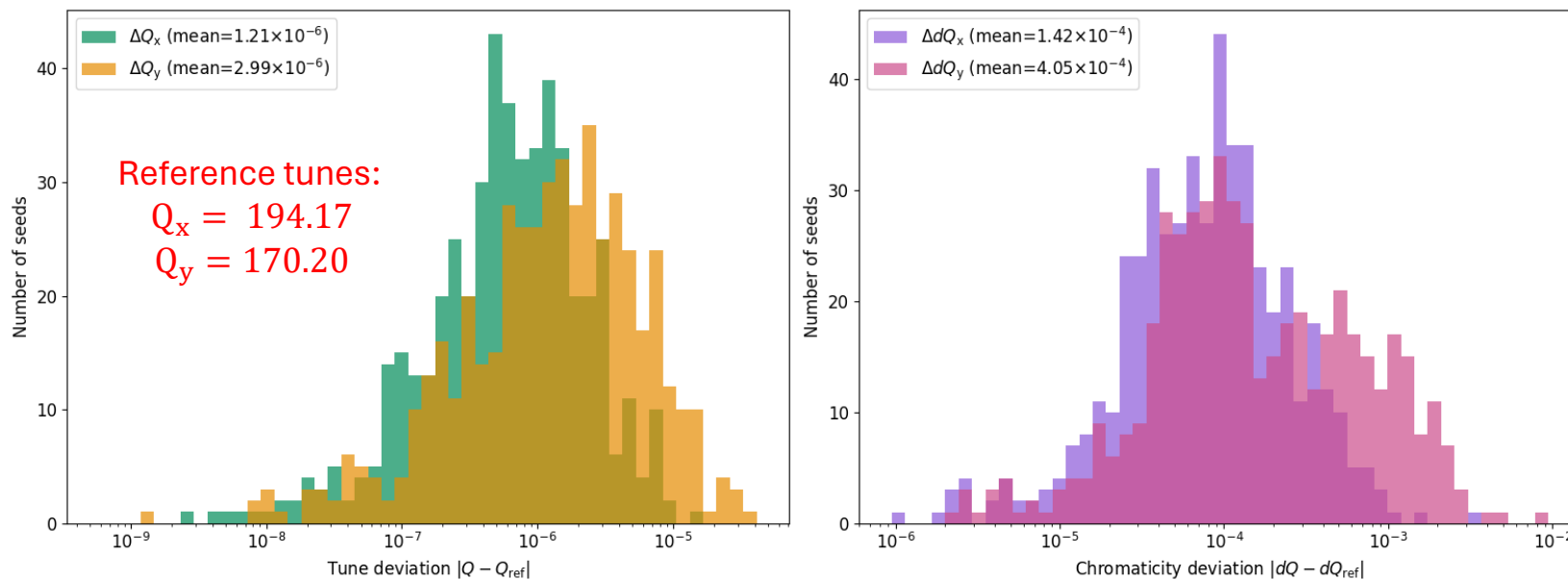
III. Correction Procedure

Statistics analysis on 500 corrected lattices

Orbit



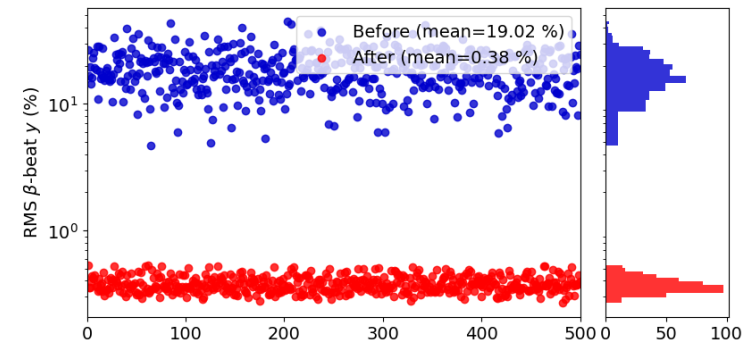
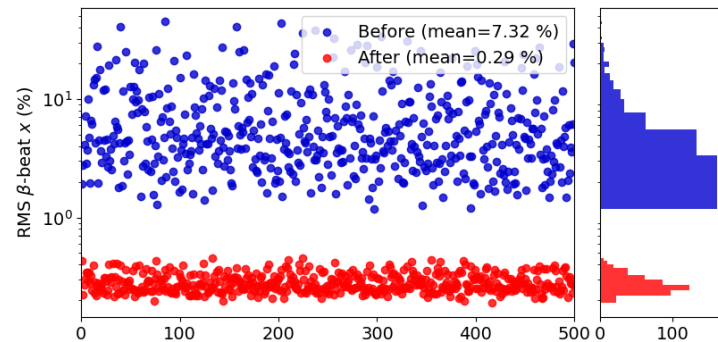
Tune and Chromaticity



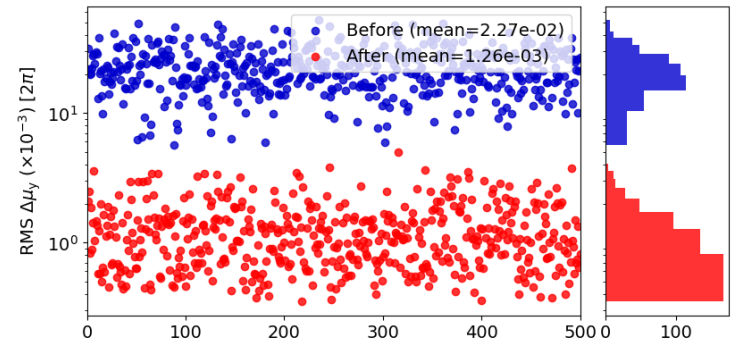
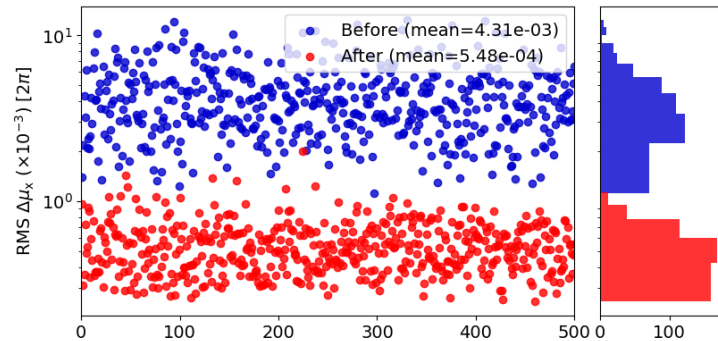
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Statistics analysis on
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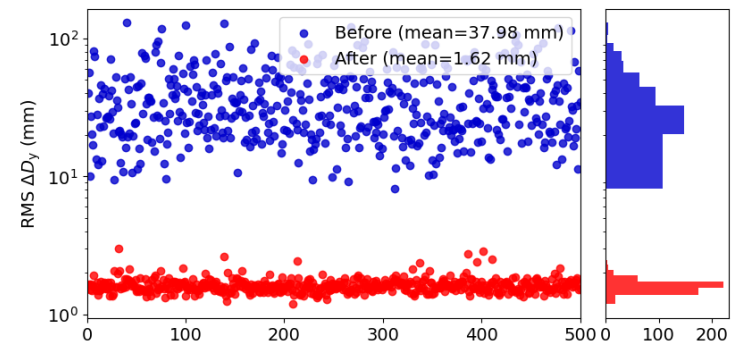
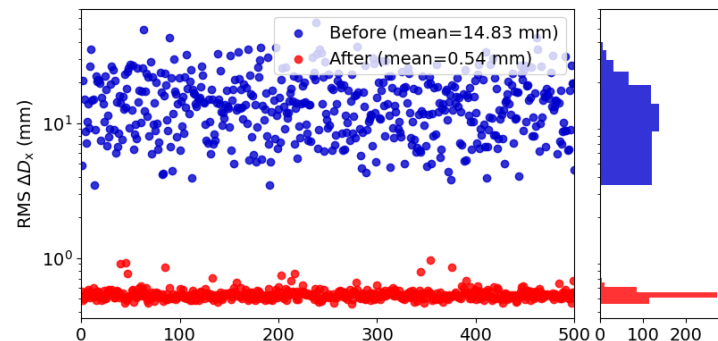
β -beating



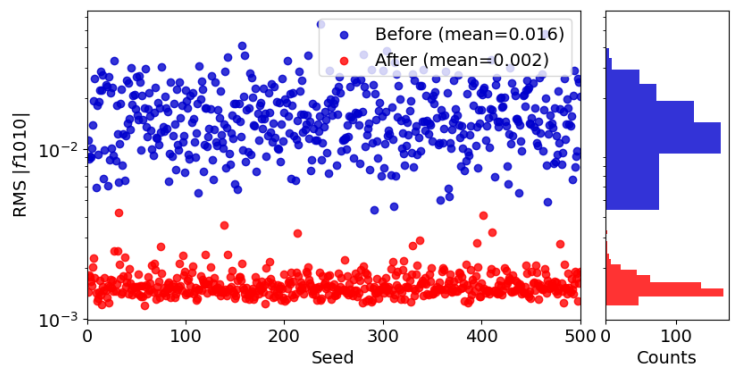
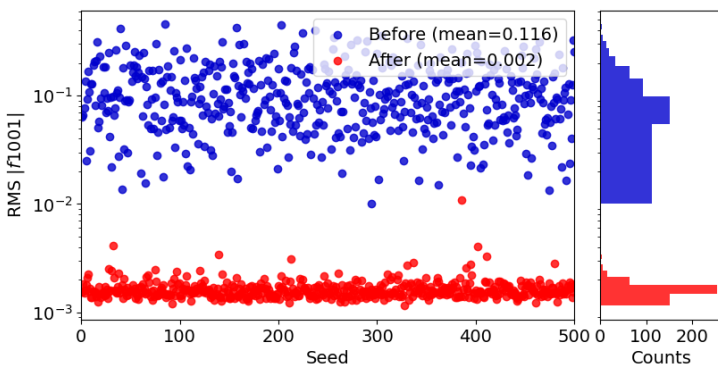
Phase adv.



Dispersion



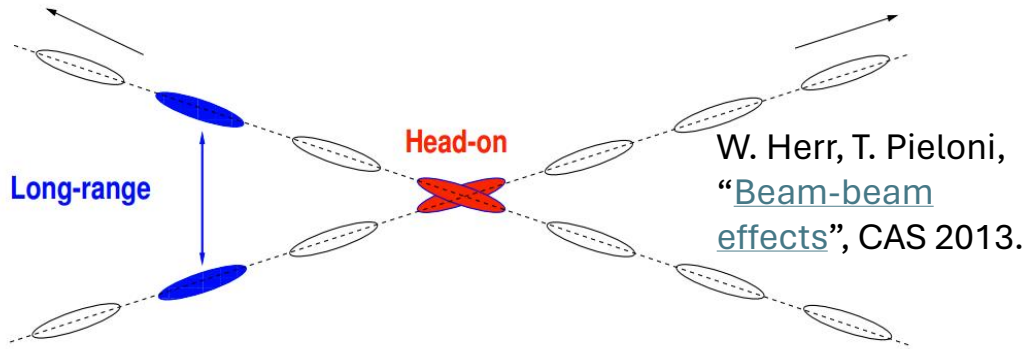
Coupling



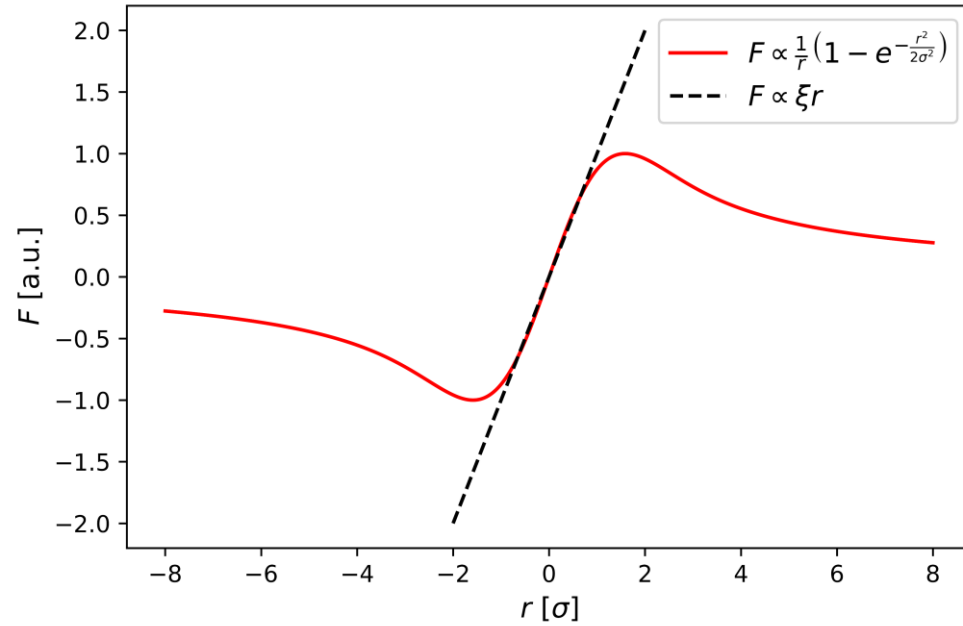
IV. Impact of Beam-Beam Effects

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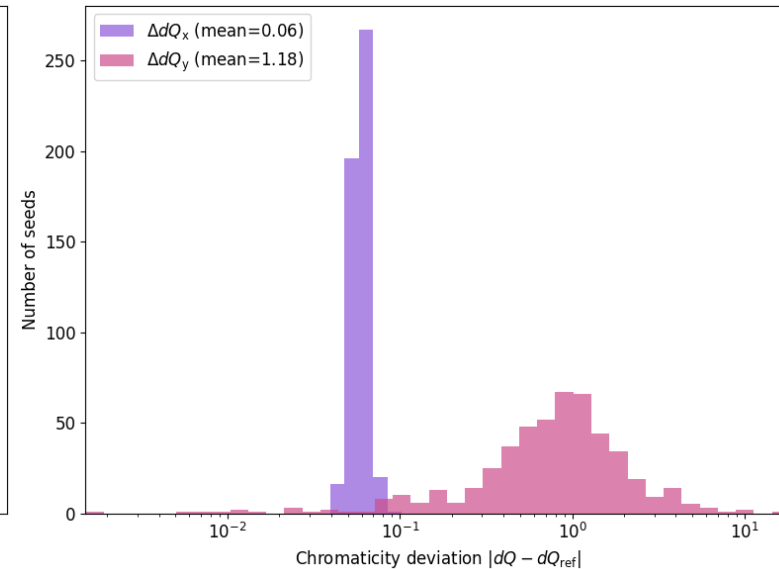
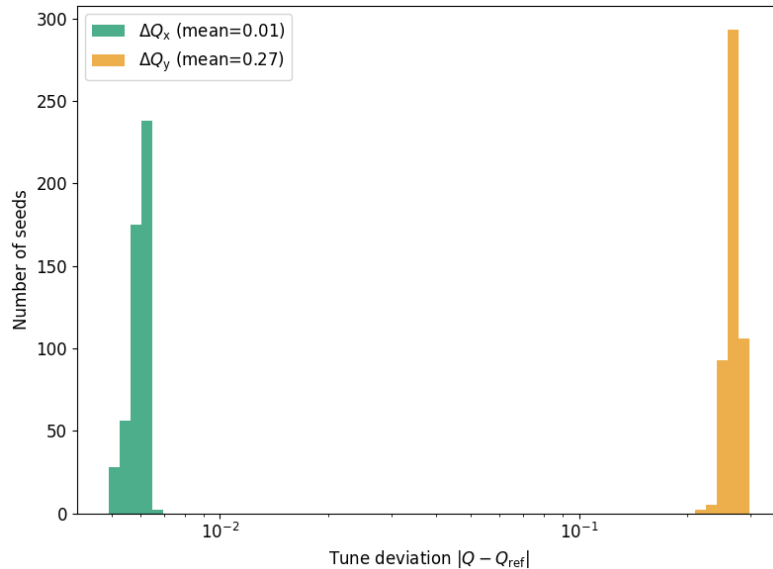
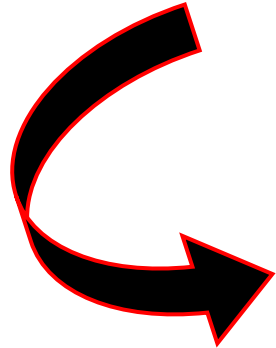
Electromagnetic perturbations
as two beams cross each other



Beam-beam kick at each IP introduces a
linear tune shift and β -beating along the ring



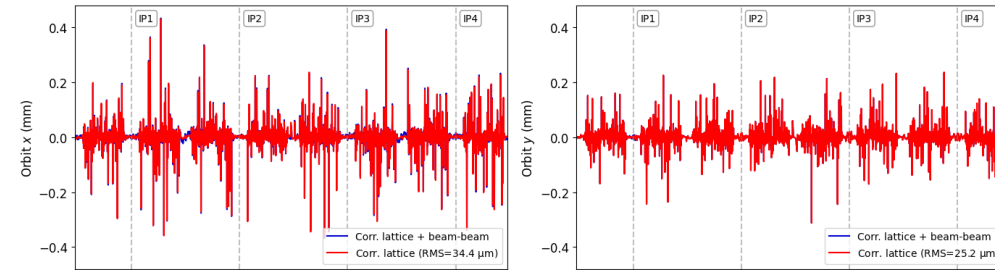
Beam-beam
parameter
 $\xi_y = 0.09$



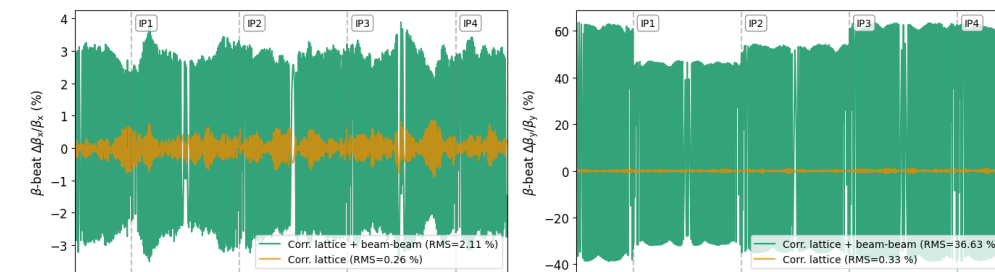
IV. Impact of Beam-Beam Effects

A corrected lattice
(global orbit and
optics correction) with
beam-beam effects

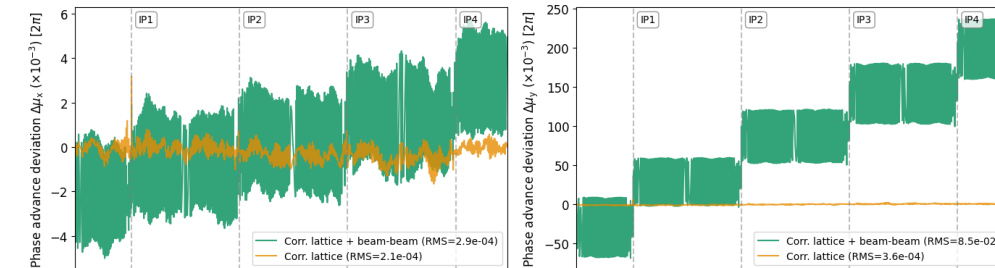
Orbit



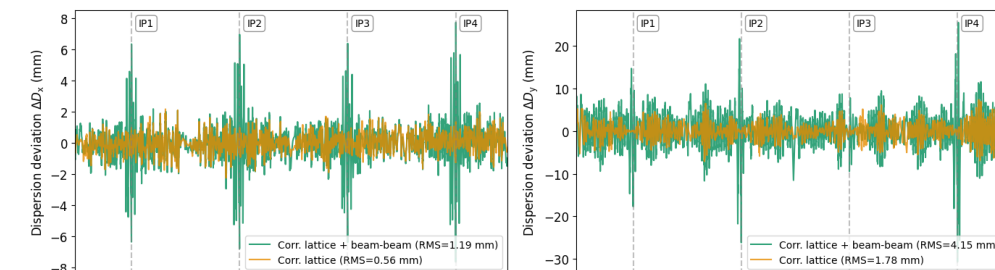
β-beating



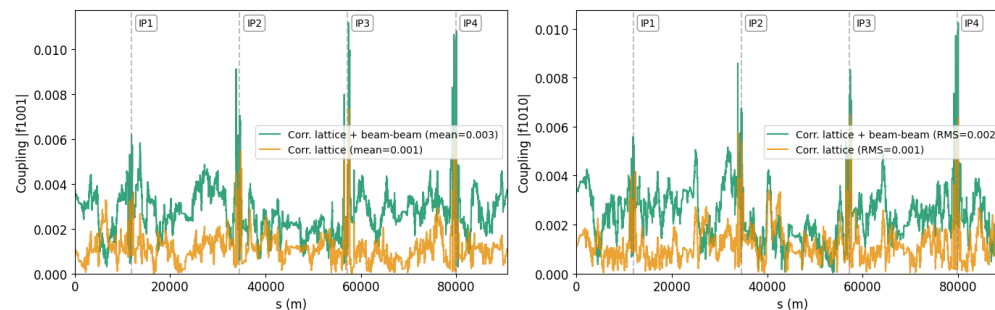
Phase adv.



Dispersion



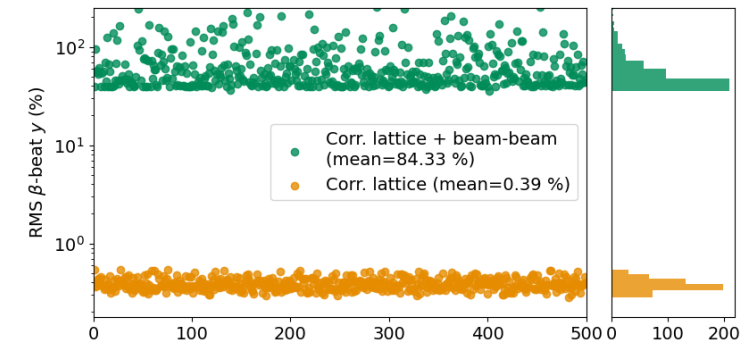
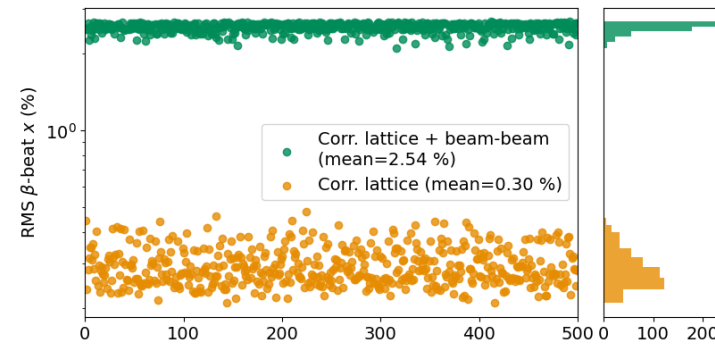
Coupling



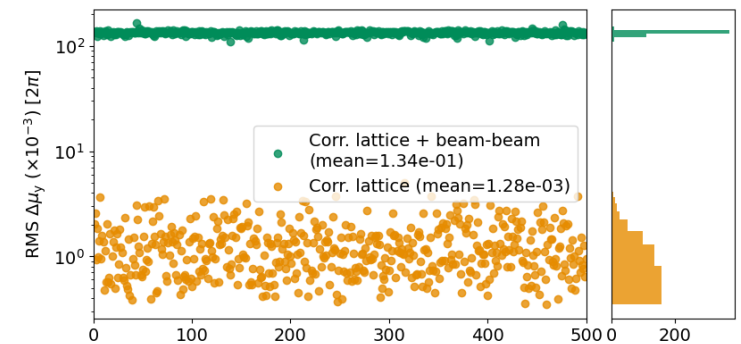
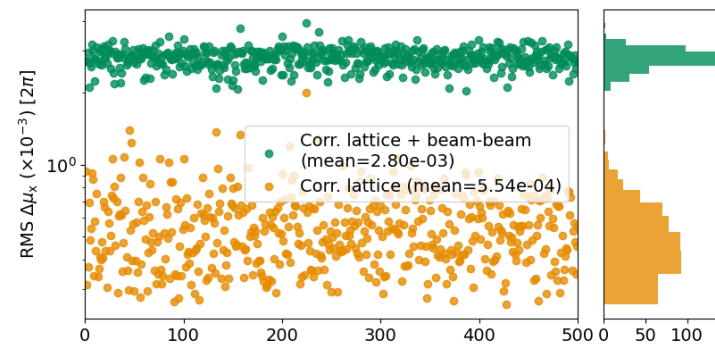
IV. Impact of BB Effects

Statistics analysis on
500 corrected lattices
with beam-beam
effects

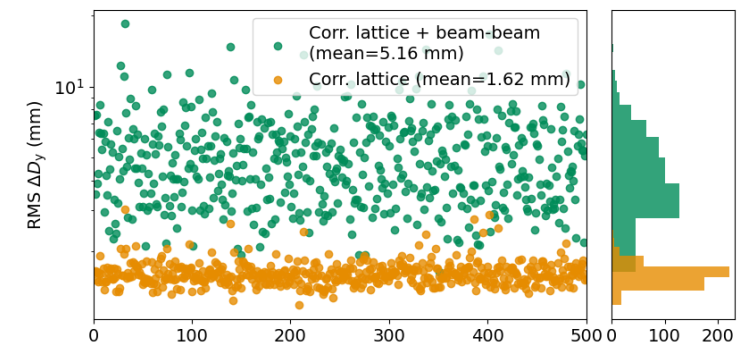
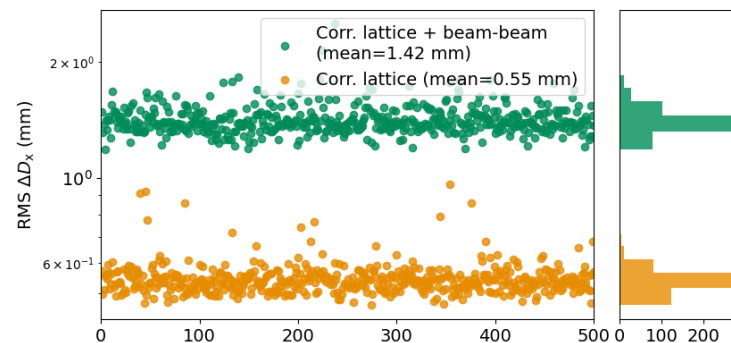
β -beating



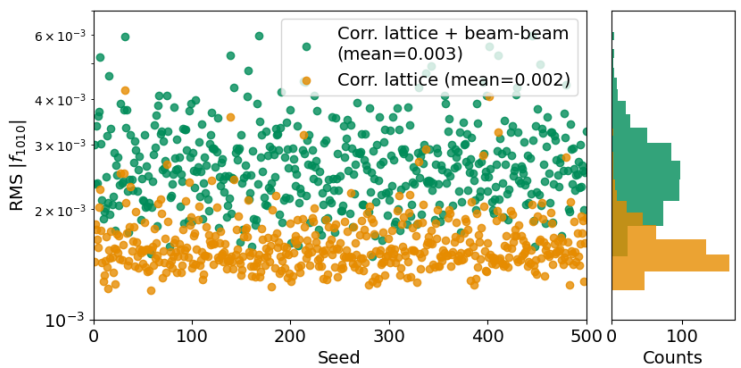
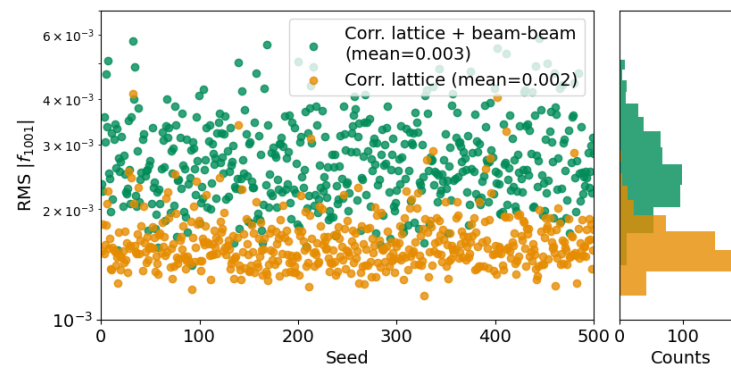
Phase adv.



Dispersion



Coupling

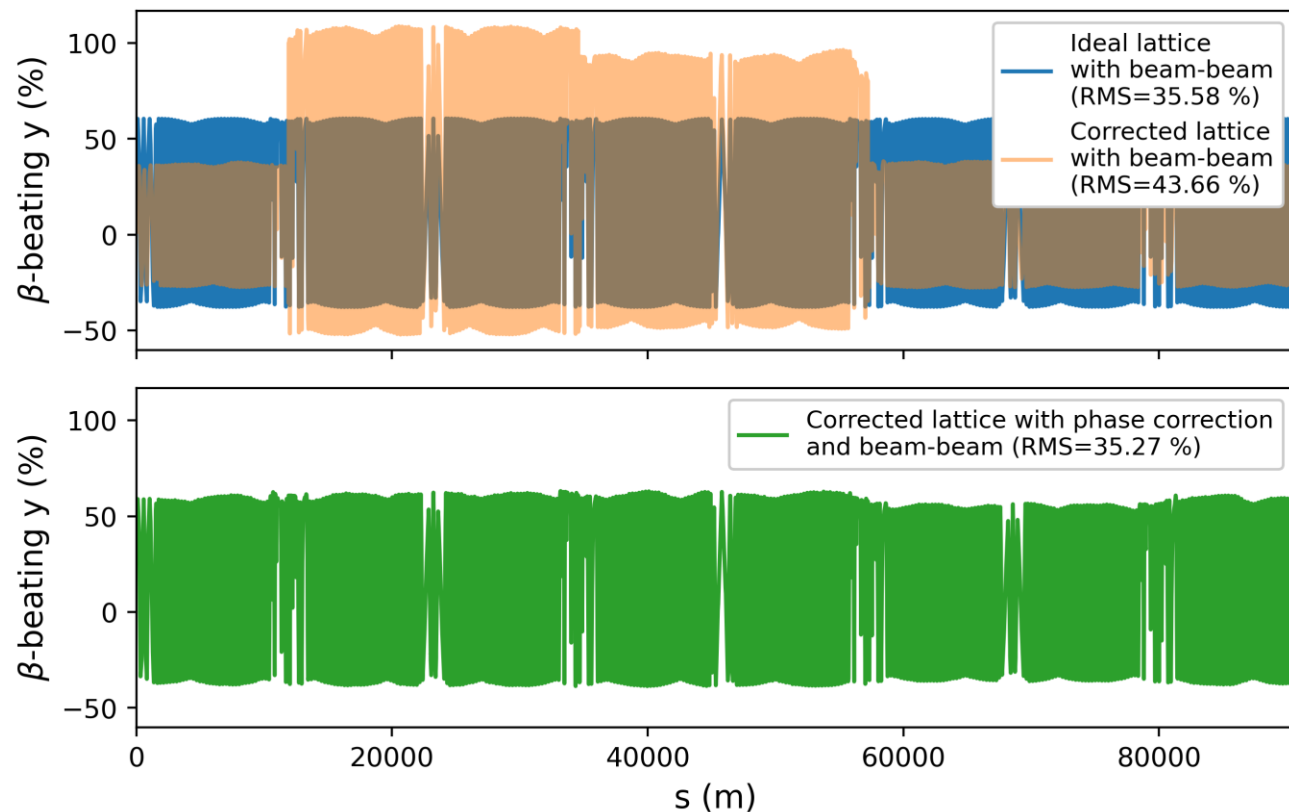


V. Impact on Performance

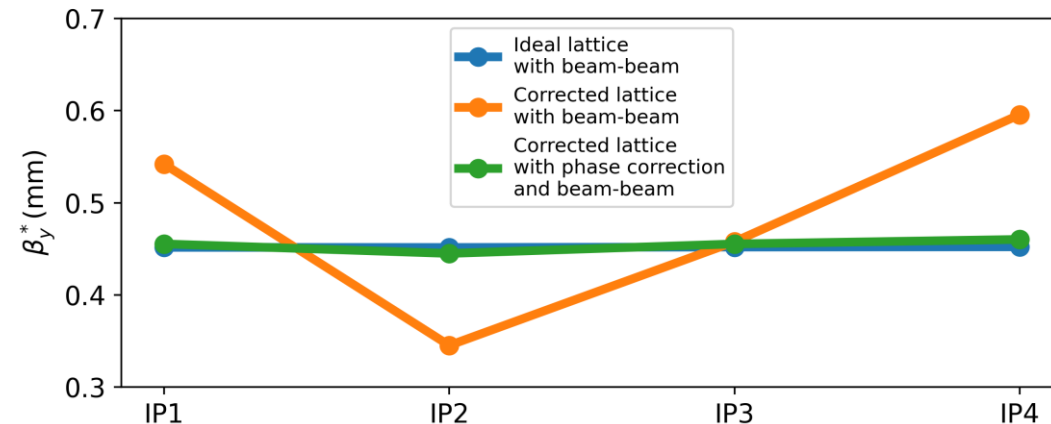
V. Impact on Performance

A first attempt of restoring the nominal optics in the lattices with beam-beam effects:

- by correcting the phase advance between IPs on top of the global correction
- using certain trim quadrupoles in the DS regions



Courtesy of T. Prebibaj

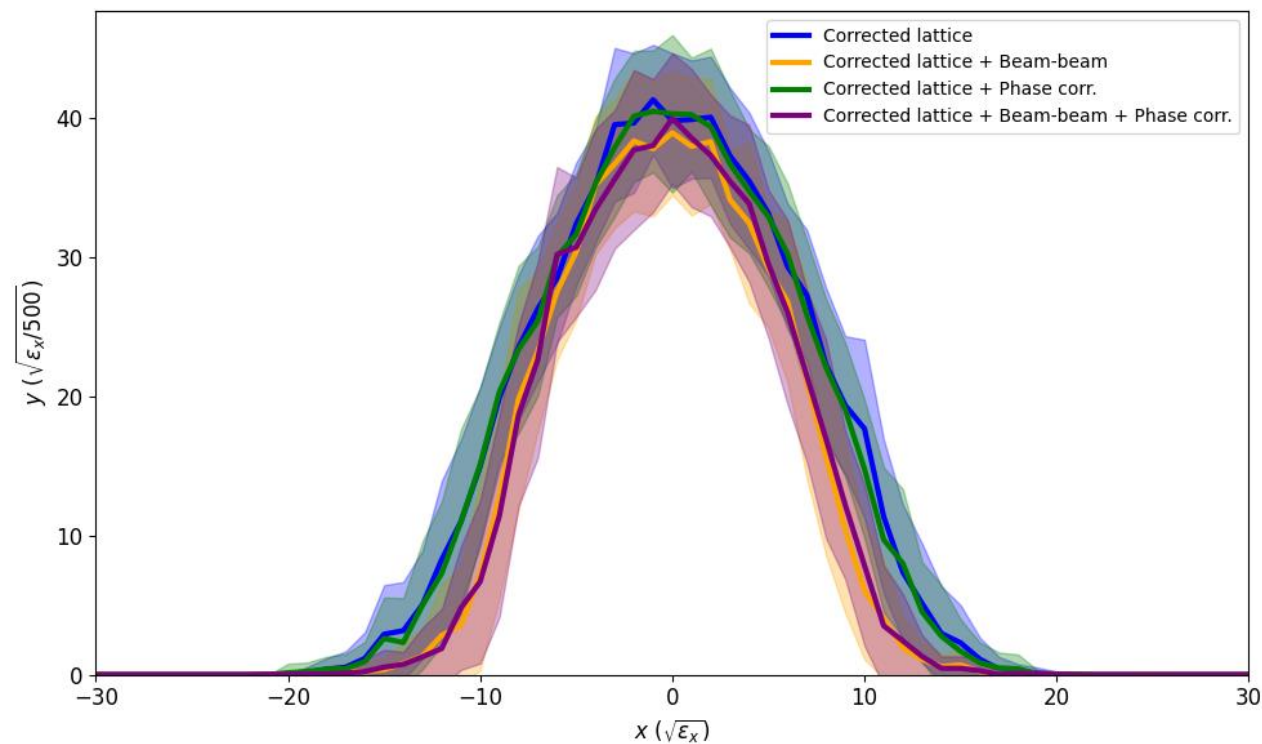


- Residual phase errors at the IPs break the lattice symmetry
 - But phase correction recovers uniform β -beating
 - It also restores the uniform β^* reduction at the IPs
- Positive impact on performance by improving the luminosity balance between the IPs

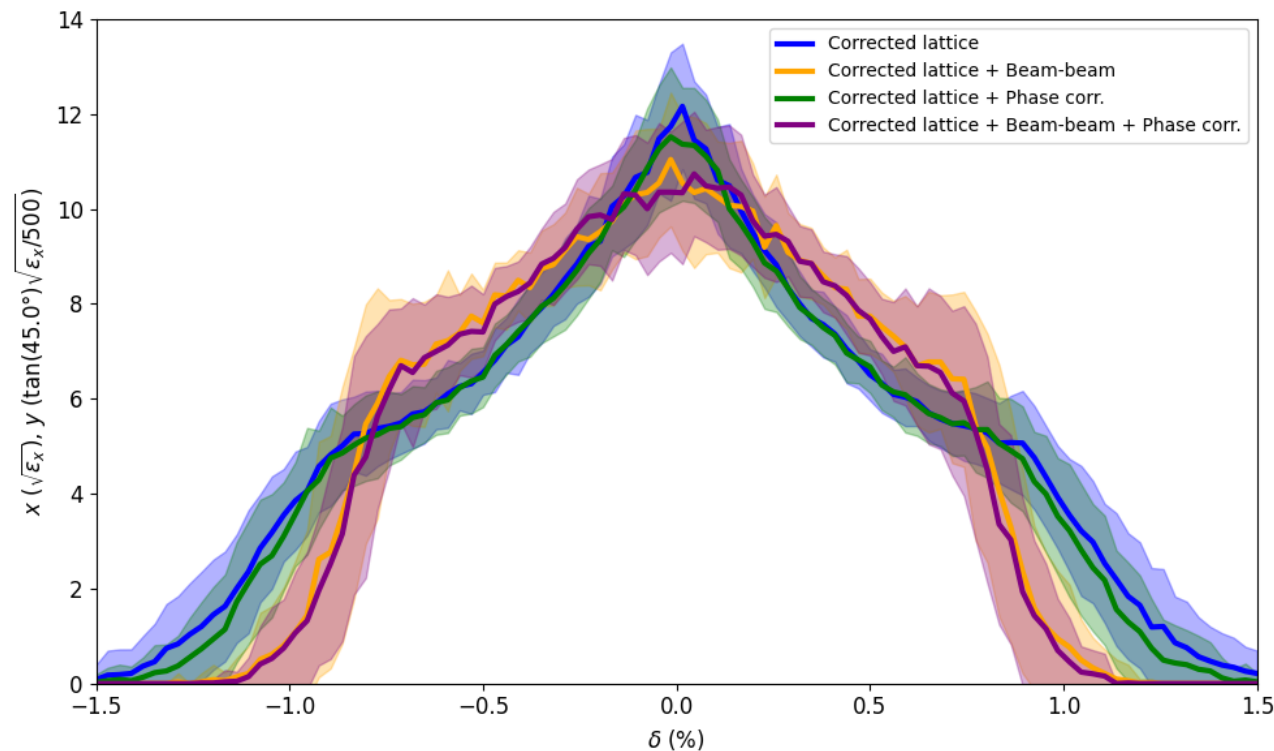
V. Impact on Performance

Tracking for 2500 turns (across 50 different seeds)
to determine the “stability region” of the lattice

DA = Dynamic Aperture

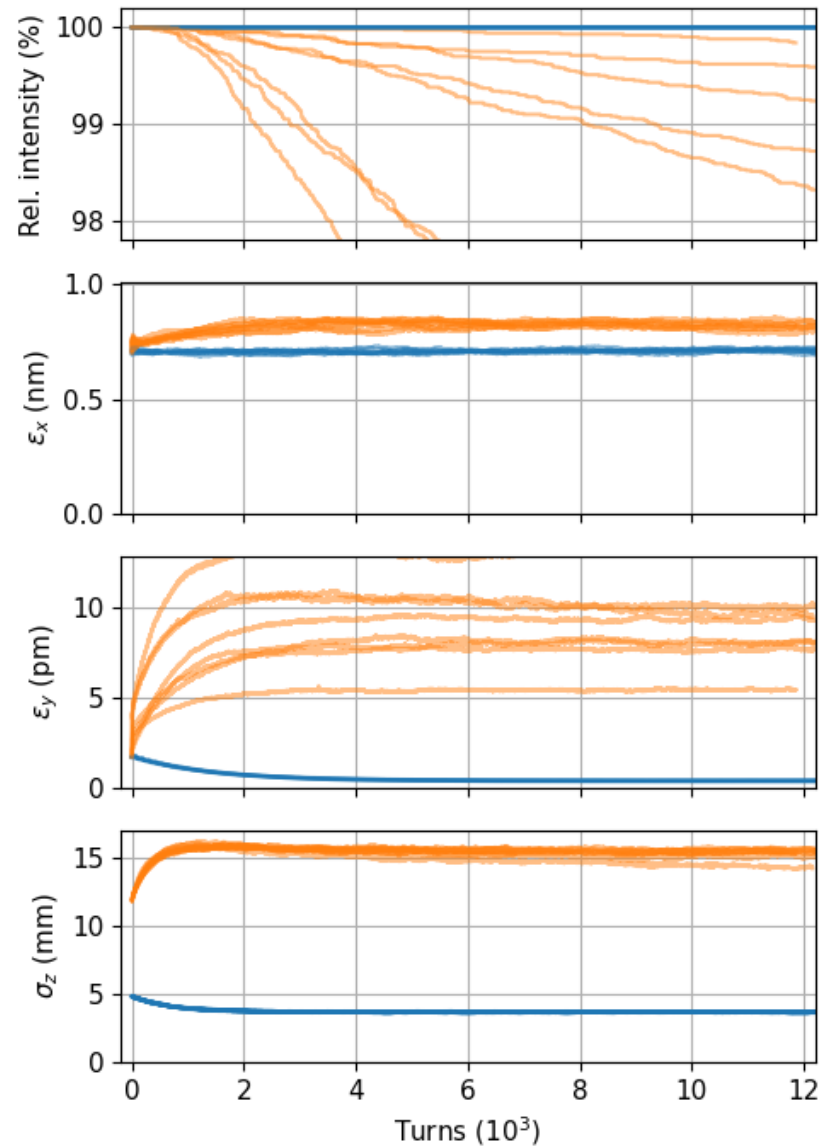


MA = Momentum Acceptance



V. Impact on Performance

Tracking of 10 000 particles (8 seeds)



Blue: w/o beam-beam
Orange: with beam-beam

Summary and Outlook

SUMMARY

- Development of an **imperfections model** of the LCC lattice for the FCC-ee
- Implementation of a **global orbit and optics correction** procedure
- Generation of 500 corrected lattices
- Statistics analysis of various optics parameters around the ring
- Introduction of **beam-beam effects** and investigation of their impact
- Analysis of the impact on **collider performance** via DA/MA scans and tracking

OUTLOOK

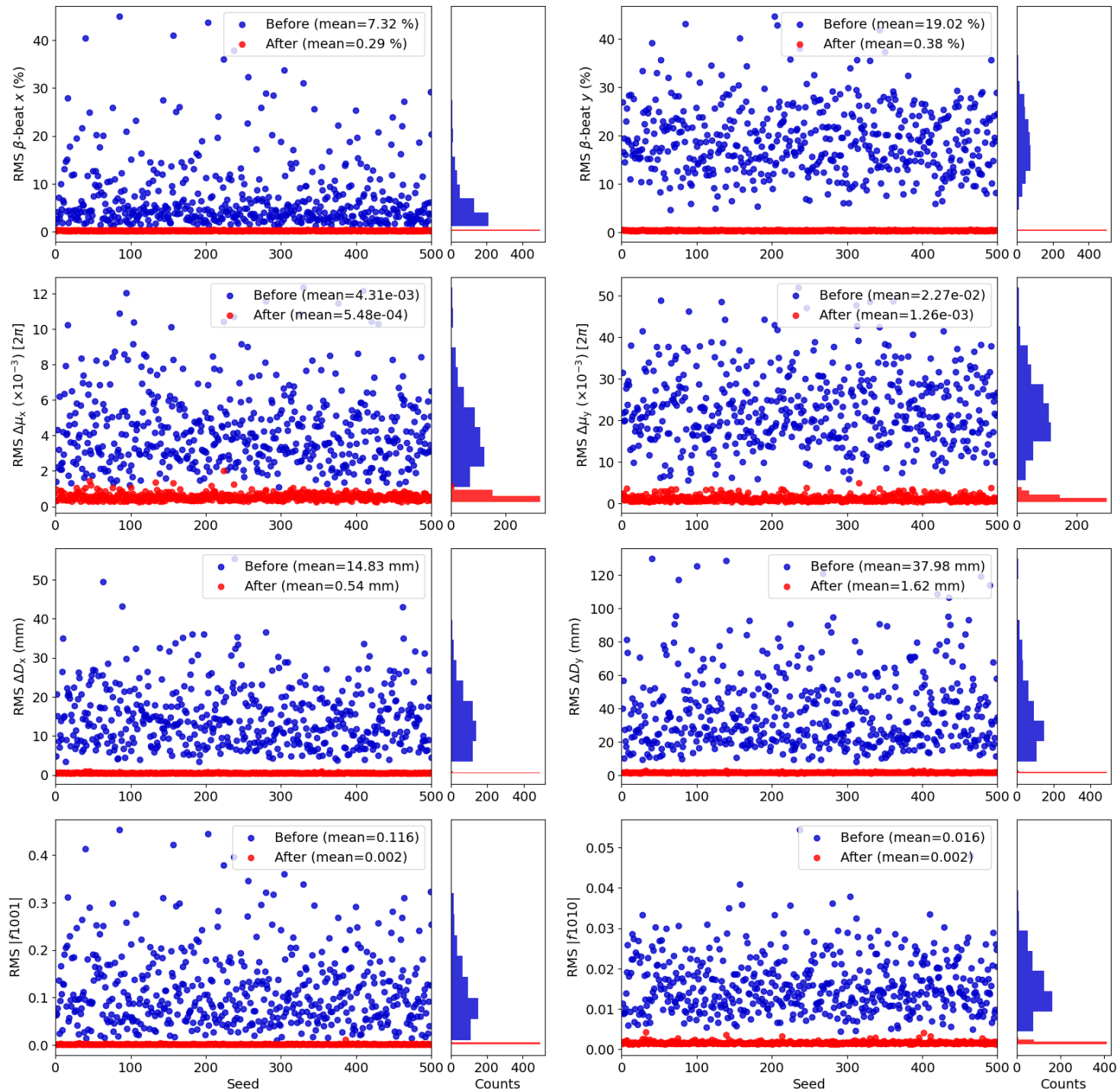
- Development of local correction knobs to counteract the distortions arising from beam-beam effects
- Comparison of different algorithms for the global correction procedure (SVD, MICADO) and further optimisation
- Use of tracking to study correlations between different performance metrics and lattice properties

Thank you!

Parameter table of the LCC lattice

Optics Mode	LCC	
	Z	\bar{t}
Beam energy E (GeV)	45.6	182.5
Circumference C (m)	90644.816	
Arc-cell setup	52°/45°	99°/77°
Momentum compaction factor α_c (10^{-6})	28.6	9.5
Energy Loss per turn W_0 (GeV)	0.035	9.01
Beam Intensity N (10^{12} particles)	2424	9.435
Bunch Intensity N_b (10^{11} particles)	2.02	2.20
Number of Bunches	12000	43
Horizontal β -function at IP β_x^* (cm)	9	90
Vertical β -function at IP β_y^* (mm)	0.7	14
Horizontal emittance ϵ_x (nm)	0.70	2.10
Target vertical emittance in collision ϵ_y (pm)	1.40	2.11
Transverse tune Q_x/Q_y	194.16 / 170.20	346.19 / 262.27
Chromaticity Q'_x/Q'_y	12 / 5	0 / 0
Harmonic number h at 400 MHz	121200	
Total RF voltage of 400 / 800 MHz (GV)	0.09	2.0 / 8.1
Synchrotron tune Q_s	0.031	0.111
RF momentum acceptance (%)	1	2
Bunch length σ_z (non coll./coll.) (mm)	5.1 / 16.7	1.9 / 2.8
Rel. mom. spread σ_p (non coll./coll.) (10^{-3})	0.39 / 1.34	1.52 / 2.33
Longitudinal damping time τ_z (turns)	1297	20
Crab-waist ratio (%)	55	40
Beam-beam parameter ξ_x/ξ_y (10^{-3})	1.4 / 80	67.1 / 120
Luminosity \mathcal{L} (10^{34} s $^{-1}$ /cm 2)	150	1.45

Statistics analysis on
500 corrected lattices
(without log-scale)



Statistics analysis on
500 corrected lattices
with beam-beam effects
(without log-scale)

