



UNIVERSITÉ  
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Swiss Accelerator  
Research and  
Technology

# IR Alignment and Xsuite Migration

Satya Sai Jagabathuni, Felix Simon Carlier, Simone Liuzzo (ESRF)

Special thanks to G. Iadarola, R. Tomas, F. Zimmermann and the entire FCC-ee optics tuning working group

**FCC WEEK 2025, Vienna, Austria**  
**20<sup>th</sup> May 2025**



**FCCIS – The Future Circular Collider Innovation Study.**  
This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

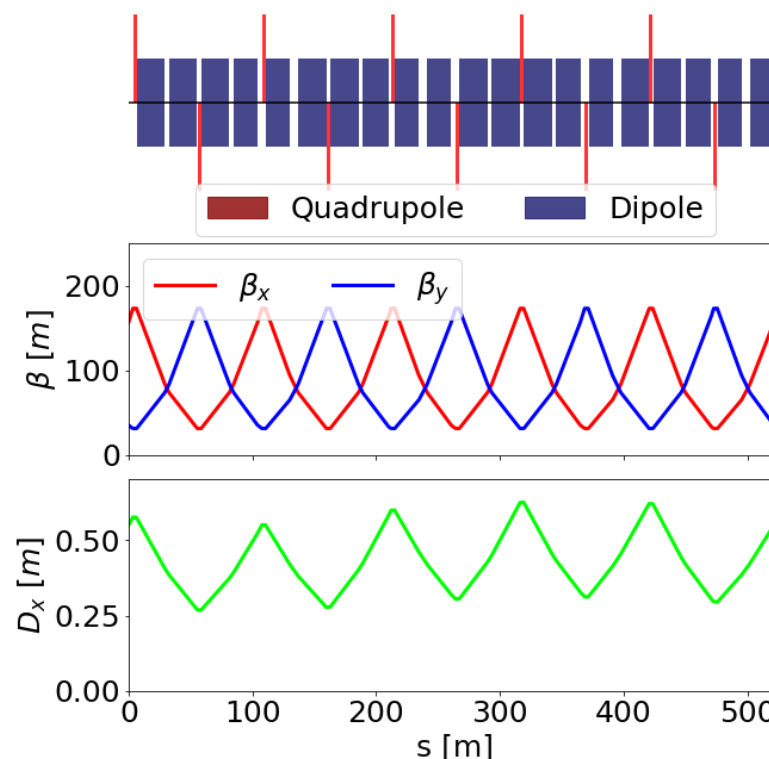
# FCC-ee Baseline optics

- 4 different energy stages, with beam energies ranging from 45.6 GeV (Z-pole) to 182.5 GeV (ttbar-threshold)
- 8 arcs designed with FODO cell structure
- Arc FODO cell length 100m/50m with  $90^\circ$  phase advance
- Non-interleaved sextupole pairs installed with  $-/$  transformation between them
- Fewer quads for low beam energies with beta functions factor 2 times larger and dispersion factor 4 times larger

## Z-operation

### WW-operation

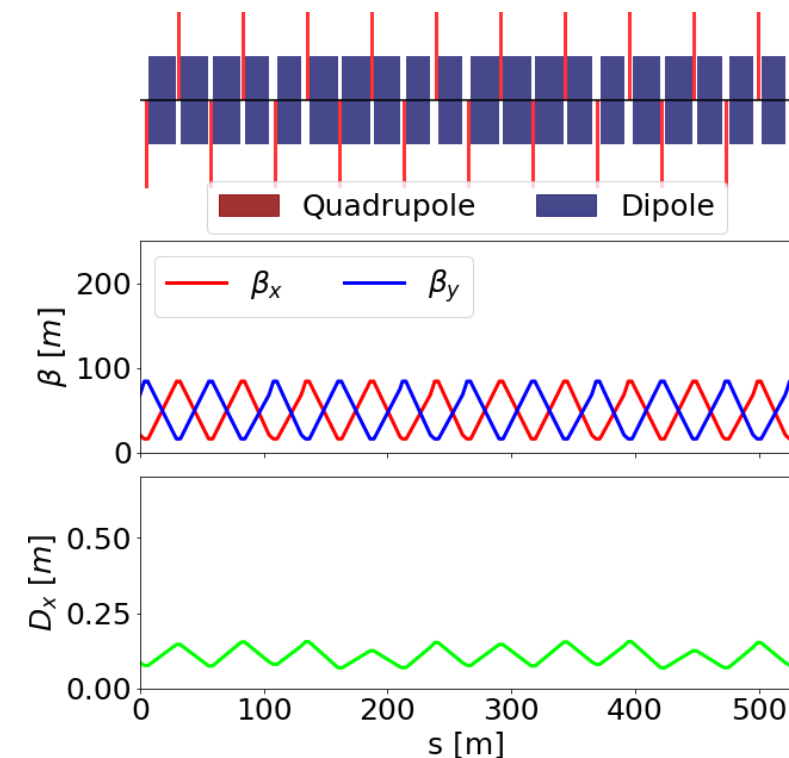
Arc FODO cell length 100 m  
 $90^\circ$  transverse phase advance



## ZH-operation

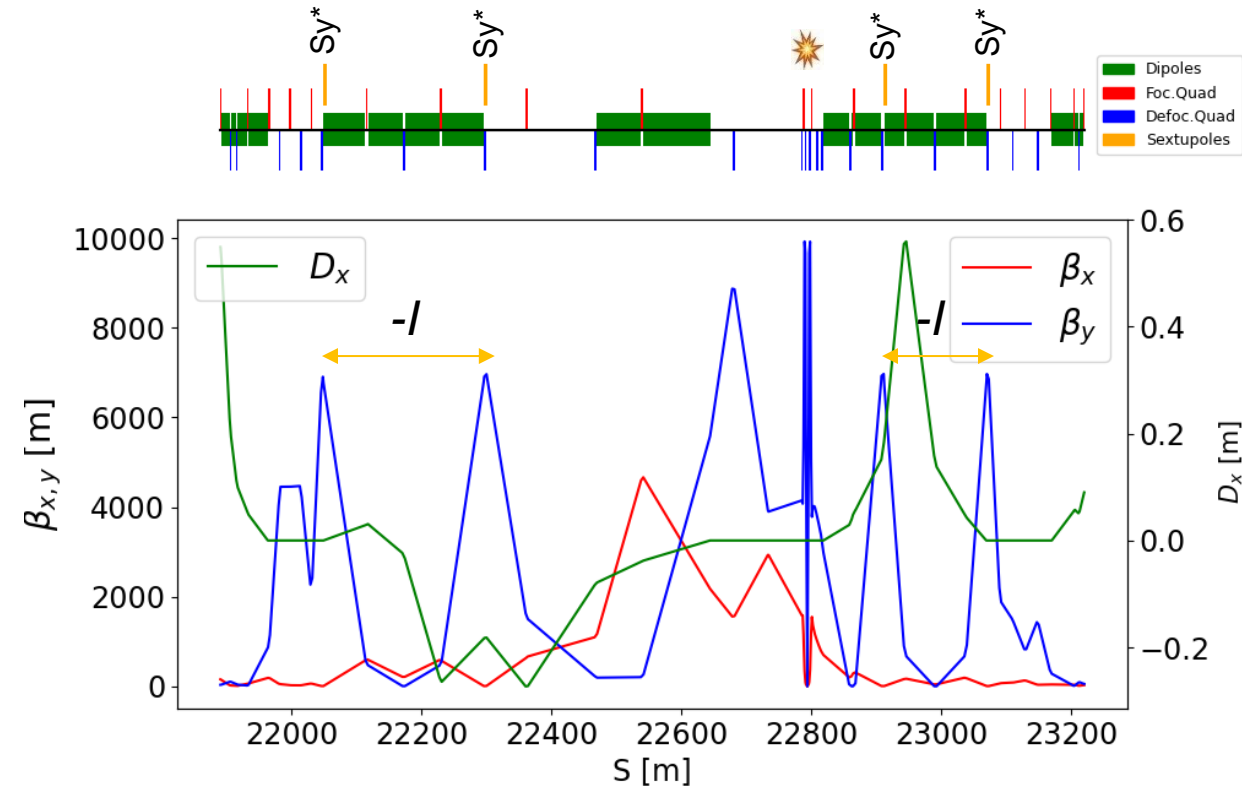
### ttbar-operation

Arc FODO cell length 50 m  
 $90^\circ$  transverse phase advance



# FCC-ee Interaction Region @Z

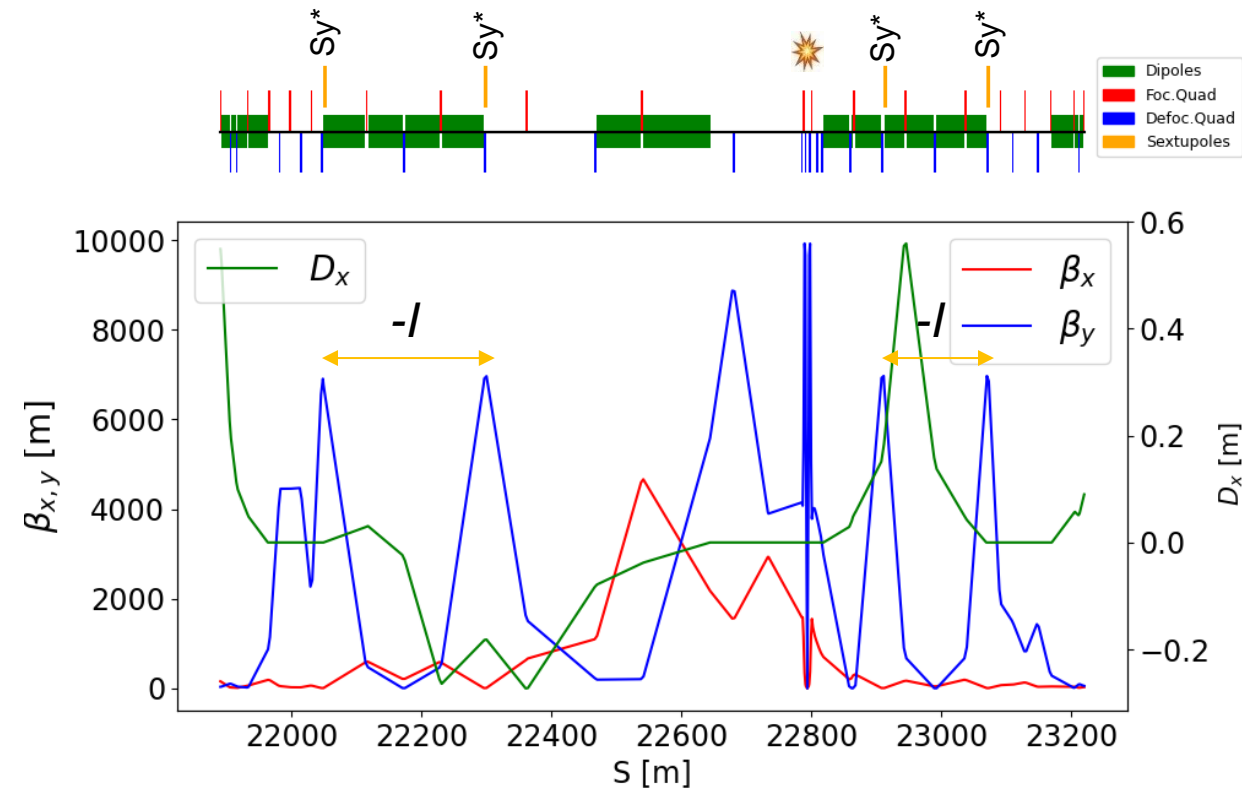
- Asymmetric layout on both sides of IP to limit the synchrotron radiation emitted towards IP
- IR region is employed with Local Chromaticity Correction Scheme (LCCS) to correct vertical chromaticity at the IP
- Non-interleaved sextupole pair on either side of the collision point
- Inner sextupoles take care of the local chromaticity with outer sextupoles to mitigate the geometric aberrations
- $\beta_x^*, \beta_y^* = 100/0.8$  [mm]



# FCC-ee Interaction Region @Z

Parameter	Units	Z
Circumference	[km]	91.174
$\epsilon_x$	[nm]	0.71
$\epsilon_y$	[pm]	1.42
Betatron tunes	[-]	214.260 / 214.380
$\beta_x^* / \beta_y^*$	[mm]	100 / 0.8
RF-frequency	[MHz]	400
Total RF voltage	[GV]	0.120
Energy acceptance	[%]	$\pm 1.3$
Luminosity / IP	$[10^{34} \text{ cm}^{-2} \text{ s}^{-1}]$	182

Table 1: Parameters of FCC-ee V22 at Z-pole energy.



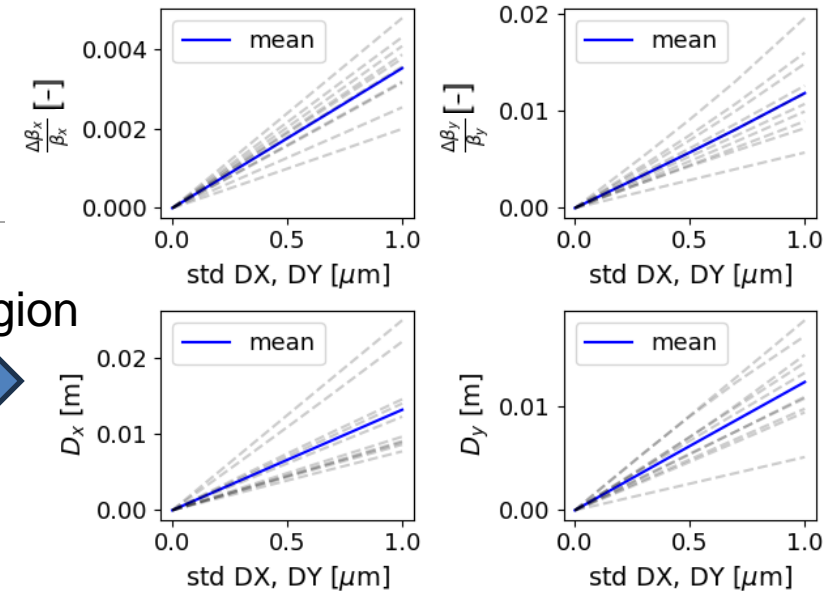
# FCC-ee optics tuning

- A comprehensive understanding of magnet tolerances are required when aiming for ultra-low emittances
- Sensitivity study indicates that the IR region is more sensitive than the arc region
- Python version of Accelerator Toolbox (pyAT) software framework is used to perform commissioning-like simulations [1]
- Optics tuning is mainly based on the computation of response matrices
- Generate response matrix (  $M_{ji}$  ) by varying the individual magnet strengths (  $\Delta k_i$  ) and monitor the changes in the observables:

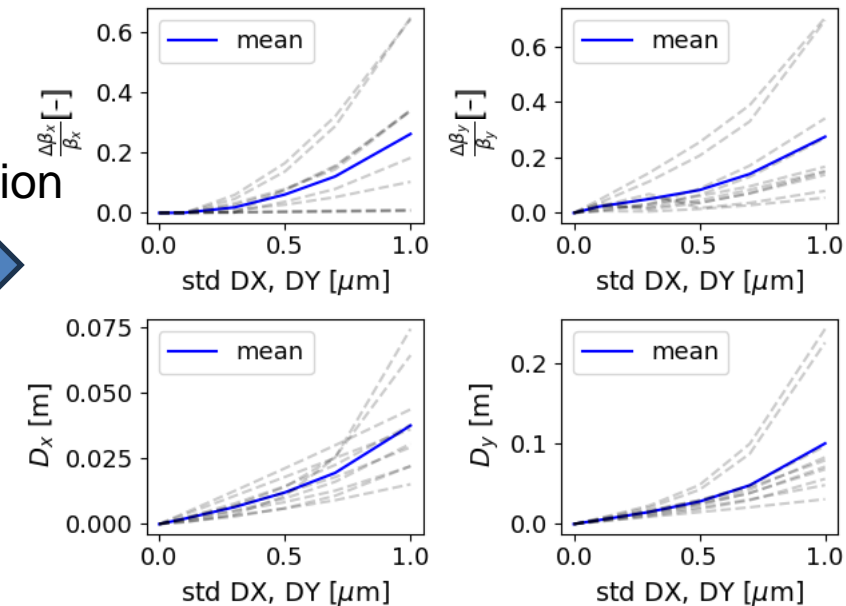
$$\Delta(\phi_{x,y}, D_x \dots \dots)_j = M_{ji} * \Delta k_i$$

- Construct the pseudo inverse of the response matrix (  $M_{ji}$  ), from which the correct setting  $k_i$  for the desired change in the target parameter is obtained:  $\Delta k_i = M^{-1} * \Delta(\phi_{x,y}, D_x \dots \dots)_j$

Arc region



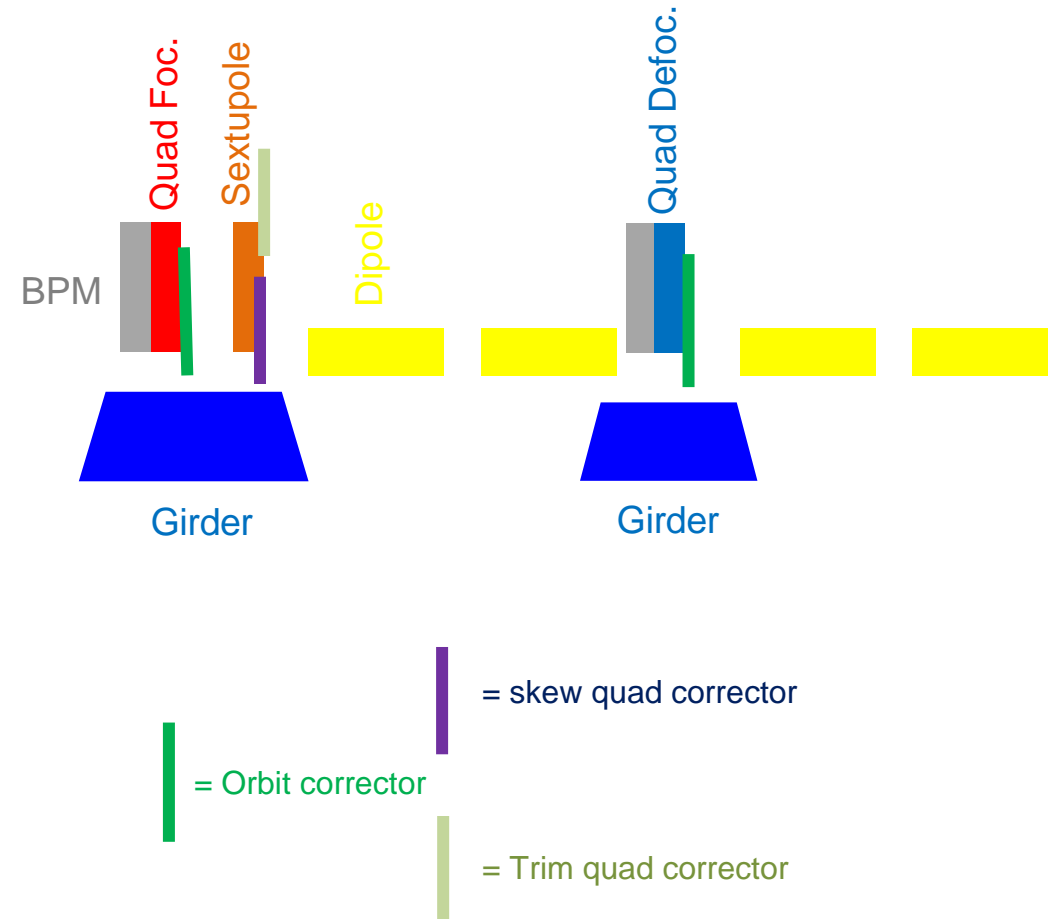
IR region



# FCC-ee tuning strategy

- BPMs and orbit correctors are placed at each quadrupole for beam-threading & closed orbit correction
- Trim quadrupole/ Trim skew quadrupole windings at the sextupoles are used for phase rematch b/w BPMs and to correct the horizontal dispersion/ to correct vertical dispersion and transverse coupling
- Arc quadrupoles and sextupoles are utilized to converge to the design tunes and chromaticity
- The tuning strategy involving the orbit and linear optics correction is reported in [2]

Fig: Magnets configuration in an arc section



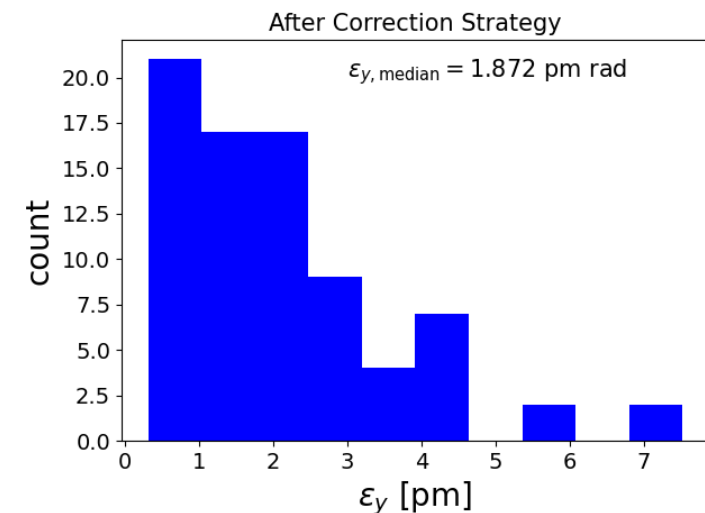
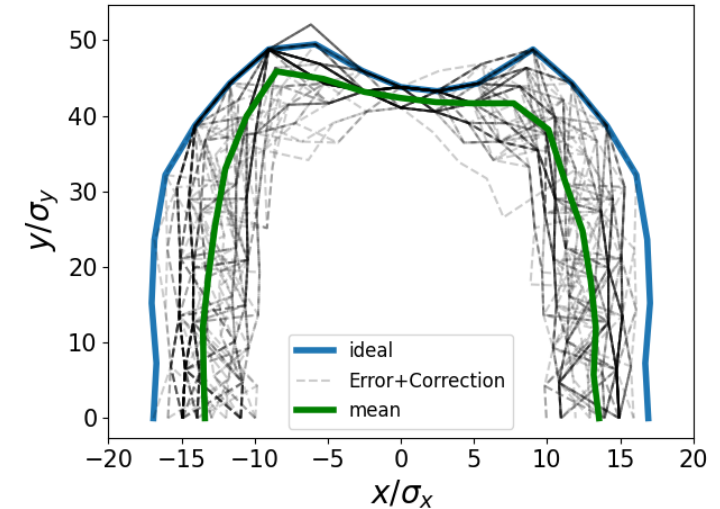
# First Studies on IR Tolerances

- Initial simulations commenced with tighter arc tolerances compared to the nominal ones as described in [3]
- In contrast, the IR errors were varied to evaluate the tolerance levels of the magnets in that region
- Errors were applied in the form of a Gaussian distribution truncated at  $2\sigma$
- Simulations run for 100 different lattice configurations, each with distinct errors, including radiation and magnet tapering
- The outcome of the simulations suggests that the final doublets and the IR sextupoles require tolerances of  $10\mu\text{m}/\mu\text{rad}$  and  $30\mu\text{m}/\mu\text{rad}$ , respectively [2]
- Tolerances beyond these values impact the vertical emittance or leading to the failure of the seeds
- This limitation on the FF-quads is to mitigate the spurious increase of vertical emittance

Type	$\Delta x$ ( $\mu\text{m}$ )	$\Delta y$ ( $\mu\text{m}$ )	Rotation ( $\mu\text{rad}$ )
Arc quadrpoles	100	100	100
Arc sextupoles	100	100	100
Quads in RFsection	100	100	100
IR quadrupoles excl. FF-quads	100	100	100
FF-quads	10	10	10
IR sextupoles	30	30	30
All Dipoles	1000	1000	1000

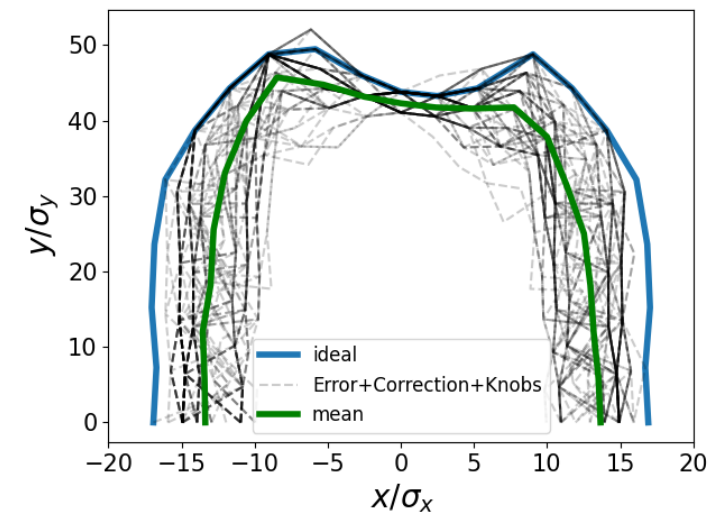
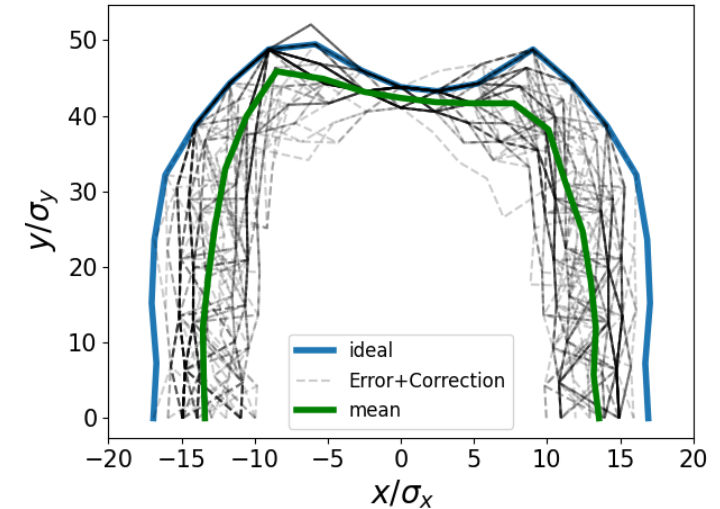
# First Studies on IR Tolerances

- Initial simulations commenced with relaxed arc tolerances compared to the nominal ones as described in [3]
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- The outcome of the simulations suggests that the final doublets and the IR sextupoles require tolerances of  $10\mu\text{m}/\mu\text{rad}$  and  $30\mu\text{m}/\mu\text{rad}$ , respectively [2]
- More than 75 out of 100 seeds were successfully converged



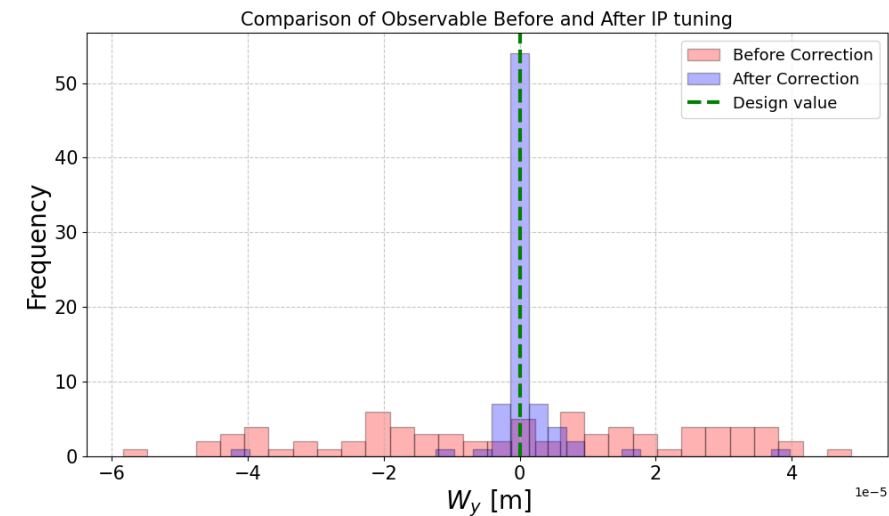
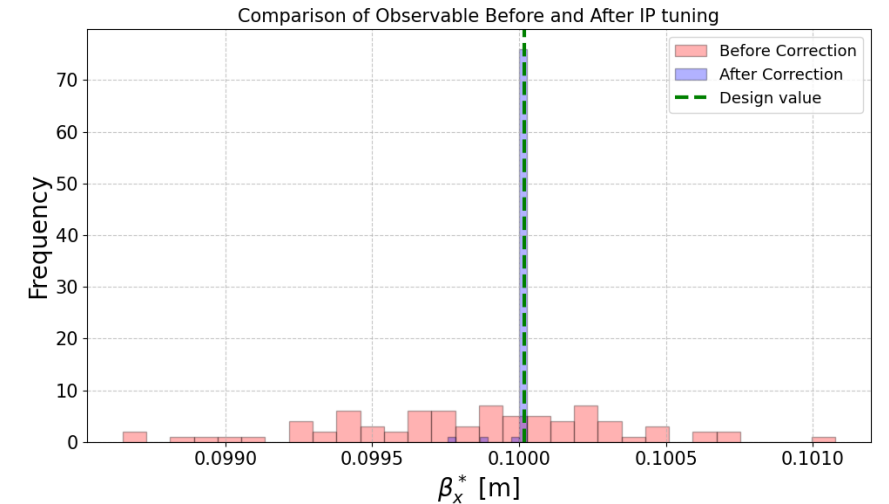
# First Studies on IR Tolerances

- IP optics aberrations persist even after the global correction
- This will impact the beam sizes at IP and thus the luminosity
- Dedicated IP tuning knobs to tune  $\beta_{x,y}^*$ ,  $w_{x,y}^*$  and  $D_y^*$  were developed
- The detailed procedure concerning the design, simulated effectiveness, and the constraints of the IP tuning knobs is fully described in [4]
- Post-correction analysis indicates that the application of tuning knobs has no impact on the DA before and after IP tuning



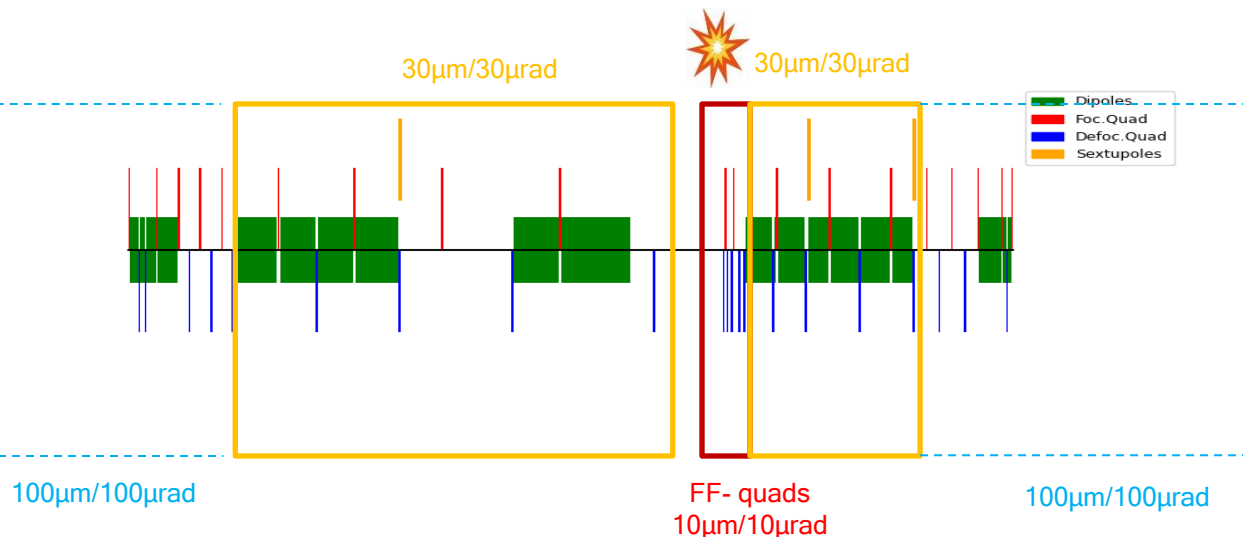
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- Post-correction analysis indicates that the application of tuning knobs has no impact on the DA before and after IP tuning
- The application of the knobs effectively compensates for the errors, resulting in final values (blue) that are closely aligned with the design value (green) at the IP2



# Tolerance studies incl. Girders

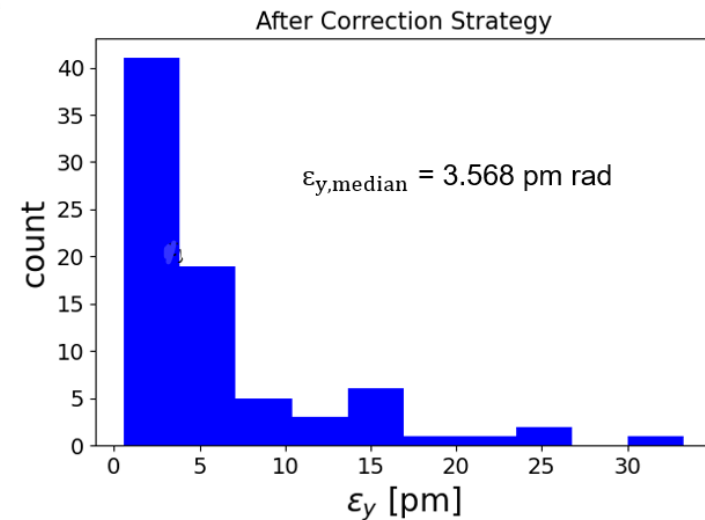
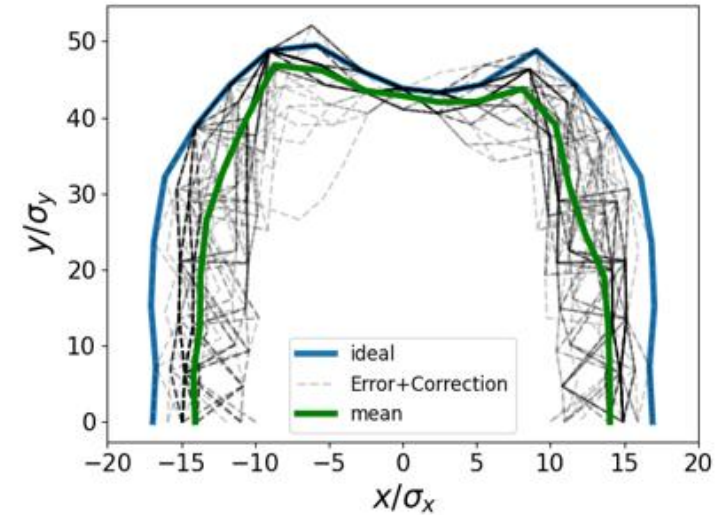
- Further studies including the girder-to-girder misalignments of  $150\mu\text{m}/\mu\text{rad}$  and BPM-to-quad misalignments of  $10\mu\text{m}/\mu\text{rad}$  after BBA [5], were conducted.
- IR tolerances were categorized by spatial segmentation rather than by magnet type to simplify the alignment strategy and facilitate practical implementation



Type	$\Delta x$ ( $\mu\text{m}$ )	$\Delta y$ ( $\mu\text{m}$ )	Rotation ( $\mu\text{rad}$ )
BPM-to-Quad	10	10	10
Girders	150	150	150
Arc quadrupoles	50	50	50
Arc sextupoles	50	50	50
Quads in RF section	100	100	100
IR section without sextupoles	100	100	100
IR section with sextupoles	30	30	30
FF-doublets section	10	10	10
All Dipoles	1000	1000	1000

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- IR tolerances were categorized by spatial segmentation rather than by magnet type to simplify the alignment strategy and facilitate practical implementation
- Simulation results yielded a mean DA of  $14\sigma$  with a median vertical emittance of  $3.5\text{pm-rad}$ , which is far beyond the design value of  $1.4\text{pm-rad}$
- Subsequent simulations revealed that the primary source of emittance growth originates from the final doublets
- To confirm this finding, final-focus quadrupoles were idealized by removing all associated errors, with all the other errors stay unchanged



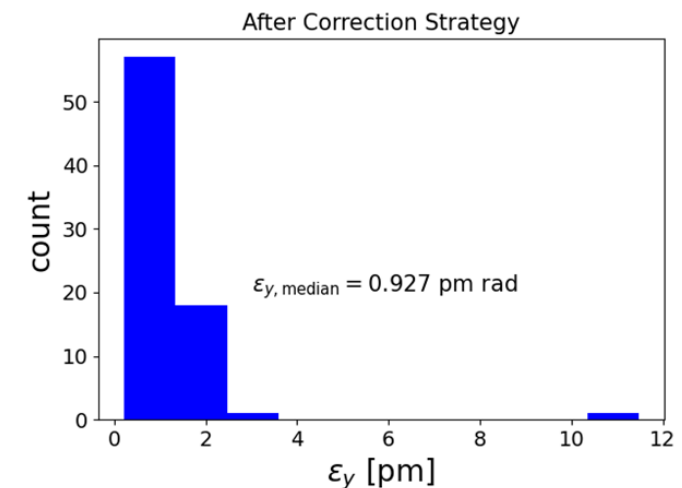
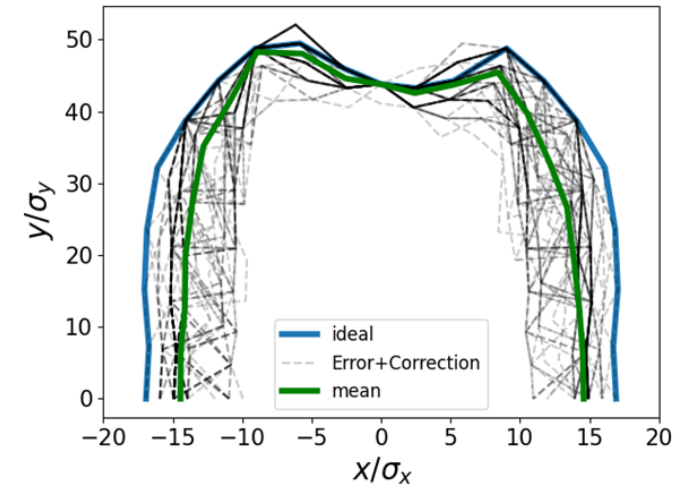
# Tolerance studies excl. FF-doublets

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FF-doublets section	-	-	-
All Dipoles	1000	1000	1000

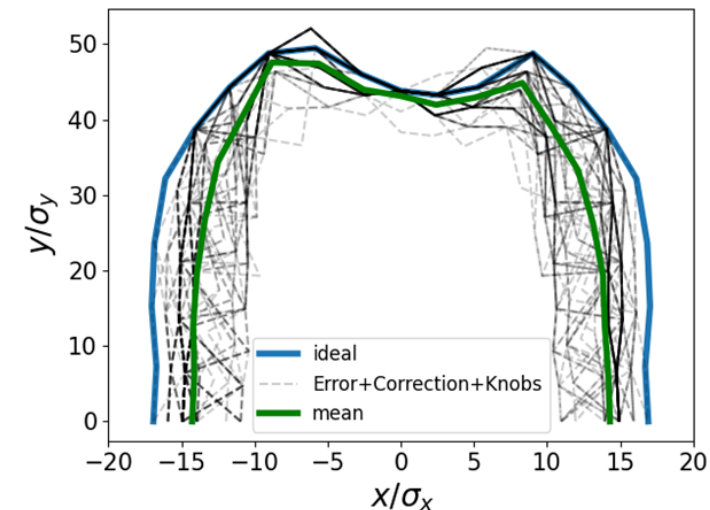
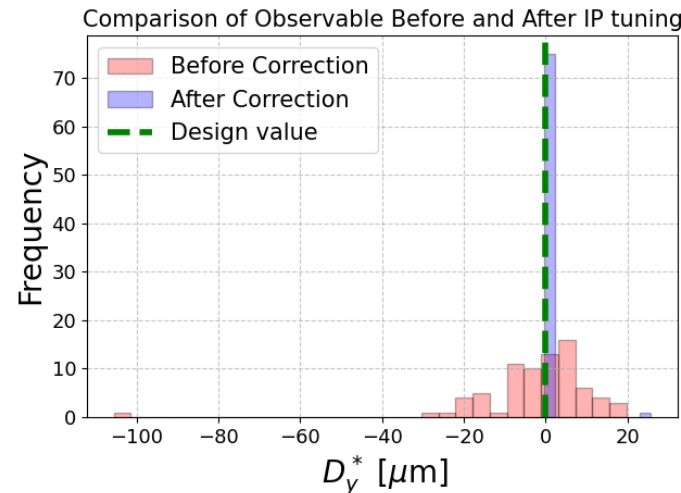
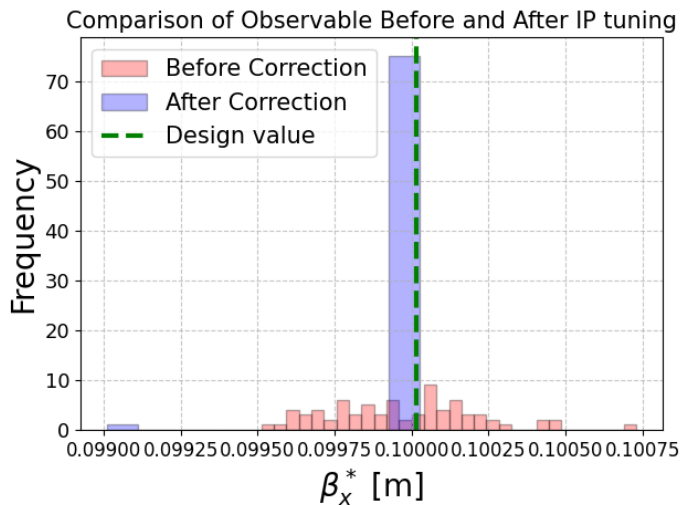
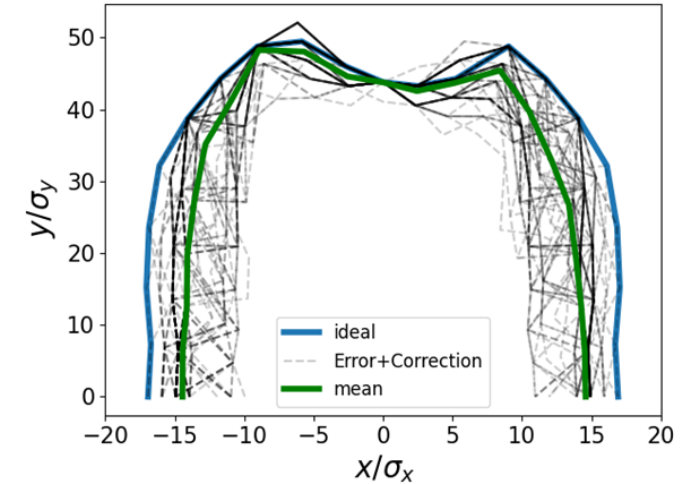
# Tolerance studies excl. FF-doublets

- Mean DA and the median vertical emittance achieved after tuning are  $15\sigma$  and  $0.927$  pm-rad, respectively
- This clearly explains that the final doublets are the actual source of emittance growth, as these are sensitive to alignment errors
- Installing skew components next to these doublets is being investigated as a mitigation strategy to improve tolerances on these elements
- However, in the absence of girder and BPM misalignments and under relaxed arc tolerances, the permissible tolerances on these doublets can increase to as much as  $10\mu\text{m}/\mu\text{rad}$
- An alternative approach is to use the relaxed optics to improve the tolerances on the FF-doublets



# Tolerance studies excl. FF-doublets

- IP optics correction is performed on the fully tuned lattices
- Tuning knobs have no impact on the resulting DA
- Optics at the IP were retrieved towards the design values
- Currently, the IP optics are obtained through a standard twiss calculation, which does not capture the real machine conditions
- Therefore, dedicated methods for reliably extracting the IP optics are needed



# First studies with Xsuite

- Xsuite [6] is a modern, open-source simulation framework developed at CERN to address the growing demands of high-fidelity beam dynamics modeling in particle accelerators
- This initial study aims to integrate linear optics tuning simulation tools originally developed in pyAT, into the Xsuite environment and then compare the results for both the tools
- The comparison highlights Xsuite's consistency and reliability in reproducing established results while also identifying areas of potential divergence due to algorithmic or modeling differences
- As a first study, simulations for 20 different seeds were performed, considering the relaxed arc tolerances as depicted in the table
- These simulations do not take into account the losses from radiation and magnetic tapering

Type	$\Delta x$ ( $\mu\text{m}$ )	$\Delta y$ ( $\mu\text{m}$ )	Rotation ( $\mu\text{rad}$ )
BPM-to-Quad	10	10	10
Girders	150	150	150
Arc quadrupoles	50	50	50
Arc sextupoles	50	50	50
Quads in RF section	100	100	100
All Dipoles	1000	1000	1000

# First studies with Xsuite

- All 20 seeds were successfully converged
- Optics tuning results show good agreement for linear optics between pyAT and Xsuite frameworks
- A discrepancy in coupling results is observed, with a factor of 3 difference between pyAT and Xsuite
- This could be due to the different techniques used in the computation of coupling (pyAT computes RDTs, whereas Xsuite computes coupling in the form of a complex coupling coefficient)
- Ongoing efforts aim to compute RDTs within Xsuite utilizing the Xsuite–MAD-NG interface
- Future work will aim at the integration of optics tuning and correction algorithms within the Xsuite framework, to reproduce the tuning results from pyAT

Parameter	RMS value	
	Xsuite	pyAT
Hort. orbit [ $\mu\text{m}$ ]	117.9	120.2
Vert. orbit [ $\mu\text{m}$ ]	117.4	119.1
$\Delta D_x$ [mm]	0.6	0.7
$\Delta D_y$ [mm]	0.4	0.4
$\frac{\Delta\beta_x}{\beta_x}$ [%]	0.1	0.1
$\frac{\Delta\beta_y}{\beta_y}$ [%]	0.2	0.1
Coupling-real [-]	0.00052	0.00019
Coupling-imag [-]	0.00053	0.000079

# Conclusions and Outlook

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- FCC-ee Z-mode lattice is so sensitive to alignment errors compared to the other energy mode, which makes this lattice well-suited for detailed tuning studies
- Necessity for a comprehensive understanding of the tolerance requirements of the magnets to define the machine performance
- Tuning simulations, including girder and BPM misalignments, resulted in a median vertical emittance of 3.5 pmrad, which is a factor of 2 more than the design value
- While removing errors on the final doublets (which is unrealistic) helps reduce emittance growth, incorporating skew quads next to these doublets could serve as a mitigation technique to improve tolerances
- Efforts are ongoing to integrate optics tuning and correction algorithms within the Xsuite framework
- Initial studies with tighter arc misalignments show good agreement between pyAT and Xsuite tuning results, except for linear coupling

## Outlook:

- Future developments aim at performing tuning simulations with relaxed optics
- Full lattice tuning including IP optics correction in Xsuite

# References

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- [1] S. M. Liuzzo, et al., "Commissioning simulations tools based on python Accelerator Toolbox", Journal of Physics: Conference Series, vol. 2687, no. 3, p. 032001. IOP Publishing, 2024.
  
- [2] S. S. Jagabathuni, et al., "First view at alignment tolerances in the FCC-ee interaction region", JACoW eeFACT 2025, paper WEB02.
  
- [3] R. Tomás, et al., "Optics tuning of the FCC-ee", presented at IPAC'25, this conference, paperID WEPR02, Taipei, Taiwan, June 2025.
  
- [4] S. S. Jagabathuni, et al., "Simulated Performance of FCC-ee IP Tuning Knobs", Proc. IPAC'24, pp.2453-2456.
  
- [5] X. Huang, "FCCee BBA simulations", presented at the FCC-ee optics tuning working group meeting, 10 Apr. 2024.
  
- [6] Xsuite, <https://xsuite.readthedocs.io/en/latest/>

# Thank you!

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