First view at alignment tolerances in the FCC-ee Interaction Region

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

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

70th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2025)

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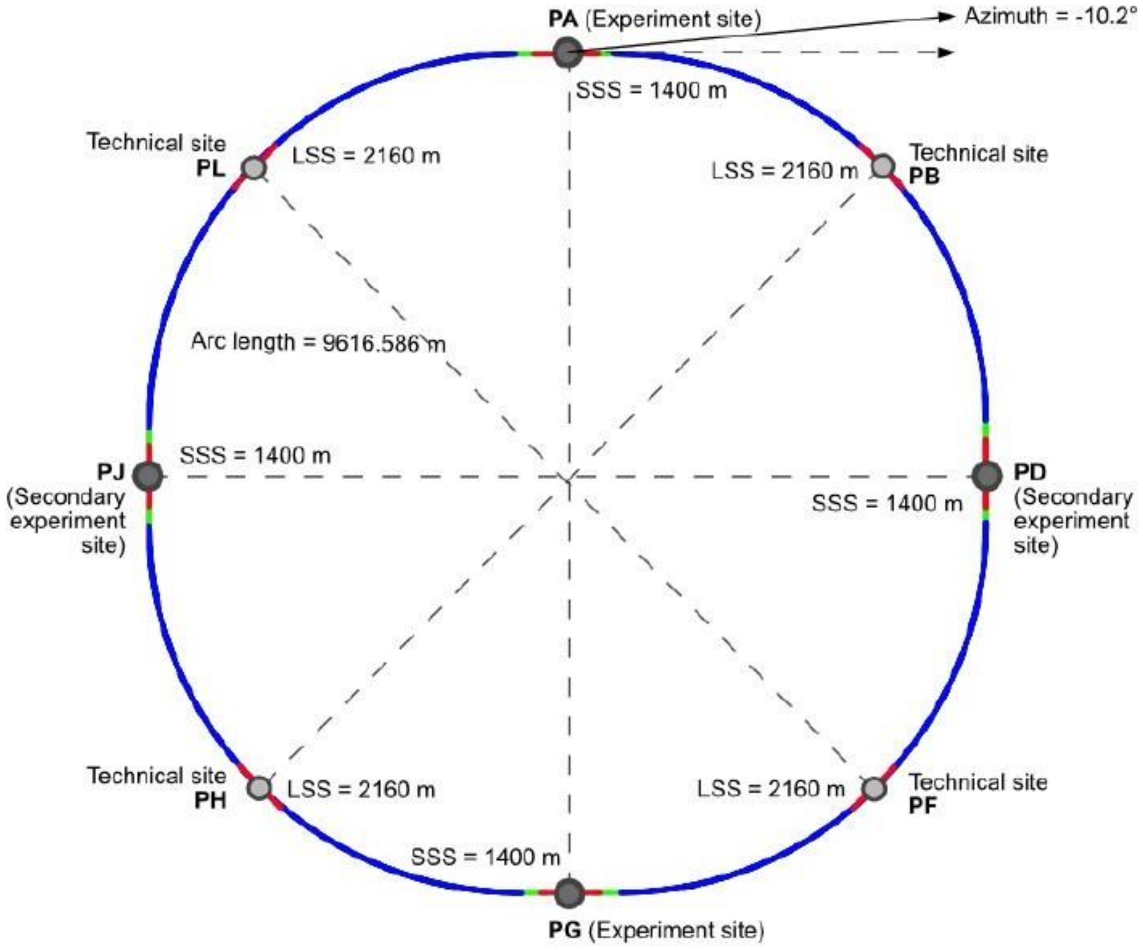
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

J. Keintzel

Introduction to FCC-ee

- FCC-ee baseline with 4 Interaction Points (IPs)
- Designed for precision physics experiments
- 4 different energy stages, with beam energies:
  - 45.6 GeV, at the Z-pole
  - 80 GeV, at the W-pair-threshold
  - 120 GeV, for ZH-operation
  - 182.5 GeV, above ttbar-threshold

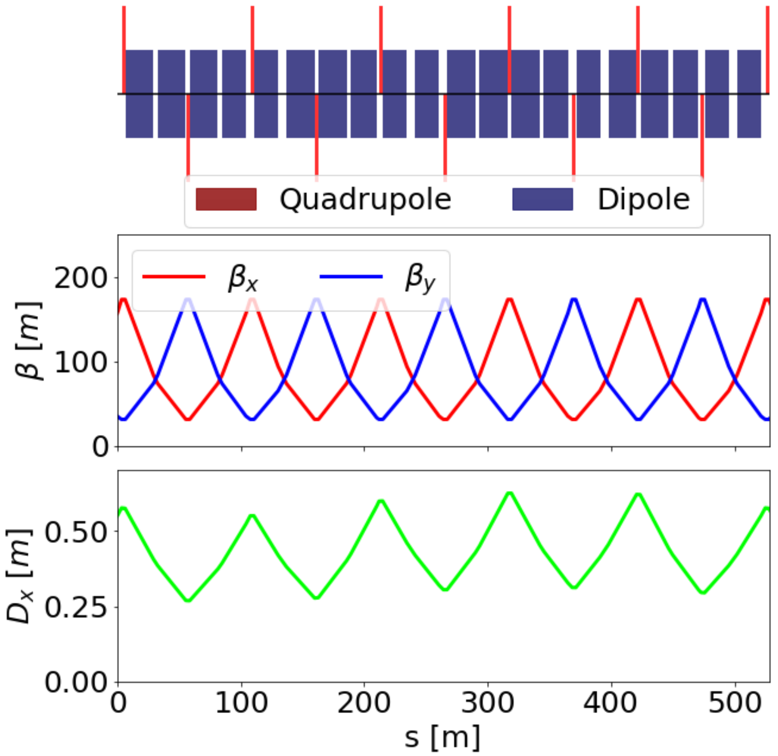


M. Hofer, K. Oide

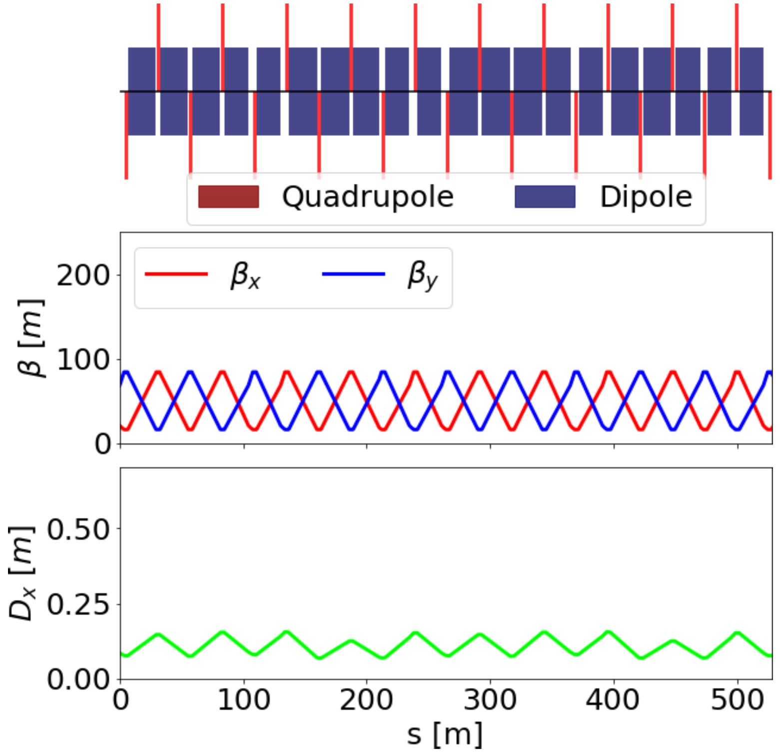
FCC-ee Baseline optics

- 8 arcs designed with FODO cell structure
- Arc FODO cell length 100m/50m with 90^0 phase advance
- Non-interleaved sextupole pairs installed with -I 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° transverse phase advance

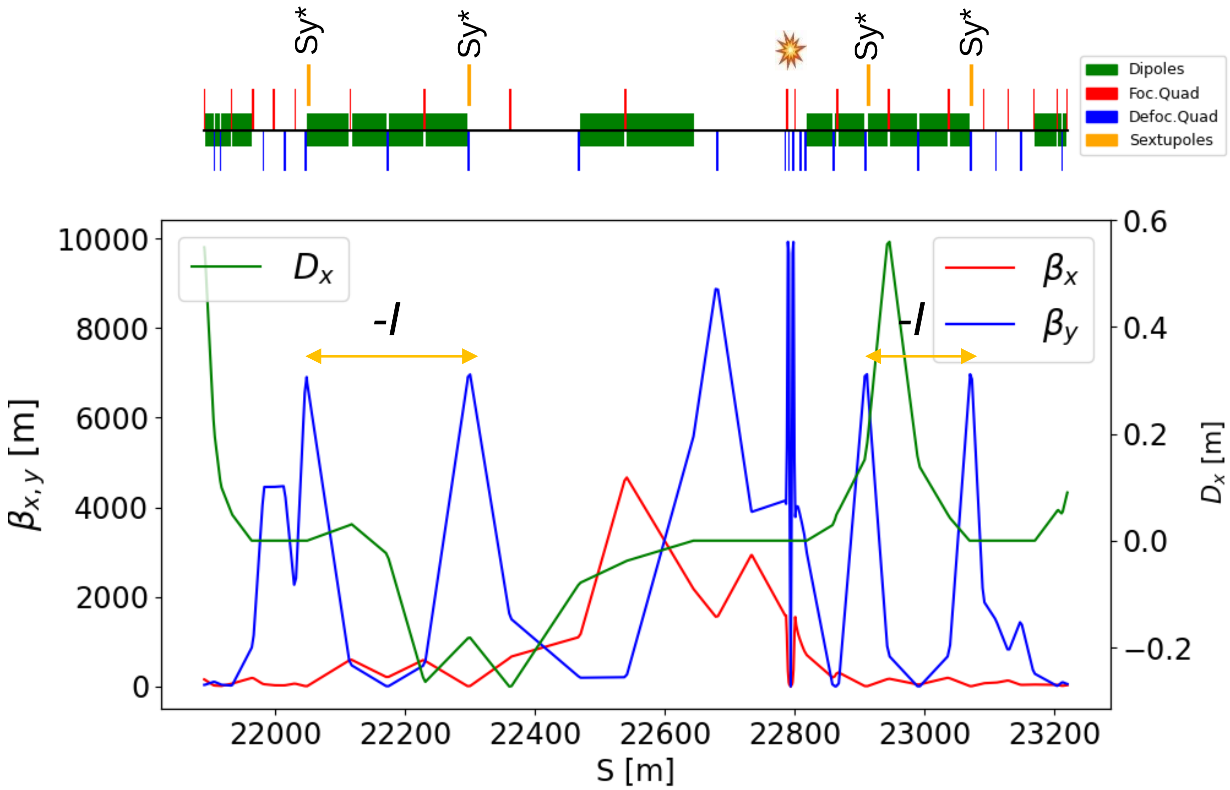


ZH-operation
ttbar-operation
Arc FODO cell length 50 m
90° transverse phase advance



FCC-ee Interaction Region @Z

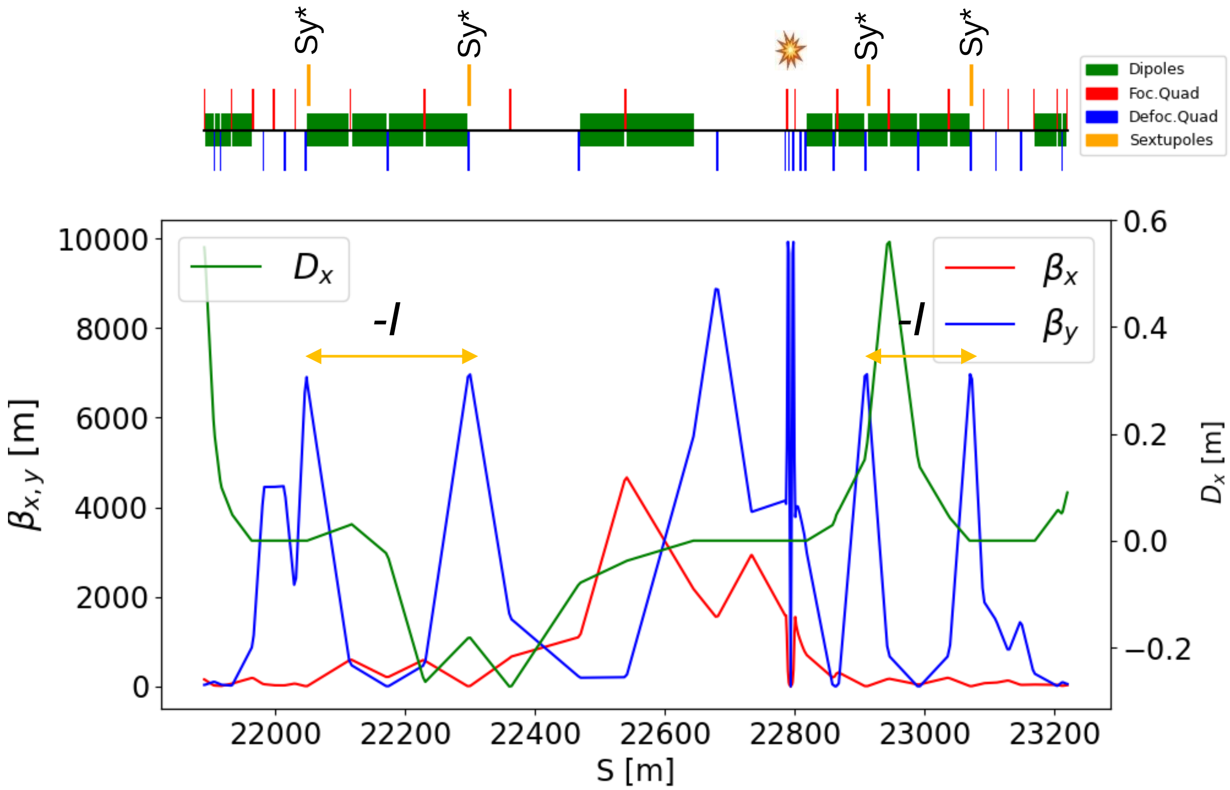
- Asymmetric layout on both sides of IP to limit the synchrotron radiation emitted towards IP
- IR region is employed with Local Chromaticity Correction Scheme (LCCS) to correct vertical chromaticity at the IP
- Non-interleaved sextupole pair on either side of the collision point
- Inner sextupoles take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



FCC-ee Interaction Region @Z

Parameter	Units	Z
Circumference	[km]	91.174
ϵ_x	[nm]	0.71
ϵ_y	[pm]	1.42
Betatron tunes	[-]	214.260 / 214.380
β^*_x/β^*_y	[mm]	100 / 0.8
RF-frequency	[MHz]	400
Total RF voltage	[GV]	0.120
Energy acceptance	[%]	±1.3
Luminostiy / IP	$[10^{34}\,\mathrm{cm^{-2}s^{-1}}]$	182

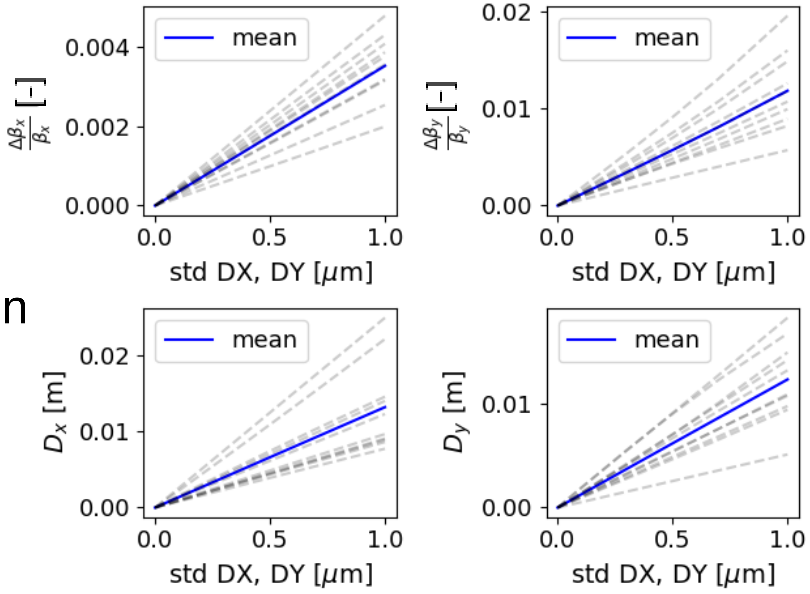
Table 1: Parameters of FCC-ee V22 at Z-pole energy.



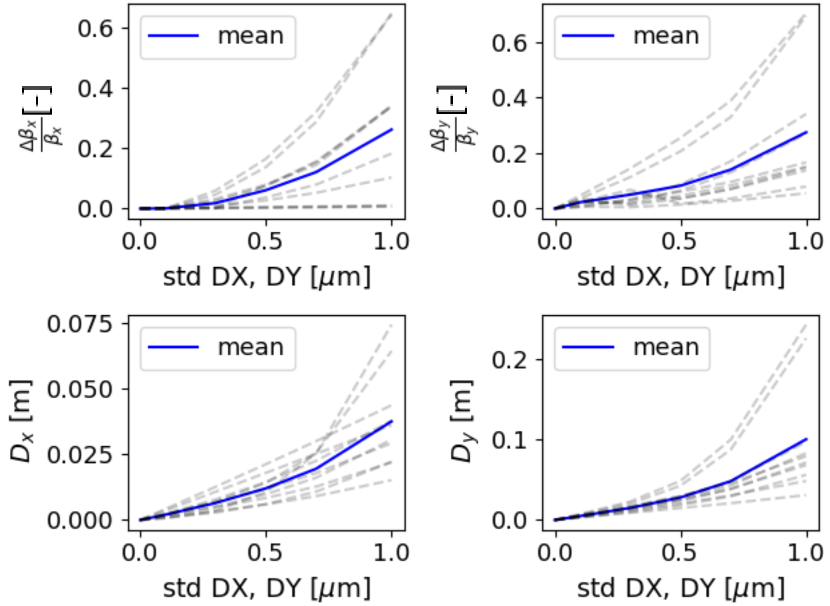
FCC-ee optics tuning

- Comprehensive understanding of magnet tolerances are required, when aiming for ultra-low emittances
- Focus is mainly on Z-energy mode, since it is more sensitive to errors compared to higher energy modes
- 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 [Simone]

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 the tunes and chromaticity

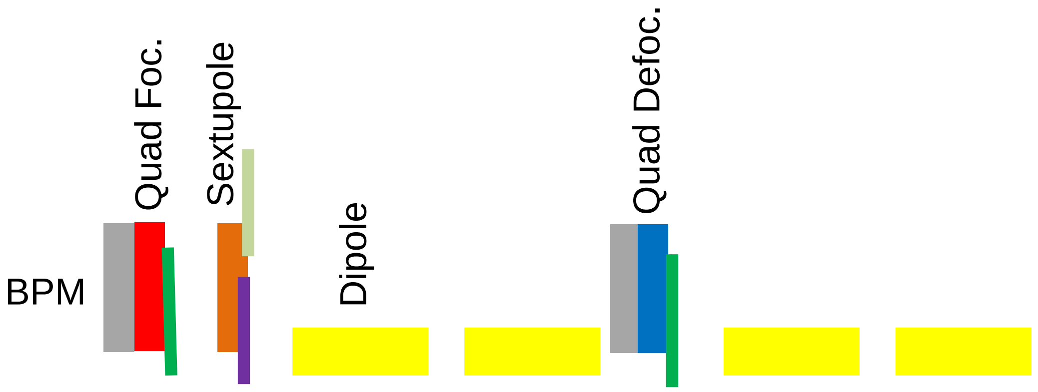
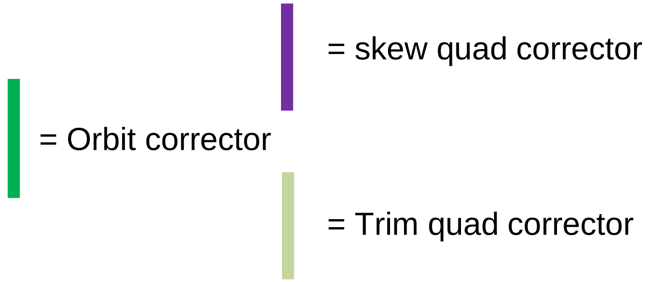


Fig: Magnets configuration in an arc section



FCC-ee tuning strategy

- Optics tuning is mainly based on the computation of response matrices
- Generate response matrix (M_{ji}) by varying the individual magnet strengths (Δk_i) and monitor the changes in the observables at the BPMs

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

- 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

$$\Delta k_i = M^{-1} * \Delta(\phi_{x,y}, D_x \ldots\ldots)_j$$

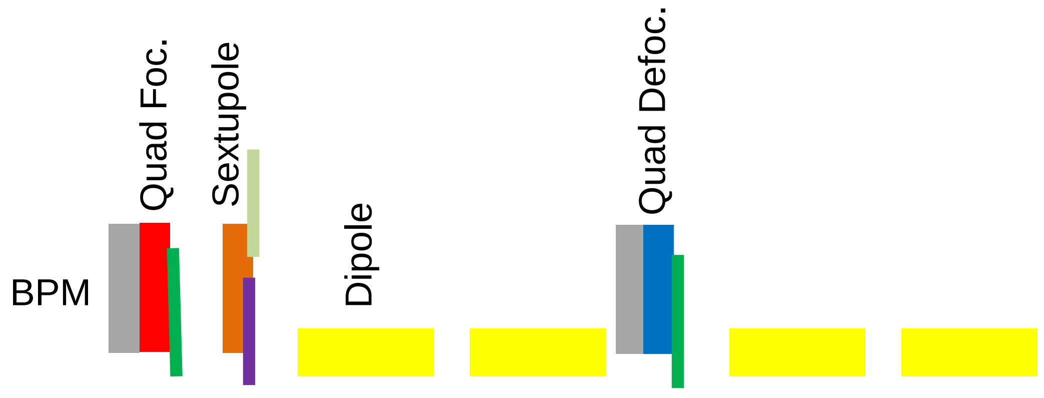
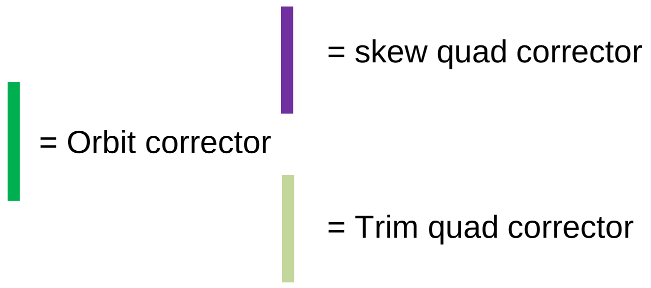
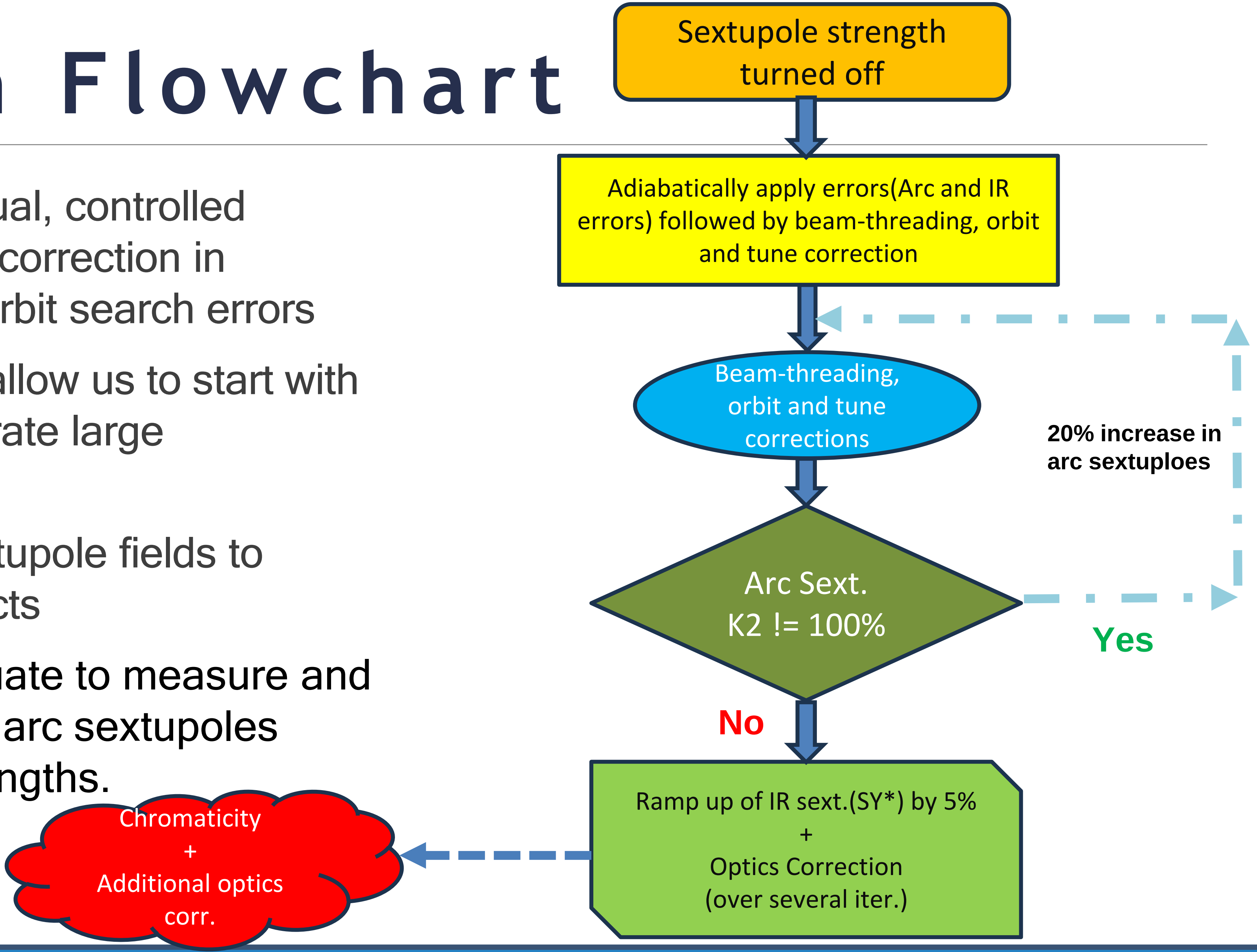


Fig: Magnets configuration in an arc section



Correction Flowchart

- Errors introduced in a gradual, controlled manner with orbit and tune correction in between mitigates closed-orbit search errors
- Turning off the sextupoles allow us to start with a linear lattice that can tolerate large imperfections
- Slowly ramp up the arc sextupole fields to manage the chromatic effects
- The beam lifetime is adequate to measure and correct the optics once the arc sextupoles attain their designated strengths.



Initial simulations

- Initial simulations commenced with fixed errors in the arcs and in all the dipoles
- In contrast, the IR errors were varied to evaluate the tolerance levels of the magnets in that region
- Errors applied in the form of gaussian distribution truncated at 2σ
- The simulations run for 5 different lattice configurations, each with five distinct errors
- Radiation and magnetic tapering are included

Type	Δx (μm)	Δy (μm)	Rotation (μrad)
Arc quadrpoles	100	100	100
Arc sextupoles	100	100	100
IR quadrupoles	40	40	40
IR sextupoles	40	40	40
All Dipoles	1000	1000	1000

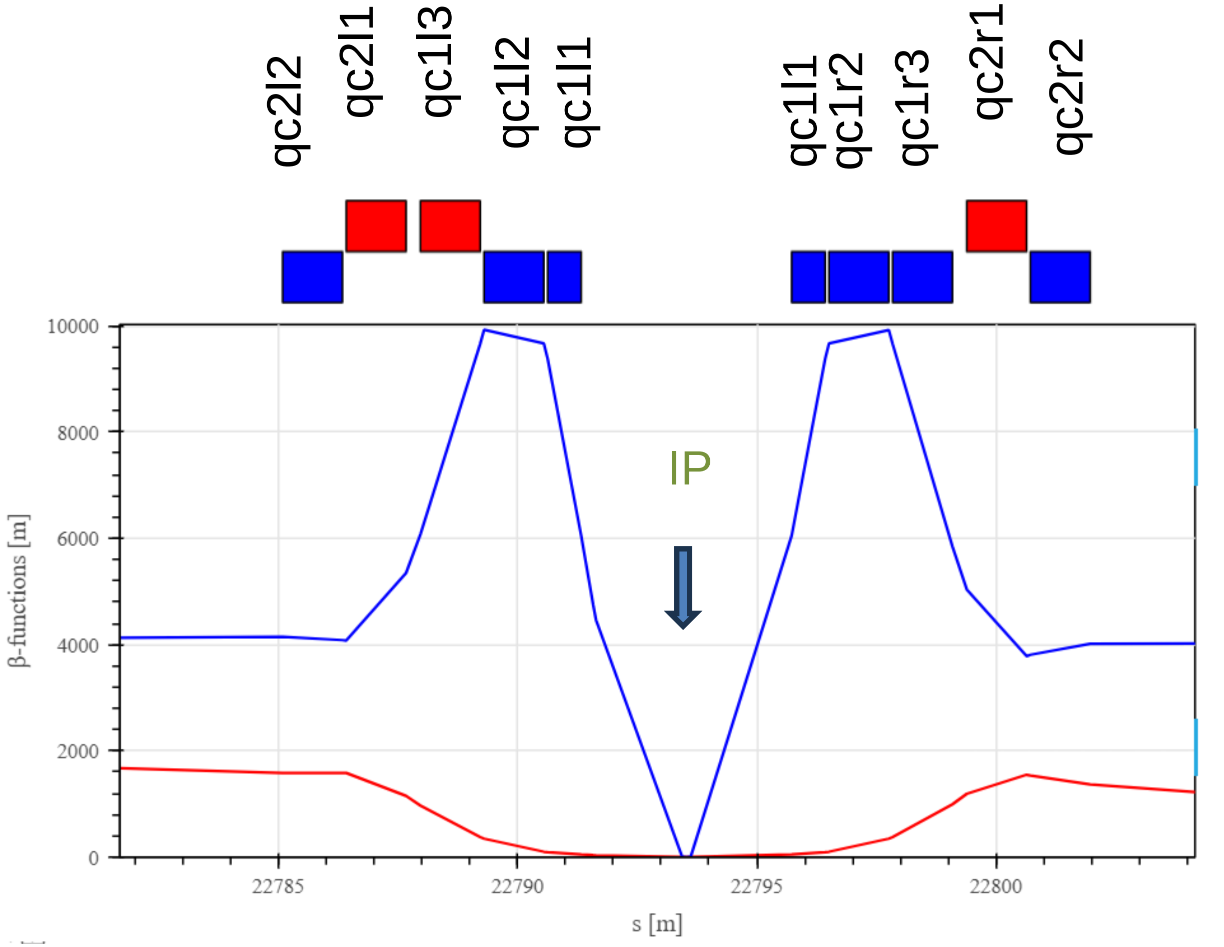
Linear Optics	Seed 0 (std)	Seed 1 (std)	Seed 2 (std)	Seed 3 (std)	Seed 4 (std)
ΔX [um]	7.308	3.185	3.416	3.187	8.781
ΔY [um]	3.617	2.518	2.424	3.775	2.749
ΔDx [mm]	1.744	1.791	1.337	0.926	1.084
ΔDy [mm]	3.884	3.915	5.101	4.357	2.827
beta-beating H [%]	0.285	0.211	0.484	0.284	0.346
beta-beating V [%]	0.443	0.404	0.615	0.451	0.472
ε_V (pm-rad)	8.75	5.01	61.68	3.45	39.04

Design value of ε_V (pm-rad) – 1.4

Limitation on FF-quadrupoles

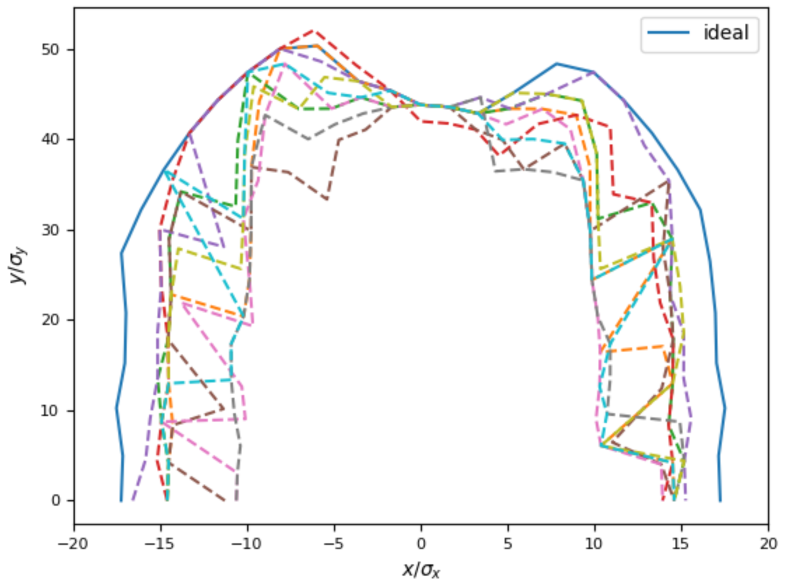
- Final-focus quads are so sensitive to alignment errors
- Even a small source of error would be amplified due to the large β-functions at that location
- This leads to the spurious increase of vertical emittance, which in turn deteriorate the dynamic aperture

$$\epsilon_y = \left(\frac{dp}{p}\right)^2 (\gamma D^2 + 2\alpha D D' + \beta D'^2)$$



Limitation on FF-quadrupoles

- The magnitude of alignment errors applied on the Final-focus quads must be reduced down to 10μm/10μrad
- Large improvement in the vertical emittance after reducing the errors on FF-quads
- DA is computed over 512 turns at the location of RF-cavity



$\sigma_x = 0.4\text{mm}$; $\sigma_y = 18\mu\text{m}$

Linear Optics	Seed 0 (std)	Seed 1 (std)	Seed 2 (std)	Seed 3 (std)	Seed 4 (std)
ΔX [um]	6.378	3.350	3.378	3.519	7.923
ΔY [um]	2.063	2.028	2.598	2.207	2.183
ΔDx [mm]	1.096	0.698	0.808	1.131	0.744
ΔDy [mm]	0.821	0.345	0.542	1.413	0.491
beta-beating H [%]	0.400	0.419	0.345	0.206	0.421
beta-beating V [%]	0.406	0.299	0.297	0.344	0.403
ε_v (pmrad)	1.06	1.78	2.50	0.35	6.06

Further simulations

- Taking into account the FF-quads tolerable values, the simulations are repeated for 100 different lattices each with unique errors (seed value)
- Errors in the other IR elements are increased to 70µm/70µrad

Type	Δx (µm)	Δy (µm)	Rotation (µrad)
Arc quadrpoles	100	100	100
Arc sextupoles	100	100	100
IR quadrupoles with. FF-doublets qc[12]*	70 10	70 10	70 10
IR sextupoles	70	70	70
All Dipoles	1000	1000	1000

Further simulations

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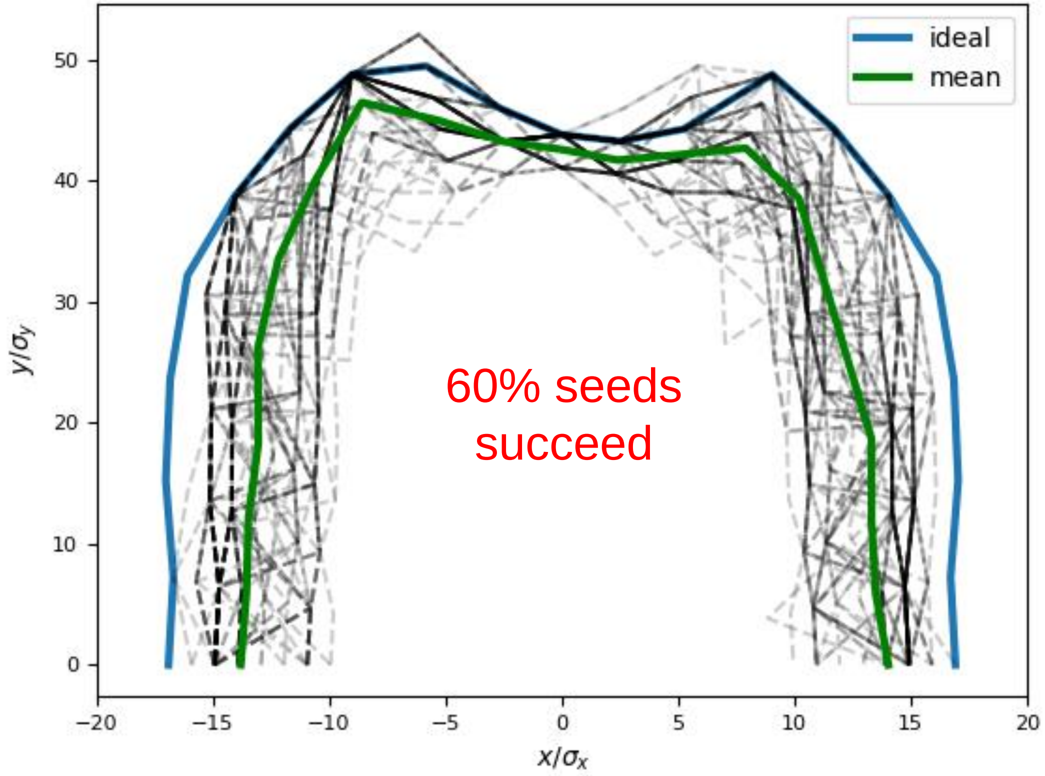
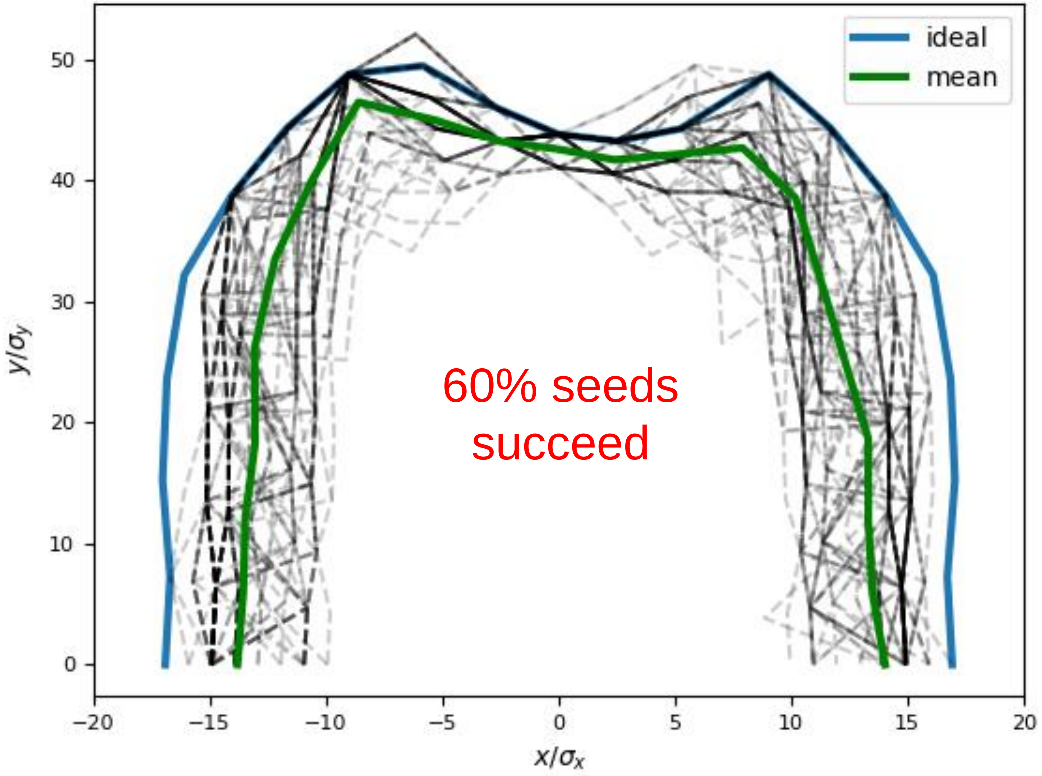


Further simulations

- This resulted in a 60% of success rate, with an average dynamic aperture exceeding 12σ horizontally and 45σ vertically
- Among the 40% failed seed, the majority were unable to converge to the actual tune
- This issue arises due to the strong non-linear behaviour from IR sextupoles in combination with tighter tolerances

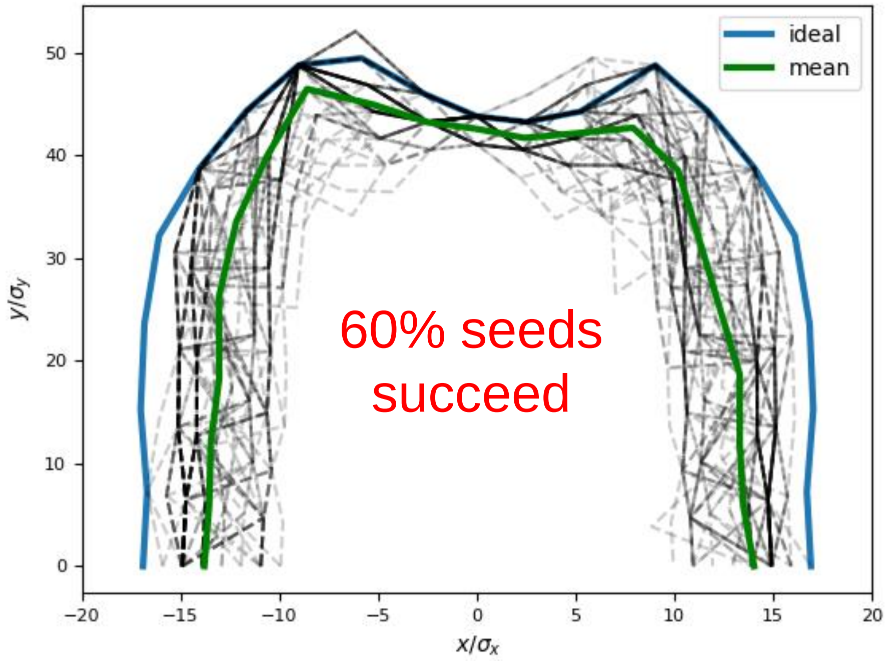


Further simulations

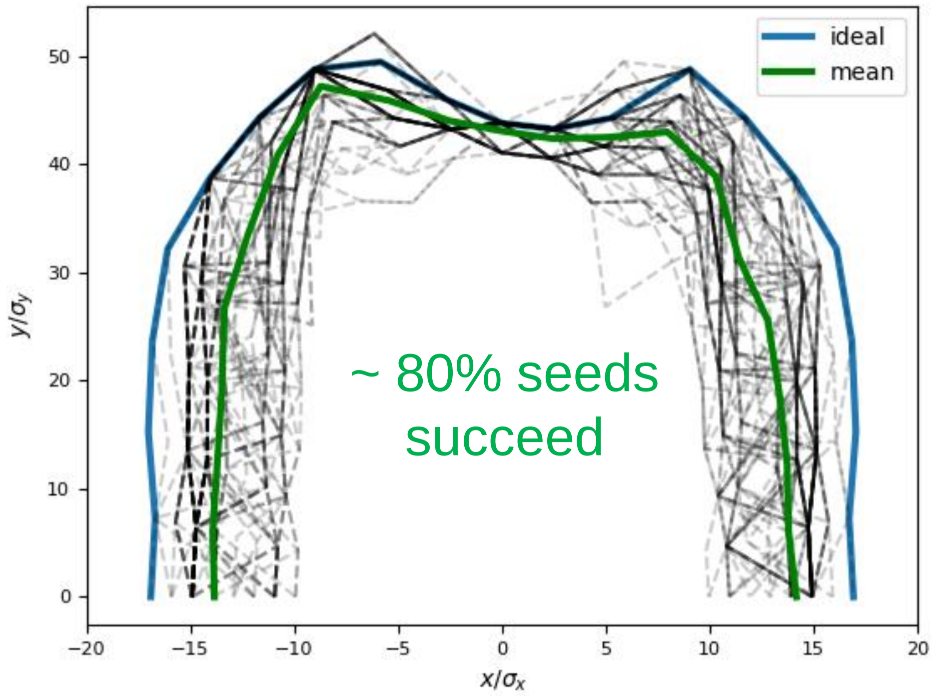
- This resulted in a 60% of success rate, with an average dynamic aperture exceeding 12σ horizontally and 45σ vertically
- Among the 40% failed seed, the majority were unable to converge to the actual tune
- This issue arises due to the strong non-linear behaviour from IR sextupoles in combination with tighter tolerances
- No errors introduced on the IR sextupoles to verify whether they are the cause for seeds failure

Type	Δx (μm)	Δy (μm)	Rotation (μrad)
Arc quadrpoles	100	100	100
Arc sextupoles	100	100	100
IR quadrupoles with. FF-doublets qc[12]*	70 10	70 10	70 10
IR sextupoles	0	0	0
All Dipoles	1000	1000	1000

Tolerances on IR sextupoles



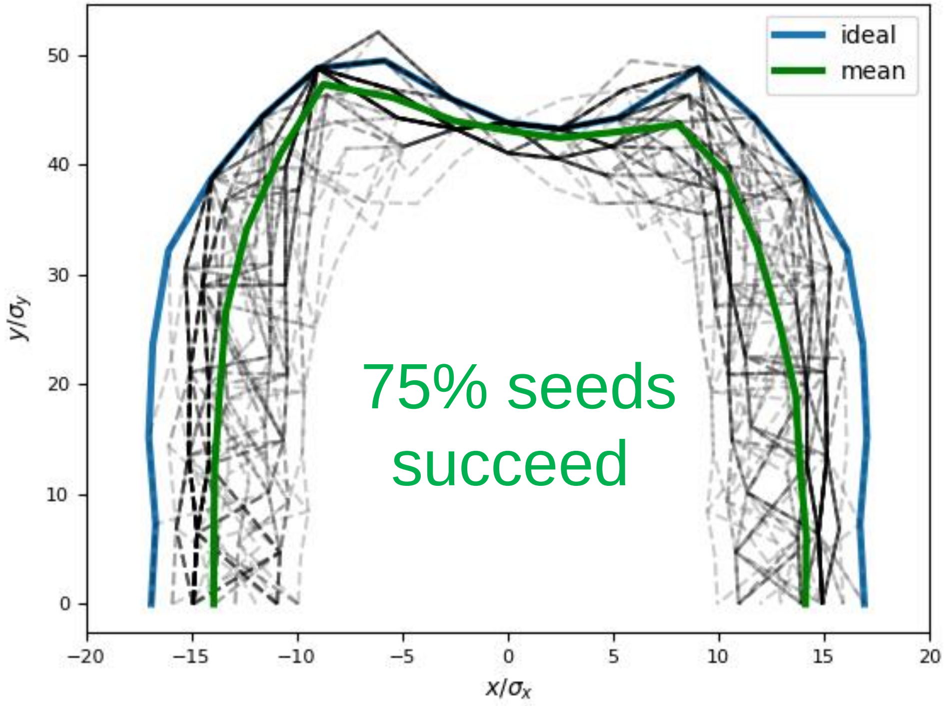
20%



- Success rate increased from 60% to 80%
- This clearly demonstrates that large errors in the IR-sextupoles result in the failure of certain seeds

Tolerances on IR sextupoles

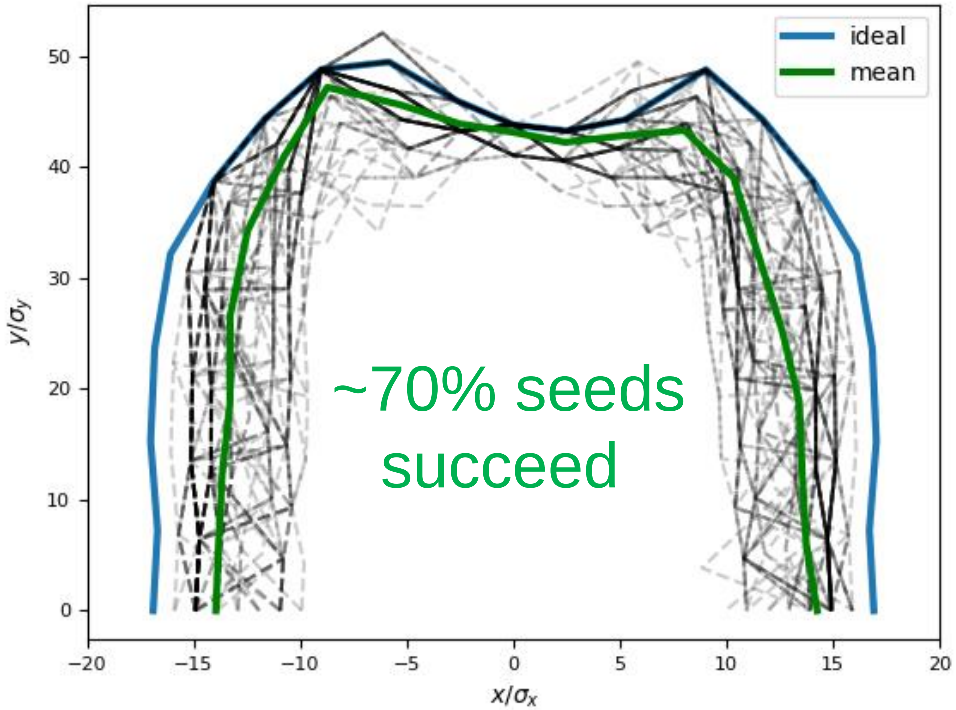
- To determine the optimal tolerable value that ensures an improved success rate, 30µm/30µrad errors are applied on IR sextupoles



Type	Δx (µm)	Δy (µm)	Rotation (µrad)
Arc quadrpoles	100	100	100
Arc sextupoles	100	100	100
IR quadrupoles with. FF-doublets qc[12]*	70 10	70 10	70 10
IR sextupoles	30	30	30
All Dipoles	1000	1000	1000

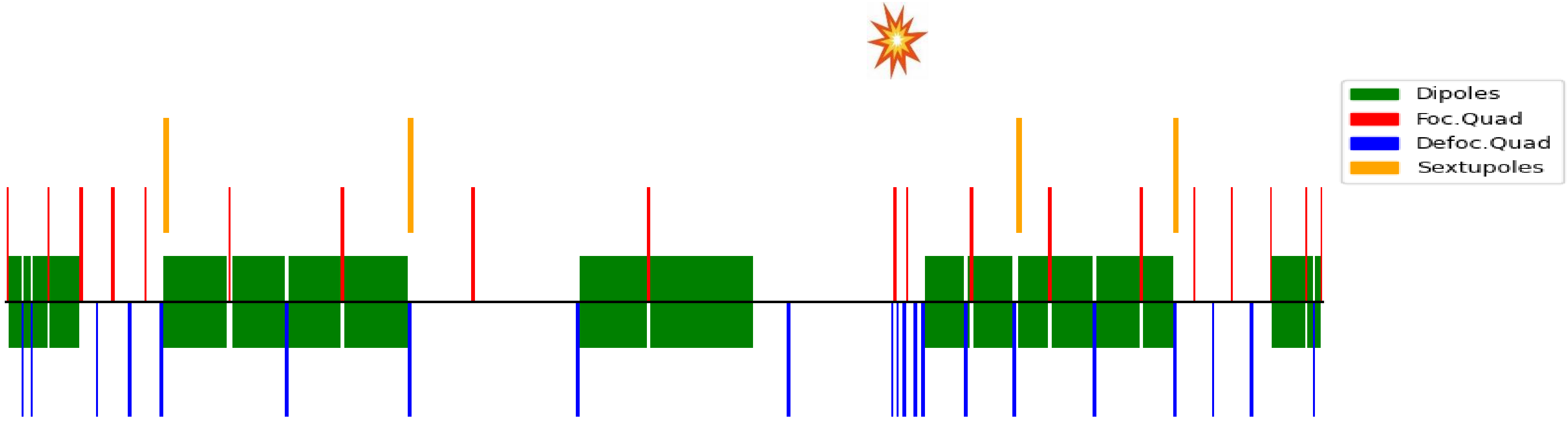
Tolerances on IR sextupoles

- To determine the optimal tolerable value that ensures an improved success rate, 50µm/50µrad errors are applied on IR sextupoles

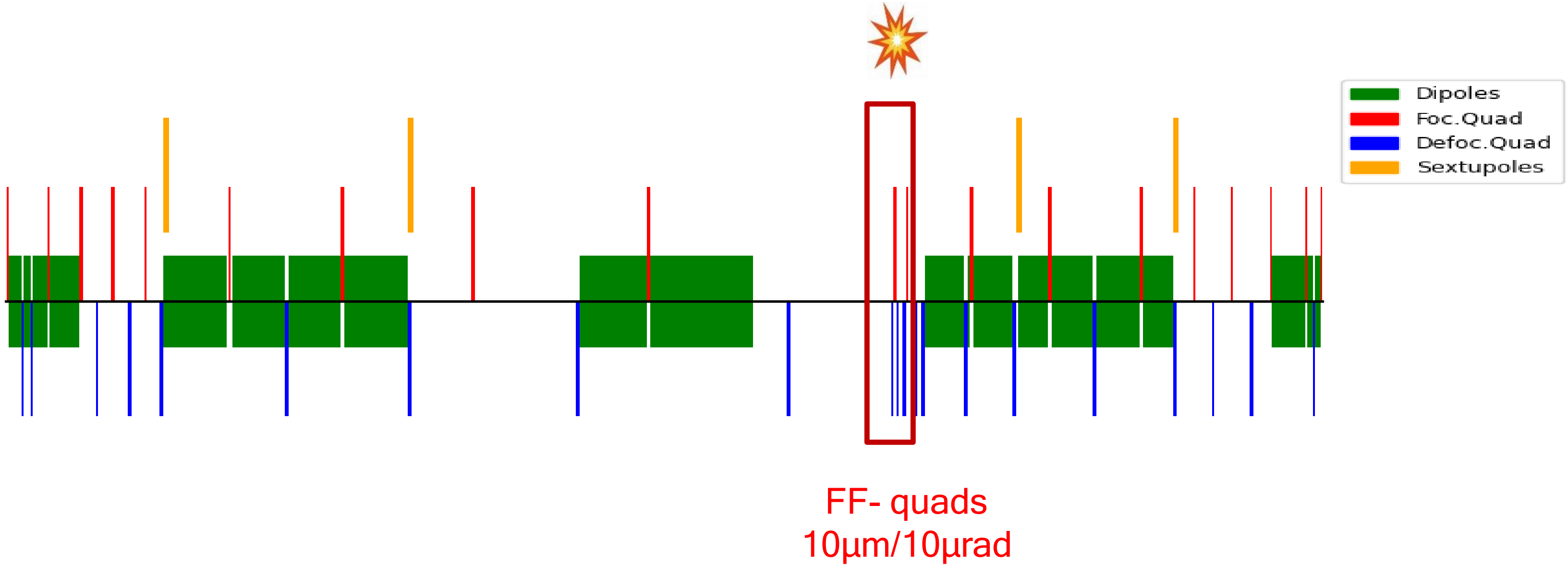


Type	Δx (µm)	Δy (µm)	Rotation (µrad)
Arc quadrpoles	100	100	100
Arc sextupoles	100	100	100
IR quadrupoles with. FF-doublets qc[12]*	70 10	70 10	70 10
IR sextupoles	50	50	50
All Dipoles	1000	1000	1000

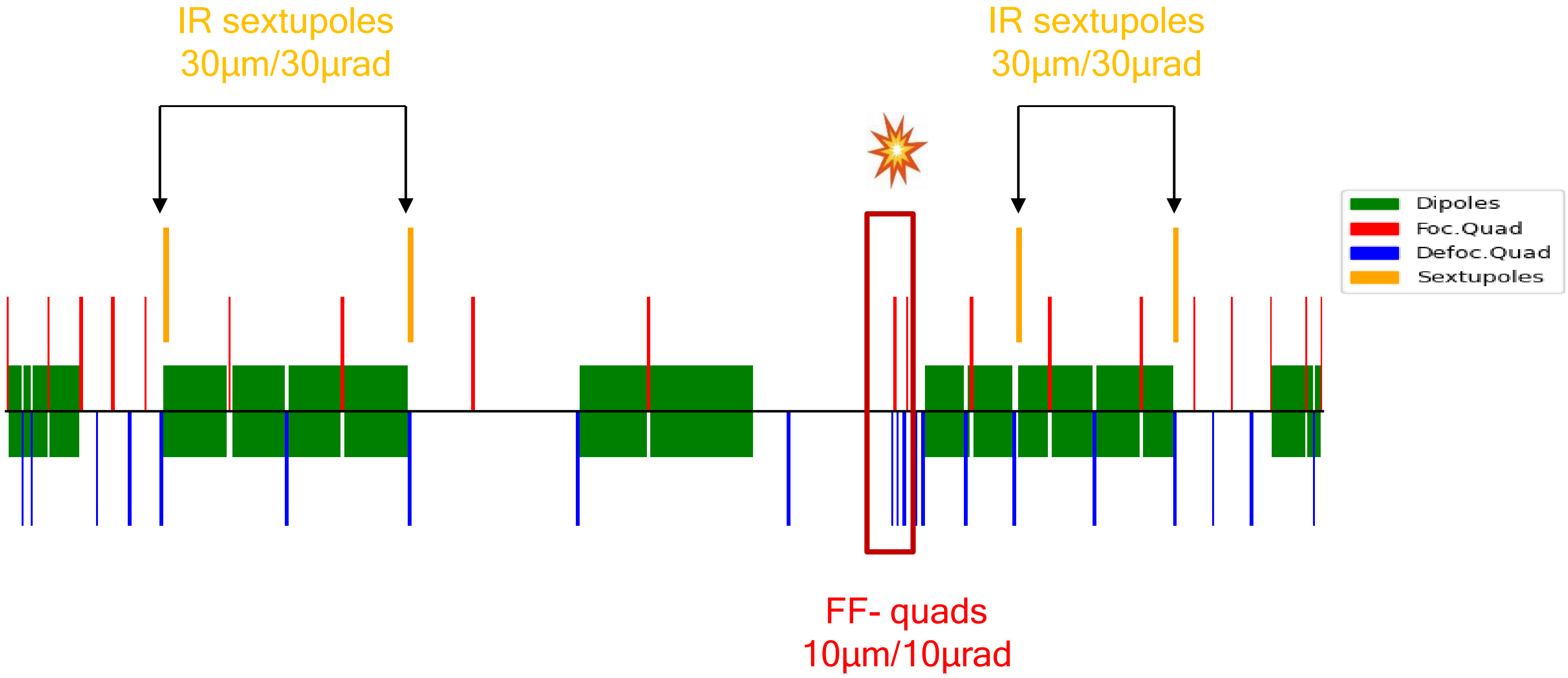
Final Tolerances on IR elements



Final Tolerances on IR elements



Final Tolerances on IR elements



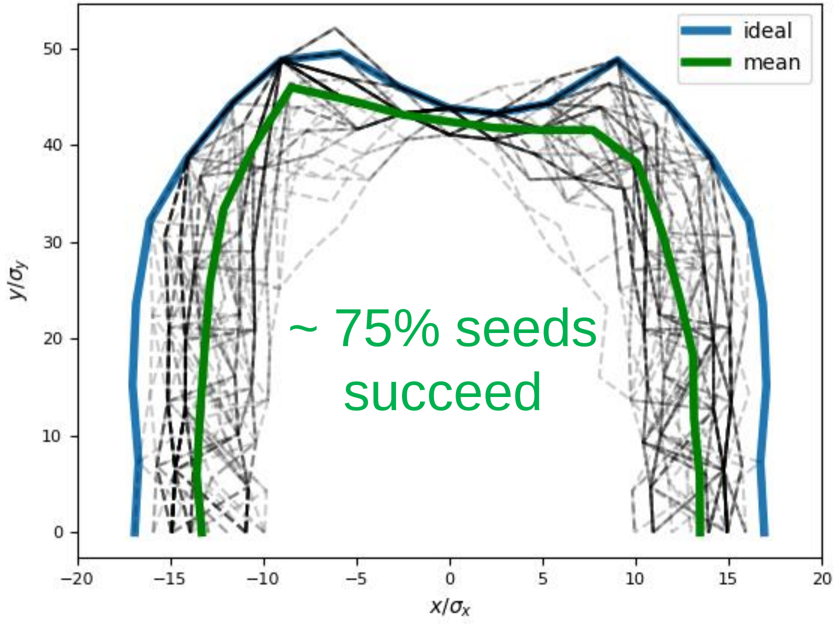
Final Tolerances on IR elements

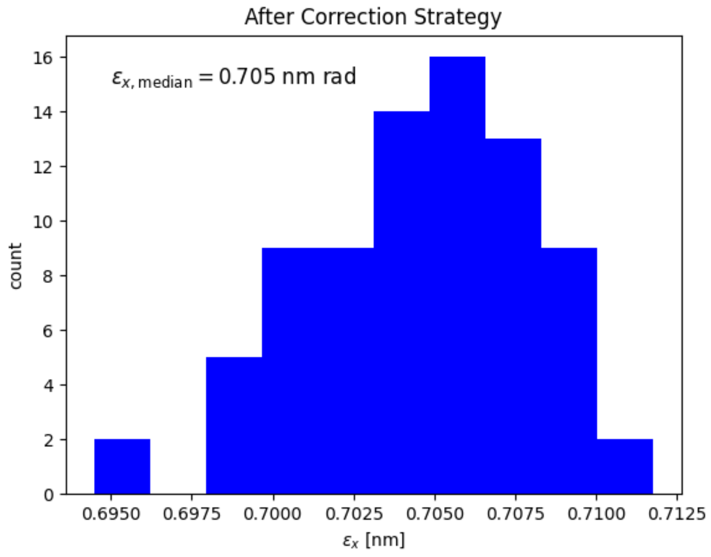
- Alignment & rot. errors of 30µm/30µrad for the IR sextupoles, 10µm/10µrad for the FF-quads represent the most acceptable tolerances in the IR region, yielding a higher number of successful seeds with sufficient DA
- With this in consideration, the tolerances on other IR quads were found to be manageable up to 100µm/100µrad, without negatively impacting the success rate

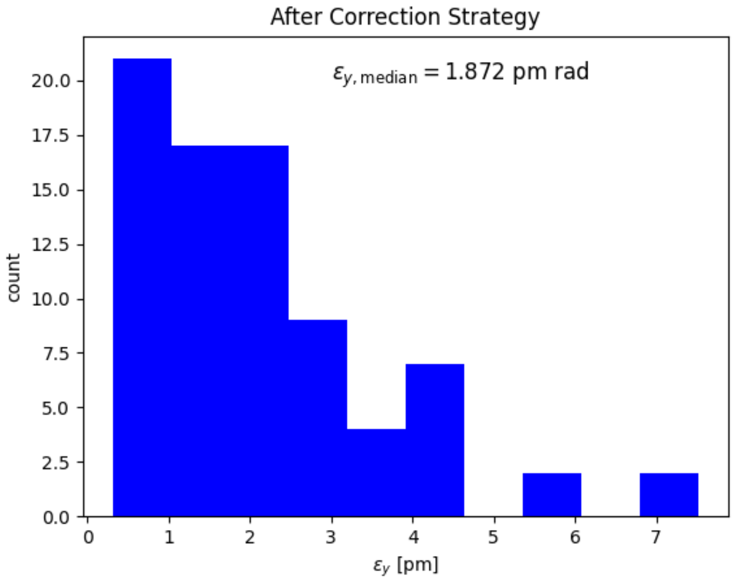
Type	Δx (µm)	Δy (µm)	Rotation (µrad)
Arc quadrpoles	100	100	100
Arc sextupoles	100	100	100
IR quadrupoles with. FF-doublets qc[12]*	100 10	100 10	100 10
IR sextupoles	30	30	30
All Dipoles	1000	1000	1000

Final Tolerances on IR elements

- Histograms represent the horizontal and vertical emittances after the correction strategy for the successful seeds
- The median value stays at 0.705 nm-rad and 1.872 pm-rad for horizontal and vertical emittances respectively
- The corresponding mean DA is 12σ horizontally and 45σ vertically







Conclusions and Outlook

- 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 tolerance requirements of the magnets to define the machine performance
- Simulations suggest that 30µm/30µrad for the IR sextupoles and 10µm/10µrad for the FF-quads are the most acceptable tolerances in the IR region with other IR elements manageable up to 100µm/100µrad
- Fully tuned lattice including the IP optics correction is available here (eeFACT2025)

Outlook:

- Include girder misalignments in the simulations to have tighter tolerances in the arcs
- Benchmark the tuning simulations between Xsuite and pyAT

References

[1] https://gitlab.esrf.fr/BeamDynamics/commissioningsimulations/-/tree/main?ref_type=heads

[2] https://github.com/fscarlier/xconverters/tree/main/xconverters

Thank you!

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