ALIGNMENT TOLERANCES AND TUNING STUDIES

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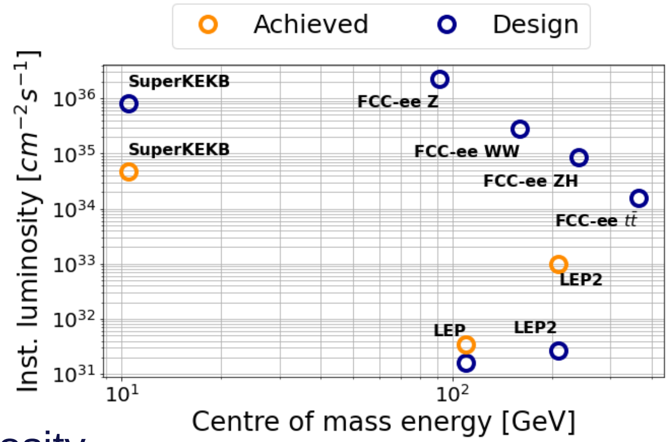
Thanks to A. Franchi, R. Tomás, K. Oide, T. Raubenheimer, S. White, F. Zimmermann

Introduction

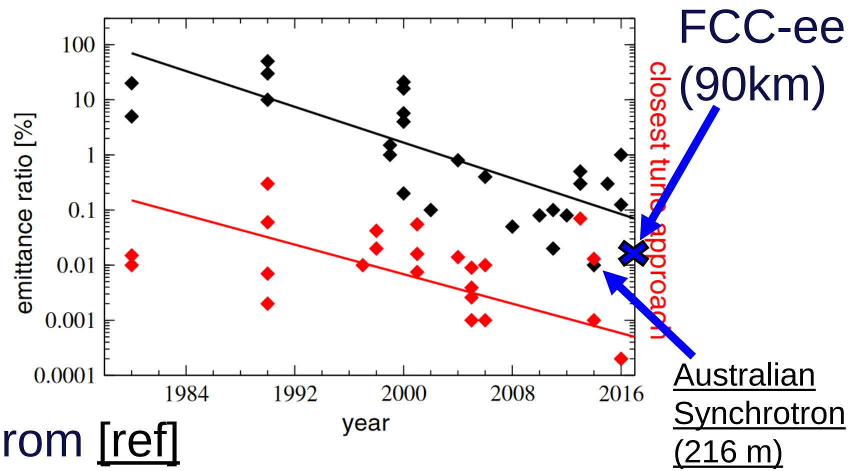
- FCC-ee targets unprecedent luminosities

- Good control of optics required to achieve target performance
  - Correction of $\frac{\Delta\beta}{\beta}$, coupling etc. to directly affect luminosity at each IP (see presentation by Satya)
  - Perturbations in entire ring contribute indirectly to luminosity via vertical emittance and dynamic aperture/momentum acceptance (with further impact on lifetime and Inj. Efficiency, ..)

- Size of the machine makes alignment a challenging and time-consuming task, with implications on the cost



Sources: 1,2,3,4

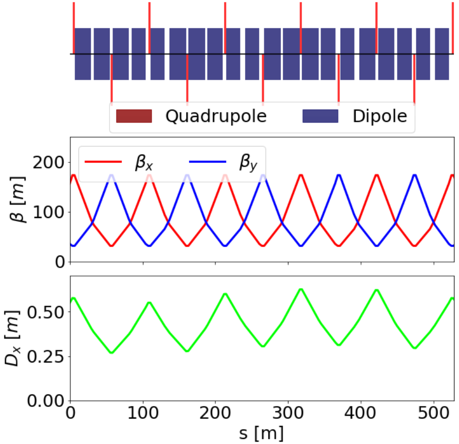


From [ref]

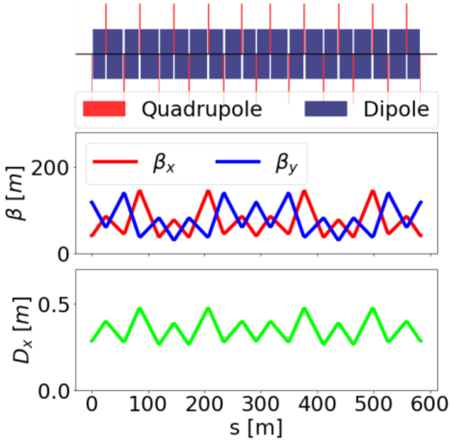
FCC-ee lattices

- Currently, two lattice design under study
  - Baseline design: variable length FODO cell with arc cell phase advance of $90^{\circ}/\ 90^{\circ}$, 73 (Z)/143 (tt) sextupole pairs used for DA/MA optimization
  - LCCO lattice (formerly Hybrid FODO HFD): with phase and beta-modulation, one sextupole family per plane

Baseline Z-lattice



LCCO Z-lattice

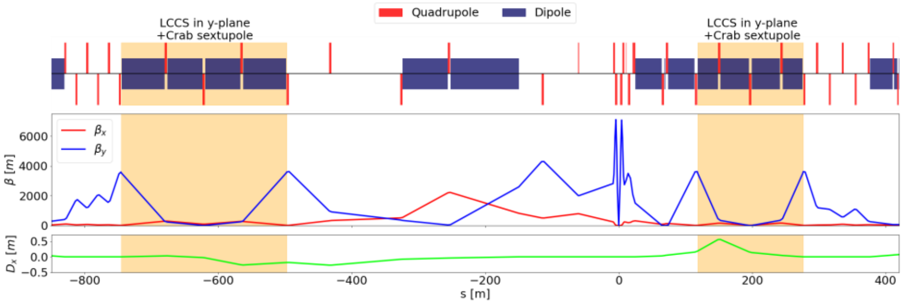


FCC-ee lattices

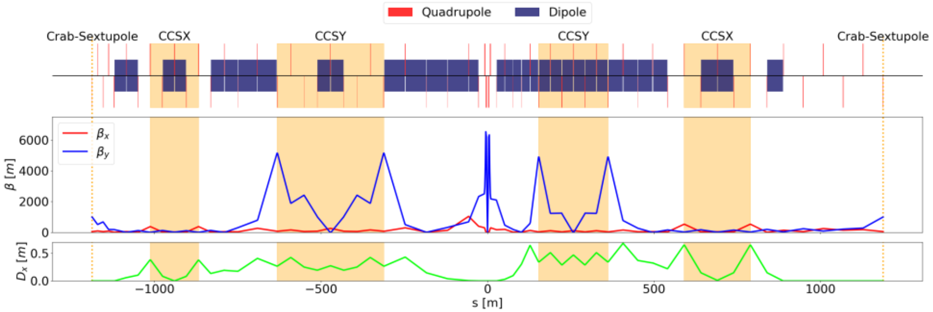
- Currently, two lattice design under study
  - Baseline design:
    Local chromaticity correction in vertical plane with virtual crab sextupole

  - LCCO lattice (formerly Hybrid FODO HFD):
    Dedicated chromaticity section in horizontal and vertical plane, as well as Crab sextupole
    - Additional sextupole at image points to reduce chromatic variation of optics

Baseline Z-lattice



LCCO Z-lattice



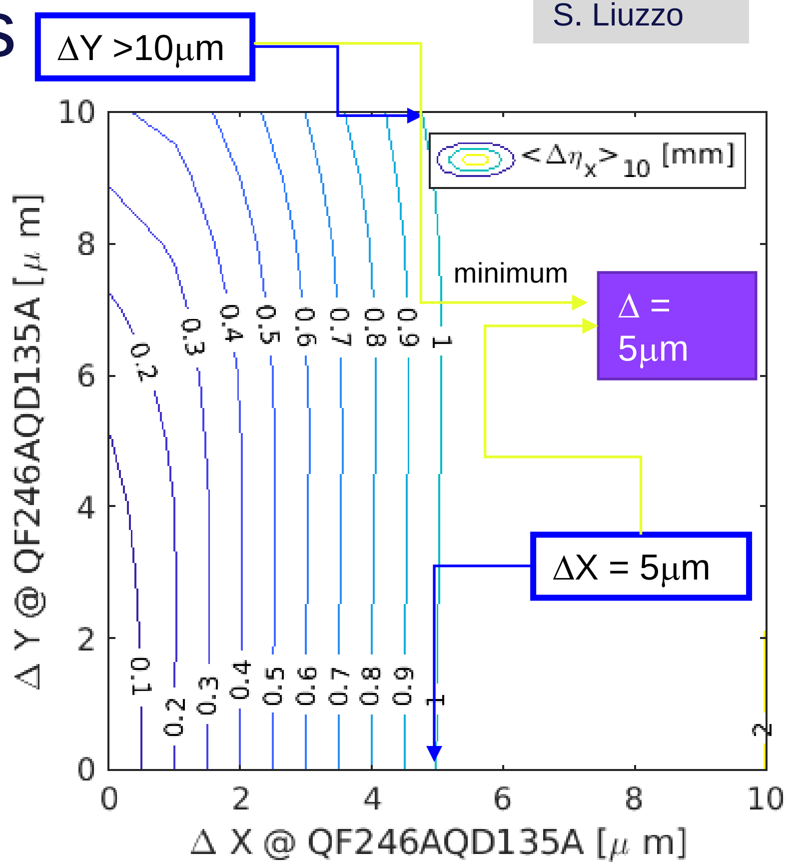
Methodology

- Study impact of errors and performance in both lattices
  - First, check sensitivities to random errors, both as input for static alignment, but also as indication for dynamic errors
  - To refine studies and guide metrology strategy, refine alignment modelling in the arcs
  - Finally, look into commissioning and correction strategies to get an idea of situation in both lattices

Studies by S. Liuzzo

Alignment error sensitivities

- First study sensitivity (not tolerance) of different magnet families to transverse misalignments
  - Scan different alignment error for given family of magnets and store beta-beating, orbit, emittance, dispersion
    - No correction applied
    - Random errors and using 10 seeds
  - Determine alignment amplitude for a set perturbation
    - E.g. alignment error that results in increase of horizontal dispersion by 1mm



Studies by
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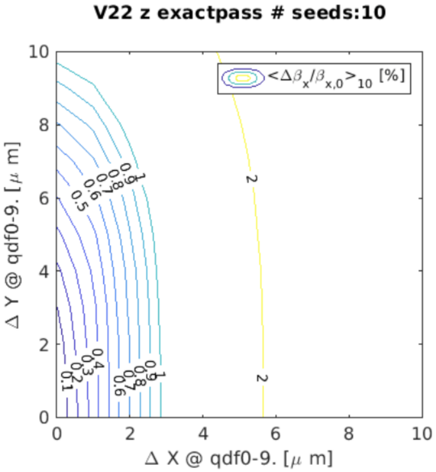
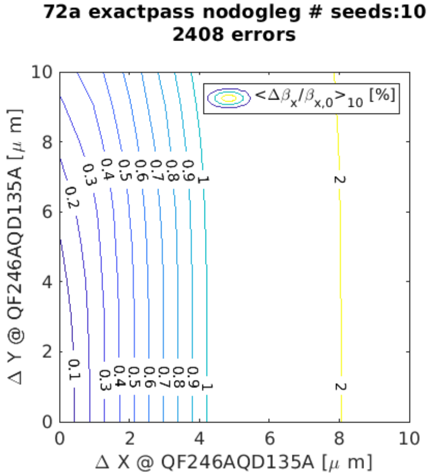
Arc quadrupole sensitivities

- Comparing sensitivity of arc quadrupoles to horizontal and vertical misalignment
  - Baseline lattice yields an average $\Delta\beta_x / \beta_x$ of 1% for $\Delta x = 2.7\ \mu m$, whereas latest LCCO finds equivalent beta-beating at $\Delta x = 4.1\ \mu m$

Baseline Z-lattice



LCCO Z-lattice



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Arc quadrupole sensitivities

- In each error category, the LCCO arc cell shows a lower sensitivity to alignment errors in the arc quadrupoles
  - Usually outperforms by a factor 2 or higher

Lattice	Operation-mode	Tolerance to reach							
		RMS Orbit (100µm)		$\Delta\beta/\beta$ (1%)		Dispersion (1mm)		Emittance ϵ (1% ϵ_h/1‰ ϵ_h)	
		Δx [µm]	Δy [µm]	Δx [µm]	Δy [µm]	Δx [µm]	Δy [µm]	Δx [µm]	Δy [µm]
Baseline V22	Z	1.9	1.9	2.9	0.7	0.1	0.1	3.0	1.0
HFD66	Z	>10	>10	>10	4.2	3.9	1.8	>10	2.7
Baseline V22	tt	1.3	1.5	1.5	0.5	0.12	0.2	0.5	0.17
HFD66	tt	2.5	2.5	5.5	2.2	2.5	1.0	9.8	0.5

Studies by S. Liuzzo

Arc sextupole sensitivities

- Thanks to weaker arc sextupoles and common powering of arc sextupoles, LCCO arc sextupoles are less sensitive to alignment errors

Lattice	Operation -mode	Tolerance to reach							
		RMS Orbit (100µm)		$\Delta\beta/\beta$ (1%)		Dispersion (1mm)		Emittance ϵ (1% ϵ_h/1‰ ϵ_h)	
		Δx [µm]	Δy [µm]	Δx [µm]	Δy [µm]	Δx [µm]	Δy [µm]	Δx [µm]	Δy [µm]
Baseline V22	Z	>100	>100	17	8.5	3.1	2.6	90	39
HFD66	Z	>100	>100	65	45	10	10	>100	>100
Baseline V22	tt	>100	>100	10	7.0	7.5	10	27	26
HFD66	tt	>100	>100	20	10	12	12	18	38

Studies by
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Final focus quadrupoles sensitivities

- Many iterations on the HFD Final focus layout to improve sensitivities
  - Baseline less sensitive to final focus quadrupole misalignments in Z operation-mode, opposite at tt operation-mode

Lattice	Operation-mode	Tolerance to reach							
		RMS Orbit (100µm)		$\Delta\beta/\beta$ (1%)		Dispersion (1mm)		Emittance ϵ (1% ϵ_h/1‰ ϵ_h)	
		Δx [µm]	Δy [µm]	Δx [µm]	Δy [µm]	Δx [µm]	Δy [µm]	Δx [µm]	Δy [µm]
Baseline V22	Z	0.8	>10	(1.5,1.2)	0.05	(0.025, 0.025)	0.01	(1.2,1.0)	0.008
HFD66	Z	3.0	1.0	1.5	2.2	<0.01	<0.01	<0.01	<0.01
Baseline V22	tt	2.0	0.35	2.1	0.22	0.24	0.04	1.1	0.06
HFD66	tt	6.2	2.0	3.5	1.0	1.0	0.05	1.0	<0.01

Studies by S. Liuzzo

Final focus sextupole sensitivities

- Despite larger number of sextupoles in final focus system, LCCO shows similar or better sensitivity to misalignments
  - Sidenote: In SKEKB, SR heating deforms beamline, resulting in orbit deviation in chromaticity correction section and leading to change of β_y^* [ref]

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		RMS Orbit (100µm)		$\Delta\beta/\beta$ (1%)		Dispersion (1mm)		Emittance ϵ (1% ϵ_h/1‰ ϵ_h)	
		Δx [µm]	Δy [µm]	Δx [µm]	Δy [µm]	Δx [µm]	Δy [µm]	Δx [µm]	Δy [µm]
Baseline V22	Z	>10	>10	>10	0.25	>10	1.2	>10	>10
HFD66	Z	>10	>10	>10	1.1	7.8	2.0	>10	>10
Baseline V22	tt	>10	>10	>10	0.5	>10	2.6	>10	8
HFD66	tt	>10	>10	>10	2.2	>10	3.5	>10	>10

Studies by
S. S. Jagabathuni

Coherent alignment in arcs

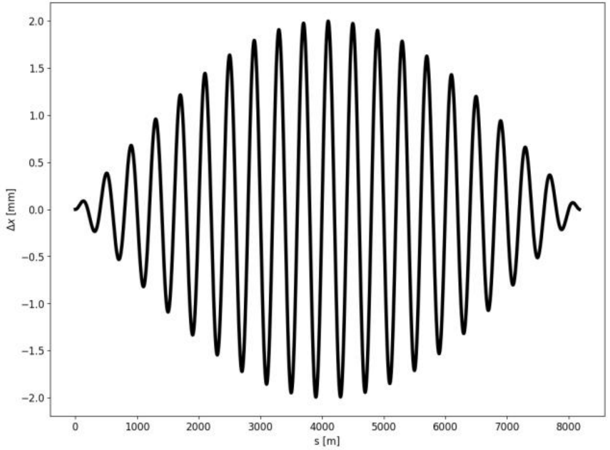
- Initially, purely random alignment errors assumed
  - As input for metrology group and alignment strategy, resonant wavelengths of the arcs to be identified

- Assign misalignment to arc quadrupoles and arc sextupoles based on

$$\Delta x = A \sin\left({}^{2\pi s}/_{\lambda}\right) \sin\left({}^{\pi s}/_{l_{arc}}\right) ,$$

where A is set Amplitude, s location in the arc,
and λ alignment wavelength

  - Assumes perfect alignment at the extremities of the arcs



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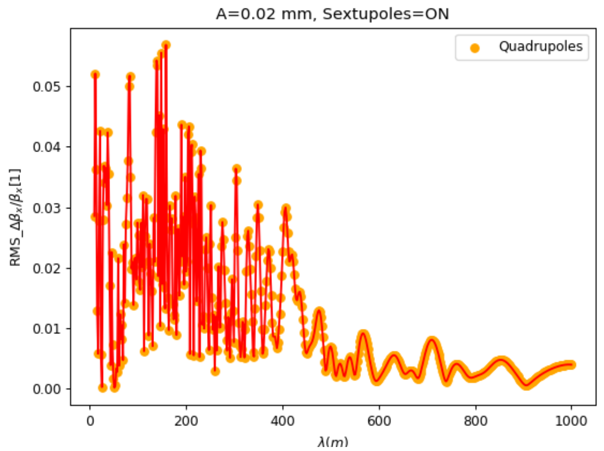
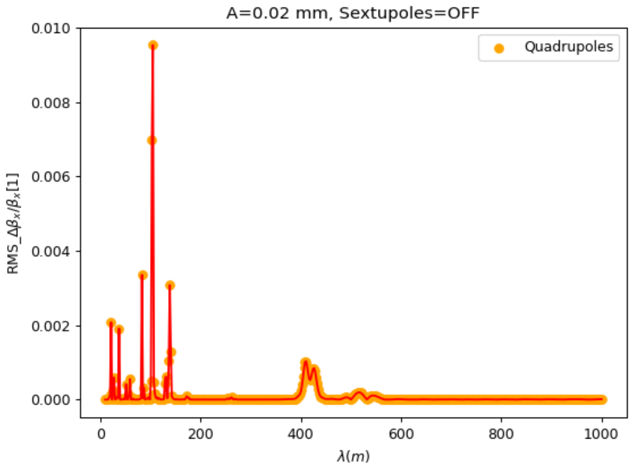
- In baseline lattice for Z operation mode,
wavelengths λ above 500m do not show significant impact
  - Lower critical wavelength found for tt operation mode





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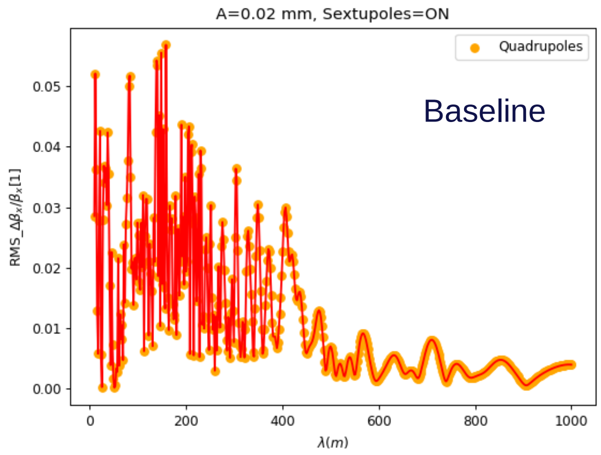
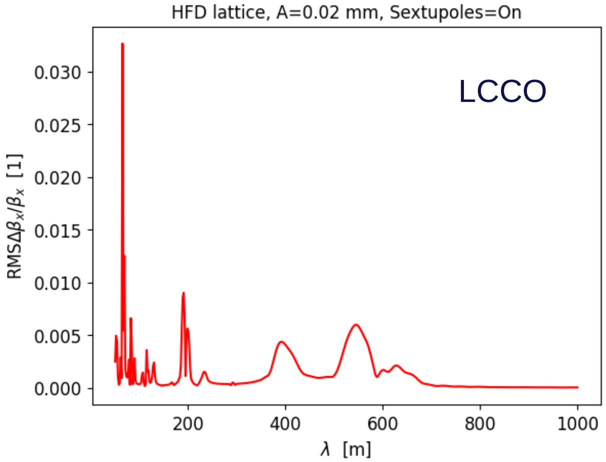
wavelengths λ above 500m do not show significant impact
  - Lower critical wavelength found for tt operation mode
- HFD lattice shows less sensitivity and similar wavelength



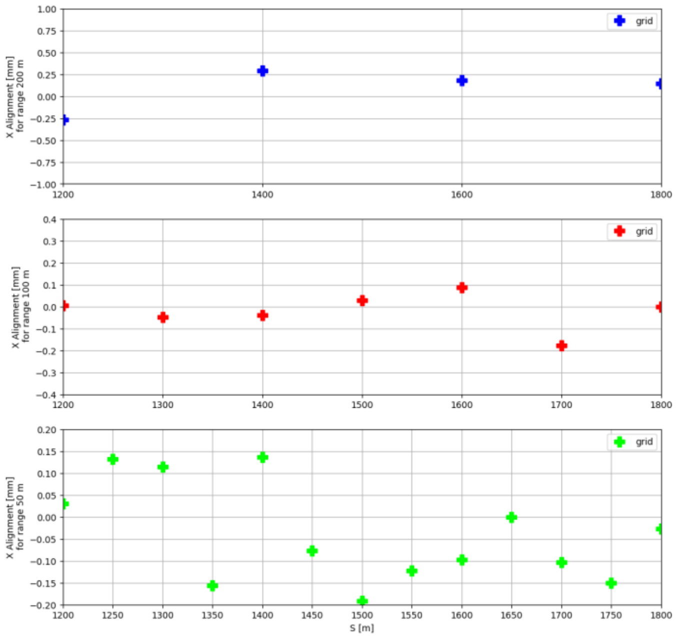


Long range alignment model

- Suggested by Tor Raubenheimer last year, alignment model for arcs further refined
  - As alignment over longer lengths scale becomes more challenging, see how beam-based alignment performs

Length scale [m]	Tolerance [μm] before BBA	Tolerance [μm] after BBA
6	20-50	10
50	200	20
200	500	20
1000	2000	100
10000	5000	1000

Initial proposal for alignments with different lengths scale



  - Developed model/script using given tolerances for different length scales

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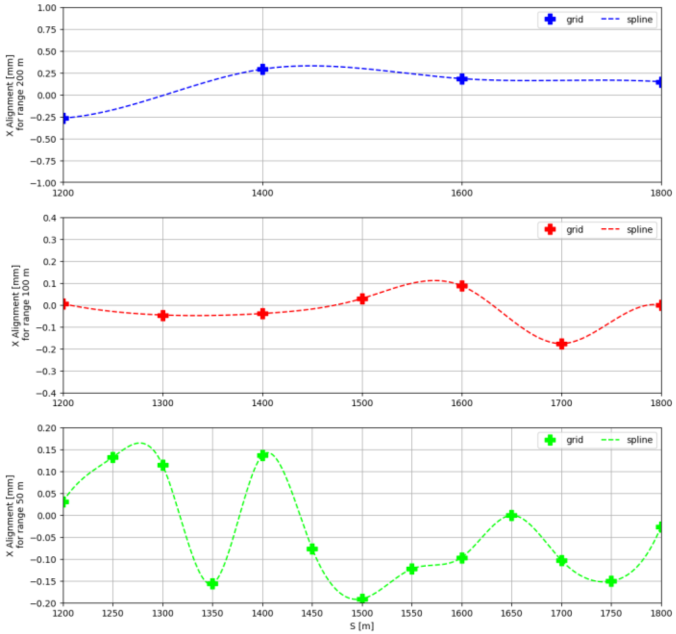

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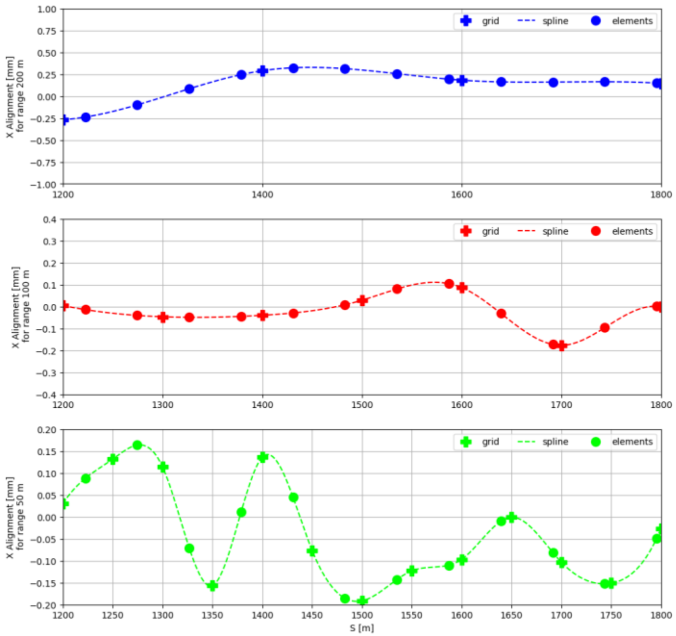

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Commissioning simulations

- Full commissioning simulations performed using pyAT and for Z operation mode
  - Evaluate in 6D and including SR Radiation and tapering

- Procedure involves:
  1. Install BPMs and orbit correctors
  2. Misalign arc quadrupoles and sextupoles with given RMS misalignment
  3. Trajectory steering and finding closed orbit (no sextupole ramp required)
  4. Correct orbit, tunes, and chromaticity
  5. Optics and coupling correction using analytic ORM
  6. Extract lattice properties ($^{\Delta\beta_{x,y}}/_{\beta_{x,y}}$, $\epsilon_{x,y}$,..)

Table 3: β-beating, dispersion and emittances after correction of 10 µm random alignment errors on dipole quadrupole and sextupole magnets for the FCC-ee lattice using analytic ORM derivative (1856 BPMs, 18 steerers). The input lattice is tested: without radiation, with radiation and with radiation and tapering. Reference lattice is in all cases without radiation.

$\langle std\rangle_{50}$ units	$\frac{\Delta\beta_h}{\beta_{h,0}}$ %	$\frac{\Delta\beta_v}{\beta_{v,0}}$ %	$\Delta\eta_h$ mm	$\Delta\eta_v$ mm	$\Delta\epsilon_v$ pm rad
4D err	3.63	61.37	118.7	82.36	-
4D cor	0.84	4.24	25.67	9.58	0.71
6D err	3.60	59.45	120.54	82.45	-
6D cor	0.81	4.29	26.0	9.57	0.17
6D err + tapering	3.61	61.33	119.59	82.96	-
6D cor + tapering	0.82	4.22	26.03	9.65	0.18

A.Franchi et al. Analytic derivative of orbit response matrix and dispersion with thick error sources and thick steerers implemented in python, MOPLO69, IPAC2023

Optics commissioning results

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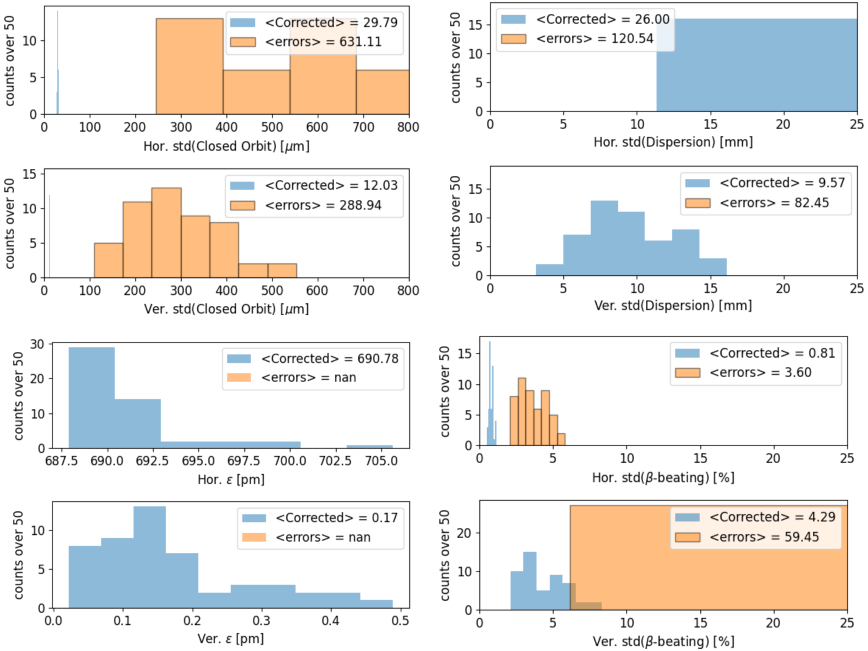
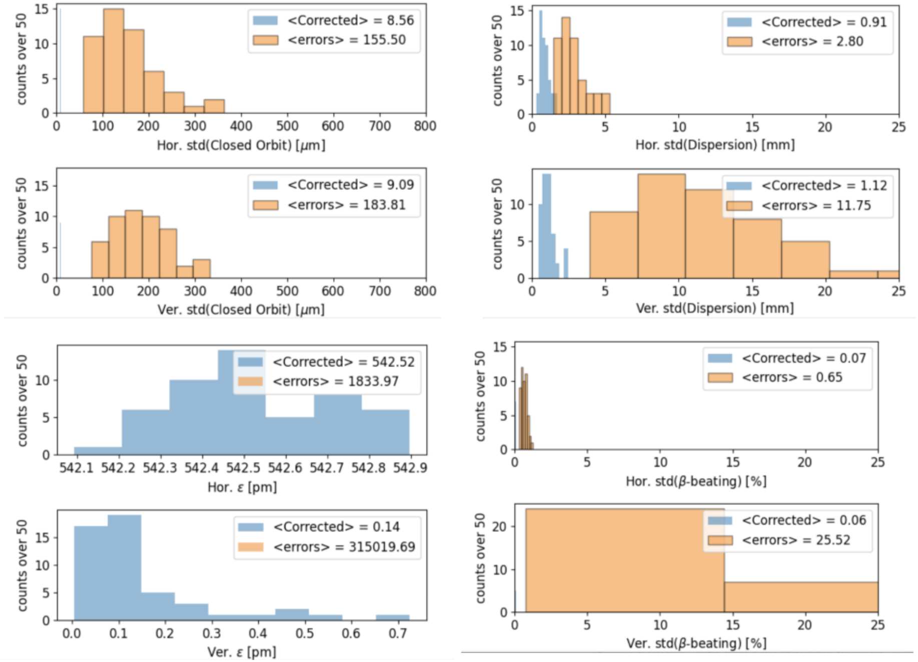
Baseline Z-lattice



LCCO Z-lattice



S.Liuzzo et al., Commissioning simulations tools based on python Accelerator Toolbox, MOPA142, IPAC2023, IOP

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Optics commissioning summary

- Correction studies performed included using only errors in the arcs, RF and Radiation/tapering and using identical correction procedures
  - Similar to sensitivities, LCCO shows smaller optics perturbations for same misalignment
    - Larger misalignment in LCCO still gives comparatively good results

Lattice	RMS alignment in arcs [µm]	orbit		Beta-beating		dispersion		emittance	
		Δx [µm]	Δy [µm]	$\Delta\beta_x/\beta_x$ [%]	$\Delta\beta_y/\beta_y$ [%]	ΔD_x [mm]	ΔD_y [mm]	ϵ_x [pm]	ϵ_y [pm]
V22	10	29.8	12.0	0.81	4.29	26.0	9.57	690.8	0.17
LCCO	10	8.6	9.1	0.07	0.06	0.91	1.12	542.52	0.14
LCCO	70	51.5	58.84	0.5	0.77	6.39	6.84	543.19	6.33

Summary

- For FCC-ee to reach the design performance, careful optics tuning required
  - Size of the machine makes alignment a challenging and costly task, with major impact on performance
- Two FCC-ee lattice concepts under study
  - LCCO option less sensitive to alignment errors in the arcs compared to baseline
  - Final focus magnets show similar sensitivity
- Arc alignment models being reviewed and refined as input for metrology group and in view of evaluating BBA
- Optics commissioning simulations performed for both baseline and LCCO lattice
  - LCCO may tolerate larger transverse misalignments

Thanks for your attention!