The 2023 International Workshop on the High Energy Circular Electron Positron Collider

FCC-ee optics tuning Working Group

R. Tomas for the FCC-ee optics working group

October 2023

https://indico.ihep.ac.cn/event/19316

FCC-ee tuning team & WG meetings

New members

CERN e-group FCCee_tuning-team: Ilya AGAPOV, Esmaeil AHMADI, Felix CARLIER, Antoine CHANCE, Tessa CHARLES, Aman DESAI, Barbara DALENA, Angeles FAUS-GOLFE, **Abid HUSSAIN**, Riccardo DE MARIA, Andrea FRANCHI, Cristobal GARCIA, Werner HERR, Michael HOFER, Patrick HUNCHAK, Satya S. JAGABATHUNI, Jacqueline KEINTZEL, Simone LIUZZO, Lukas MALINA, Elaf MUSA, Eva MONTARBON, Katsunobu OIDE, Tobias PERSSON, Tatiana PIELONI, Freddy POIRIER, Pantaleo RAIMONDI, Tor RAUBENHEIMER, Guillaume SIMON, Rogelio TOMAS, Fani VALCHKOVA-GEORGIEVA, Leon VAN RIESEN-HAUPT, Yiwei WANG, Simon WHITE, Yi WU, Renjun YANG, Zhandong ZHANG, Frank ZIMMERMANN **+ *Anyone is welcome!***

22 meetings so far: 17 Oct, 14 Sept, 26 Jul, 29 Mar, 17 Mar ,2 Feb, 2 Dec, 1 Dec, 10 Nov, 3 Nov, 22 Sept, 25 Aug, 21 July, 14 Jul, 30 Jun, 9 Jun, 22 Apr, 22 Mar, 17 Mar, 10 Feb, 17 Nov and 10 Nov 2021.

Last tuning team reports in: 157th FCC-ee Optics Design, FCC week 23

FCC-ee tuning team by institutes

CERN e-group FCCee_tuning-team:

Ongoing discussions with Colombia & Spain https://www.ipac23.org/preproc/pdf/WEPL023.pdf

14th International Particle Accelerator Conference,Venezia JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: https://doi.org/10.18429/JACoW-IPAC-23-WEPL023

PROGRESS OF THE FCC-ee OPTICS TUNING WORKING GROUP

J. Bauche, F. Carlier, R. De Maria, M. Hofer, J. Keintzel, M. Koratzinos, F. Valchkova-Georgieva, H. Mainaud, T. Lefevre, K. Oide, T.H.B. Persson, P. Raimondi, D. Shatilov, G. Simon, R. Tomás*, F. Zimmermann, Y. Papaphilippou, CERN, Geneva, Switzerland, T. Charles, University of Liverpool Liverpool, UK, A. Franchi, S. Liuzzo, S. White, ESRF, Grenoble, France, E. Ahmadi, ILSF, Qazvin, Iran, I. Agapov, L. Malina, E. Musa, DESY, Hamburg, Germany, B. Dalena, T. da Silva, A. Chance, CEA, Paris, France, T. Raubenheimer, X. Huang, SLAC, Menlo Park, USA T. Pieloni, C. Garcia, L. van Riesen-Haupt, Y. Wu, EPFL, Lausanne, Switzerland, Y. Wang, IHEP, Beijing, China, A. Faus-Golfe, IJCLab, Paris, France, Y. Onishi, KEK, Tsukuba, Japan

Abstract

FCC-ee is a proposed lepton collider with a circumference close to 100 km to produce an unprecedented amount of luminosity. The FCC-ee optics tuning working group is addressing one of the most critical aspects of the FCC-ee, that is the recovery of the optics design performance in presence of realistic imperfections. Various teams from laboratories all around the world have got together to assess field quality tolerances and review and share experience gained at synchrotron light sources and lepton colliders such as SuperKEKB. This paper reports the latest results on optics measurements and tuning simulations for various techniques, the development of simulation tools, and possible layout

sextupoles vertical misalignments up to 10 μm, without applying corrections [11]. From first polarization simulations it is observed that vertical orbits with rms deviations up to 150 μm from the flat machine achieve above 80% polarization [12].

Achieving good optics quality and maintaining it will require sophisticated optics measurement and BBA techniques that can be performed with design beam parameters. Current colliders as SuperKEKB and LHC can only perform optics measurements at low intensity which results in unforeseen perturbations at high intensity from collective effects, temperature shifts [8] or the need to introduce Landau damping [13].

https://link.springer.com/content/pdf/10.1140/epjti/s40485-023-00096-3.pdf

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RESEARCH ARTICLE Open Access

Alignment & stability challenges for FCC-ee

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Abstract

In order to achieve its ultra-low vertical emittance (1 pm) and high luminosity (of up to 230 × 10^{34} cm^{-2} s^{-1} per collision point), the e^+e^- Future Circular Collider (FCC-ee) requires a well-informed alignment strategy, powerful correction methods, and good understanding of the impact of vibrations. The large ring size, high natural chromaticity, small β^*, and the low coupling ratio make the FCC-ee design susceptible to misalignment and field errors, which if not properly addressed, threaten to increase the horizontal and vertical emittances and adversely affect the luminosity. Tight alignment tolerances around the 100 km ring would be a major cost driver and therefore alignment and stability need to be carefully studied. In this paper we present a status update, in which we apply analytical estimate methods, verified with simulation data, to determine the influence of the alignment of specific magnet types with the result informing the relative alignment tolerances. This is followed by simulations of a correction strategy that includes a large set of magnet misalignments and field errors. Finally, we also consider the tolerances on vibrations of quadrupoles through evaluating three cases: coherent vibration due to external seismic motion, vibrations resonant with the betatron frequency, and non-resonant, incoherent vibration.

https://indico.cern.ch/event/1242395/

FUTURE CIRCULAR COLLIDER

Optics Tuning and Corrections for Future colliders workshop

26–28 Jun 2023
CERN
Europe/Zurich timezone

Enter your search term

More than 70 participants registered from more than 20 labs.

- Overview
- Timetable
- Contribution List
- Registration
- Participant List
- Program committee
- Accommodation
- CERN lightweight account application

The workshop will bring together experts from the circular and linear collider community and the high brightness synchrotron radiation sources to discuss the tuning and correction of beam optics.

Topics to be covered are:

- correction of linear and nonlinear beam optics through the accelerator;
- sensitivity and optimization of dynamic aperture;
- impact of collective effects on the beam optics;
- component errors, drifts, and correlations;
- transport and preservation of polarization;
- modeling tools and optimization techniques.

The workshop plans to be in-person and will support some virtual participation.

Initial assumptions on misalignments

T. Charles

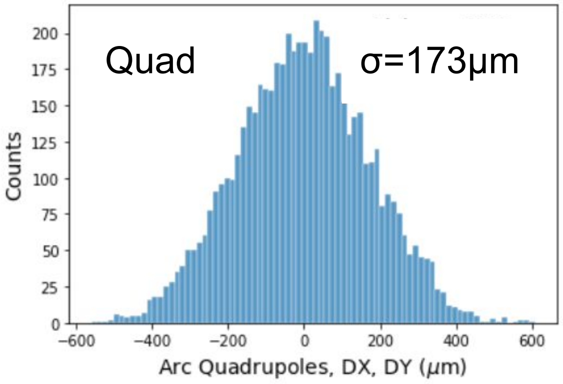
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔDTHETA (μrad)	ΔDPHI (μrad)	Field Errors
Arc quadrupole*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	1000	1000	300	1000	0	0	$\Delta B/B = 1 \times 10^{-4}$
Girders	150	150	-	1000	-	-	-
IR quadrupole	100	100	250	250	100	100	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	100	100	250	250	100	100	$\Delta k/k = 2 \times 10^{-4}$

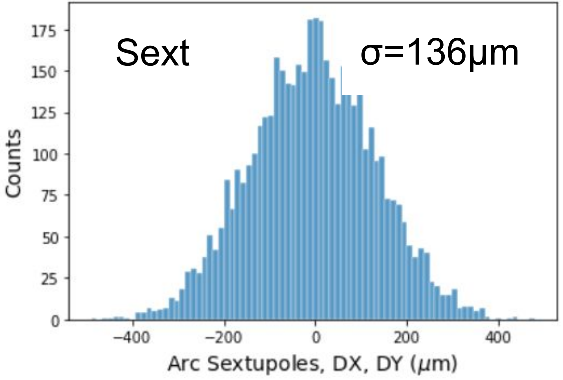
* misalignment relative to girder placement

Misalignments are randomly distributed via a Gaussian distribution, truncated at 2.5 sigma.

This table is not the final set of tolerances.

Distributions of arc quadrupoles and sextupoles, total DX and DX misalignments:



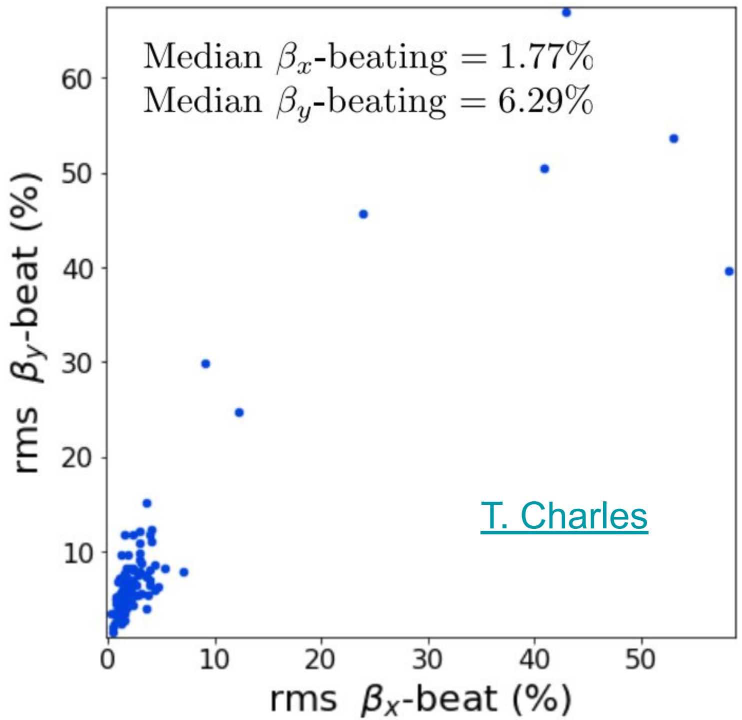


Global optics and emittances OK after tuning but difficulties encountered when doing the chromaticity correction, giving also very low DA.

Assumption: 10 μm after beam-based alignment

Type	ΔX (μm)	ΔY (μm)
Arc quadrupole*	50	50
Arc sextupoles*	10	10
Dipoles	1000	1000
Girders	150	150
IR quadrupole	100	100
IR sextupoles	10	10

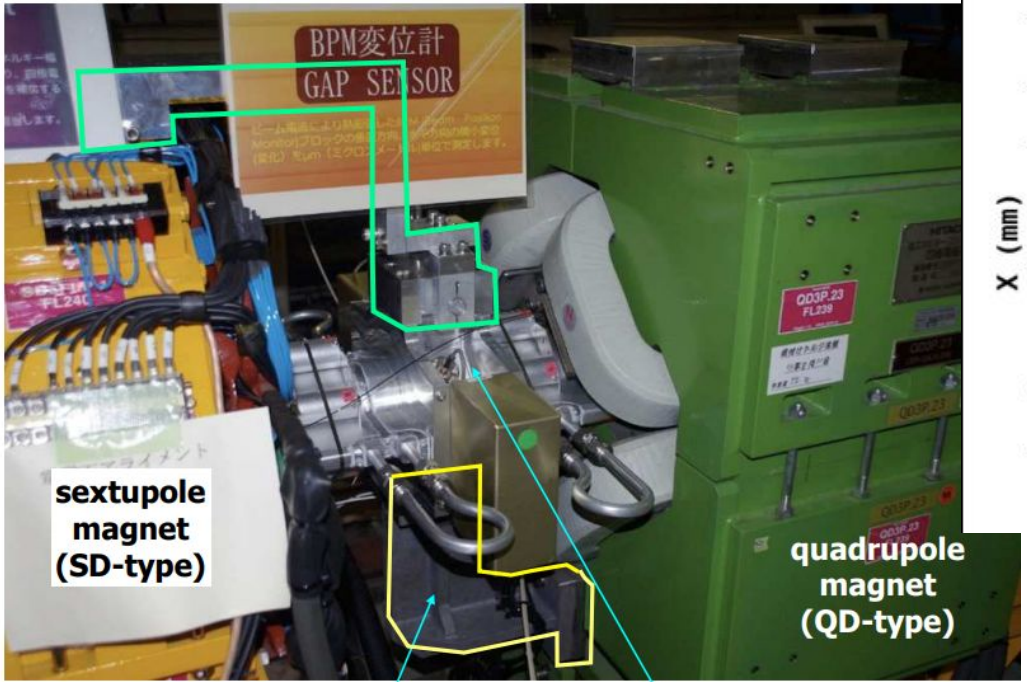
Assuming beam-based alignment possibly with movers+BPMs+displacement sensors (**design concept needed to reach 10 μm and better**).

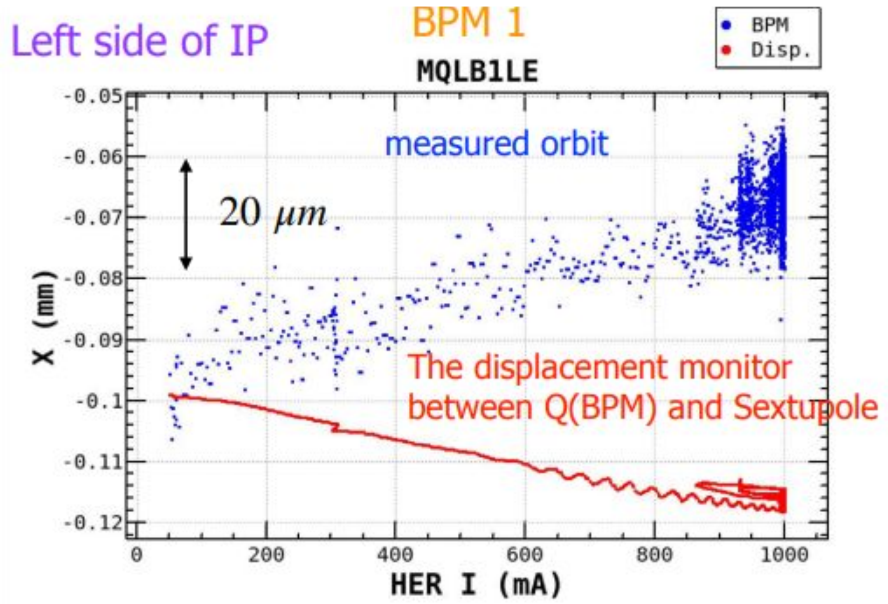


Very promising improvement in the tuning of the FCC-ee linear optics, including chromaticity correction. To-do: include BPM alignment errors, IP tuning, DA & lifetime optimization. Yet, need to monitor IR sextupole drifts at 1μm level.

BPM and Displacement Monitor (Gap Sensor)

BPM is fixed at quadrupole magnet and displacement monitor measures a relative deviation (horizontal and vertical) between the BPM and the sextupole magnet.





Y. Onishi's slides in BI workshop

The support arm fixes the alignment of BPM and quadrupole magnet.

BPM

Reliability of movers and gap sensors challenging.

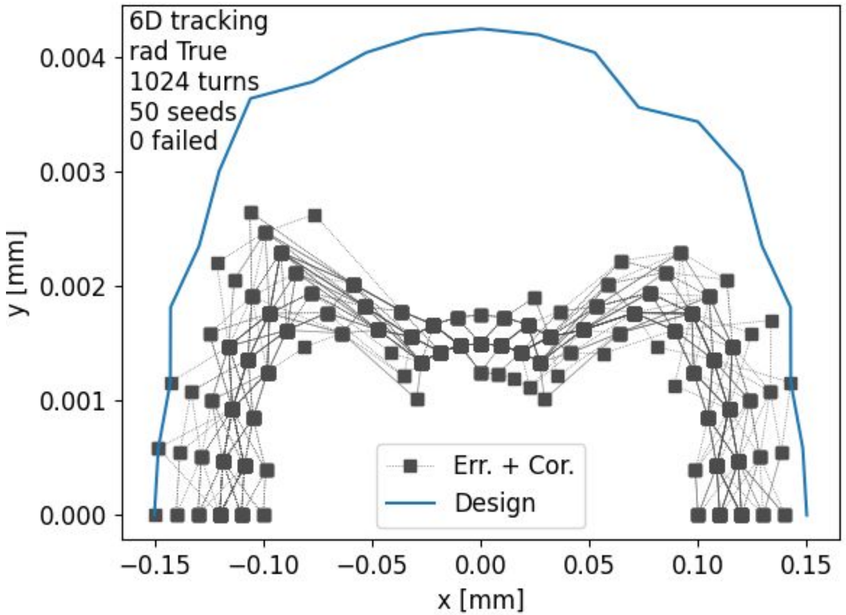
→***Need thorough engineering for FCC-ee at 1um in the IR!!!!***

Tuning simulations with pyAT (S. Liuzzo & A. Franchi)

Lattice: FCC-ee V22 Z

Assuming just 10 μm H&V alignment errors in **arc** quadrupoles and sextupoles and performing orbit and linear optics corrections:

	Unit	Before corr. H	Before corr. V	After corr. H	After corr. V
$\Delta\beta/\beta_{rms}$	%	3.6	59.5	0.8	4.3
$\Delta\eta_{rms}$	mm	120	82.6	26.0	9.4
$\Delta\epsilon_{h,v}$	pm	-	-	3.1	0.17
Orbit rms	μm	631	289	29.8	12.0



Linear optics and emittances are successfully corrected, yet, even with just 10 μm errors in arcs, DA gets severely reduced (IP parameters have not been checked yet)

→*The challenge is confirmed with pyAT simulations*

Comparison to Pantaleo's new lattice proposal (S. Liuzzo)

	$\Delta\beta/\beta$		$\Delta\eta$		$\Delta\epsilon$	
	H	V	H	V	V	
criteria	1 %	1 %	1 mm	0.05 mm	1‰ ϵ_h	
arc sextupoles tolerances [μm]						Tunes
V22@Z	19	10	4	30	40	(0.26, 0.38)
HFD51@Z	59	45	8	>100	»100	(0.22, 0.32)
V22@t	10	8	8	85	15	(0.26, 0.38)
HFD51@t	19	10	10	»100	32	(0.24, 0.31)

At Z, Pantaelo's lattice features arc sextupole alignment tolerances larger by a factor 2 at least.
Nevertheless, at tt the gain seems to be lower, below a factor 2.
See Pantaleo's presentation this Thursday.

New misliagments proposal in the midterm report

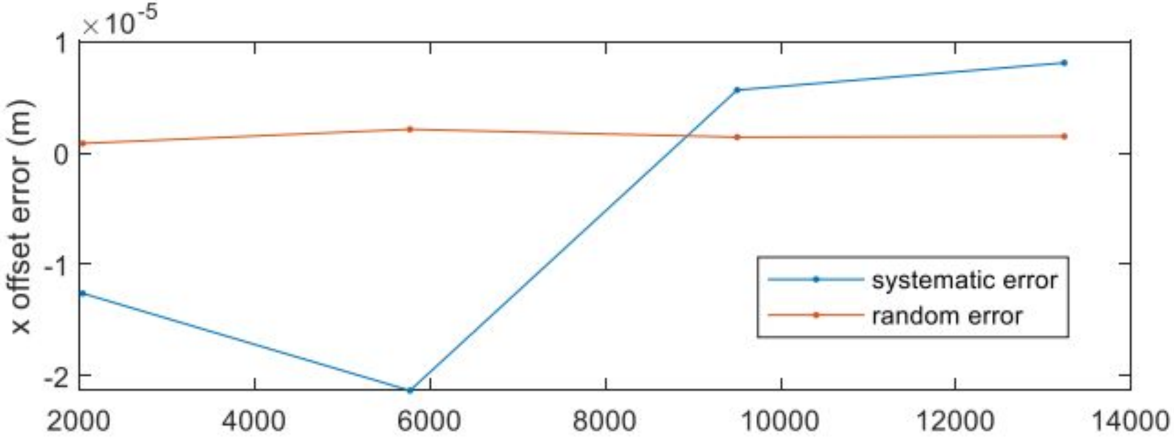
Initial Mechanical alignment		
Length scale	tolerance	
6	20 to 50 um	mechanical installation tolerance of components on quad/sext girder - main issue is corrector and
50	200 um	mechnical installation and alignment of girder to girder - need to be able to transport first beam
200	500 um	mechnical installation
1000	2 mm	mechnical installation smoothed around the ring
10000	5 mm	Installation tolerance based on surface alignment network and GPS

Significantly larger than assumed so far. First simulations with larger errors show poorer tuning performance both in the collider and the booster: 14th Sept

Length correlations assigned to a closed ring similarly as to Perlin noise, see implementation in Michael’s slides.

Beam-Based Alignment (BBA) performance?

Advanced BBA techniques are simulated in [Xiaobiao's slide](), including quad modulation of dk/k =1%, BPM reading error of 1um, alignment error 0.2mm,

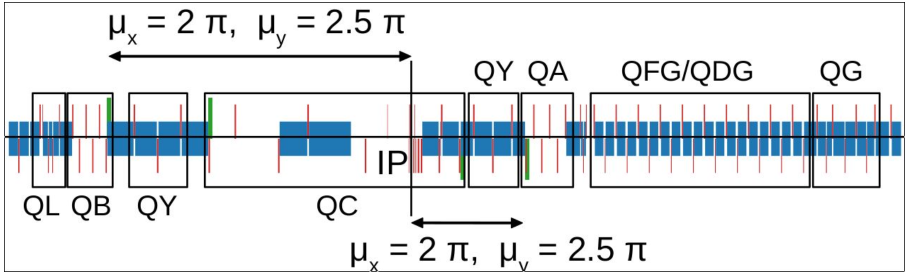


Achieved performance is 50um when using 8 quads at same time and 20um when using 4 quads. Source of uncertainty is the lack of knowledge of entrance angles of the beam at quadrupoles. Further improvements are needed!

First magnetic field quality tolerances (E. Ahmadi)

Lattice: FCC-ee V22, errors are in 10^{-4} @ 10mm

Error & maget type	Z	tt
b_3 in arc dipoles	2	2
b_3 in IR dipoles	0.1	0.5
b_3 in arc quadrupoles	10	8
b_3 in QY	0.1	8
b_3 in QC, QT, QA, QB, QG, QH, QL, QR, QU, QI	1	8
a_3 in QC1, QC2	1	5
b_4 in arc quadrupoles	10	10
b_4 in QC, QY	0.01-0.1	0.1
b_4 in QT, QA, QB, QG, QH, QL, QR, QU, QI	1	1
b_6 in arc quadrupoles	5	5
b_6 in IR quadrupoles	0.01	1



Tolerances based on DA calculations without SR (pessimistic):

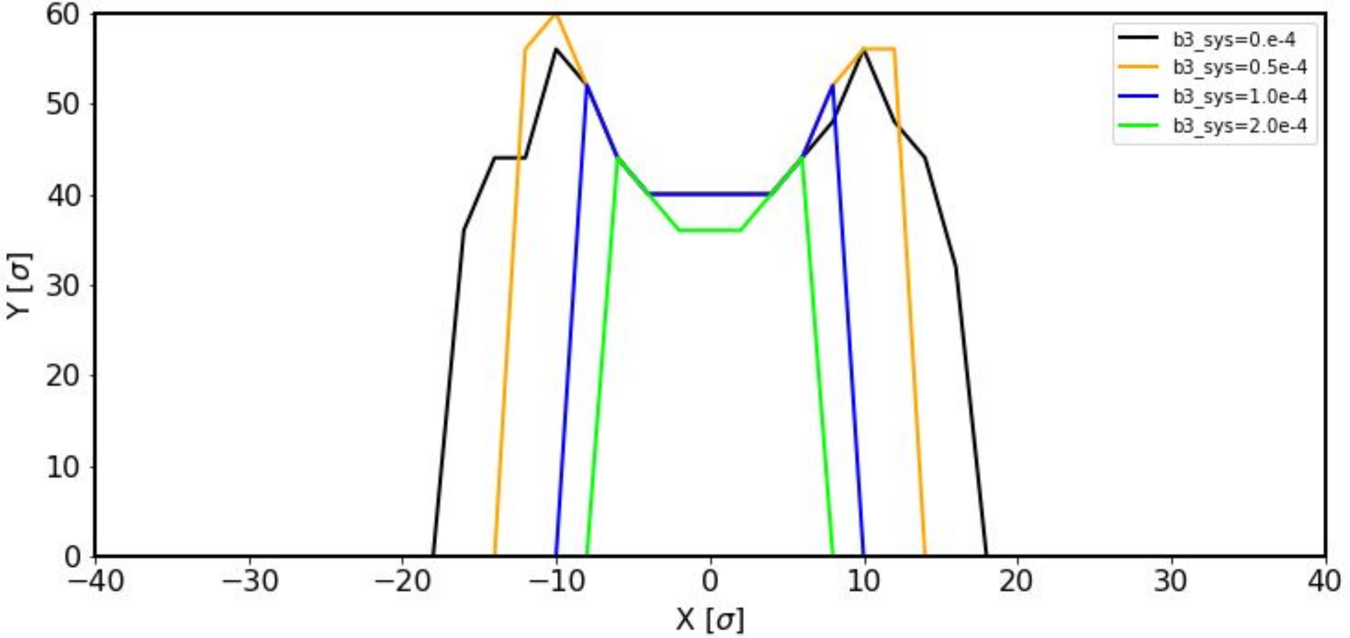
- Arc magnet field quality can be met.
- IR magnet field quality, specially QC and QY is challenging (even measuring 0.01 units is a challenge!).
- Z clearly more challenging

→*Need to include SR in calculations*

→*Corrector circuits in the IR?*

First magnetic field quality tolerances **with SR** (A. Hussain)

Scan of sextupolar components in **arc dipoles (b3)** in the range 0-2 10^{-4} units.



Both systematic and random dipole b3 cause significant loss of DA with b3=0.5x10^{-4} units !! Will we need correctors?

Parameter evolution of Z baseline in 2023

	Qx	**Qy**	**Qy-Qx**	**β^*y [mm]**
February	214.26	214.38	**0**.120	0.8
April	214.129	214.2	**0**.071	0.8
June	218.158	222.2	**4**.042	0.7

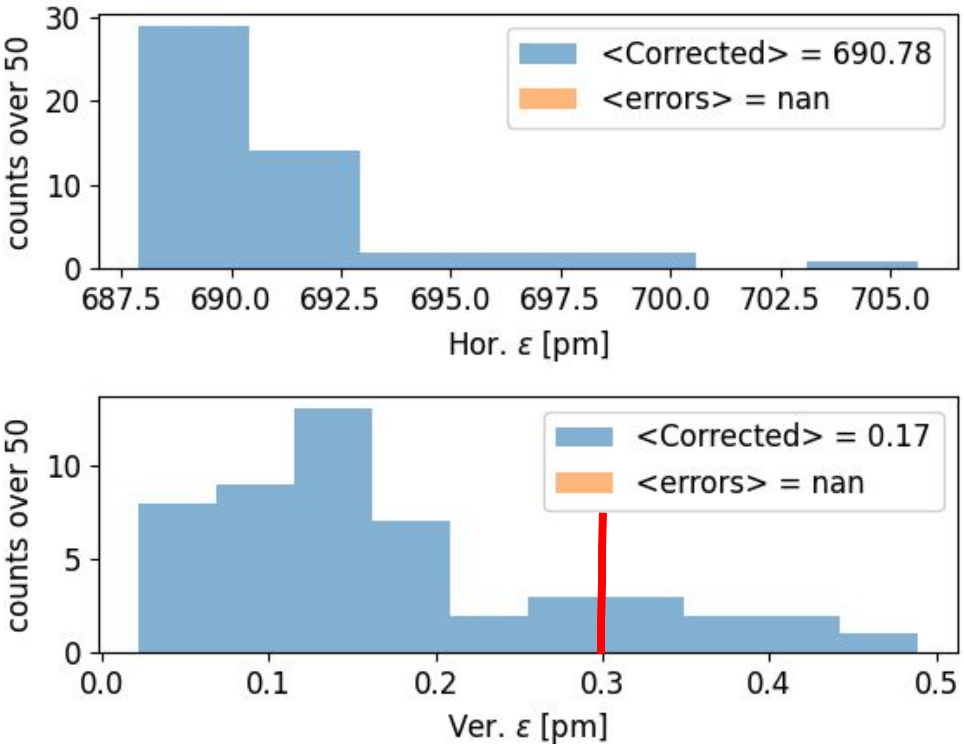
See Oide-san's presentations in the FCCee optics meetings: https://indico.cern.ch/category/6528/

Latest tunes are closer to integer resonances by about factor 2 and closer to coupling resonance by about factor 3. Sensitivities to errors will change accordingly.
Change in the integer tune split affects coupling correctability. Lower β^*y…

In addition margin for V emittance from lattice errors has been reduced to **0.3 pm.**

→*Need to redo previous simulations*

Illustrating margin of 0.3 pm on previous simulations



Updated plots from [Simones's slides]

εy/εx = 0.0004

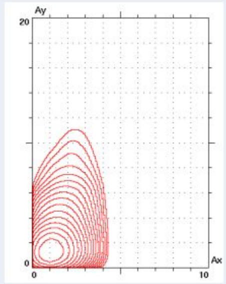
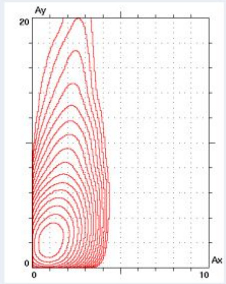
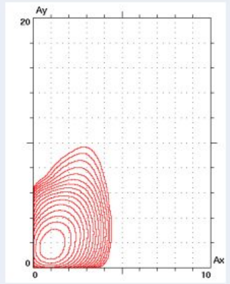
Current record in ALS = 0.0001 ([PRST-AB 2011])

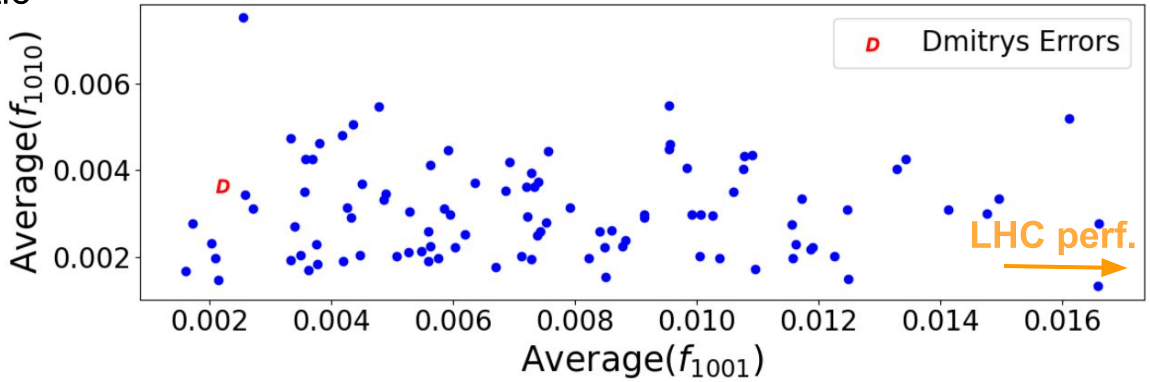
About 16% of seeds would not meet new margin in these simulations with only 10 µm misalignment errors in the arc magnets. New tunes likely to deteriorate this…

Coupling studies

- Dmitry concluded that vertical misalignments of about 10 µm in arc sextupoles can be tolerated without corrections from beam-beam studies (see slides)
- This generates coupling resonance terms about factor 10 lower than in LHC after correction (see M. Hofer's slides).
- Need to ensure improved coupling measurement and correction wrt LHC→BPM resolution, tilts, systematic errors, machine drifts, etc.

In general, all measurement techniques have to be reviewed to include systematics from SR effects and to define specs.

Misalignments	OFF	X and Y	
Beamstrahlung	ON		OFF
L / IP [10^{36}]	0.95	~ 0.5	0.8
Lifetime (bb) [min.]	35	4	> 600
Density contour plots			



Summary & Outlook

The FCC-ee performance with realistic errors is one of the fundamental questions to answer by 2025.

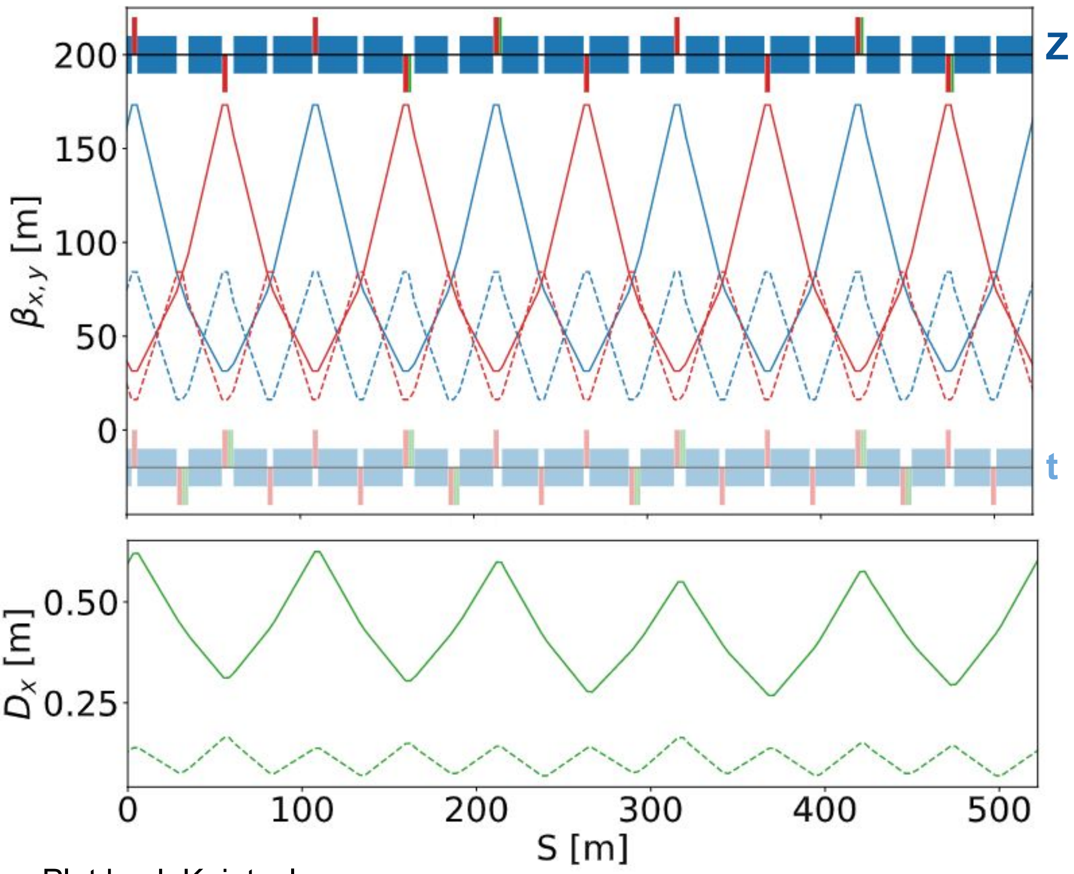
Excellent progress in the last year in identifying key problems, tools and progress with simulations and new concepts.

Lots of challenges ahead!!!

Synergies with CEPC should be exploited. Could someone apply same tuning simulations for both machines for comparison?

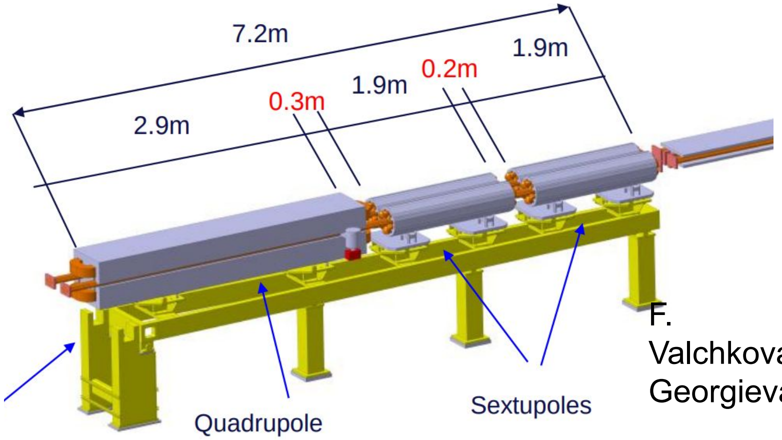
Back-up slides

FCC-ee FODO super-cell and correctors at **t** and **Z**



Plot by J. Keintzel

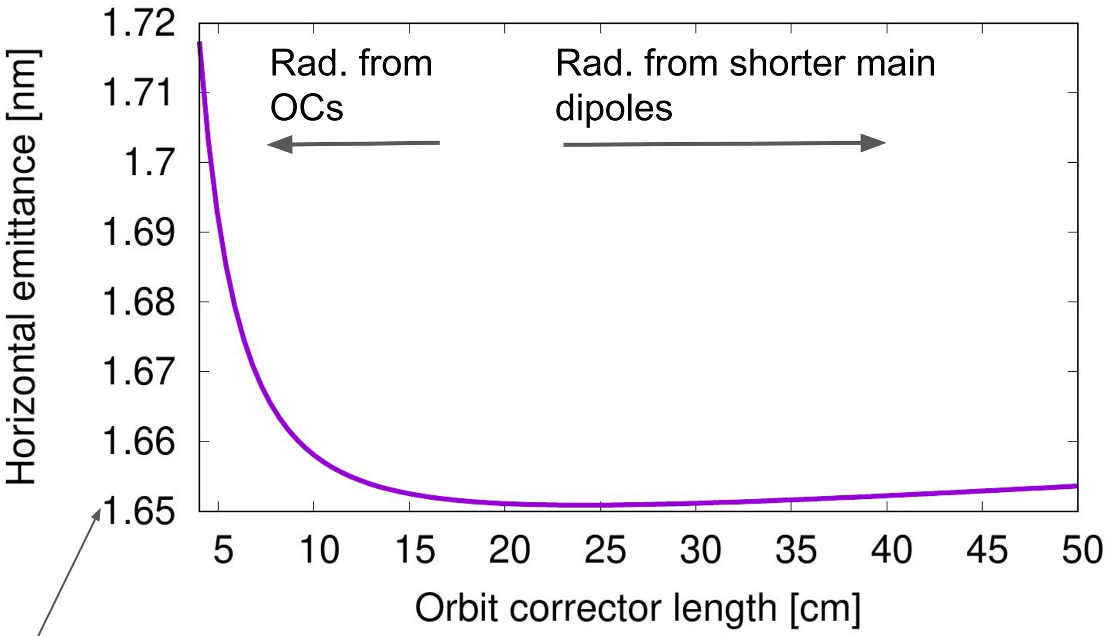
-Lattice orbit correctors and skew quadrupoles are assumed to be placed at sextupoles (with extra coils).
-At **t** only 2 over 5 quads have sextupoles attached (at most 1 over 2 if **Z** sexts are kept).
-Current tuning simulations assume one orbit corrector at every quadrupole → Need to add correctors or demonstrate tuning with fewer correctors



F. Valchkova-Georgieva

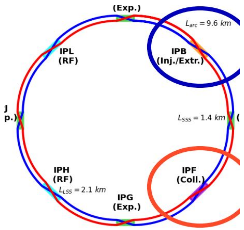
Orbit corrector length

Optimum corrector length is 25cm (10cm maybe still OK). Further studies needed.

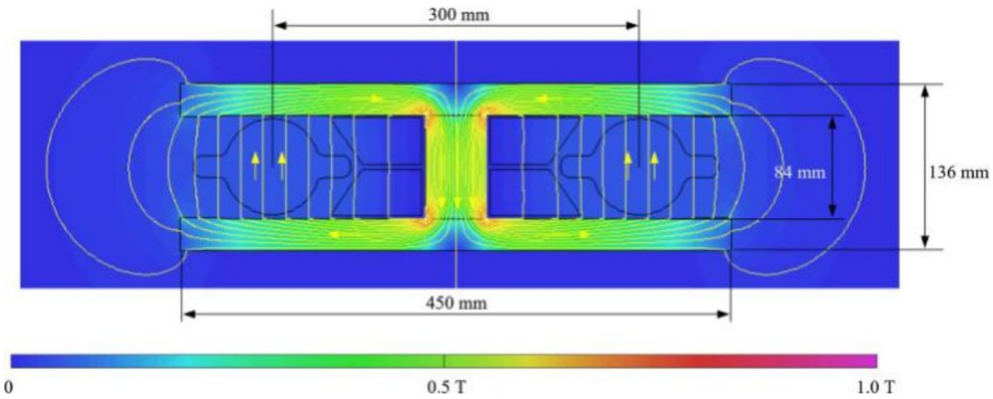


Actual value of emittance not representative as it is just for one tuned seed.

Dipoles

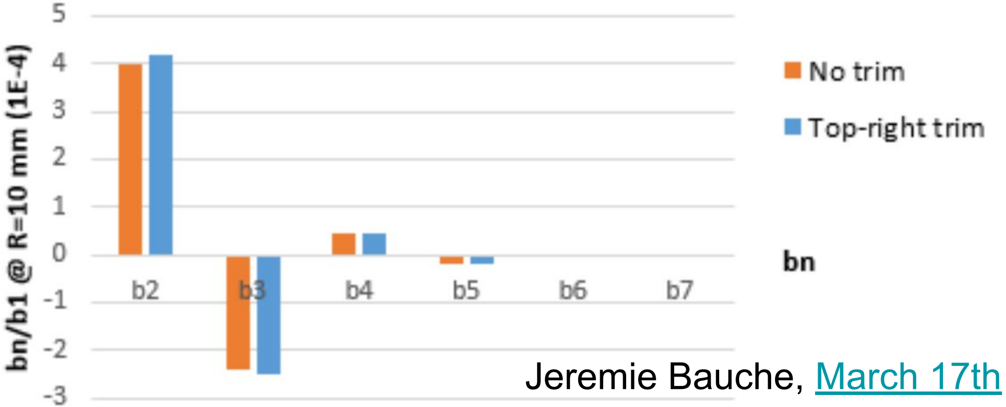


- Need to converge on tapering design (how many FODO per tapering unit? 4?)
- Need to consider **b2 of 4 units** (sign changing arc-by-arc)
- **b3 of 2 units**: Causes 10 units of chroma at **tt** and **70** at **Z**. Impact on DA, lifetime and tuning?



Magnetic model cross-section (CDR), B_0 max = 57 mT

Strength, 45.6 GeV–182.5 GeV	mT	14.1–56.6
Magnetic length	m	21.94/23.94
Number of units per ring		2900
Aperture (horizontal × vertical)	mm	130 × 84
Good field region (GFR) in horizontal plane	mm	±10
Field quality in GFR (not counting quadrupole term)	10^{-4}	≈1



Jeremie Bauche, March 17th

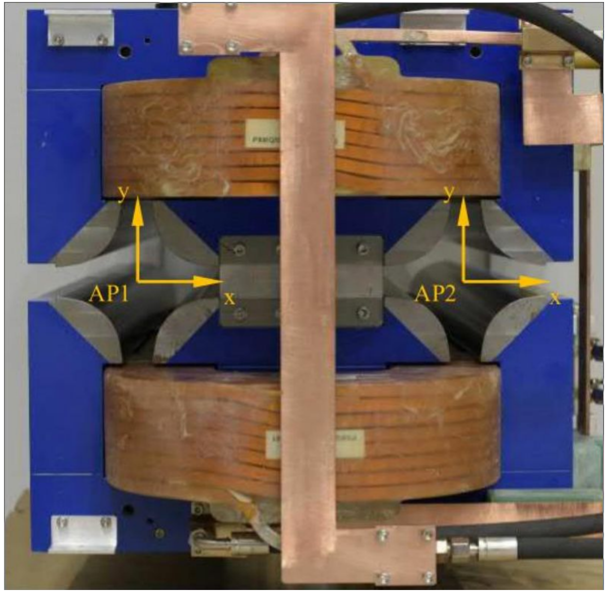
Dipole b2 errors

Tessa's slides: Systematic b2 in dipoles does not affect resulting emittance after tuning (no chroma. corr.) but need more iterations (19 seeds did not converge for lack of CPU time). DA not checked.

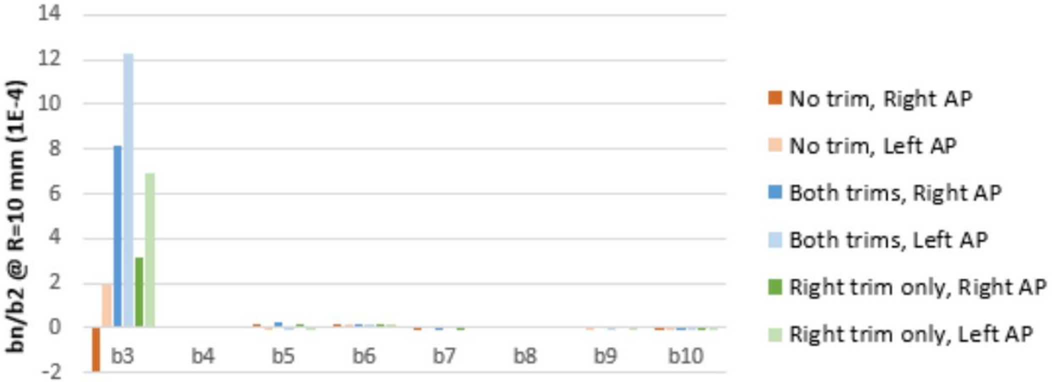
Cristobal's slides: b2=4 units generates above 2% beta-beating. 1.6 units needed to get 1% beta-beating. Yet arc/IR optics rematching can absorb the b2 errors, see Cristobal's slides this Thursday.

Quadrupole

- Measured shift of quadrupole centers separation by **0.4mm** between **Z** and **t** operation. This is not seen in simulations.
- Independent powering of apertures (for tapering or tuning) challenging: induced quadrupole offsets (**0.2mm**) and large **b3 (10 units).** As expected from simulations.

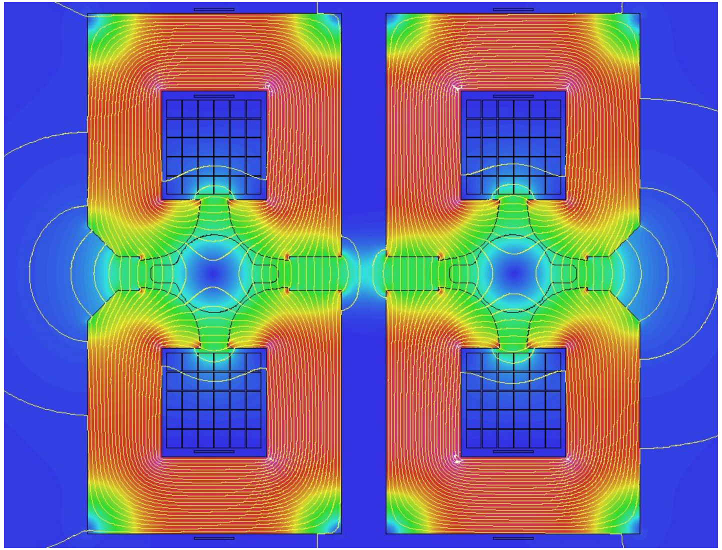


Jeremie Bauche, [March 17th]



New quadrupole design

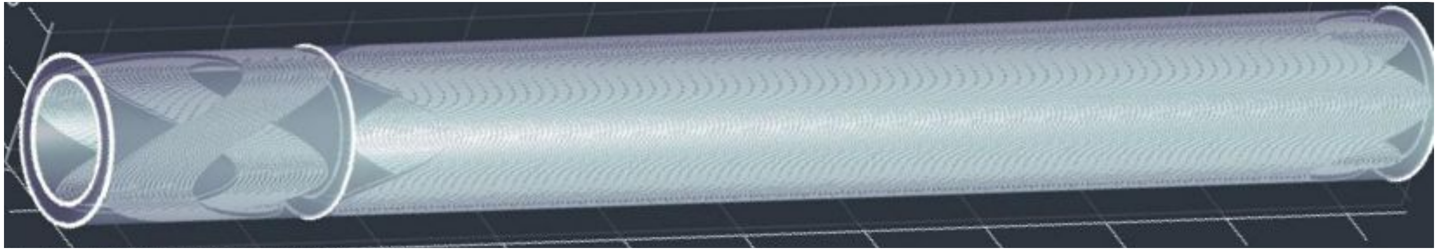
- Prototype not yet manufactured. Field offsets between **Z** and **t** for new design **unknown**.
- Independent powering of apertures (for tapering or tuning): induced quadrupole offsets reduced (**0.03mm**), as well as **b3 (2 units)** →**Field quality OK**
- Jeremie requested an increase of beams separation from 300mm to 350mm in the [160th FCC-ee design meeting](), approved, that should reduce aperture cross talk and improve field quality.



Jeremie Bauche, [FCC week 2022]()

Superconducting Short Straight Section

Mike's slides



- Possibility to put 2 or 3 layers of SC magnets to include: Dipole, Quad, sextupoles and correctors.
- This reduces SR power → First lattice design by Cristobal in EPFL-LPAP activity meeting
- No space limitations for correctors.
- Magnetic field quality to be assessed.

T. Charles, March 2022

H. Mainaud, 10 Feb: *"The actual value of tolerances will not be the cost driver, being 'size' the main driver."*

Factor 2 lower tolerances should be considered (at least).

RMS misalignment and field errors tolerances:

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
Arc quadrupole*	50	50	300	150	70	70
Arc sextupoles*	50	50	300	150	70	70
Dipoles	1000	1000	300	1000		
Girders	150	150	-	1000		
IR quadrupole	100	100	250	200	70	70
IR sextupoles	100	100	250	200	70	70

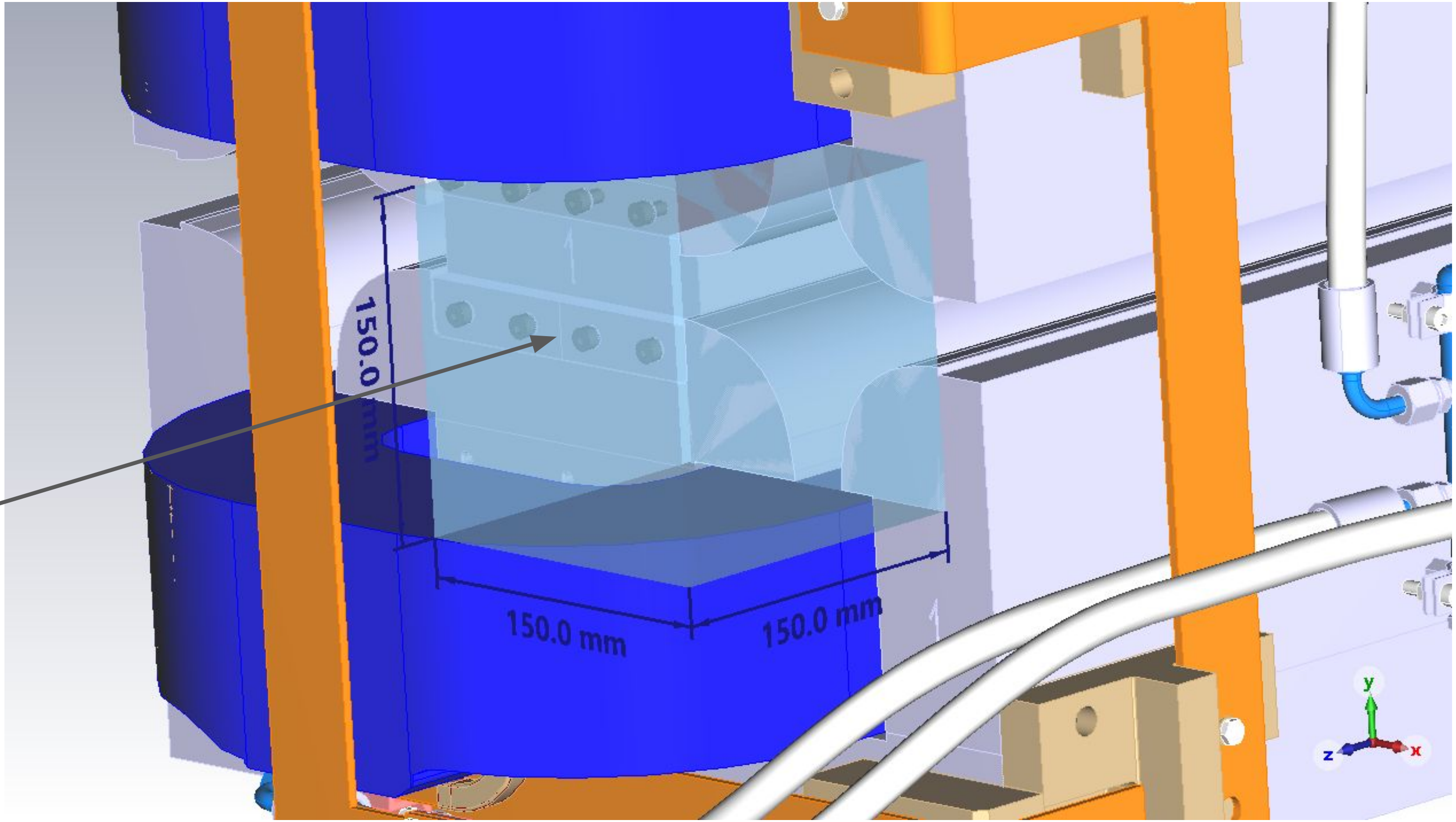
* misalignments relative to girder placement

Type	Field Errors
Arc quadrupole*	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	$\Delta B/B = 1 \times 10^{-4}$
Girders	-
IR quadrupole	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	$\Delta k/k = 2 \times 10^{-4}$

Only non-linear error so far: arc sextupole strengths.

Note: BPM errors not included

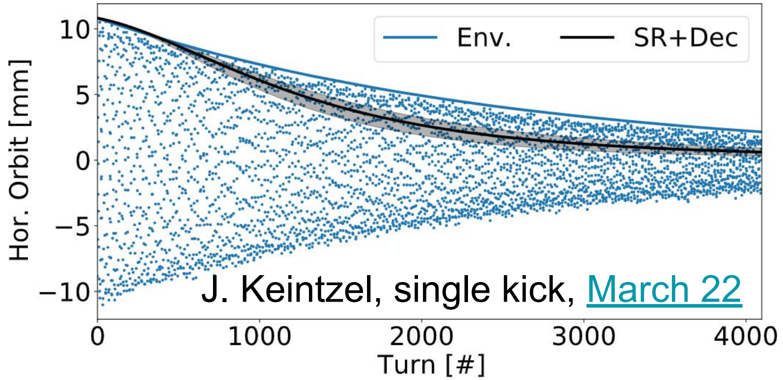
BPMs fit in the quadrupoles (M. Wendt, April 22)



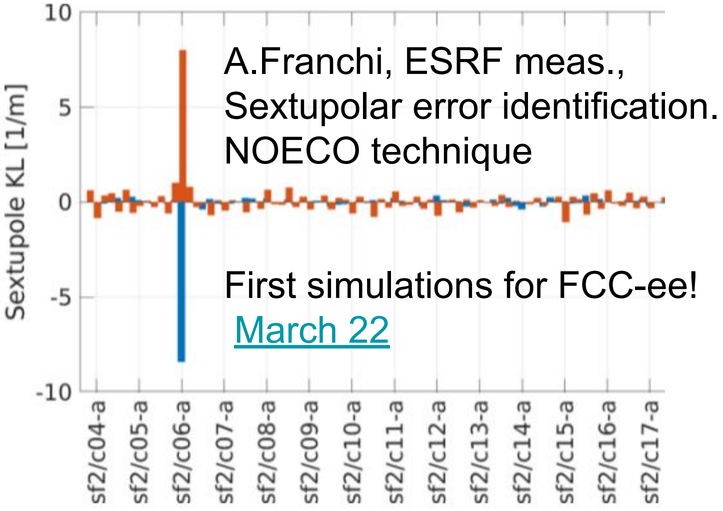
BPM fits in
this blue box

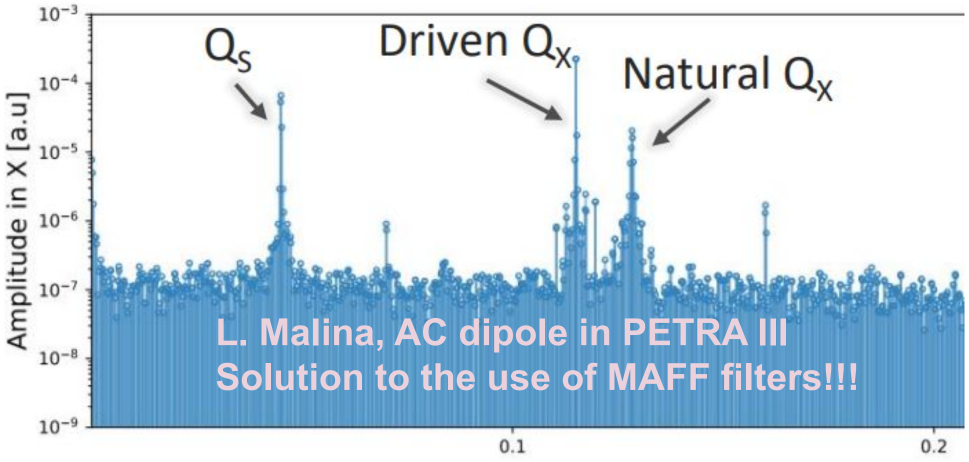
Optics measurements in FCC-ee

- Current tuning simulations assume ideal optics measurements
- Large energy loss in FCC-ee, fast damping or chromaticity may induce systematic errors in all techniques: single kick, AC dipole, NOECO and LOCO-like



For LOCO-like: see S. Liuzzo's presentation today





Single kick feasibility at Z and Top

J. Keintzel's poster

While the single kick technique is appropriate for the Z energy it is not feasible at the Top for the too fast damping.

Need to study AC dipole and ORM or LOCO at the Top energy!

(teams at DESY, ESRF & CERN already at it!)