News from the Tuning Working Group

J. Keintzel and R. Tomas

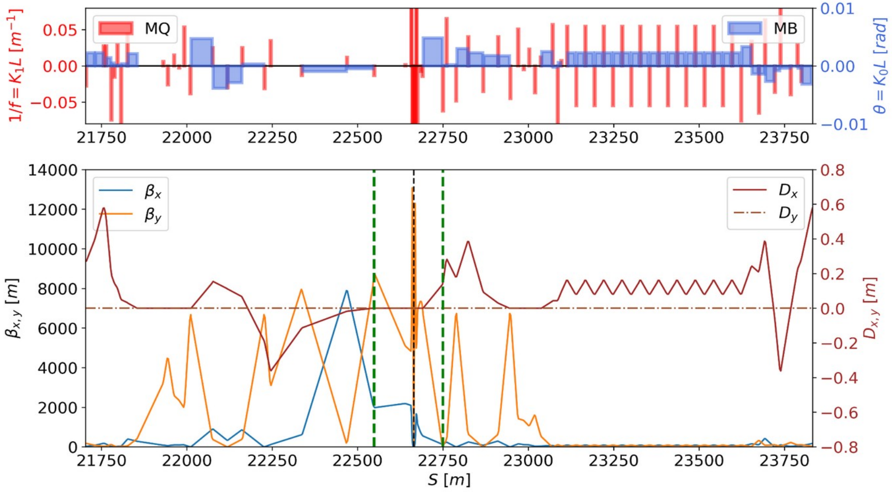
For the FCCee Optics tuning WG

FCC-ee Accelerator Design Meeting

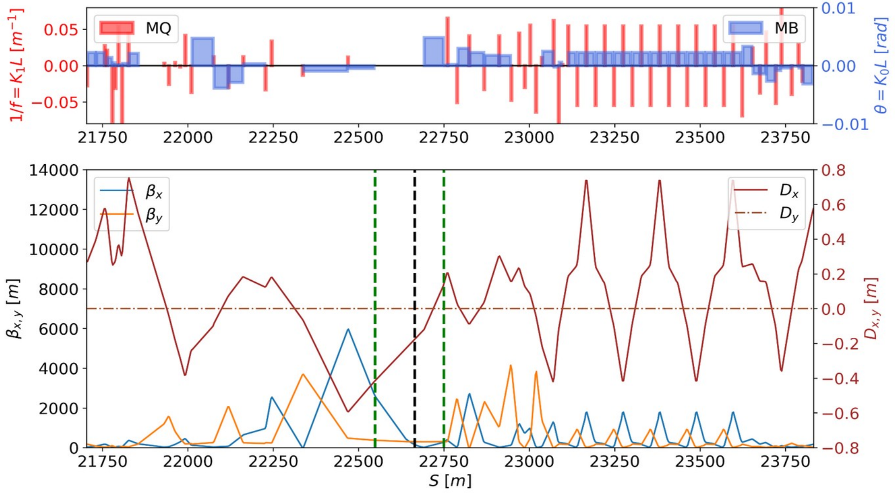
27 November 2024

Ballistic Optics: Turn off quads 200 m around IP & all IR sextupoles

Baseline lattice K. Oide



Ballistic lattice C. Garcia

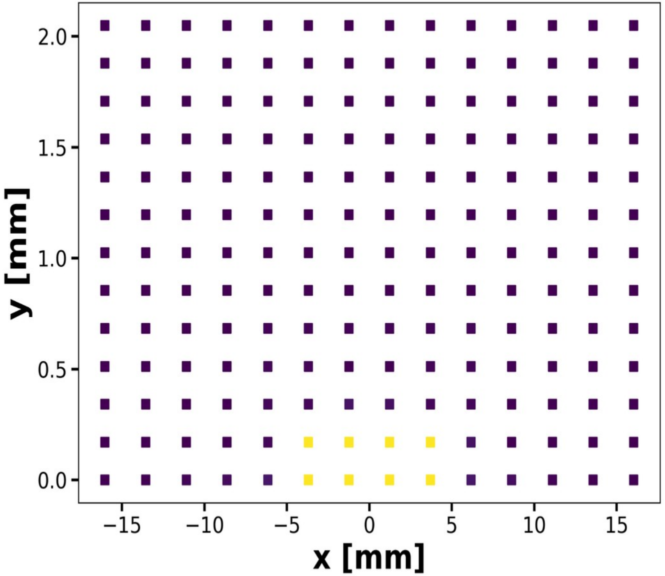


Merits of the ballistic optics: Reduce chromaticity, peak beta functions, IR aberrations, remove Synchrotron Radiation from Final Doublet, mitigate instabilities with reduced sextupole strength and establish a straight line reference trajectory around the IP.

→ *Ideal for the first commissioning phases*

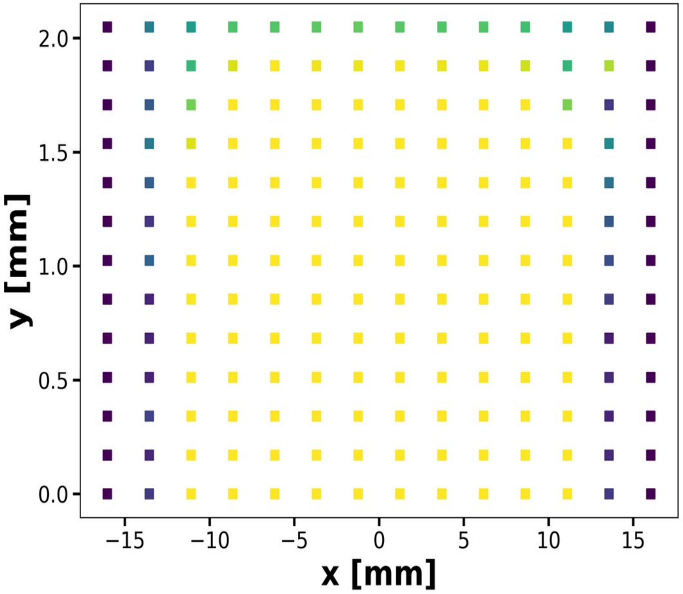
Ballistic Optics: Larger DA

Baseline lattice



Ballistic lattice

C. Garcia



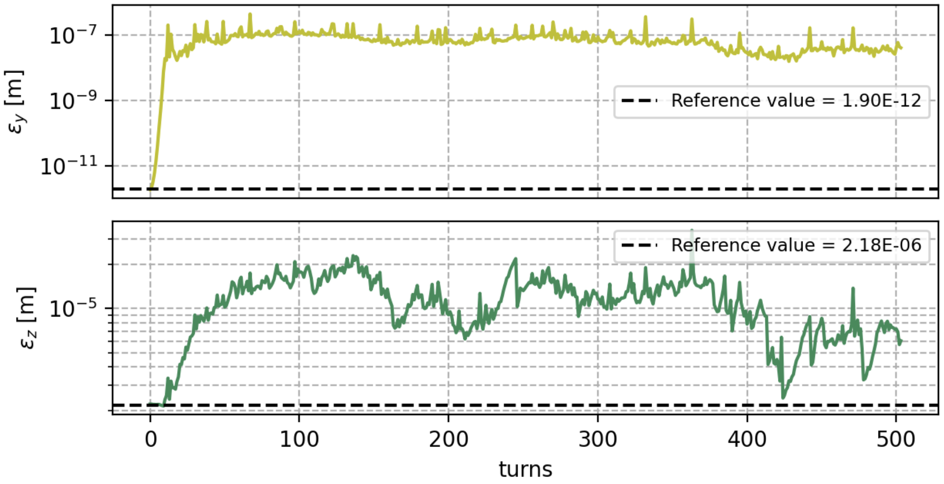
Larger DA with Ballistic optics by factors of 2 and 6 in x and y, respectively
Momentum acceptance for ballistic is sufficient but not yet as good as for the baseline (further optimizations on-going).

Ballistic optics: mitigation of instabilities with half sextupole strength

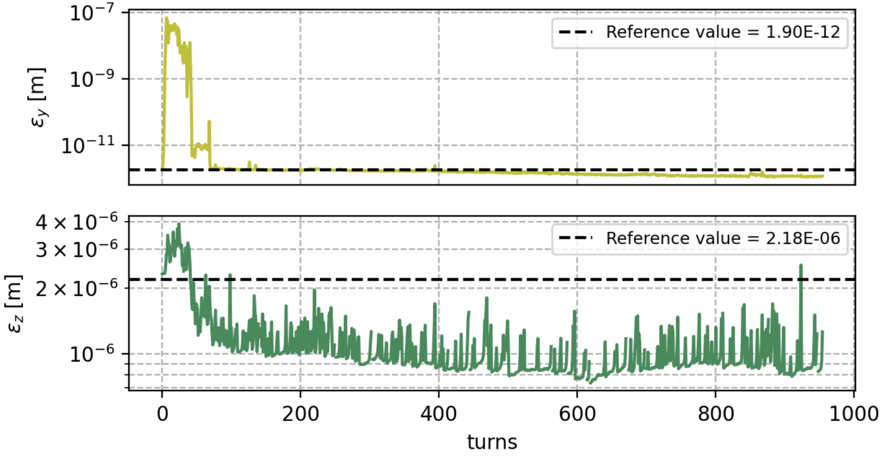
Relaxed lattice design by K. Oide

Tracking by K. Skoufaris

v24.3-GHC with relaxed β* =(33,0.7)cm



v23-GHC ballistic (alternative) β* = (151,300)m



First commissioning phases require lower sextupole strength, but this is impractical in the baseline optics (even with relaxed β*), while OK with ballistic.

Ideal commissioning sequence

With up to 60 bunches @ Z due to MP, A. Lechner et al

Ballistic optics

Orbit threading (Sexts Off) → Disp. free steering → Sexts On → LOCO corrections → Arc BBA → Optics corrections →

Relaxed optics (various iterations decreasing β*)

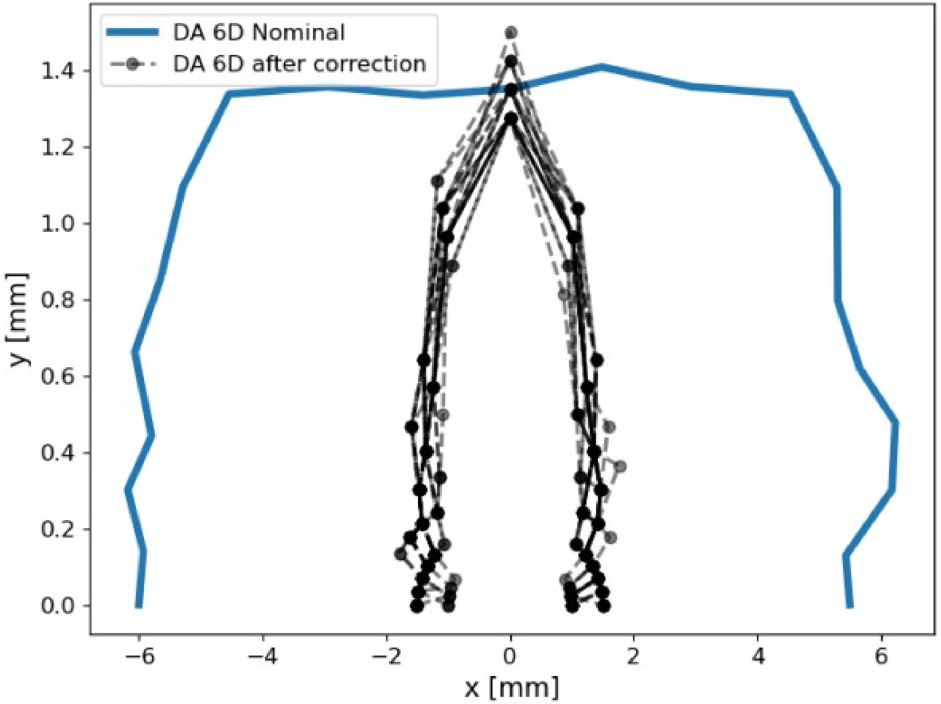
Orbit correction → IR + Arc BBA → Optics corrections → Non-linear optics corr. → IP tuning →

Baseline optics

Orbit correction → Optics corrections → Non-linear optics corr. → IP tuning → …

Commissioning: Ballistic after Dispersion Free Steering

Nominal errors including the initial BPM-to-Quad alignment of 100 μm.
Sextupoles Off

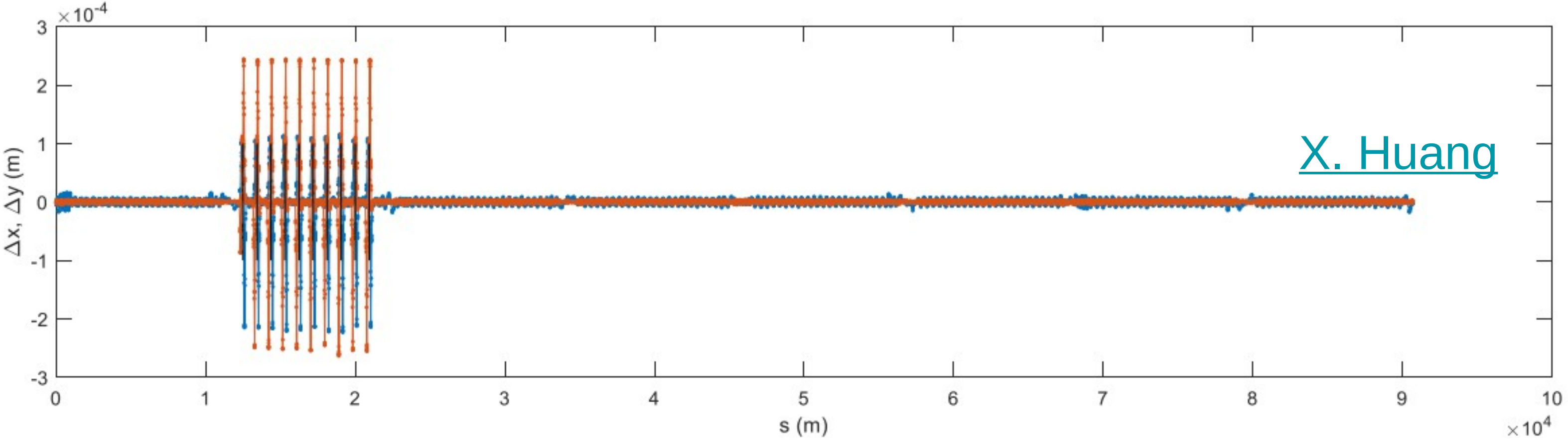


rms	**DFS**	**w/o DFS**
y orbit [μm]	255	222
ΔDx [mm]	70	446
ΔDy [mm]	39	416
ϵ_y [pm]	4	659

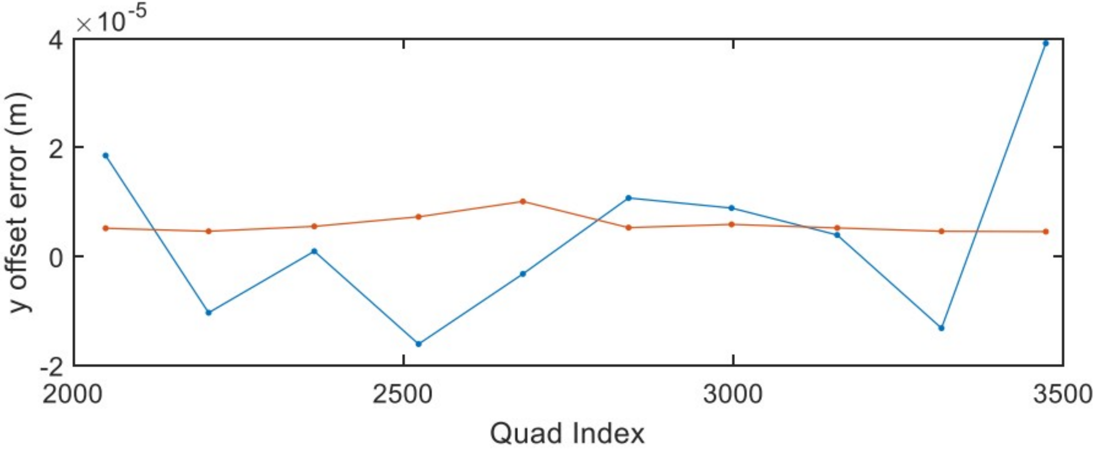
E. Musa

DFS is fundamental at this stage. Now it is possible to proceed to BBA and optics corrections.

BBA: Parallel Quadrupole Modulation - 1st technique



[X. Huang]

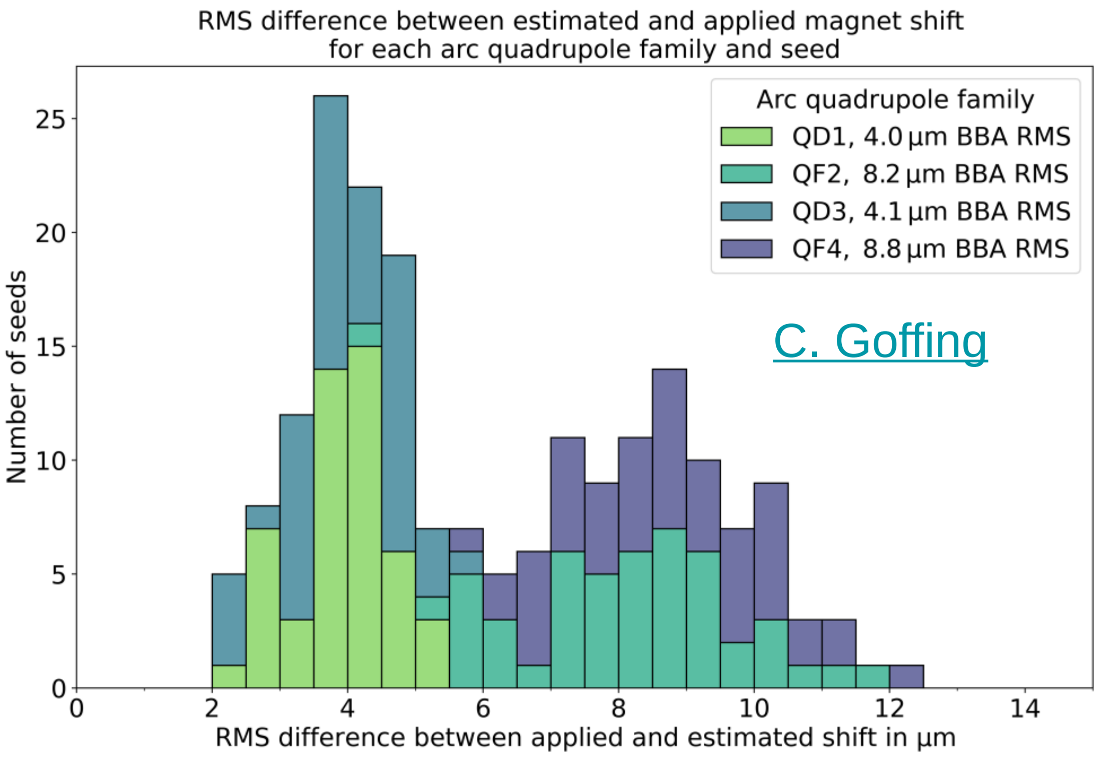


Orbit bumps at 10 quadrupoles that are modulated with $\Delta k/k=2\%$. Orbit response is used to deduce beam-quadrupole offset using a calibrated model.

BBA rms error of 10-20 μm.

Need about 400 modulations!

BBA: Parallel Quadrupole Modulation - 2nd technique



8 quadrupoles modulated with $\Delta k/k$=1%. Orbit corrector at quad used to minimize orbit response (no calibrated model used).

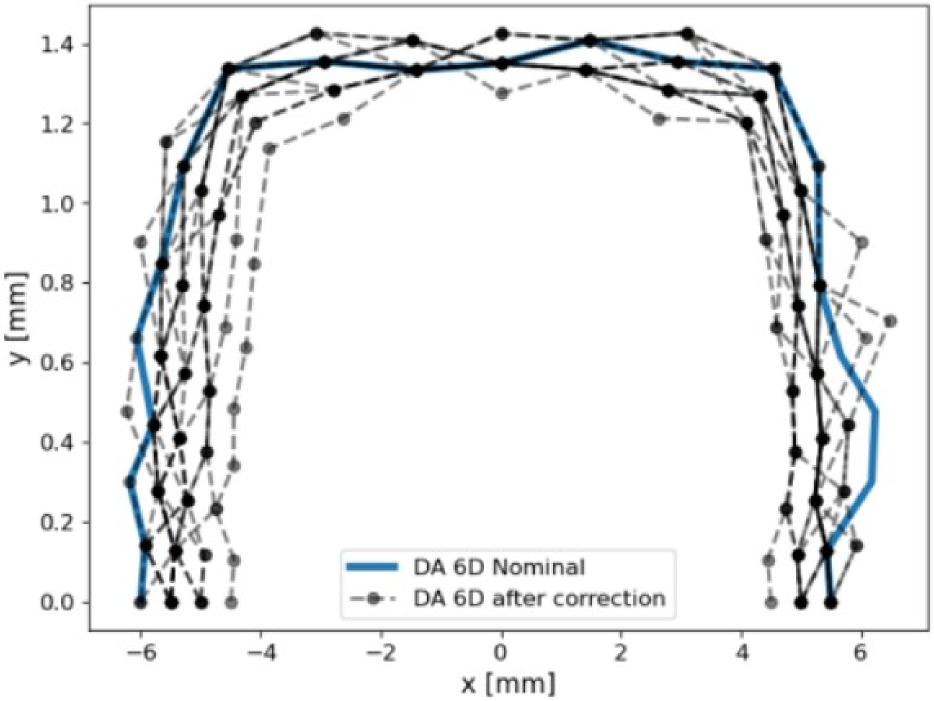
BBA rms errors of 4 µm in QD and 9 µm in QF.

Caveats:
- Only for vertical BBA
- Expected quad center shifts of 3 µm when modulating by 1% should increase BBA rms error.
- BBA reproducibility in SuperKEKB ≈100µm (orbit drifts?)

https://indico.cern.ch/event/1403458/

Commissioning: Ballistic after BBA and optics corrections

Nominal errors including **IR quads misalignments of 50 µm** and BPM-to-Quad alignment of 10 µm thanks to BBA. Sextupoles On.

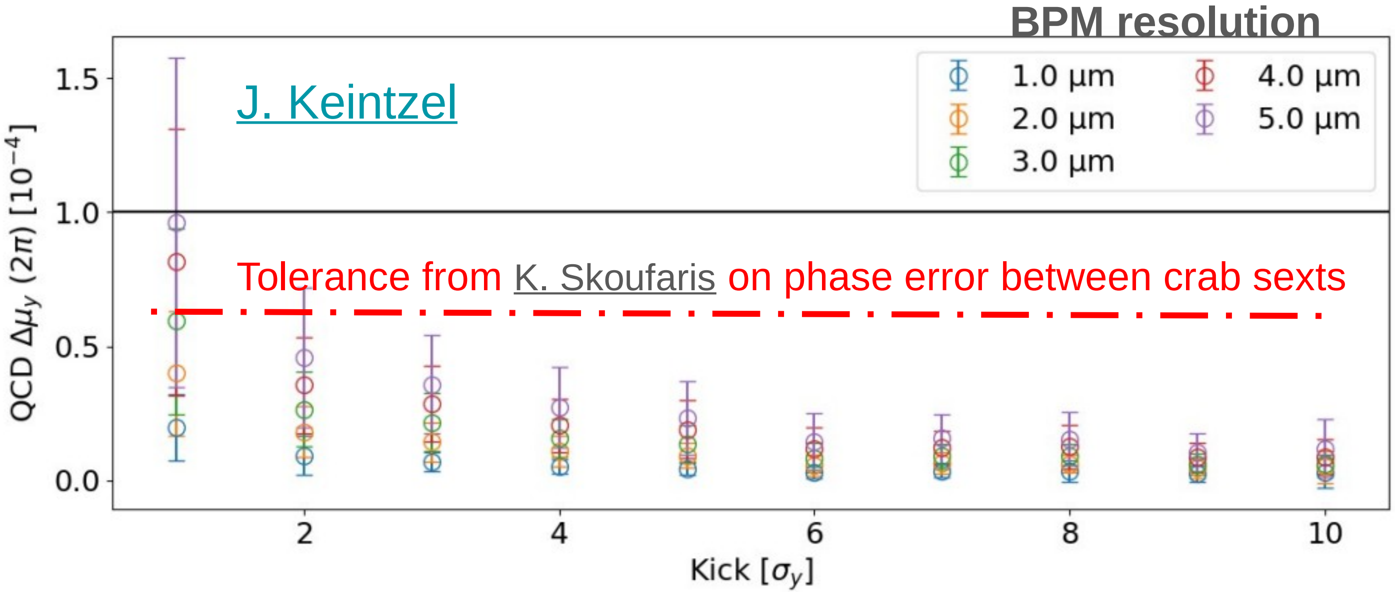


rms	
y orbit [µm]	155
ΔDx [mm]	0.9
ΔDy [mm]	1.7
ϵ_y [pm]	0.3

E. Musa

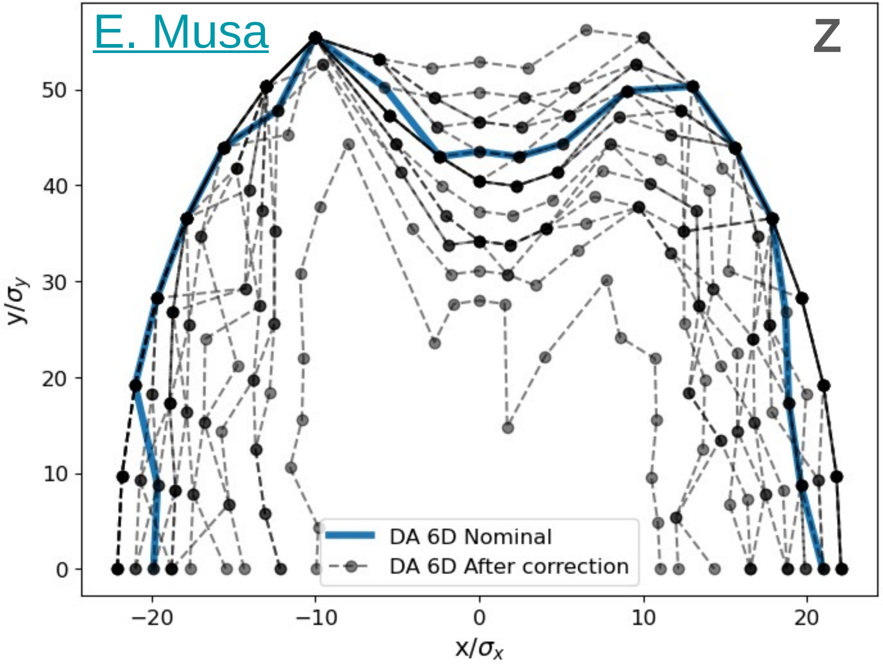
Success even including IR errors!
3 seeds failed out of 20 → More iterations needed and maybe better ballistic optics.

Optics measurements: Phase advance



Simulations show that good phase advance measurements require 50000 turns of forced betatron motion using AC dipoles at 1σ amplitude and BPMs with about 1 µm resolution in turn-by-turn mode (baseline optics).

Optics corrections with baseline optics and arc nominal errors

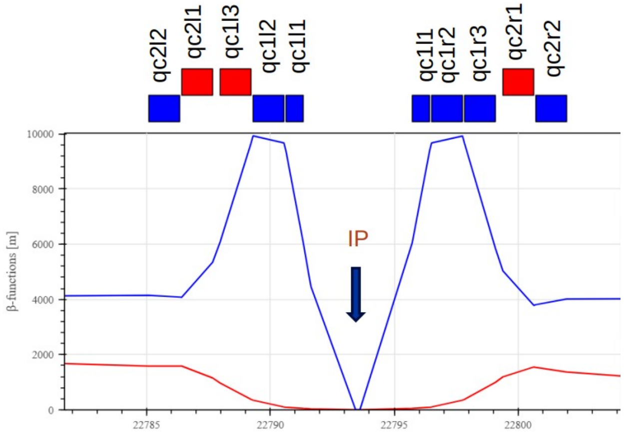


rms	
y orbit [μm]	37
Δβ/βx [%]	1.3
Δβ/βy [%]	13
ΔDx [mm]	15
ΔDy [mm]	0.9
ϵy [pm]	0.04

Best tuning results obtained so far with baseline optics and arc nominal errors.

BPM to quad misalignment of 10 μm after BBA currently being included in simulations.

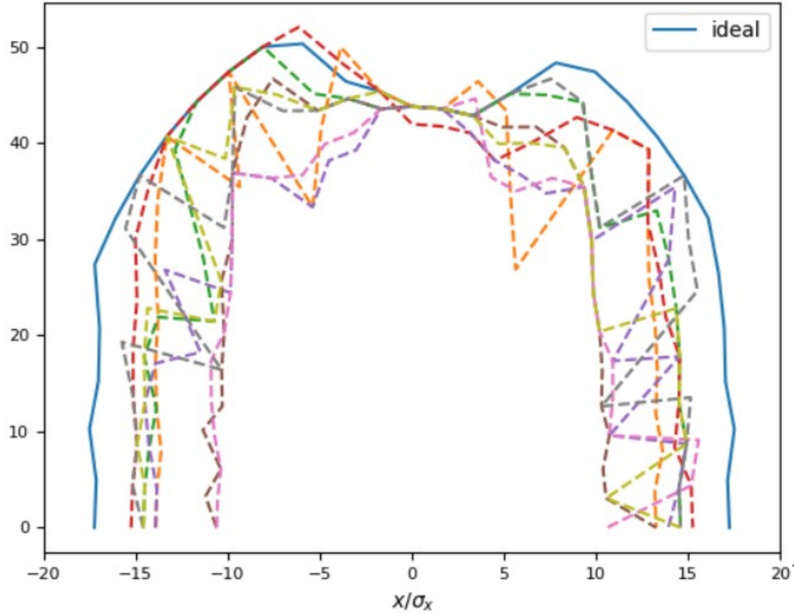
First look at IR errors S. Jagabathuni



Type	Δx (μm)	Δy (μm)	Rotation (μrad)
Arc quadrpoles	100	100	100
Arc sextupoles	100	100	100
IR quadrupoles with. FF-doublets qc[12]*	40/60 10	40/60 10	40/60 10
IR sextupoles	40/60	40/60	40/60
All Dipoles	1000	1000	100

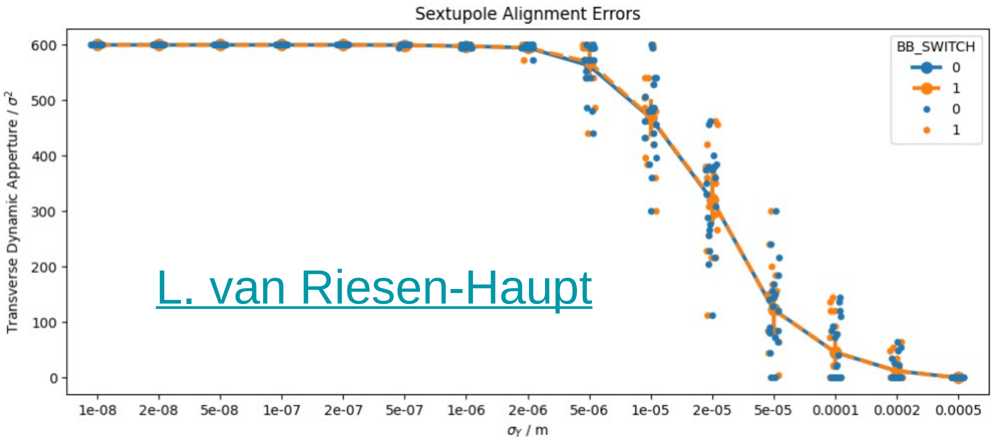
Successful tuning simulations are achieved for the GHC v22 lattice with 60 μm errors in the IR magnets and 10 μm in the Final Doublet (arc errors are slightly lower than nominal).

First IP tuning with knobs also demonstrated in other studies by S. Jagabathuni. First ML luminosity tuning studies by V. Gawas.

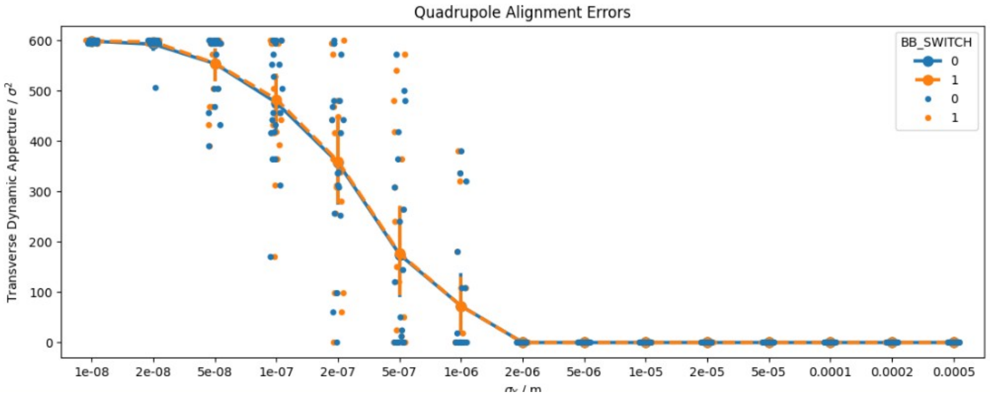


DA with beam-beam

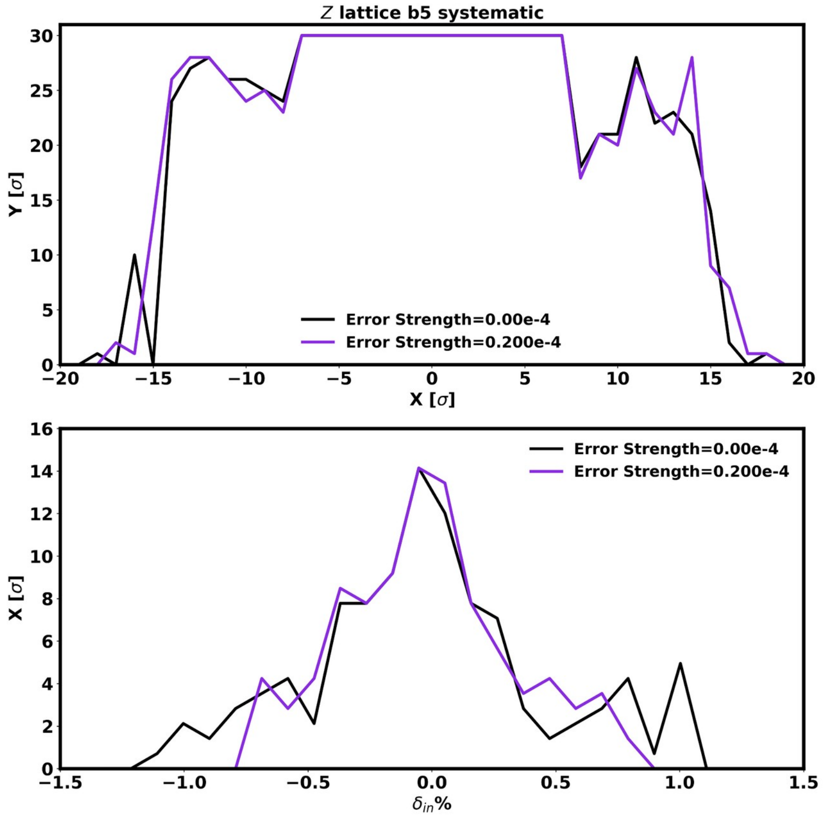
Simulations in XSUITE show very low impact of beam-beam element on average DA (evaluated as largest ellipse)



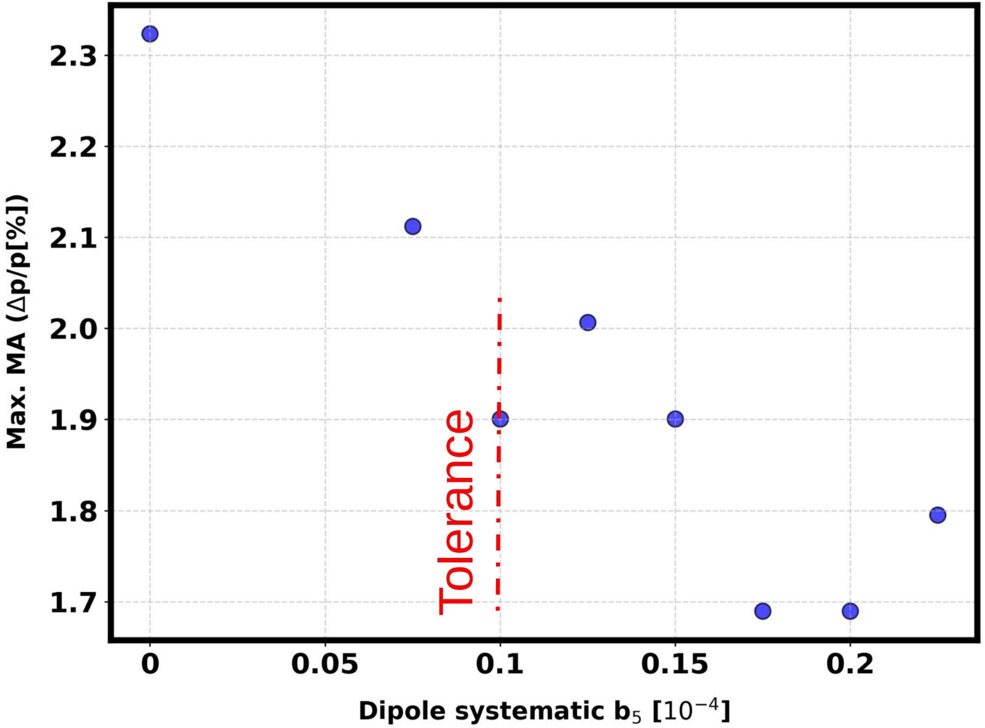
L. van Riesen-Haupt



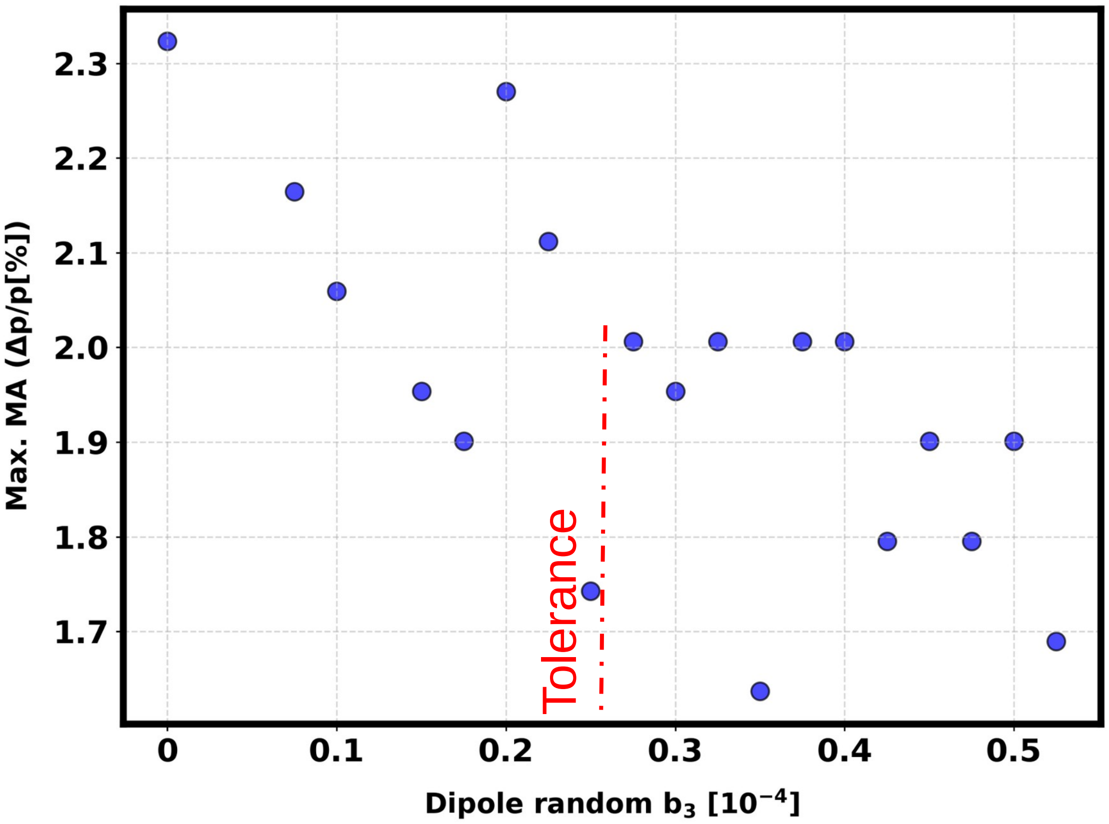
Computing multipolar tolerances: Dipole systematic b5



A. Hussain



Computing multipolar tolerances: Dipole random b3



A. Hussain

Random components show larger fluctuations and need further studies.

Preliminary results follow.

Multipolar tolerances in units of 10^{-4}@10mm for GHC Z

No Q' correction, no beam-beam

Error	ARC Quadrupoles		ARC Dipoles		ARC Sextupoles		IR Quadrupoles		IR Dipoles	
	Rand.	**Syst.**	**Rand.**	**Syst.**	**Rand.**	**Syst.**	**Rand.**	**Syst.**	**Rand.**	**Syst.**
a3	1	2								
b3	1.5	1.5	0.25	0.1					1	1
b4			0.5	0.25			0.1	0.4		
a4					30	25				
b5			0.3	0.1	36	25			1.5	0.6
a5					30	25				
b6	1	0.5								

A. Hussain Magnet slides

Sextupole: Nested skew quad (0.6T) a4=65 > 30 → not OK

Nested vertical orbit corrector (0.02 Tm) induces a5=25 → OK!

These are raw tolerances without applying corrections. Dedicated correction circuits will also be investigated, also for LCC lattice.

Multipolar tolerances in units of 10^{-4}@10mm for GHC tt

No Q' correction, no beam-beam

Error	ARC Quadrupoles		ARC Dipoles		ARC Sextupoles		IR Quadrupoles		IR Dipoles	
	Rand.	Syst.	Rand.	Syst.	Rand.	Syst.	Rand.	Syst.	Rand.	Syst.
a3	5	2								
b3	10	10	1	0.5					2	2
b4	4	1	1.4	0.5						
a4					36	30				
b5					30	20				
a5					36	36				
b6	10	4								

A. Hussain

See Carl and Jeremie's talk

In general, tolerances are more relaxed for the tt lattice!

Multipole tolerances with beam-beam and Q' correction (Z)

A. Hussain

Error	Arc Dipoles			
	Random		Systematic	
	previous	current	previous	current
b3	0.250	0.250	0.100	0.200
b4	0.500	0.550	0.250	0.325
b5	0.300	0.350	0.100	.125

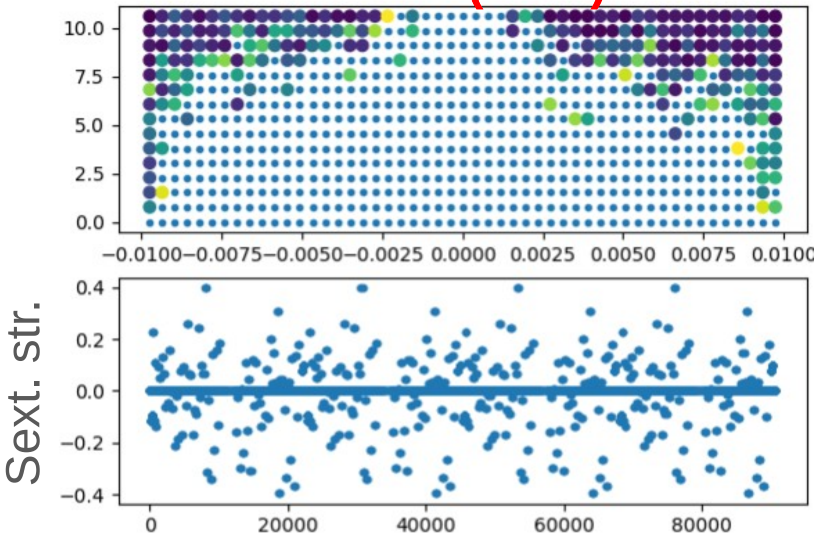
Beam-beam and Q' correction have relaxed some multipolar tolerances, yet further studies are needed with more seeds and combining all the identified tolerances. Dedicated non-linear corrections will increase tolerances but need to be studied

Sextupole optimization in Xsuite

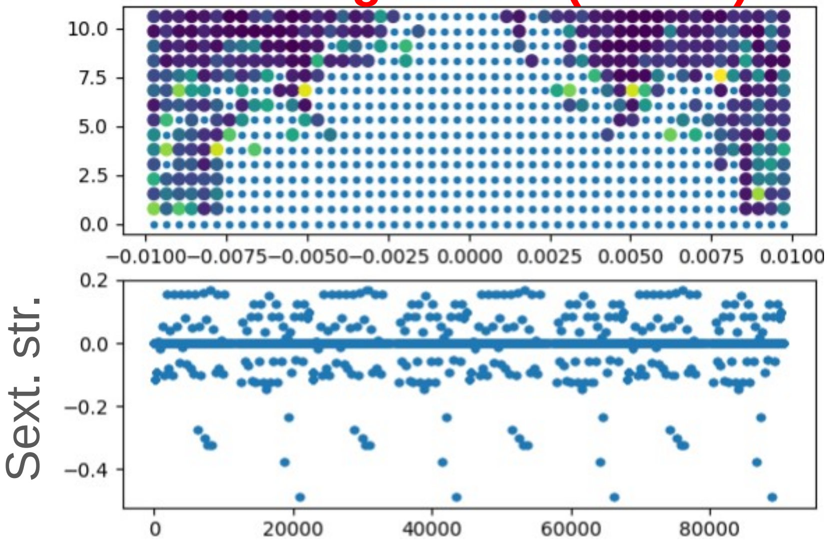
K. Skoufaris et al

Tool available in Xsuite to optimize sextupoles to maximize momentum acceptance. Currently simplified approach to be improved. Yet rather good first results!! (already used for Ballistic optics). Can be used to mitigate known errors (e.g. sys. b3) and unknown errors beam-based.

Baseline (SAD)



Starting from 0 (Xsuite)



Polarization

Off Z pole scan

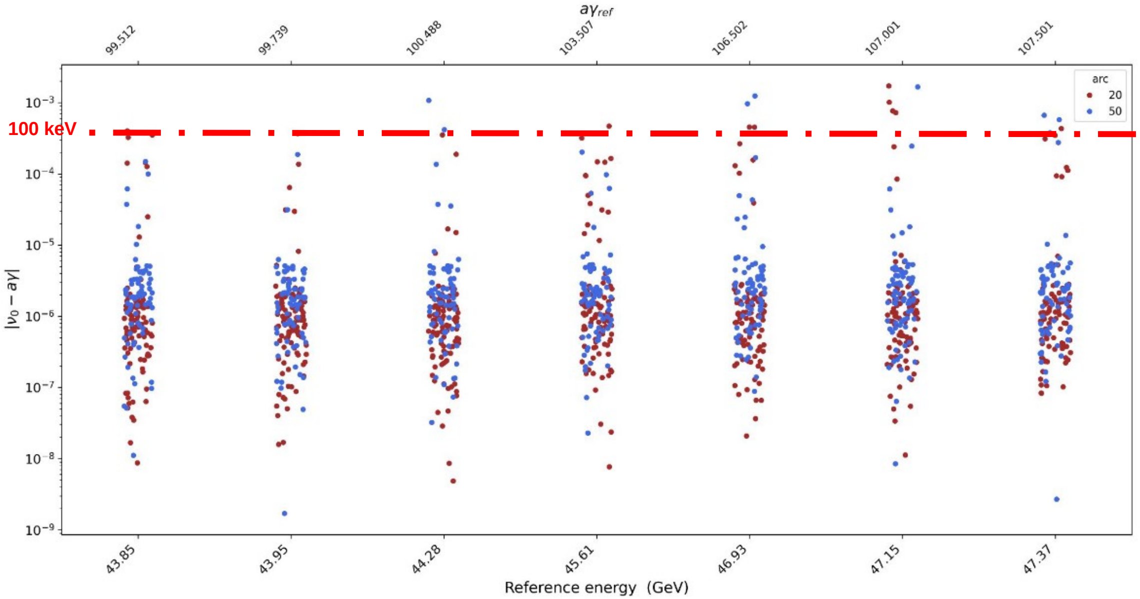
Y. Wu

20/50μm in arc
10μm in IR

Z pole uncertainties	stats	$\Delta\sqrt{s}_{abs}$	$\Delta\sqrt{s}_{syst-ptp}$
Observable		100 keV	**40 keV**
m_Z (keV)	4	100	**28**
Γ_Z (keV)	4	2.5	**22**

arXiv:1909.12245

Scan point	$\sqrt{s}$ (GeV)	E_b (GeV)	Spin tune
$\sqrt{s_-}$ A	87.69	43.85	99.5
$\sqrt{s_-}$ Request	87.9	43.95	99.7
$\sqrt{s_-}$ B	88.57	44.28	100.5
$\sqrt{s_0}$	91.21	45.61	103.5
$\sqrt{s_+}$ A	93.86	46.93	106.5
$\sqrt{s_+}$ Request	94.3	47.15	107.0
$\sqrt{s_+}$ B	94.74	47.37	107.5



Larger misalignments and corrections could contribute to large part of absolute error of beam energy measurements, selected seeds to be better understood.

Summary and Outlook

Commissioning sequence established. Optics and DA under control with nominal misalignments in the arcs.

Great progress on different arc quadrupole BBA strategies to achieve ~ 10 – 20 μm goal

Fundamental to measure and correct phase advances and coupling with AC dipoles.

Excellent progress with polarization and energy calibration, yet it remains challenging to achieve 100 keV systematic uncertainty even at 20-50 μm in the arcs

First progress with the IRs: FD at 10 μm and other IR magnets at 60 μm

Field quality tolerances: Further studies needed, likely dedicated correctors needed.

Skew quad in the sextupoles generates too large a4: standalone skew quad?

Strength errors, multipolar errors, IP tuning, long range misalignments to be added to tuning simulations.

Back-up

FCC-ee tuning team by institutes

CERN e-group FCCee_tuning-team:

Fully signed agreement with Colombia!

New indico category: https://indico.cern.ch/category/18470/

J. Keintzel and R. Tomas on behalf of the

FCC-ee Tuning Team

Tremendous progress on tuning aspects:

Goal of the tuning WG

Demonstrate the feasibility of the FCC-ee in presence of errors.

Errors	Measurements	Corrections	Tolerances & specs.
Misalignments Strength err. Tilts Multipoles (FQ) *Beam-beam interaction and synchrotron rad. may enhance the impact of errors.*	Orbit Orbit response (LOCO). Optics via beam excitation (AC dipole) and turn-by-turn BPM data. K-modulation. (De)polarization …	Orbit Beam-Based alignment. LOCO. Phase advance, Disp., coupling. Non-linear corrections. IP tuning.	Magnetic field quality Correction magnets Instrumentation: BPMs AC dipole Beam size monitors …

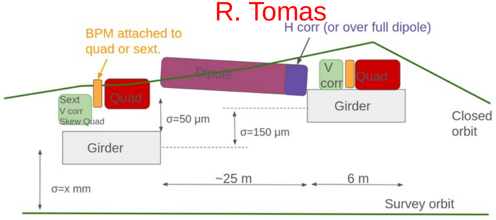
FCC-ee tuning team by institutes

CERN e-group FCCee_tuning-team:

Ongoing discussions with Colombia & Spain

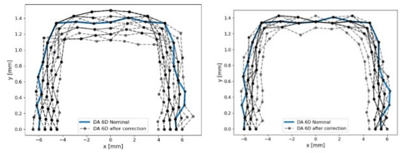
Half cell illustration

R. Tomas



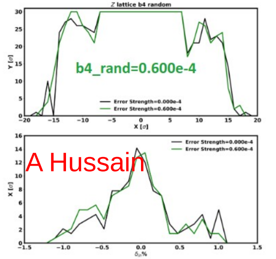
Clear preference for BPMs attached to quadrupoles

E. Musa



Definition of magnet field tolerances

A Hussain

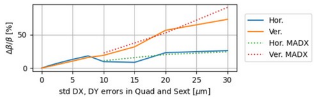


Definition of

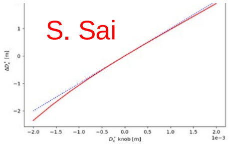
- → **A more detailed lattice design**
- → **Concrete commissioning strategy**
- → **Tuning and optimization for performance**

Many tuning studies including dedicated IP tuning knobs

S. Liuzzo

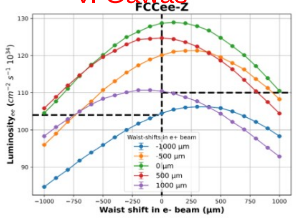


S. Sai



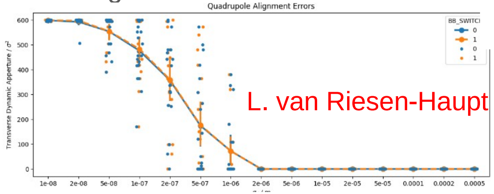
Luminosity for various waist shifts calculated

V. Gawas



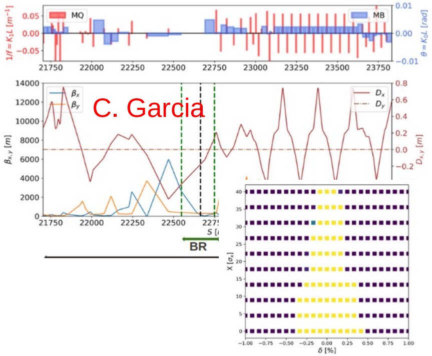
New insights to DA and beam-beam

L. van Riesen-Haupt



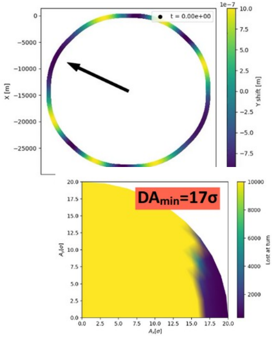
New Ballistic FCC-ee Optics with sextupole optimization designed for commissioning

C. Garcia



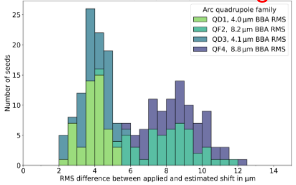
DA in presence of ground waves

K. Skoufaris

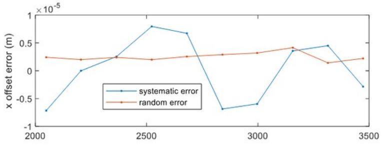


Beam-based alignment show ~ 20 μm arc quadrupole alignment feasible with 2 different approaches

C. Goffing

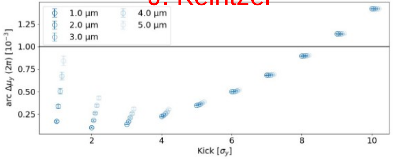


X. Huang



Definition of BPM resolution requirements

J. Keintzel



Goal of the FCC-ee tuning WG

Demonstrate the feasibility of the FCC-ee in presence of errors.

Errors
Misalignments
Strength err.
Tilts
Multipoles (FQ)

Beam-beam interaction and synchrotron rad. may enhance the impact of errors.

Measurements
Orbit
Orbit response (LOCO).
Optics via beam excitation (AC dipole) and BPM data.
K-modulation.
(De)polarization
…

Corrections
Orbit
Beam-Based alignment (BBA).
DFS. *New!*
LOCO.
Phase advance, Dispersion, coupling.
Non-linear corrections.
IP tuning.

Tolerances & specs.
Magnetic field quality.
Corrector magnets.

Instrumentation:
BPMs
AC dipole
Beam size monitors

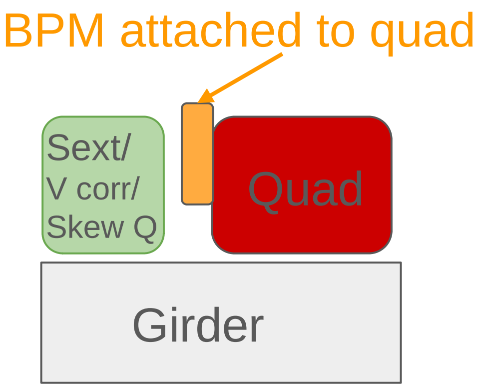
New!
Dedicated optics
Ballistic
Relaxed β*

Tolerances of arc elements

1σ values

Element	Transverse [μm]	Tilt [μrad]
Girder	150	150-300
Quadrupole*	50	50
Sextupole*	50	50
Dipoles	1000	1000

**Tolerances on top of girder*



T. Charles et al.
EPJ Techniques and Instrumentation vol. 10: 8 (2023)
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H. Mainaud in ATDC #2

BPM-to-Quadrupole misalignment

Initially: 100 μm

After BBA: 10 μm

X. Huang in FCC week

BPM resolution

Orbit mode: 0.1 μm

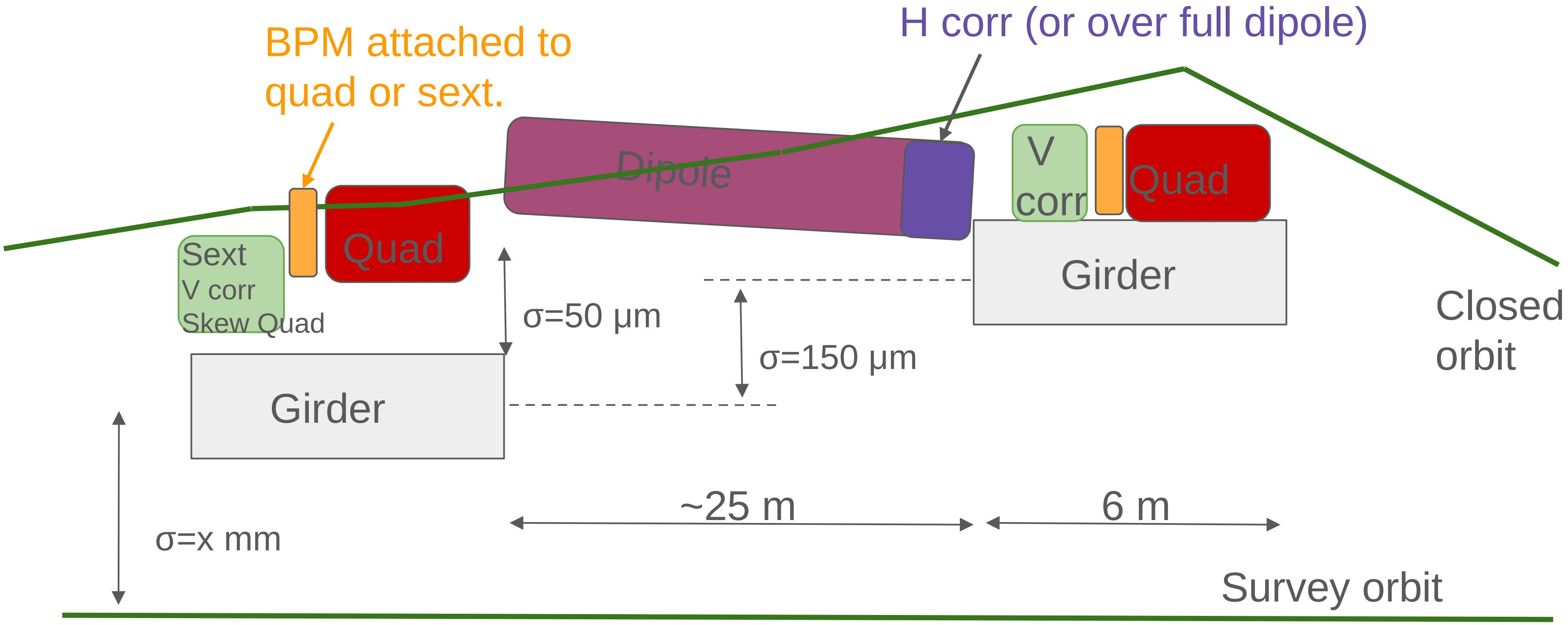
Turn-by-turn mode: 1 μm

E. Howling et al. ATDC #2

Magnet Field Quality

See later. A. Hussain in tuning WG

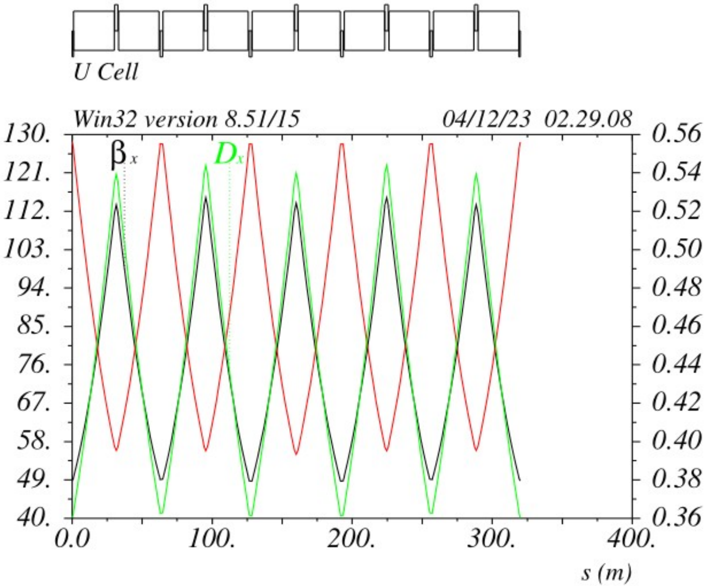
Half cell illustration

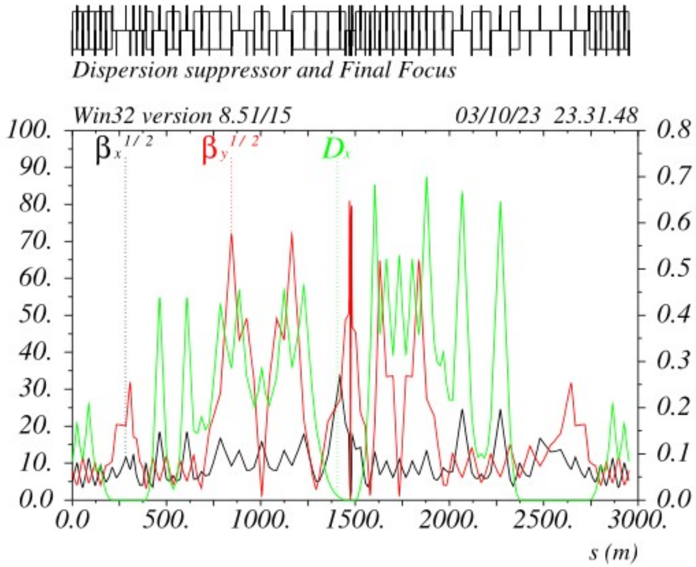


A note of the LCC optics designed by P. Raimondi

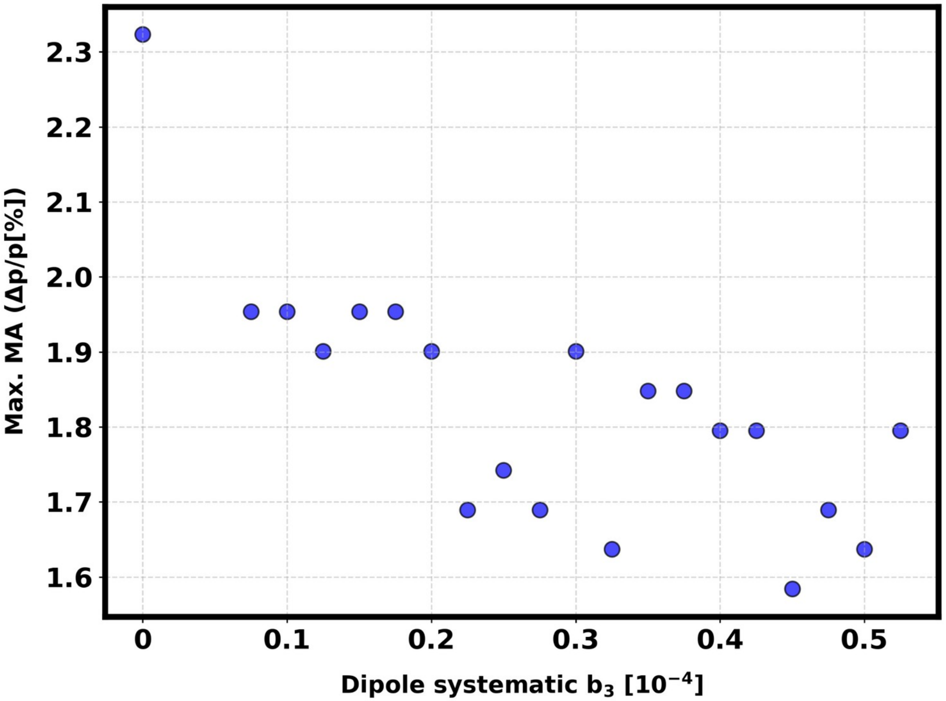
LCC is considered the alternative design optics. In general, LCC is less sensitive to arc errors than GHC.

Full demonstration with GHC guarantees LCC feasibility too, therefore we focus on the current GHC baseline.



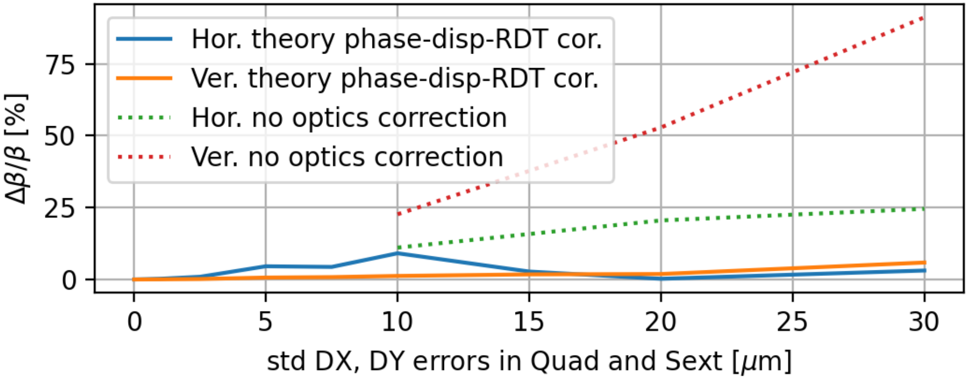


Multipolar tolerances: systematic b3 in dipoles



Impact of adding phase advance correction in pyAT

S. Liuzo's slides



Huge improvement in optics quality and emittance thanks to adding phase advance & RDT correction

E. Musa's slides

Optics correction using Phase advance and RDTs/ηy

50 seeds (mean values)		rms orbit x (μm)	rms orbit y (μm)	Δβx/βx %	Δβy/β y%	Δ ηx (mm)	Δ ηy (mm)	ε_h (nm)	ε_v (pm)
100 μm on arc	Final cor. result	8.55	8.35	0.35	0.89	2.94	4.37	0.70	0.73

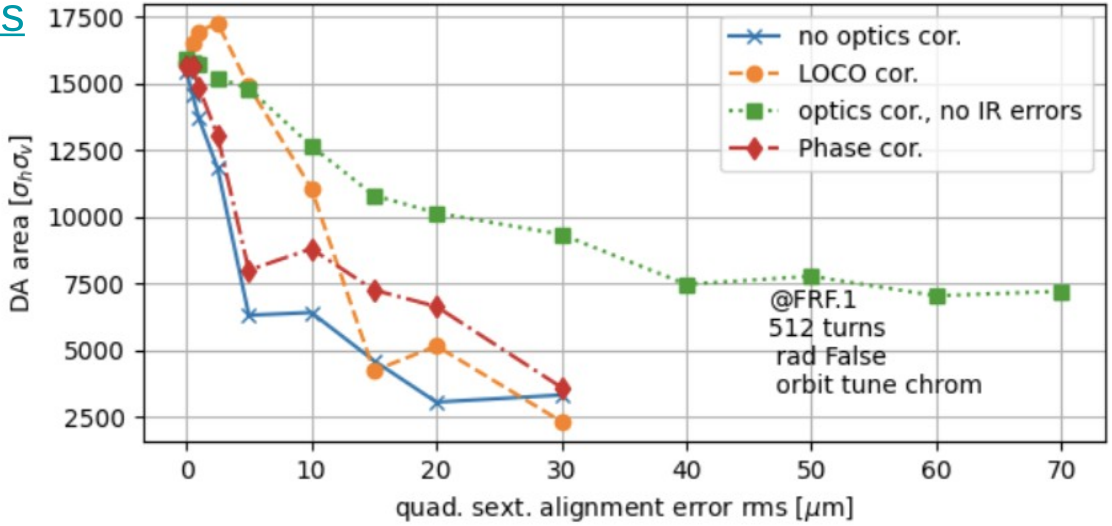
Optics correction using LOCO

50 seeds (mean values)		rms orbit x (μm)	rms orbit y (μm)	Δβx/βx %	Δβy/β y%	Δ ηx (mm)	Δ ηy (mm)	ε_h (nm)	ε_v (pm)
100 μm on arc	Final cor. result	8.56	8.35	1.93	3.23	4.95	2.92	0.70	5.99

See E. Musa's poster on Thu poster session!

DA after optics tuning simulations with sextupole ramp-up

S. Liuzzo's slides



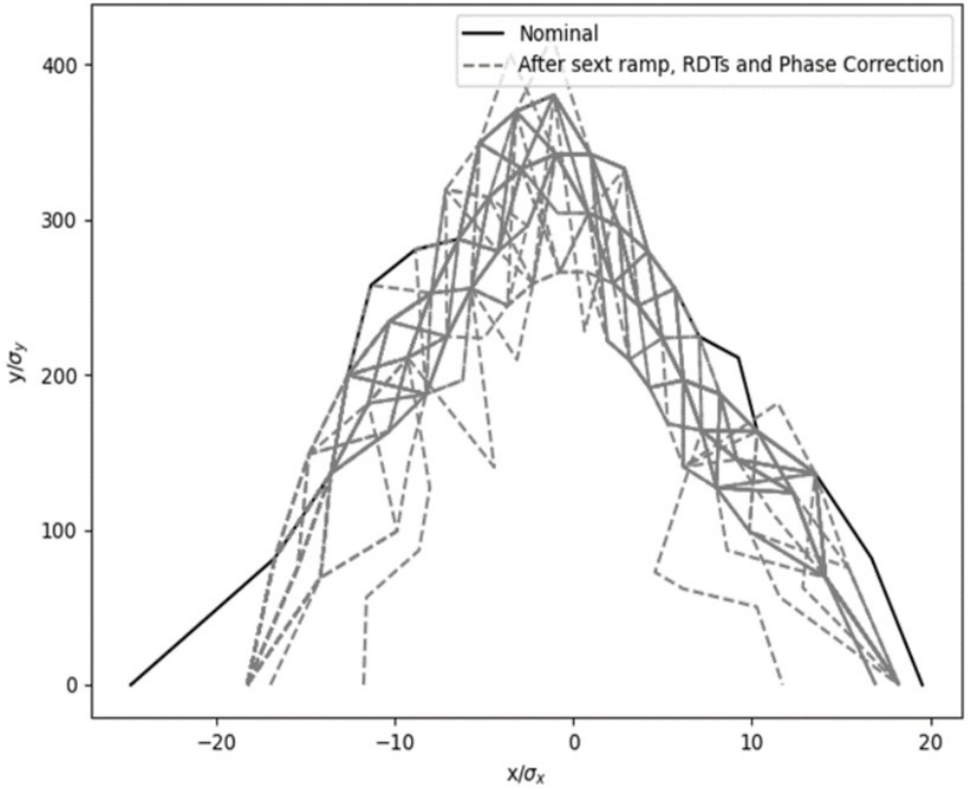
GHC Z lattice

Severe reduction of DA with IR errors → Dedicated alignment system might be needed.

Mild reduction of DA when errors only applied to arcs up to 70 μm and likely beyond.

Phase advance correction does not show significant improvement for DA…

DA after optics tuning simulations: 100 μm in arcs



E. Musa's slides

See
E. Musa's poster on
Thu poster session!

Mild reduction of DA when errors only applied to arcs up to **100 μm**.

Phase advance and RDT correction were key in these simulations to improve DA.

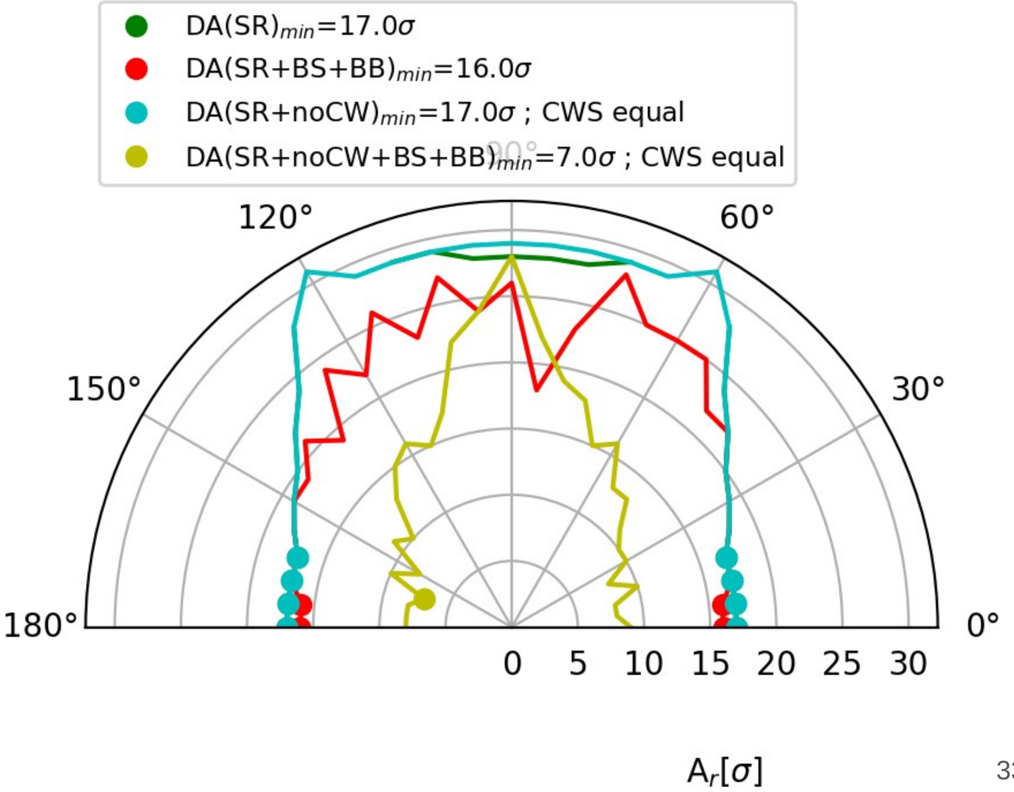
Including errors also in the IR ongoing

DA with SR and beam-beam for V23 of GHC Z lattice

K. Skoufaris, using Xsuite

The minimum DA when adding SR and beam-beam in the ideal lattice is 16σ (in red).

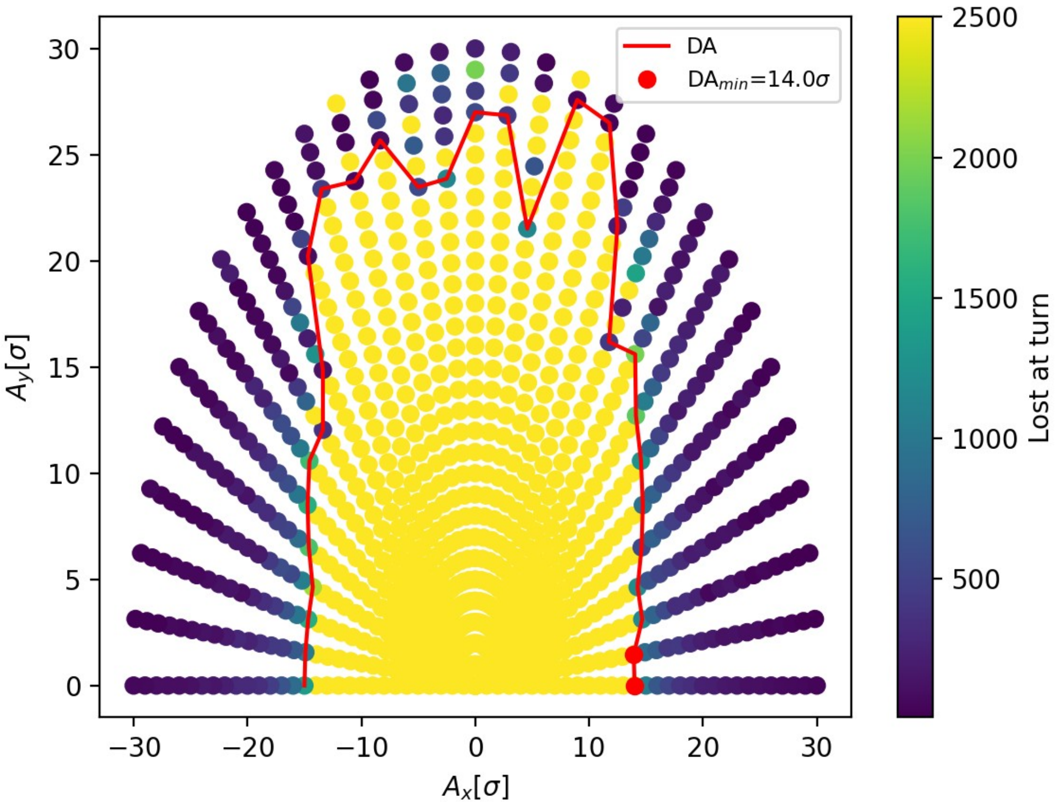
Without beam-beam DA is larger, min of 17σ with Crab Waist or without Crab Waist.



DA with 7x10^{-4} 2π rad rms phase advance errors between arc sextupoles

K. Skoufaris

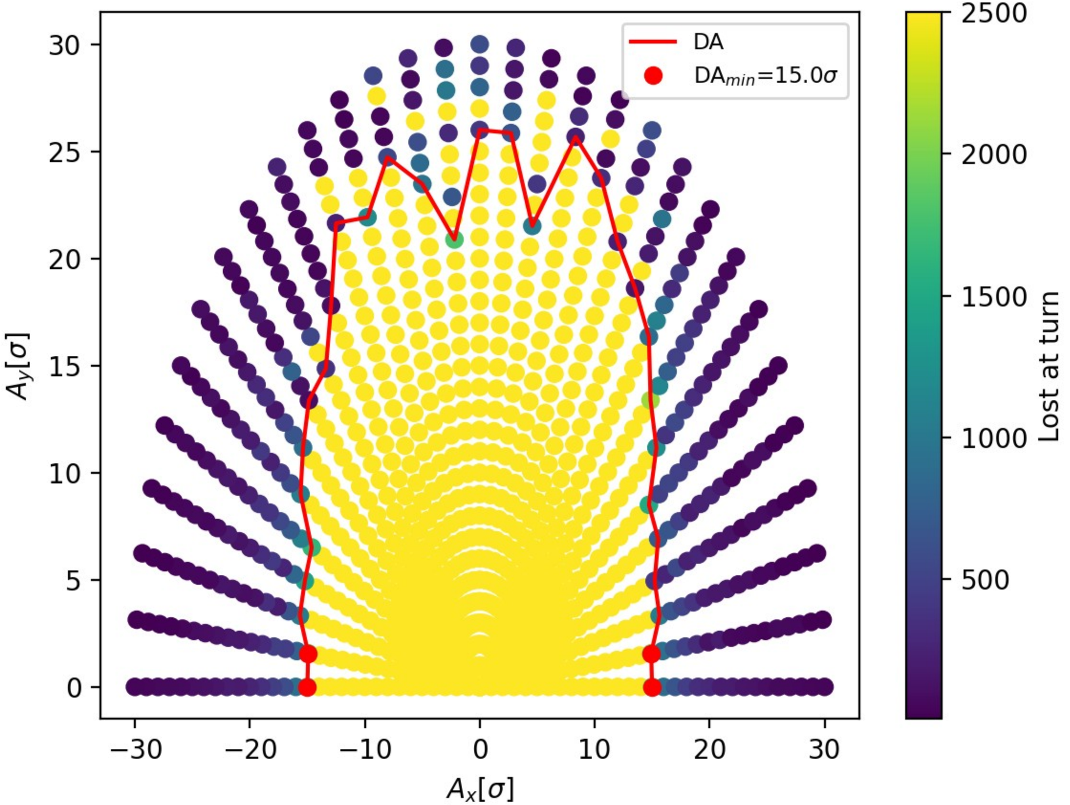
Measurement techniques along with BPM resolution should guarantee phase advance measurements better than 10^{-3} 2π rad in the arcs.



DA with 0.6x10^{-4} 2π rad rms phase advance errors between IR sextupoles

K. Skoufaris

Measurement techniques along with BPM resolution should guarantee phase advance measurements better than 10^{-4} 2π rad in the IRs.



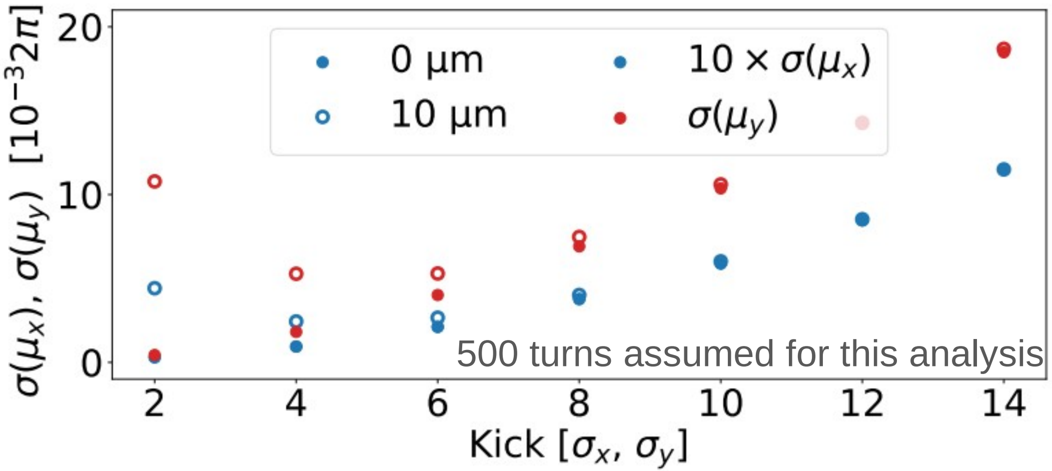
Measuring the phase advance with Turn-by-Turn BPMs

J. Keintzel et al. IPAC22 and FCC BI slides

Even with 0 μm BPM noise kick amplitudes of 4σ or larger exceed target resolution of 10^{-3} 2π rad in arc BPMs.

→AC dipoles to excite for about 50000 turns at ≈2σ amplitude with BPMs of <10 μm TbT noise is needed (could be with ≈60 bunches @ Z, A. Lechner et al.).

Further studies needed, specially for IR BPMs, target resolution of 10^{-4} 2π rad.



BPM Parameter	Requirement
Orbit resolution	0.1 μm
TxT resolution	< 10 μm

E. Howling et al. A TDC #2

What about the sextupole ramp-up for optics tuning?

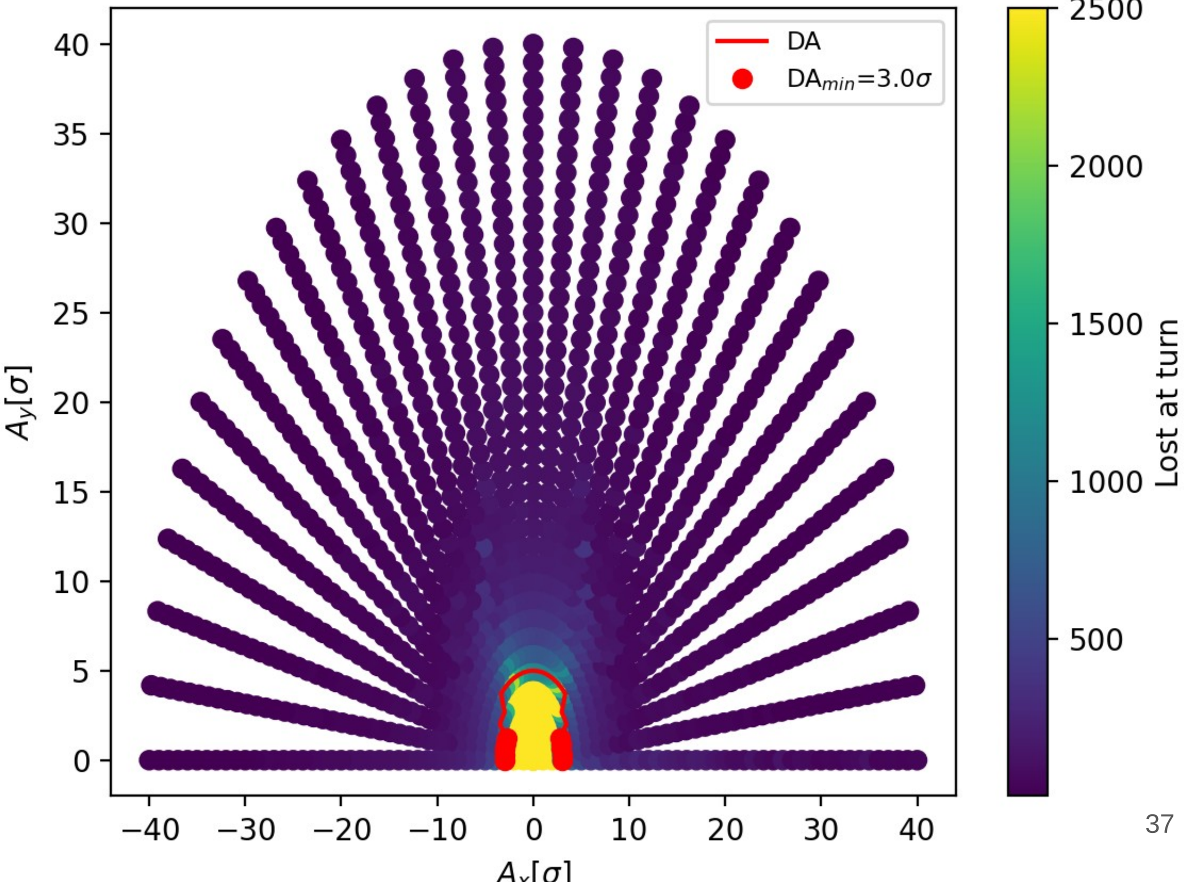
DA drops to 3σ when all sextupoles are reduced by a factor 2.

→Need a □* squeeze[†] and sextupole ramp-up scheme for the optics commissioning.

[†]IPAC24

[L. van Riesen-Haupt et al. Relaxed IR optics…]()

K. Skoufaris

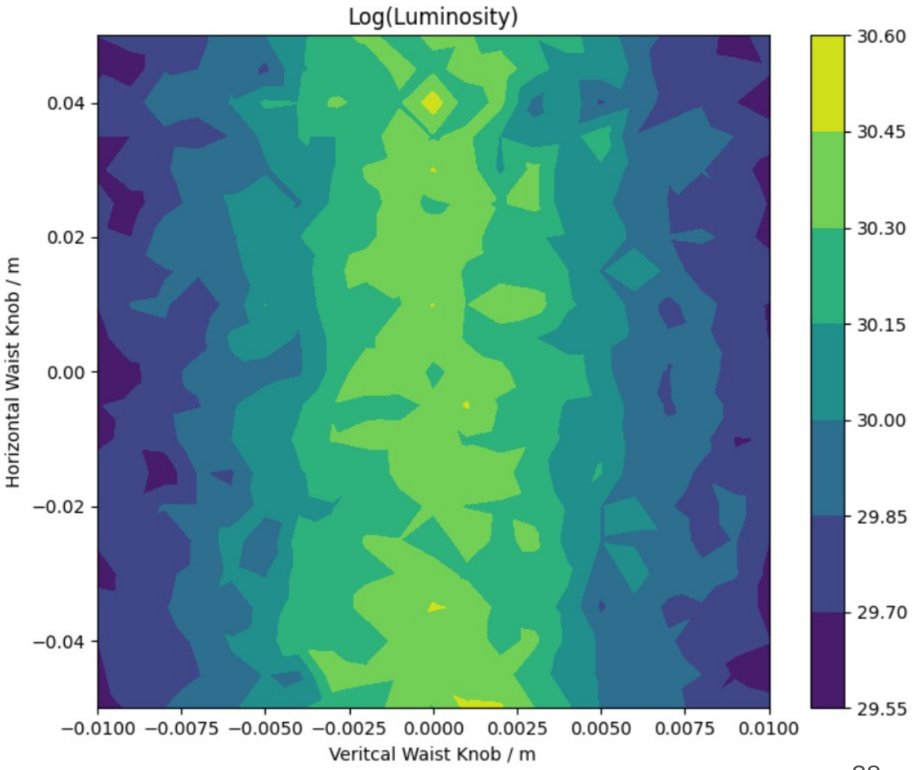


IP tuning knobs

First demonstration of IP optics correction using knobs by S. Jagabathuni et al.:

	Pre-knob	Post-knob
□*$_x$ [m]	0.97	1.0
ω_x [m]	0.01	0.00
Dy [µm]	1.6	0.00
…		

First luminosity waist knob scan by L. van Riesen-Haup et al.:



Dynamic stability (MTR)

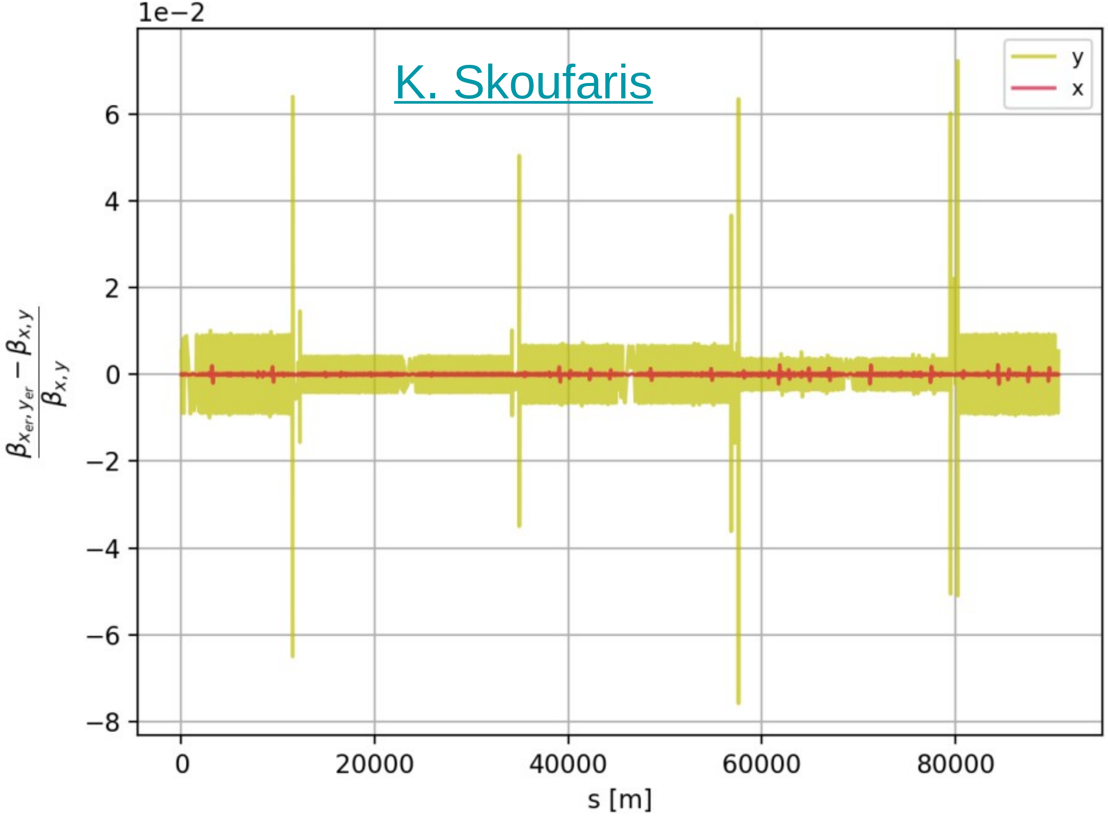
Table 101 Proposed dynamic stability requirement presented by T. Raubenheimer at FCC IS workshop [242] .

Frequency Range	Tolerance	Correlation
400 Hz > f > 100 Hz	1 nm	none
100 Hz > f > 10 Hz	5 nm	none
10 Hz > f > 1 Hz	20 nm	none
1 Hz > f > 0.01 Hz	100 nm	none
1 Hz > f > 0.01 Hz	1 μm	10 km

Freddy A. Poirier is covering this topic in detail.

→ Here we focus on beta-beating and DA

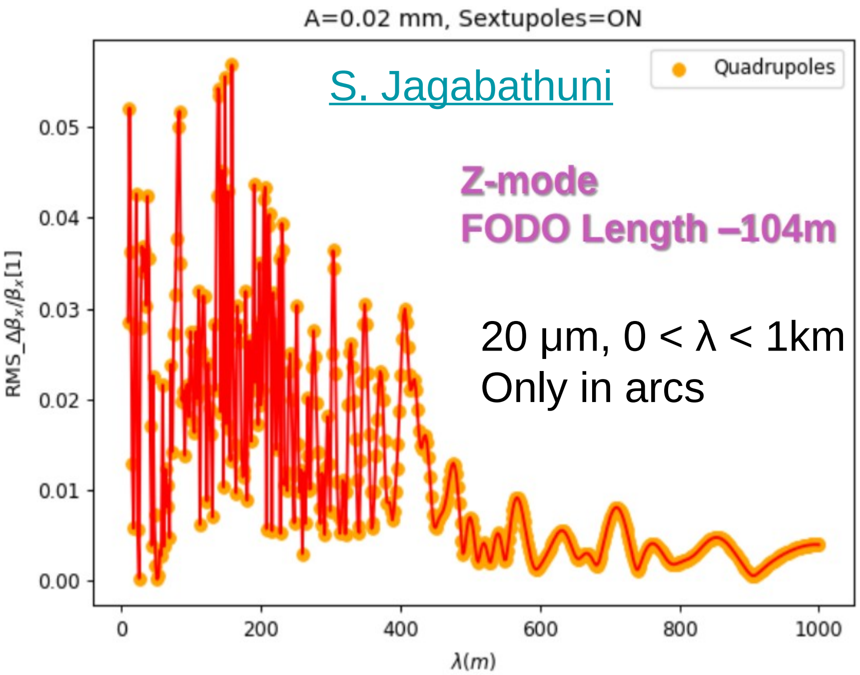
Uncorrelated 100 nm at 1-0.01 Hz

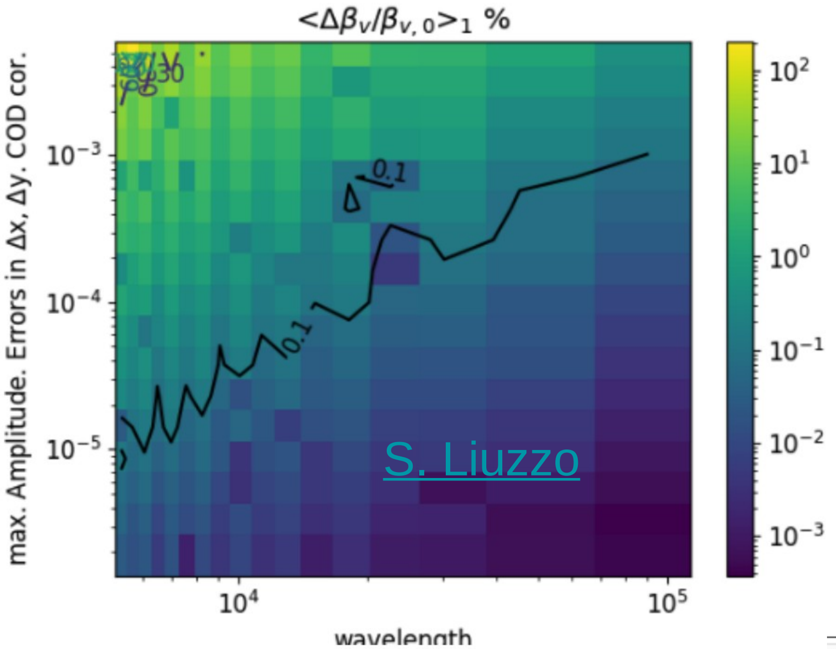


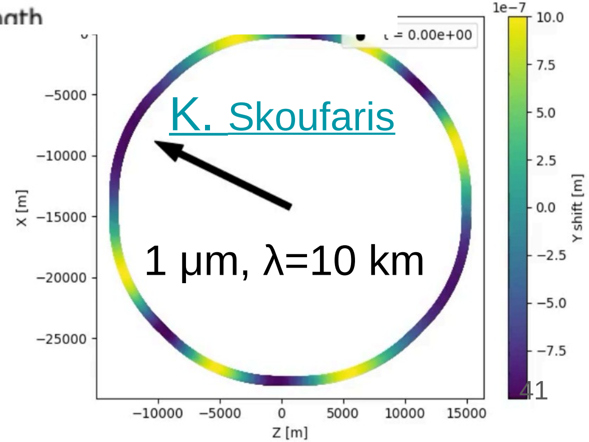
Above 5% V beta-beating and 0.5mm orbit induced by the uncorrelated 100 nm sfhits.

Orbit feedback should correct for most of this beta-beating, to be studied.

Correlated waves







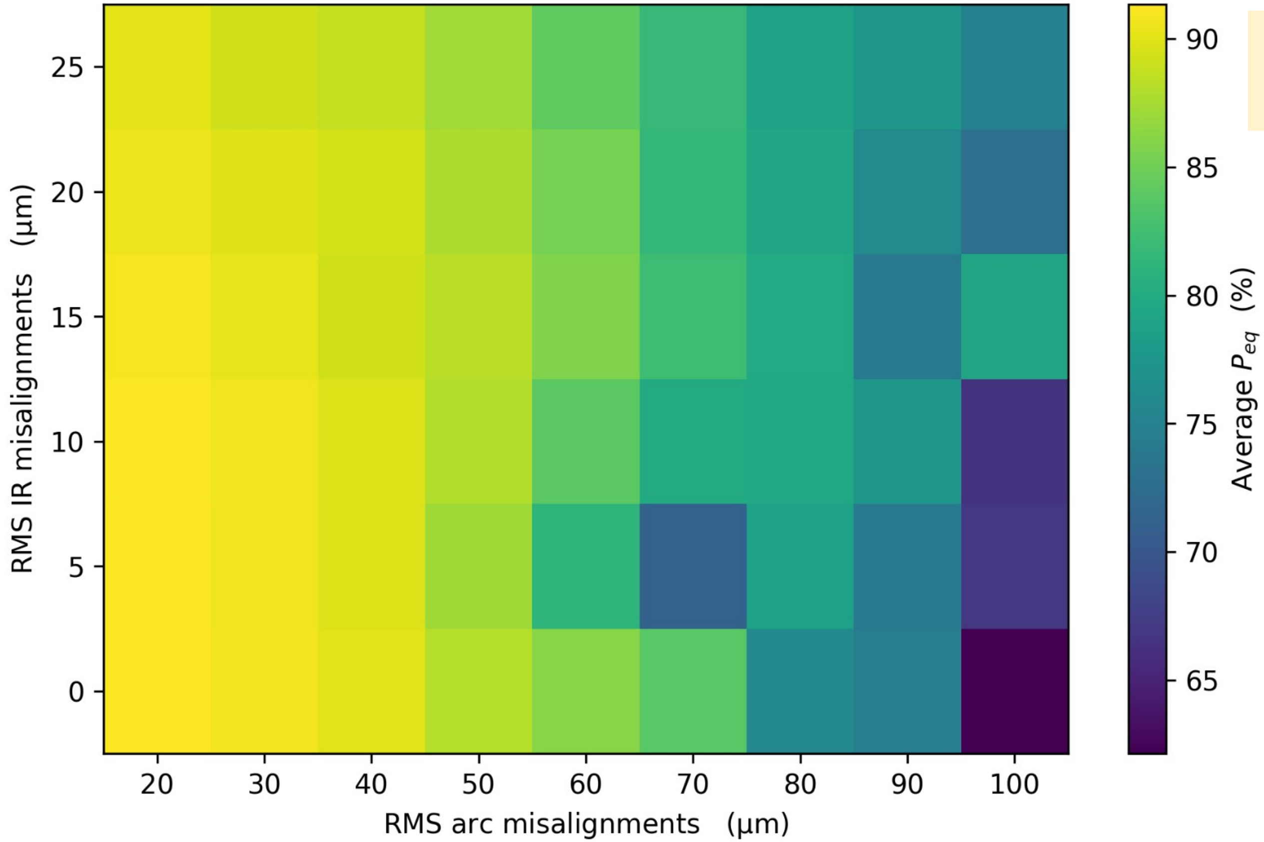
Sharp resonance peaks in beta-beating and dispersion occur at certain wavelengths λ⩽500m (Z-mode).

At 20µm, λ=21.9m → 5% rms beating.

At 1µm, λ=10km there is no impact on beta-beating or DA.

At 2mm, λ=1km there is ≈30% beta-beating!

Polarization with quadrupoles and sextupoles misalignments



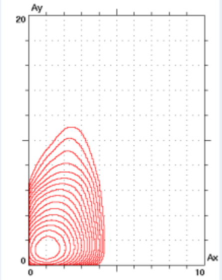
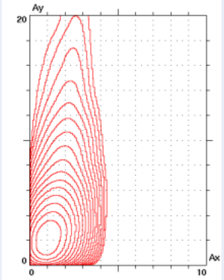
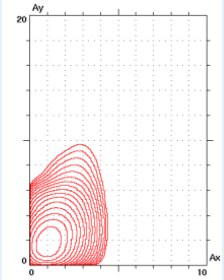
See Yi Wu's talk on Thu

Polarization is good up to 70-80 µm arc miaslignments.

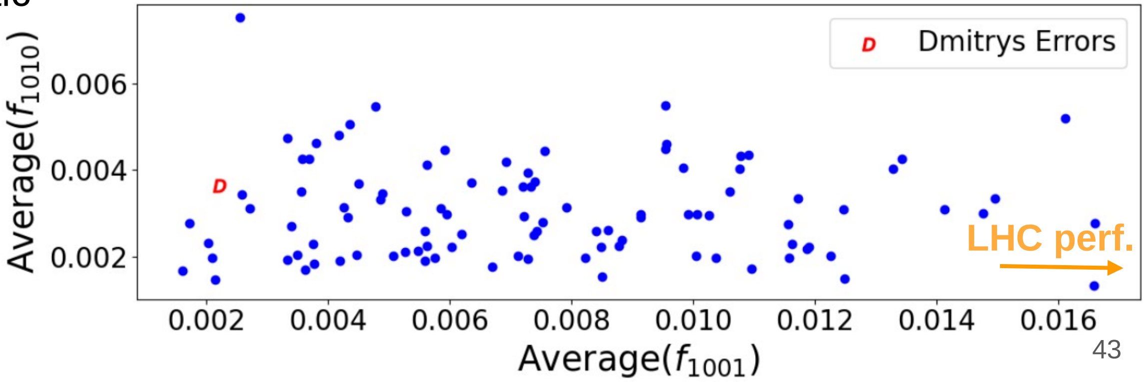
Impact of BPM misalignments to be studied.

Coupling studies with beam-beam

- 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.

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			

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



Status of alignment system (Helene Mainaud)

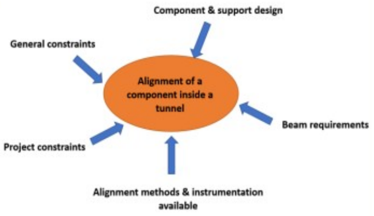
Conclusions

FCC — Jean-Paul Burnet / Tor Raubenheimer

Recall, what need to be done to complete the feasibility study

Impact of alignment requirement
- Can change the design of accelerator supports
- Can bring additional equipment to be installed in the tunnel (motorized jack…)
- Can add a lot of cables
- Can increase the cost

Related to accelerator design



Still a lot of unknowns: the alignment tolerances of the booster, confirmation of the main ring alignment tolerances, alignment tolerances of the injectors, access to the components, radiation level, thermal stability, etc. and on top of this we have currently no solutions available (studied and qualified) for the position determination in the MDI and in the arcs.

We have to start ASAP the R&D on this very preliminary concept and develop alternatives. The feasibility studies on alignment will not be finalized before the end of the year, as they have just started with a very limited workforce. **Additional resources are needed** to conclude on the most urgent items. **The development of a chained FSI technology is key** to decrease the number of cables but is currently at its premises.

We have to perform the studies in the right order: we have first to develop and qualify the concepts, before looking at their automation (robot or train solution) or at their low-cost industrialization (jacks).

Relaxing the alignment requirements should not be the only target: given the number of components and the brand-new deforming tunnel, we will need anyway alignment sensors. **We should focus our energy on finding sustainable and affordable solutions.**

After Quadrupole BBA

Many questions:
Stability of BBA / magnets/BPM?

Better trough sextupole center?