Correction and tuning strategies for the FCC-ee

Jacqueline Keintzel and Rogelio Tomas
On behalf of the FCC-ee tuning team

FCC Week 2025
Vienna, Austria
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FCC-ee Tuning Team

OPTICS TUNING OF THE FCC-ee* **IPAC 2025: WEPR02**

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What does this work include?

Goal: demonstrate ways to achieve design performance in realistic machine

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Measurements

- Orbit response measurements
- Turn-by-turn measurements
- K-modulation

Corrections

- Orbit and optics correctings
- Beam based alignment
- IP-tuning

Hardware specifications

- BPM tolerances
- Magnetic field tolerances
- Misalignment tolerances

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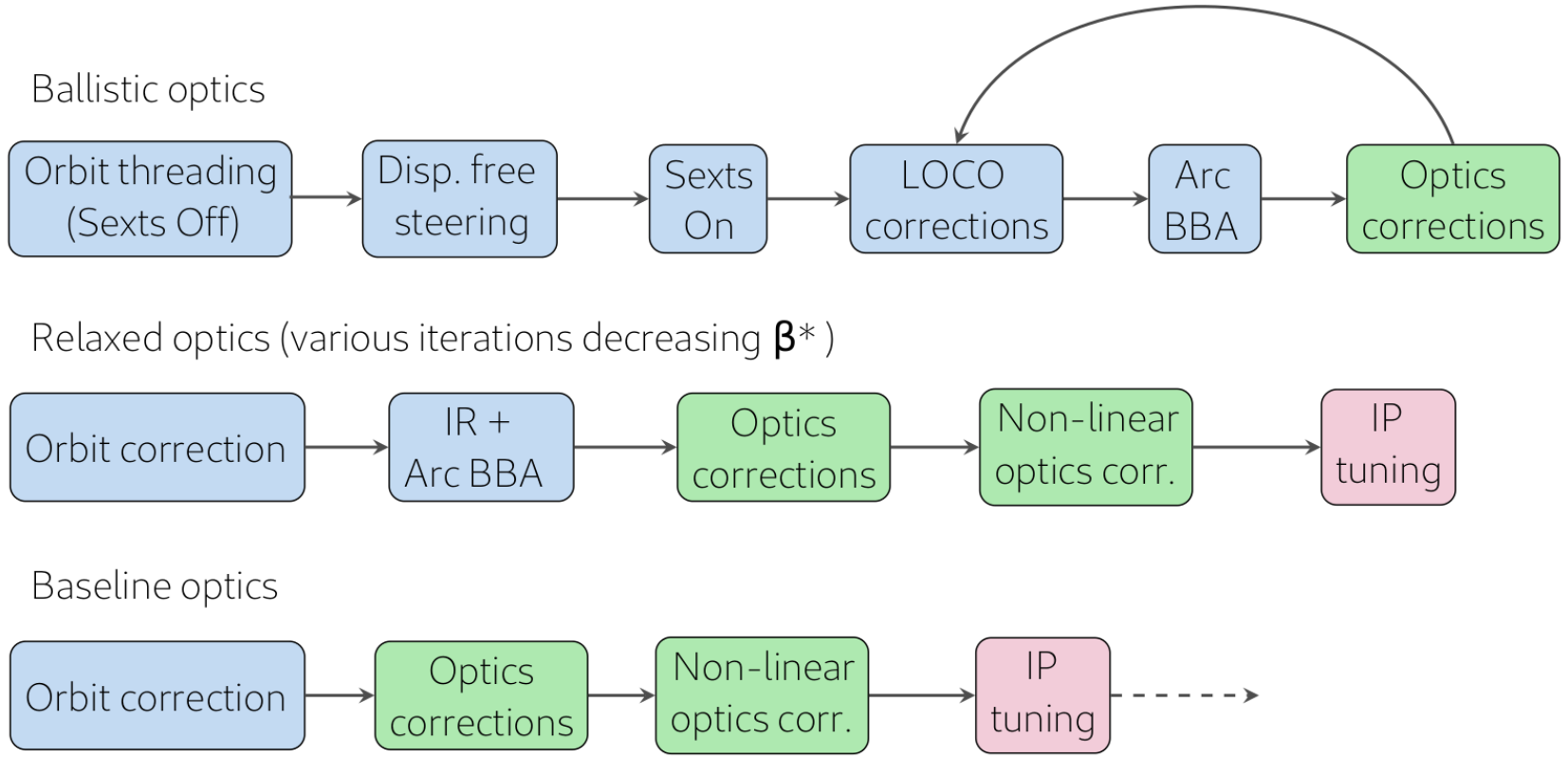
Lessons learned from existing machines

SuperKEKB, DAFNE, LHC, light sources e.g. KARA, EBS

Where is tuning and correction relevant?

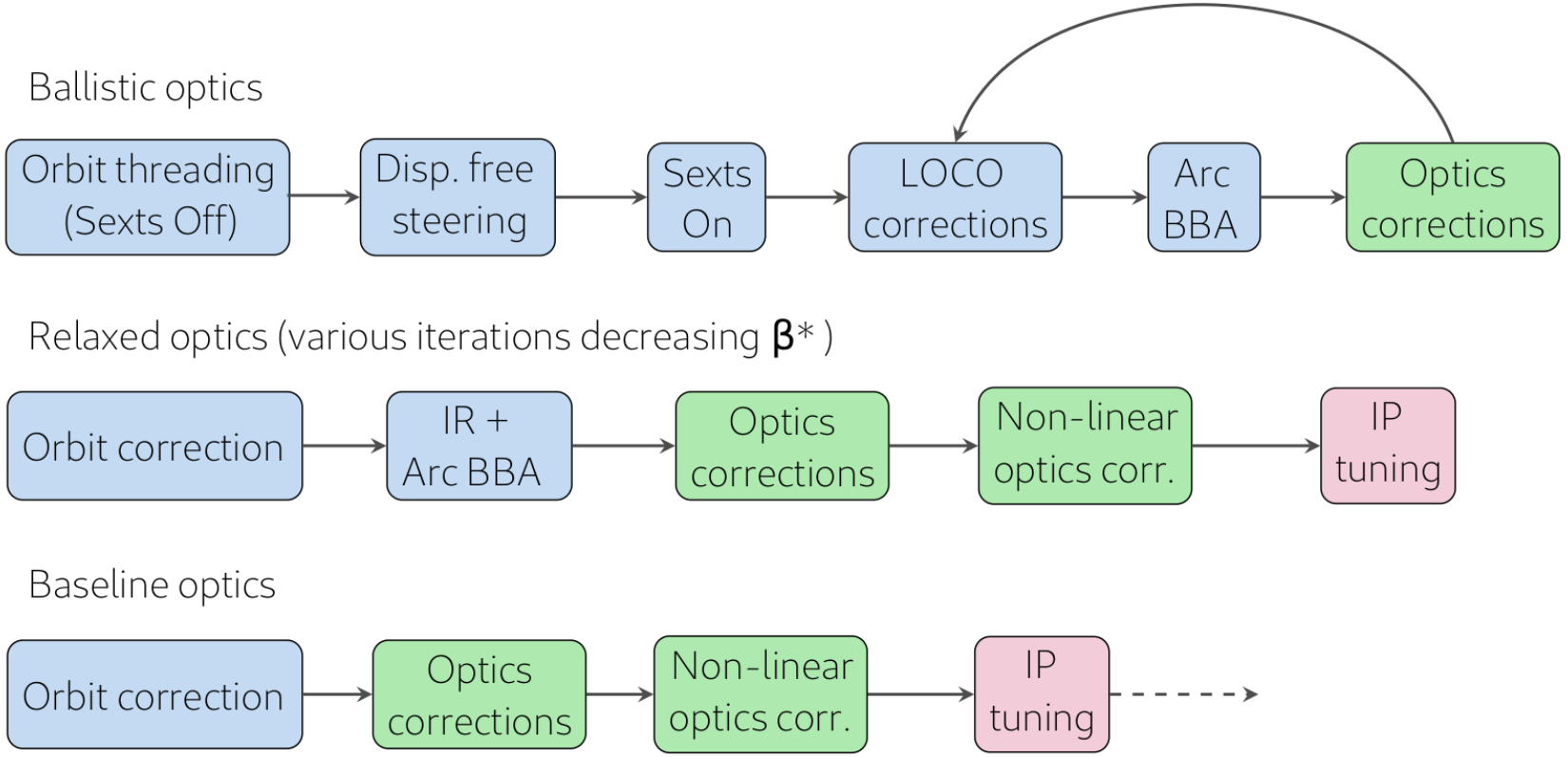
- At every step during commissioning, and operation at all beam energies



R. Tomas

Where is tuning and correction relevant?

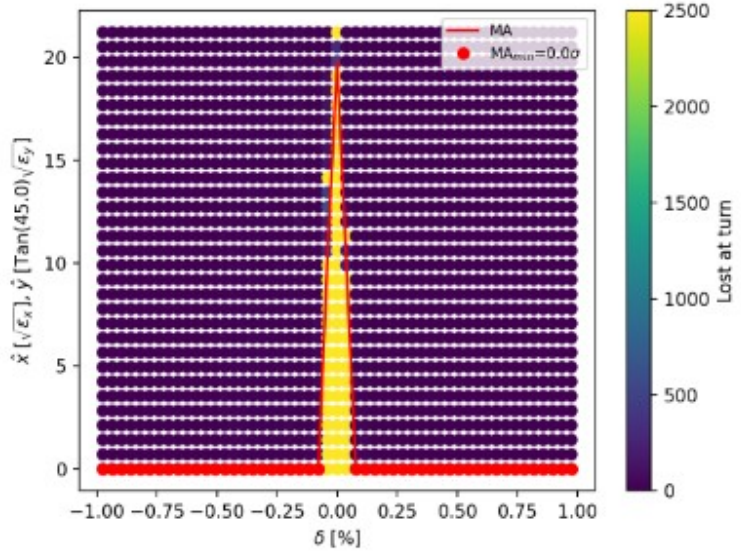
- At every step during commissioning, and operation at all beam energies → **everywhere**

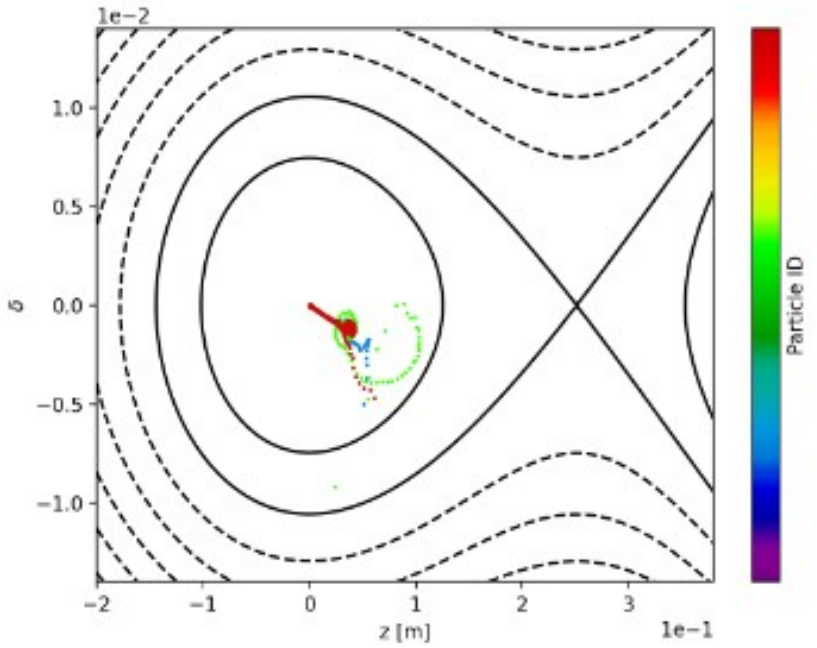


R. Tomas

Sextupole optimization

- Commissioning sequence to be started with ballistic optics (quadrupoles around IP switched off)
- Reducing sextupole stengths reduces MA significanlty → path lengthening could be one of the reasons
- → Careful evaluation of best sextupole settings essential at every commissioning step

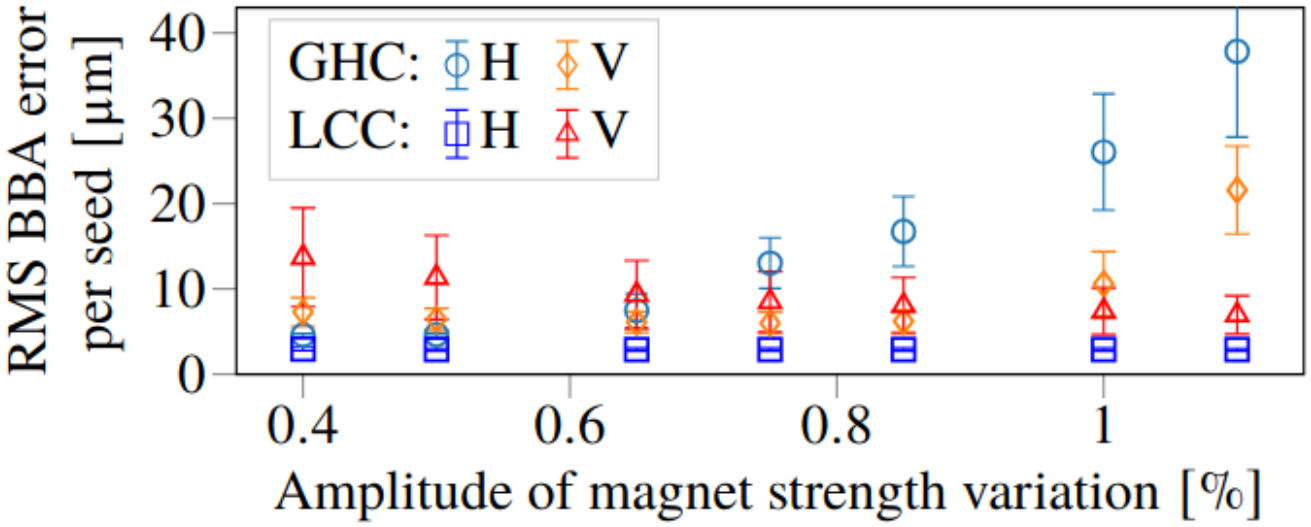




Talk: K. Skoufaris

Beam based alignment

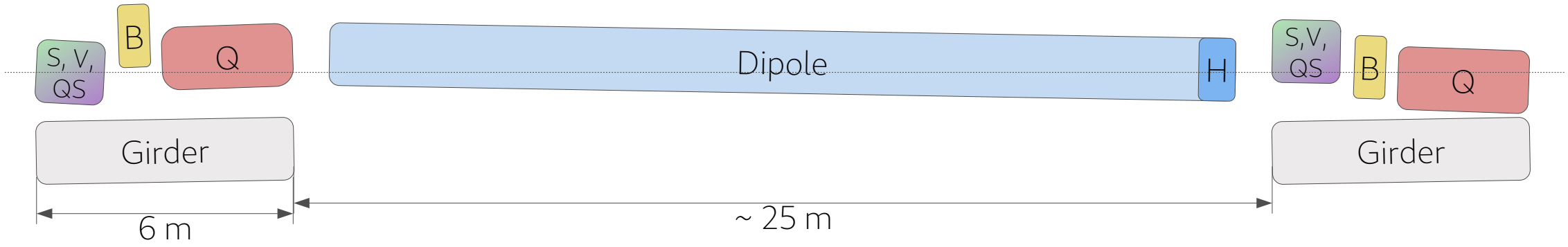
- Goal: measure offset between BPM and quadrupole and steer beam through its magnetic center
- Aim for 10 to 20 μm effective misalignment after BBA for quadrupoles and sextupoles
- Explore various parallel techniques to reduce time required for BBA



Talk: C. Goffing

Tuning studies: Towards a detailed design

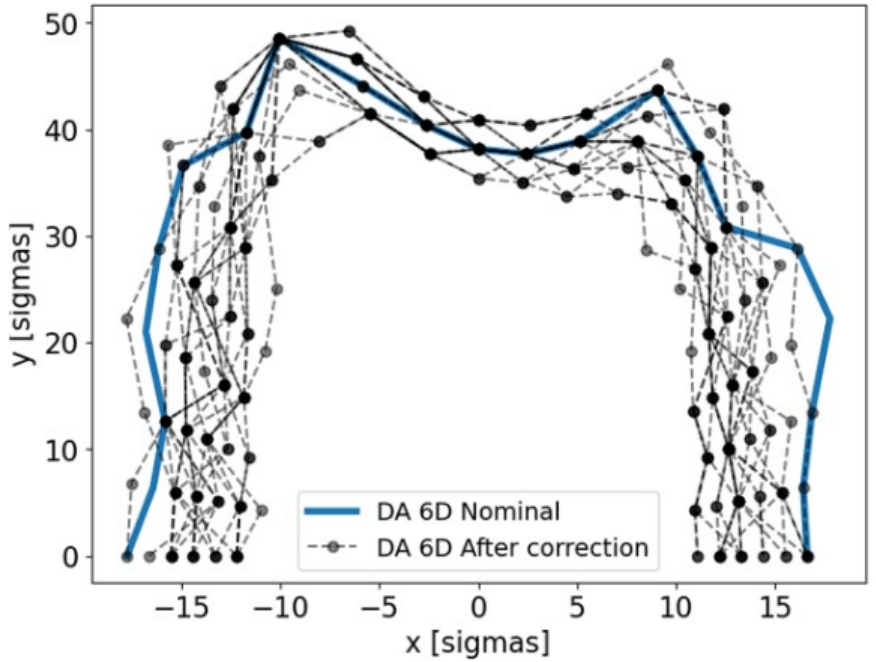
- Arc structure with quadrupoles (Q), sextupoles (S) and Beam Position Monitors (B) on girders
- Beam dynamics simulations define tolerances on mechanical alignment and field tolerances
- Skew Q (QS) and vertical orbit correctors (V) integrated with S; horizontal orbit corrector (H) possibly with dipole

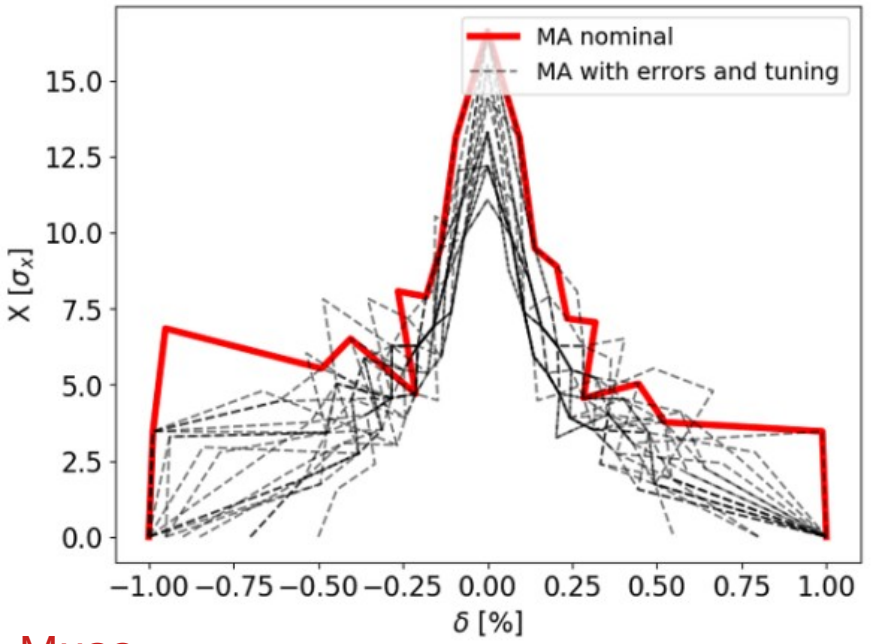


Elements	Transverse tolerance [μm]	Rotation tolerance [μrad]	Field tolerance [10^{-4}]
Arc quadrupoles	50	50	2
Arc sextupoles	50	50	2
Dipoles	1000	1000	2
Girders	150	150	-
BPM to quadrupole	100	-	-

Global optics tuning performance

- Neither IR nor non-linear errors are considered so far in optics and emittance tuning studies
- Only orbit and linear optics corrected by phase advance correction leads to significant DA and MA reduction
- Few percent beta-beating and low emittances reached → non-linear optics ?





Talk: E. Musa

Multipole tolerances

- Evaluated by tracking studies
- Time consuming studies
- No dedicated corrections yet applied
- Tolerances below 1 unit in general very challenging

Error	Arc Quadrupoles		Arc Dipoles	
	Random	Systematic	Random	Systematic
a_3	0.4	0.17	—	—
b_3	1.1	0.7	0.25	0.1
b_4	—	—	0.5	0.05
b_5	—	—	0.3	0.06
b_6	1	0.5	—	—
	IR Quadrupoles		IR Dipoles	
	Random	Systematic	Random	Systematic
b_3	—	—	0.17	0.1
b_4	0.1	0.4	—	—
b_5	—	—	0.12	0.05
	Arc Sextupoles			
	Random	Systematic		
a_4	30	25		
a_5	30	25		
b_5	36	25		

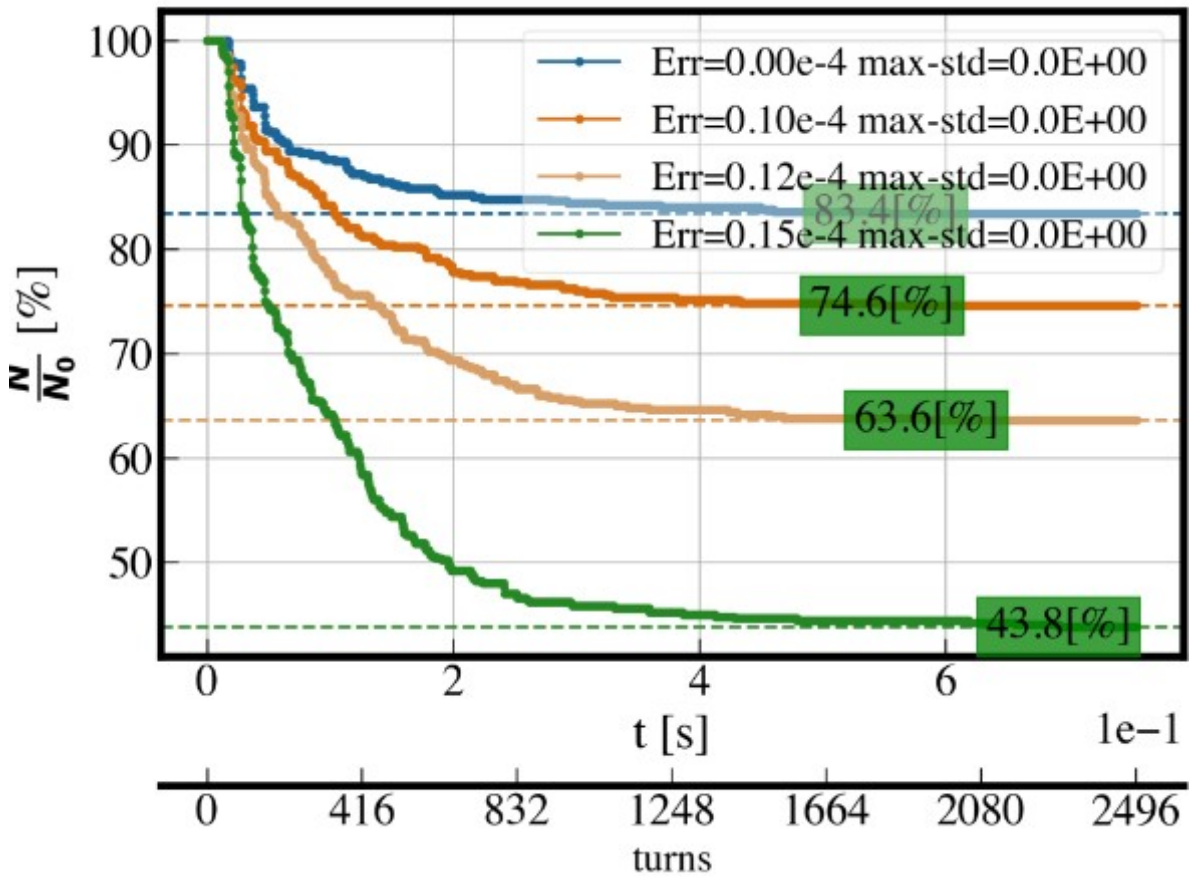
Values given in 10^{-4} at 10 mm reference radius at Z

A. Hussain

Multipole tolerances

- Evaluated by tracking studies
- Time consuming studies
- No dedicated corrections yet applied
- Tolerances below 1 unit in general very challenging

- Injection efficiency limited due to tight tolerances
- Sensitiviy depends on injection scheme
- Hybrid scheme tentatively more relaxed tolerances than purely off energy injection
- Including errors drastically limits injection efficiency



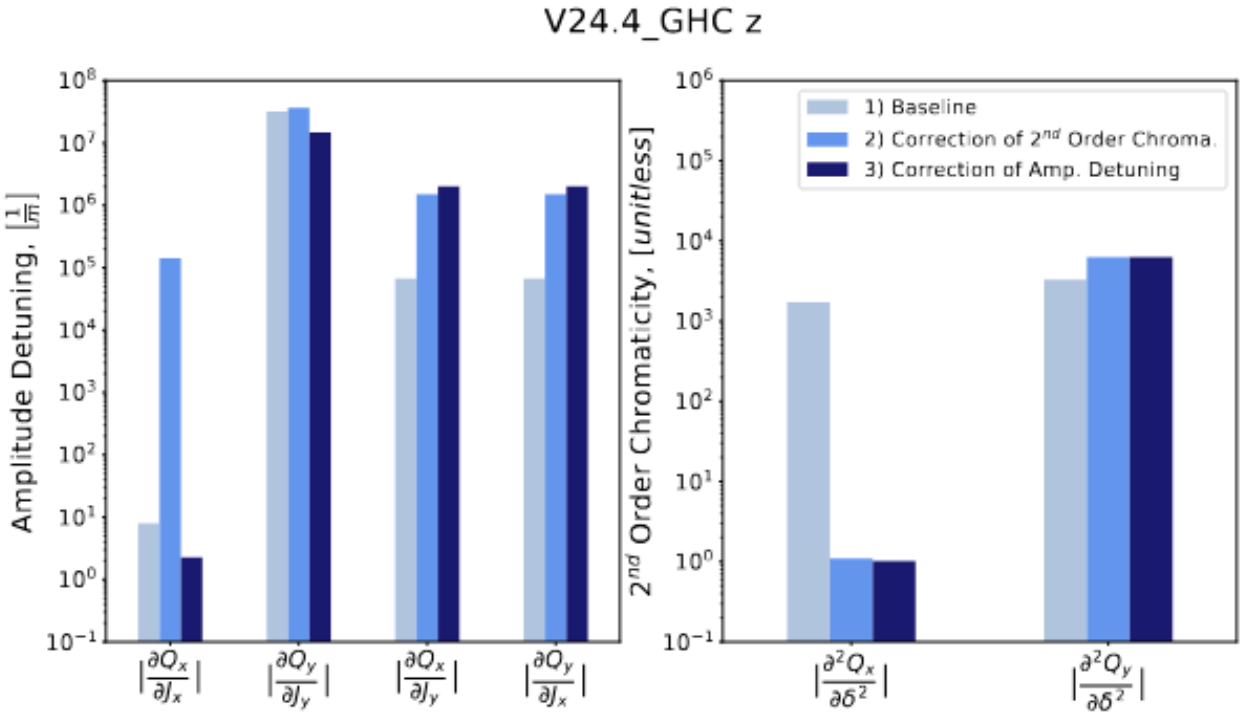
b3 errors in arc dipoles

Talk: K. Skoufaris

Talk: Y. Dutheil

Exploring non-linear regime

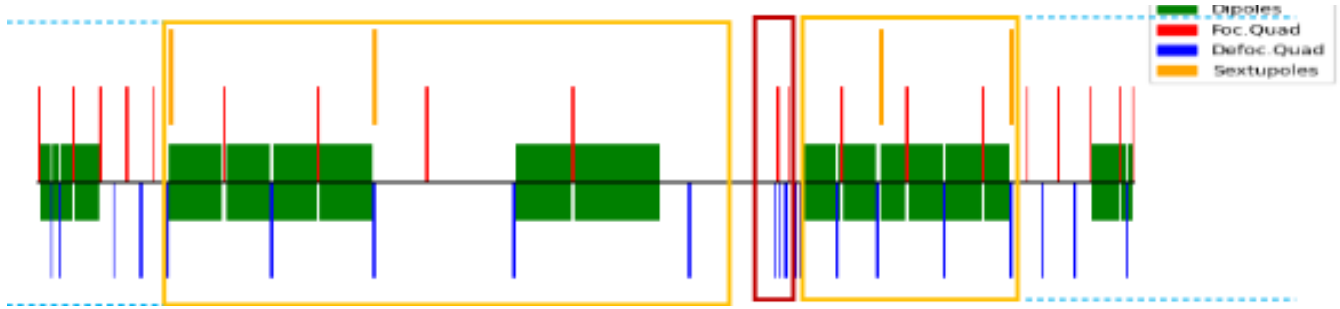
- High-performing colliders are impacted more by non-linear optics
- Tight tolerances for multipole field errors could be relaxed when appropriate correction is applied
  - For example: spool piece sextupoles next to dipoles in LHC
- Case study: aim correcting amplitude detuning and second-order chromaticity at the same time
  - 4 octupoles installed
  - Correction sequence successfully demonstrated
  - Impact on DA and MA under investigation

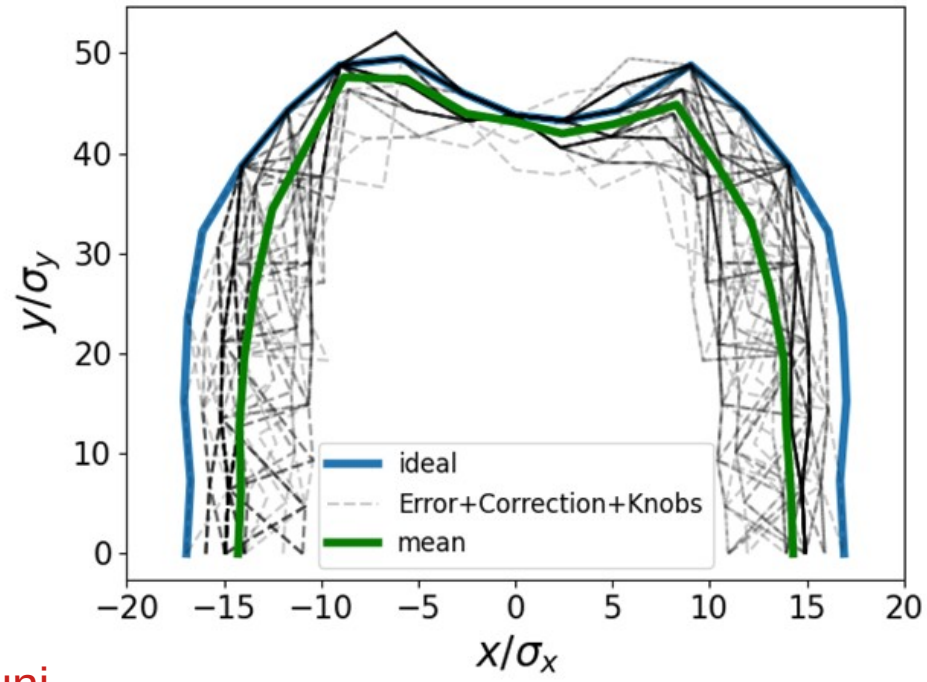


Poster: P. Hunchack

IP-tuning

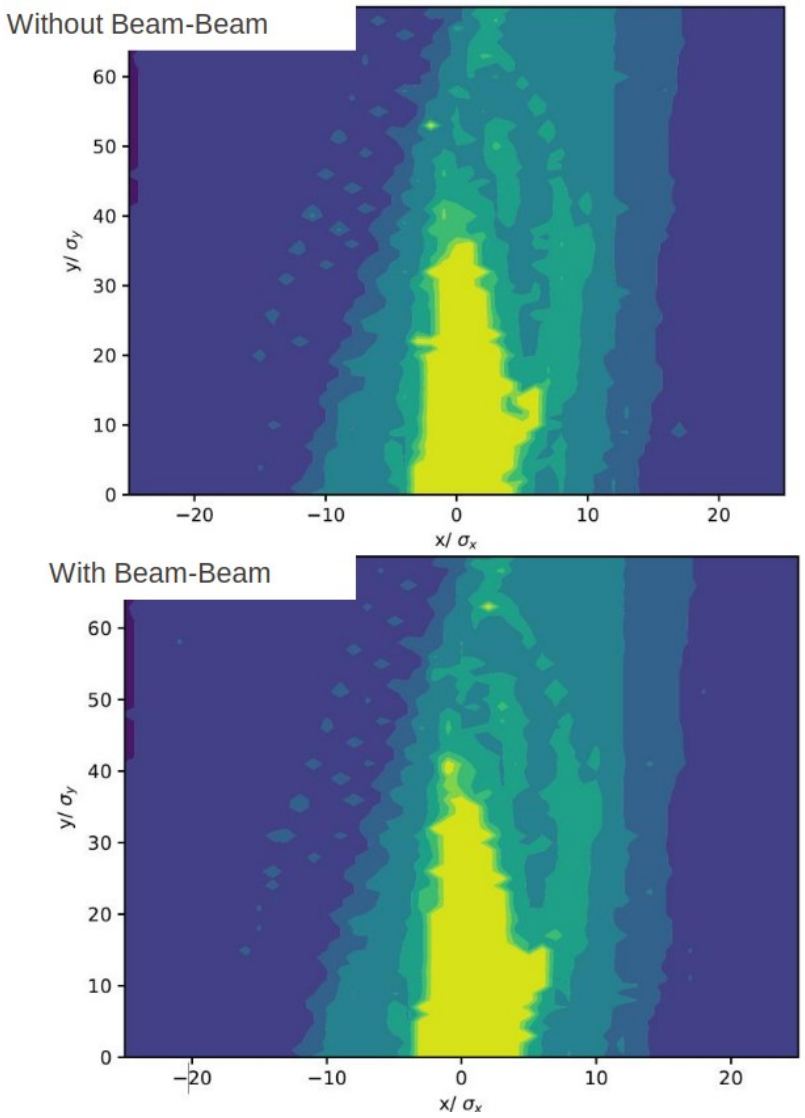
- Global optics tuning does not include interaction region → design of dedicated IP tuning knobs
- Tuning knobs correct successfully beta, waist and dispersion without affecting DA or MA
- However 1 μm final focus misalignment already leads to emittance blow-up by ~1 pm
- → Very challenging IR optics
- → IR requires dedicated alignment strategy
- → Reviewed correction locations



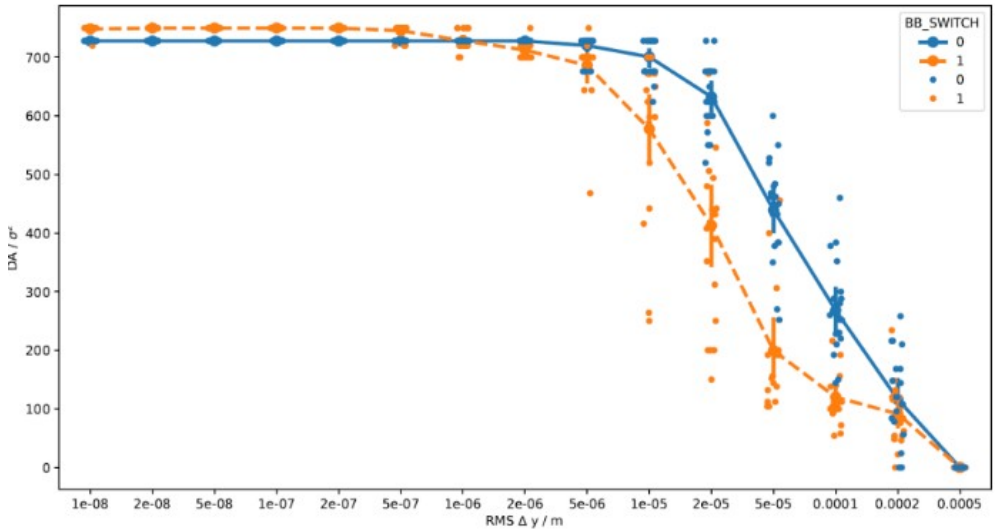


Talk: S. Jagabathuni

IP aberrations with beam-beam



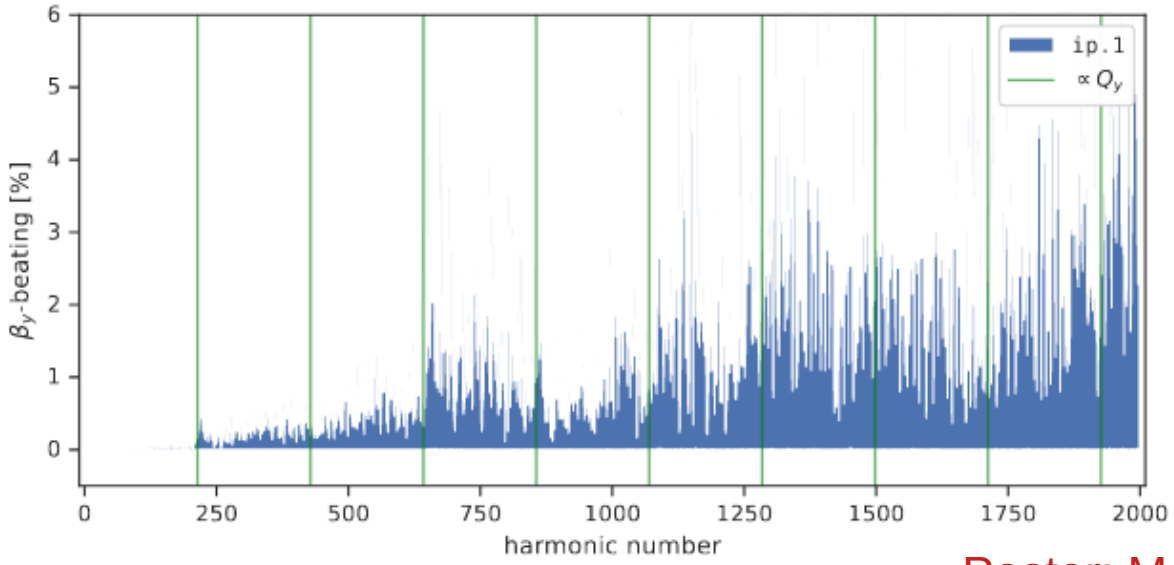
- Beam-beam interactions in combination with misalignments reduce DA and MA further
- Although acceptable DA lifetime reduced to only ~2 s
- → Possibly caused by MA reduction

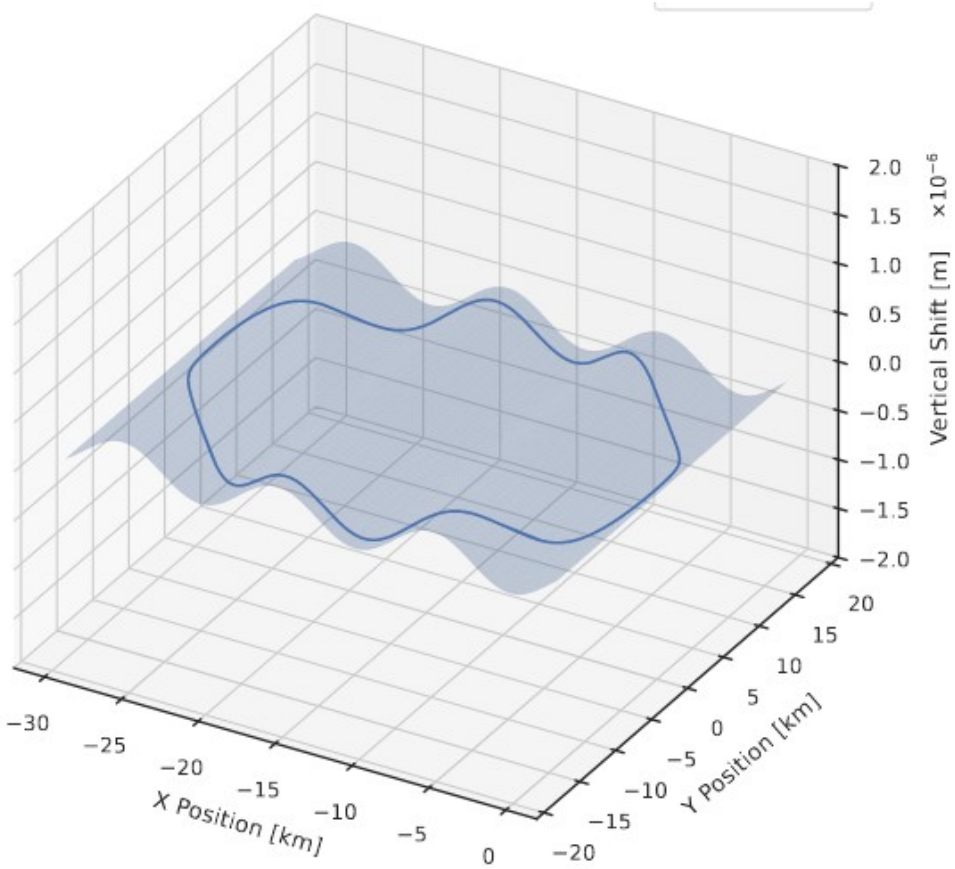


Talk: L. van Riesen-Haupt

Dynamic misalignments: Ground waves

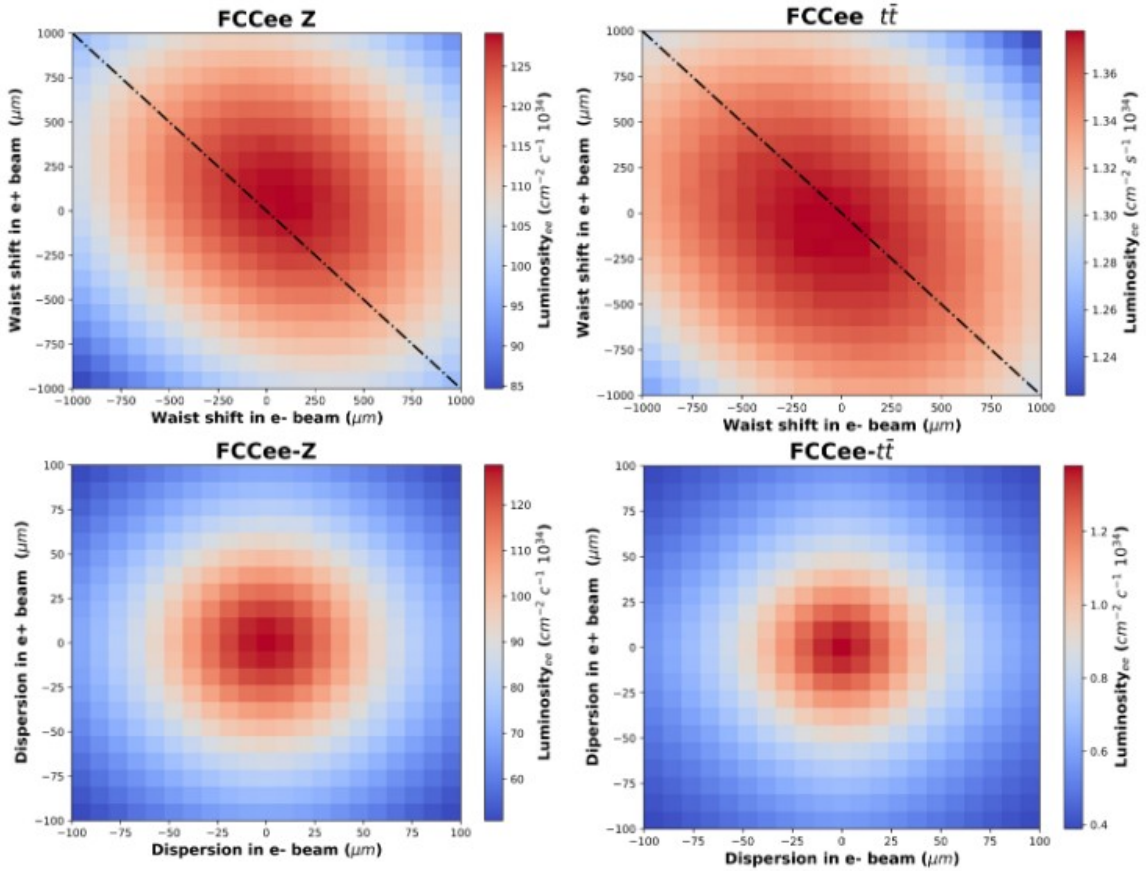
- First studies assume fixed ground waves at various harmonics
- Beta-beating increases with higher-order harmonics
- IP offset scales with amplitude of wave, ~ independent of harmonic
- Dynamic studies with tracking remain to be performed





Poster: M. Le Garrec

Luminosity optimization

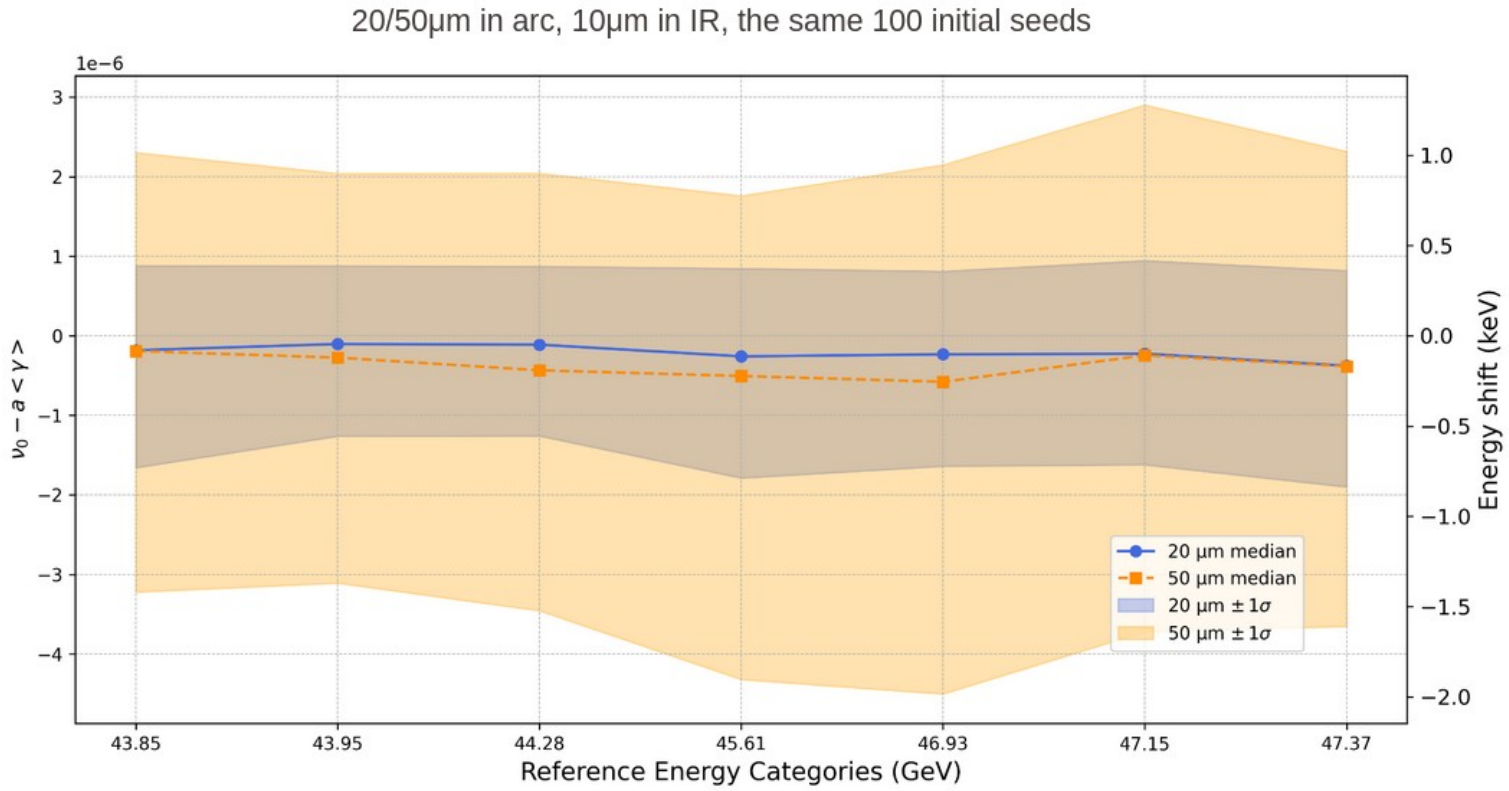


- Requires measuring Bhabha scattering, beamstrahlung and vertex detector hits
- At ttbar luminosity drops to
  - About 85% for ± 1 mm waist shift
  - About 40% for ± 0.1 mm vertical dispersion
- At Z slighty more sensitive
- Degradation of emittances to be included

Poster: V. Gawas

Polarization and spin tuning

- Orbit and optics errors could lead to depolarization effects and spin tune shifts
- Goal: below 100 keV systematic spin tune shift for realistic machine achievable for 50/ 10 μm arc/IR misalignments

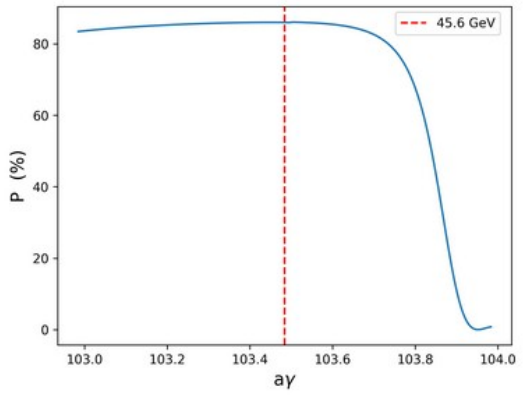


Talk: Y. Wu

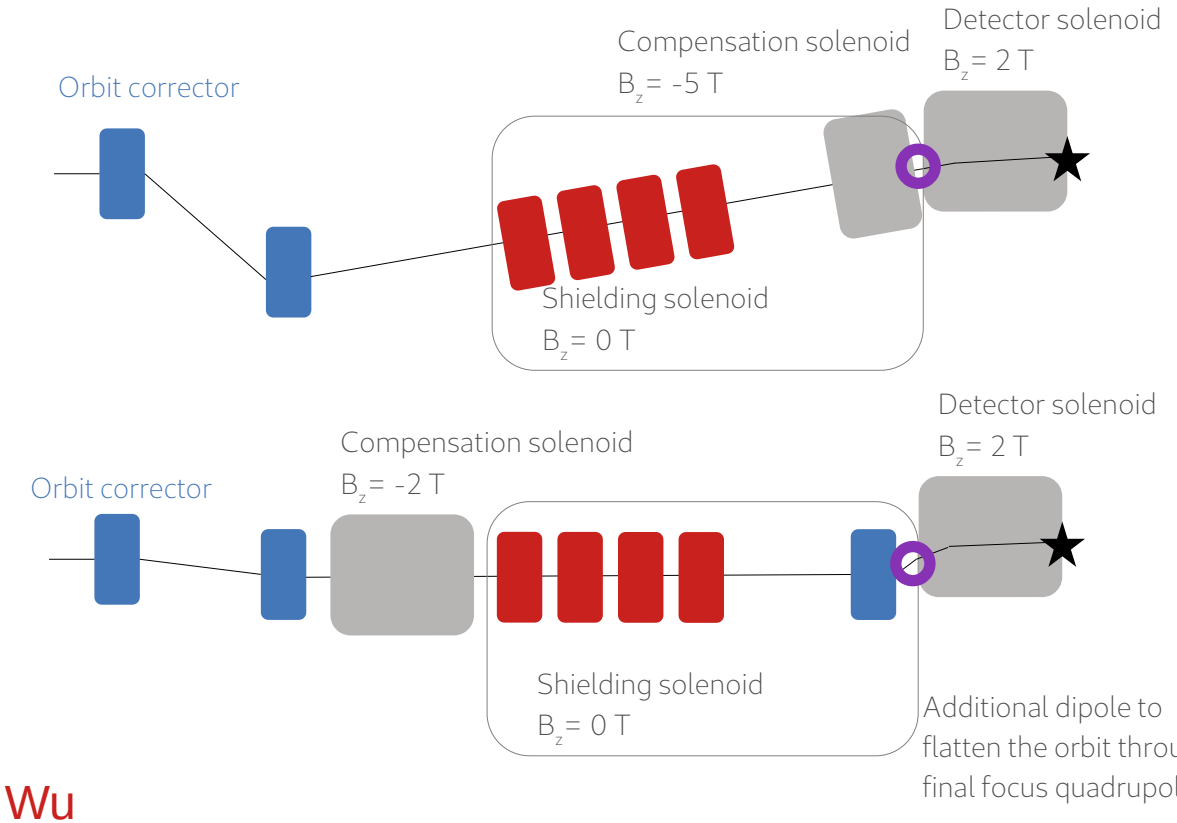
Non-local solenoid compensation scheme

- Compensation solenoids to correct for effects from detector solenoids
- Compensation solenoid either before or after final focus

- Studies performed in BMAD for non-local scheme
- Sufficient polarization for ideal lattice



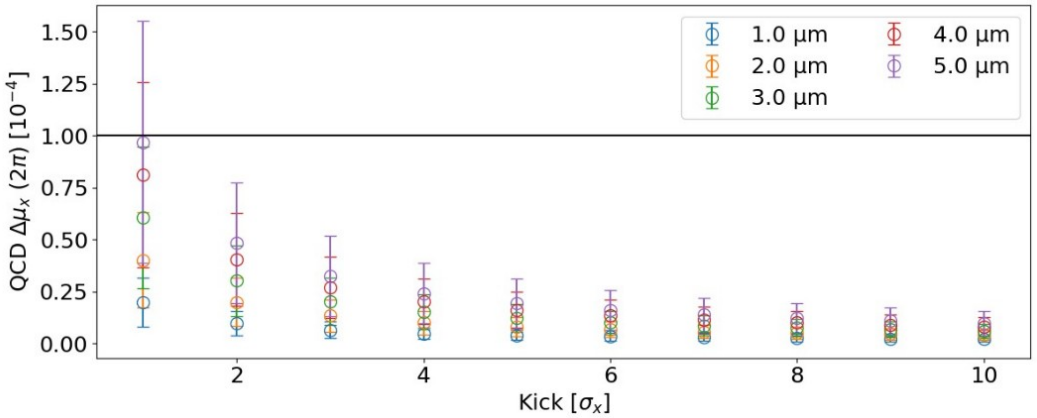
first order P near nominal energy



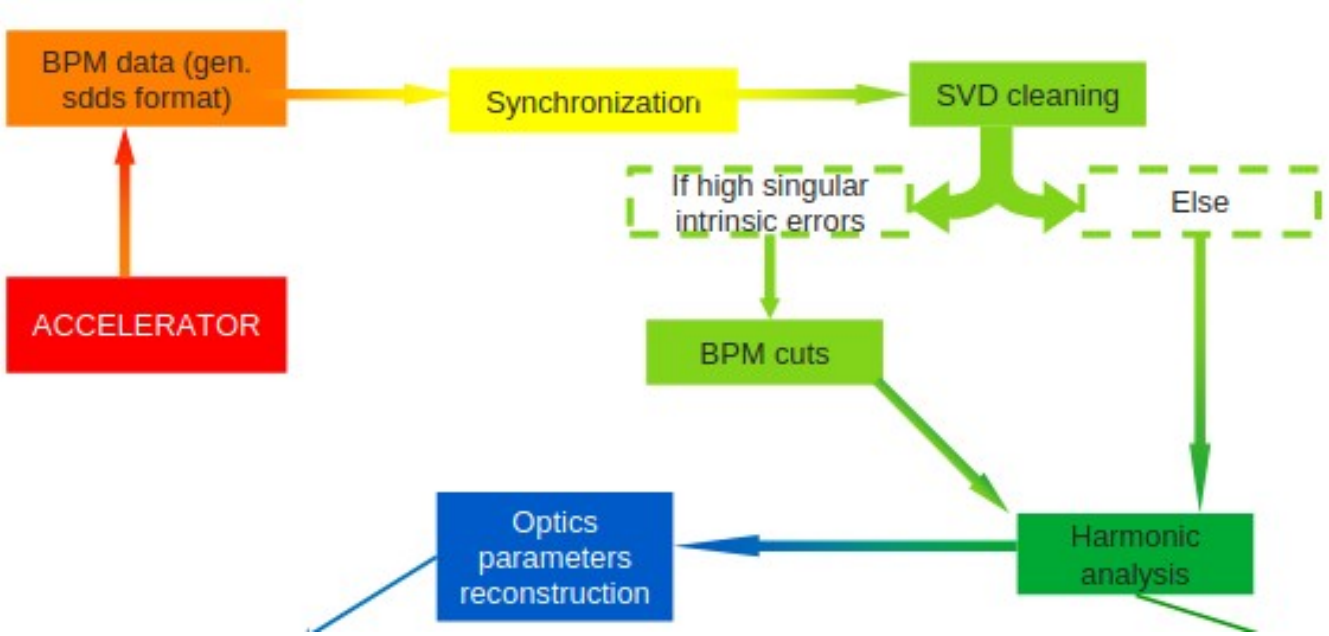
Talk: Y. Wu

Beam Position Monitors

- Installing them next to quadrupoles favorable over next to sextupoles
- Tight tolerances of about 1 μm for turn-by-turn reading and < 1 μm for orbit measurements
- Exploring of techniques to improve BPM reading
  - Special BPM selection
  - Machine learning

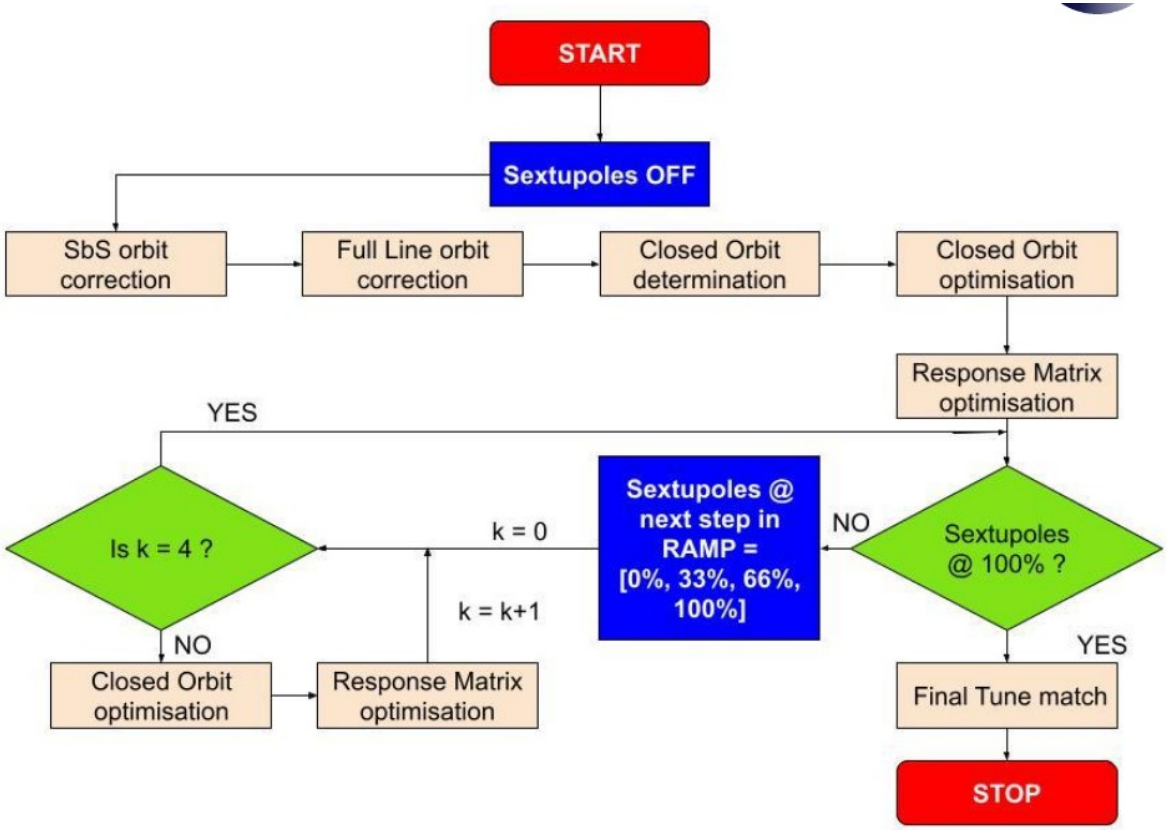


J. Keintzel

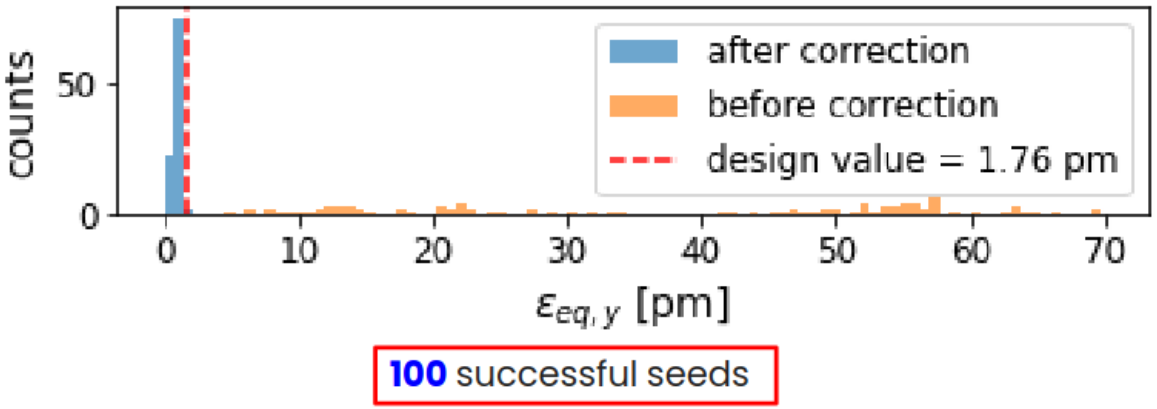


Poster: Q. Bruant

High energy booster tuning



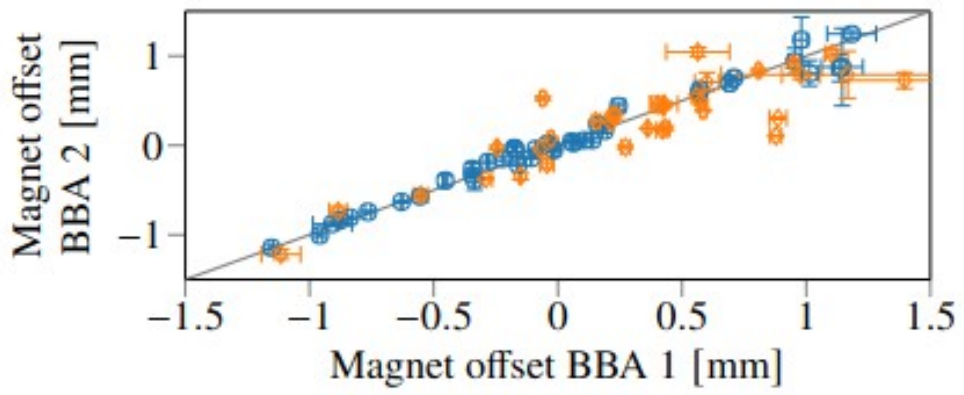
- Improved tuning algorithm developed
- Ramping sextupoles included
- Design emittance reached for almost all seeds

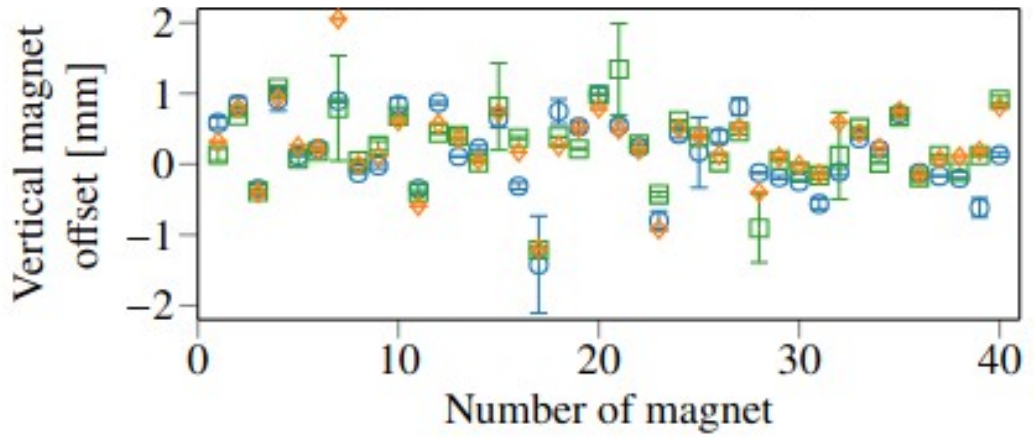


Poster: Q. Bruant

KARA – Beam based alignment

- Various parallel quadrupole BBA explored and deployed to synchrotron light source KARA at KIT
- Reproducibility studies perfomed
  - Results very reproducable if same method applied within several minutes
  - For different explored techniques errors of 242 µm horizontally and 351 µm vertically
  - Orbit drifts could be one of the main reasons

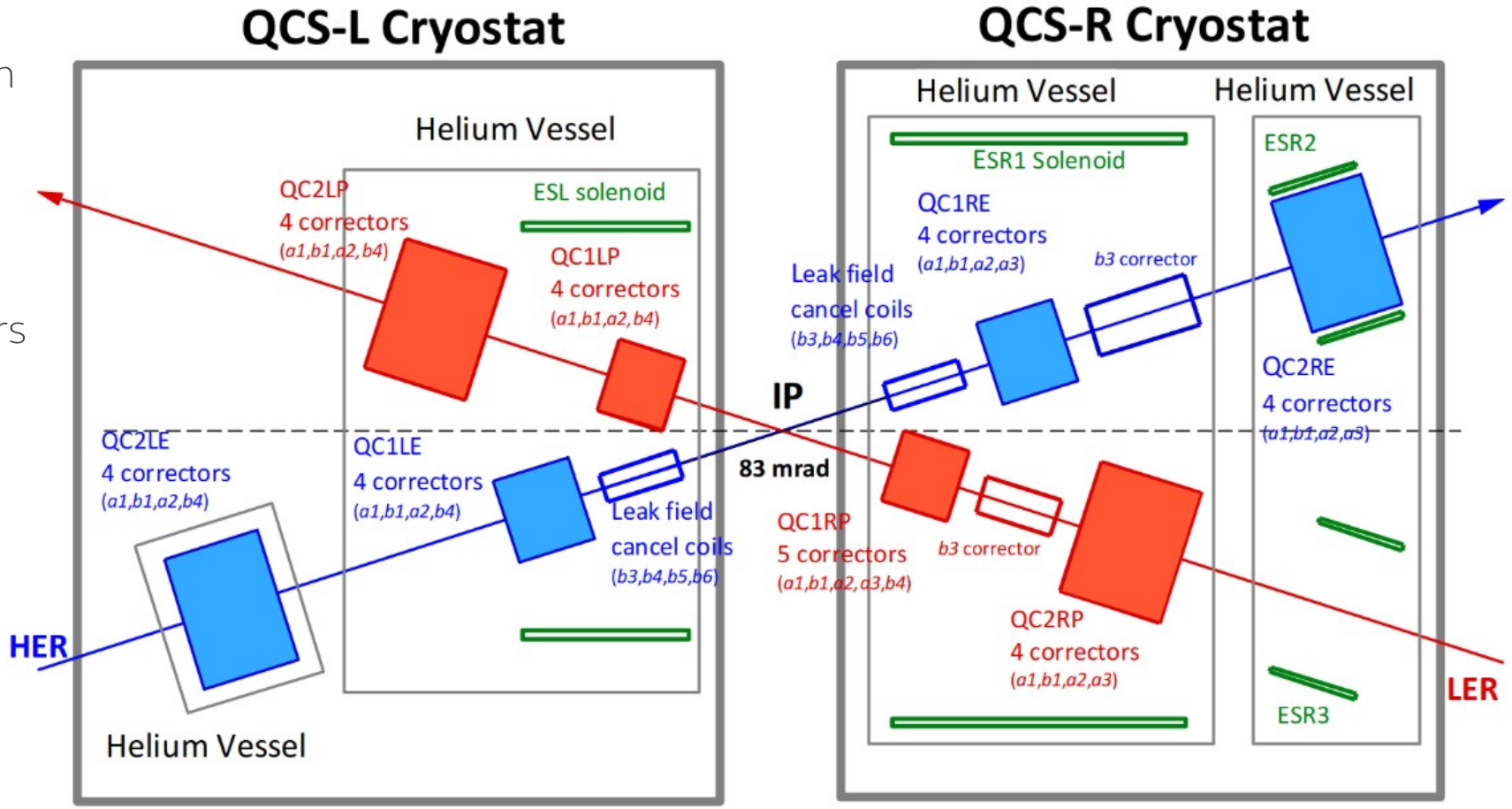




Talk: C. Goffing

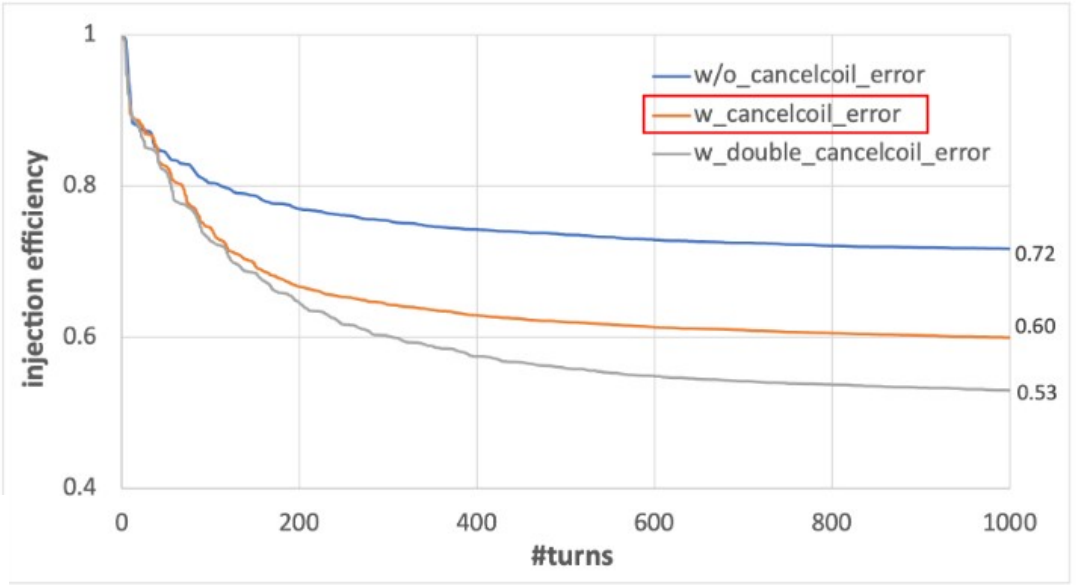
SuperKEKB – IR design

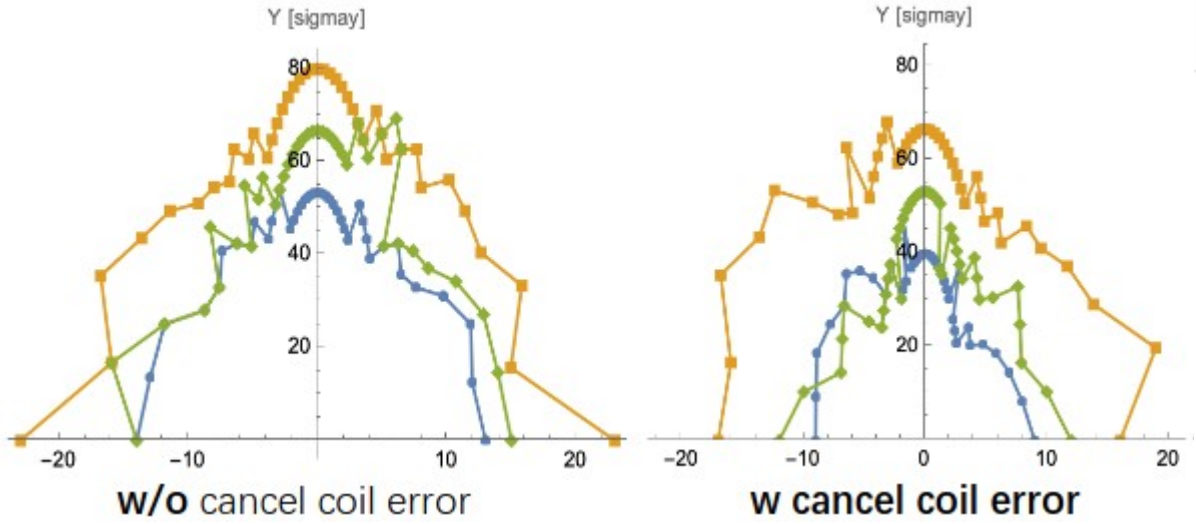
- Very complex design
- Straight magnet reference system
- Ballistic optics impossible
- Challenging alignment
- Cancel coil and leakage field errors



SuperKEKB – Cancel coil error

- In HER to correct leakage fields
- Due to manufacturing mistake → skew sextupole and octupole do not cancel
- → Decreases injection efficiency
- → Decreases DA

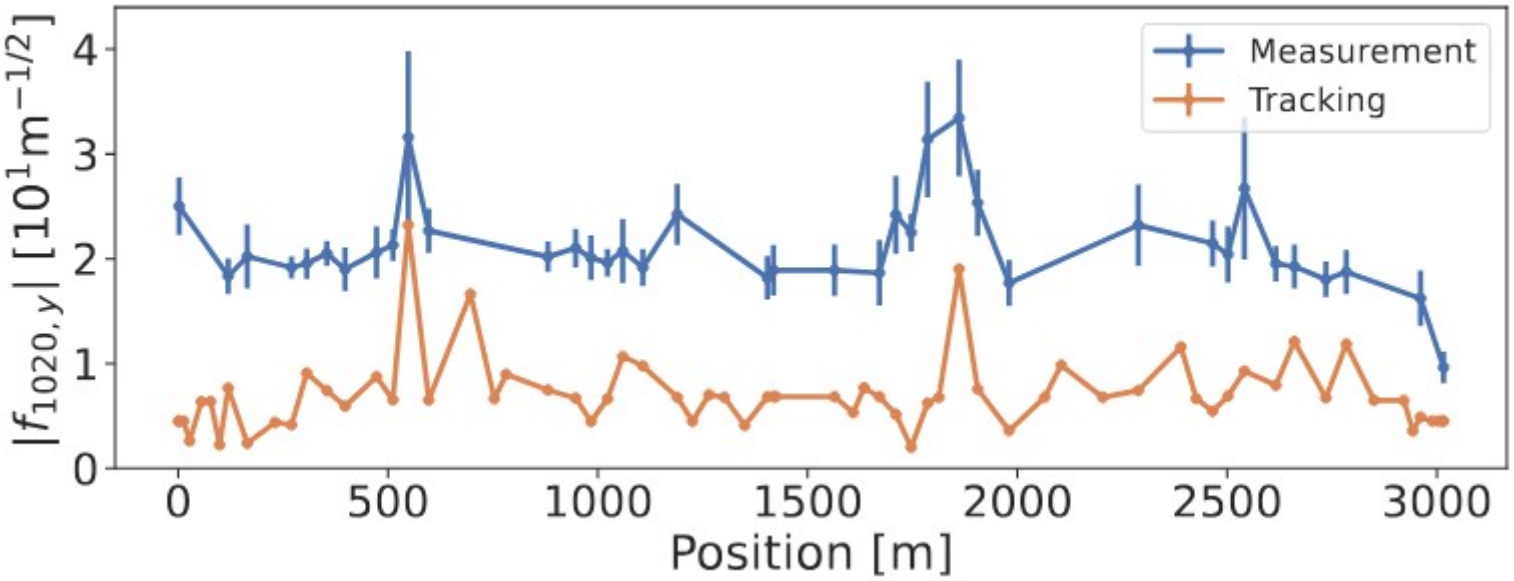




M. Li

SuperKEKB – Non linear optics

- First RDT measurements show descrepancy with model
- Further analysis needed to include correction for SR, decoherence, etc

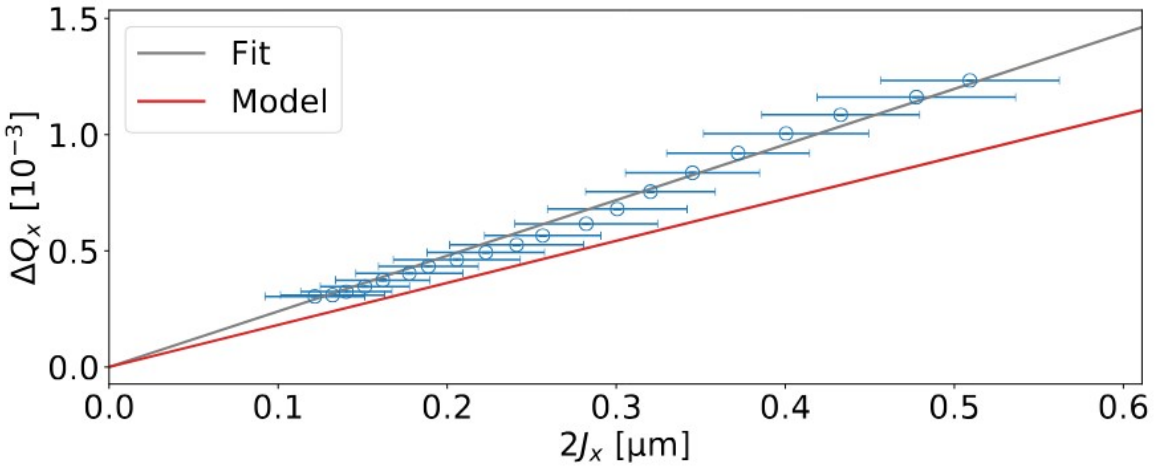


M. Le Garrec

SuperKEKB – Non linear optics

- First RDT measurements show descrepancy with model
- Further analysis needed to include correction for SR, decoherence, etc

- Discrepancy between measured and model amplitude detuning
- Tentatively larger error for more relaxed optics → to be understood



J. Keintzel

Summary and outlook

- FCC comissioning and tuning strategy developed and progress made at all steps

- Many lessons to be learned from SuperKEKB to understand colliders with significant SR losses
  - → Huge international team interested to tackle various observations
  - → SuperKEKB model in Xsuite currently being benchmarked against SAD

- FCC studies focus on studies on GHC optics at Z-energy
  - → Perform studies for other energy modes
  - → Perform studies for LCC lattice

Thank you !

Jacqueline Keintzel and Rogelio Tomas
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