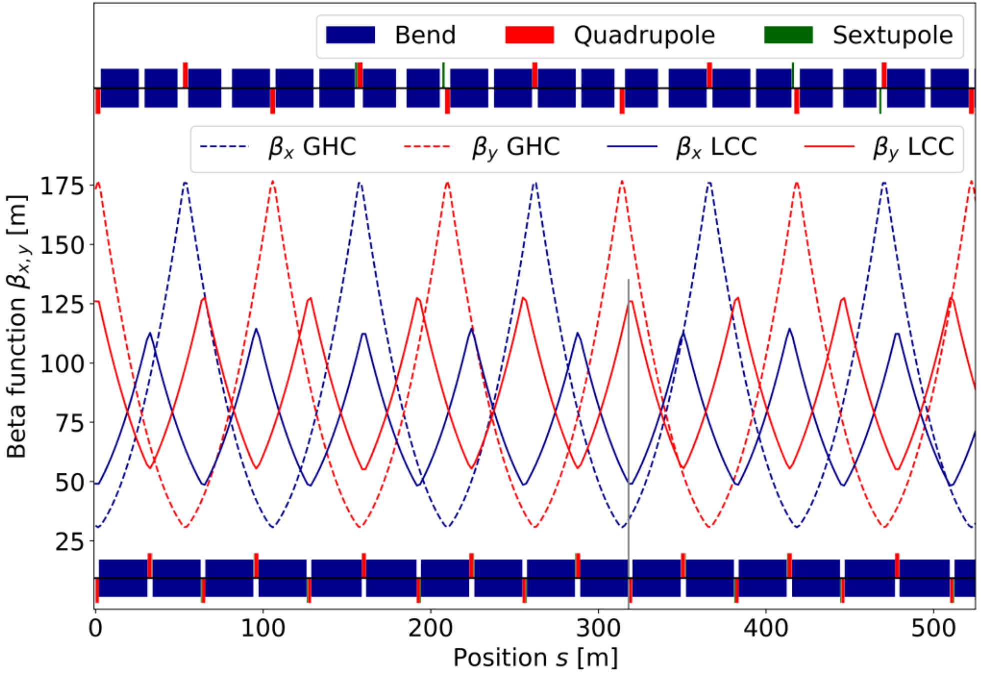
BBA for FCC-ee and Beam Test at KARA

C. Goffing, J. Keintzel, A.-S. Müller, M. Reißig, F. Zimmermann

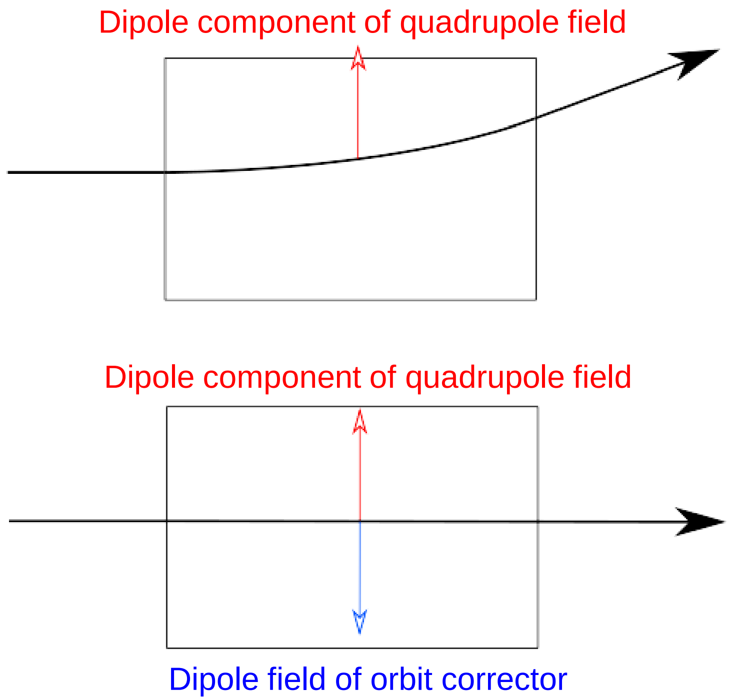
Motivation for BBA

- High demands on accelerator optics
- Around 80 km arc section
- Focus on arc quadrupole BBA
- Use BBA to relax mechanical alignment tolerances for quadrupoles and sextupoles
- Reduce effective misalignment by steering beam towards centre of magnets
- Parallel BBA for fast offset estimation
- 2 proposed lattices GHC and LCC



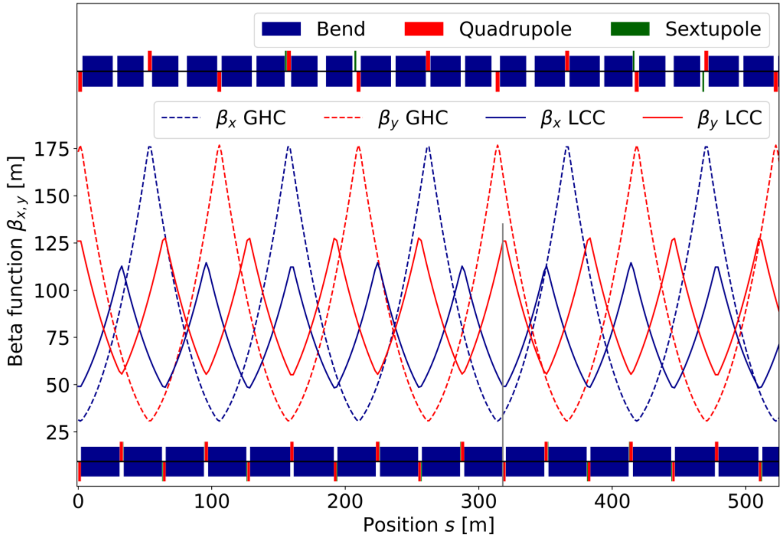
BBA Approach

- Compensate kick of dipolar field components using orbit corrector
- Variation of quadrupole strength
- Leads to different kick and different corrector strength → Keep orbit constant
- Magnet offset proportionality factor between quadrupole and corrector strength
- Lower accuracy expected if fields do not overlap



Simulation Settings

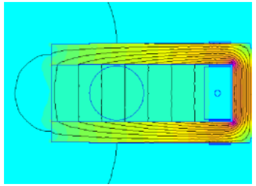
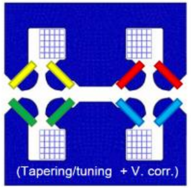
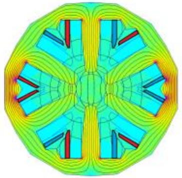
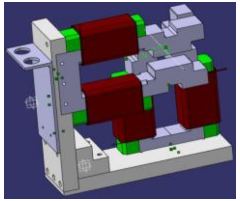
- Xsuite simulation using 51 seeds
- GHC and LCC lattice (V24_3)
- High β* optics
  - β^*_x 33 cm (30 cm) for GHC (LCC)
  - β^*_y 7 mm
- Arc quadrupole misalignment of 100 μm standard deviation
- 1 μm BPM noise
- BBA for one focusing and defocusing family



Quadrupole family	Strength in Tm^{-1} GHC	Strength in Tm^{-1} LCC	Length in m GHC	Length in m LCC
QD3	-1.451	-2.071	2.90	1.86
QF4	1.451	1.709	2.90	2.40

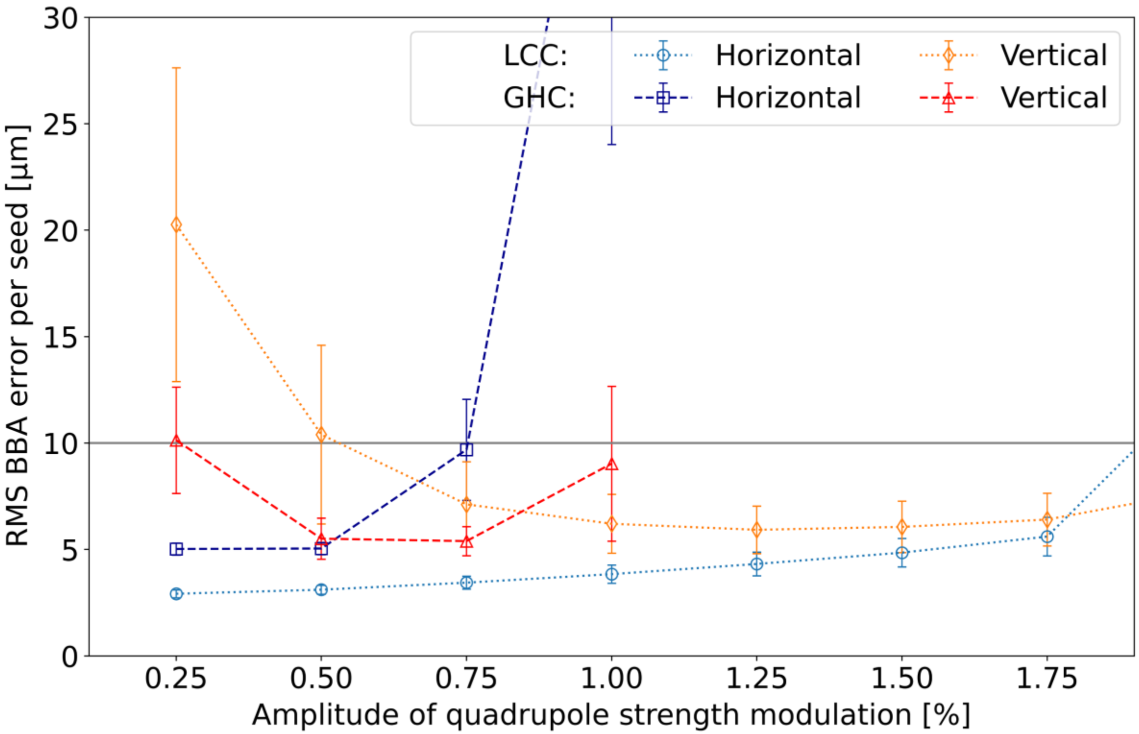
FCC Corrector Layout Options

References on Slide 16

Location	Corrector Type		Corrector plane	Advantage	Disadvantage
Dipole	Trim windings		Horizontal	No additional space required	Contribution of higher order magnet field components and possible shift of magnetic centre
Quadrupole	Trim windings		Vertical (and horizontal)		
Sextupole	Trim windings		Horizontal and vertical		
Dedicated magnet	Corrector magnet		Horizontal and vertical	Easier magnet design	Additional space required

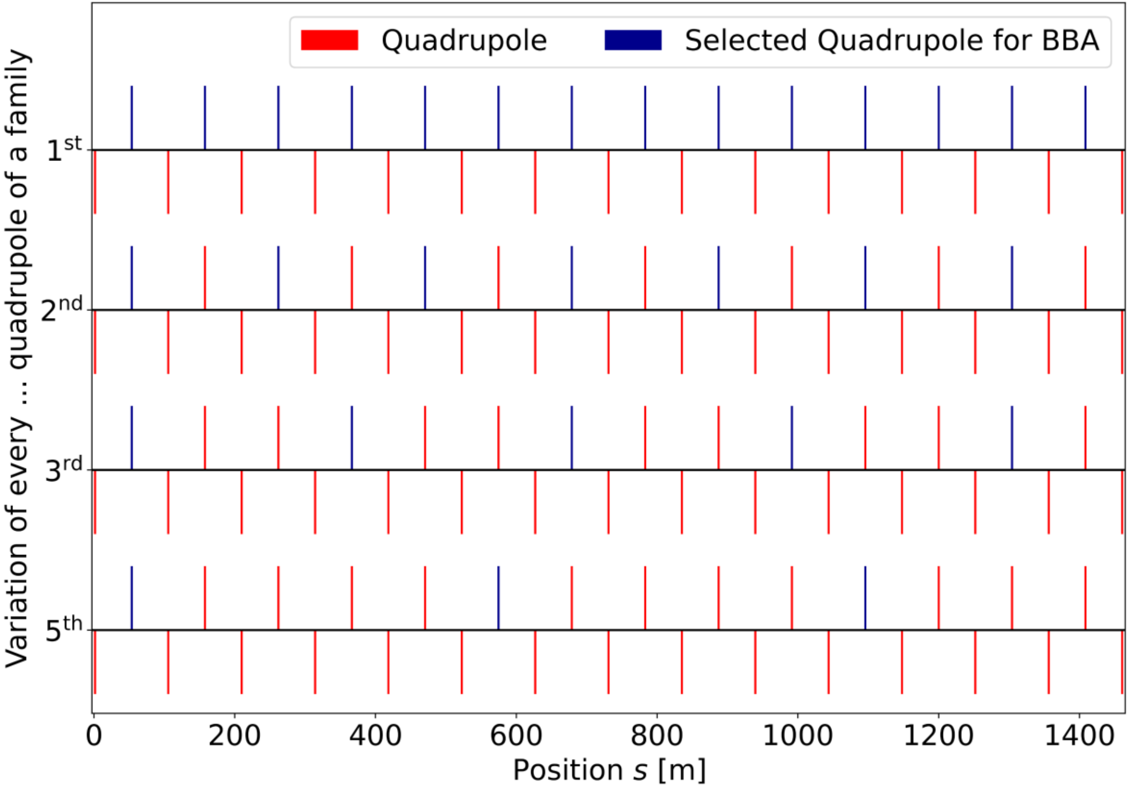
Dependence on Modulation Amplitude

- Modulation of every 3rd magnet
- In vertical plane parabola like curve with optimum
- Lower amplitudes better in horizontal plane
- Amplitudes for highest accuracy:
  - around 0.5 % (GHC)
  - around 1 % to 1.5 % (LCC)



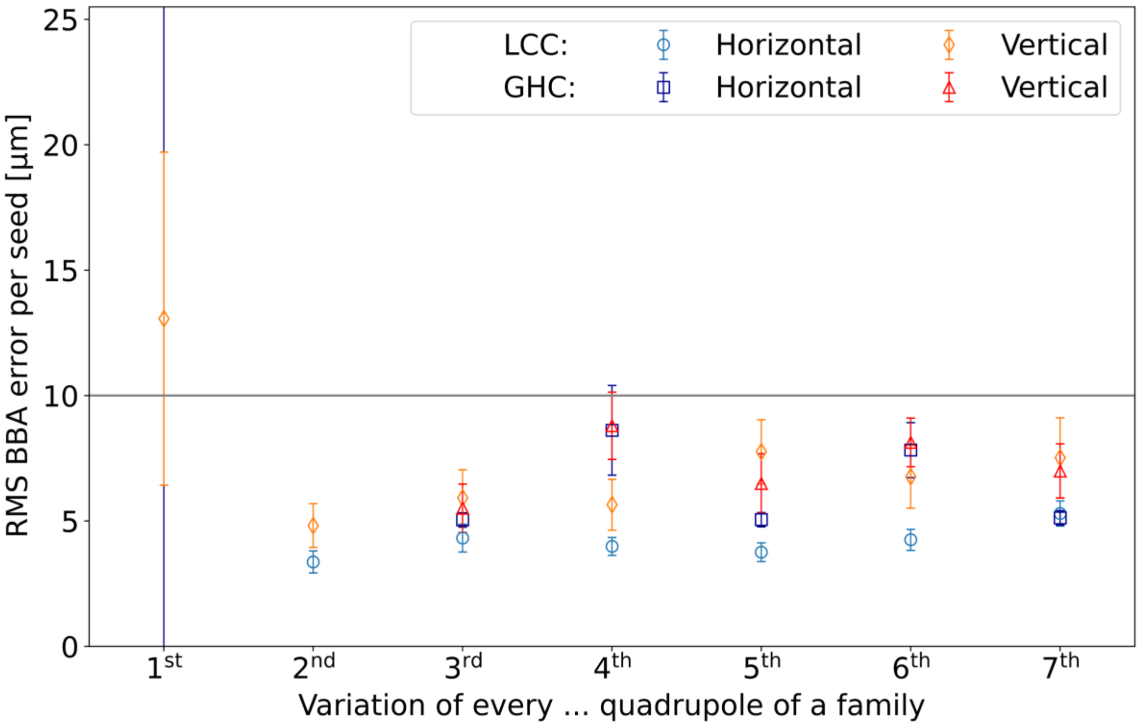
Dependence on Magnet Selection

- Variation of number and distance between modulated quadrupoles



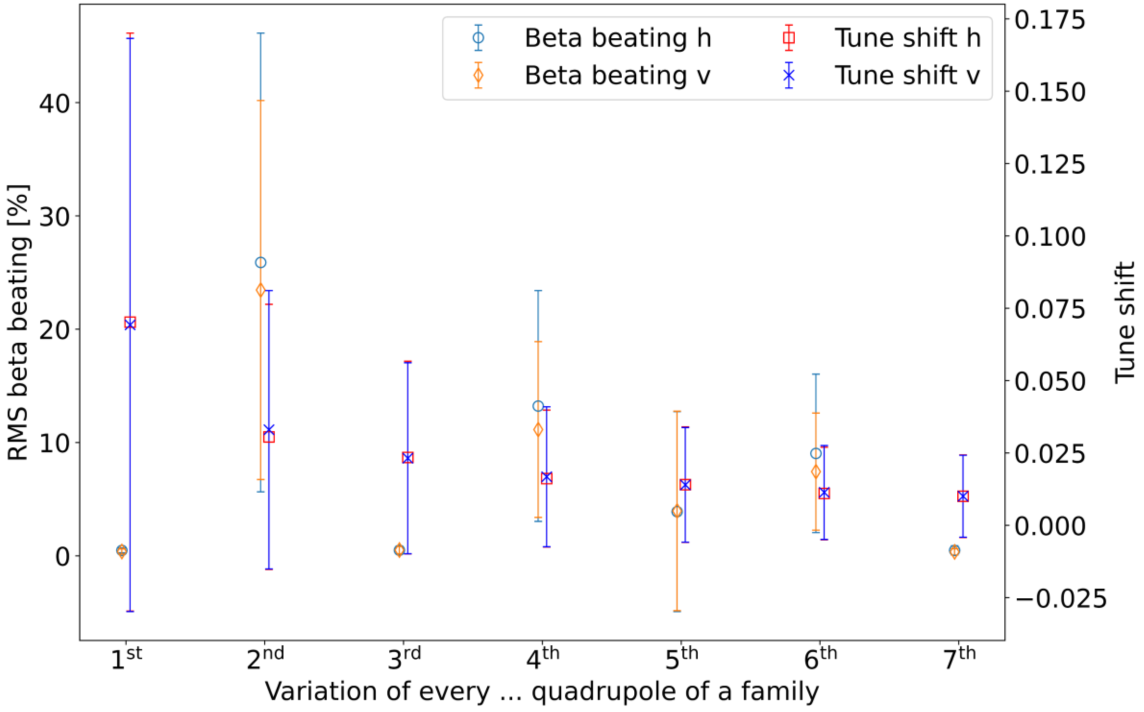
Dependence on Magnet Selection

- Modulation amplitude
  - 0.5 % for GHC
  - 1.25 % for LCC
- Modulation of all magnets of a family (or every second for GHC) in an arc section has a much larger errors
- Up to 30 magnets could be modulated simultaneously
- Optics changes could limit magnet number and modulation amplitude



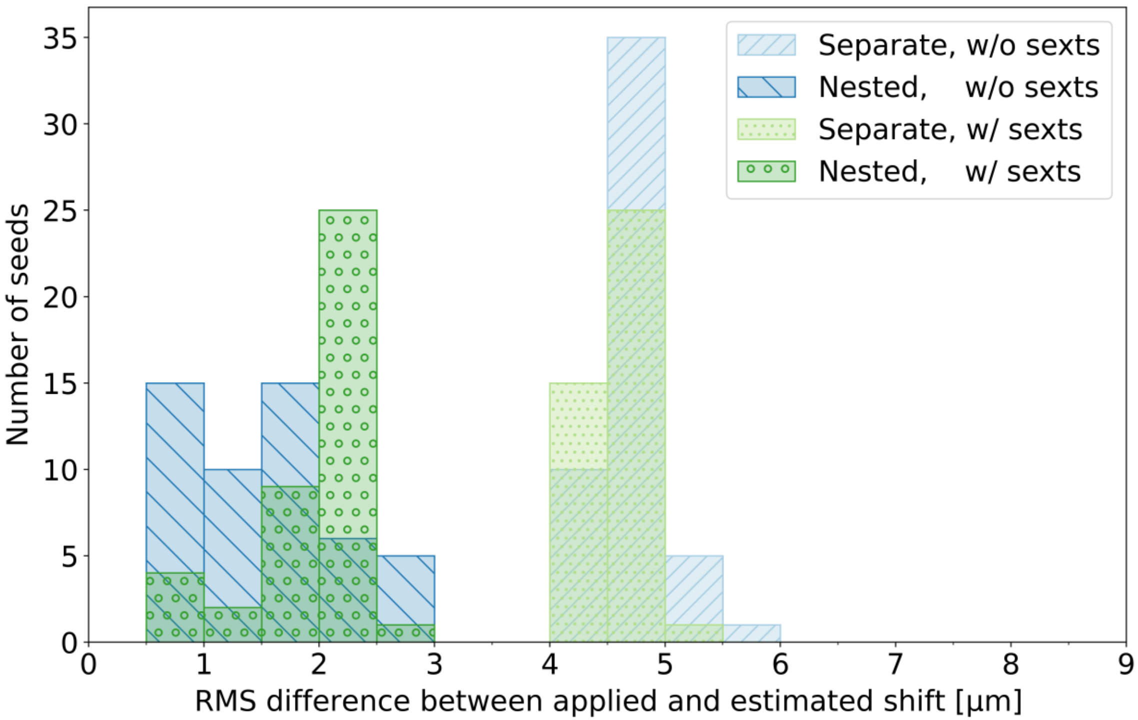
Optics change during BBA

- Optics changes possible limitation for number of magnets and modulation
- GHC lattice with 10 seeds
- Tune shifts decrease with fewer modulated quadrupoles
- Beta beating depends on magnet selection
    - For every, every 3rd and 7th low beta beating due to favourable phase difference
    - Every 5th equal to unit cell of lattice
    - Large beating for every 2nd or multiples thereof



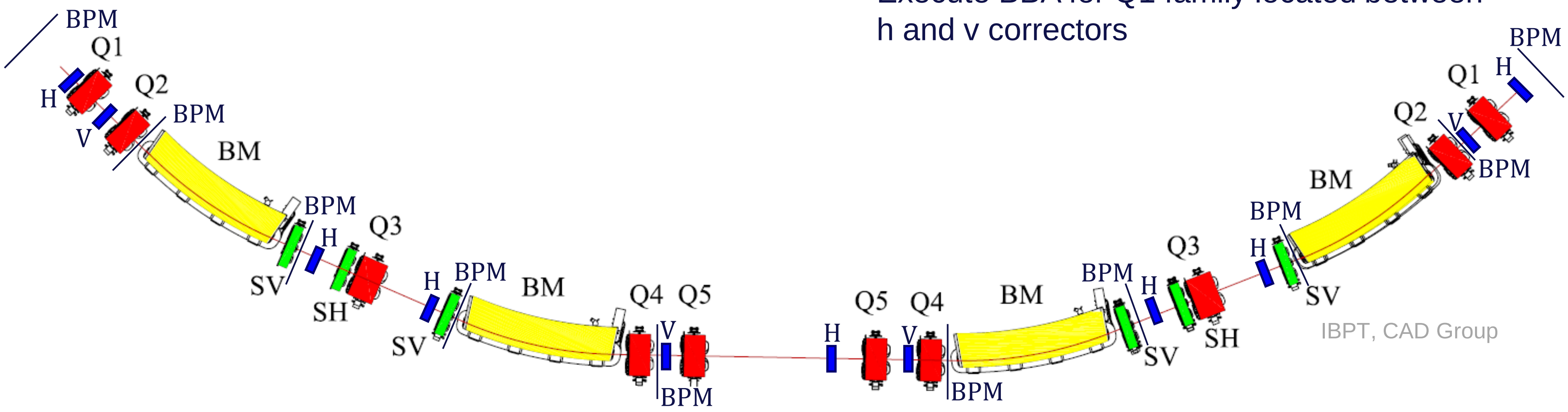
Impact of Corrector Location and Sextupoles

- Vertical BBA for GHC lattice
- Nested correctors in quadrupoles
- Separate correctors 10 cm behind quadrupoles
- Sextupoles turned off or with nominal strength do not change the BBA accuracy
- Accuracy decreases with larger distance between quadrupole and corrector



KArlsruhe Research Accelerator (KARA)

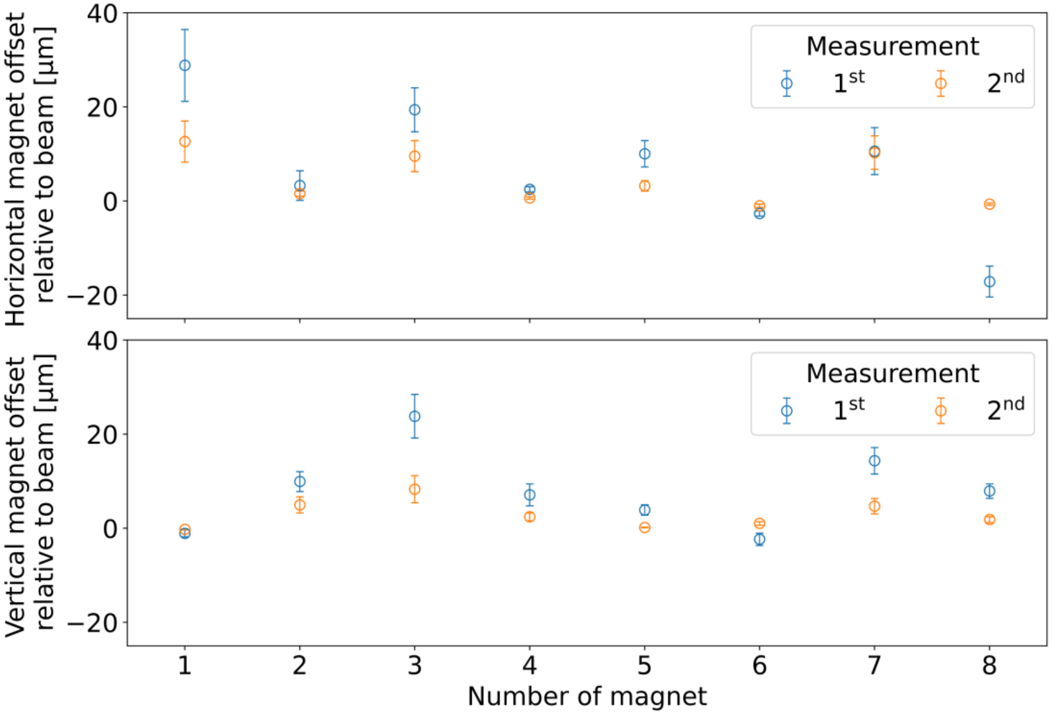
- Double bend achromat lattice
- 5 quadrupole families
  - 8 magnets in each family connected in series
  - 3 horizontal focusing
  - 2 horizontal defocusing
- Orbit correctors
  - 28 horizontal
  - 16 vertical
- 39 beam position monitors
- Execute BBA for Q1 family located between h and v correctors



IBPT, CAD Group

Beam test at KARA

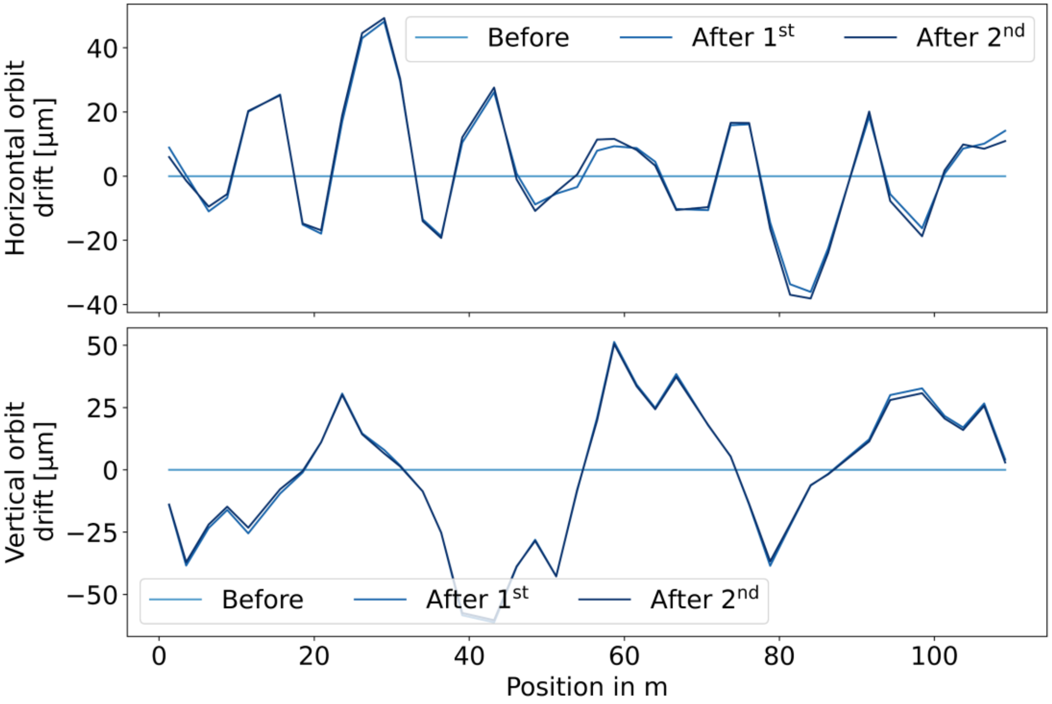
- Proof-of-principle
- Variation of strength of whole magnet family
- Use orbit correctors close to selected magnets for orbit correction
- One fill
- Multiple measurements with different modulation amplitudes
- Offset reproduction within 20 µm



Beam test results

Requirements for BBA

- Large orbit change for good orbit correction
- Small strength variation to minimise optics changes
- High BPM resolution
- Corrector magnets located close to quadrupoles
- Different BBA results if orbit drifts due to the estimation of the quadrupole offset relative to the beam



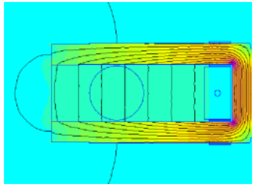
Summary and Outlook

- First BBA simulations with smaller misalignment
- For FCC target accuracy of 10 μm to 20 μm seems achievable
- Similar accuracies for GHC and LCC achievable
- Tuning parameters:
  - Magnet selection
  - Modulation amplitude
- First proof-of principle test at KARA

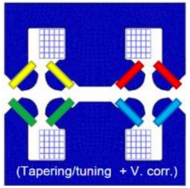
- Further studies using
  - Realistic misalignment of dipoles, quadrupoles, sextupoles, girders and BPMs
  - Different orbit corrector locations
  - Different quadrupole selection for BBA
- BBA for quadrupoles in interaction regions
- Sextupole BBA

Thank you
for your attention.

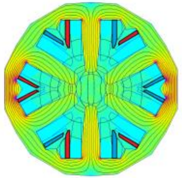
FCC Corrector Layout Options - References



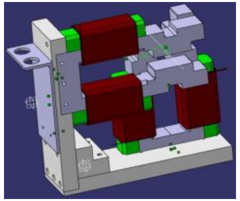
M. Benedikt *et al*., Future Circular Collider Feasibility Study Report Volume 2: Accelerators, technical infrastructure and safety, CERN Geneva, Tech. Rep., 2025 DOI: 10.1103/CERN.EBAY.7W4X



J. Bauche, TE-MSC Seminar, https://indico.cern.ch/event/1277275/



M. Benedikt *et al*., Future Circular Collider Feasibility Study Report Volume 2: Accelerators, technical infrastructure and safety, CERN Geneva, Tech. Rep., 2025 DOI: 10.1103/CERN.EBAY.7W4X



B. Keil, https://indico.psi.ch/event/10519/contributions/26688/attachments/17693/26658/2020_1130__DLS2-SLS2-Echange-Meeting_Keil_02_FOFB.pdf