Beam-Based Alignment
and
Optics Measurements

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FCC Week 2023
London, United Kingdom
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Overview FCC-ee

- 4-fold superperiodicitiy, super-symmetry and possible Interaction Points (IPs)

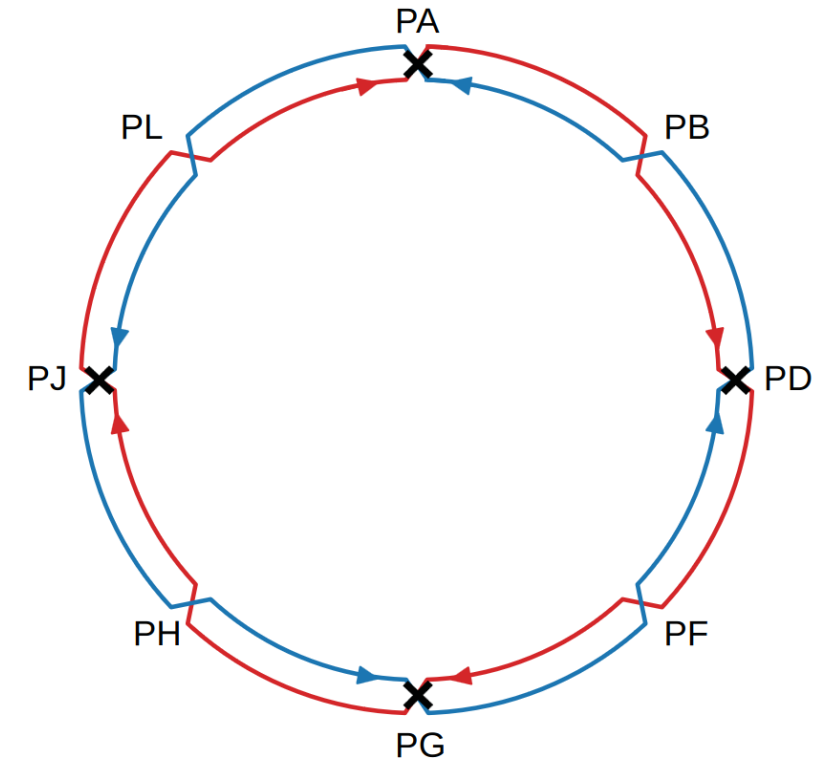- Designed for high precision physics experiments

  - Center-of-mass energy (E_{CM}) and boost determination

    - → ECM calibration, polarization and monochromatization

      Sessions: Wednesday 13:30 – 15:00, Thursday 08:30 – 10:00

  - Well controlled orbit and optics

    - → Optics tuning team

      Session: Wednesday 08:30 – 10:00

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FUTURE
CIRCULAR
COLLIDER

Achieving the Design Values

•

• Mechanical alignment

• Orbit and optics measurements

• Beam based alignment

• Optics and emittance tuning

Achieving the Design Values

Challenging and time
consuming for ~ 100 km
circular machine

Extrapolation:
25 teams in 4 months for main
components

H. Mainaud Durand

-
- **Mechanical alignment**

- Orbit and optics measurements

- Beam based alignment

- Optics and emittance tuning

Idea/Goal:
Relax mechanical
alignment tolerances and
use beam for alignment

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Achieving the Design Values

-

- Mechanical alignment

- Orbit and optics measurements

- **Beam based alignment**

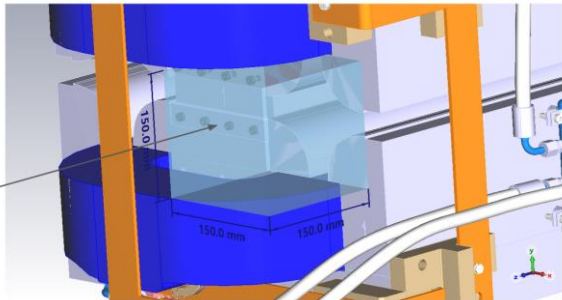- Optics and emittance tuning

Relaxes mechanical alignment tolerances

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Achieving the Design Values

Beam based measurements depend on precision of beam instrumentions (BPMs, etc.)
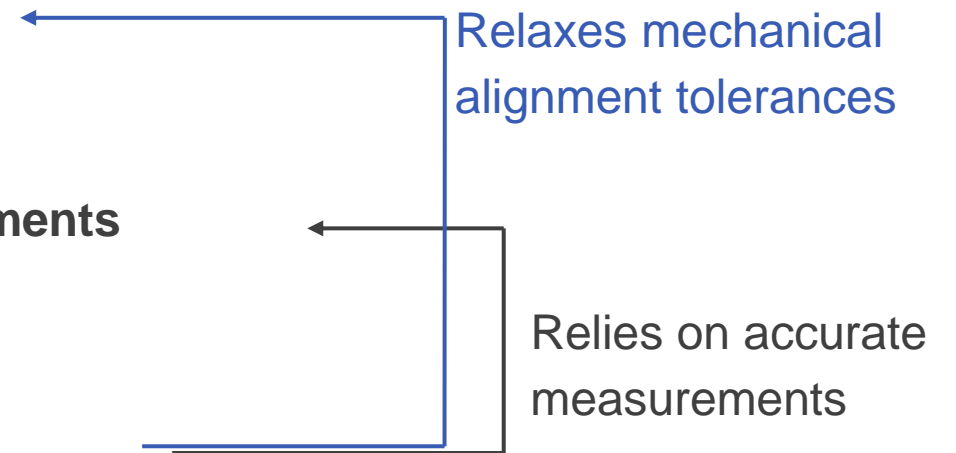
BPM fits in this blue box

150.0 mm

Courtesy: M. Wendt

-

- Mechanical alignment

- **Orbit and optics measurements**

- **Beam based alignment**

- Optics and emittance tuning

Relaxes mechanical alignment tolerances

Relies on accurate measurements

Achieving the Design Values

-
  - Mechanical alignment

  - Orbit and optics measurements

  - Beam based alignment

  - **Optics and emittance tuning**

Relaxes mechanical alignment tolerances

Relies on accurate measurements

Target parameters easier reached

Achieving the Design Values

-

- Mechanical alignment

Explored here with focus on the arcs for the Z-lattice

- Orbit and optics measurements

- Beam based alignment

- Optics and emittance tuning
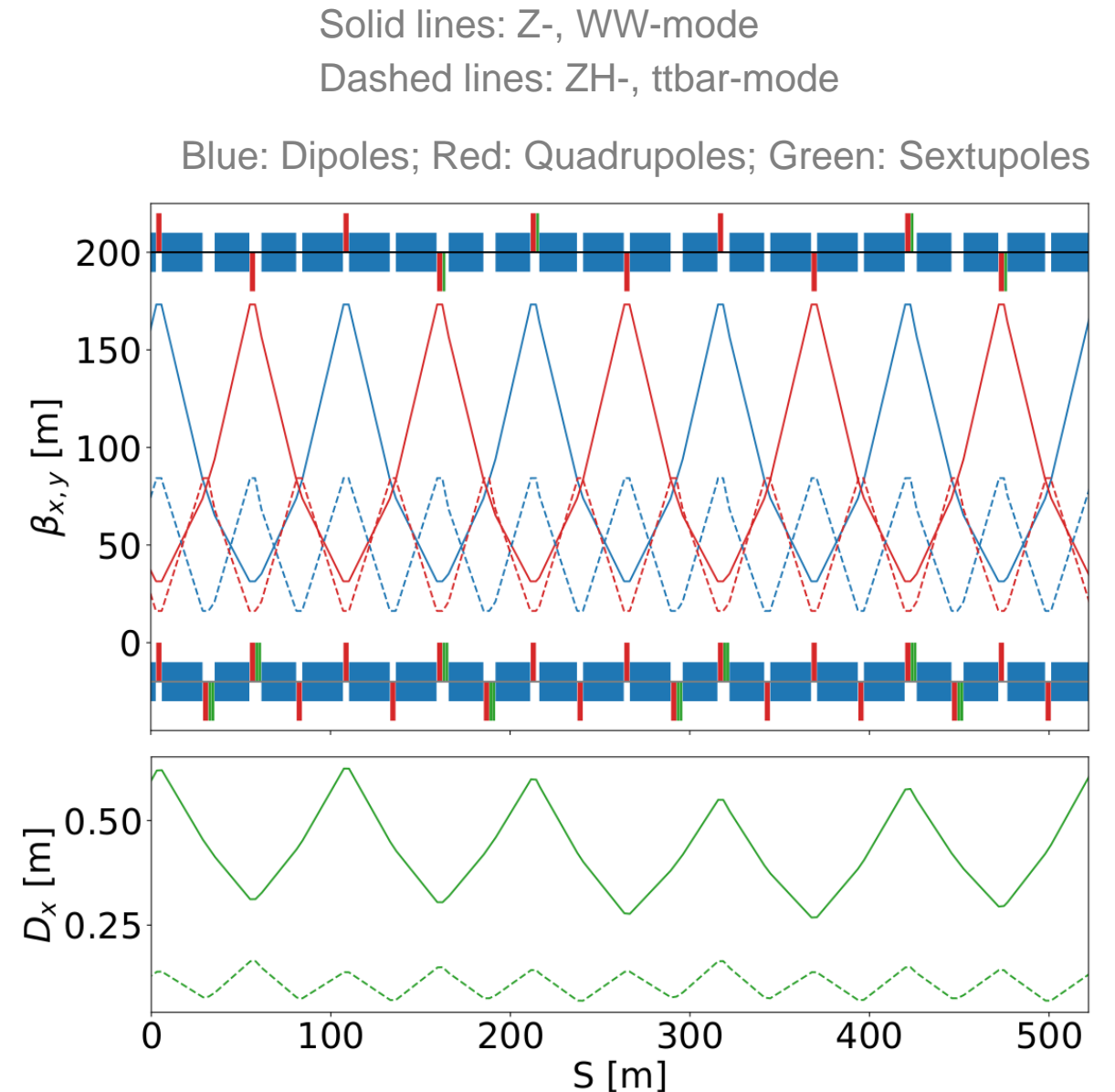
Relaxes mechanical alignment tolerances

Relies on accurate measurements

Target parameters easier reached

Arc Lattice

- Periodic FODO-cell structure

- Make up about 80 % of the FCC-ee lattice

- Dipole lengths: 20 - 30 m

- Quadrupole lengths: 2.9 m or 1.8 m

- Placement and number of orbit correctors and BPMs to be decided

Solid lines: Z-, WW-mode
Dashed lines: ZH-, ttbar-mode

Blue: Dipoles; Red: Quadrupoles; Green: Sextupoles

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Short Straight Section

Arc Sextupoles (S.)

- ~ 600 elements installed
- Non-interleaved scheme
- Strong impact on optics
- More critical than quadrupoles

BPM

- ~ 1500 elements installed
- H and V measurement
- Here: 0 m length
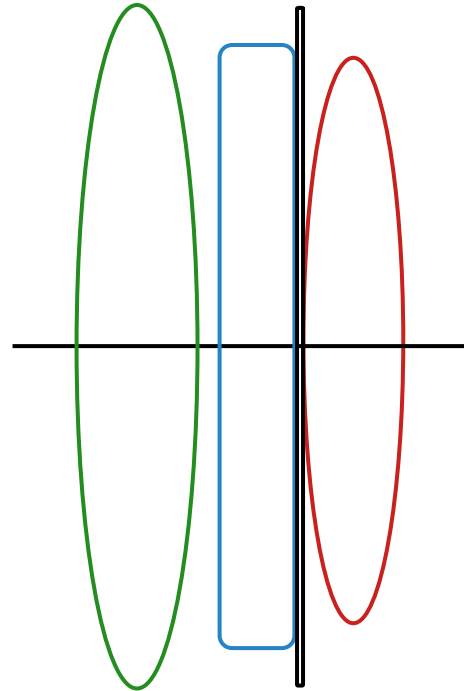
Arc quadrupole (Q.)

- ~ 1500 arc quadrupoles
- In series with other quadrupoles of same type
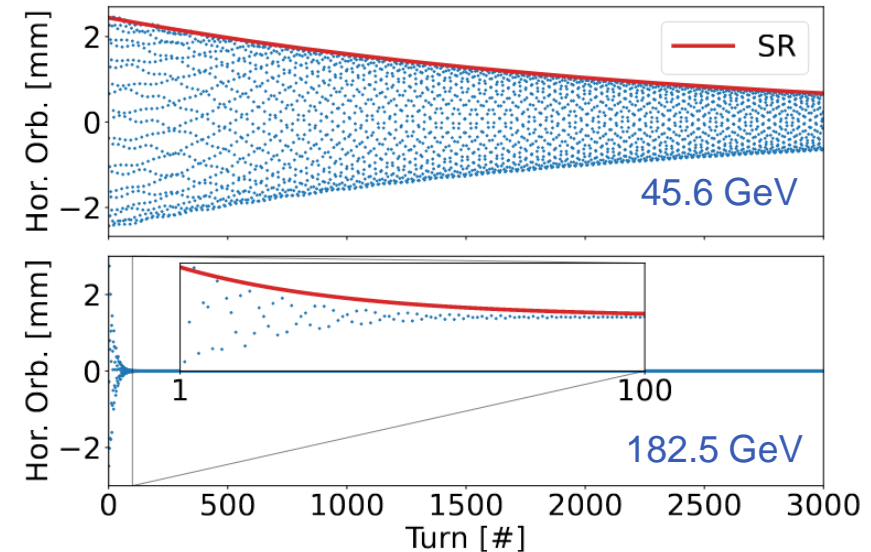- Additional individually powered trim circuit installed

Orbit correctors (C.)

- ~ 1500 elements installed
- 10 cm length
- Individual H and V trim
- Here: no strength limit

Optics Measurements

- **Record orbit over several turns**

- Used for orbit measurements

- Orbit response matrix measurements
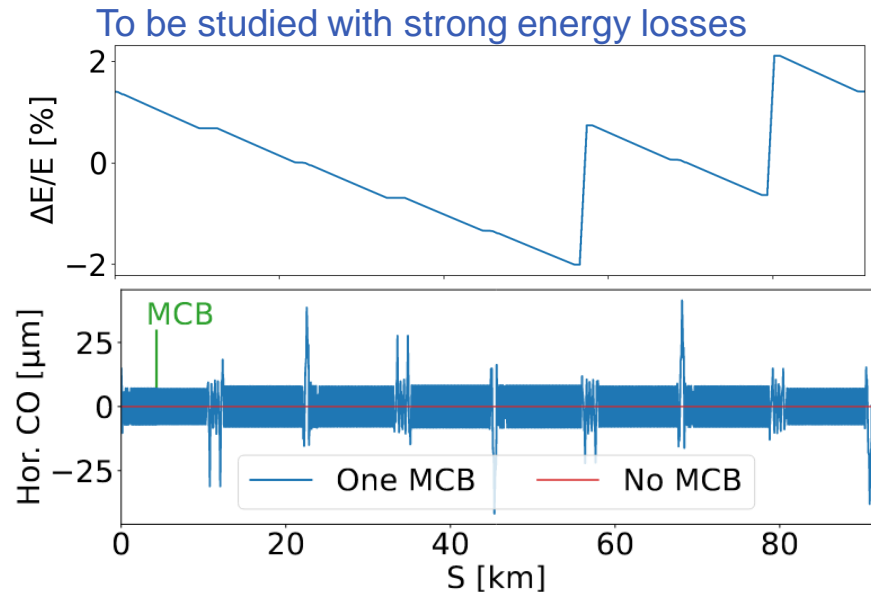
Higher BPM resolution: < 1 μm

- **Turn-by-turn measurements**

- And bunch-by-bunch measurements

- Measurement of frequency spectrum

Poorer BPM resolution: < 10 μm

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Turn-by-Turn BPM Resolution

- Goal: Phase advance error wrt model **< 1 x 10^{-3}**

- Phase advance errors depends on BPM resolution and applied kick strength

- Z- lattice
- No synchrotron radiation and sextupoles off

BPM resolution: 5 μm

BPM resolution: 2 μm

Horizontal

Vertical
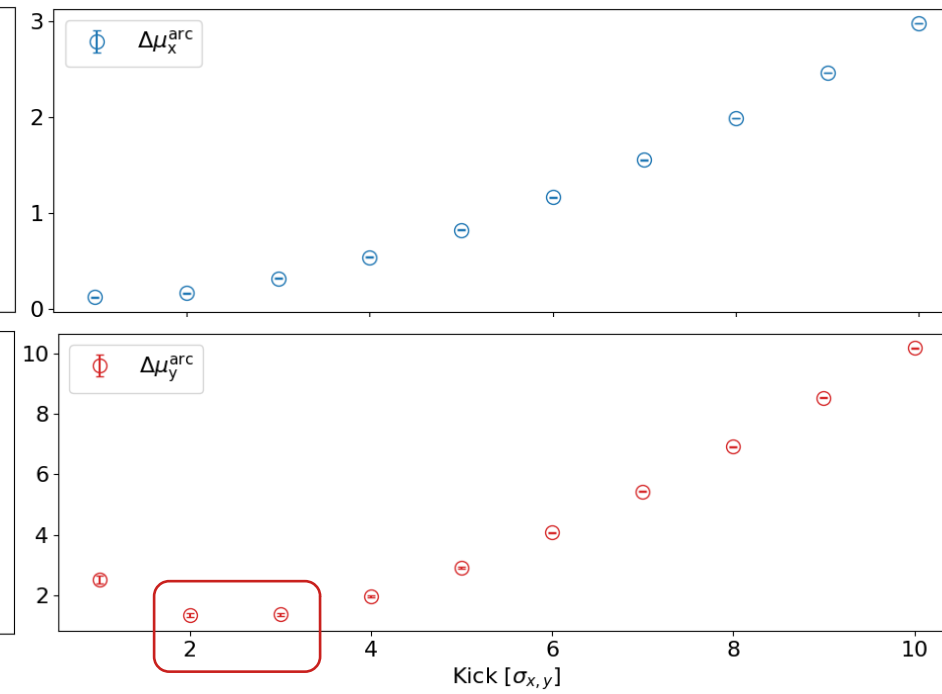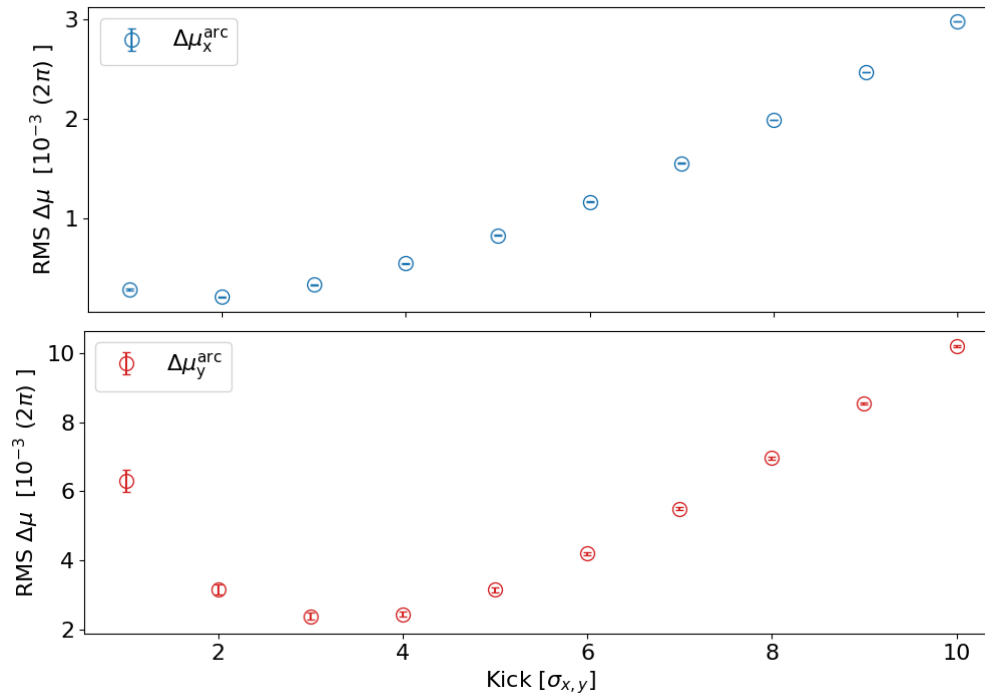
Phase advance error goal only achievable with high resolution BPMs (~ 2 μm)
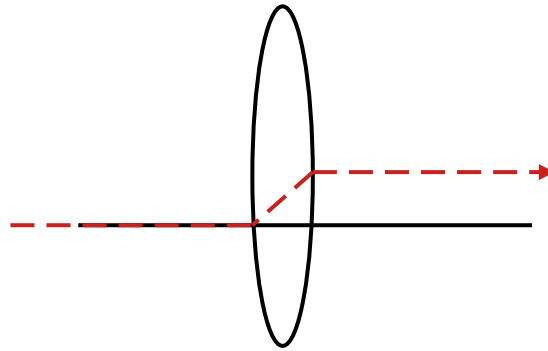
Principle of Beam Based Alignment

- **Goal for FCC-ee: 10 μm residual alignment for arc quadrupoles and sextupoles**

- Example: quadrupole with transverse offset
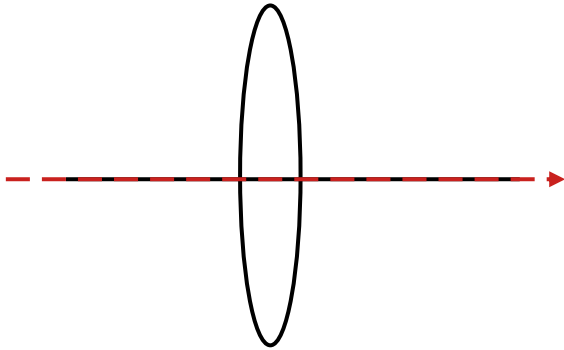
Aligned quadrupole
Beam passed through center

Quadrupole modulation does not change orbit

Misaligned quadrupole
- Beam does not pass through center
- Leads to dipole kick due to feed-down
- Orbit offset propagates to other elements

Quadrupole modulation changes orbit
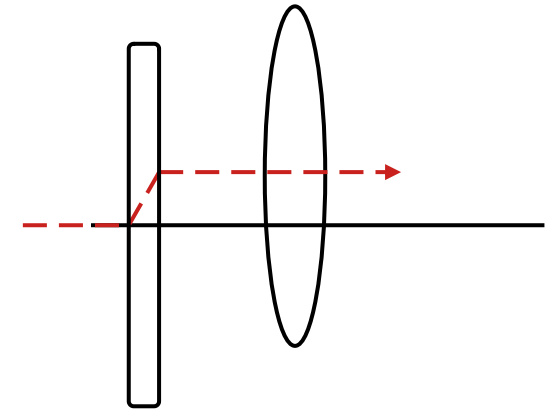
**Misaligned quadrupole
and adjusted orbit kicker**
- Beam passes through center again
- No feed-down from this quadrupole
- Orbit offset propagestes to other elements

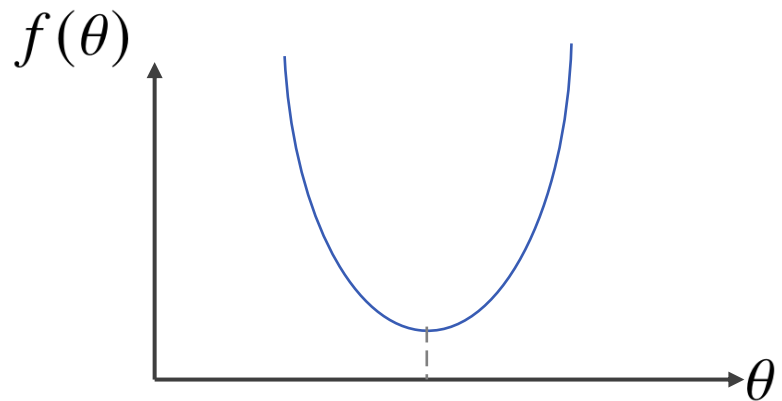Quadrupole modulation does not change orbit

Cost Function Quadrupole Offset

$$f(\theta) = \frac{1}{N_{\mathrm{BPM}}} \sum_{\mathrm{BPM}} \left(x(\theta, +\Delta k_1) - x(\theta, -\Delta k_1) \right)^2$$

Cost function for one generated orbit

Orbit offset from positive quadrupole modulation
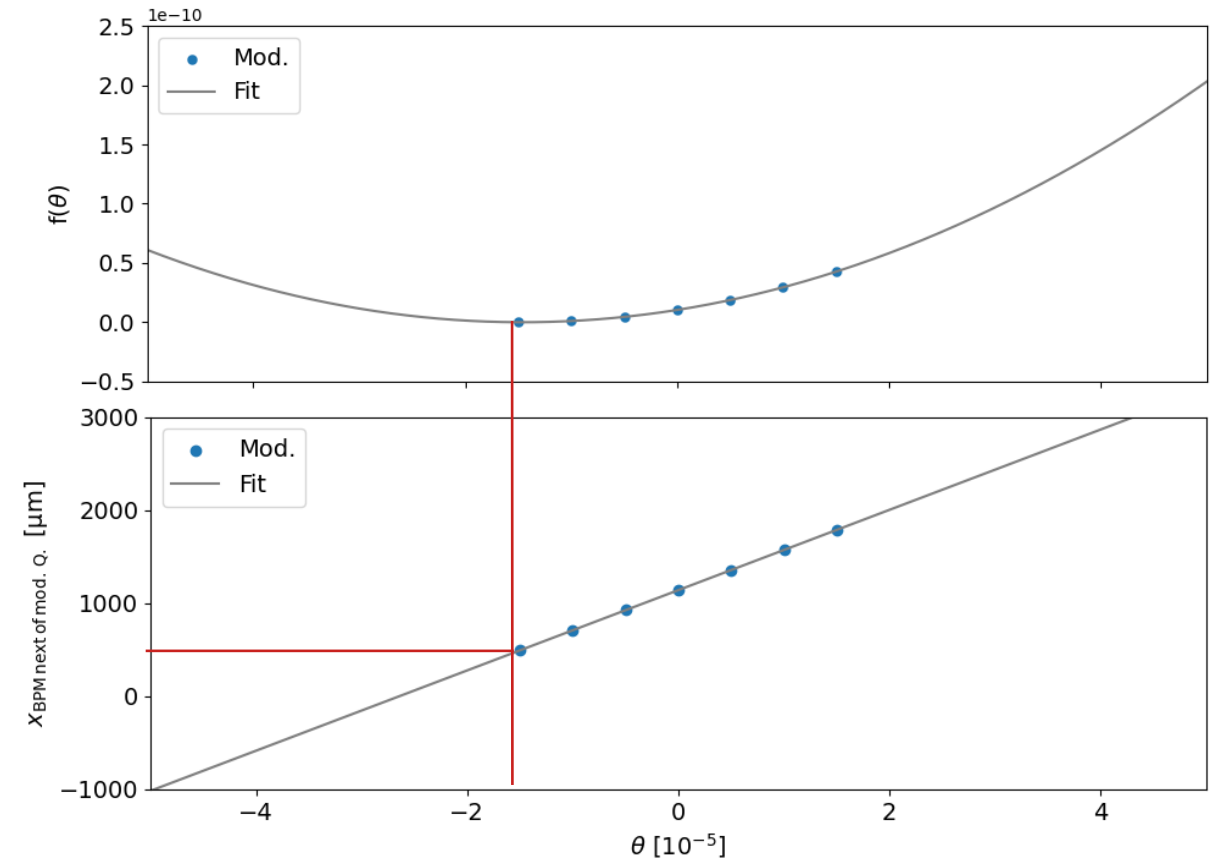
Orbit offset from negative quadrupole modulation
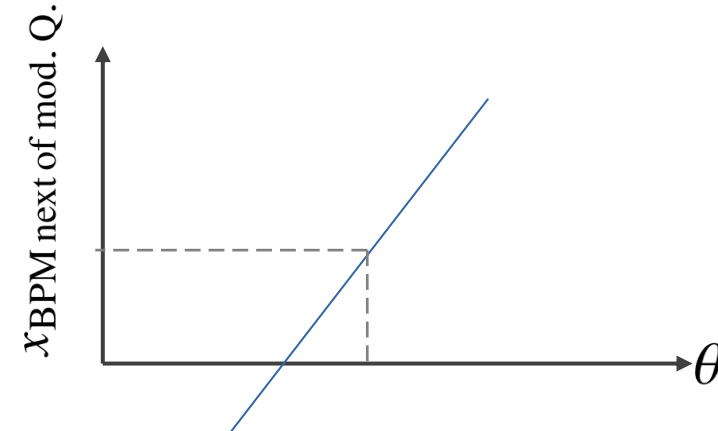
Single Quadrupole

- $\Delta x = \Delta y = 500$ μm

- Propagating orbit bump

- Measured:

- $\Delta x = 491$ μm

- $\Delta y = 523$ μm

What happens if all quadrupoles are misaligned?

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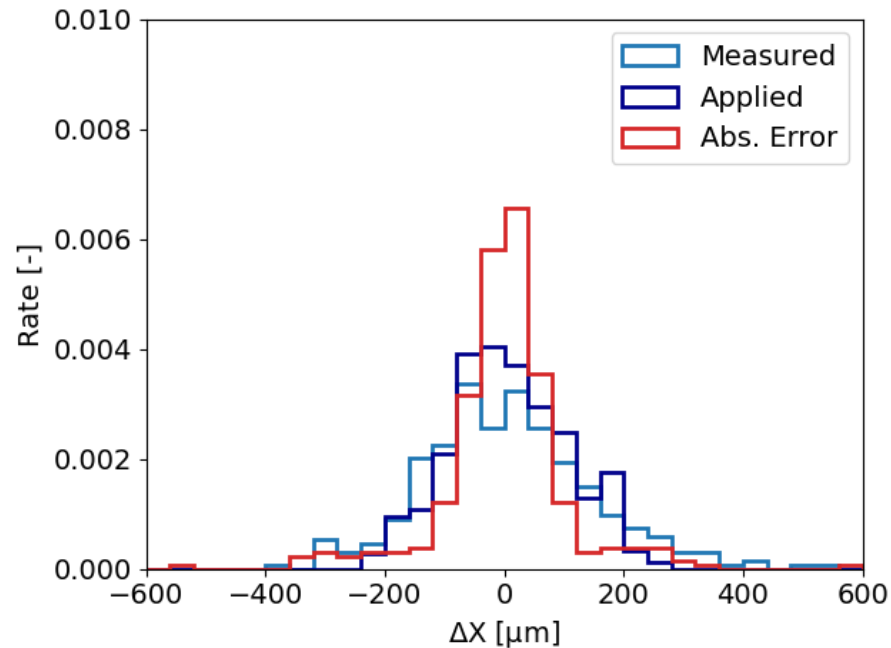**07 JUNE 2023**

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All Quadrupoles

- $\Delta x = \Delta y = Gauss(0, 100\ \mu m)$

- Propagating orbit bump

Errors mainly up to +/- 100 μm

Outliers up to +/- 2000 μm

~Gauss(0, 117 μm)
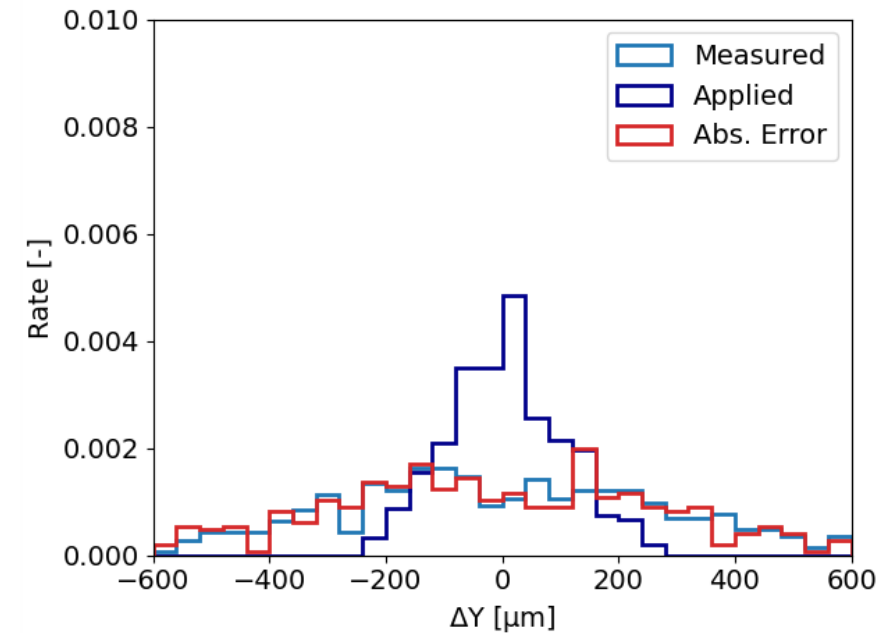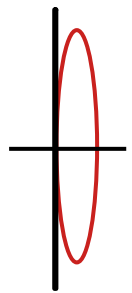
Large errors in measurements

Outliers up to +/- 1400 μm

~Gauss(0, 278μm)

Error Sources and Solutions

- **Initial Angle**

- Here: BPM at beginning of Q.

$$\begin{pmatrix} u(s) \\ u'(s) \end{pmatrix} = \mathbf{M} \begin{pmatrix} u(0) \\ u'(0) \end{pmatrix}$$
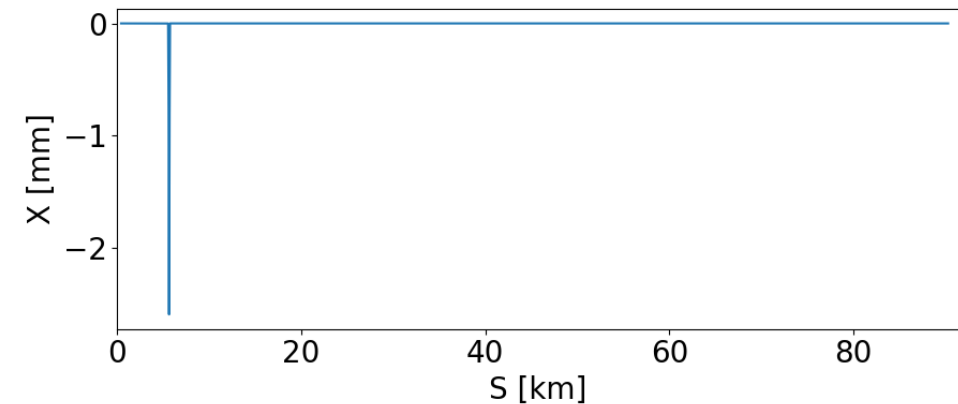
For example: u' = 100 µrad
→ Δu over L~2.9 = ~ 290 µm
→ Apply small kicks or include u'

- Solution:

- Include/limit angle in offset measurement

- Assumption: Measuring at BPM

- **Orbit Bump**

- Here: Propagating bump
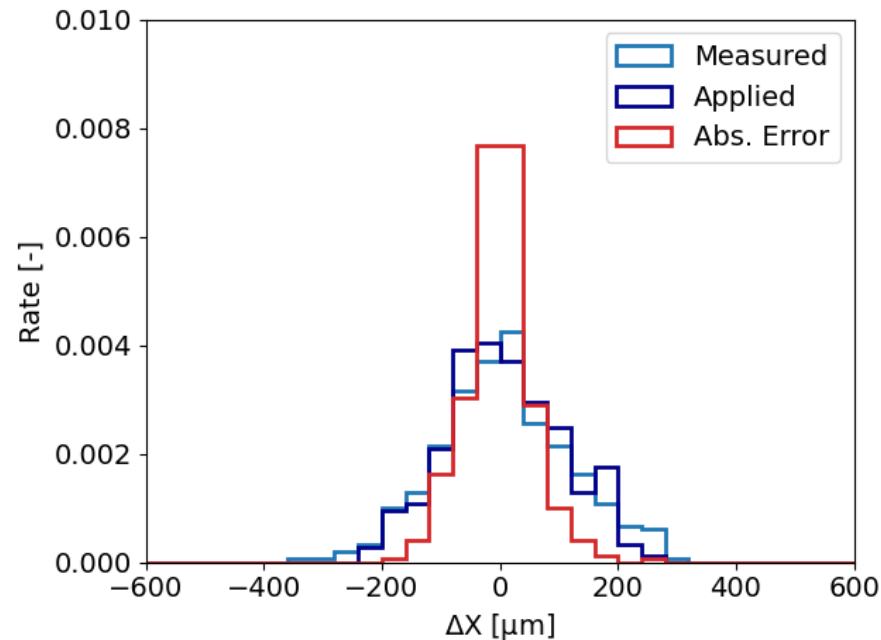
- → Feed-down effect from all Q.
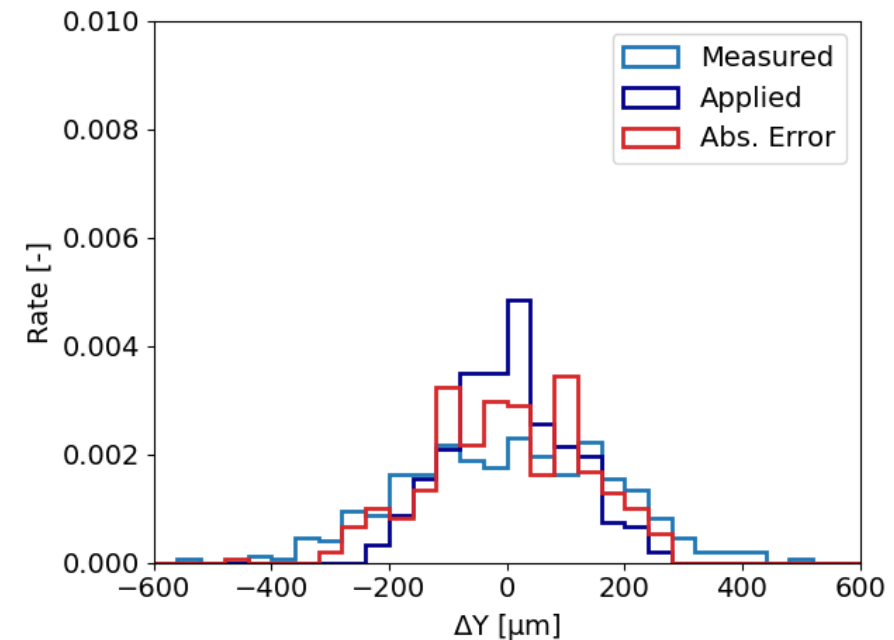

- Solution:

- Closed orbit bump (COB) around mod. Q.

+ Closed Orbit Bump

- $\Delta x = \Delta y$ = Gauss(0, 100 μm)

- **COB** (u' ~ 10 μrad) and **including angle**

No severe outliers
~ Gauss(0, 55 μm)

Only 2 severe outliers (not shown here)
~ Gauss(0, 130 μm)

Controlling Initial Angles

- **Initial Angle**

- Initial angles/orbits must be corrected

- → Assume MICADO with all orbit kickers

- RMS X = Y ~ 10 µm

- How can we measure u' at each BPM

- → Could require more (~factor 2) more BPMs!

Blue: before correction; Orange: after correction

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+ Orbit Correction

• $\Delta x = \Delta y = $ Gauss(0, 100 µm)

• COB (u' ~ 10 µrad), including angle and **orbit correction**

Resulting alignment: ~**Gauss(0, 35 µm)**
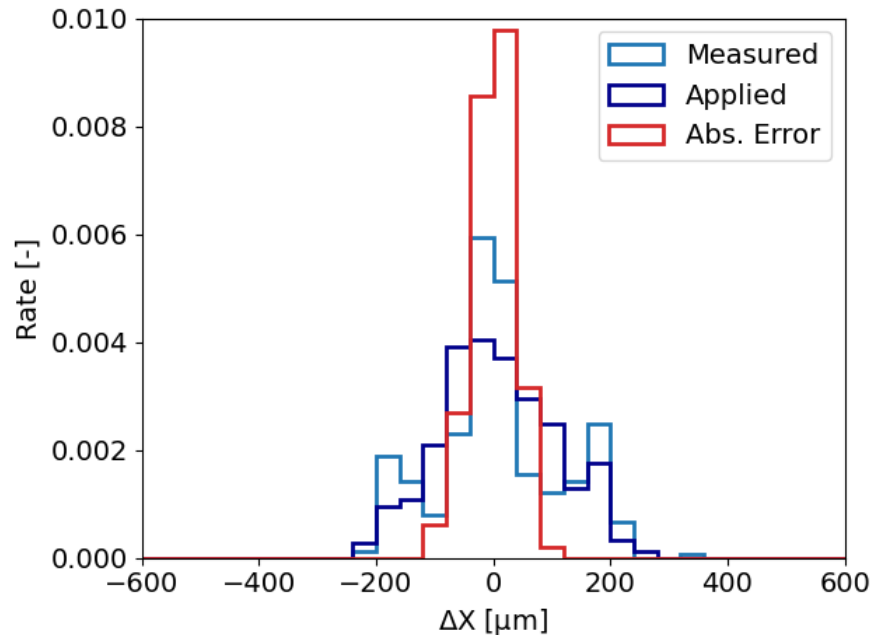
+ BPM Resolution

- Relaxed Z- lattice with $\beta_{x,y}^* = 27$ cm, 2.4 mm
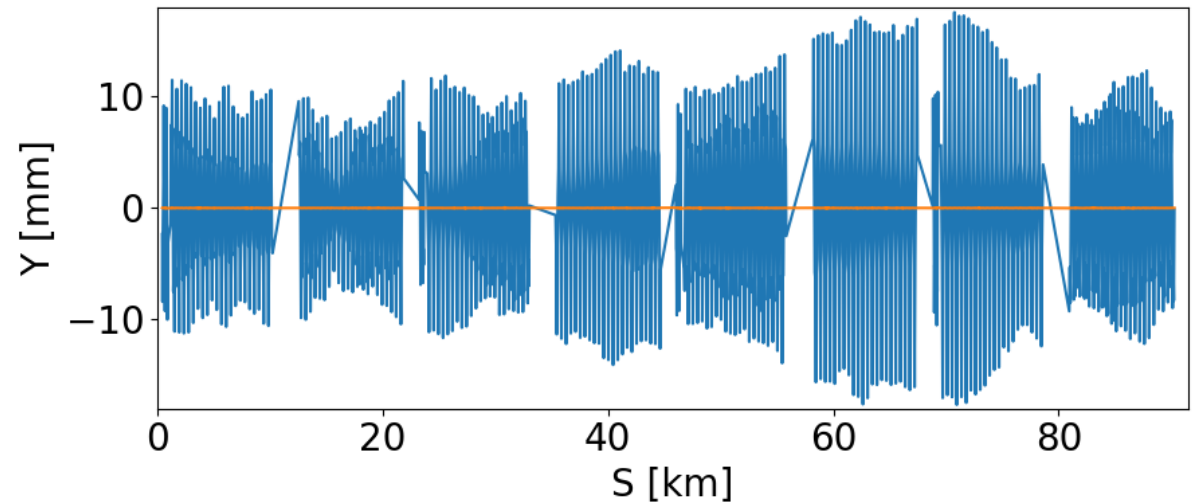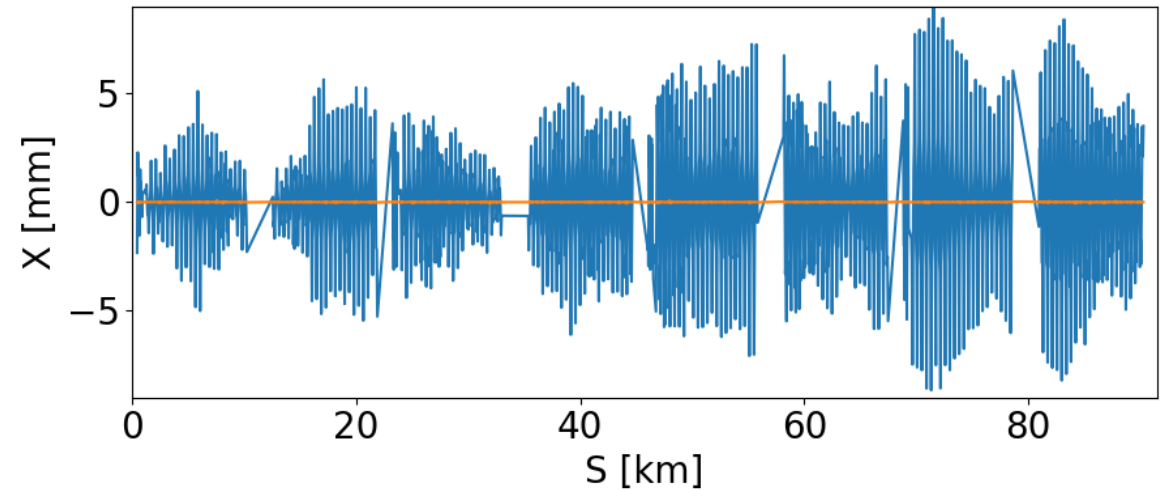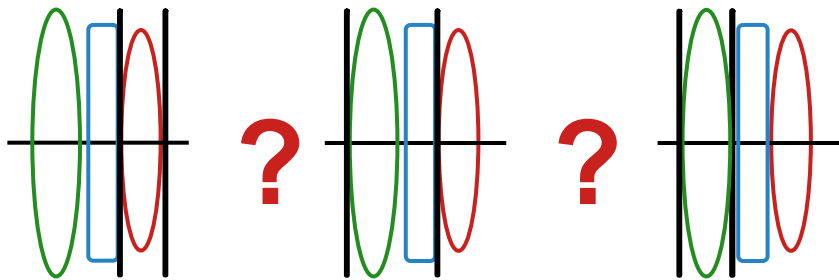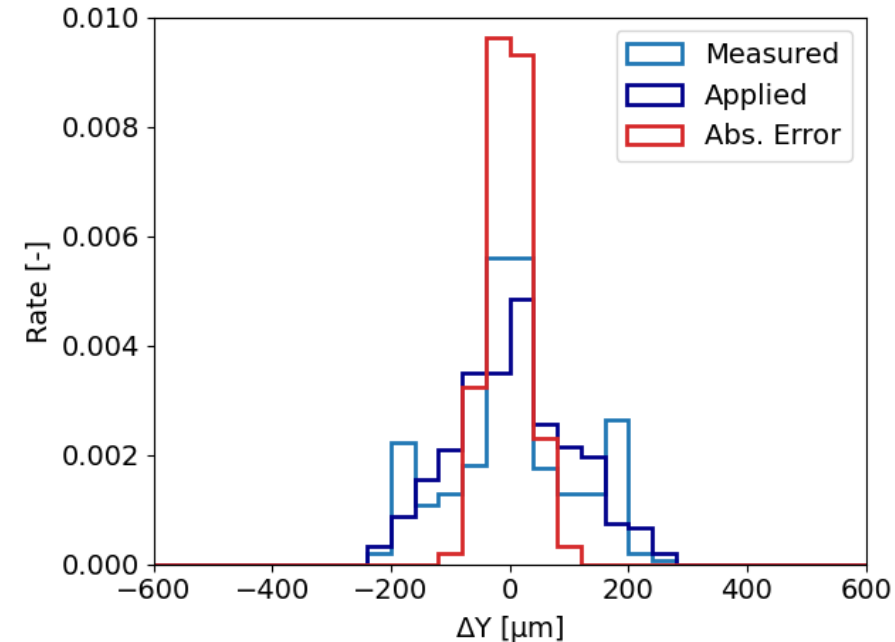- No synchrotron radiation and sextupoles off
- All quadrupoles misaligned

- $\Delta x = \Delta y = \text{Gauss}(0, 100 \, \mu m)$

- COB (u' ~ 10 µrad), including angle, orbit correction and **1 µm BPM resolution**

Resulting error: ~**Gauss(0, 56 µm)**
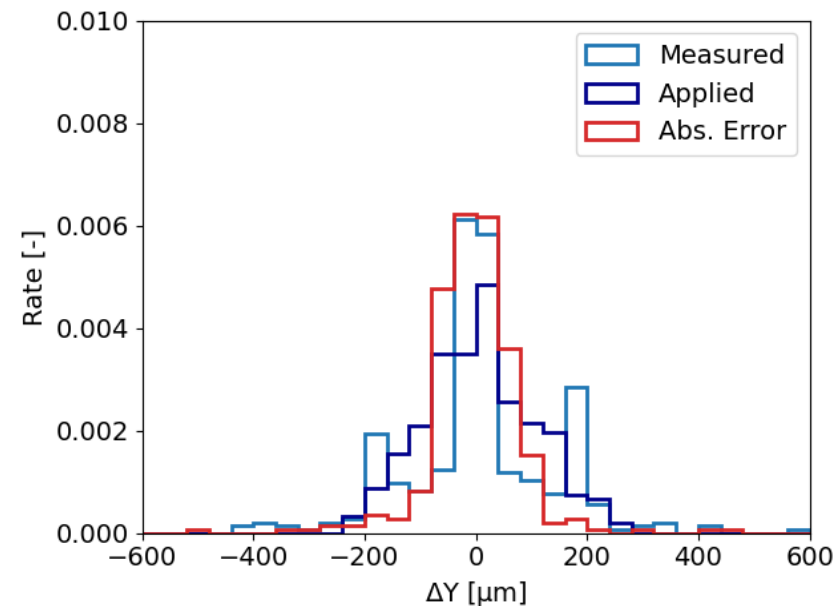
Resulting error: ~**Gauss(0, 83 µm)**

1 µm BPM resolution increases errors by factor 2-3 → Better resolution required

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+ BPM Resolution

- Relaxed Z- lattice with $\beta_{x,y}^* = 27$ cm, 2.4 mm
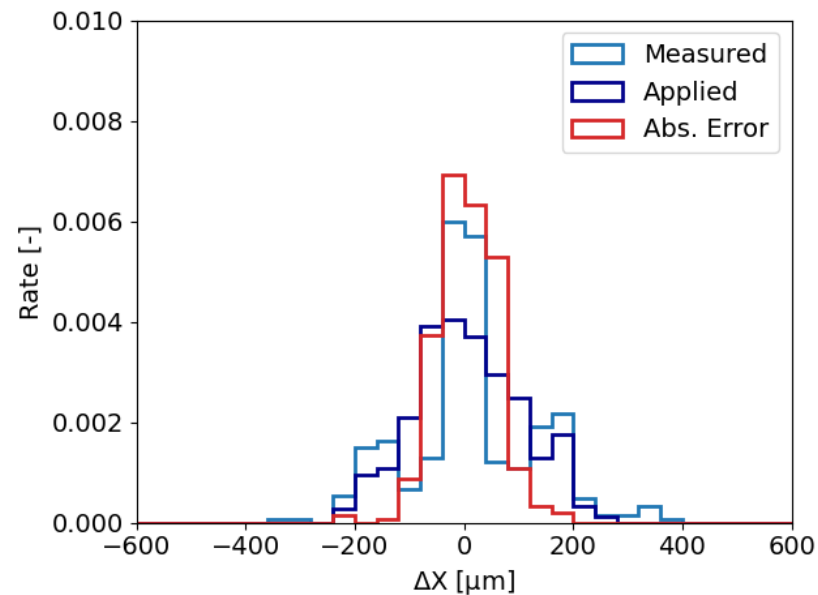- No synchrotron radiation and sextupoles off
- All quadrupoles misaligned
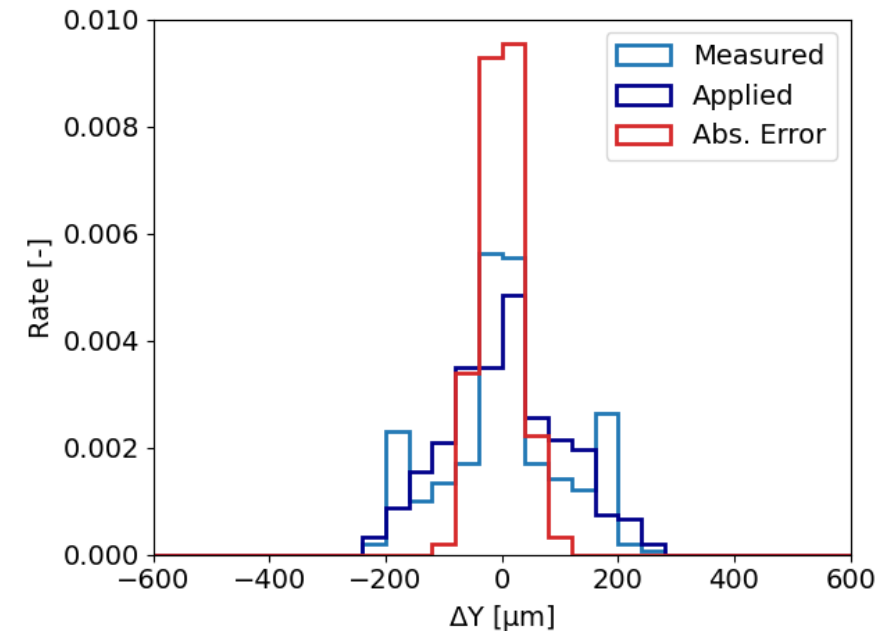
- $\Delta x = \Delta y = \text{Gauss}(0, 100\ \mu m)$

- COB (u' ~ 10 µrad), including angle, orbit correction and **0.05 µm BPM resolution**
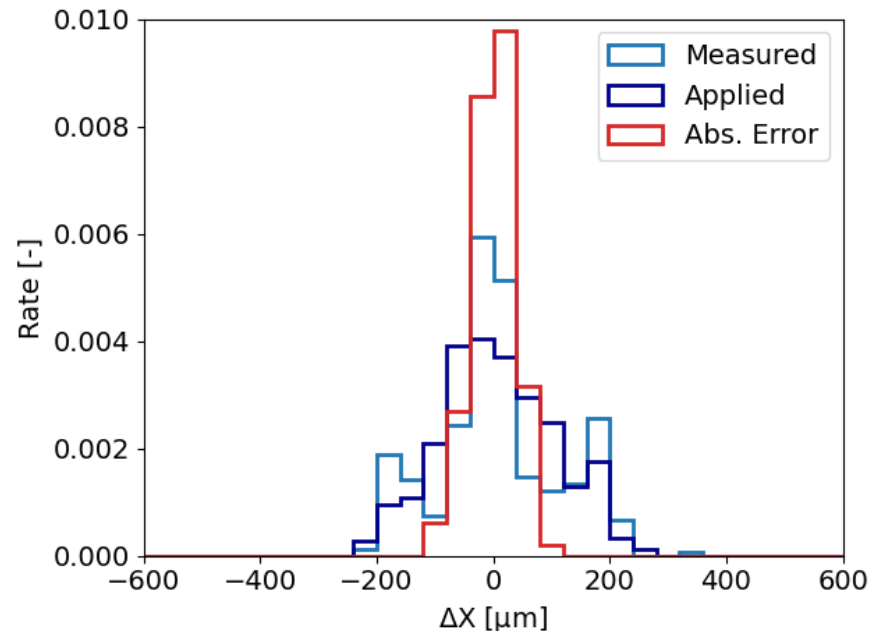
Resulting alignment: ~**Gauss(0, 35 µm)**
BUT: vertically few outliers (not shown here)

Controlling Orbit Bumps

- **Orbit Bump**

- Model orbit bump not closed with errors

- How can we close it?

- → Use 3 orbit kickers!

- Orbit change at modulated quadrupole only from COB and not prapagated feed-down from other elements

Work in progress!
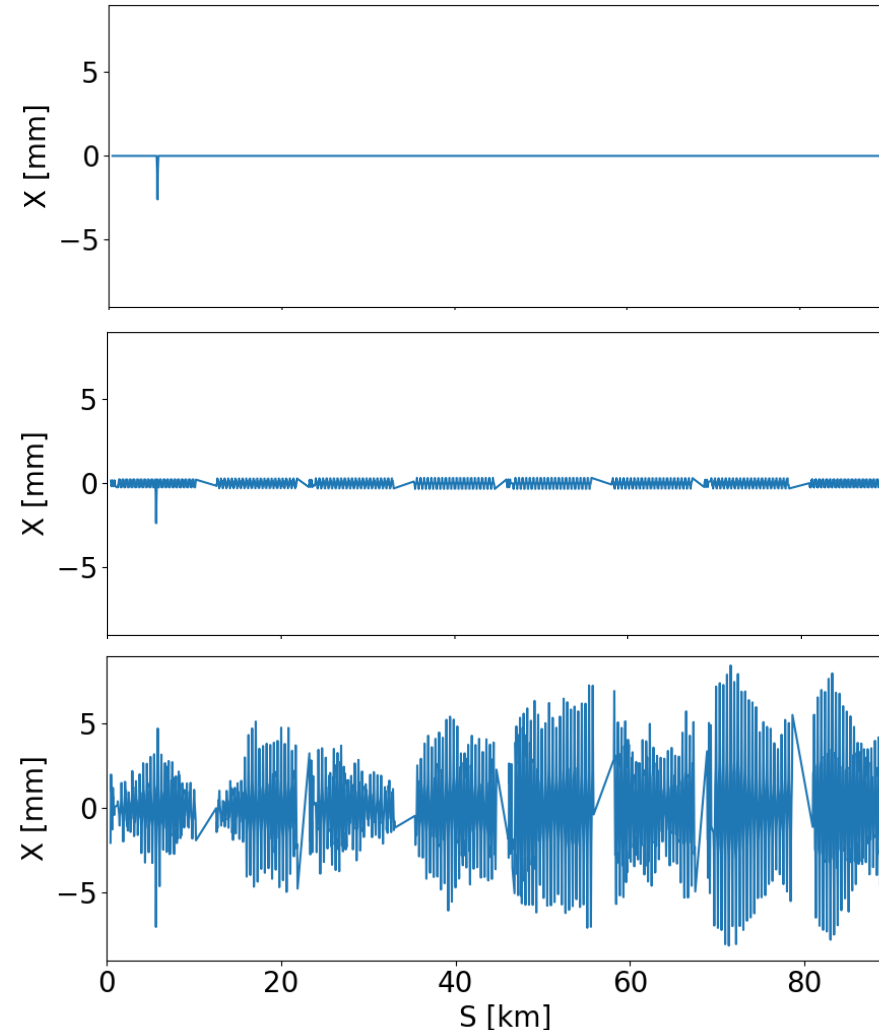
Designed COB with 2 kicker magnets, 180° apart

No longer closed when 1 quadrupole is misaligned

Feeddown effects from all misalinged elements

Summary

- Higher resolution BPMs required for optics measurements and beam-based alignment

  - ~2 µm resolution in turn-by-turn mode

  - < 1 µm in closed orbit mode

Orbit bump	Initial u' [y/n]	BPM Res. [µm]	H/V [µm]
Open	n	0	117/278
COB	y	0	55/130
+ orbit cor.	y	0	35/35
+ orbit cor.	y	1	56/83
+ orbit cor.	y	0.05	35/35

- First beam-based alignment techniques explored

- for arc quadrupoles without radiation and sextupoles

- Outlook:

  - Aim achieving **10 µm after beam-based alignment** with misalignment and multipole errors in all elements

  - Techniques for monitoring possible element drifts, also in squeezed optics

Thank you!

Beam-Based Alignment
and
Optics Measurements
Jacqueline Keintzel

Acknowledgements: Michael Benedikt, Tor Raubenheimer, Rogelio Tomas, Leon van Riesen-Haupt, Frank Zimmermann

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Bunch Parameters

Parameter		FCC-Z	FCC-ttbar
Bunch intensity [10^{11}]	Low-intensity pilot High-intensity non-colliding High-intensity colliding	~0.1 1.51 1.51	~0.1 1.55 1.55
Bunch length [mm]	Low-intensity pilot High-intensity non-colliding High-intensity colliding	< 5.6 5.6 12.7	< 1.81 1.81 2.17
Number of bunches [-]	Low-intensity pilot High-intensity non-colliding High-intensity colliding	~200 A few 15880	- - 60

For energy calibration: 100-200 bunches with low-intensity at Z-pole

→ Optics measurements and corretions: Could correspond to measurements with e.g. ~ 20 bunches each with 10^{11}