Beam-Based Alignment in the FCC-ee

Jacqueline Keintzel

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

Optics Tuning for Futue Colliders Workshop
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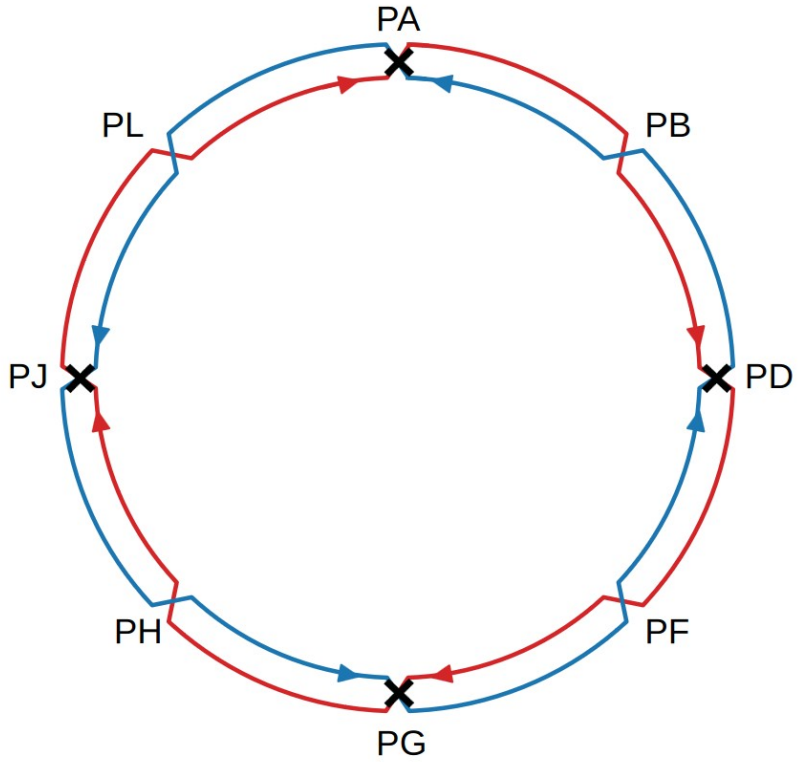
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

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
  - Well controlled orbit and optics
    - → Optics tuning team



Achieving the Design Values

- Mechanical alignment
- Orbit and optics measurements
- Beam based alignment
- Optics and emittance tuning

Achieving the Design Values

- **Mechanical alignment**

Challenging and time consuming for ~ 100 km circular machine

Extrapolation:
25 teams in 4 months for main components

- Orbit and optics measurements
- Beam based alignment
- Optics and emittance tuning

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

Talk: H. Mainaud Durand

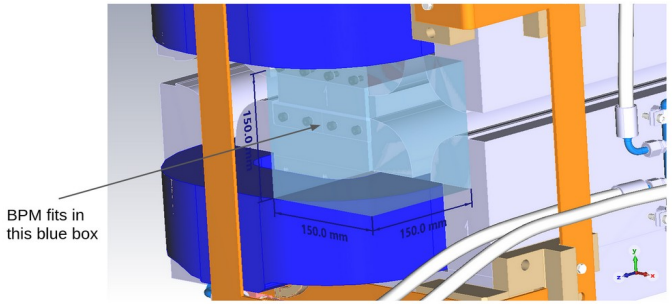
Achieving the Design Values

- Mechanical alignment
- Orbit and optics measurements
- **Beam based alignment**
- Optics and emittance tuning

Relaxes mechanical alignment tolerances

Achieving the Design Values

Beam based measurements depend on precision of beam instrumentions (BPMs, etc.)



Courtesy: M. Wendt

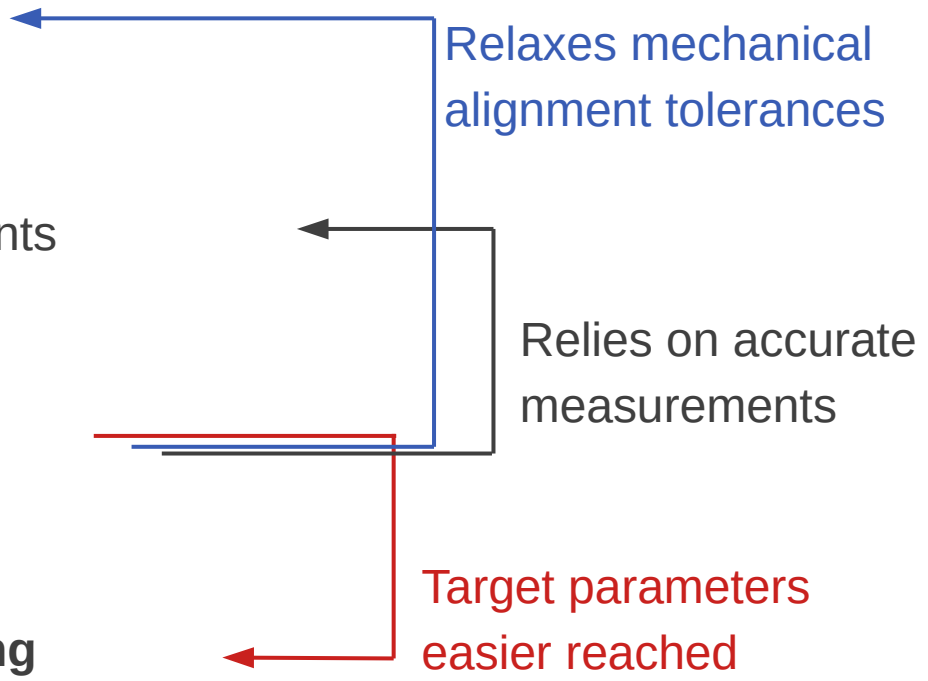
- Mechanical alignment
- **Orbit and optics measurements**
- **Beam based alignment**
- Optics and emittance tuning

Relaxes mechanical alignment tolerances

Relies on accurate measurements

Achieving the Design Values

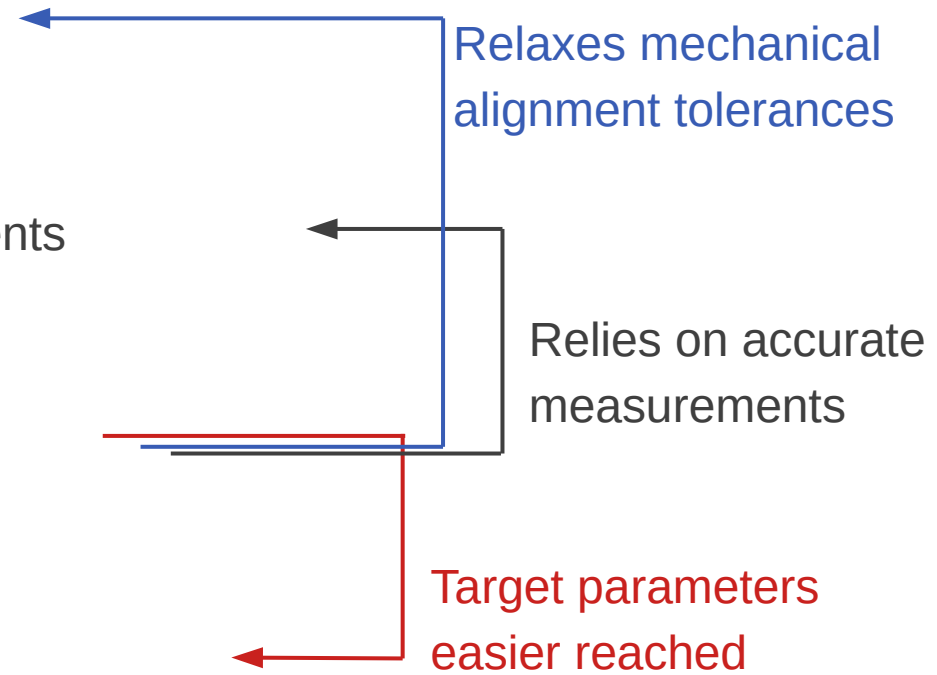
- Mechanical alignment
- Orbit and optics measurements
- Beam based alignment
- **Optics and emittance tuning**



Achieving the Design Values

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

- Mechanical alignment
- Orbit and optics measurements
- Beam based alignment
- Optics and emittance tuning

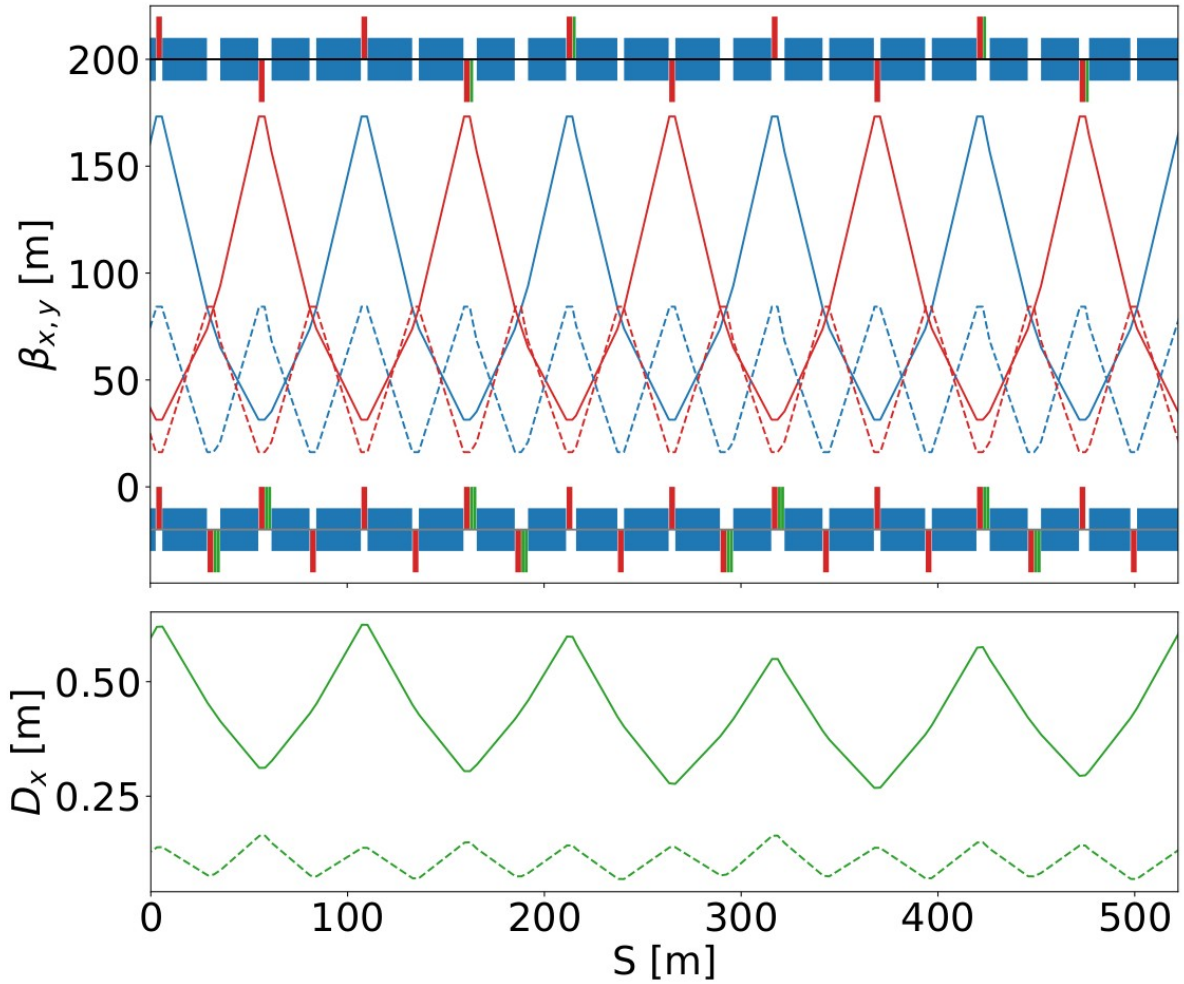


Arc Lattice

- 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

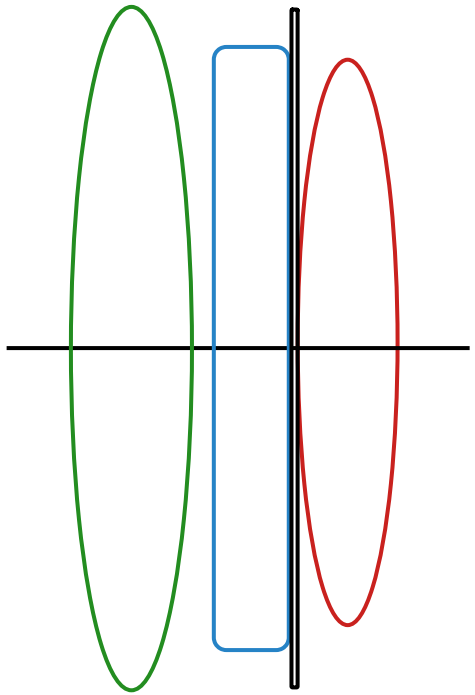
Blue: Dipoles; Red: Quadrupoles; Green: Sextupoles



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



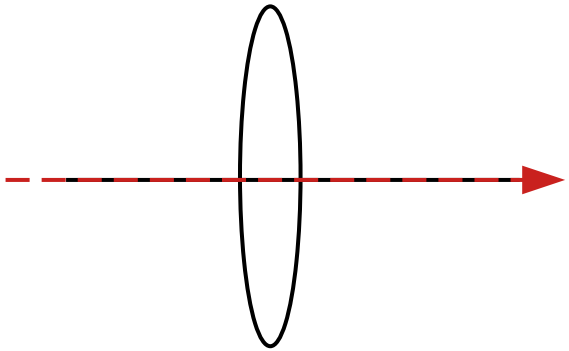
Orbit correctors (C.)
- ~ 1500 elements installed
- 10 cm length
- Individual H and V trim
- Here: no strength limit

Arc quadrupole (Q.)
- ~ 1500 arc quadrupoles
- In series with other quadrupoles of same type
- Additional individually powered trim circuit installed

Principle of Beam Based Alignment

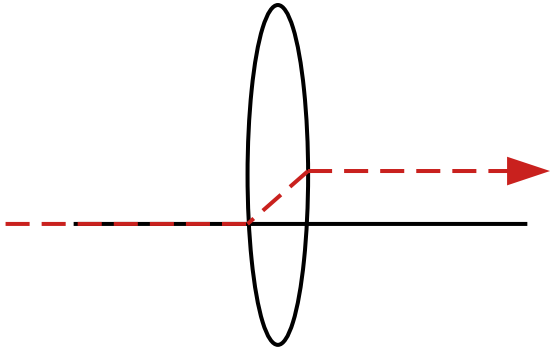
Goal for FCC-ee: 10 µm residual alignment for arc quadrupoles and sextupoles

Example: quadrupole with transverse offset



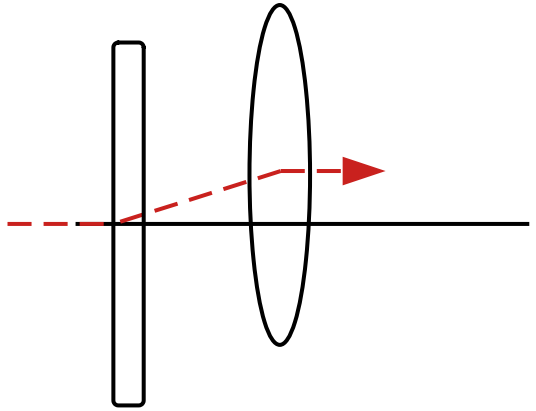
Aligned quadrupole
Beam passed through center

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

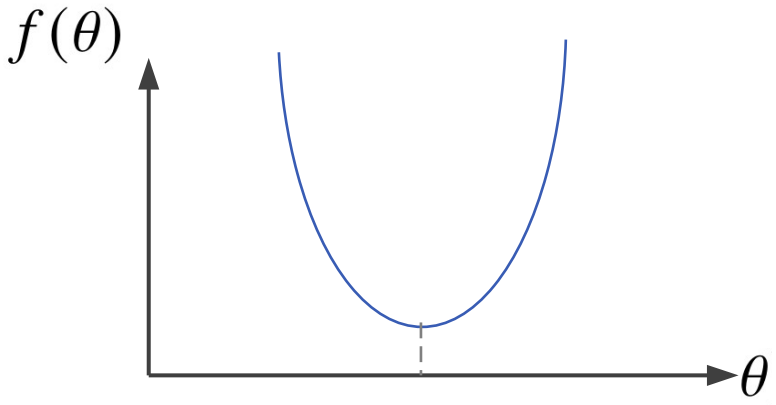
Cost Function Quadrupole Offset

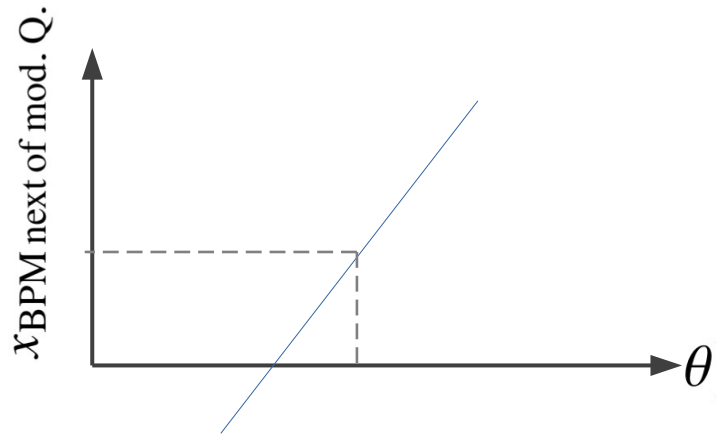
$$f(\theta) = \frac{1}{N_{\mathrm{BPM}}} \sum_{\mathrm{BPM}} \left(x(\theta, +\Delta k_1) - x(\theta, -\Delta k_1) \right)^2$$

Cost function for one generated orbit

Orbit offset from positive quadrupole modulation

Orbit offset from negative quadrupole modulation



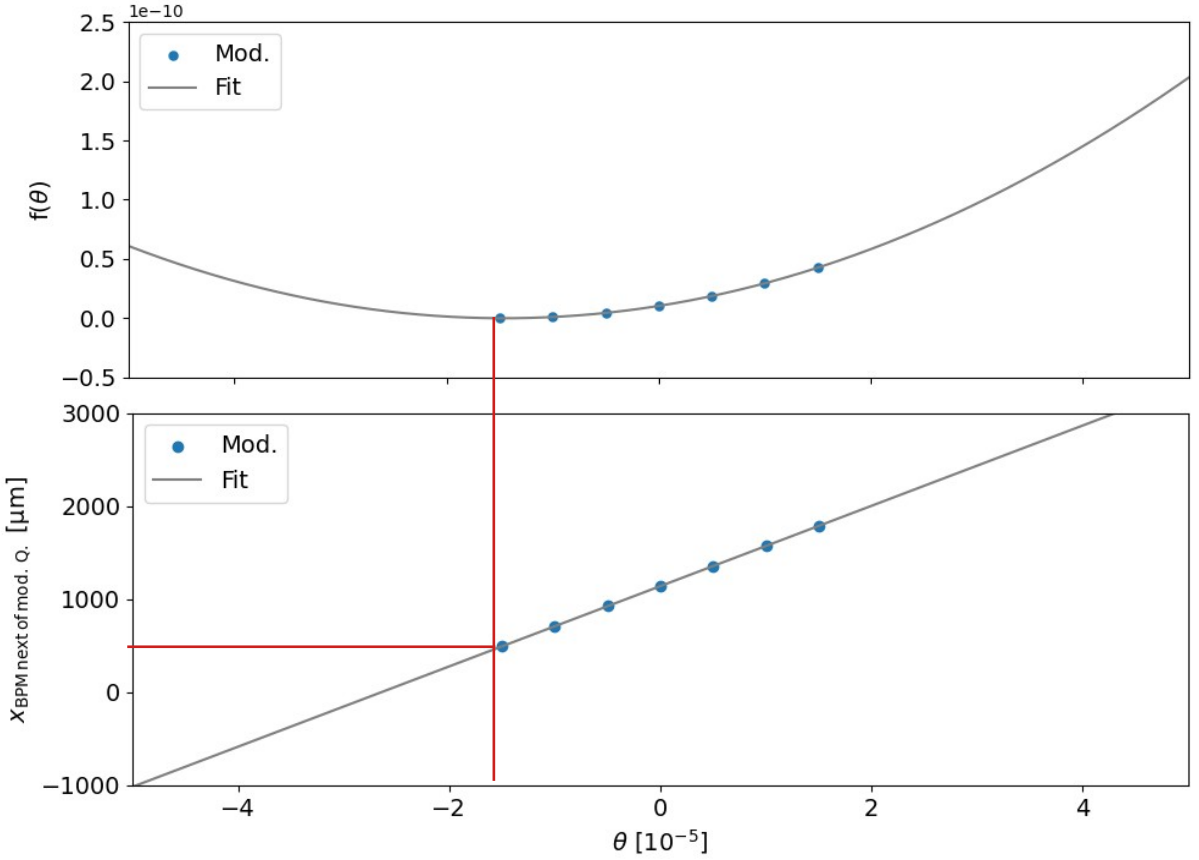


Single Quadrupole

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

- $\Delta x = \Delta y = 500$ µm
- Propagating orbit bump

- Measured:
- $\Delta x = 491$ µm
- $\Delta y = 523$ µm

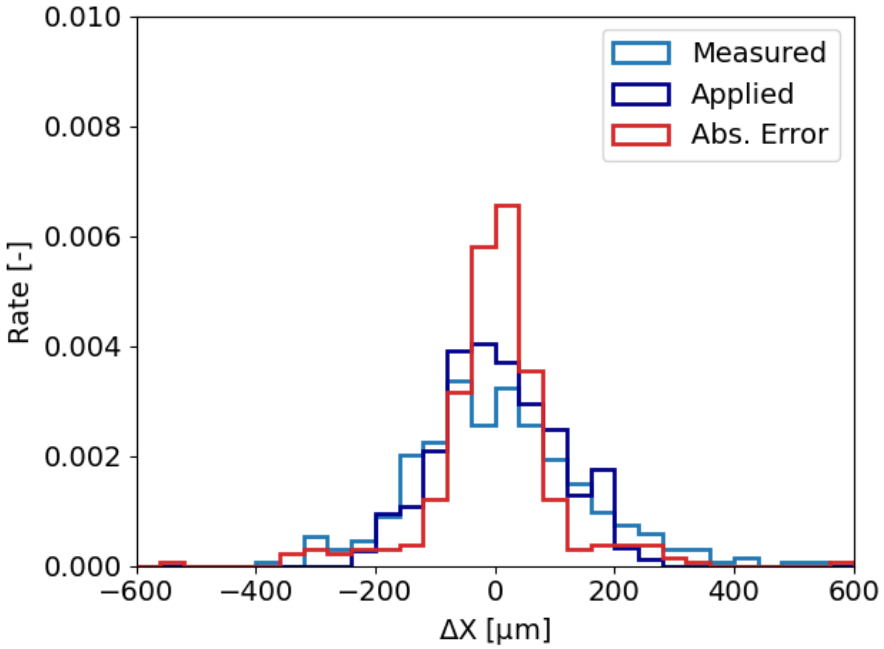


What happens if all quadrupoles are misaligned?

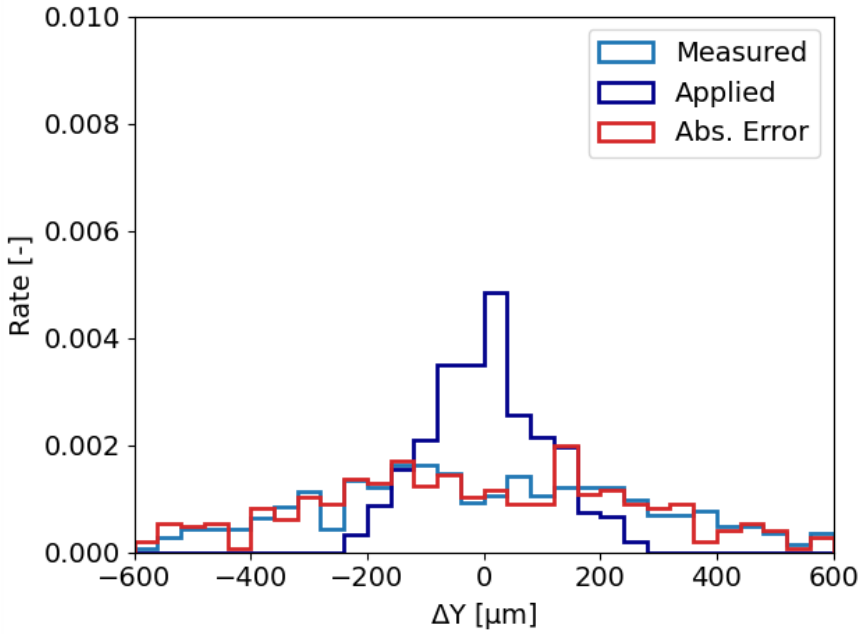
All Quadrupoles

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

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



Errors mainly up to +/- 100 μm
Outliers up to +/- 2000 μm
~Gauss(0, 117 μm)

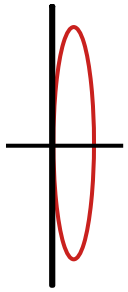


Large errors in measurements
Outliers up to +/- 1400 μm
~Gauss(0, 278μm)

Error Sources and Solutions

Initial Angle

- Here: BPM at beginning of Q.



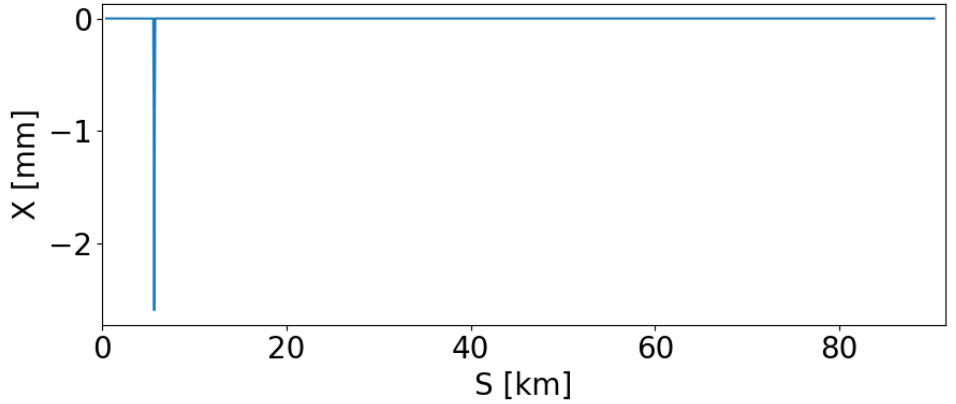
$$\begin{pmatrix} u(s) \\ u'(s) \end{pmatrix} = \mathbf{M} \begin{pmatrix} u(0) \\ u'(0) \end{pmatrix}$$

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.

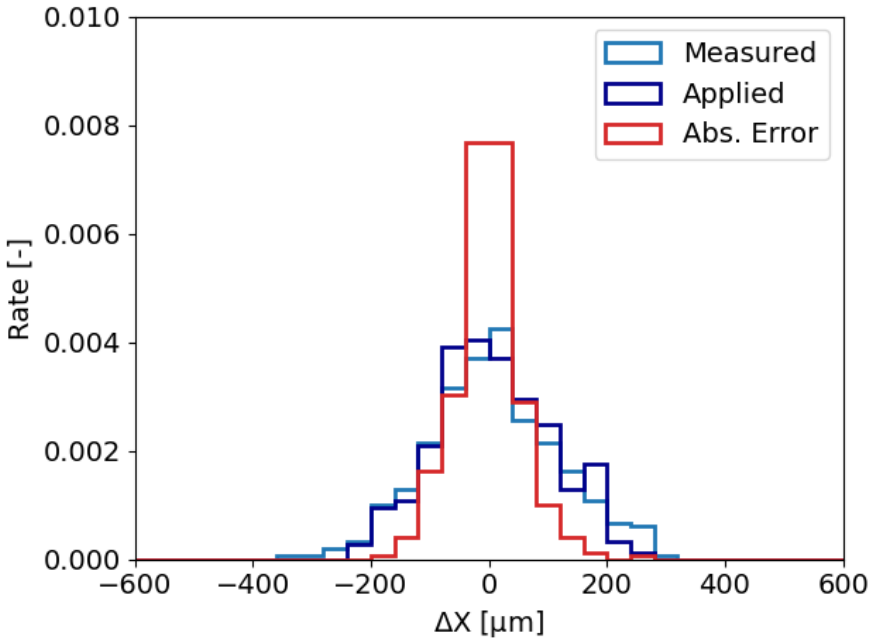


- Solution:
- Closed orbit bump (COB) around mod. Q.

+ Closed Orbit Bump

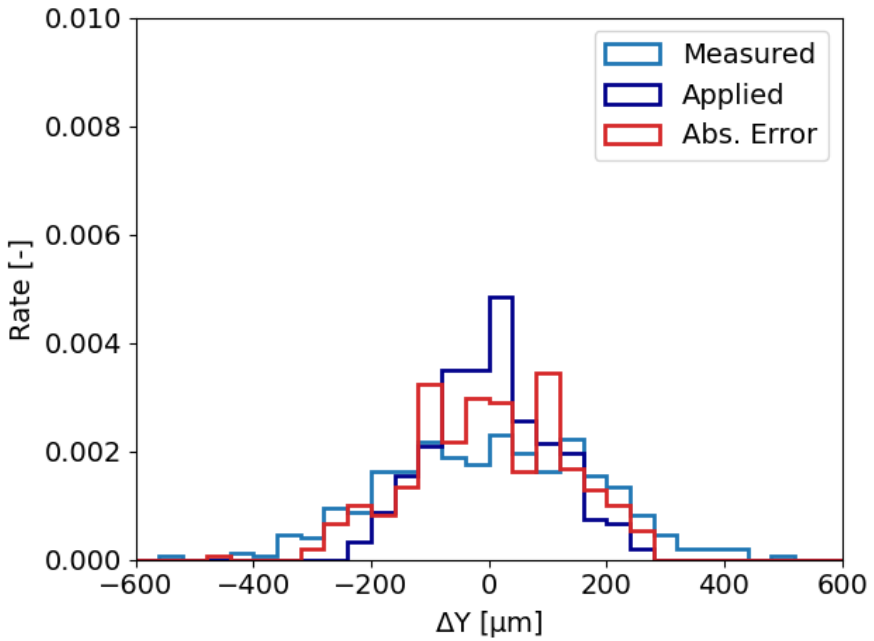
- Relaxed Z- lattice with $\beta_{x,y}^*$ = 27 cm, 2.4 mm
- No synchrotron radiation and sextupoles off
- All quadrupoles misaligned

- $\Delta x = \Delta y$ = Gauss(0, 100 µm)
- **COB** (u' ~ 10 µrad) and **including angle**



No severe outliers

~ Gauss(0, 55 µm)



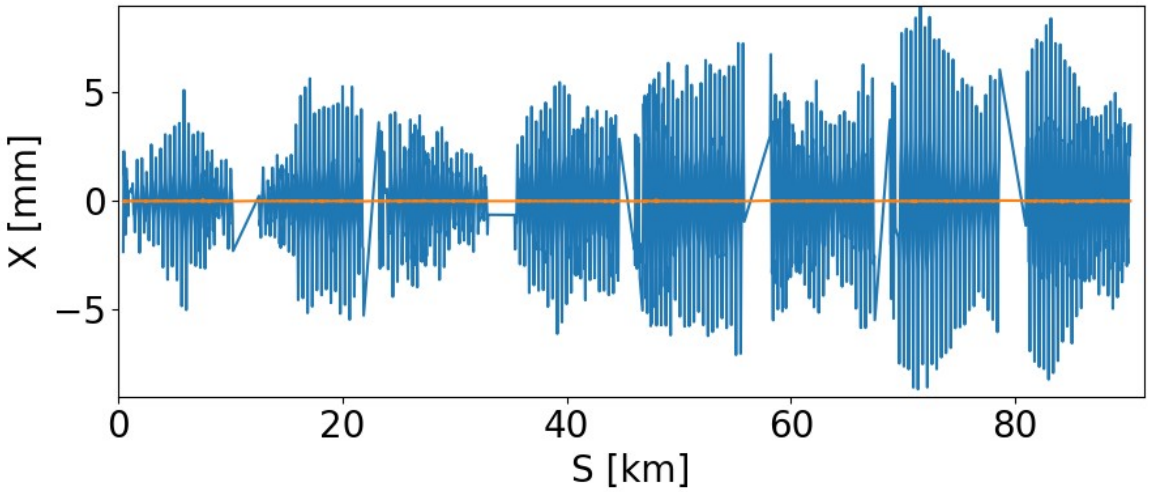
Only 2 severe outliers (not shown here)

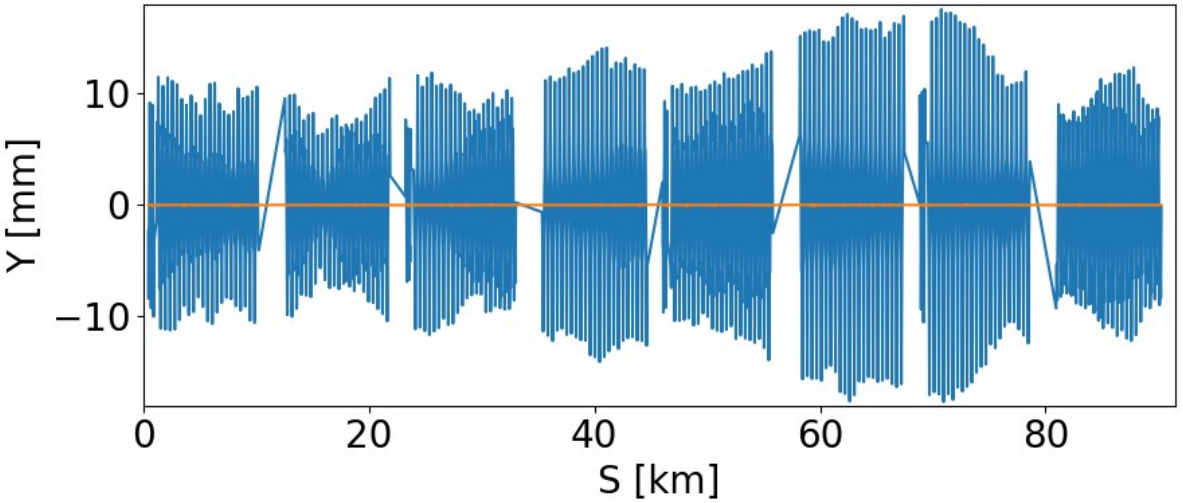
~ Gauss(0, 130 µm)

Controlling Initial Angles

Initial Angle

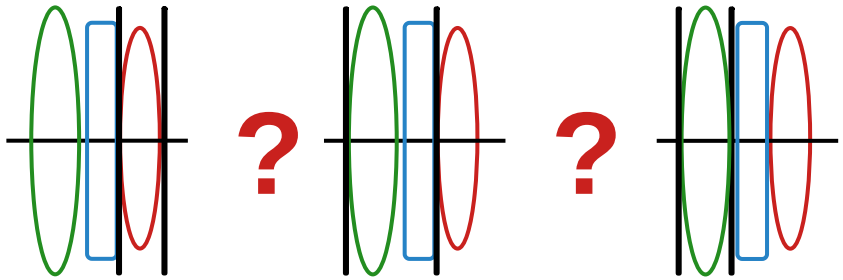
- Initial angles/orbits must be corrected
- → Assume MICADO with all orbit kickers
- RMS X = Y ~ 10 µm





Blue: before correction; Orange: after correction

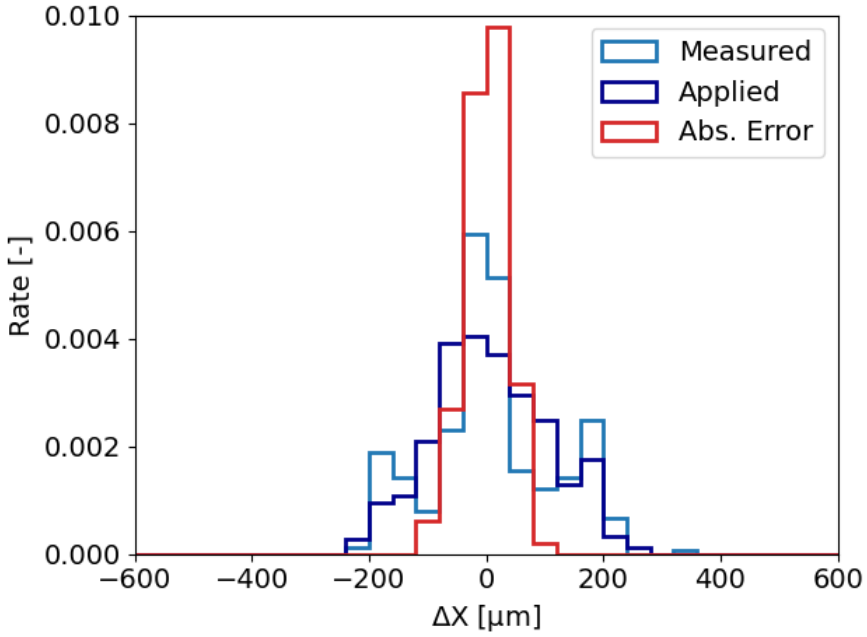
- How can we measure u' at each BPM
- → Could require more (~factor 2) more BPMs!

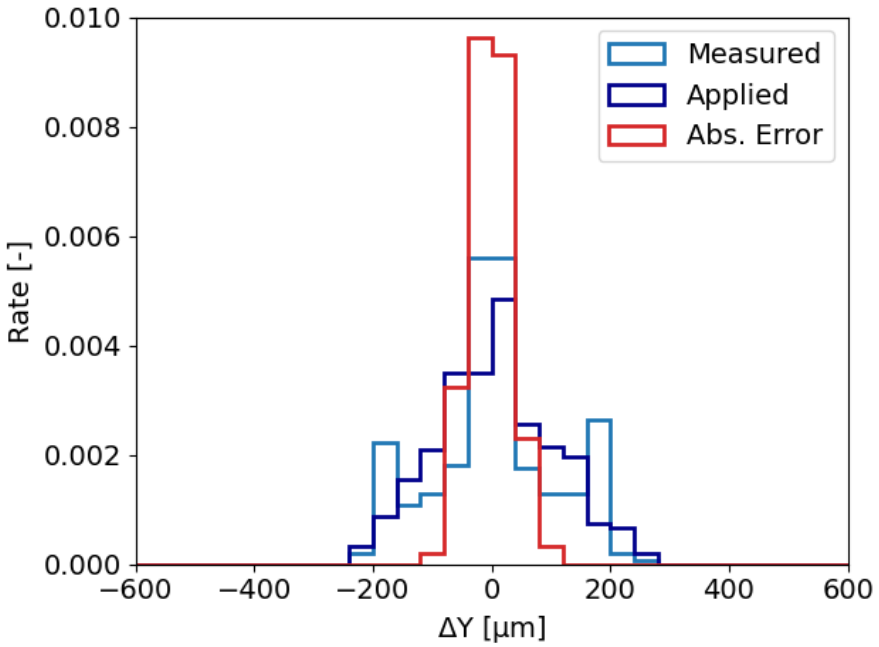


+ Orbit Correction

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

- Δx = Δy = Gauss(0, 100 µm)
- COB (u' ~ 10 µrad), including angle and **orbit correction**



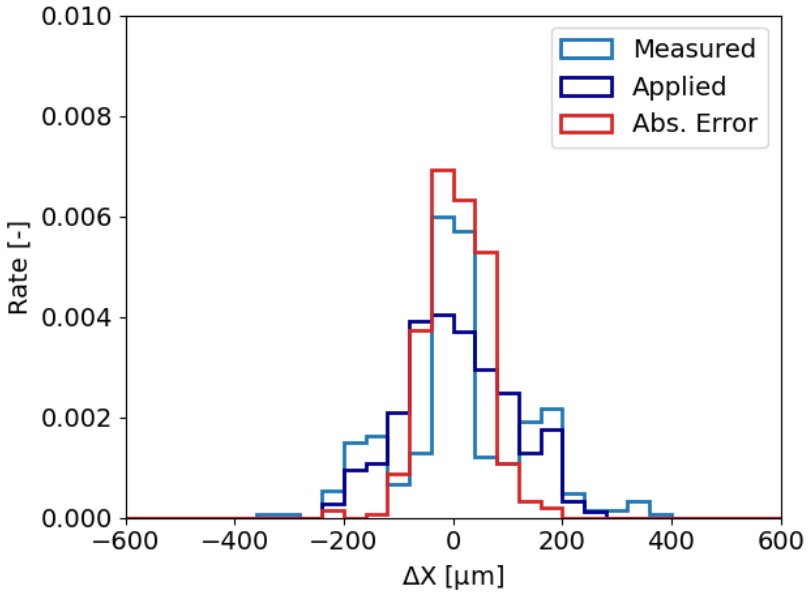


Resulting alignment: ~**Gauss(0, 35 µm)**

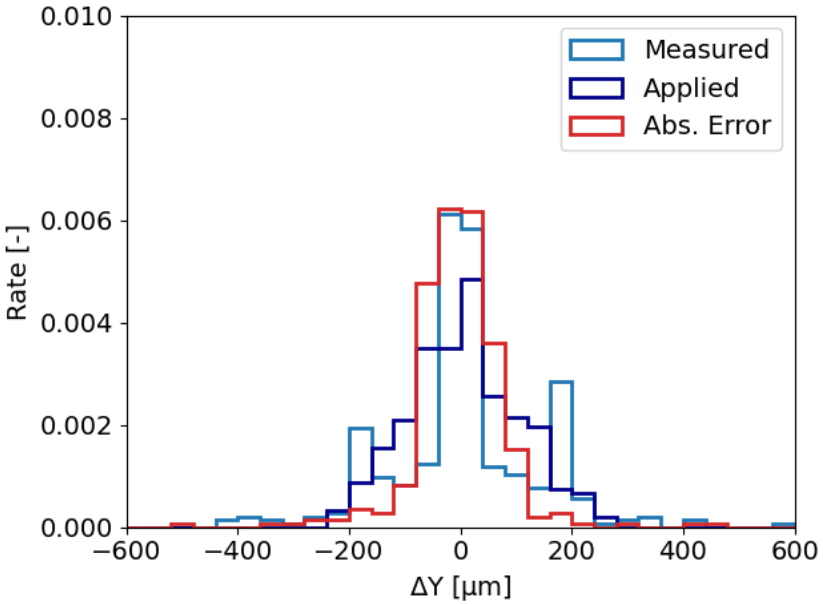
+ BPM Resolution

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

- $\Delta x = \Delta y$ = Gauss(0, 100 µm)
- COB (u' ~ 10 µrad), including angle, orbit correction and **1 µm BPM resolution**



Resulting error: ~**Gauss(0, 56 µm)**



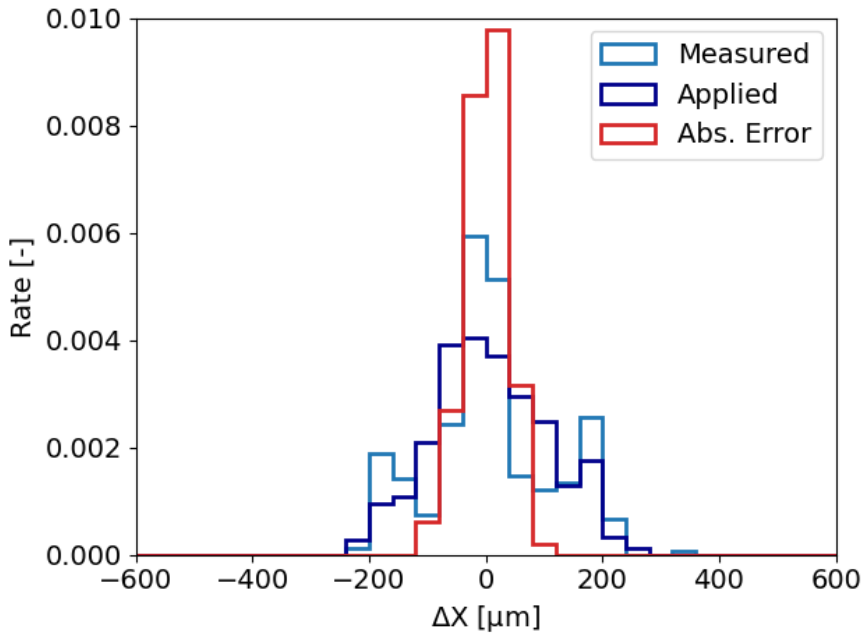
Resulting error: ~**Gauss(0, 83 µm)**

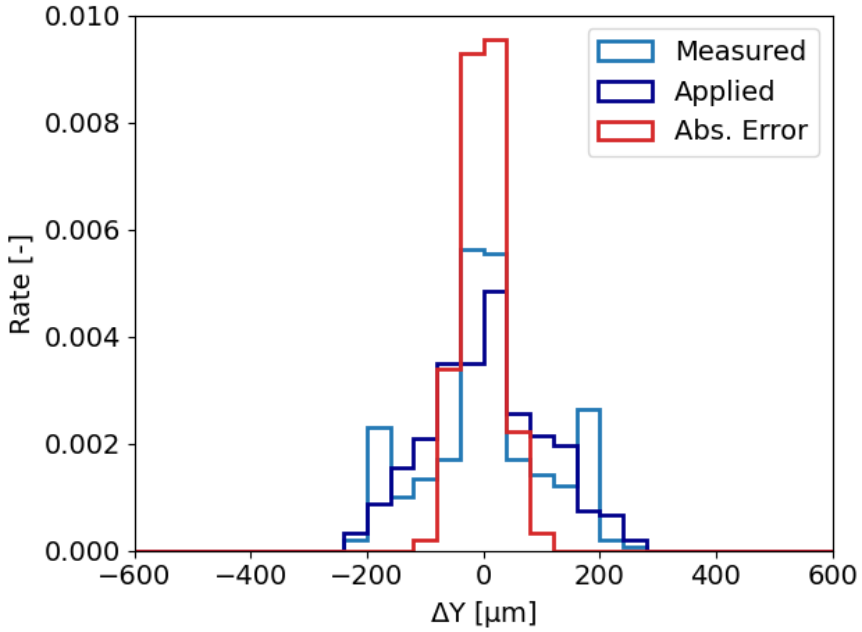
1 µm BPM resolution increases errors by factor 2-3 → Better resolution required

+ BPM Resolution

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

- Δx = Δy = Gauss(0, 100 µm)
- COB (u' ~ 10 µrad), including angle, orbit correction and **0.05 µm BPM resolution**





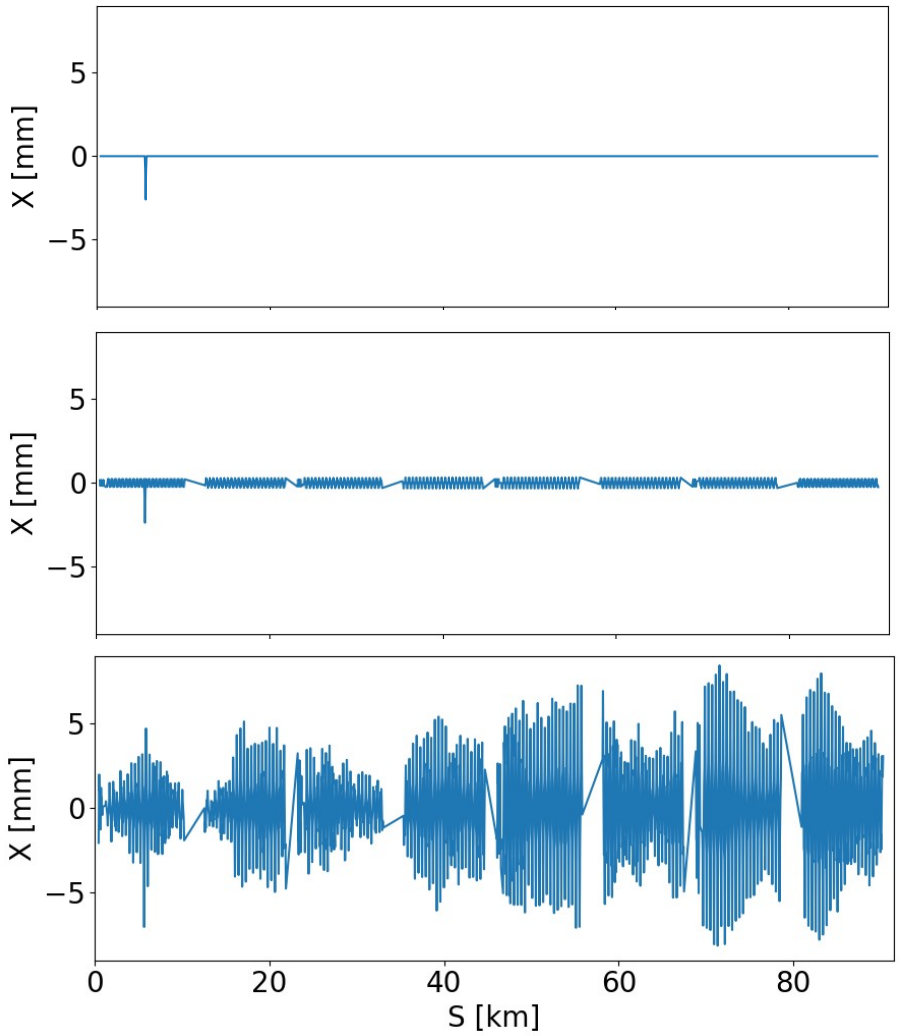
Resulting alignment: ~**Gauss(0, 35 µm)**

BUT: vertically few outliers (not shown here)

Orbit Bumps

Orbit Bump

- Model orbit bump not closed with errors
- How can we close it?
- → What is the introduced error?
- Orbit change at modulated quadrupole only from COB and not prapagated feed-down from other elements



Designed COB with 2 kicker magnets, 180° apart

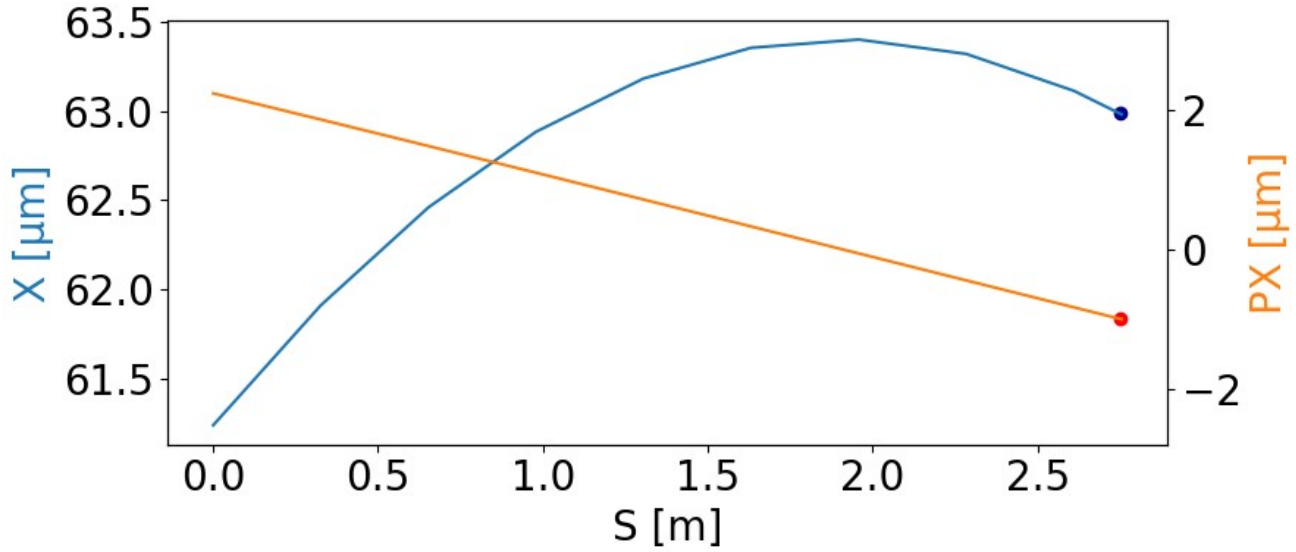
No longer closed when quadrupole is modulated

Feeddown effects from all misalinged elements

Orbit Through Magnet

No Misalignment

- Quadrupole sliced in 10 slices
- X, PX measured at beginning
- Dots: Propagated with transfer matrix



$$\begin{pmatrix} u(s) \\ u'(s) \end{pmatrix} = \mathbf{M} \begin{pmatrix} u(0) \\ u'(0) \end{pmatrix}$$

$$\mathbf{M}_{\text{f. qu.}} = \begin{pmatrix} \cos\left(\sqrt{k_1}l\right) & \frac{1}{\sqrt{k_1}}\sin\left(\sqrt{k_1}l\right) \\ -\sqrt{k_1}\sin\left(\sqrt{k_1}l\right) & \cos\left(\sqrt{k_1}l\right) \end{pmatrix}$$

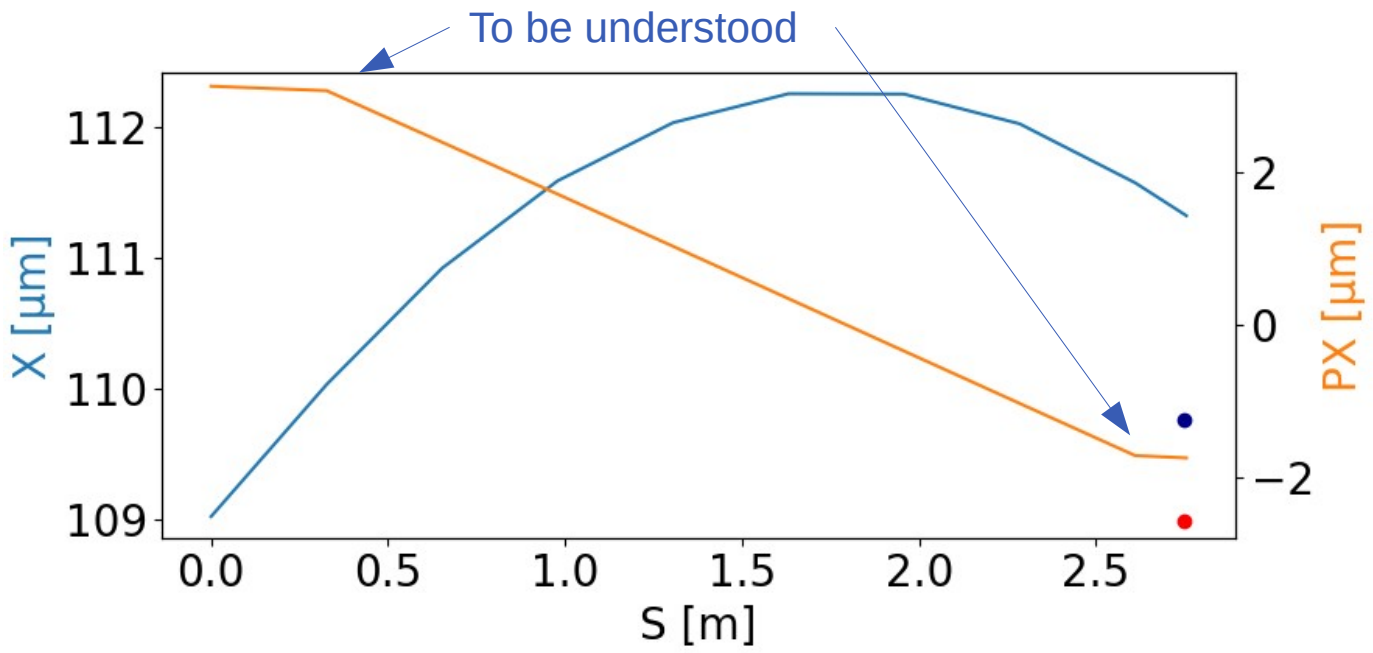
Orbit Through Magnet

Misalignment of 1 Quadrupole

- Quadrupole sliced in 10 slices
- X, PX measured at beginning
- Dots: Propagated with transfer matrix

$$\begin{pmatrix} u(s) \\ u'(s) \end{pmatrix} = \mathbf{M} \begin{pmatrix} u(0) \\ u'(0) \end{pmatrix}$$

$$\mathbf{M}_{\text{f. qu.}} = \begin{pmatrix} \cos\left(\sqrt{k_1}l\right) & \frac{1}{\sqrt{k_1}}\sin\left(\sqrt{k_1}l\right) \\ -\sqrt{k_1}\sin\left(\sqrt{k_1}l\right) & \cos\left(\sqrt{k_1}l\right) \end{pmatrix}$$



Feeddown: dipole field created by misaligned quadrupole

→ Strength of dipole component proportional to offset

→ **Aim: Explore comparing propagated and measured X, PX to directly extract the transverse offset**

→ **Will require ~ 2 BPMs per short straight section**

Summary

- Requirements for BPMs presently being defined for optics measurements and beam-based alignment
  - ~2 µm resolution in turn-by-turn mode
  - << 1 µm in closed orbit mode
  - ~ 2 BPMs for short straight section necessary?

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 in the FCC-ee

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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

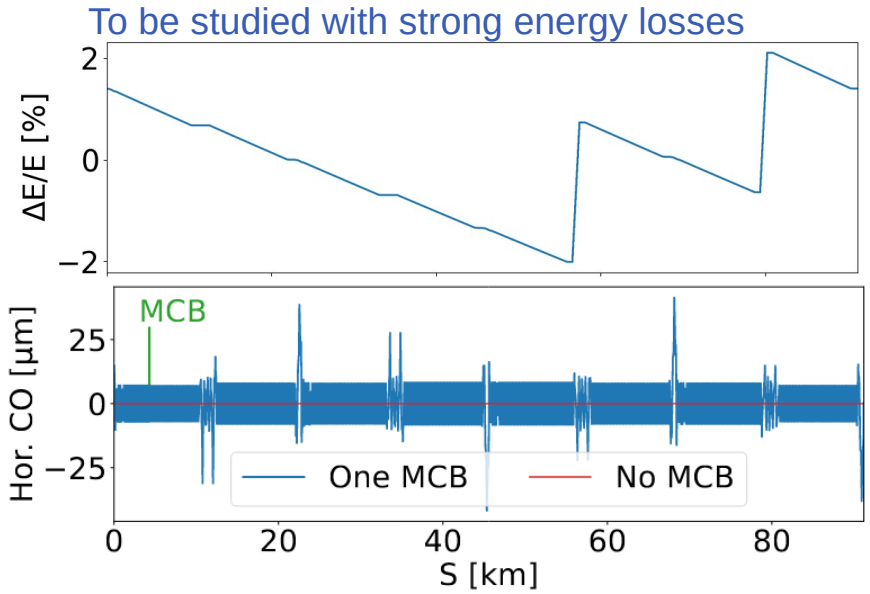
→ Optics measurements and corretions: Could correspond to measurements with e.g. ~ 20 bunches each with 10^{11}

Optics Measurements

Record orbit over several turns

- Used for orbit measurements
- Orbit response matrix measurements

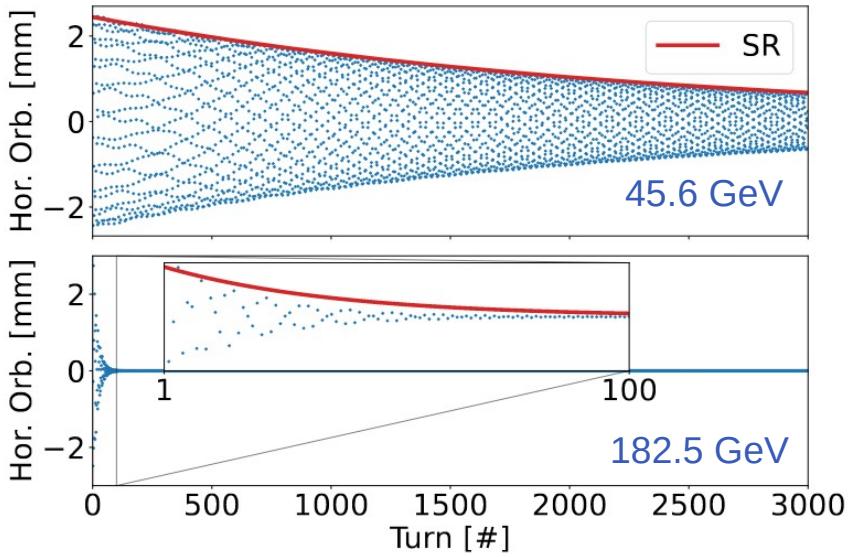
To be studied with strong energy losses



Higher BPM resolution: < 1 μm

Turn-by-turn measurements

- And bunch-by-bunch measurements
- Measurement of frequency spectrum



Poorer BPM resolution: < 10 μm

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

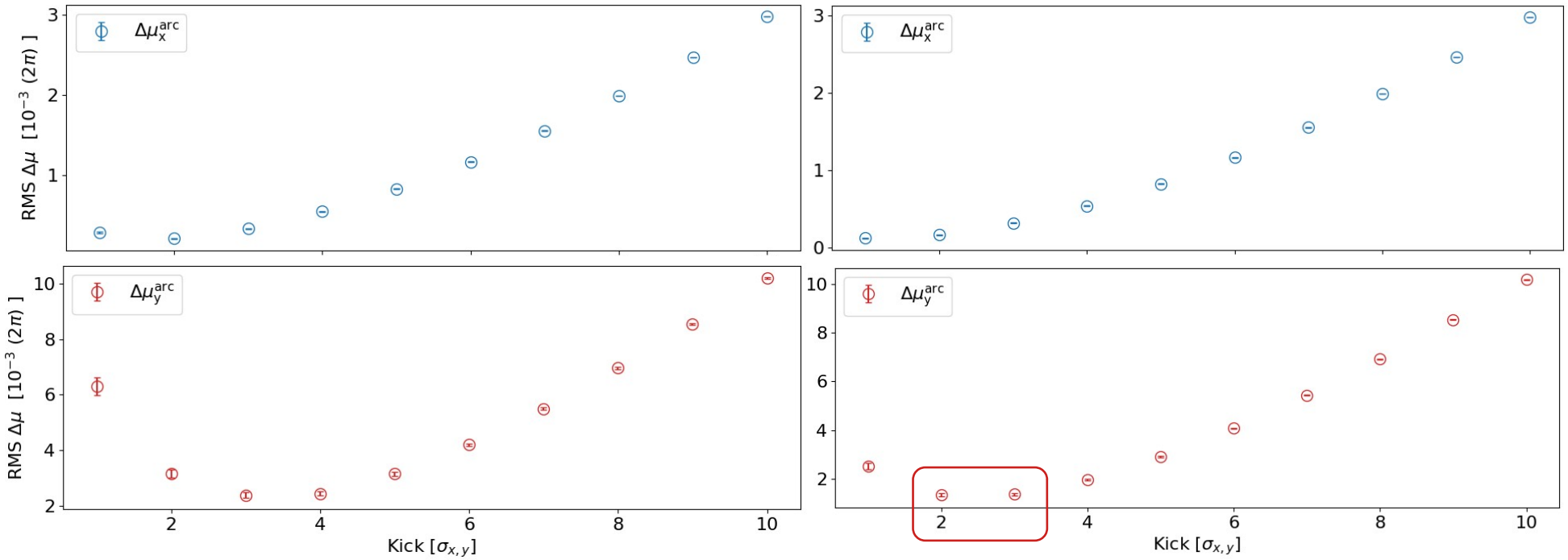
- Z- lattice
- No synchrotron radiation and sextupoles off

BPM resolution: 5 µm

BPM resolution: 2 µm

Horizontal

Vertical



Phase advance error goal only achievable with high resolution BPMs (~ 2 µm)