Beam-based Alignment (BBA) Simulations for the FCC-ee Lattice

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Xiaobiao Huang

SLAC National Accelerator Laboratory

U.S. DEPARTMENT OF ENERGY Office of Science

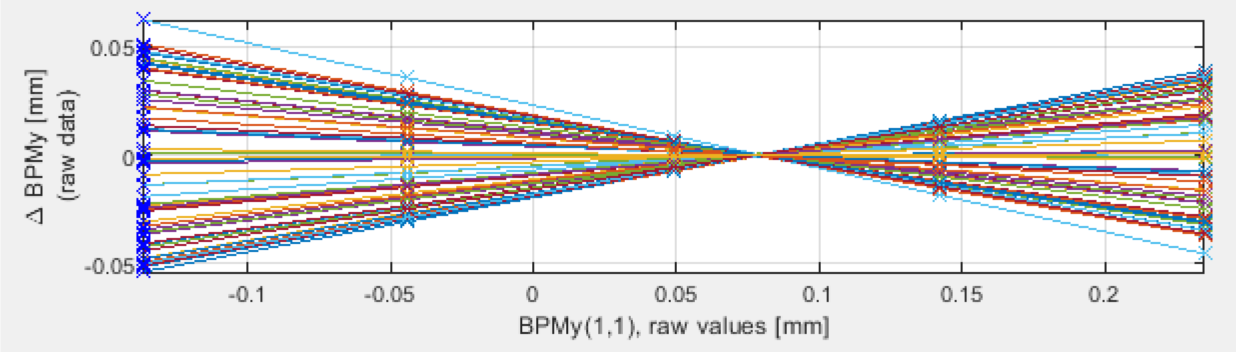
SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Two methods for parallel BBA
  - Method 1: correction of induced orbit shifts
  - Method 2: deduce offsets w/ model and steering
- BBA setup for FCC-ee – an example
  - Lattice w/ alignment errors
  - Group of quads: QF2, group 8 (w/ 8 quads)
- Test results in simulation
  - Method 1
  - Method 2
- Summary

The need for parallel BBA

- In the usual BBA, we target one quadrupole at a time



- Parallel BBA: to determine the centers of multiple quadrupole magnets at the same time
- Scenarios where parallel BBA is needed or desired
  - Multiple magnets share a common power supply – a common scenario
  - Fast BBA measurements

Currently BBA measurement for SPEAR3 takes ~3 hrs
APS-U BBA measurement is estimated to take ~50 hrs

Method 1: PBBA by correcting the induced orbit drift

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- The induced orbit shift (IOS): orbit changes when the strengths of the group of targeted quadrupoles are modulated
- We can correct the orbit for it to go through the quadrupole centers such that the IOS is zero (or minimized)
  - Correction goal: set IOS to zero
    - Need not to know the orbit at the quadrupoles for correction
  - Actuators: corrector magnets
  - Correction method: the corrector-to-IOS response matrix

The IOS response matrix $$\mathbf{R} \equiv \frac{\partial \boldsymbol{\xi}}{\partial \boldsymbol{\theta}} = -\mathbf{A}\mathbf{k}\mathbf{C}$$

$\boldsymbol{\xi}$, IOS at BPMs
$\boldsymbol{\theta}$, kicks by correctors

A, orbit response from kicks at quadrupole location to BPM
C, orbit response from correctors to quadrupole location
k, modulation pattern in a diagonal matrix

After the IOS correction, the orbit is at the quadrupole centers. Record the orbit reading with nearby BPMs.

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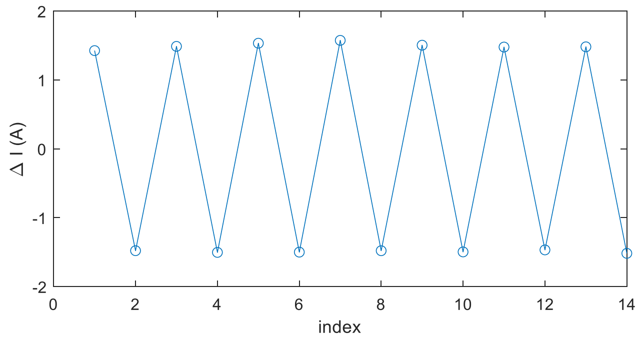
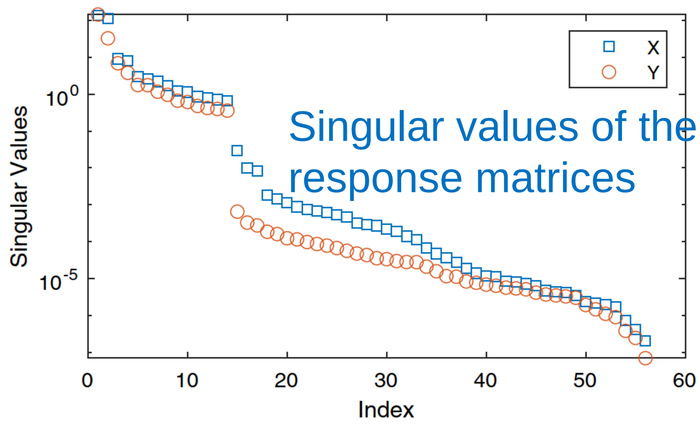
Test of Method 1 on SPEAR3 in experiments

- Modulate 14 QF quadrupoles at a time, w/ alternate signs

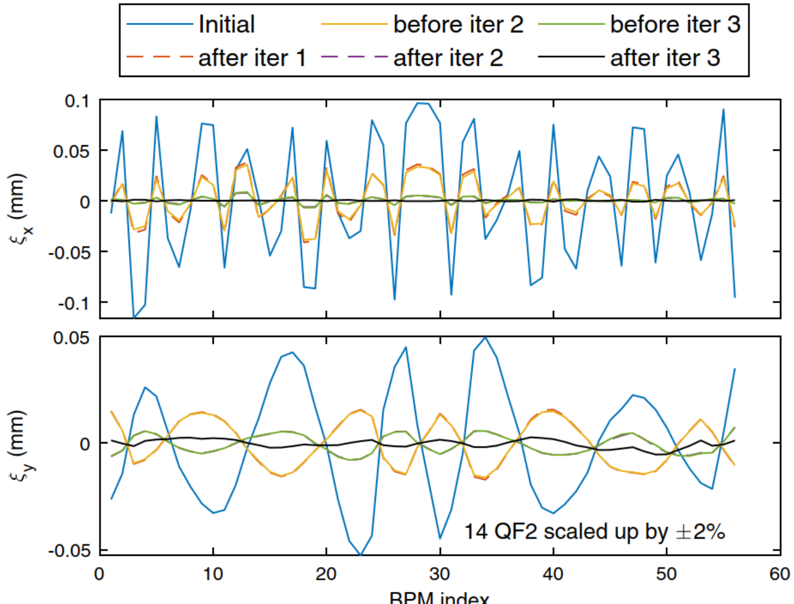


The modulation pattern

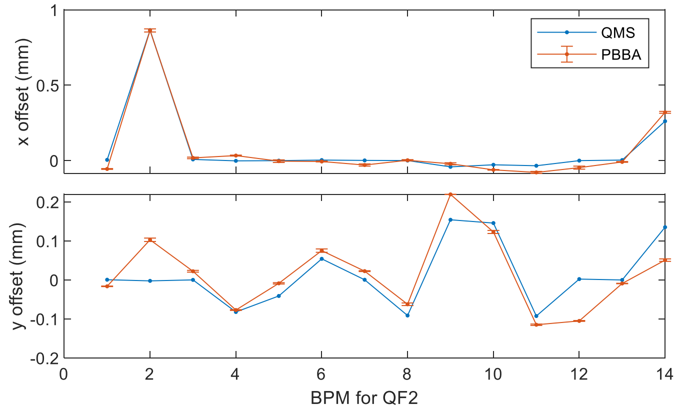


Singular values of the IOS response matrices

- BBA results



The quadrupole centers agree with the usual BBA method (QMS)



Method 2: deduce quadrupole kicks from IOS w/ model, use steering to find quadrupole centers

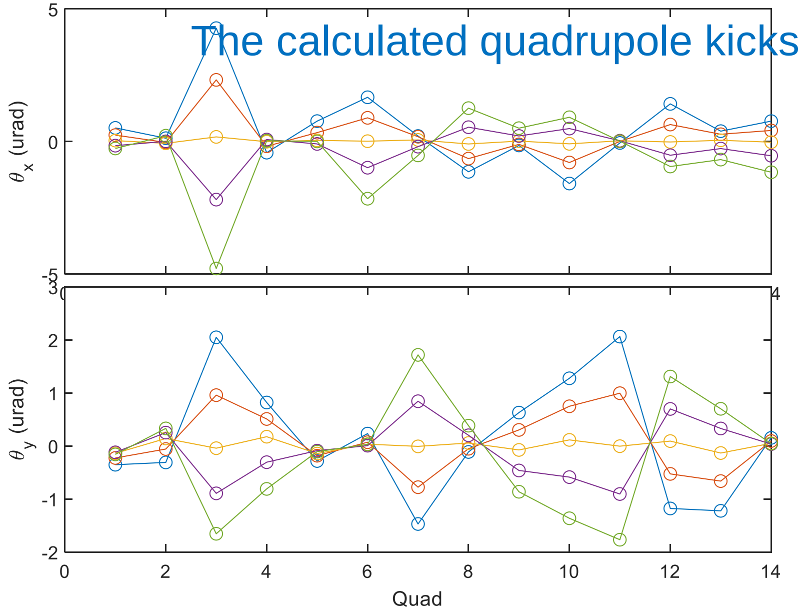
- Assuming the machine lattice is close to the model, we can calculate the kicks by the quads from IOS measurement
  - By inverting the quadrupole-to-BPM response matrix
- By steering the beam orbit and repeating the measurements, we can determine the quadrupole centers
  - In the same fashion as the usual 'bowtie' method
  - A kick-vs-orbit plot for each quadrupole is obtained. Quadrupole center is the zero-crossing of IOS.
  - Two correctors (w/ ~90° phase advance) are used to steer the beam (instead of one in the usual method), so that orbit is shifted at all quadrupoles
    - Or a set of selected correctors forming desired orbit shift patterns.

This method may be called 'parallel QMS' since the usual bowtie method is called QMS.

Test of Method 2 on SPEAR3 in experiments

- The same QF quadrupole group is used

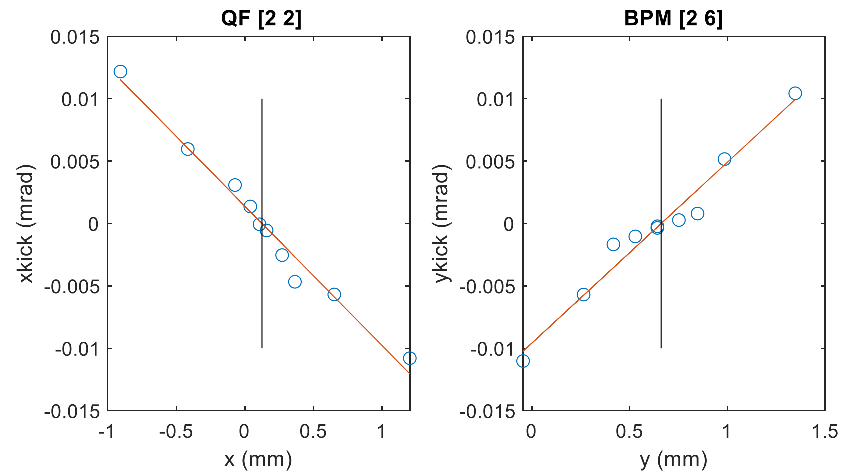
The calculated quadrupole kicks



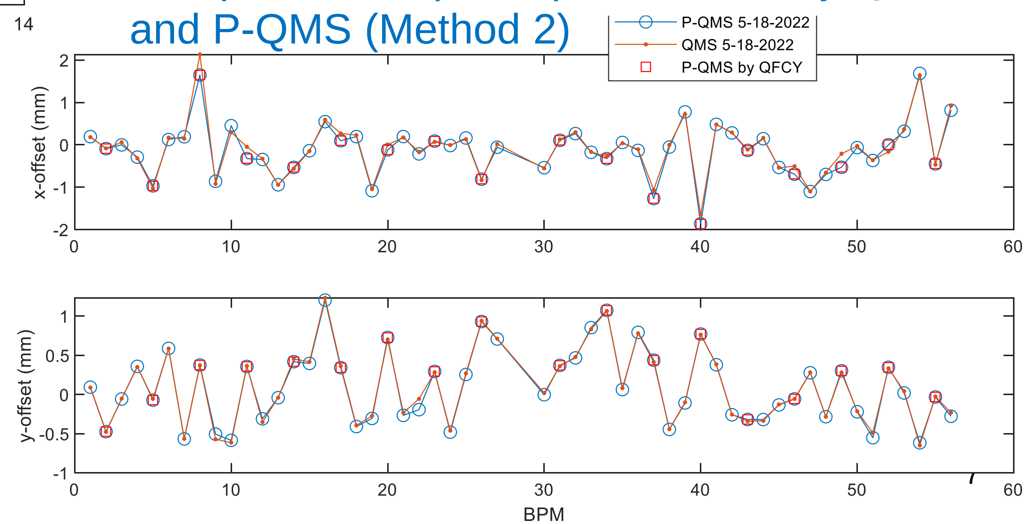
For each IOS measurement, we 'solve' for kicks at the quads

Large errors only for the QFC and QFY group, which are modulated with the same sign.

Fitting to find zero-crossing



Comparison of quadrupole centers by QMS and P-QMS (Method 2)



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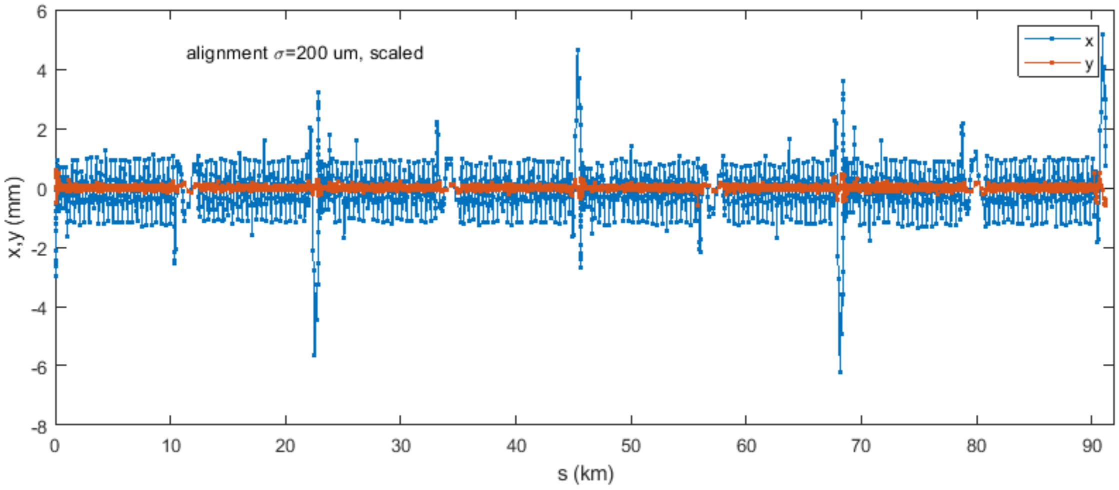
BBA simulation setup for FCC-ee

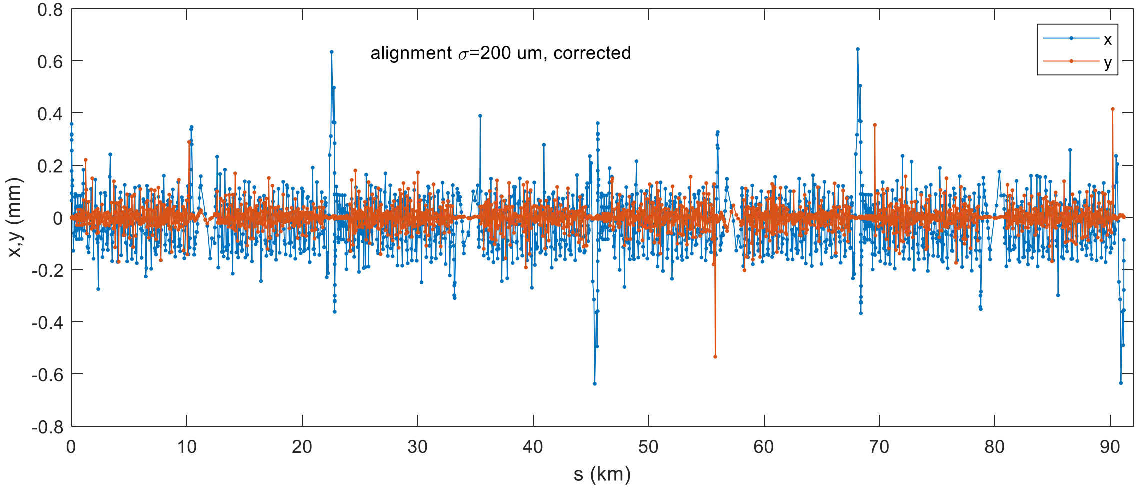
- The lattice version V22_z (45.6 GeV) is used
  - AT lattice file came from Simone Liuzzo
- BPMs and orbit correctors are placed at the entrance of each quadrupole (thin elements)
- Add misalignment (DX, DY) to all arc quadrupoles (1420 total)
  - QD1 (360), SF2 (360), QD3 (348), QF4 (352)
- Correct orbit with correctors, then scale both misalignment and corrector strength
  - Initially add misalignment w/ rms of 25 um in both planes
  - Correct with arc correctors only
  - Scaled to rms=200 um

Scaled to 200 um (rms misalignment errors)

Orbit was first corrected before scaling misalignment



Orbit errors (before corr):
Sigma_x = 0.83 mm
Sigma_y = 0.11 mm

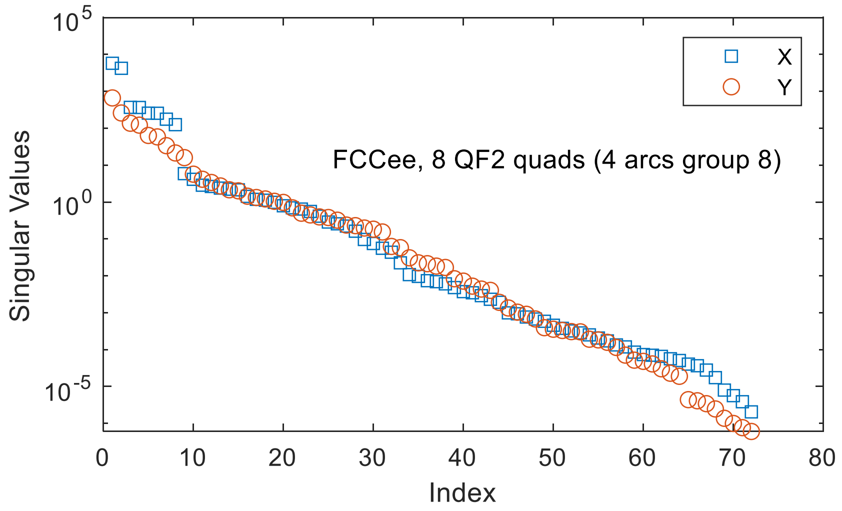


Orbit errors (after corr):
Sigma_x = 0.11 mm
Sigma_y = 0.05 mm

This is the lattice for BBA simulations.
Can do better in orbit correction.
Leaving orbit errors to be more realistic.

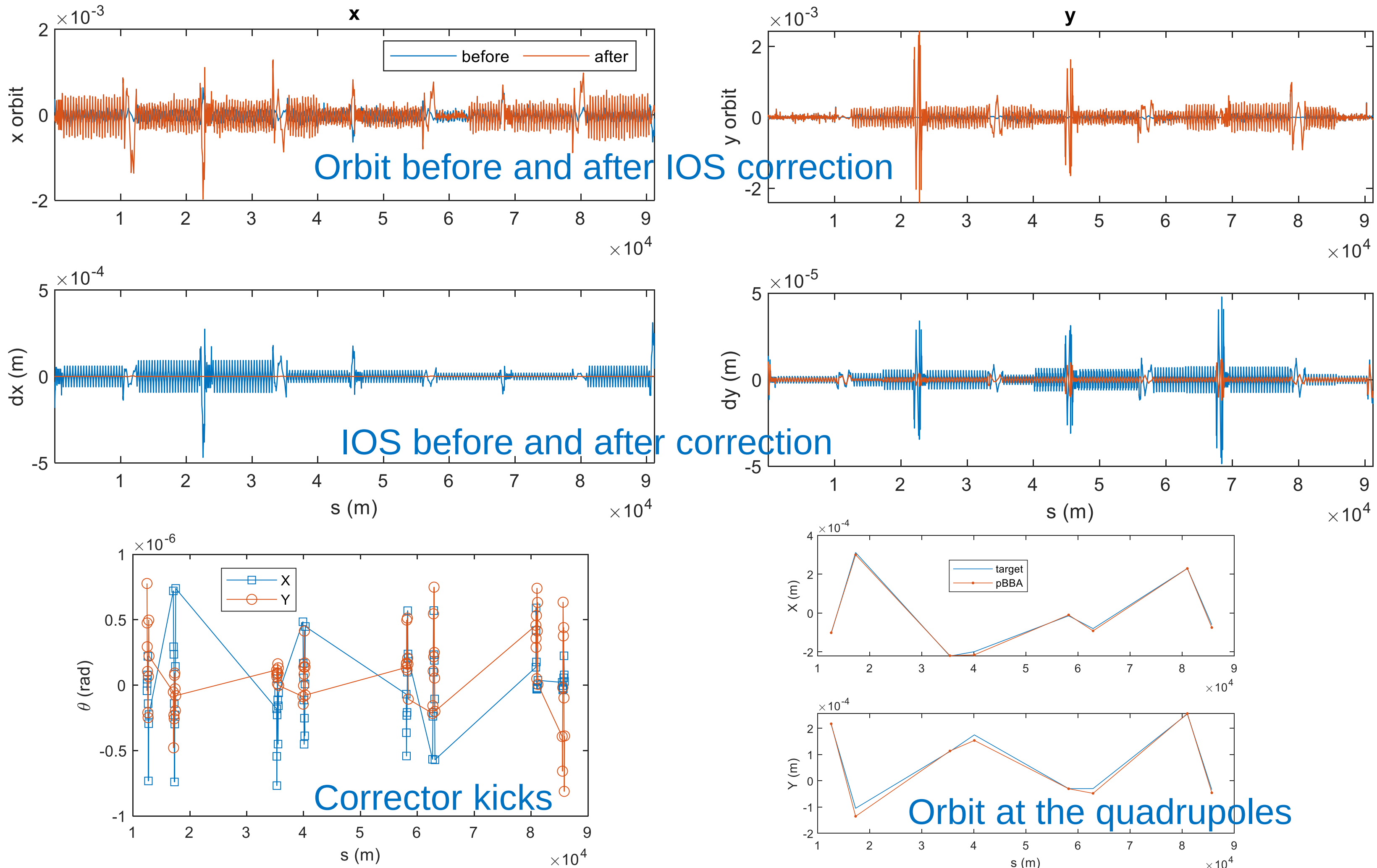
The group of quadrupoles selected for the test

- 8 QF2 quadrupoles on the arcs (choose 1:45:360, i.e., every 45th QF2)
  - 9 near-by correctors (on each plane) are selected for IOS correction
  - Modulate quadrupoles by $\pm 2\%$ alternately
  - IOS response matrix: 1856 (all BPMs) by 72 correctors



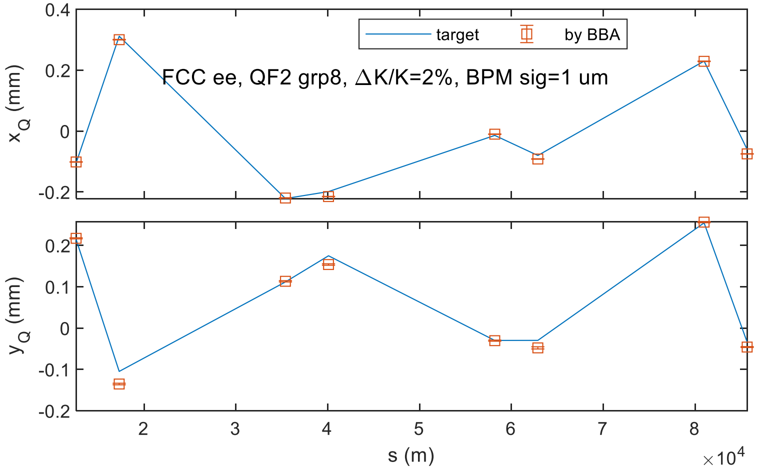
Correction of IOS (Method 1)

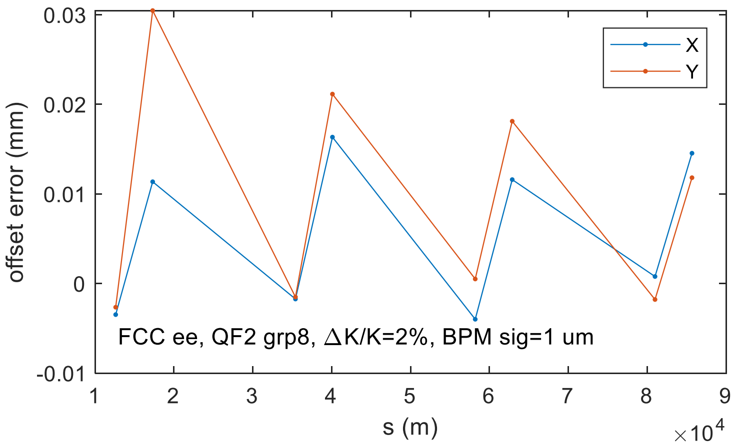
- Correction of IOS by shifting orbit to quadrupole centers



BBA Errors (Method 1)

- Repeat 20 times, with random BPM noise (sigma=1 um)
- The systematic errors with this configuration is on the 10-30 um level.
  - Larger errors for Y-plane because of QF magnets

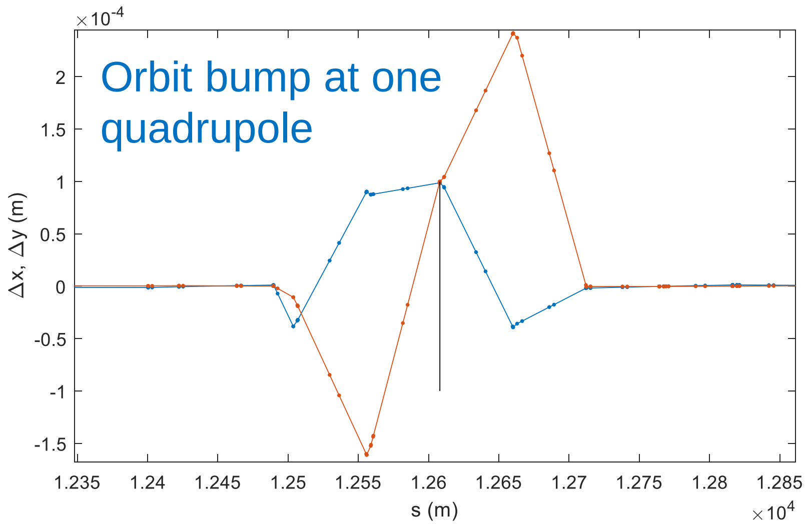


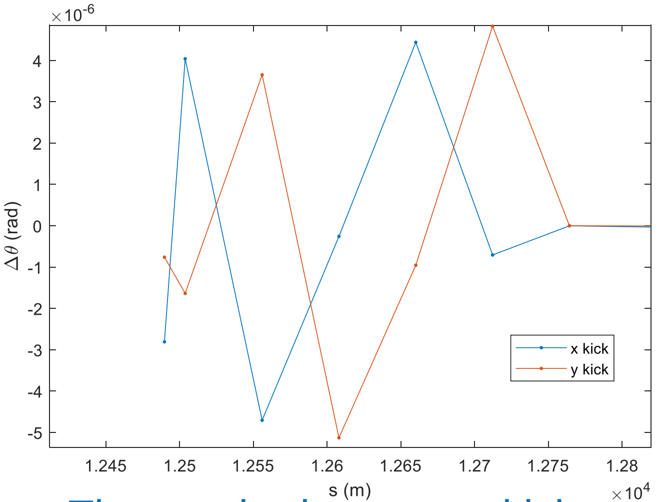


Ideas for improvement: correction of IOS with local orbit bumps around targeted quadrupoles; better correction algorithm.

Method 2 modification for FCC – closed-orbit bump

- In view of the long and weak FCC quadrupole, it seems important to minimize the angle at the targeted quadrupoles
  - Assuming the angle alignment error is small compared to the orbit steering
  - So we make closed orbit bumps with zero angle at the target quadrupoles – one bump for each quad
  - We steer the orbit with the orbit bump and modulate quadrupoles at each stop



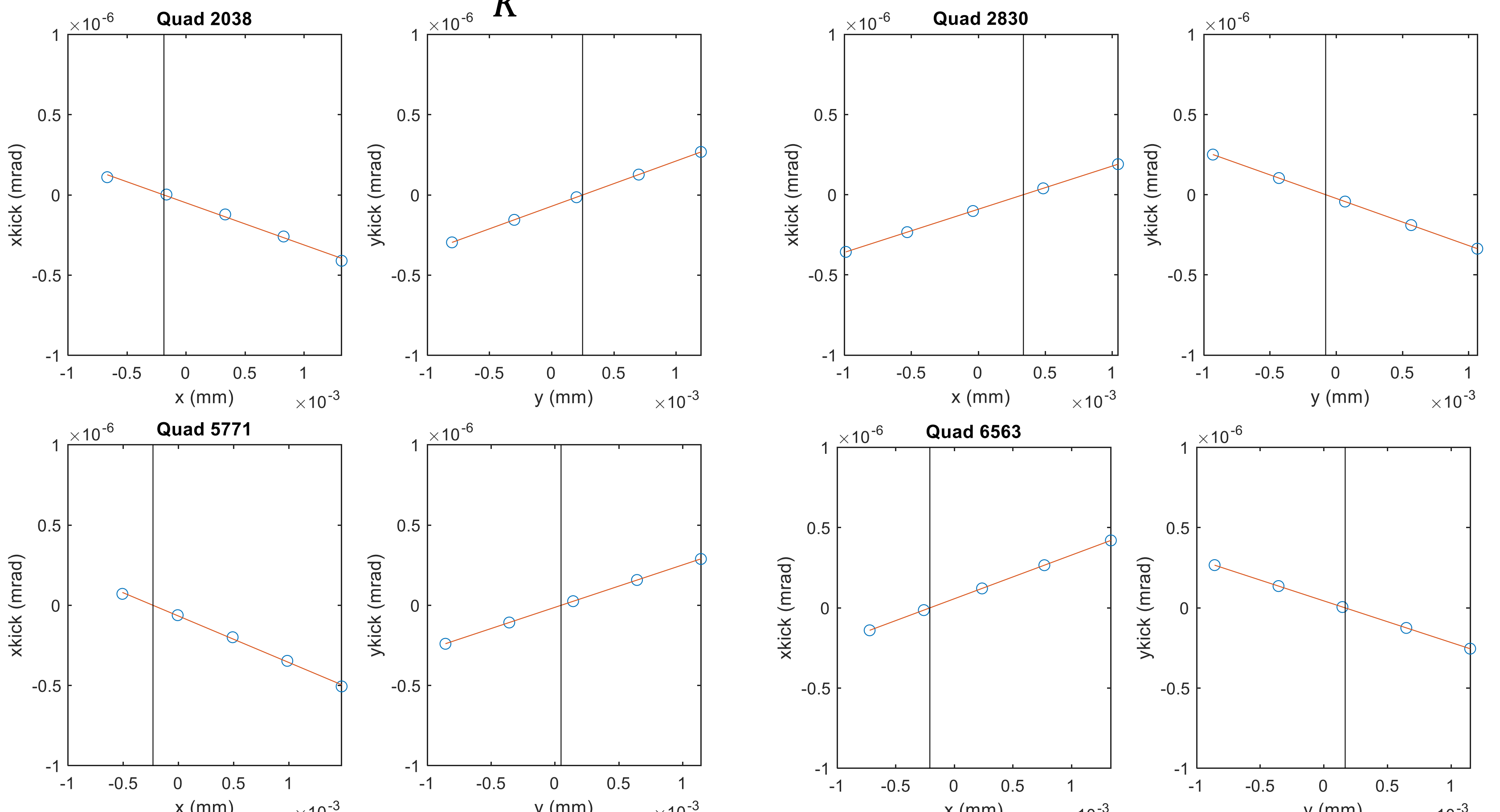


The required corrector kicks

P-QMS results, no random error

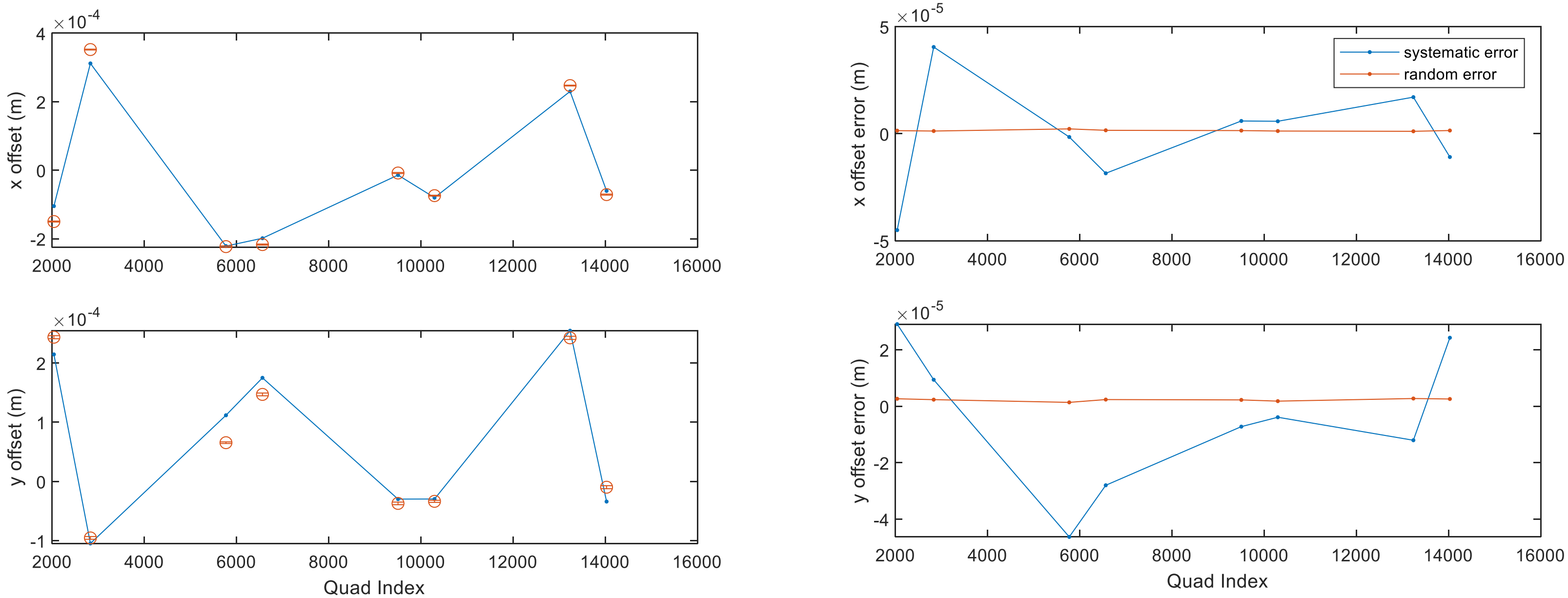
- Steer by +/- 1 mm (note simulated alignment error is 0.2 mm rms), modulation by $\frac{\Delta K}{K} = 1\%$

Showing 4 quadrupoles as examples



BBA results w/ Method 2

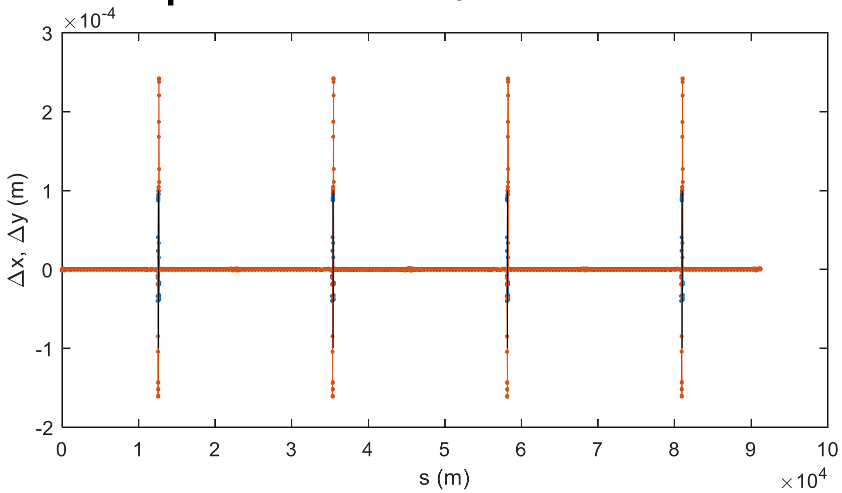
- Use only BPMs next to arc quadrupoles to measure IOS
- Repeat 10 times to estimate random errors (BPM noise sigma=1 um)

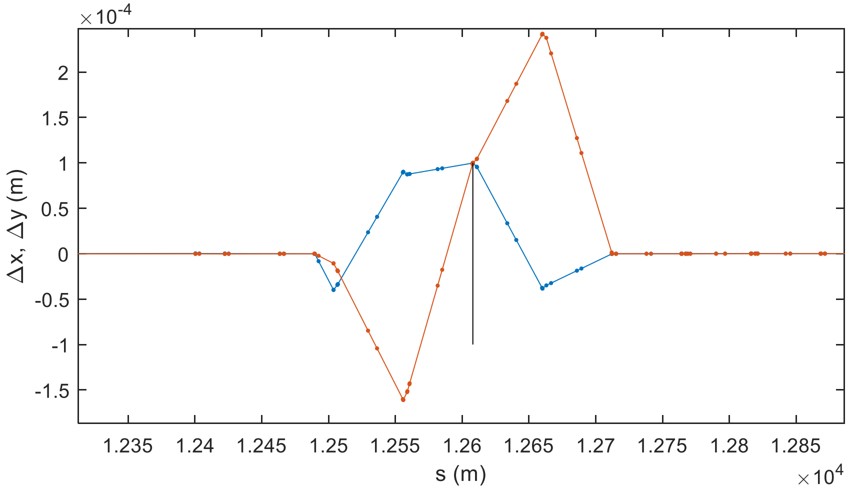


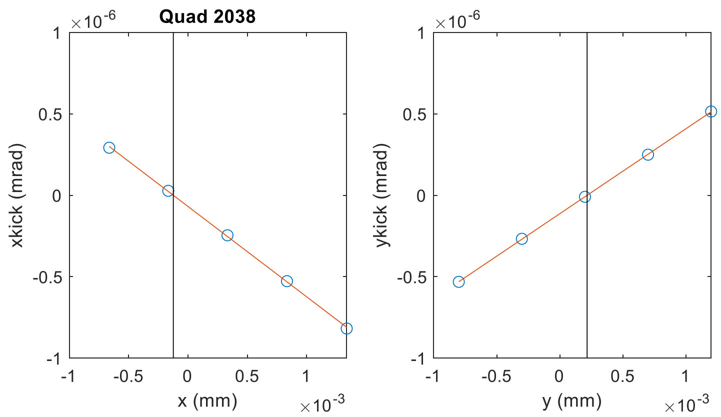
Systematic errors are up to 50 um (while mostly lower)

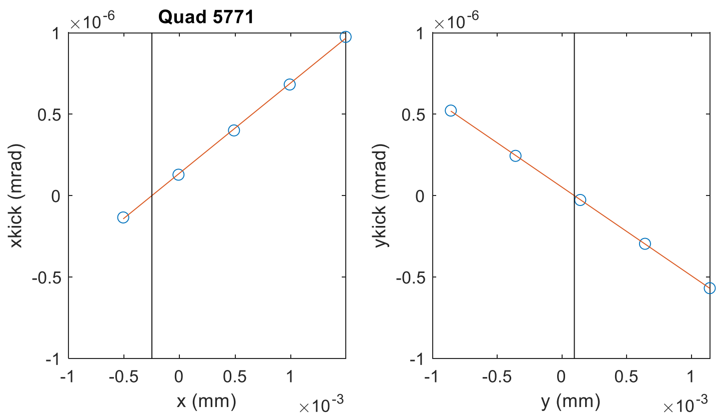
Would fewer quadrupoles in the group help?

- Same procedure, but work with only a half of the quads



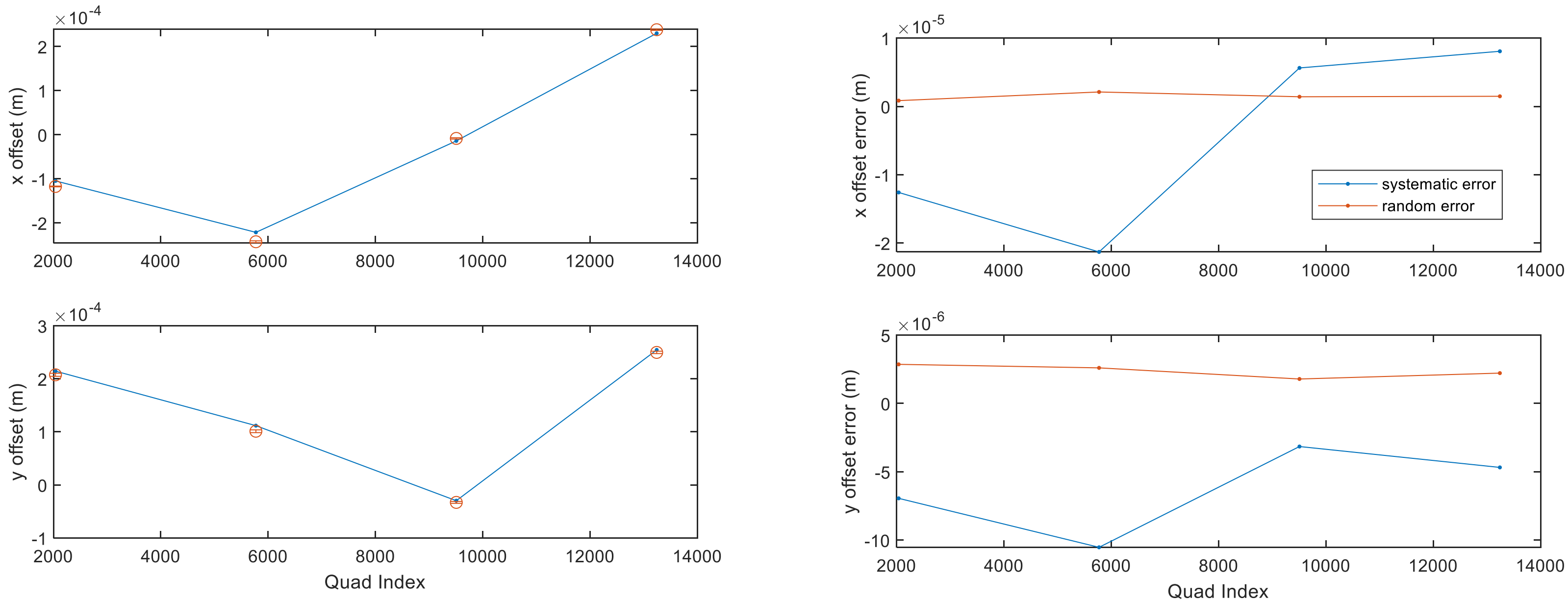






Systematic errors are reduced

- Now the systematic errors is only up to 20 ums



The errors may come from the ambiguity in finding the kicks at quadrupoles, given that the angle effects are not included in the quad-to-BPM response matrix.

Next steps

- The biggest issue is the systematic errors in the BBA results
- For both methods, we need to understand the sources of the systematic errors
  - Size of the group
  - Better isolation of the quadrupoles in the group with local bumps
  - Effect of entrance angles (of the orbit) to the quadrupoles
  - Selection of correctors and BPMs
  - Better correction algorithm (Method 1) or inversion for kicks (Method 2)
- Divide all quadrupoles into groups for tests

Summary

- Two methods can be used for parallel beam-based alignment for FCC-ee
  - Both tested on existing machine in experiments
- Simulation has been done to test the methods for FCC-ee lattice
  - w/ independent alignment errors in quadrupoles with rms DX, DY=200 um
- Both methods work for FCC-ee, but with some systematic errors
  - Method 1: 10-30 um systematic errors for the 8-quad test example
  - Method 2: Up to 50 um but most are smaller for the same example, smaller (<20 um) if using a 4-quad group
- Future work to understand and mitigate systematic errors