Beam-based alignment simulations for FCC-ee

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Xiaobiao Huang

SLAC National Accelerator Laboratory

U.S. DEPARTMENT OF ENERGY

Office of Science

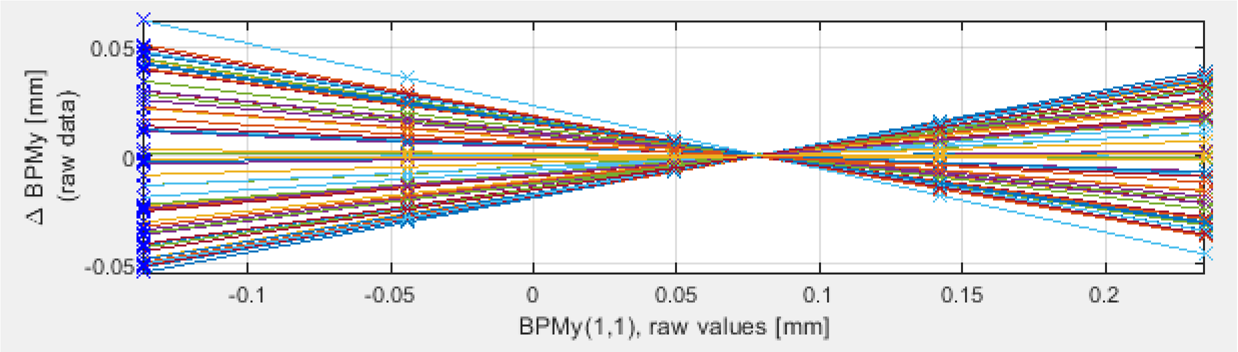
SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Parallel BBA methods
  - PBBA
  - P-QMS
  - Experimental tests
- Simulations for FCC-ee
  - Lattice setup
  - Quadrupole BBA
  - Sextupole BBA
- Summary

Parallel BBA are preferable for FCC

- The traditional BBA method is time consuming as it handles one quadrupole at a time



- A large machine would benefit greatly from parallel BBA, as multiple magnets can be measured simultaneously
  - Parallel BBA can also work for magnets with common power supply

Method 1: PBBA by correcting the induced orbit drift

- 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 $$\mathbf{R} \equiv \frac{\partial \boldsymbol{\xi}}{\partial \boldsymbol{\theta}} = -\mathbf{AkC}$$

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

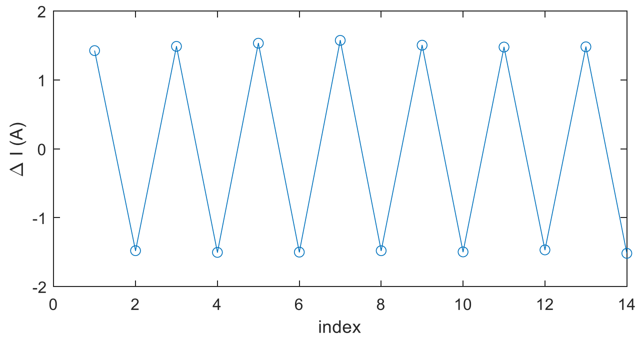
A, orbit response from kicks at quadrupole location to BPM
C, orbit response from correctors to quadrupole location
k, modulation pattern in a diagonal matrix

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

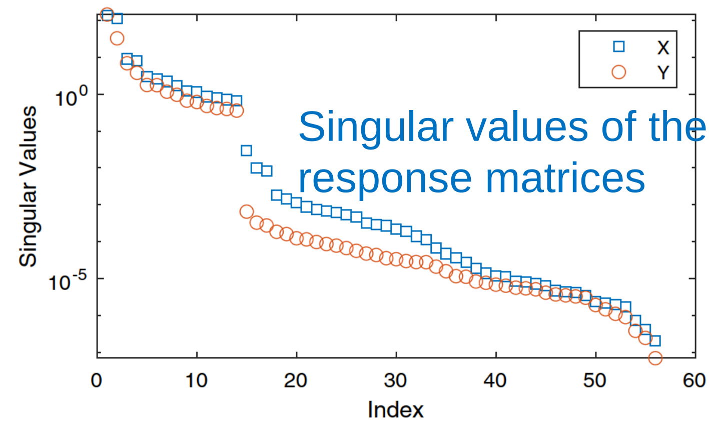
X. Huang, PRAB 25, 052802 (2022)

Test of Method 1 on SPEAR3 in experiments

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

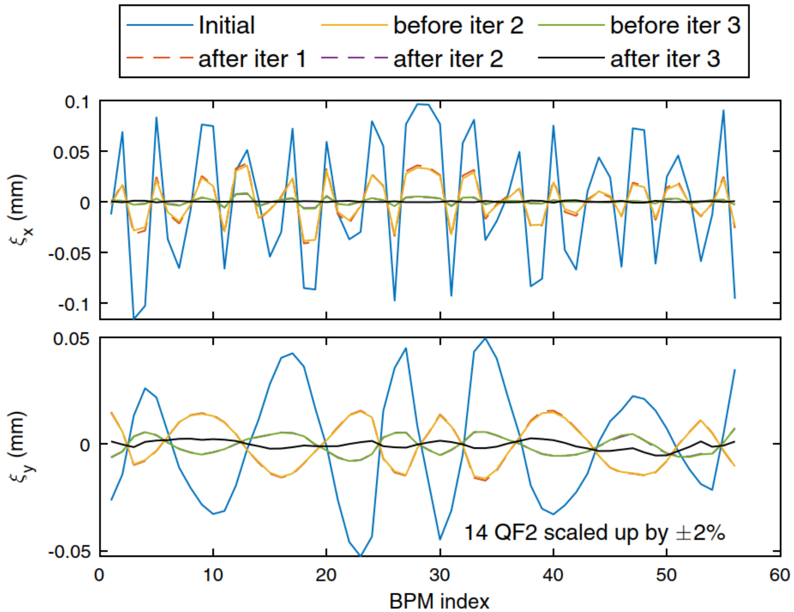


The modulation pattern

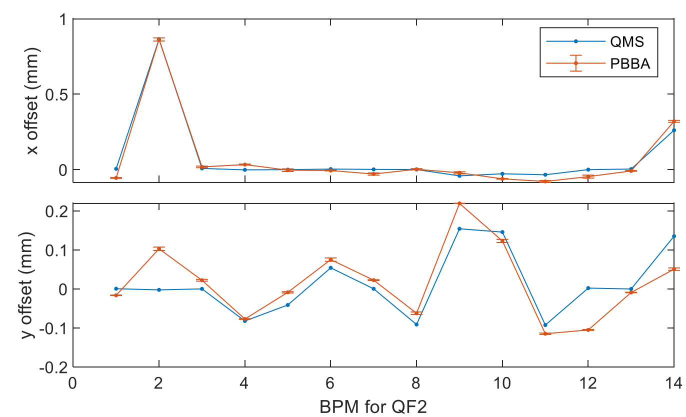


Singular values of the IOS response matrices

- 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, $\boldsymbol{R}_q$

$$\Delta\theta_q = \left(\mathbf{R}_q^T \mathbf{R}_q\right)^{-1} \mathbf{R}_q^T \Delta\mathbf{x}.$$

- 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 point of IOS.
  - Originally proposed to use two correctors (w/ ~90° phase advance) instead of one in the usual method. More recently use closed-orbit bump for each quadrupole

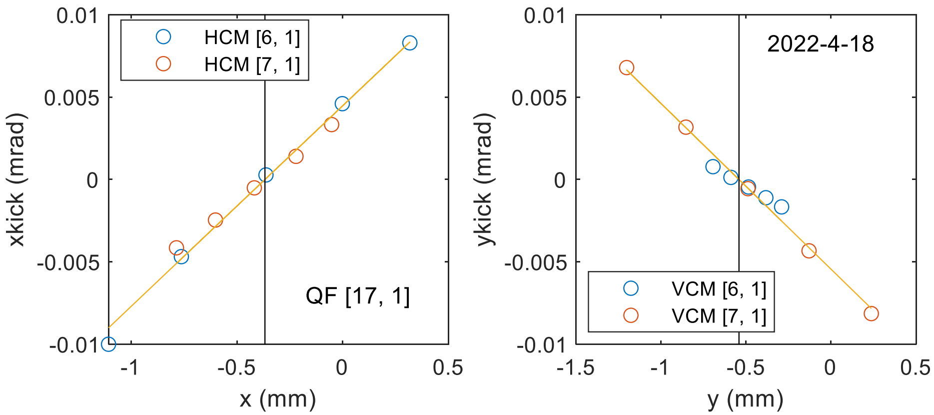
This method may be called ‘parallel QMS’ since the usual bowtie method is called QMS.

X. Huang, IPAC’24 (2024), THPG37

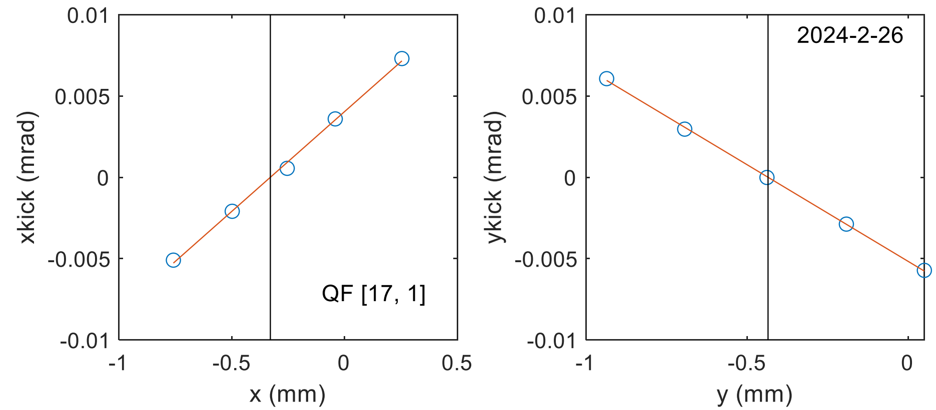
Test of Method 2 on SPEAR3 in experiments

- The same QF quadrupole group is used

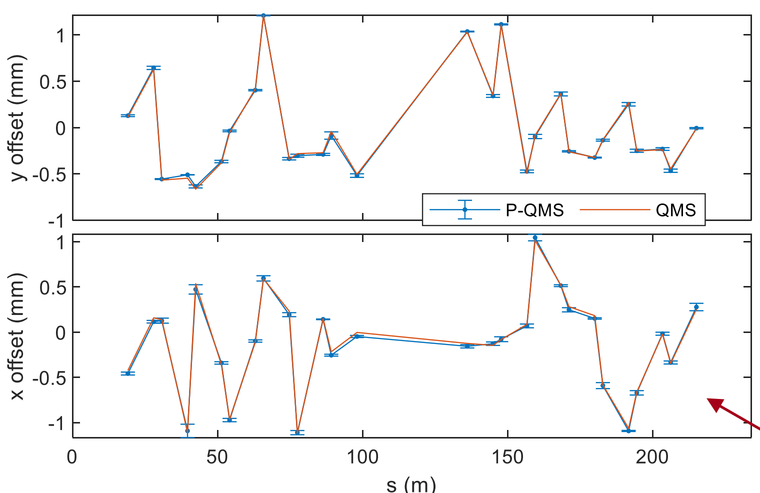
Fitting to find zero-crossing



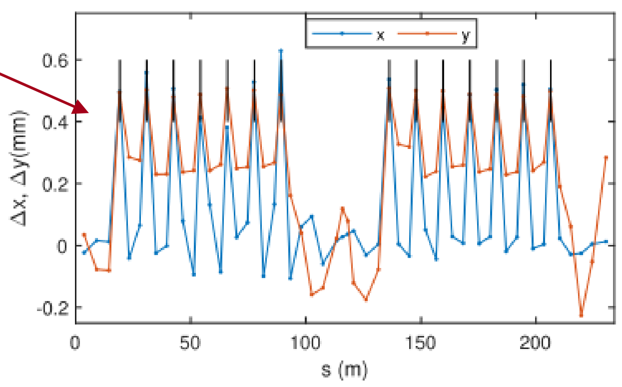
Using two correctors to shift orbit



Using closed orbit bump to shift orbit



Orbit bumps for the measurement



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

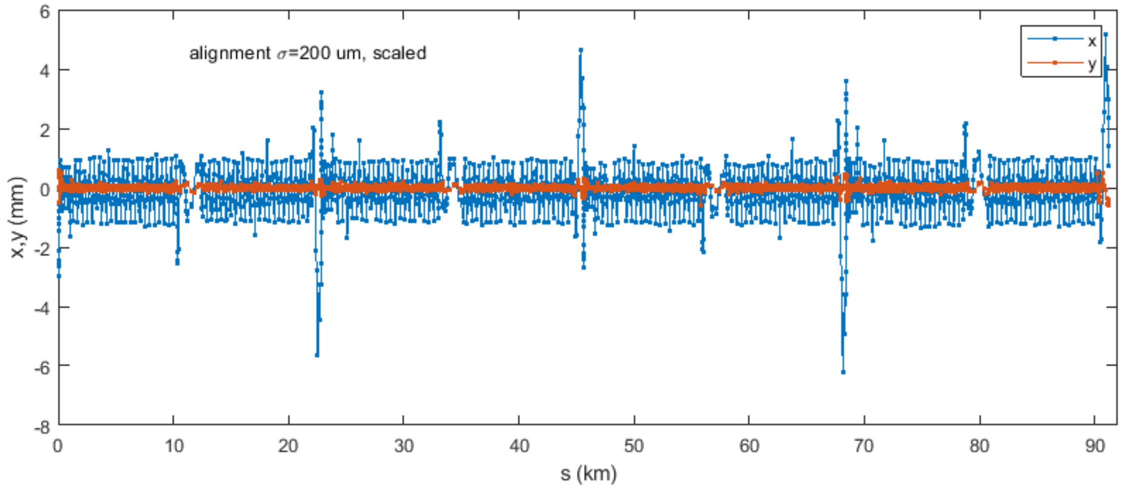
BBA simulation setup for FCC-ee

- The lattice version V22_z (45.6 GeV) is used
- 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

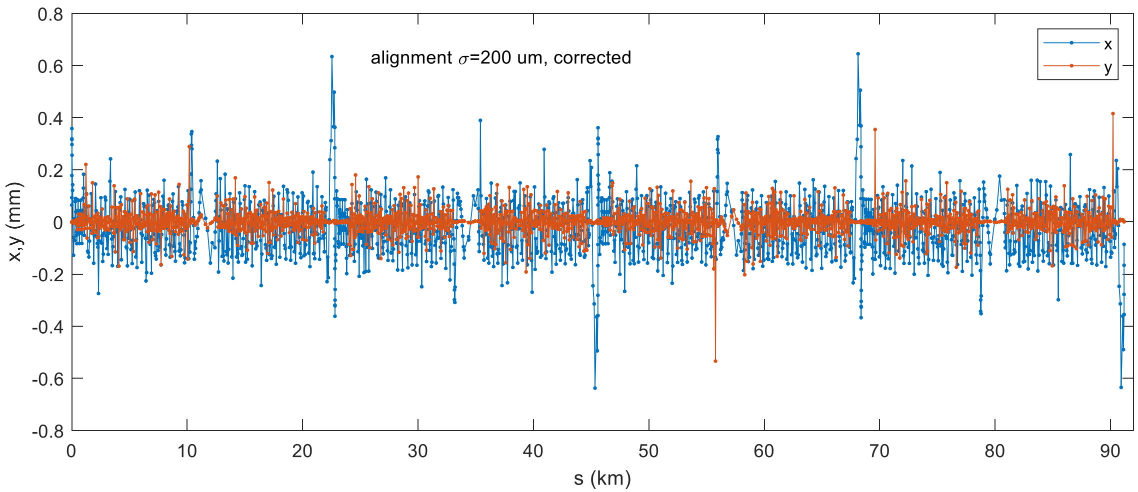
Orbit errors in the simulation lattice

SLAC

Orbit was first corrected before scaling misalignment



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



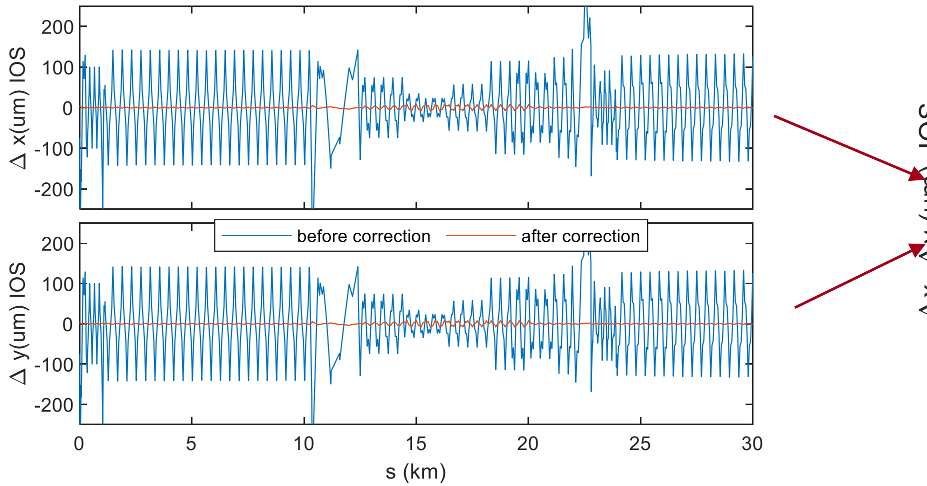
Orbit errors (after corr):
Sigma_x = 0.11 mm
Sigma_y = 0.05 mm

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

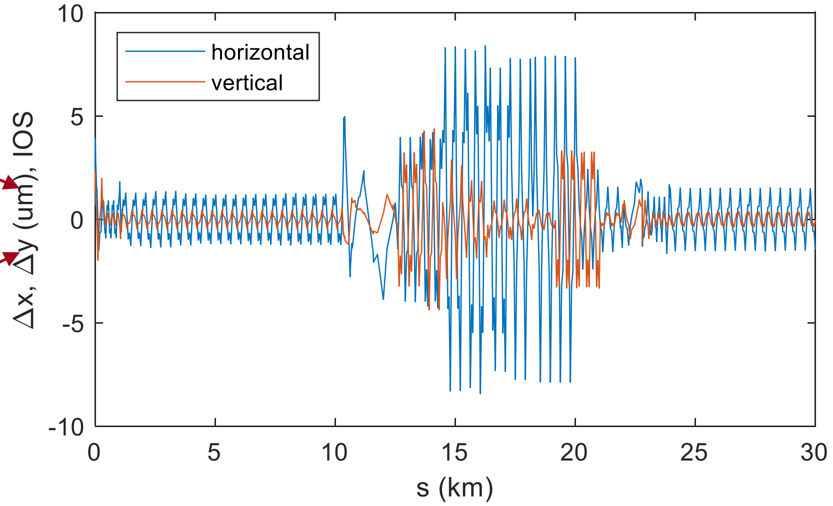
Application of PBBA

- Choose a group of 10 QF2 quadrupoles for the test
  - QF2 magnet length 2.9 m, gradient $K_1 = 9.5372 \times 10^{-3}$ m^{-2}
  - Modulate by $+/-2\%$ in quadrupole strength

The correction greatly reduces the IOS



But there are still some residual IOS

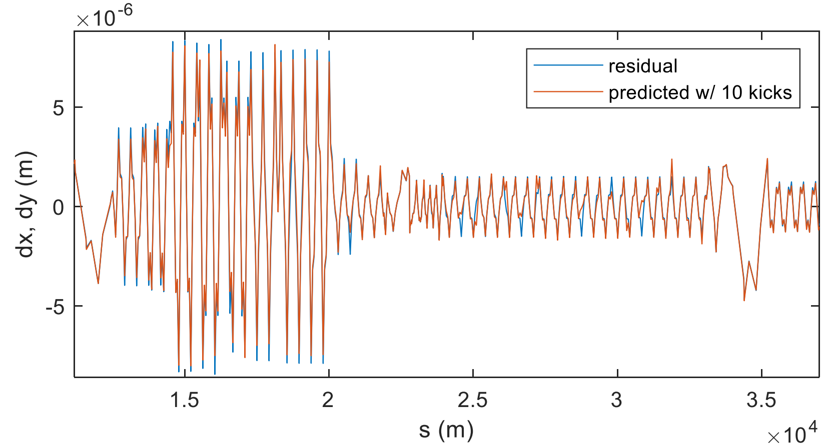


The residual IOS errors cause a systematic error to the quadrupole centers found by PBBA, unless we find a better way to correct

Improving IOS correction

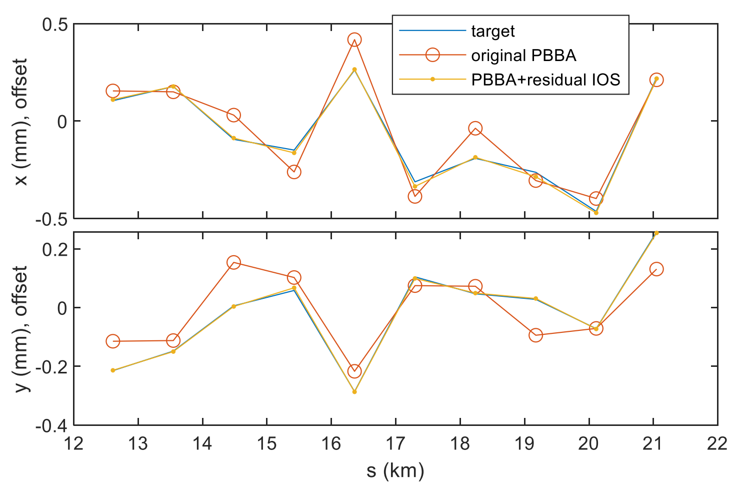
- The residual IOS errors are still caused by kicks by the modulated quadrupoles

The kicks calculated by the residual IOS with quadrupole-to BPM response matrix can explain the residual IOS.



A correction to the quadrupole center can be made from the residual IOS, along with the modulation strength

$$\Delta x_c = -\frac{1}{\Delta KL}\Delta\theta_x, \quad \Delta y_c = \frac{1}{\Delta KL}\Delta\theta_y.$$

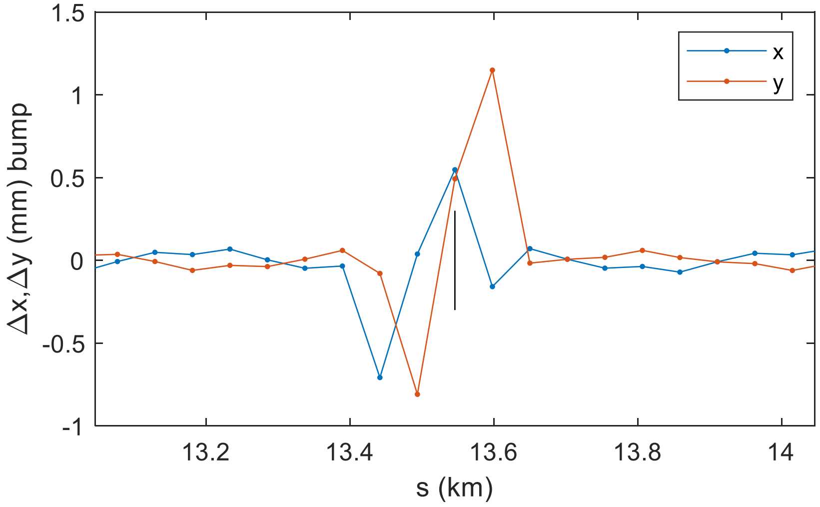


Or, the IOS correction can be improved by correcting the orbit to the predicted quadrupole center.

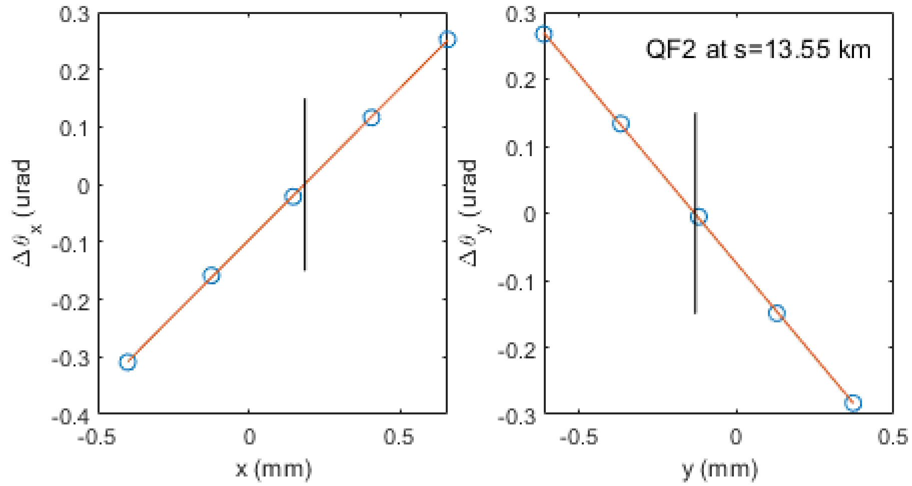
Application of P-QMS

- The same QF2 group is used for testing. Flat-top local orbit bumps are used to steer the orbit

Flat-top orbit bump for one quadrupole



Fitting kick angles vs. orbit at the quad

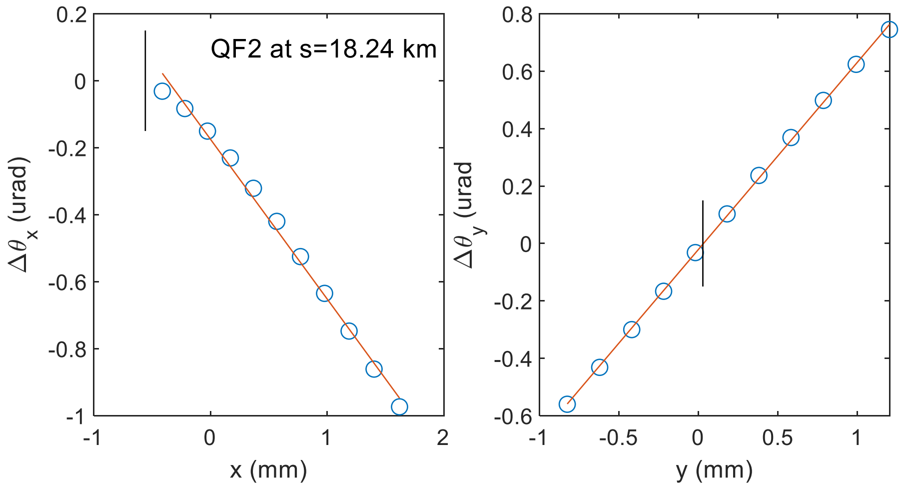


(The local orbit bumps could be used as correction knobs in PBBA)

Possible issues with P-QMS

- P-QMS is reliable, but can also suffer systematic errors in some circumferences
  - If the quadrupole center falls outside of scanned range
  - When lattice nonlinearity affects the linear fitting

Example of needing extrapolation and impact from nonlinearity (with 10-point scan for illustration)

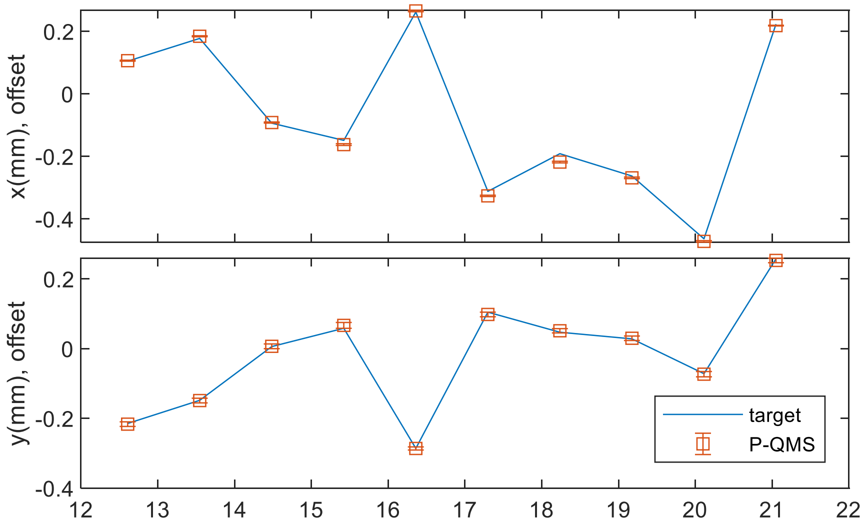


We want to launch the scan from the vicinity of the quadrupole center and with a relatively small range.
Not a problem. PBBA can get close to the quadrupole centers

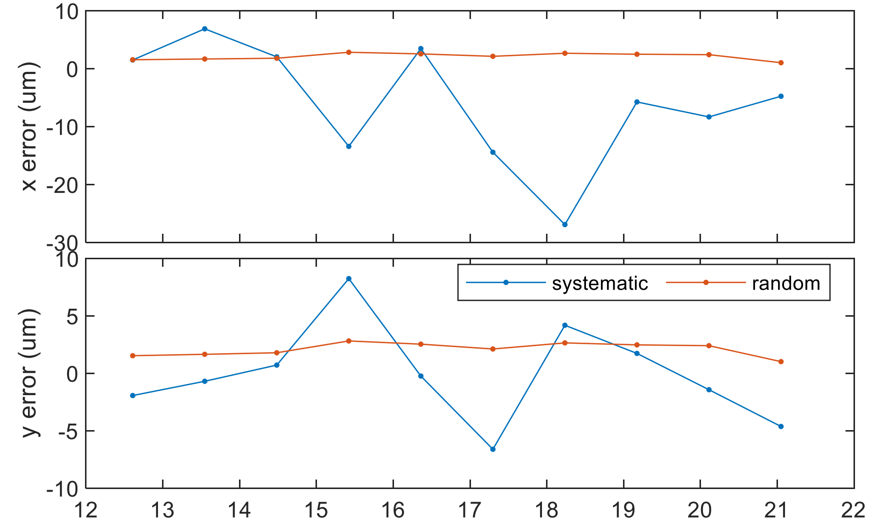
P-QMS test results

- Testing P-QMS w/ first performing IOS correction with PBBA
  - Scanning range is $+/-0.5$ mm
  - Repeating 10 times with random BPM errors

Comparison of quadrupole centers found by P-QMS to target



Systematic (blue) and random (red) errors. BPM noise sigma = 1 um.

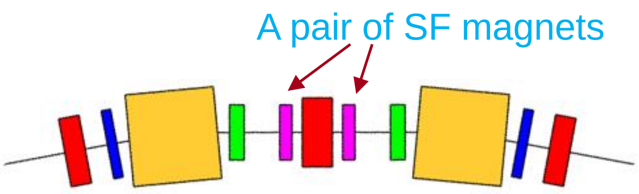


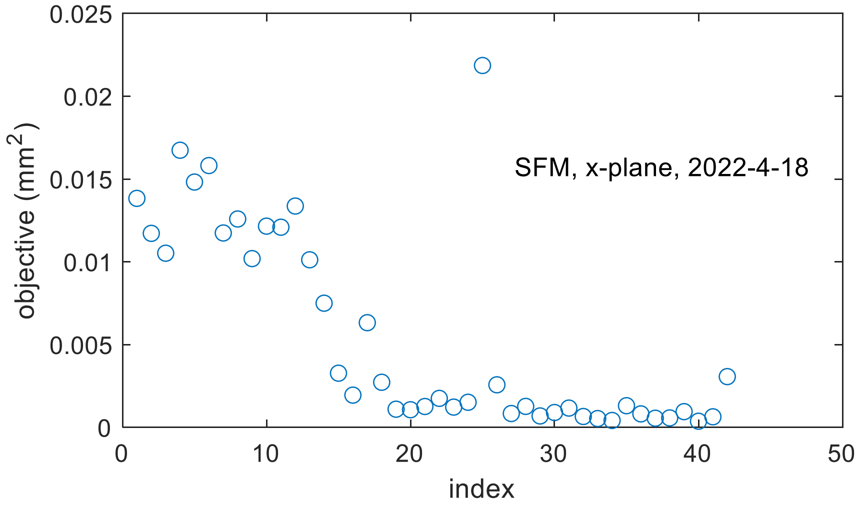
PBBA for sextupoles

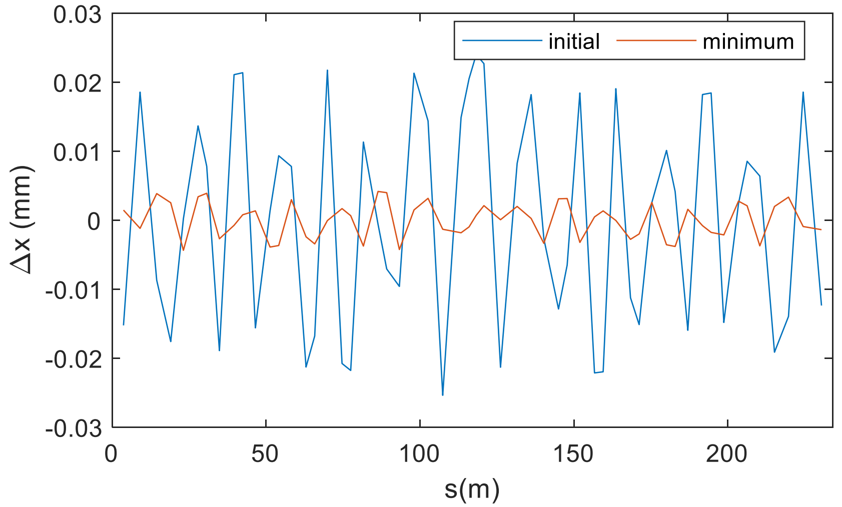
- It may be advantageous to steer the beam orbit through the sextupole centers (as opposed to quadrupole centers)
  - Minimizing linear optics errors and coupling errors
  - This requires BBA for sextupoles
- The PBBA principle is applicable to sextupoles – by minimizing IOS due to sextupole strength modulation, the orbit goes through the sextupole centers
  - But we can’t use the response matrix method to ‘correct’ the IOS since the response is not linear
  - We can use an optimizer to turn the corrector knobs
  - The principle has been tested on the SPEAR3 ring

PBBA experiment on SPEAR3

- Tested with a group of 4 sextupole pairs with a common power supply (2 per cell, 4 cells)
  - Modulation strength = -20%
  - Use 12 correctors as tuning knobs (3 per cell)







Convergence may be faster if we use local orbit bumps as tuning knobs

But this does not scale well with multiple sextupoles as the required number of evaluations increases as the number of knobs increases.

Another parallel sextupole BBA method

- The method is based on the ability to separate the kicks applied by the magnets from the IOS – similar to P-QMS

$$\Delta\theta_x = (R^T_{q,xx} R_{q,xx})^{-1} R^T_{q,xx} \Delta x_{\mathrm{IOS}},$$
$$\Delta\theta_y = (R^T_{q,yy} R_{q,yy})^{-1} R^T_{q,yy} \Delta y_{\mathrm{IOS}}.$$

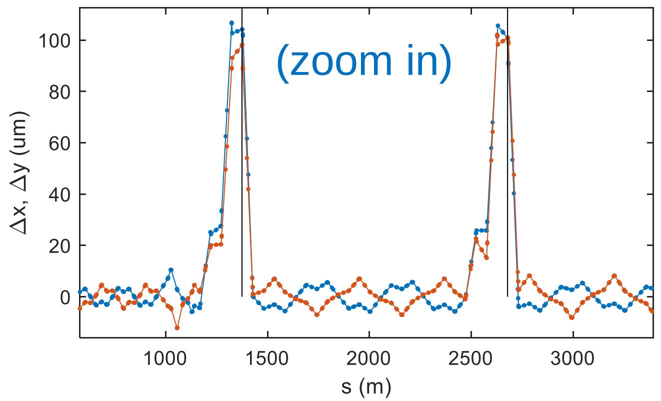
- Scan the orbit at the sextupoles and determine the position with zero kicks by fitting.

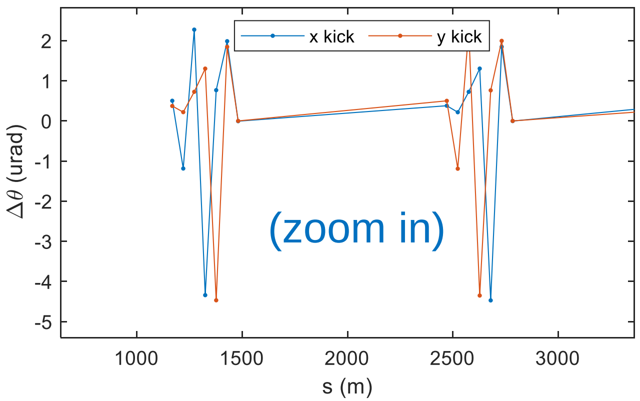
$$-[\Delta K_2 L]\frac{1}{2}\left((x_s - x_0)^2 - (y_s - y_0)^2\right) = \Delta\theta_{x,s},$$
$$[\Delta K_2 L](x_s - x_0)(y_s - y_0) = \Delta\theta_{y,s},$$

This method is similar to P-QMS, only we don’t fit a linear curve, but a parabola.

Sextupole BBA Simulation Setup

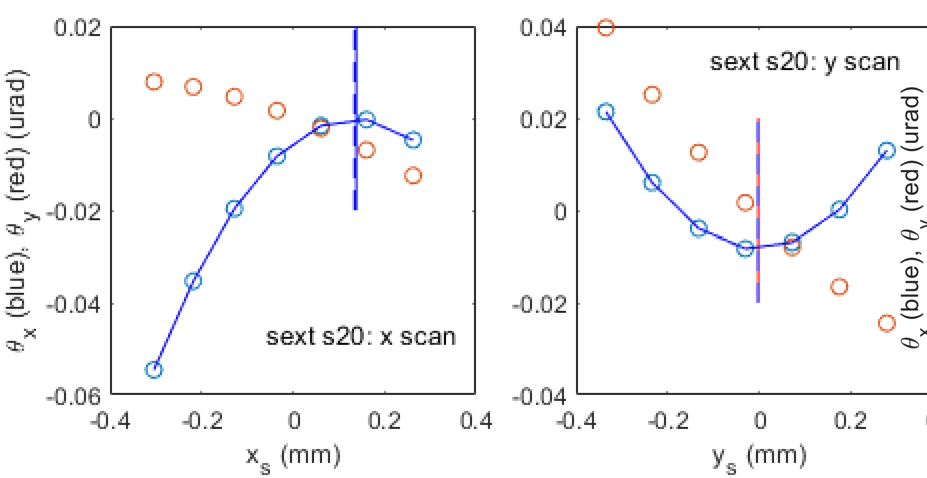
- Add random misalignment errors to sextupoles w/ rms DX, DY= 0.2 mm (same as quads)
  - w/ quads misalignment error included as in quads PBBA study
- We use local orbit bumps as knobs for PBBA, instead of individual correctors.
  - No orbit distortion for other sextupoles to cause optics distortions



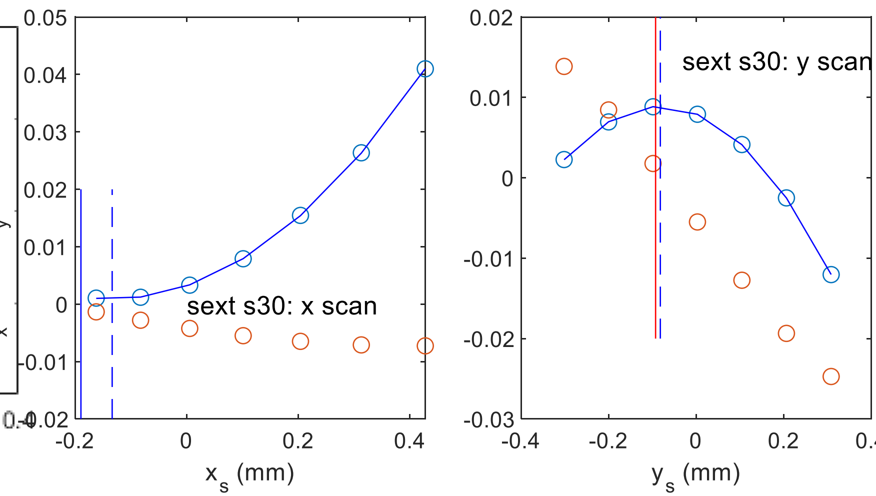


Orbit Scanning and Fitting

- Sextupole modulation is -100% (turning off)
- Perform two linear orbit scans, one for each transverse plane
- We fit the horizontal kick angle $\theta_x \sim x, y$
  - Could fit both θ_x and θ_y
  - BPM noise sigma of 1 um is added to orbit measurements



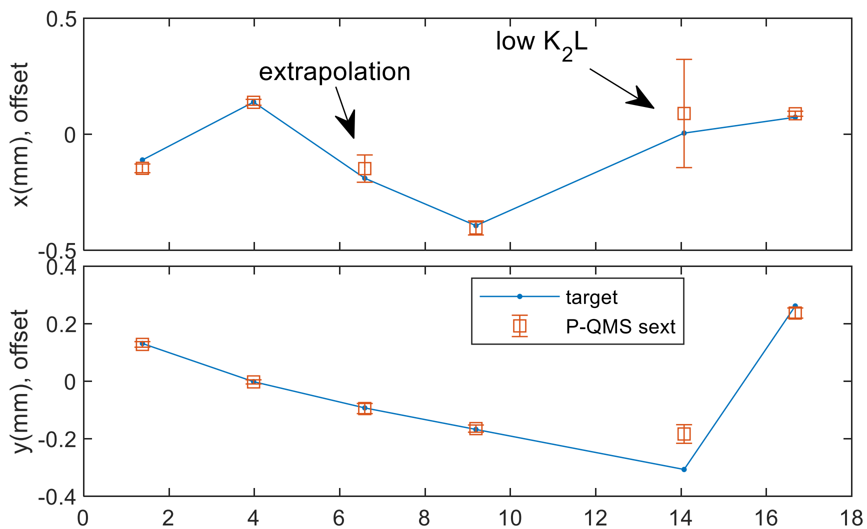
Sextupole located at s=3.98 km

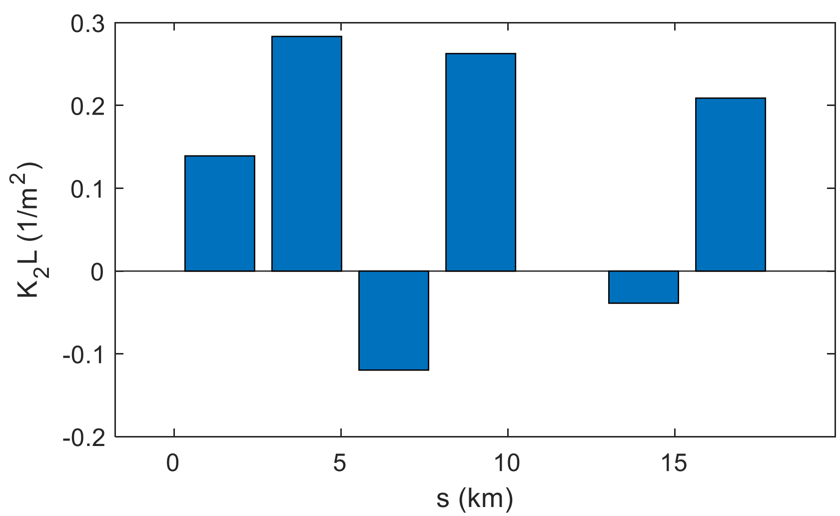


Sextupole located at s=6.59 km

Comparison of sextupole BBA with target

- Sextupole centers found by BBA agree with target
  - Error sigmas are estimated by repeating simulation 10 times
  - Large error sigma occur when
    - The center lies outside of the scanned range
    - The sextupole modulation strength is low
- The typical error bar is ~20 um for $K_2L{\sim}0.2\,m^{-2}$.





Summary

- Two approaches can be used to perform BBA of multiple magnets in parallel
  - Minimizing the induced orbit shifts due to magnet strength modulations
  - Determining kick angles and fitting for individual magnet for zero-crossing point
  - The principles have been tested in experiments
- Simulation with FCC-ee lattice show that the methods work for both quadrupoles and sextupoles
  - Error sigma on the order of 10 um can be reached for quadrupoles
  - Error sigma on the order of 20 um can be reached for sextupoles (depends on the integrated strength of the magnets)