Optics Correction and Beam-based Alignment (BBA) for Low Emittance Rings – some recent progress

The 9th Low Emittance Rings Workshop
CERN
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Outline

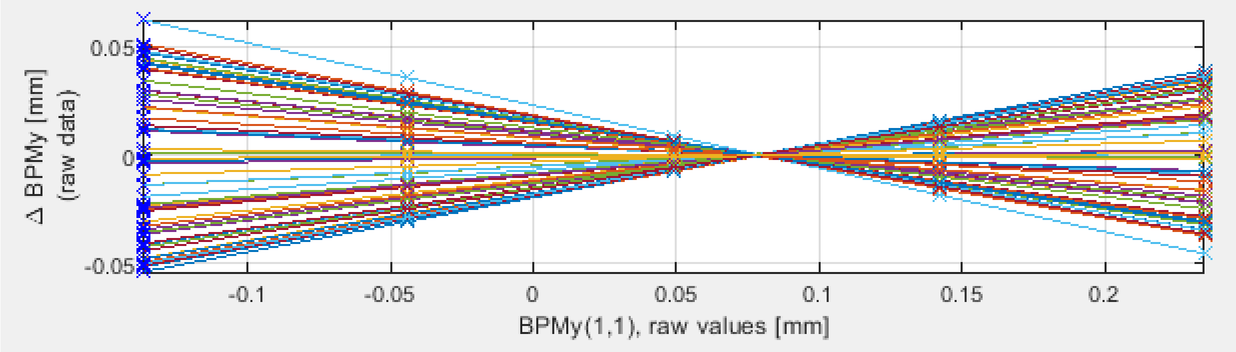
- Parallel beam-based alignment (PBBA)
- Optics and coupling correction with driven closed orbit oscillation (LOCOM)
- Autoresonant driving for linear and nonlinear optics measurement (and correction)
- Summary

Parallel Beam-based Alignment (PBBA) and Parallel Quadrupole Modulation System (P-QMS)

See X. Huang, Phys. Rev. Accel. Beams **25**, 052802, May 2022

The need for parallel BBA

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



Measured w/ Matlab Middle Layer

- 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 (per V. Sajaev)

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

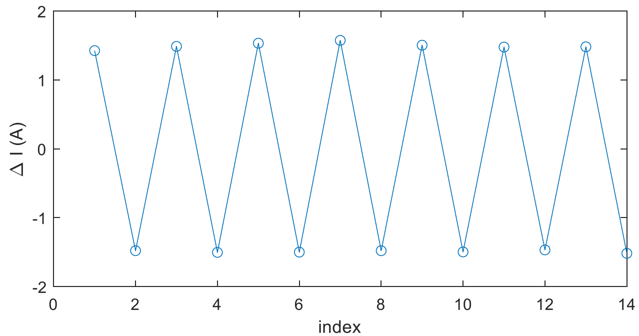
A, orbit response from kicks at quadrupole location to BPM
C, orbit response from correctors to quadrupole location
k, modulation pattern in a diagonal matrix

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

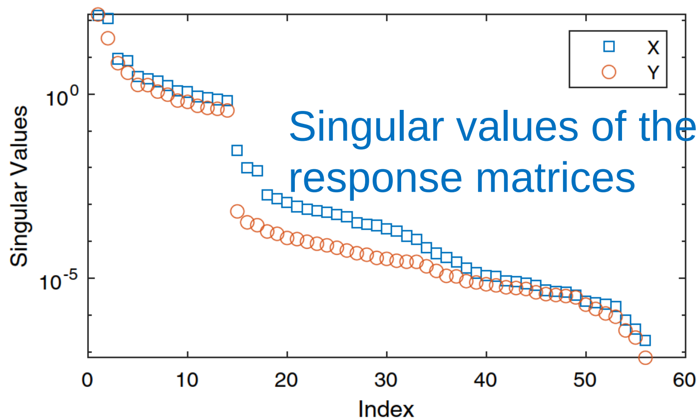
X. Huang, PRAB 25, 052802 (2022)

Test of Method 1 on SPEAR3 in experiments

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

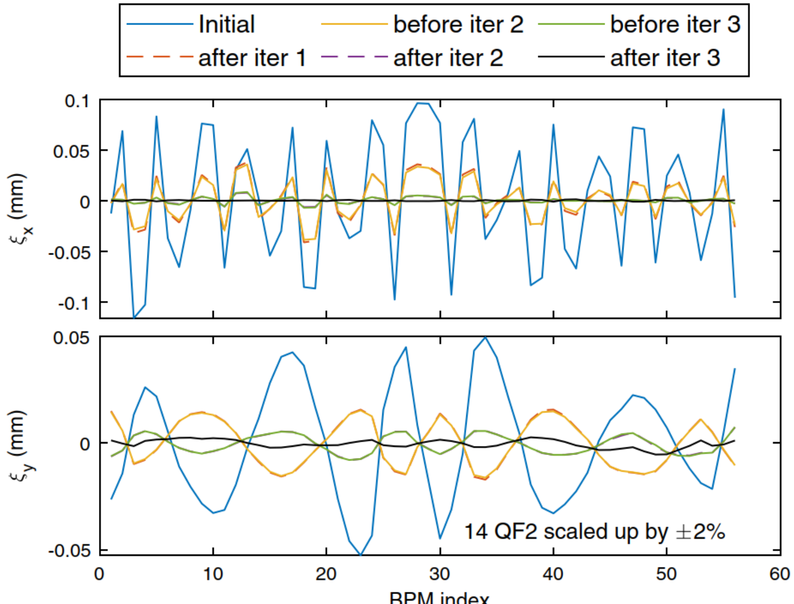


The modulation pattern

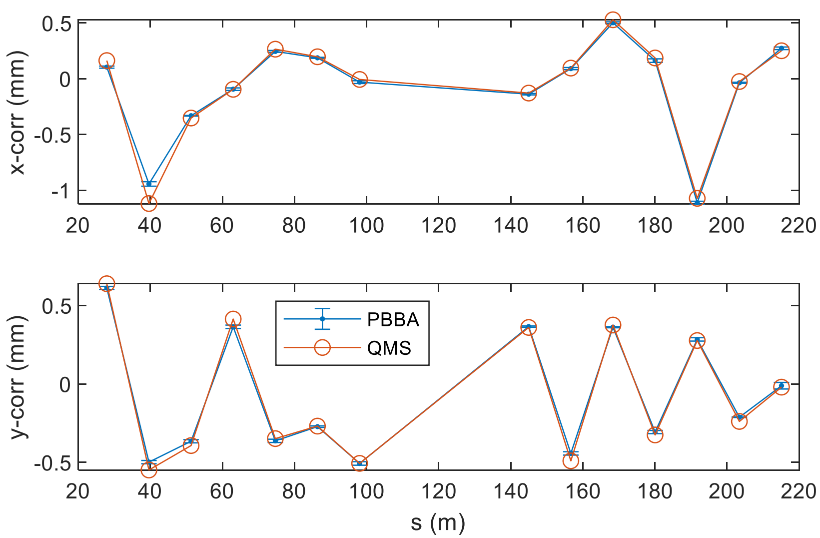


Singular values of the IOS response matrices

- BBA results



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



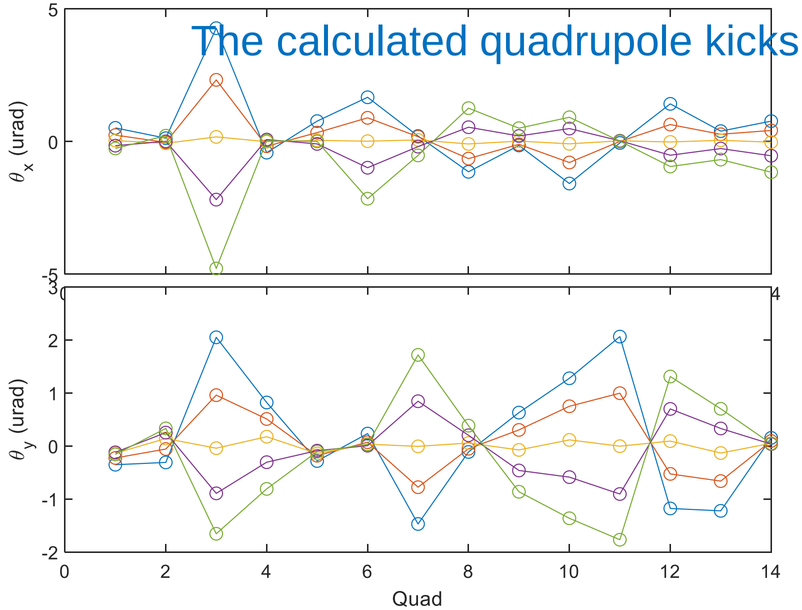
Method 2: deduce quadrupole kicks from IOS w/ model, use steering to find quadrupole centers

- 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
- 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.

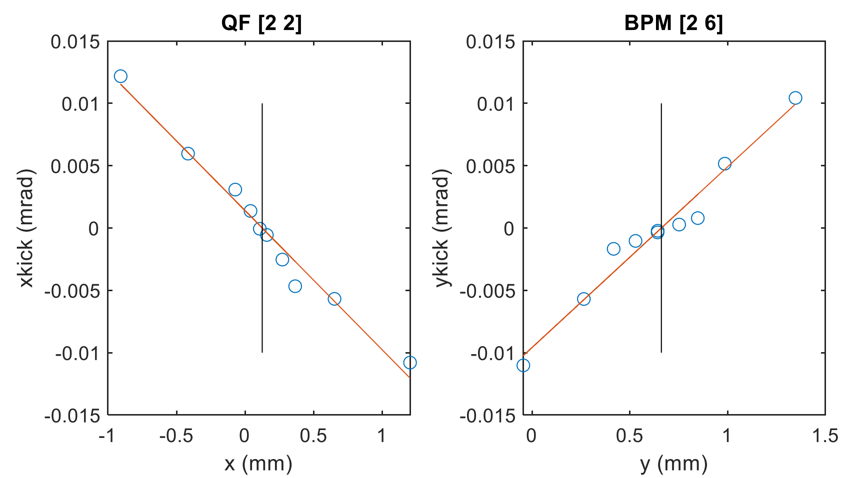
This method may be called ‘parallel QMS’ since the usual bowtie method is called QMS.

Test of Method 2 on SPEAR3 in experiments

- The same QF quadrupole group is used

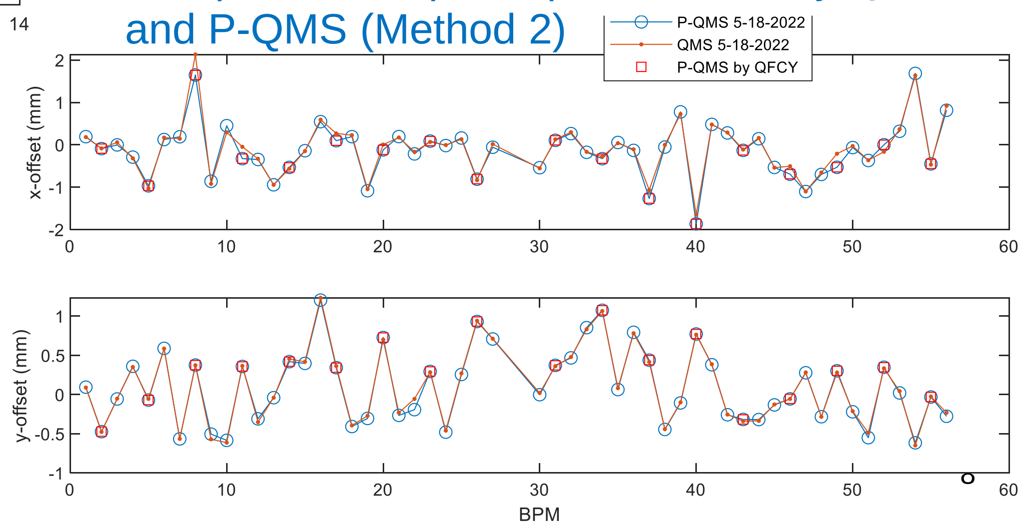


Fitting to find zero-crossing



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

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



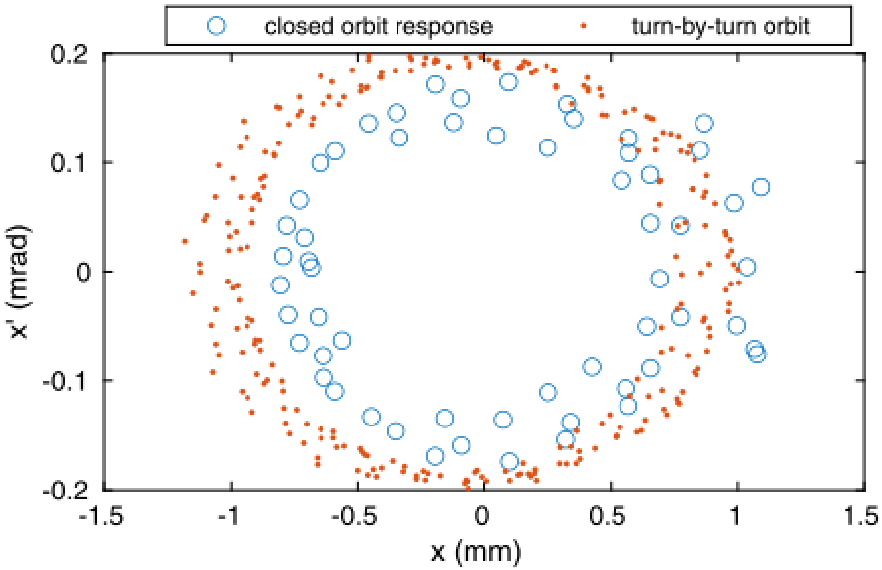
Large errors only for the QFC and QFY group, which are modulated with the same sign.

Linear optics (and coupling) from closed orbit modulation (LOCOM)

See X. Huang, Phys. Rev. Accel. Beams 24, 072805, July 2021 and
X. Huang and X. Yang, Phys. Rev. Accel. Beams 26, 052802, May 2023

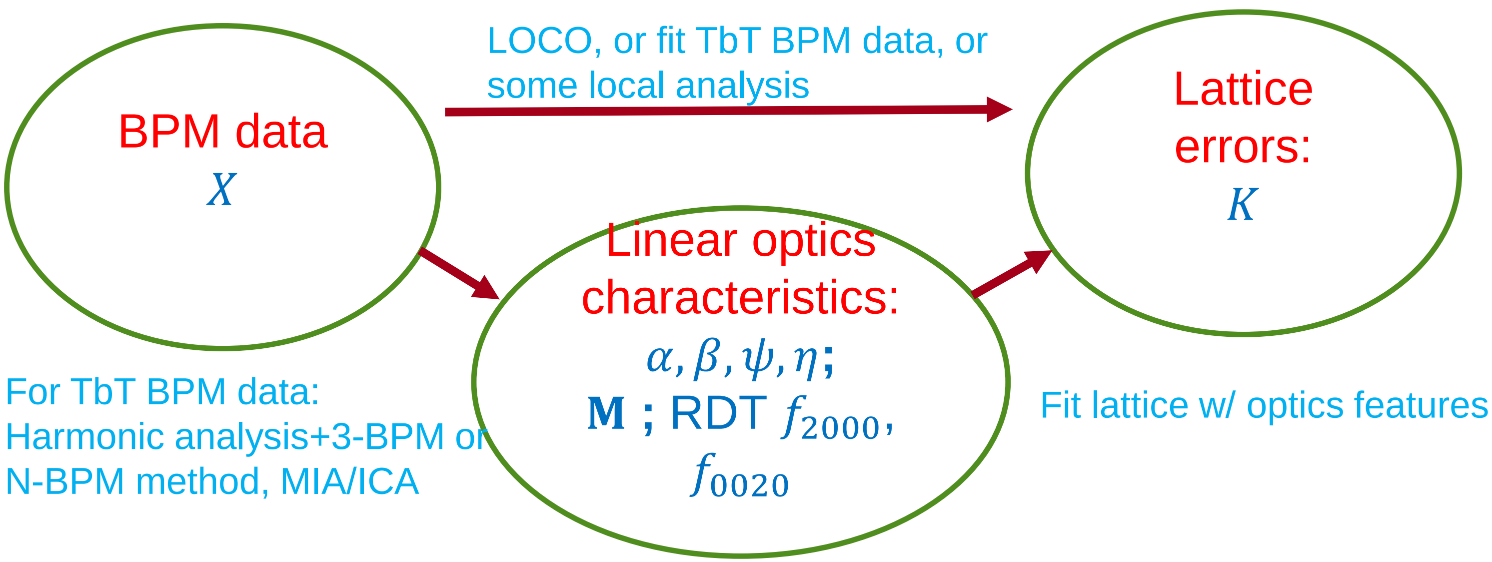
Sampling linear optics with BPM data

- Linear optics impacts the beam motion; conversely, beam motion, observed by BPMs, reflects linear optics.
  - Linear optics is characterized by Twiss functions and betatron phase advances, or equivalently, the transfer matrices
  - Beam motion is characterized by deviation from a reference orbit
  - The connection: $\mathbf{X}_j = \mathbf{M}(j|i)\mathbf{X}_i$, where $\mathbf{X} = (x, x')^T$, or $\mathbf{X} = (y, y')^T$
- Two types of BPM data
  - Closed orbit deviation,
  - e.g., orbit response matrix data
    - Static, measured with high accuracy
  - Turn-by-turn (TbT) measurement
    - Fast changing, lower accuracy
    - But can acquire lots of data



Determination and correction of lattice errors

- Lattice errors affect linear optics characteristics, which can be used to determine and correct linear optics.



Examples of local analysis

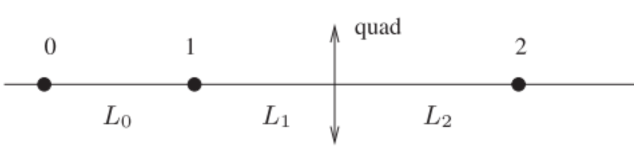
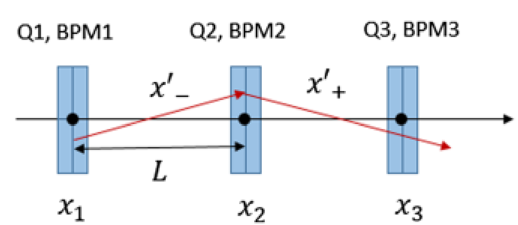


FIG. 1. Calibration of one quadrupole with three BPMs.

X. Huang, et al, PRSTAB 13, 114002 (2010)

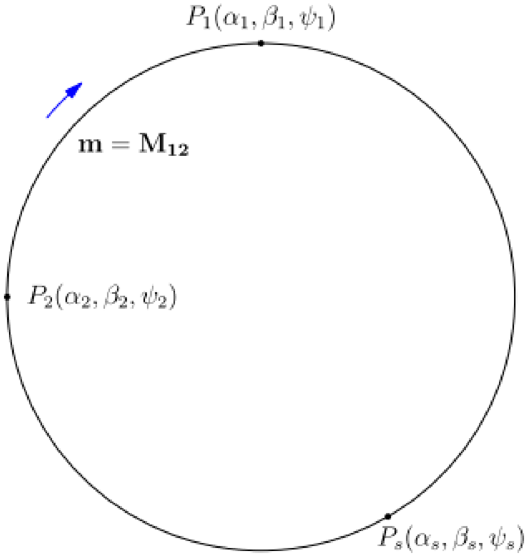


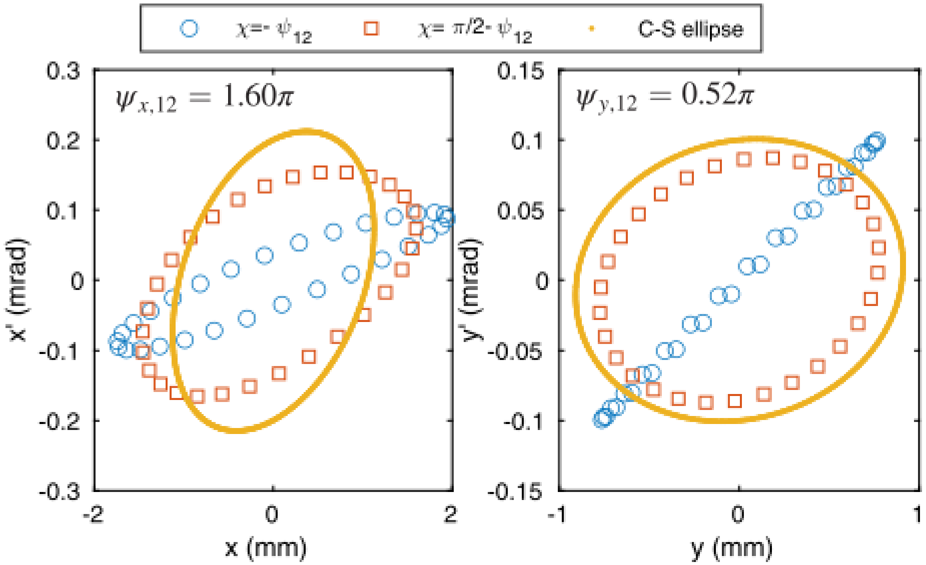
T. Zhang, et al, PRSTAB 21, 092801 (2018)

Closed-orbit oscillation as an effective sampling method

- Two correctors, separated in phase advances (preferred to be $\sim 90^\circ + 180^\circ \times n$), are modulated with sinusoidal waveforms

$$\theta_1 = \theta_{\text{amp}} \sin\phi, \qquad \theta_2 = \sqrt{\frac{\beta_1}{\beta_2}}\theta_{\text{amp}} \cos(\phi + \chi), \qquad \text{with} \qquad \chi = \frac{\pi}{2} - \psi_{12}$$

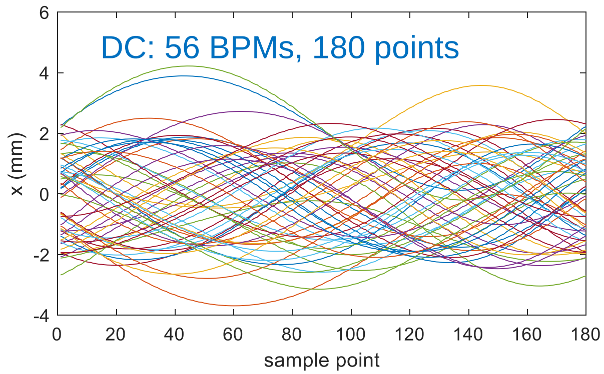


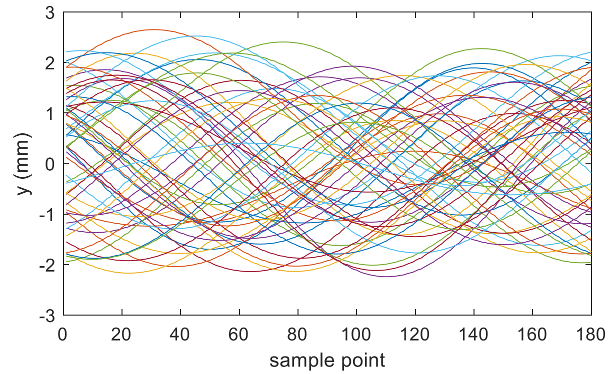


Closed orbit obtained this way is similar to orbit responses of individual correctors - the only difference is that orbit responses have discontinuities at the corrector locations

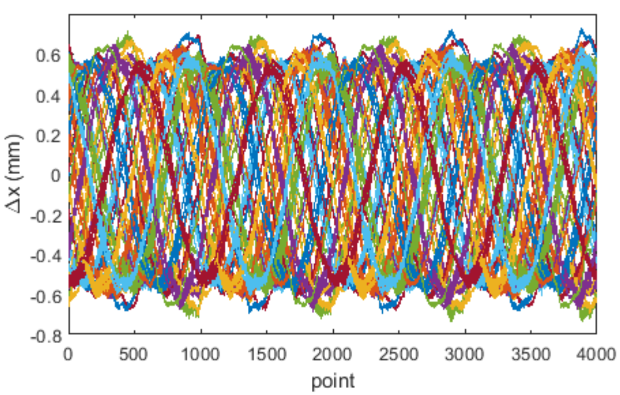
Example of experimental data from SPEAR3

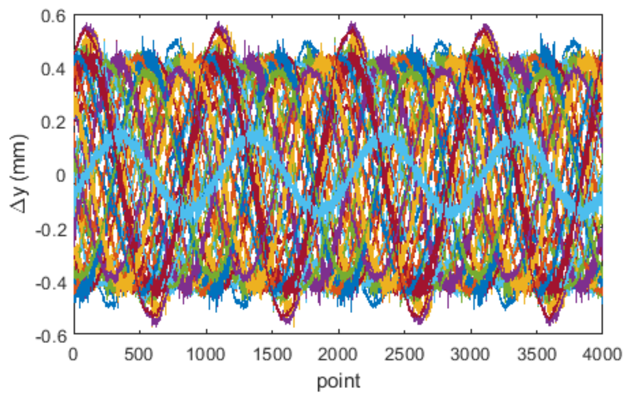
- Two ways to measure orbit modulation data
  - DC: step the correctors according to the waveforms (or not)
  - AC: drive the correctors synchronously with sinusoidal waveforms



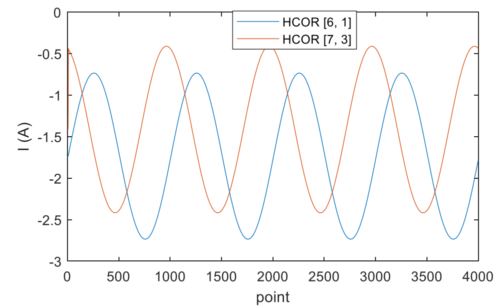


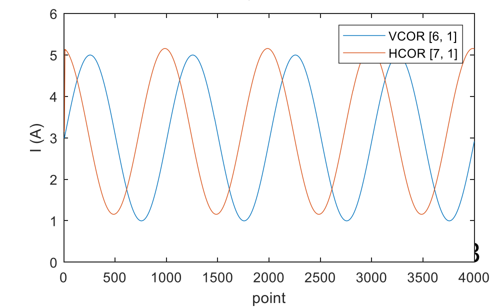
AC: 56 BPMs, 4 kHz, 1 second





Corrector waveforms for SPEAR3 AC-LOCOM





Extracting features from modulated orbit for fitting

- Direct fitting of large amount of orbit data is cumbersome. It's better to extract features that represent the linear optics

The orbit modulation can be decomposed into two modes (for each plane)

$$x_i(n) = A_i \sin(2\pi\nu n + \phi_i) = A_{si} \sin 2\pi\nu n + A_{ci} \cos 2\pi\nu n,$$

(If we choose modulation frequency, $\nu = \frac{1}{N}$)

$$A_{si} = \frac{2}{N}\sum_{n=1}^{N} x_i(n) \sin\frac{2\pi n}{N},$$
$$A_{ci} = \frac{2}{N}\sum_{n=1}^{N} x_i(n) \cos\frac{2\pi n}{N}.$$

The mode amplitudes (A_s and A_c) are related to driving waveforms and the transfer matrices:

If the coordinates at downstream of second corrector are

$$\mathbf{y}_1(n) \equiv \begin{pmatrix} y_1 \\ y_1' \end{pmatrix} = \mathbf{Q}_1 \begin{pmatrix} \cos 2\pi\nu n \\ \sin 2\pi\nu n \end{pmatrix}$$

The closed orbit at BPM P (downstream of the 2nd corrector)

$$\mathbf{Y}_P(n) = \mathbf{M}_{P1}(\mathbf{I} - \mathbf{M}_1)^{-1}\mathbf{Q}_1 \begin{pmatrix} \cos 2\pi\nu n \\ \sin 2\pi\nu n \end{pmatrix}$$

The mode amplitudes represent the linear optics (and coupling) in the same manner as beta functions and phase advances.

Lattice fitting, with coupling included

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- Fitting data: 8 mode amplitude per BPM, plus H/V dispersion
  - 4 in-plane (2 H + 2 V) amplitudes, 4 cross-plane amplitudes
  - $10\ N_P$ data points total
- Fitting parameters:
  - N_Q, Quadrupoles in lattice
  - N_{SQ}, Skew quadrupoles
  - $4N_P$, BPM gains and coupling coefficients
  - 8, Corrector gains and coupling coefficients
- Fitting method: same as LOCO and other optics correction methods
  - Levenberg-Marquadt with penalty term to slow down divergence on under-constrained directions*

*X. Huang, et al, ICFA Newsletter 44, 60 (2007)

Experiments at NSLS-II
Test case 1 – change one quadrupole

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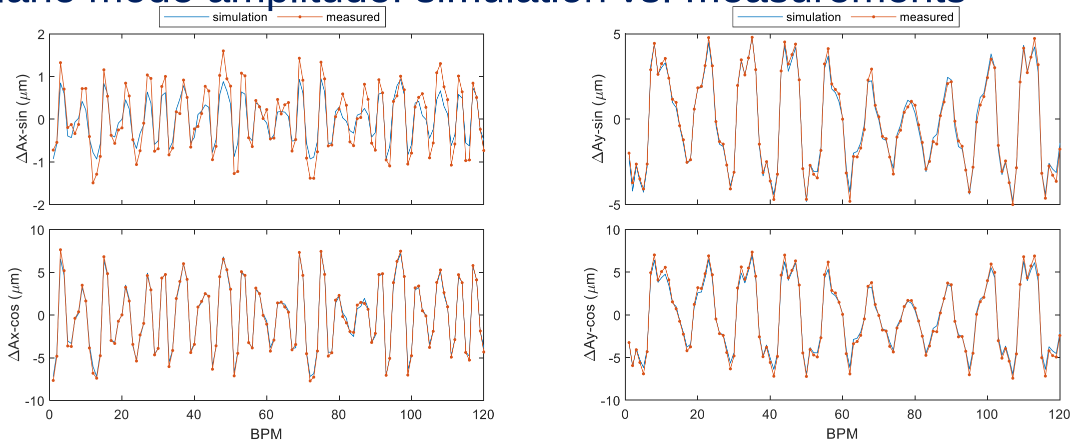
- One quadrupole was changed by 1%

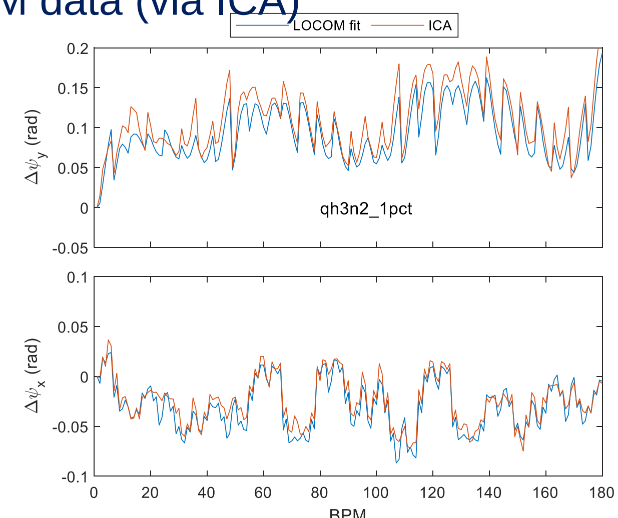
The change of in-plane mode amplitude: simulation vs. measurements

Contribution of baseline optics is subtracted



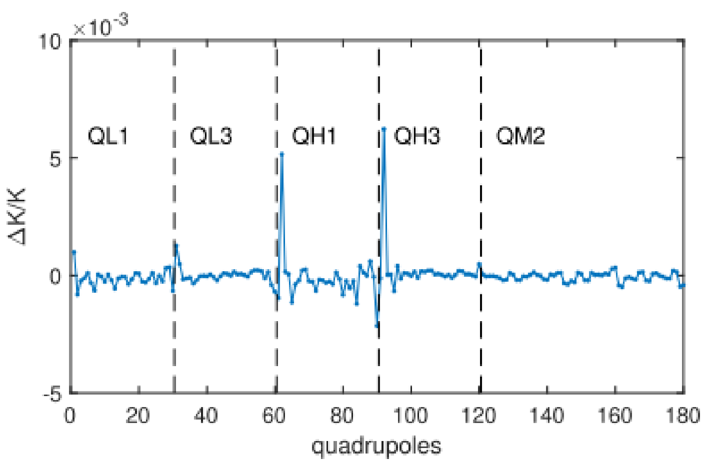
Phase advance errors obtained by fitting LOCOM data or by TBT BPM data (via ICA)

Including optics errors in the baseline optics



Fitted quadrupole errors by LOCOM

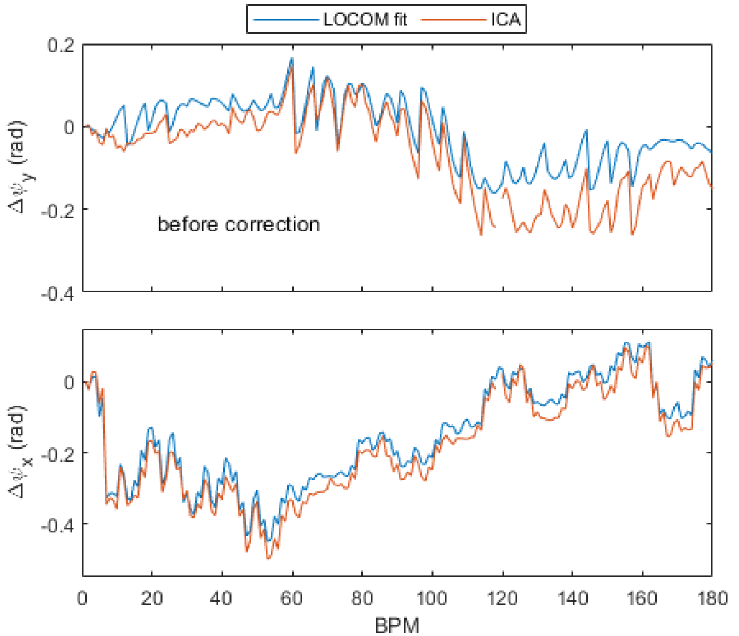
Contribution of baseline optics is subtracted



Test case 2 – random errors

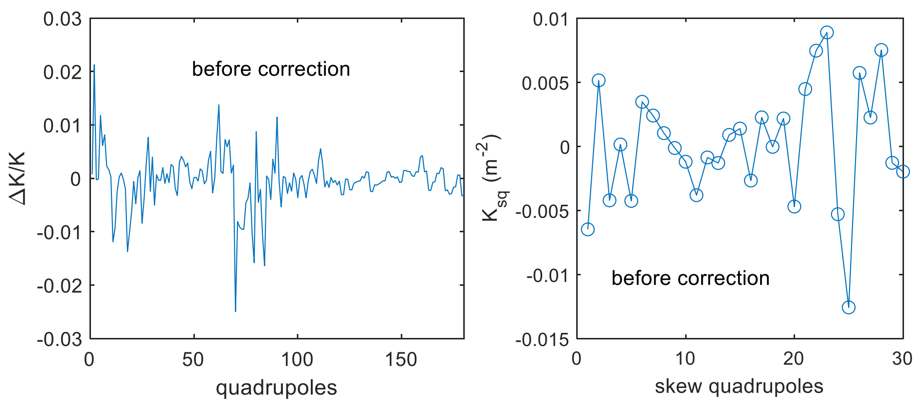
- Initial machine condition: operation lattice plus random errors to 300 quadrupoles, with 30 skew quads turned off
  - Rms $\frac{\Delta K}{K}$ was 1% for the random changes

Phase advance errors obtained by fitting LOCOM data or by TBT BPM data (via ICA)



(One BPM (#119) was not giving valid TBT data)

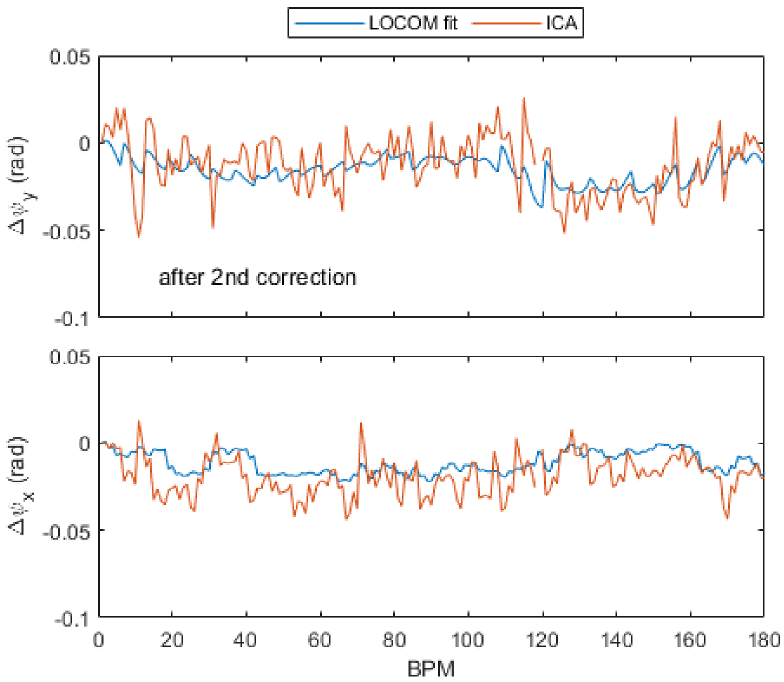
Fitted quadrupole and skew quadrupole errors by LOCOM



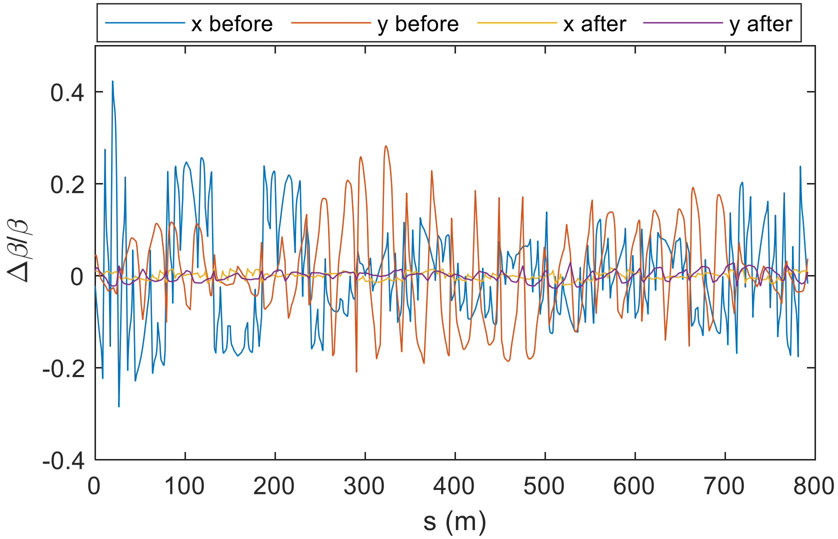
The results were applied on the machine for correction.

After the 2nd correction

- After the 2nd correction, beta beating and coupling are reduced to a low level
  - After the 2nd correction, rms beta beating becomes 0.8% (H) and 1.1% (V)



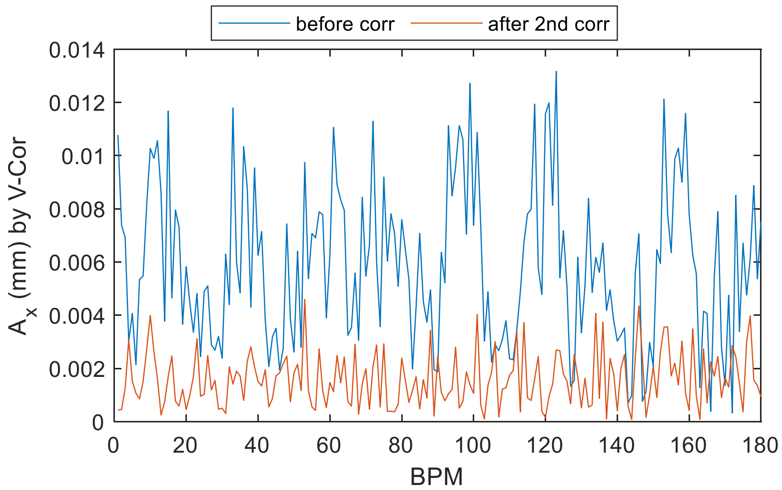
Beta beating from the fitted lattice (by LOCOM), before correction, and after the 2nd correction

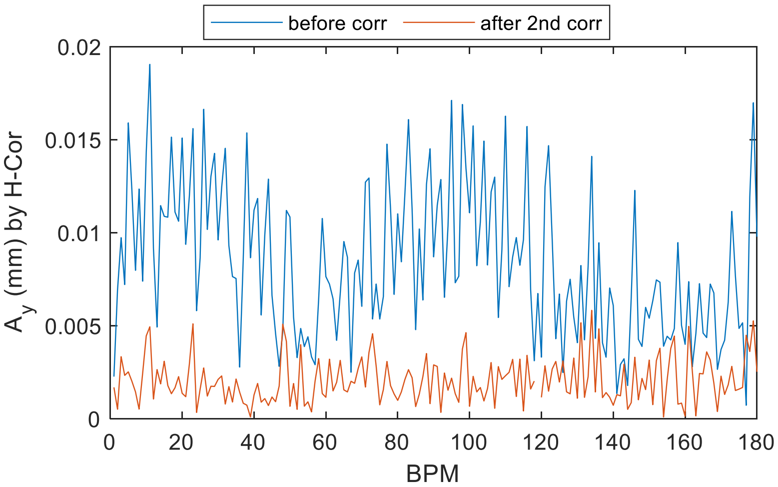


Direct evidence of coupling reduction

- The cross-plane orbit modulation amplitude is a model-independent measure of the level of coupling

The cross-plane amplitude ($A_y = \sqrt{A_{ys}^2 + A_{yc}^2}$ by H-correctors, and similarly for A_x by V-correctors)





The mean cross-plane amplitude was reduced from 8.4 um to 2.1 um for A_y, and from 5.9 um to 1.6 um for A_x (a factor of 4).
Roughly speaking, the emittance ratio should have gone down by a factor of 16.

LOCOM advantages

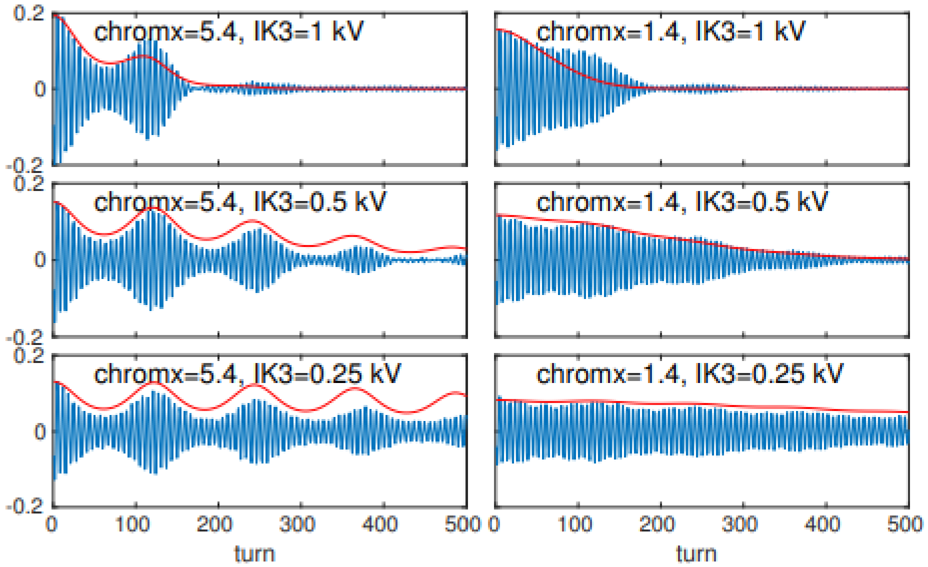
- Compared to LOCO, the advantages of LOCOM include
  - It uses fewer correctors; it can have more data points
  - It takes data faster (sweeps with small steps)
  - AC-LOCOM is faster than AC-LOCO, and data processing is easier
    - Only 1 shot is needed; no mixing of different frequencies
  - Sinusoidal waveforms help eliminate certain measurement errors
- Compared to TBT BPM data, LOCOM
  - Does not need pinger/kicker for the other plane (other than the injection plane)
  - Uses high-accuracy closed orbit data
  - Does not suffer from decoherence from kicked beam motion
    - It is big issues for high chromaticity, high amplitude dependent detuning rings (which are becoming common)
  - Does not suffer from signal mixing, contamination, or deterioration (resulting bad TBT data)

Autoresonant driving for linear and nonlinear optics measurement and correction

See J. Safranek, X. Huang, J. Corbett, J. Sebek, A. Terebilo, PAC'09 pp 3928-3930 and
M. Song, L. Spentzouris, X. Huang, and J. Safranek, Phys. Rev. Accel. Beams 25, 074001, July 2022

The need for strong turn-by-turn BPM signals

- Strong turn-by-turn BPM signals are key to probing linear and nonlinear beam dynamics in rings
  - But TBT data of kicked beam motion suffers from decoherence from high chromaticity and/or large kicks

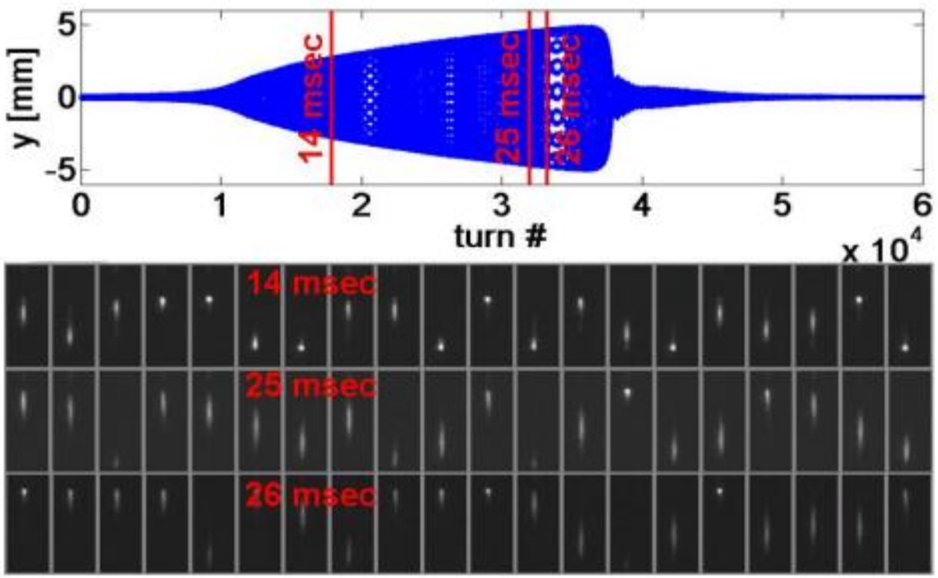


Decoherence on temporal pattern of ICA modes of APS beam motion after being kicked.
(X. Huang, et al, IPAC'21)

To study nonlinear dynamics, we need large oscillation amplitude (and likely high chromaticity as well).

The difficulty of driving a nonlinear oscillator

- Resonant driving would solve the problem. But it has difficulties when the ring has large amplitude dependent detuning
  - The tune shifts away and falls out of resonance as the amplitude grows
- Sweeping the frequency can address the detuning issue
  - We did it on SPEAR 2008-2009. There were questions:



J. Safranek, et al, PAC'09

- Sometimes the sweep driving works, but there were times it failed, and we didn't understand why.
- Can we measure beam dynamics parameters (detuning, RDT, etc) on the ramp up with driving oscillation? (back in 2008 we only used free oscillations after driving stopped)

Recent progress on the topic

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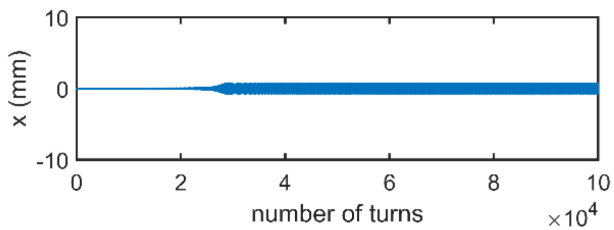
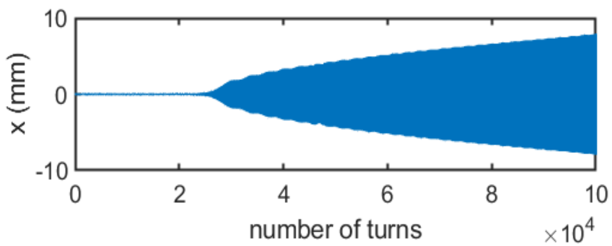
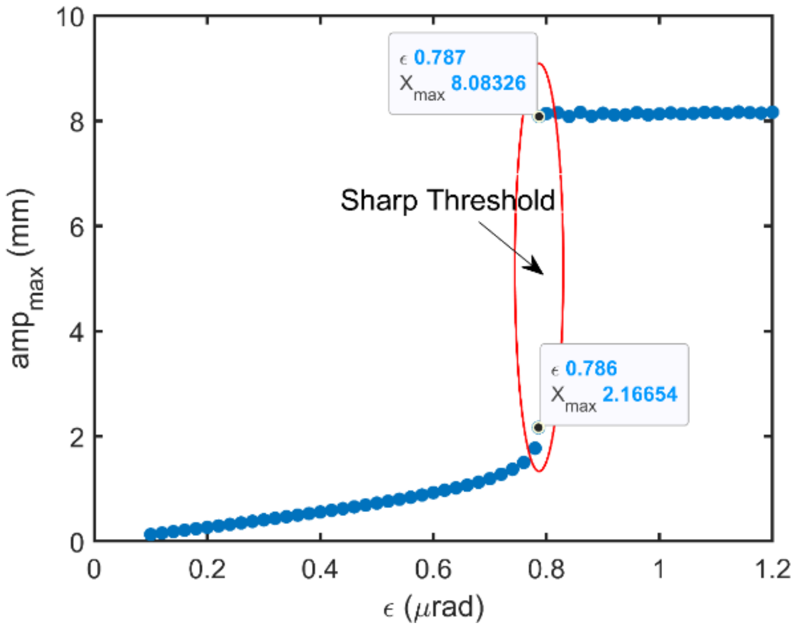
- Successful sweep driving has a threshold
  - Simulation reproduced earlier experimental observations and revealed the existence of a threshold of driving amplitude
  - It is ‘auto-resonant excitation’, a common phenomenon in nonlinear oscillators



Weak drive, ε = 0.5μrad, fail



Strong drive, ε = 1.0μrad, success



(Minghao Song thesis, IIT 2022)

The threshold has been derived and verified

- Analytic work has led to formulas for the threshold

$$\tilde{H}(J_x, \phi_x; \theta) = \nu_{x,0} J_x + \frac{1}{2}\alpha_{xx} J_x^2 + \frac{\sqrt{2}}{4\pi}\sqrt{\beta_{x,d}}\epsilon J_x^{\frac{1}{2}} \cos(\phi_x - \phi_d).$$

With tune sweep rate $\alpha = \frac{d\nu}{dn}$

Undamped: $$\epsilon_{th} = 4\sqrt{2}\pi(\beta_{x,d}|\alpha_{xx}|)^{-\frac{1}{2}}(\frac{|\alpha|}{6\pi})^{\frac{3}{4}}.$$

Damped: $$\epsilon_{th} = 4\sqrt{2}\pi(\beta_{x,d}|\alpha_{xx}|)^{-\frac{1}{2}}(\frac{|\alpha|}{6\pi})^{\frac{3}{4}}(1 + 1.06\gamma + 0.67\gamma^2).$$

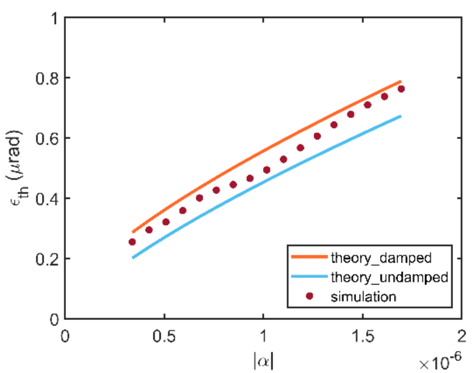
$$\gamma = \lambda_x|\alpha|^{-1/2}$$

Damping coefficient

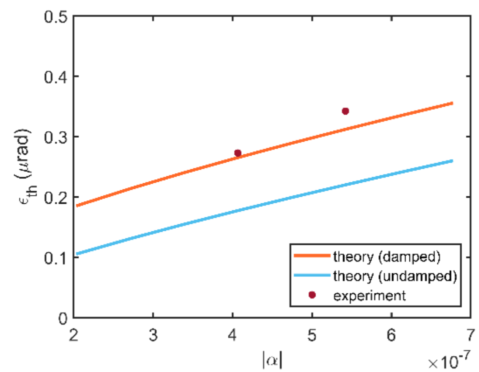
(1) M. Song, L. Spentzouris, X. Huang, J. Safranek, PRAB 25, 074001 (2022).
(2)J. Fajans, E. Gilson and L. Friedland, PRL 82:4444, 1999.
(3)O. Naaman, J. Aumentado, L. Friedland, J.S. Wurtele, and I. Siddiqi, PRL 101 117005 (2008).

- The formulas have been tested against simulations and experimental data

SPEAR3 simulations



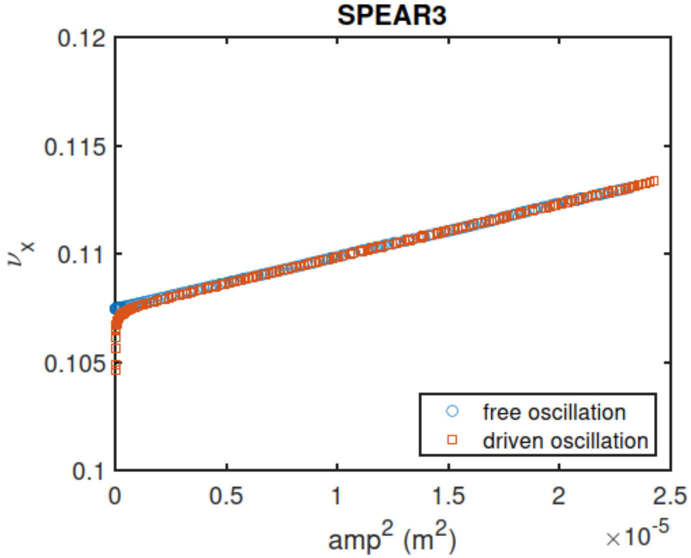
SPEAR3 Experiment

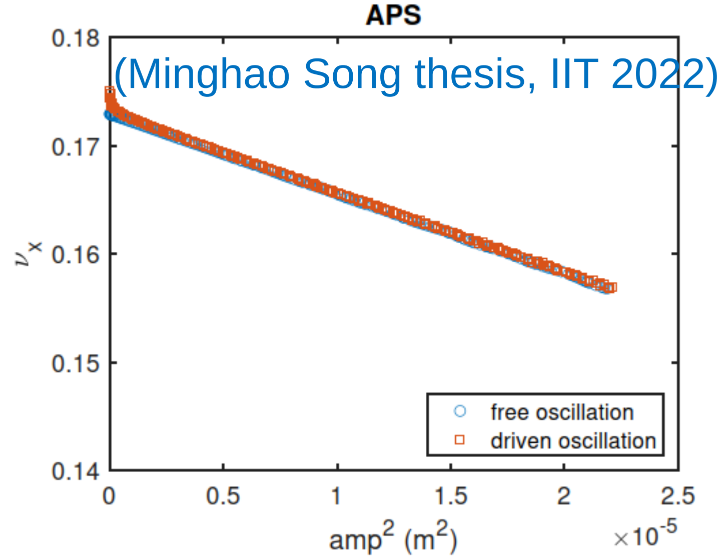


M. Song, L. Spentzouris, X. Huang, J. Safranek, PRAB 25, 074001 (2022).

Data on the ramp are good for dynamics measurement

- Beam oscillation is in resonant condition with the ring lattice on the ramp when in 'auto-resonance'
- Simulation shows the tune vs. amplitude relationship is the same for auto-resonant driving or free oscillation





The nonlinear dynamics measurement can be done in one sweep!

Summary

- Parallel BBA methods have been proposed and demonstrated in experiments
  - Benefit ring commissioning and routine operation
- Linear optics and coupling correction by closed orbit modulation has been demonstrated in experiment
  - With advantages over LOCO and TBT BPM-based methods
- Driving beam to large amplitude with auto-resonant excitation is a great way for optics and nonlinear dynamics measurement
  - Better understood with recent analytic and simulation work
  - Could be applied for nonlinear lattice correction in the future.