Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Implementation of AC- LOCO, LOCOM, and NOECO using fast correctors in AT and Matlab Middle Layer environment

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Outline

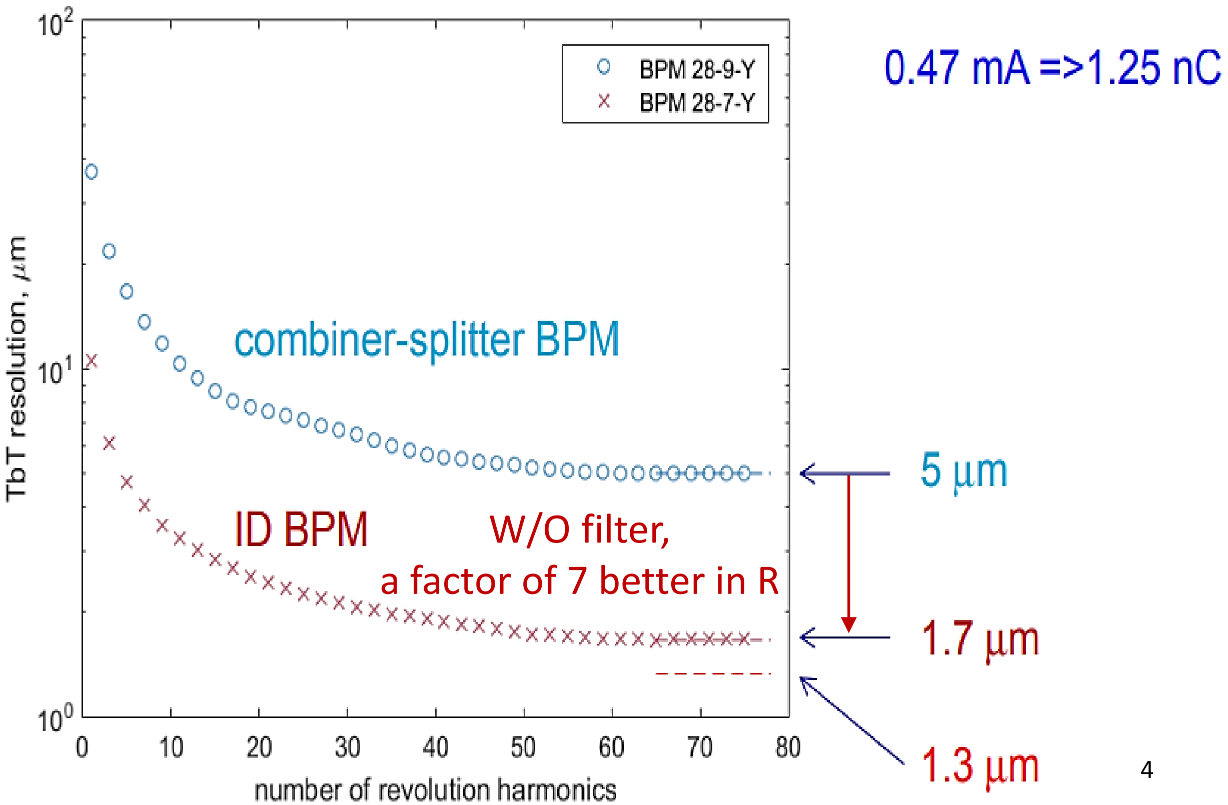
- Motivation
- Sine-wave (AC) beam excitation-based optics correction
- Implementation of AC- LOCO, LOCOM, and NOECO
- Performance comparison with DC and TbT based techniques
- Main challenges and solutions for AC-based optics correction
- Proof-of-principle experiments
- Conclusions

Introduction

- **Global optics correction by fitting lattice model to data**
  - Orbit response matrix data: LOCO
  - Extraction of optics functions from turn-by-turn (TbT) BPM data: ICA
  - Fitting TbT BPM data directly to model
  - Closed-orbit modulation and decomposition: LOCOM
- **Difficulty with the measurement and fitting approaches:**
  - Systematic errors: slow drifts of machine parameters in the measurement, and hysteresis effects of orbit correctors
  - Reduced precision with TbT data: much faster but at the cost of reduced resolution in TbT BPM mode
  - Degeneracy: quadrupole errors predicted by fitting are too big
- **Overcome the difficulty:**
  - AC excitation using fast orbit correctors: faster and more accurate
  - A novel method for optics and coupling correction via closed-orbit modulation
  - Fitting parameter and method choices for mitigating the degeneracy
- **Other applications related to AC local orbit bump**

Sampling linear optics with BPM data

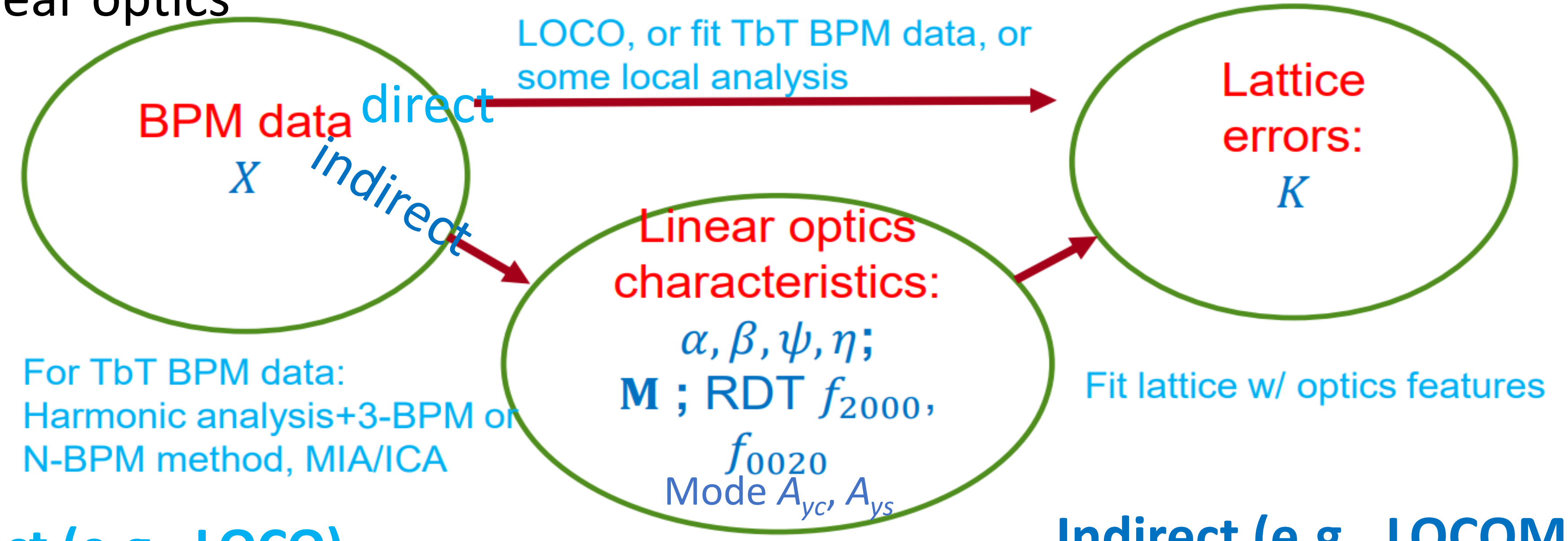
- **Linear optics affects beam motion; alternatively, observed beam motion via BPMs reflects linear optics**
  - Linear optics is characterized by Twiss functions and betatron phase advances, equivalently transfer matrices.
  - Beam motion is described as deviation from a reference orbit
  - Linear optics and beam motion connection: $X_j = M(j|i)\,X_i$, where $X = (\boldsymbol{x}, \boldsymbol{x'})^{\boldsymbol{T}}$, or $X = (\boldsymbol{y}, \boldsymbol{y'})^{\boldsymbol{T}}$
- **BPM data types:**
  - Closed orbit deviation
    - E.g., orbit response matrix data
    - Static, measured with high accuracy (≥ 0.1 μm)
  - AC orbit
    - Narrow band excitation
    - Resolution at $f = 20\ Hz$: ~15 nm
  - Turn-by-turn measurement
    - Fast changing, lower accuracy (≥ 1 μm)
    - Large amount of data



IPAC'16

Determination and correction of lattice errors

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



Direct (e.g., LOCO)

- Orbit response matrix (*ORM*) $\boldsymbol{R}\Delta\theta = \Delta X$
- Calculation of response matrix

$$M\Delta X + \Delta\theta_{xj} = \Delta X, \rightarrow \Delta X = (\boldsymbol{I} - \boldsymbol{M})^{-1}\Delta\boldsymbol{\theta}_{xj}$$

M: 1 turn transfer matrix at corrector; $\Delta\boldsymbol{\theta}_{xj} = [0, \Delta\theta_j, 0,0,0,0]$;

$$\Delta x\,(s) = \frac{\sqrt{\beta(s)\beta_0}\Delta\theta_j}{2\sin\pi\nu}\cos(|\psi(s) - \psi(s_0)| - \pi\nu)$$

- Fitting *ORM* to lattice model can recover the machine to model

J. Safranek, M. Lee, SLAC-PUB-6442 (1994)
J. Safranek, NIMA, 388, 27 (1997)

Indirect (e.g., LOCOM)

- Decompose orbit into orthogonal modes with amplitudes as feature
- Corrector pair waveforms $\theta_1(n) = \theta_{1m}\sin(2\pi\nu n + \phi_1)$, $\theta_2(n) = \theta_{2m}\sin(2\pi\nu n + \phi_2)$,

$$Q_{1,11} = m_{12}\theta_{2m}\sin\phi_2,\quad Q_{1,12} = m_{12}\theta_{2m}\cos\phi_2,$$
$$Q_{1,21} = m_{22}\theta_{2m}\sin\phi_2 + \theta_{1m}\sin\phi_1,\quad Q_{1,22} = m_{22}\theta_{2m}\cos\phi_2 + \theta_{1m}\cos\phi_1.$$

- Coordinate at downstream of cor. 1

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

- Closed orbit at a BPM downstream of cor. 1

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

- Mode amplitudes A_{yc} and A_{ys} are equal to (1,1) and (1,2) elements
- Mode amplitudes are features of linear optics and dependent on corrector waveforms, thus, can be used to fit lattice.

Turn-by-turn BPM data for optics calibration

TbT BPM data indirectly sample machine optics

- Beam coordinates at turn n, $X_n = (x, x', y, y')_n^T$, is given by $X_{n+1} = MX_n$
- Beta functions and betatron phase advances can be derived from TbT BPM data with beam oscillation
  - P. Castro's method [1]
  - MIA [2] and ICA [3]
- Measured beta and phase can be used to fit lattice model [3].

[1] P. Castro, et al, PAC 93
[2] Chun-xi Wang, et al. PRSTAB 6, 104001 (2003)

$$f(\mathbf{q}) = \chi^2 = \frac{1}{2}\sum_{i=1}^{240} r_i^2, \qquad r_i = \frac{y_i(\mathbf{q}) - y_i^d}{\sigma_i},$$

$$\mathbf{y} = (w_1\boldsymbol{\beta}_x, w_2\Delta\psi_x, w_3\boldsymbol{\beta}_z, w_4\boldsymbol{\Delta\psi}_z, w_5\mathbf{D}_x),$$

This approach has been extended to include coupling

[3] X. Huang, et al, PRSTAB, 8, 064001, (2005)
[4] X. Yang and X. Huang, NIMA 828, 97 (2016)

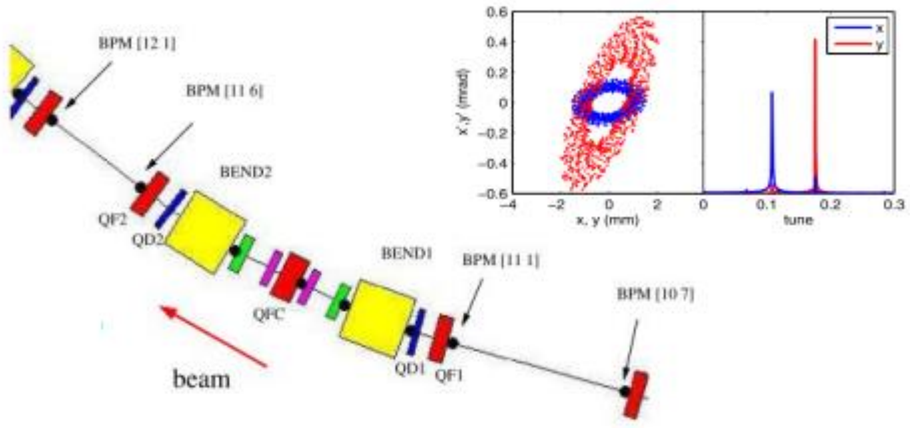
Fit TbT BPM data directly for lattice errors

- Directly fitting TbT BPM data for lattice errors was tested in SPEAR3

$$\chi^2 = \sum_{n=1}^{N}\sum_{i=2}^{M+1}\left[\left(\frac{x_i(n) - \tilde{x}_i[\mathbf{p}; \mathbf{X_1(n)}]}{\sigma_{xi}}\right)^2 + \left(\frac{y_i(n) - \tilde{y}_i[\mathbf{p}; \mathbf{X_1(n)}]}{\sigma_{yi}}\right)^2\right],$$

- The key is to use two BPMs separated by a drift to calculate angle coordinates, to be used in tracking.

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



Lattice fitting with coupling included

- **Fitting data (e.g., LOCO):**
  - Measured orbit response matrix and dispersion functions
- **Fitting parameter:**
  - Quadrupole strengths (gradients) in model
  - Skew quadrupole
  - BPM and correction calibration parameters (gains, rolls and crunch)

$$\begin{pmatrix} x_{meas} \\ y_{meas} \end{pmatrix} = \begin{pmatrix} g_x & c_x \\ c_y & g_y \end{pmatrix} \begin{pmatrix} x_{beam} \\ y_{beam} \end{pmatrix}$$

Note the difference between c_x and c_y accounts for BPM "crunch" (deformation from ideal configuration).

  - Corrector gains and coupling coefficients
- **Objective function:** $f(\boldsymbol{p}) = \chi^2 = \sum_{i,j} \frac{\left(R_{ij}^{beam} - R_{ij}^{model}\right)^2)}{\sigma_i^2} + \sum_i \frac{\left(D_{xi}^{beam} - D_{xi}^{model}\right)^2}{\sigma_{xi}^2} + \frac{\left(D_{yi}^{beam} - D_{yi}^{model}\right)^2}{\sigma_{yi}^2},$

  where $\boldsymbol{p}$ includes all fitting parameters.

- **Solving the least-square problem with an iterative method:**

$f(\boldsymbol{p}) = \boldsymbol{r}^{\boldsymbol{T}}\boldsymbol{r}$ with residual vector $\boldsymbol{r}$. Calculate Jacobian matrix $\boldsymbol{J}$ with $J_{ij} = \frac{\partial r_i}{\partial p_j}$.

Solve $\boldsymbol{J}\boldsymbol{\Delta}\mathbf{p} = -\mathbf{r_n}$ at each iteration and move to $\mathbf{p}_{n+1} = \mathbf{p}_n + \boldsymbol{\Delta}\mathbf{p}$

J. Safranek, NIMA, 388, 27 (1997)

Difficulty with global optics fitting and solutions

- When fitting optics model to orbit response matrix data, it often happens the predicted ΔK is too large.
  - It can be too large to be reasonable. Sometimes iterative fitting won't work since the second iteration lattice has no closed orbit.
  - It can happen even in simulation without random noise in data (Fermilab Booster [1]).
  - More common for other rings is that optics correction with the fitted ΔK fails.
- Causes of the difficulty: correlation between fitting parameters.

Correlation of two parameters

$$\rho_{12} = \frac{\mathbf{J}_1^T \mathbf{J}_2}{\|\mathbf{J}_1\| \|\mathbf{J}_2\|}$$

$\mathbf{J}_i$ is the column in the Jacobian matrix for parameter i.

Large correlation between two parameters indicates that their effects on the objective function are similar and thus hard to resolve.

- Solutions:
  - Choose fitting parameters to mitigate the degeneracy
  - Levenberg-Marquadt with penalty term to slow down divergence on under-constrained directions

[1] X. Huang, et al, PAC'05, (2005)
[2] X. Huang, et al, ICFA Newsletter 44, 60 (2007)

AC LOCO

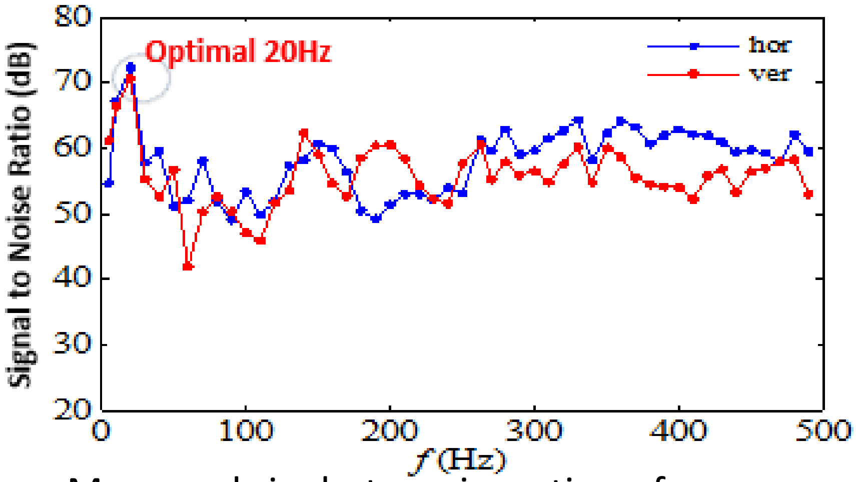
- **AC beam excitation via fast correctors**
  - Narrow band beam excitation and measurement suppress effectively beam position noise
- **Measurement technique**
  - A standard synchronous detection technique for BPM data processing

$$U_{ref}(t) = a_{ref}\sin(\omega_0 t + \varphi_{ref})$$
$$U_{bpm}(t) = a_{bpm}\sin(\omega_0 t + \varphi_{bpm}) + \varepsilon(t).$$

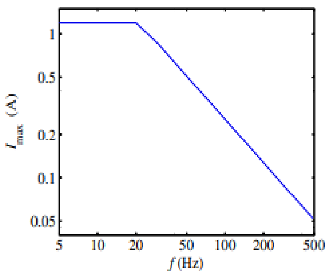
$$U_{mix} = U_{ref}U_{bpm}$$
$$\overline{U_{mix}} \equiv \frac{1}{T}\int_0^T U_{mix}(t)dt$$

$$a_{bpm} = \frac{2\overline{U_{mix}}}{a_{ref}\cos(\varphi_{bpm} - \varphi_{ref})} - \delta a$$
$$\delta a = \frac{2\int_0^T \varepsilon(t)\sin(\omega_0 t + \varphi_{ref})dt}{T\cos(\varphi_{bpm} - \varphi_{ref})}$$

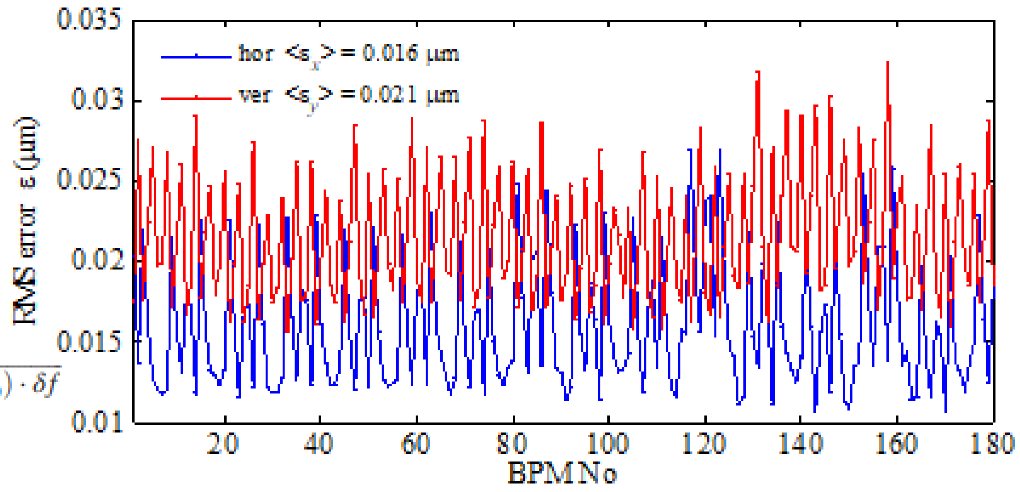
  - Accuracy analysis



Measured single-to-noise ratio vs frequency: horizontal (blue) and vertical (red)



$\delta f = \frac{1}{T} = 0.2$ Hz.
the BPM noise is obtained via $\sqrt{\mathrm{PSD}(f_0)\cdot\delta f}$
0.013 μm.



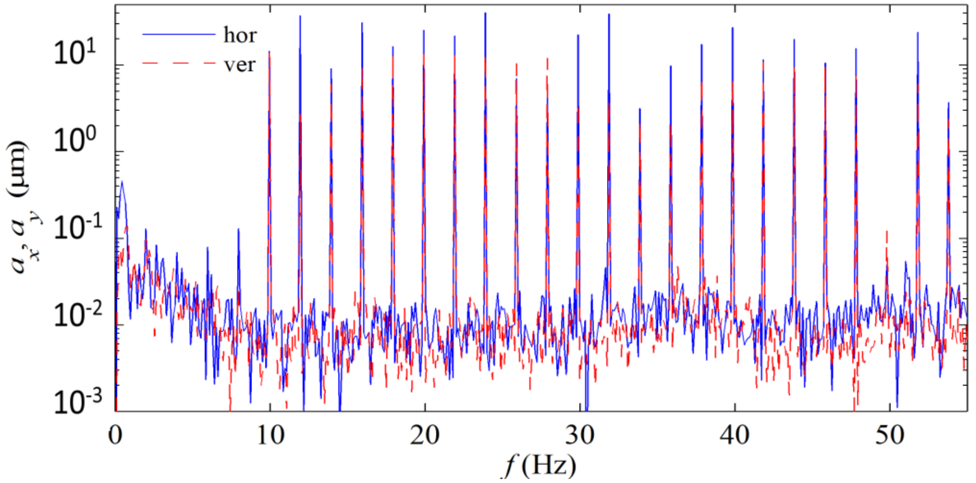
RMS amplitude errors at 20 Hz within the measurement BW of 0.2Hz

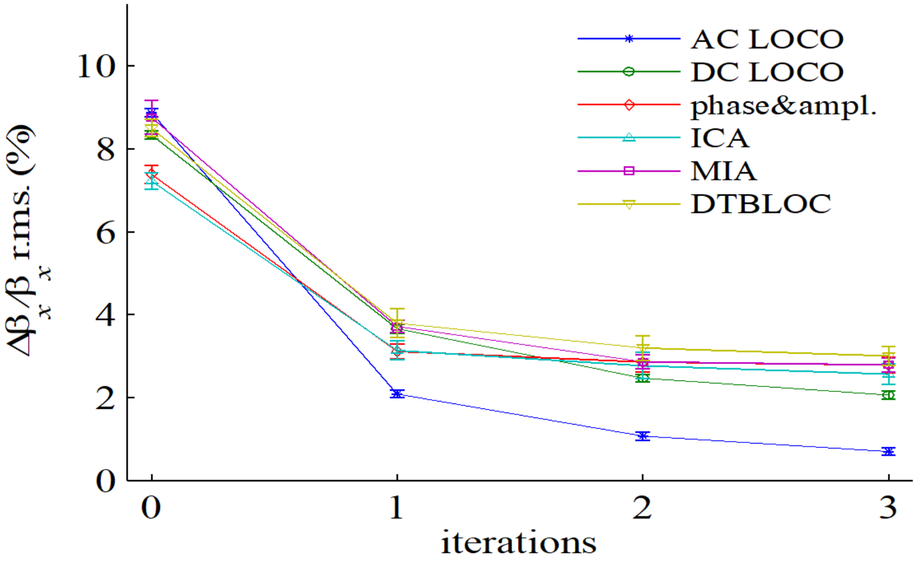
X. Yang, et al., PRAB 20, 054001 (2017).

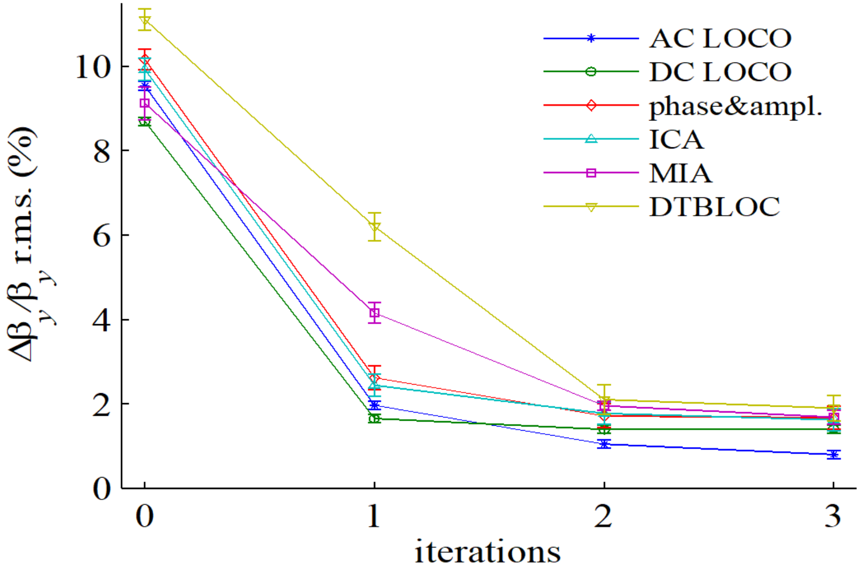
AC-LOCO improve linear optics correction

- **Noise-induced BPM errors at 20 Hz**
  - Achieve 15-nm BPM precision in x and y directions
- **Multi-frequency excitation (N=30)**
  - Faster than traditional LOCO method (<2 minutes vs >1 hour)
- **AC-LOCO provides better lattice corrections**
  - A standard synchronous detection technique for BPM data processing
  - Convergence of beta function: horizontal (left) and vertical (right).

We were able to keep measurement accuracy in nanometer level for all the excitation frequencies in the 10 – 68 Hz range



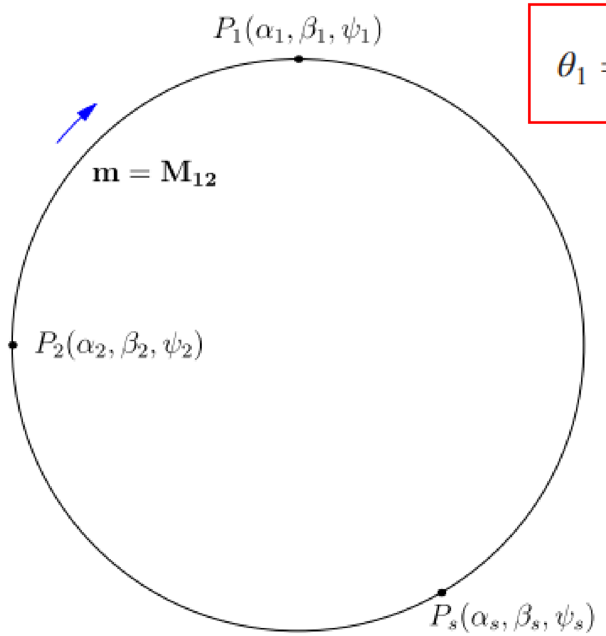




X. Yang, et al., PRAB 20, 054001 (2017).

LOCOM Method

- Two correctors in each plane (x & y) modulate the closed orbit in appropriate pattern to sample the linear optics

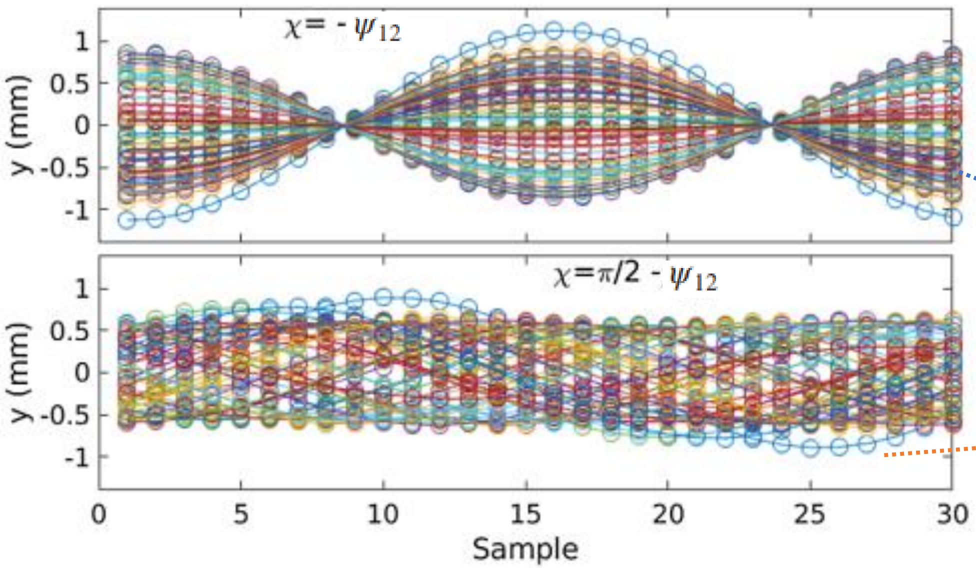


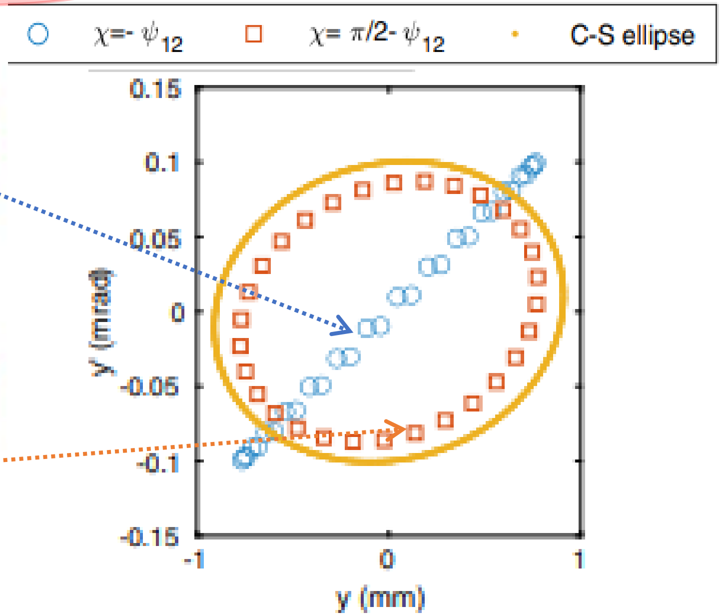
$$\theta_1 = \theta_{\text{amp}} \sin\phi, \qquad \theta_2 = \sqrt{\frac{\beta_1}{\beta_2}}\theta_{\text{amp}} \cos(\phi + \chi), \quad \chi = \frac{\pi}{2} - \psi_{12}$$

Ideally $\psi_{12} = k\pi + \frac{\pi}{2}$ → $\theta_1 = \theta_{\text{amp}} \sin\phi$ and $\theta_2 = \sqrt{\frac{\beta_1}{\beta_2}}\theta_{\text{amp}} \cos\phi$

$$M = \begin{pmatrix} \sqrt{\frac{\beta}{\beta_o}}(\cos\varphi + \alpha_o \sin\varphi) & \sqrt{\beta\beta_o}\sin\varphi \\ \frac{\alpha_o - \alpha}{\sqrt{\beta\beta_o}}\cos\varphi - \frac{1 + \alpha_o\alpha}{\sqrt{\beta\beta_o}}\sin\varphi & \sqrt{\frac{\beta_o}{\beta}}(\cos\varphi - \alpha\sin\varphi) \end{pmatrix}$$

$$\mathbf{m}\begin{pmatrix} 0 \\ \theta_2 \end{pmatrix} + \begin{pmatrix} 0 \\ \theta_1 \end{pmatrix} = \begin{pmatrix} \sqrt{\beta_1\beta_2}\theta_2 \sin\psi_{12} \\ \theta_1 + \sqrt{\frac{\beta_2}{\beta_1}}\theta_2(\cos\psi_{12} - \alpha_1 \sin\psi_{12}) \end{pmatrix}$$





Comparison of vertical orbit samples for the SPEAR3 example with $\chi = -\psi_{y,12}$ (top) or $\chi = \frac{\pi}{2} - \psi_{y,12}$ (bottom).

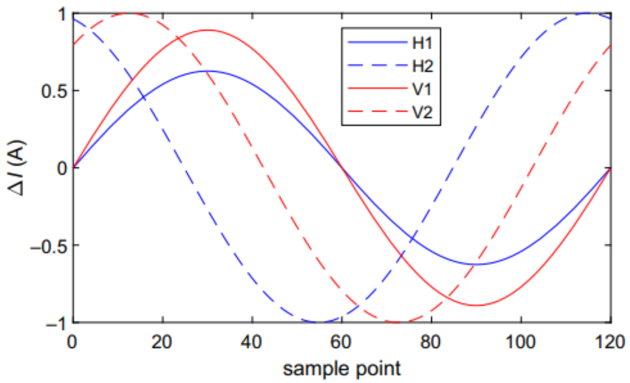
XIAOBIAO HUANG
PHYS. REV. ACCEL. BEAMS **24,** 072805 (2021)
PHYSICAL REVIEW ACCELERATORS AND BEAMS **26,** 052802 (2023)

Implement LOCOM at NSLSII

- Select horizontal and vertical pairs
- Exam BPM responses

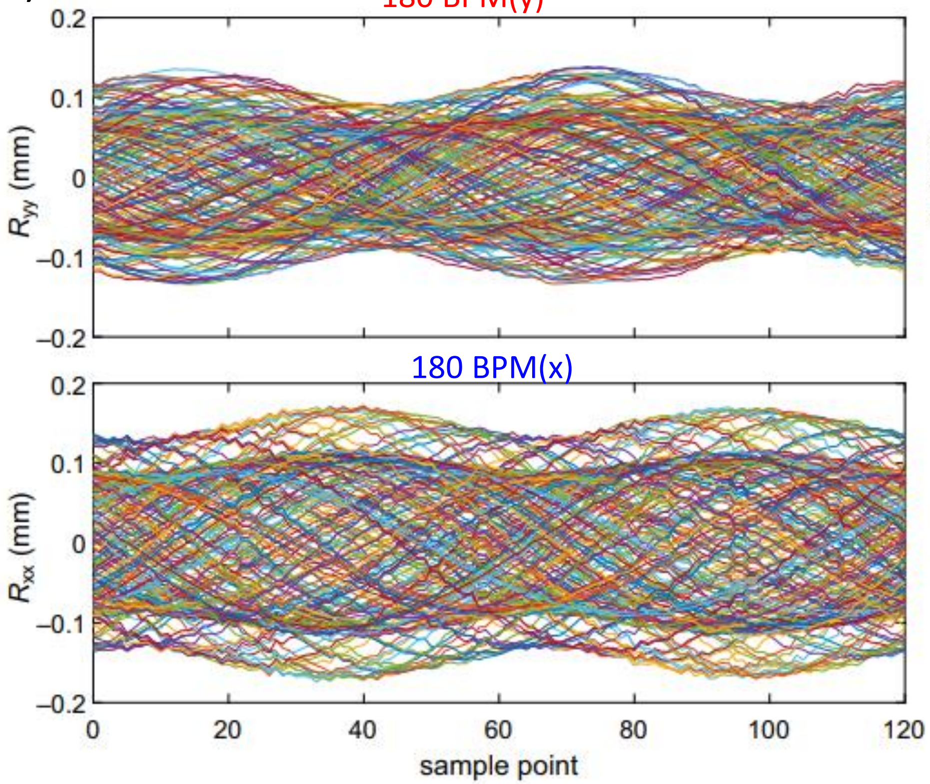
Drive signals

(hor. & ver. corrector waveforms)



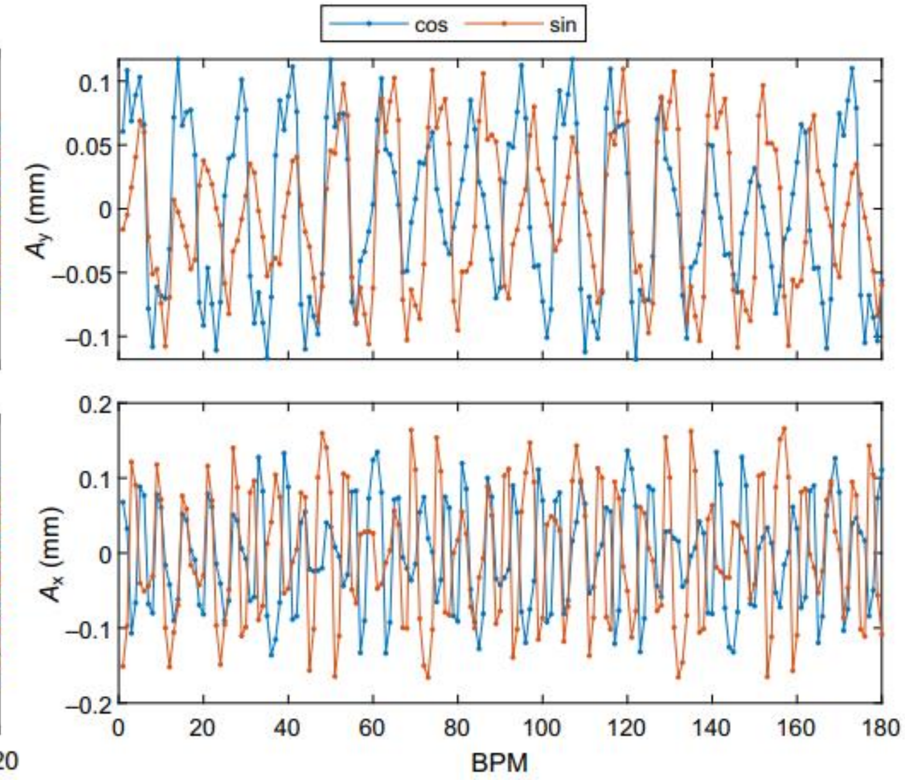
The corrector waveforms used in NSLS-II dc LOCOM measurements. Horizontal correctors are in blue; vertical correctors in red. The modulation amplitude is 1.0 A.

BPM signals



LOCOM data in an NSLS-II measurement

sin & cos modes



The horizontal (bottom) and vertical (top) mode amplitudes in the NSLS-II dc LOCOM measurement

Xiaobiao Huang and Xi Yang

PHYSICAL REVIEW ACCELERATORS AND BEAMS **26**, 052802 (2023)

Implement LOCOM at NSLSII

- The rms $\frac{\Delta k}{k}$ is 1% for the 300 quadrupoles. In addition, the skew quadrupoles were turned off.
- The rms beta beating is 11.5% (H) and 10.1% (V) → after the 2nd correction, rms beta beating becomes 0.8% (H) and 1.1% (V)
- ICA and LOCOM agree.
- Greatly reduce Jacobian size: (4+1)*360*(360+360+4+4+210)=1.6*10^6 (green: orbit number; red: fit parameter number)
- LOCO ((360+2)*360)*(360+360+4+4+210)= 1.2*10^8

Beta beating before correction

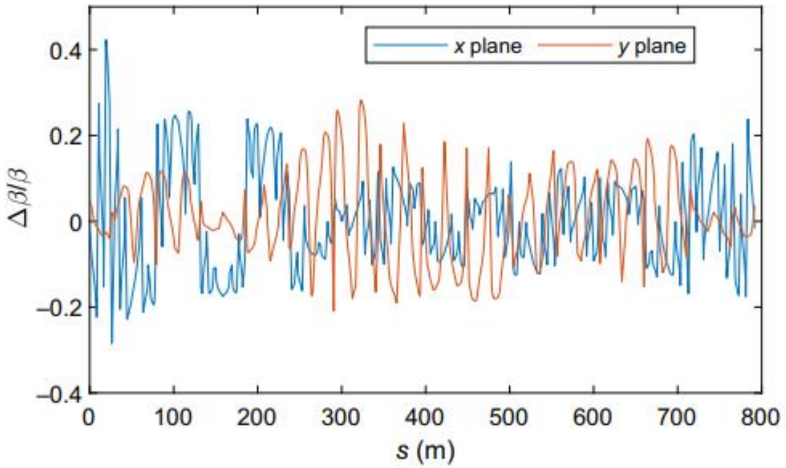


FIG. 9. Beta beating for the machine with initial quadrupole errors obtained by fitting the LOCOM data.

After the 2nd correction

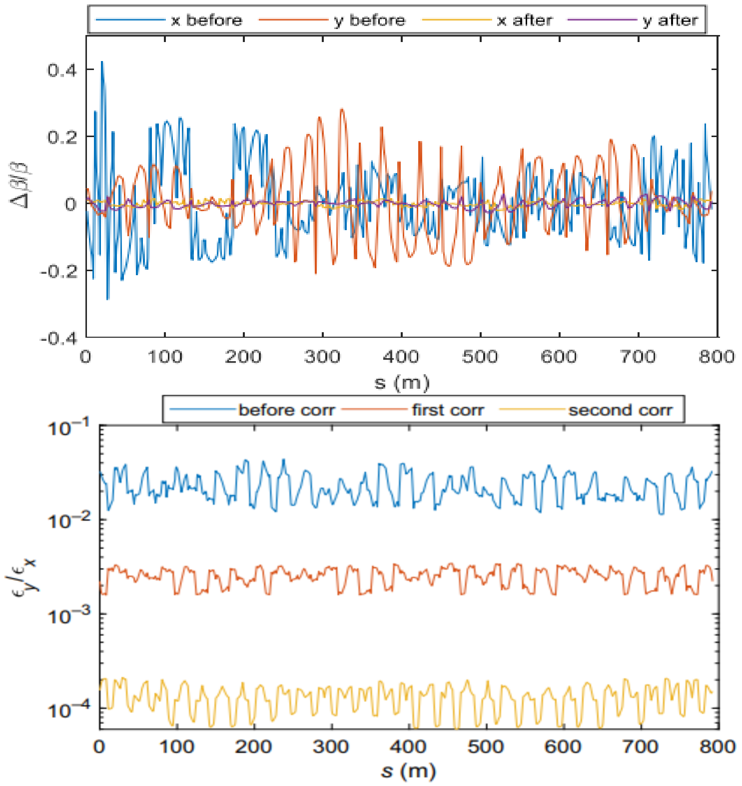


FIG. 14. The emittance ratio before the correction, after the first correction, and after the second correction, obtained from the fitted lattices by LOCOM.

Comparison of phase error between LOCOM and ICA

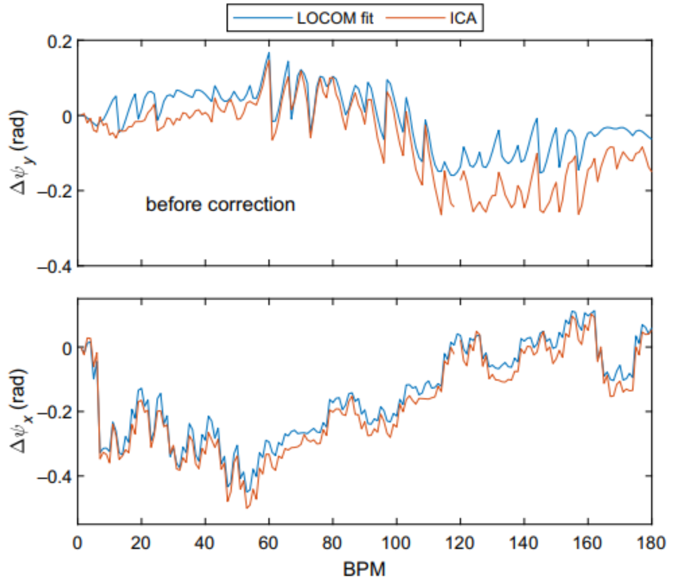
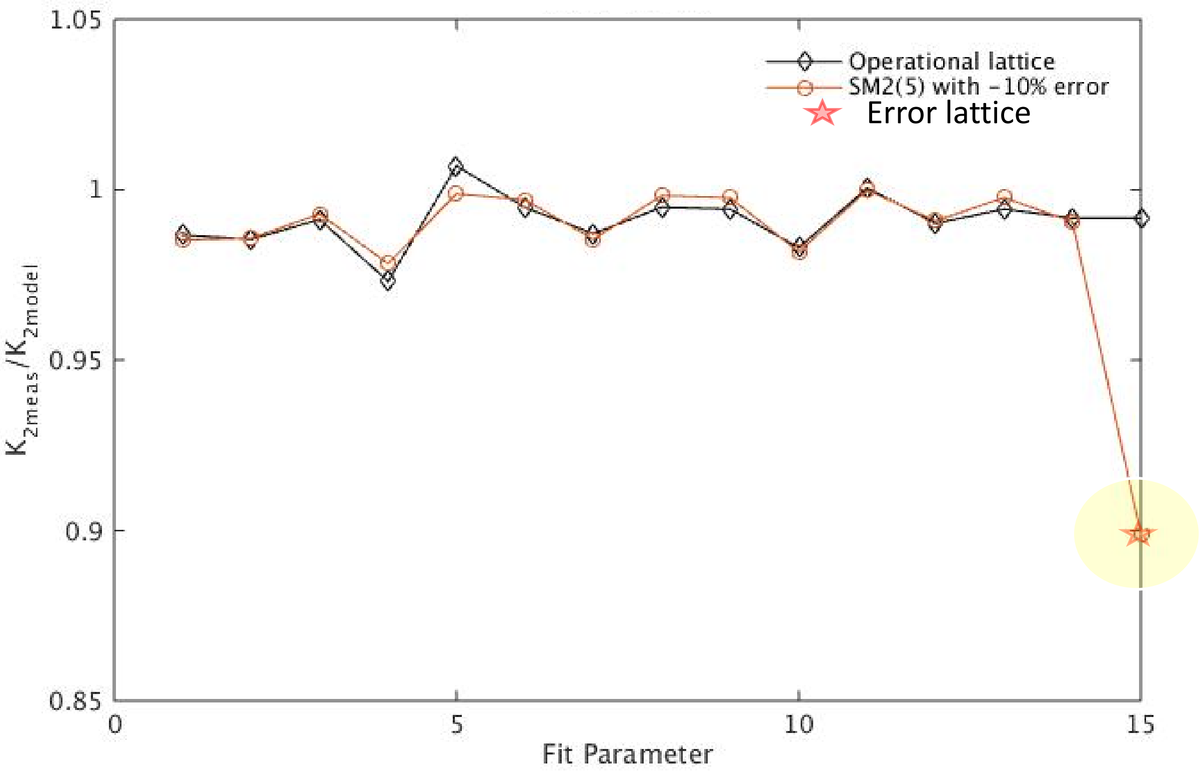


FIG. 8. Phase advance errors with initial random quadrupole errors obtained with TBT BPM data ("ICA") or by fitting LOCOM data.

Preliminary result of NOECO at NSLSII

- Preliminary implementation of NOECO:
  a) At the nominal and Δf = +/- 1 kHz RF frequency, measure the lattice via TbT.
- Generating chromatic sextupole error via reducing SM2 family power supply at the last Pentent in lattice by 10%, and repeat the measurement:
  b) at the nominal and Δf = +/- 1 kHz RF frequency, measure the lattice via TbT.
- Conclusion: as the yellow highlight, measured result (red circle) agrees well with error lattice (red star).



Conclusions

- All those optics correction methods are in AT and Matlab Middle Layer environment
- AC-LOCO
  - **Developed a fast LOCO algorithm using sinusoidal beam excitation with fast correctors**
  - **Achieve 15-nm BPM precision, thus a factor of 2 (y) to 5 (x) reduction in the residual beta-beating and dispersion errors**
  - **Prove-of-principal experiment for MF-ACLOCO: simultaneously driving 30 correctors at different frequencies has been tested with the similar BPM precision. Measurement time reduction: 1hr to 2 mins for 10s BPM data**
- AC-LOCOM
  - **We improved a previously proposed closed-orbit modulation for linear optics and coupling correction**
  - **Instead of fitting individual closed orbits, the improved method decomposes orbit oscillation into 2 orthogonal modes and fits mode amplitudes of all BPMs**
  - **Measurement is faster and Jacobian size is 10s to 100 times smaller compared to conventional LOCO**
  - **It has been successfully applied to NSLS-II linear optics and coupling corrections**
- AC-NOECO
  - **Implemented ICA-NOECO**
  - **In the process of implementing NOECO based on AC-LOCOM**

Acknowledgements

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  - BNL: Victor Smaluk, Lihua Yu, Yuke Tian, and Kiman Ha
  - SLAC: Xiaobiao Huang

Thank you!

- Q: mml compatibility with MATLAB newer than 2017b?