Sextupole Characterisation through Off-Energy ORM and High Order Dispersion Measurements

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Motivation

Achieve nominal 2nd order optics – Nominal DA and lifetime

Two different approaches:

- Characterizing and correcting second order optics
  - Symmetrize 2nd order optics
- Beam-based sextupole calibration
  - Symmetrize sextupoles within the magnet family

Builds on work done at ESRF presented at NOCE2017.

Chromatic Functions

$$\frac{d\beta}{d\delta}(z) = \frac{\beta}{2\sin 2\pi\nu_0}\int_z^{z+L} \beta(k - m\eta)\cos\left[2\nu_0\left(\varphi_z - \varphi_\zeta + 2\pi\right)\right]d\zeta$$

$$\frac{d\eta}{d\delta}(z) = \eta + \frac{\sqrt{\beta}}{2\pi\sin\pi\nu_0}\int_z^{z+L} \eta\left(k - \frac{1}{2}m\eta\right)\sqrt{\beta}\cos\left[\nu_0\left(\varphi_z - \varphi_\zeta + \pi\right)\right]d\zeta$$

Linear in sextupole strength - m

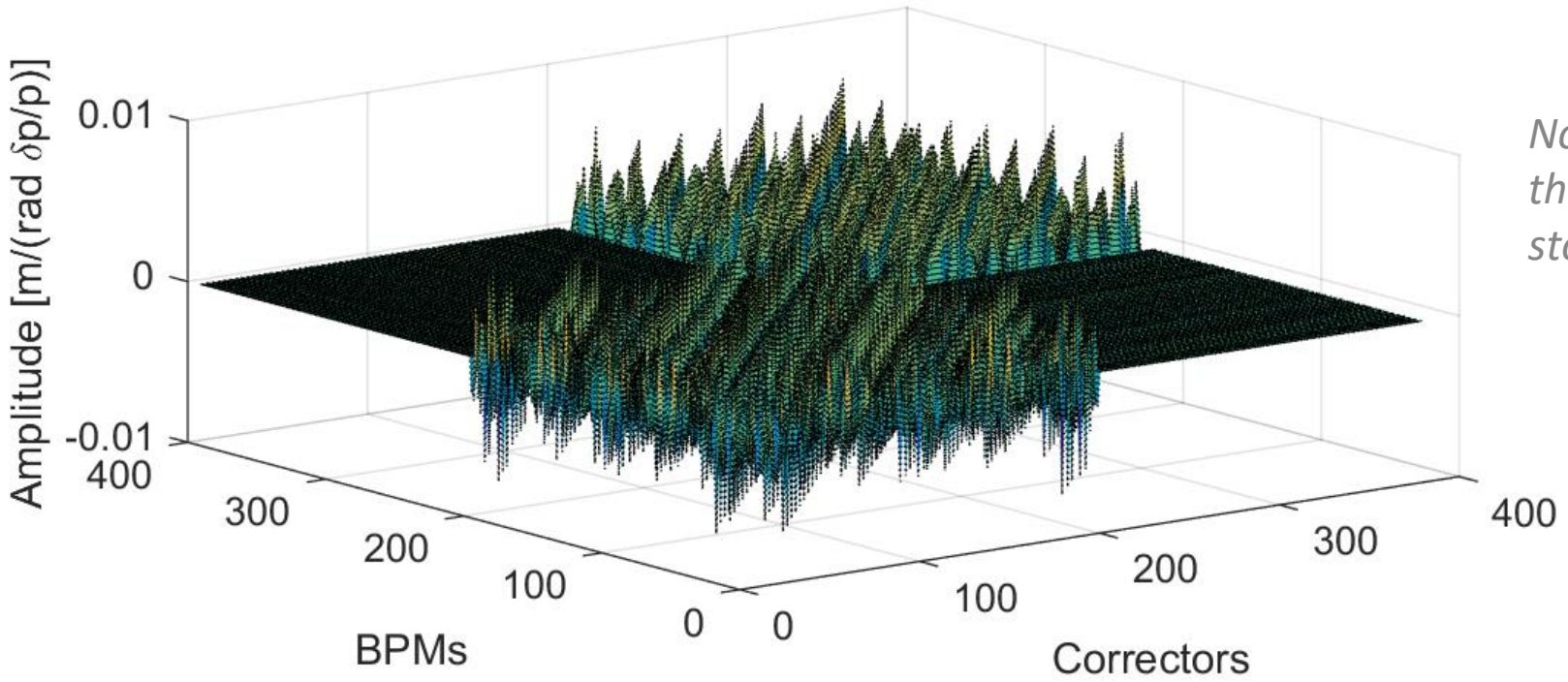
Progress

- 2nd order optics through Off-Energy Orbit Response Matrix (OEORM)
  - Simulation
    - Evaluate linearity of OEORM - Done!
    - Symmetrise second order optics in simulation - Done!
  - Measurement
    - Find procedure for reliably measuring OEORM - In Progress
    - Symmetrise second order optics of machine - In Progress
    - Evaluate lifetime and DA of symmetrised optics
- 2nd Order Dispersion
  - Measure 2nd order dispersion - Done!
  - Use 2nd order dispersion to calibrate sextupoles - In Progress

2nd Order Optics Symmetrisation through OEORM

OEOR – Off-Energy Orbit Response

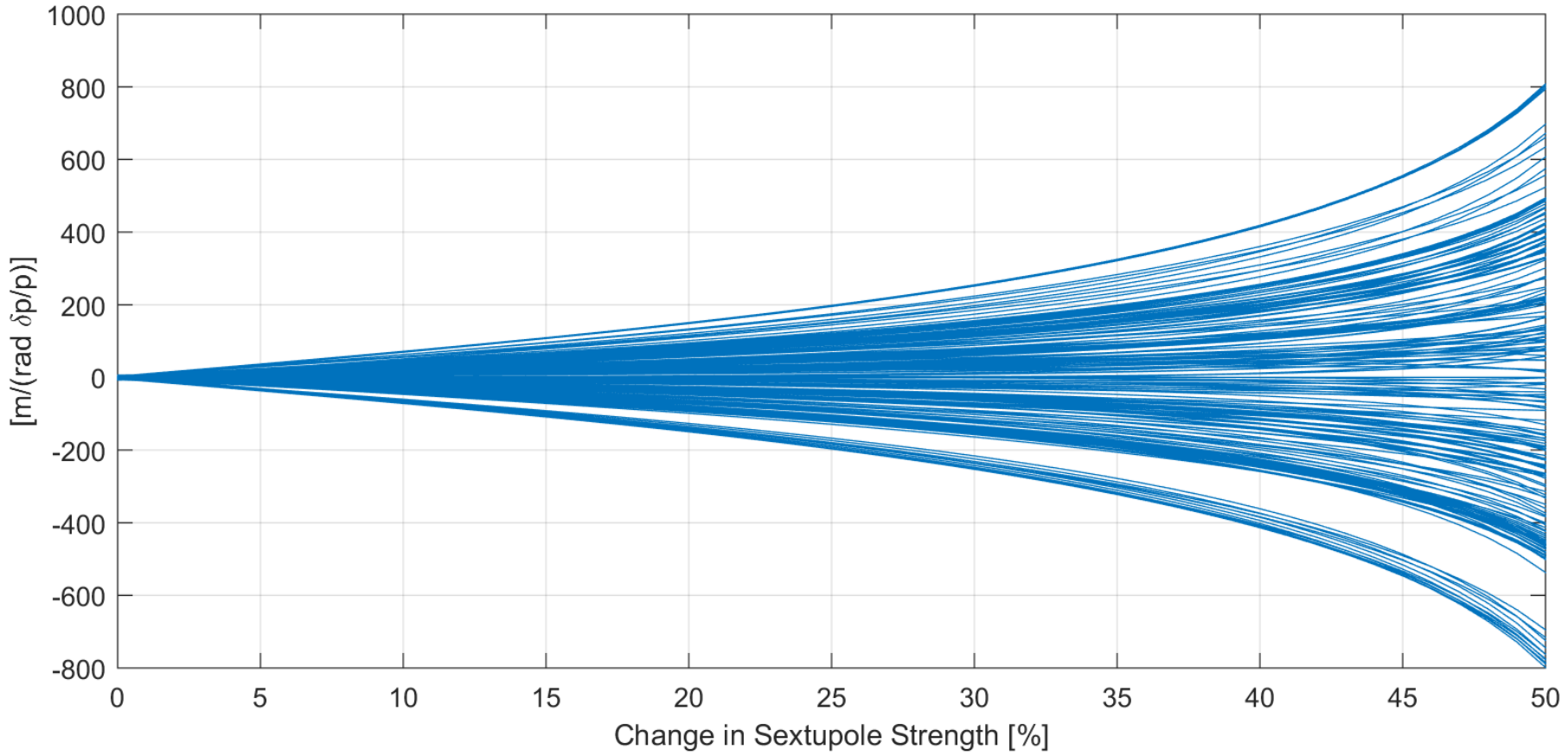
- The off-energy orbit response is how the orbit response changes with a change in momentum.
- It can be measured by taking the difference in orbit response at $+\delta = +{}^{\Delta p}/_{p}$, and $-\delta = -{}^{\Delta p}/_{p}$.



Nominal OEORM of the MAX IV 3 GeV storage ring

OEORM

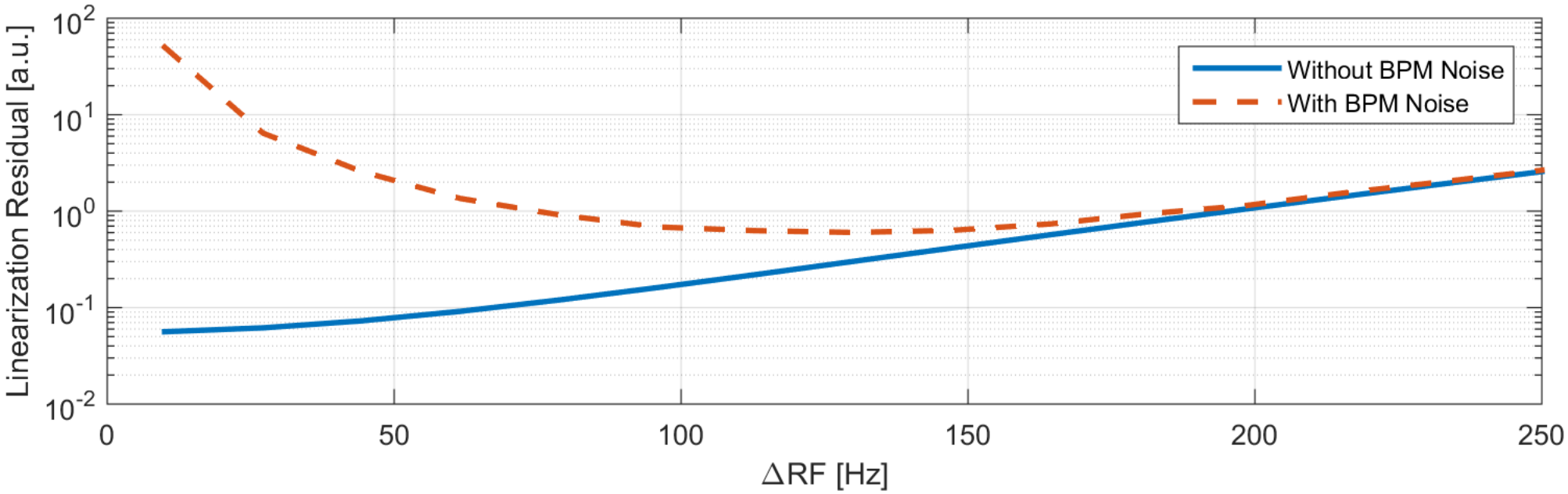
- The off-energy orbit response is linear with sextupole strength for a relative change of approx. ± 20 %



Each line is the OEOR in a BPM

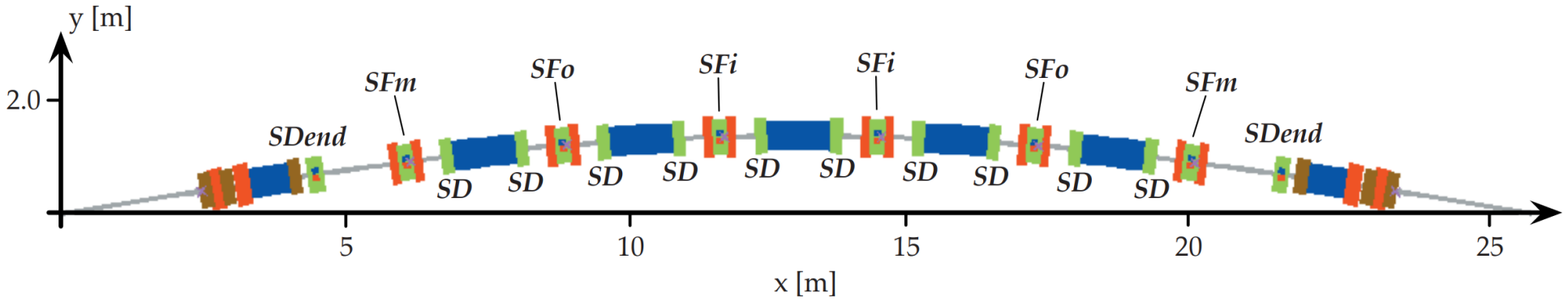
OEORM

- The beating in OEOR was simulated for changes in sextupole strength of ± 10 % for a range of changes in energy.
- A linear fit was done for each energy, with and without simulated BPM noise.
- Linearisation residual has a minimum around $\sim 100 \ - 150$ Hz.



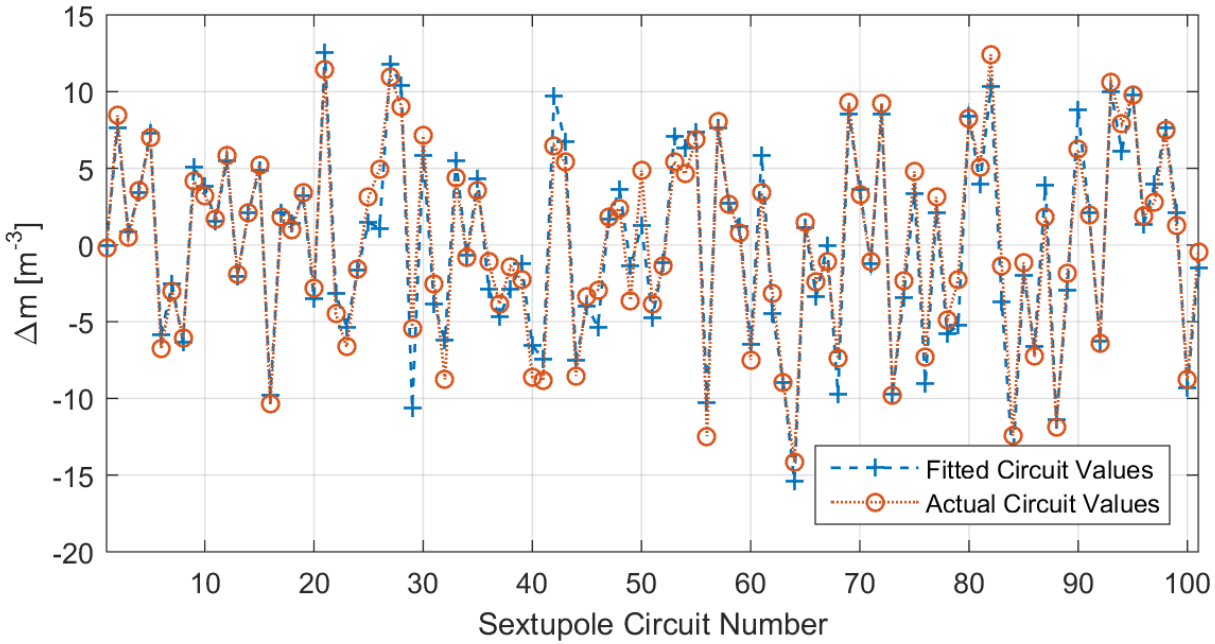
The MAX IV 3 GeV Sextupoles

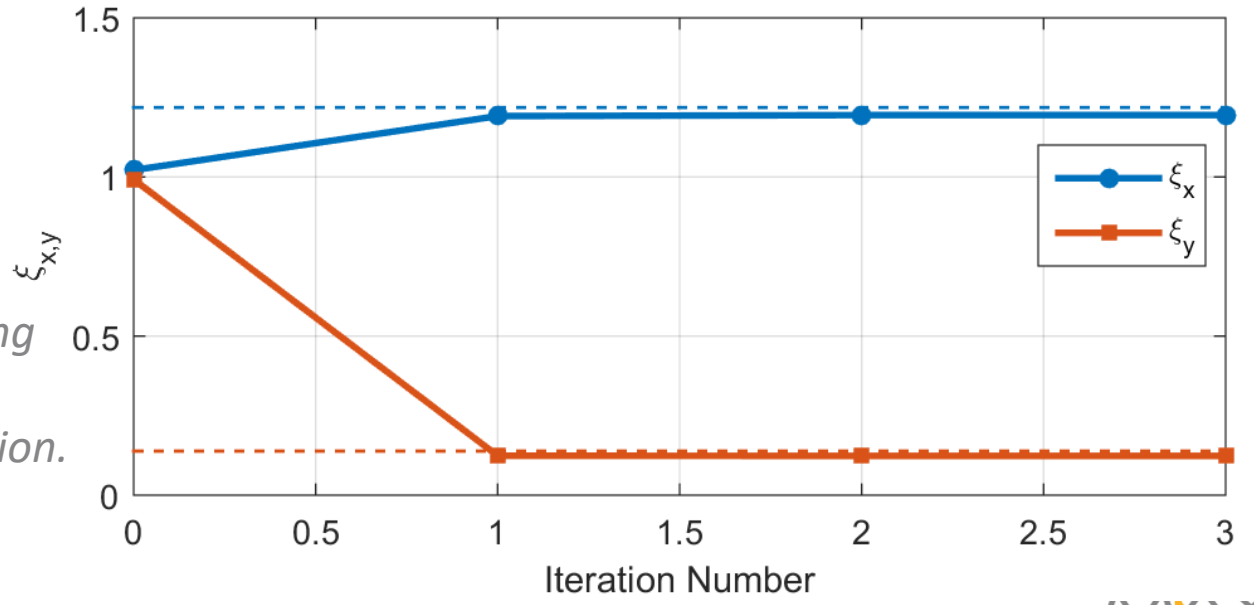
- 18 sextupoles per achromat, all are chromatic.
- One family with 10 magnets per circuit.
- Remaining families have 2 magnets per circuit.
- A single sextupole circuit is split up to one magnet per power supply.



OEORM - Simulations

- Introduce sextupole strength errors by sextupole **circuit**.
- Identify errors by fitting model to OEORM with sextupole **circuits** as fit parameters.
- OEORM simulated with BPM noise.





Chromaticity convergence of fitting procedure.
Dashed – Chromaticity of simulation.
Solid – Chromaticity of fit.

OEORM - Simulations

- Introduce sextupole strength errors by sextupole **magnet**.
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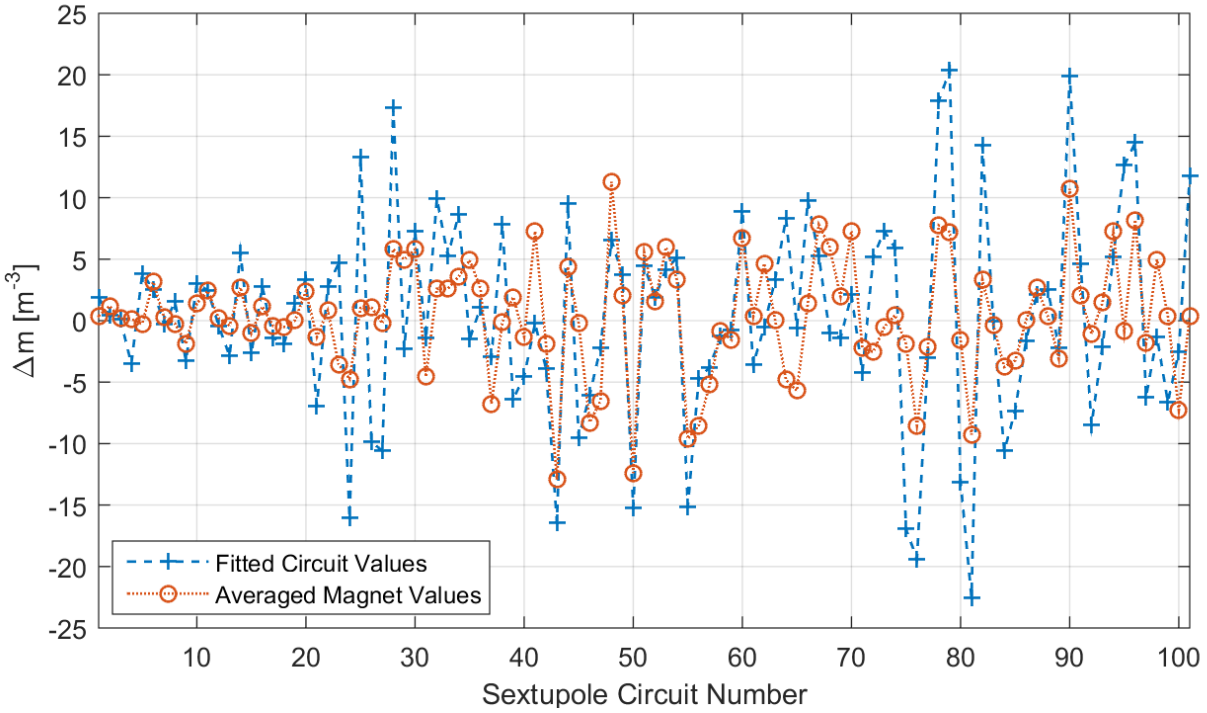
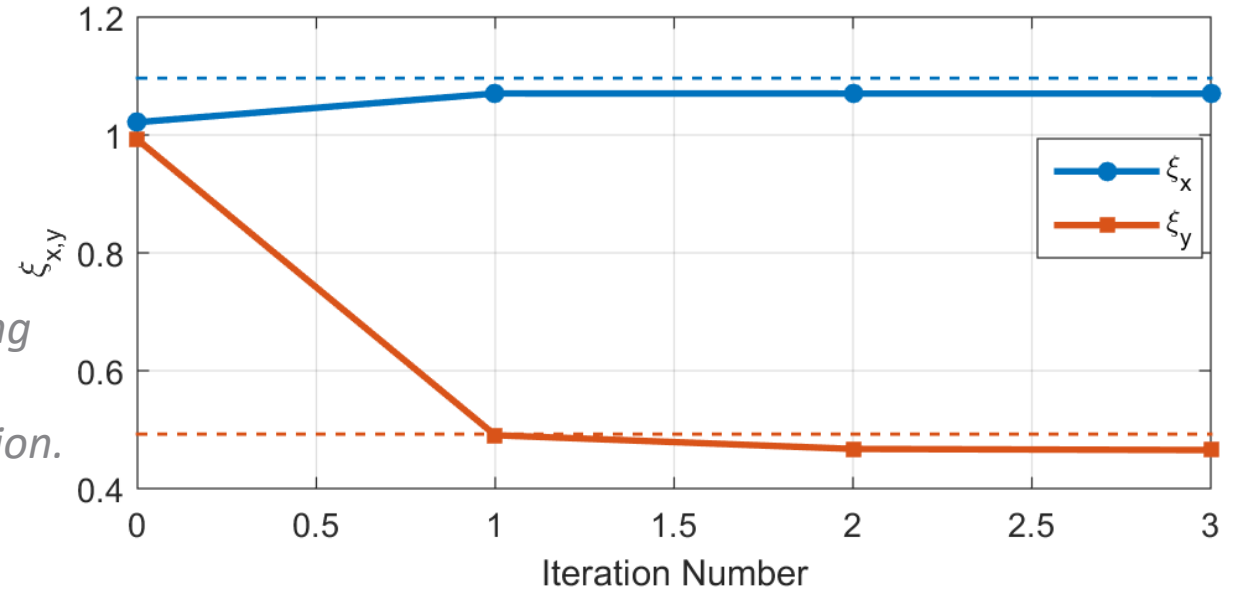
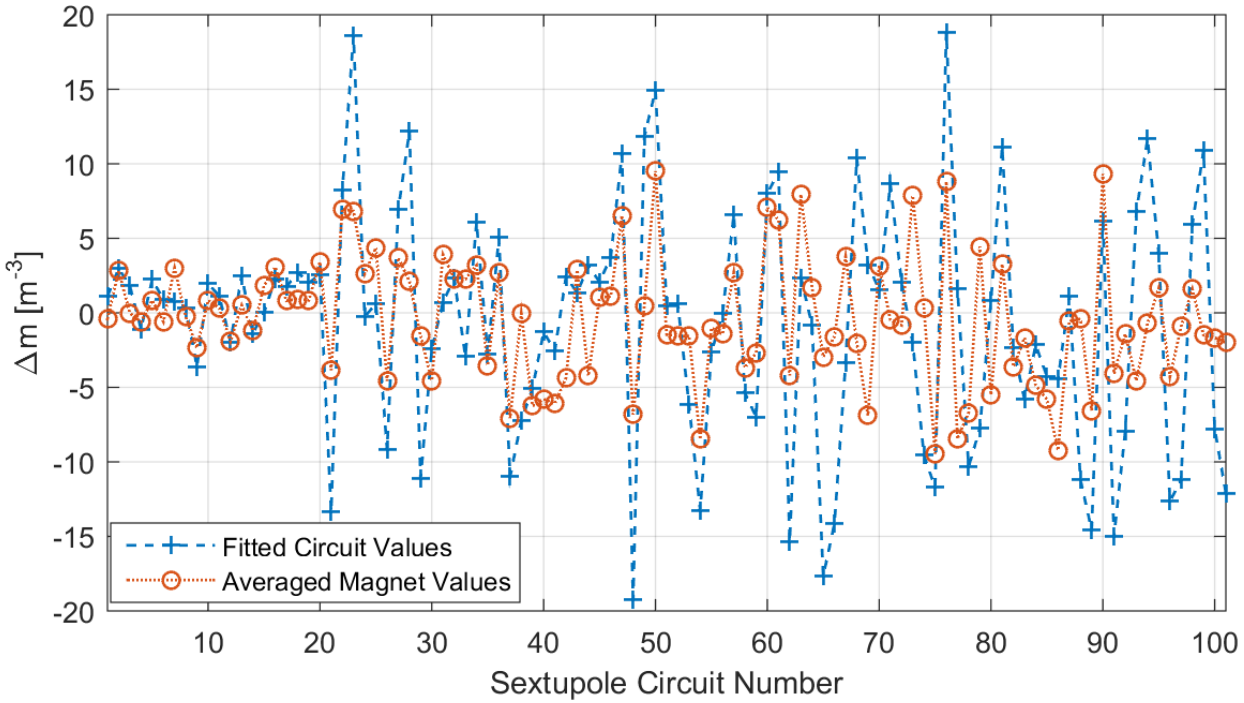


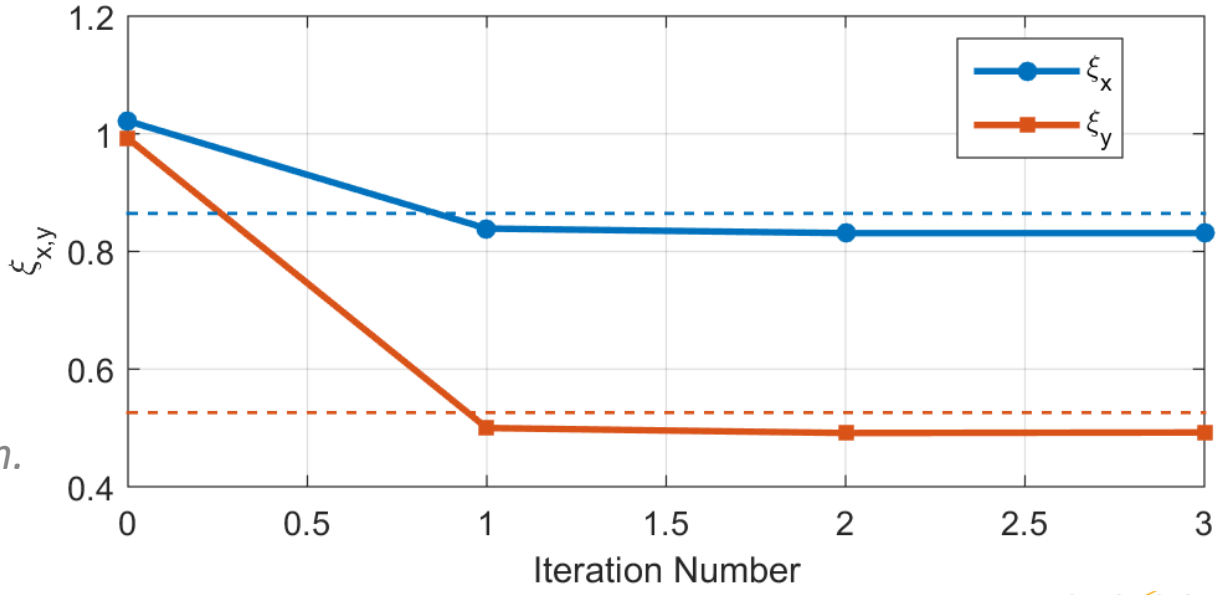


Chromaticity convergence of fitting procedure.
Dashed – Chromaticity of simulation.
Solid – Chromaticity of fit.

OEORM - Simulations

- Include transverse **alignment errors** in all magnets, as well as strength errors by magnet
- Identify errors by fitting model to OEORM with sextupole **circuits** as fit parameters.
- OEORM simulated with BPM noise.



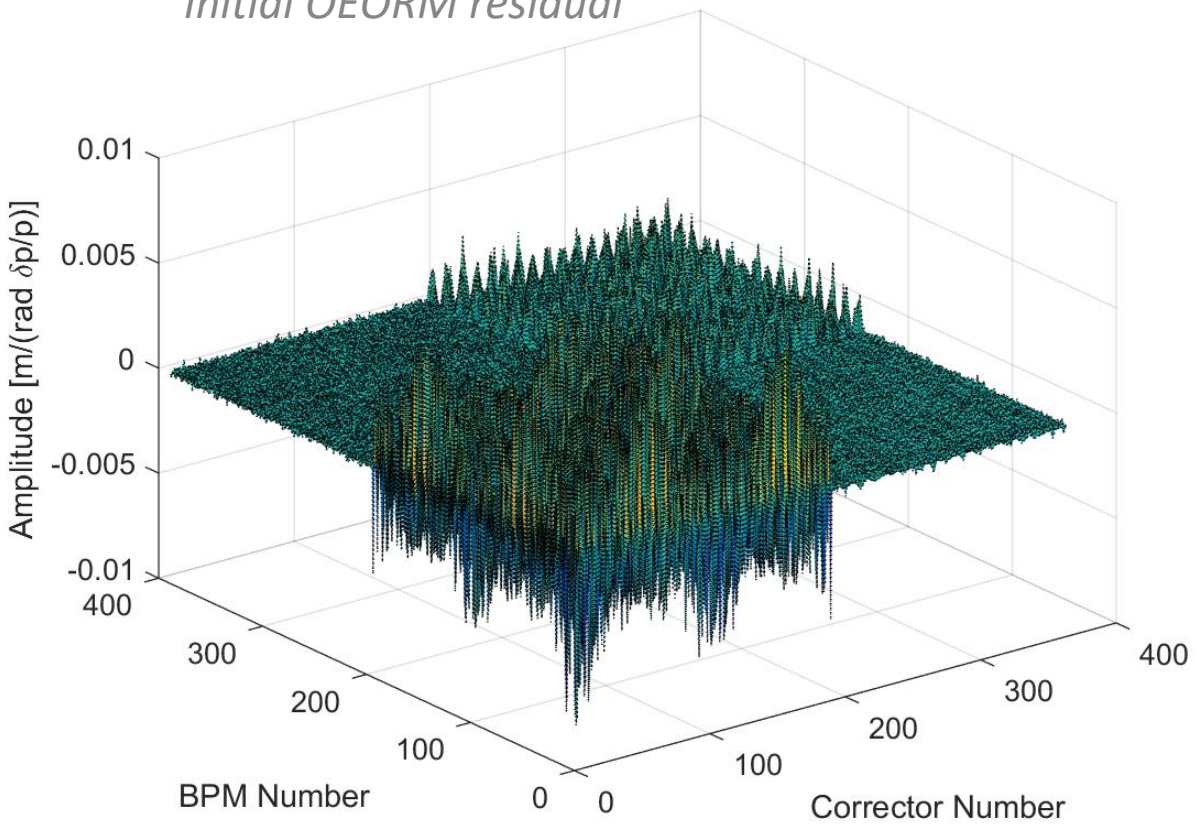


Chromaticity convergence of fitting procedure.
Dashed – Chromaticity of simulation.
Solid – Chromaticity of fit.

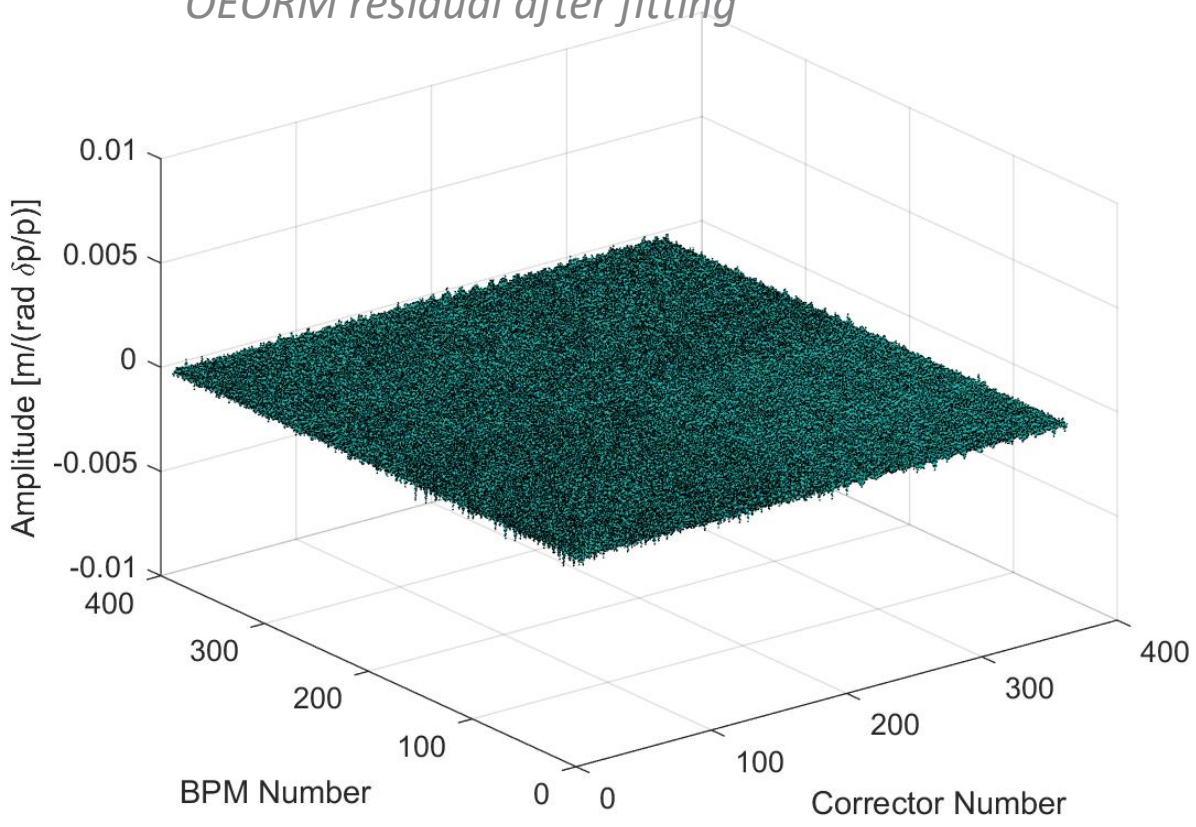
OEORM

- Five sextupole circuit errors where introduced to the real machine: $-20\ \%$, $-15\ \%$, $-10\ \%$, $-5\ \%$, $-2\ \%$

Initial OEORM residual

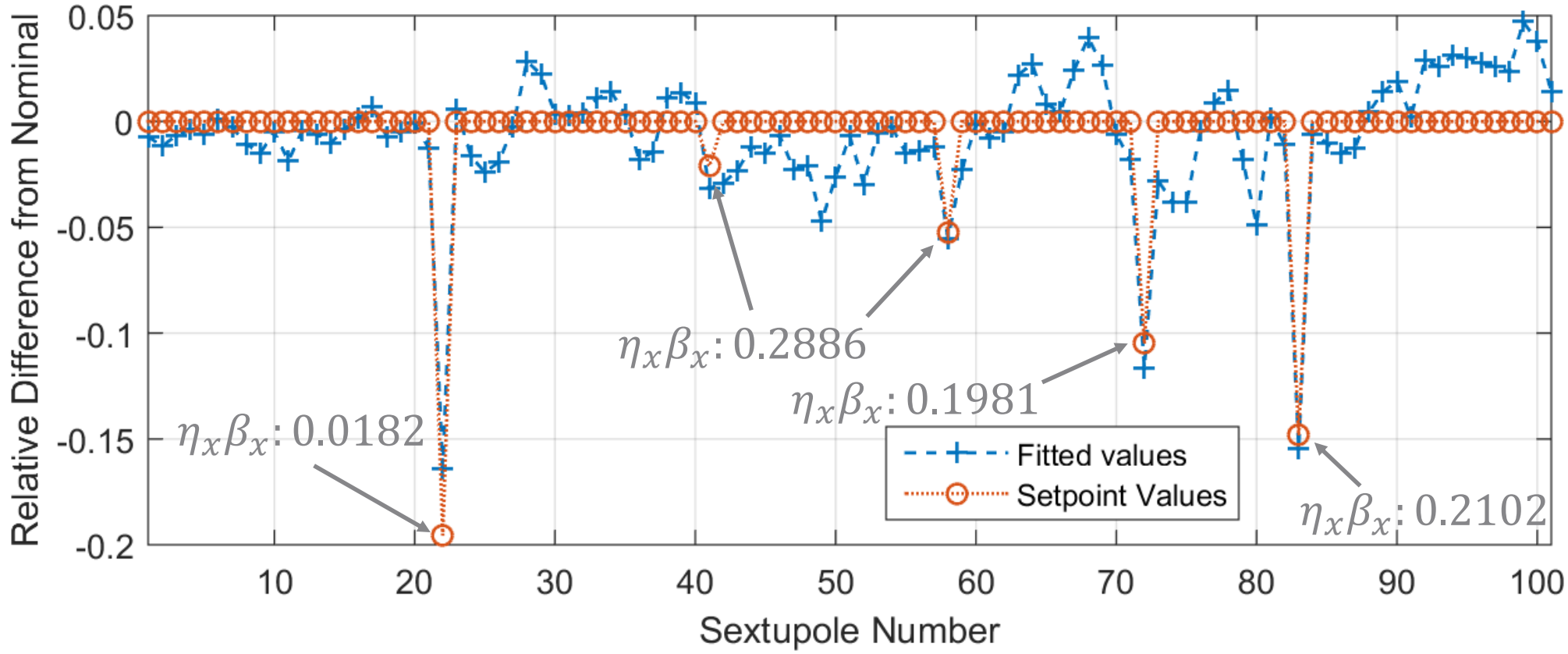


OEORM residual after fitting



OEORM

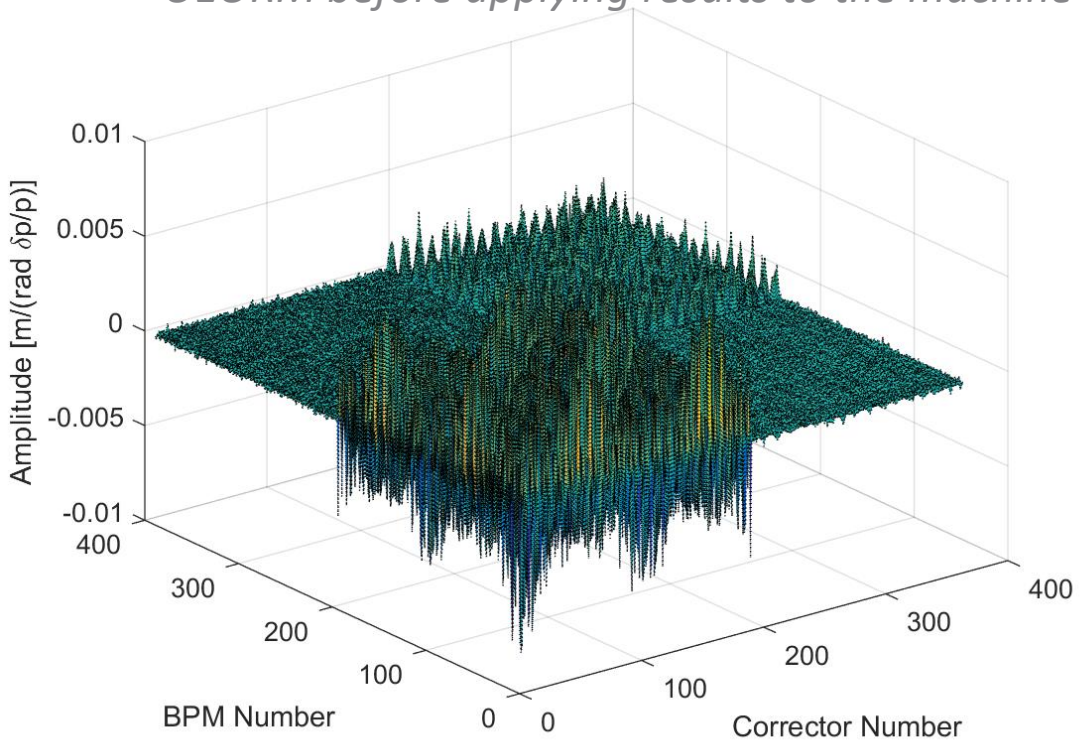
- Identified sextupole errors from fitting model to measured OEORM.



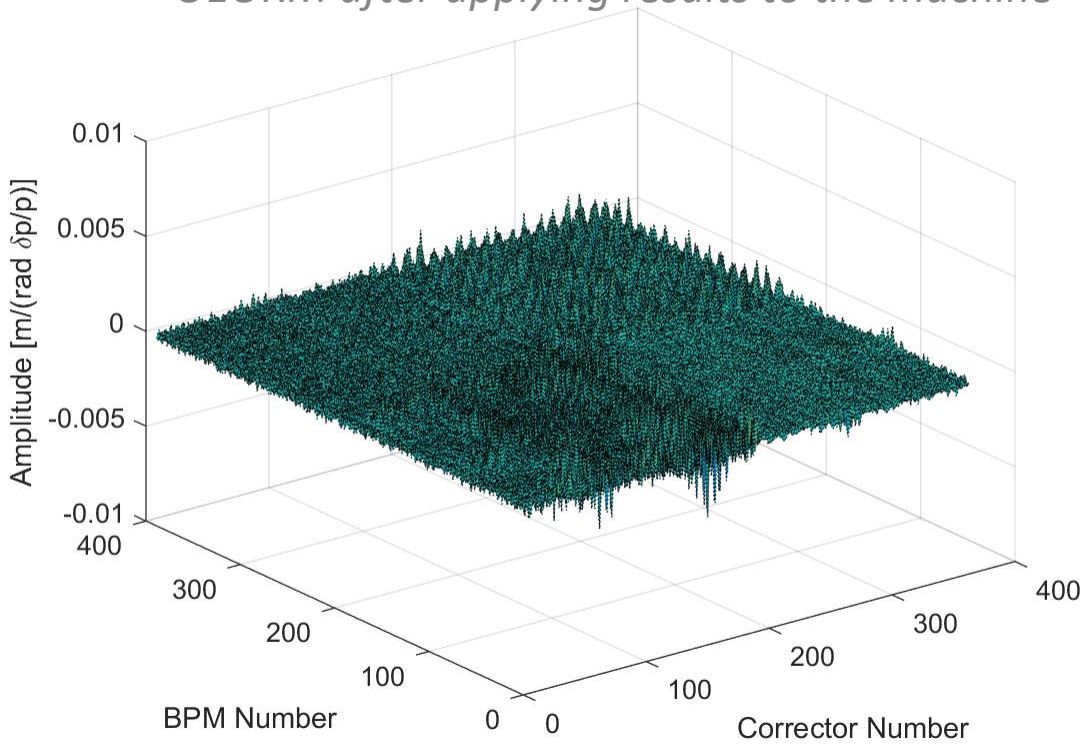
OEORM

- Initial chromaticity: 2.9354 / 1.6135
  Chromaticity after introducing errors: 2.5291 / 1.7867
  Post correction: 1.2111 / 1.1683 (nominal 1.0 / 1.0)

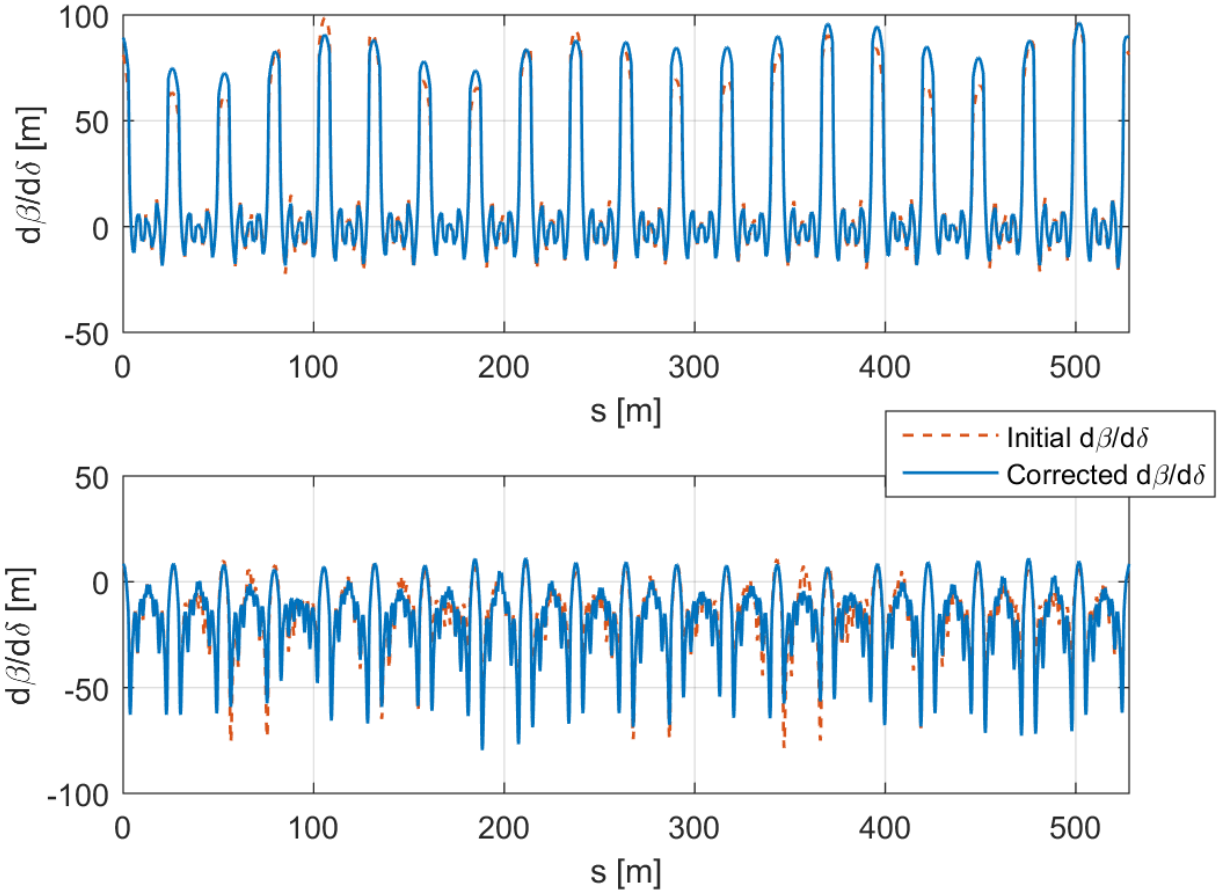
OEORM before applying results to the machine



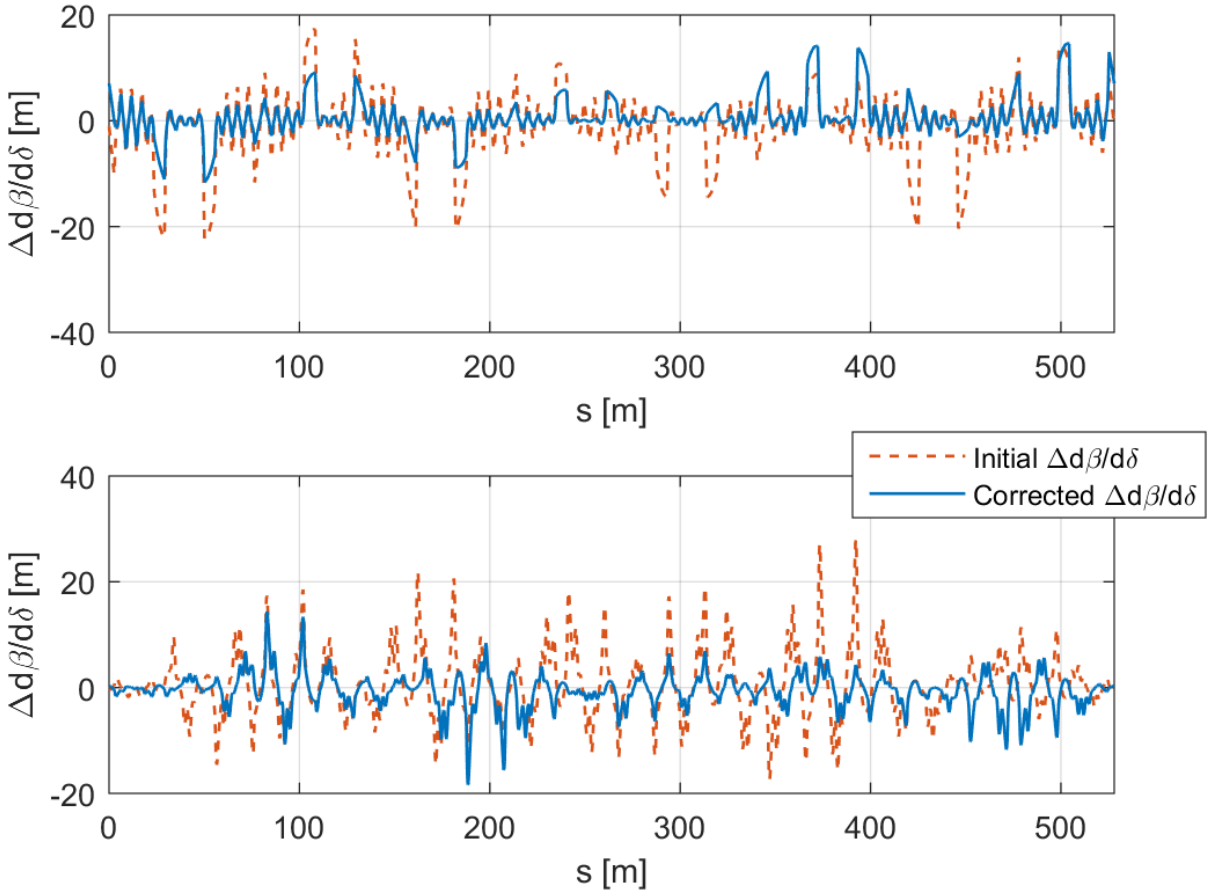
OEORM after applying results to the machine



Chromatic Functions



Initial and corrected (from evaluation fit) horizontal (top) and vertical (bottom) chromatic functions



Initial and corrected (from evaluation fit) horizontal (top) and vertical (bottom) chromatic beating

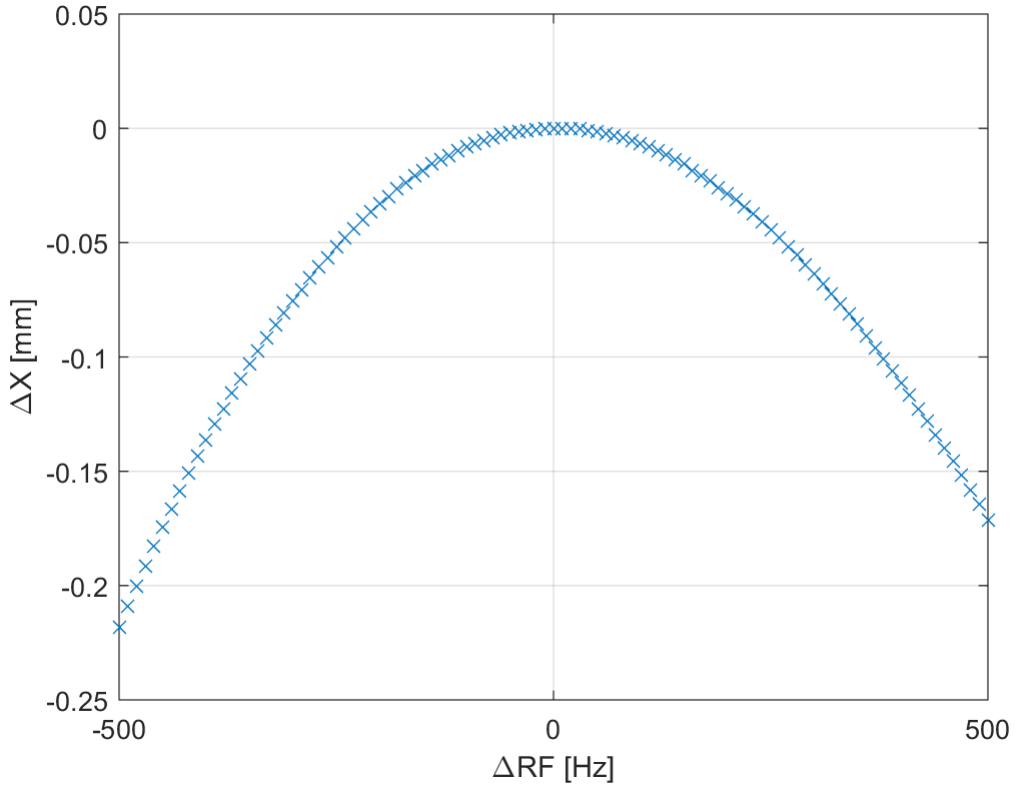
Summary

- Off-Energy Orbit Response measurements and fits have been used to characterize and correct 2nd order optics.
- Measurements and corrections have reduced chromatic function beating by a factor ~2 and corrected chromaticity.
- Work remains to be done on the reproducibility of the measurements and more thorough evaluation of the corrected optics.
- Goal is to fully symmetrize 2nd order optics.

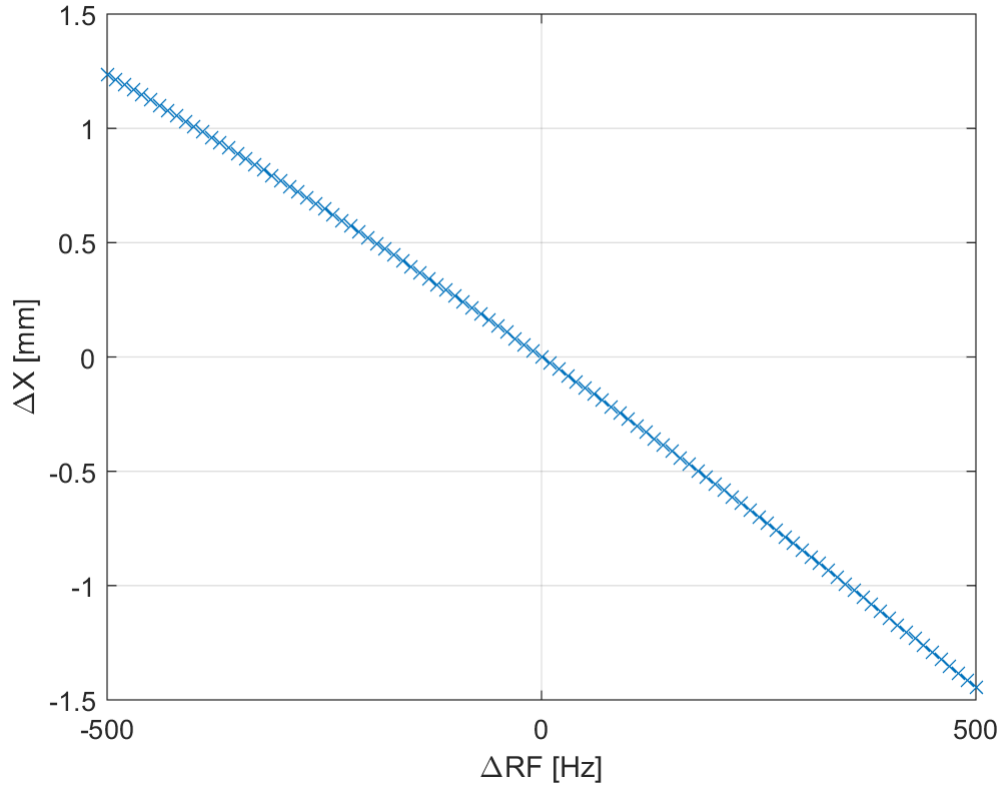
2nd Order Dispersion Sextupole Calibration

2nd Order Dispersion

- Measured closed orbit in the range ± 500 Hz at steps of 10 Hz
- 2nd order dispersion is extracted by fitting a fourth order polynomial to each BPM



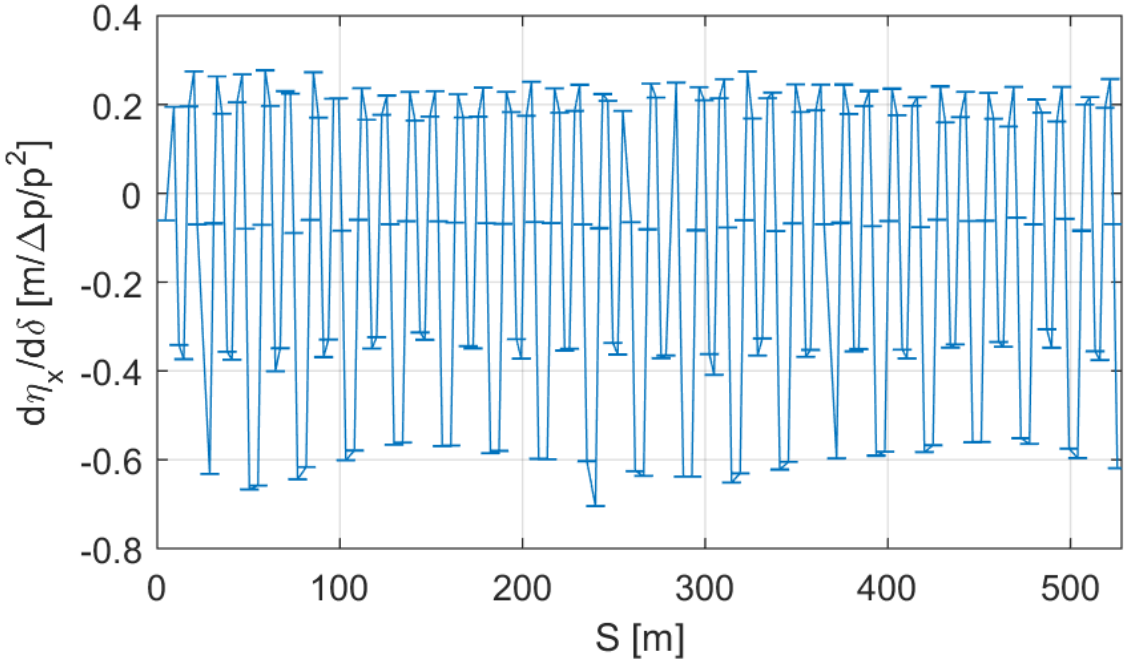
Low dispersion BPM



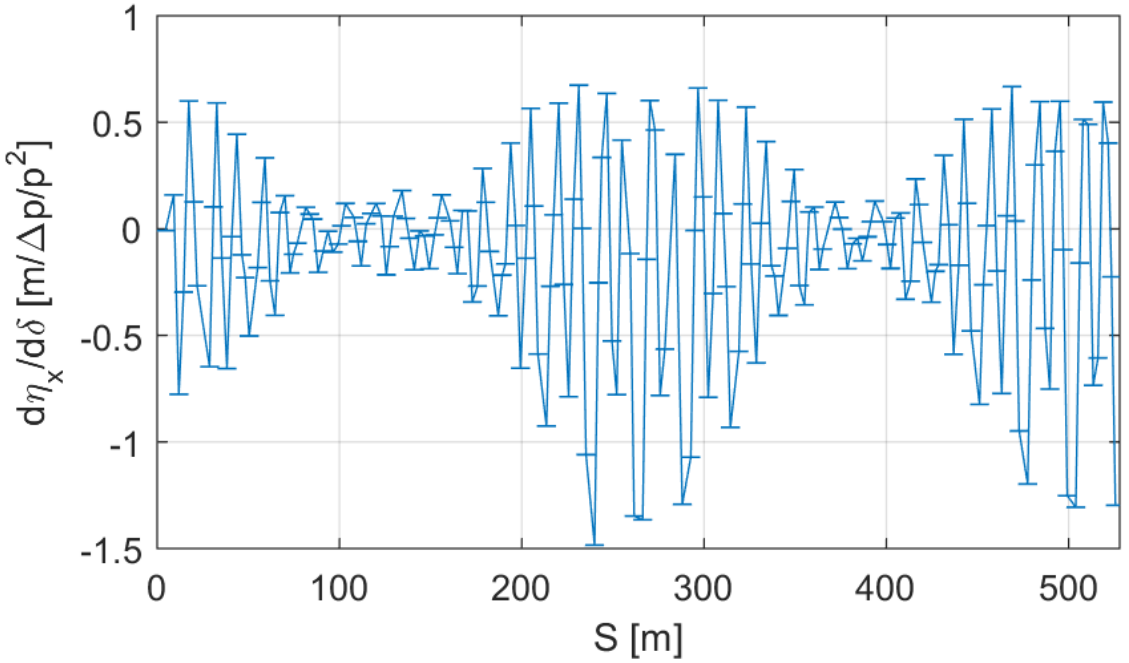
High dispersion BPM

2nd Order Dispersion

- Change the strength of a sextupole to induce a 2nd order dispersion beating



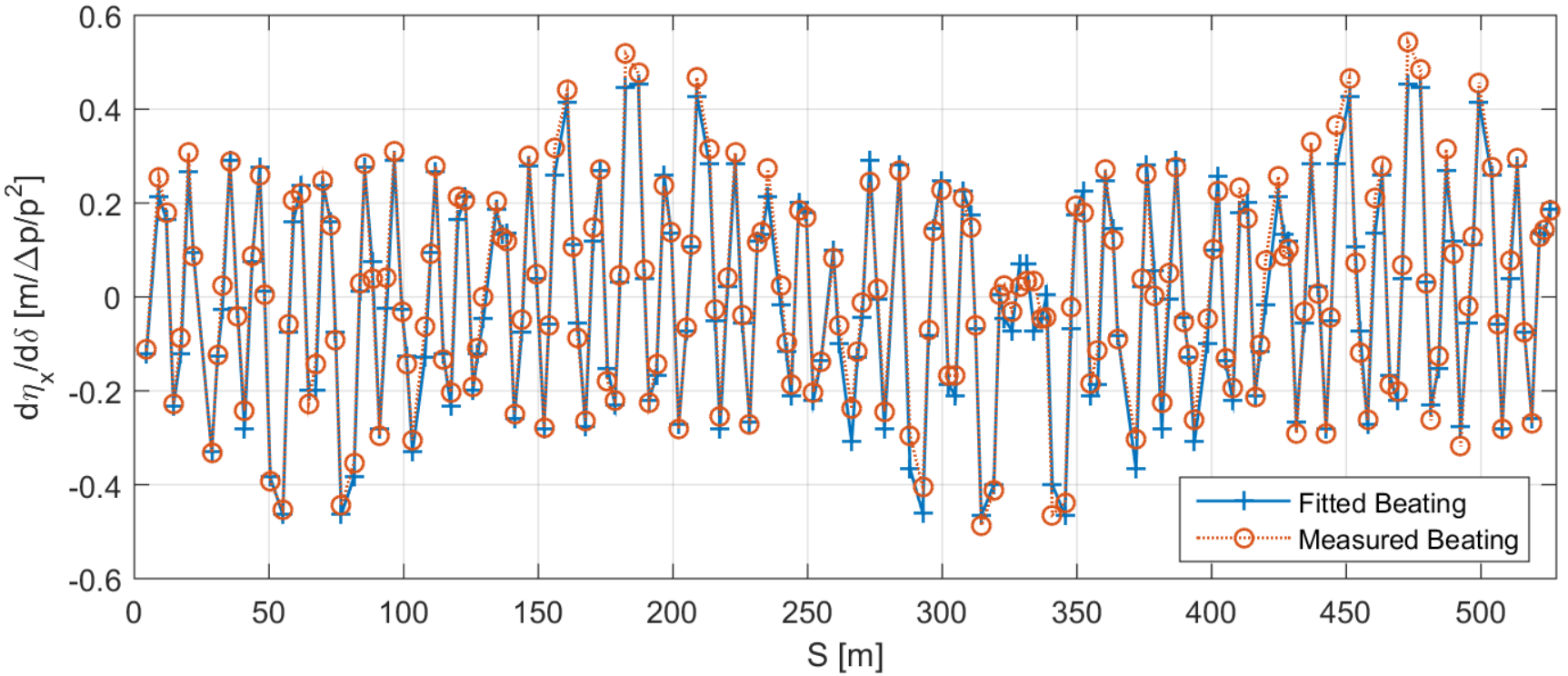
Initial horizontal 2nd order dispersion



Horizontal 2nd order dispersion after significantly reducing the strength of a single sextupole

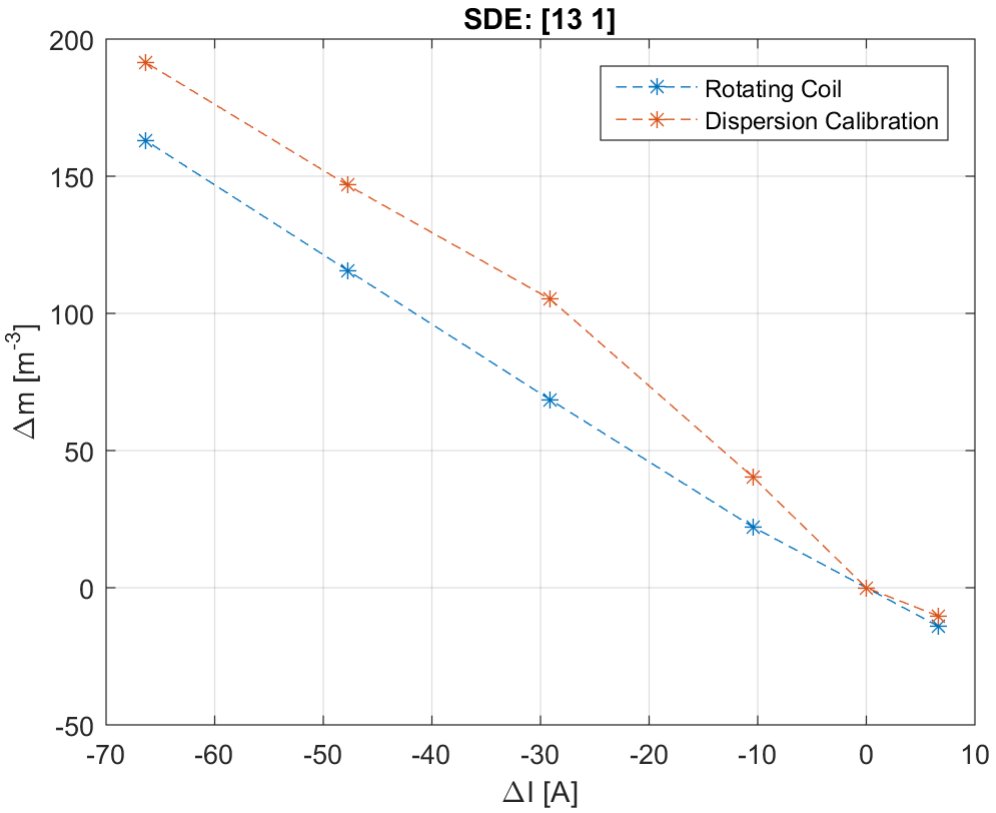
2nd Order Dispersion

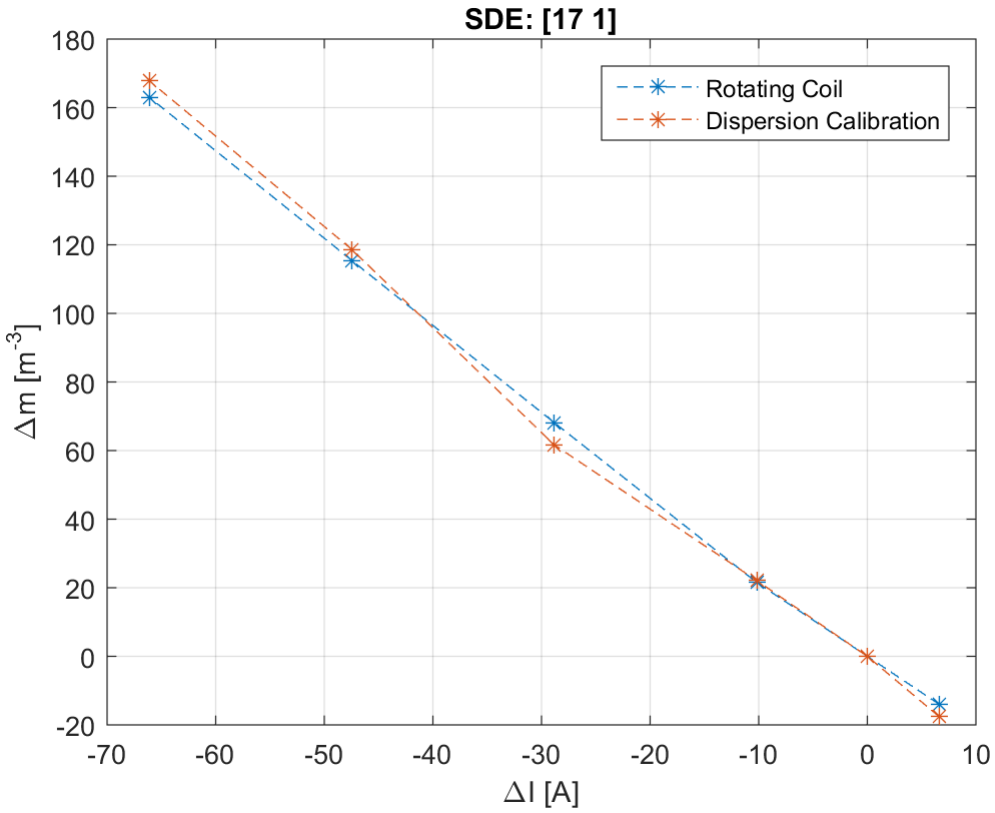
- Simulator beating pattern can be fitted to measured beating pattern and the corresponding change in sextupole strength can be extracted.
- Measurements and fits done at magnet currents corresponding to rotating coil measurements.



2nd Order Dispersion

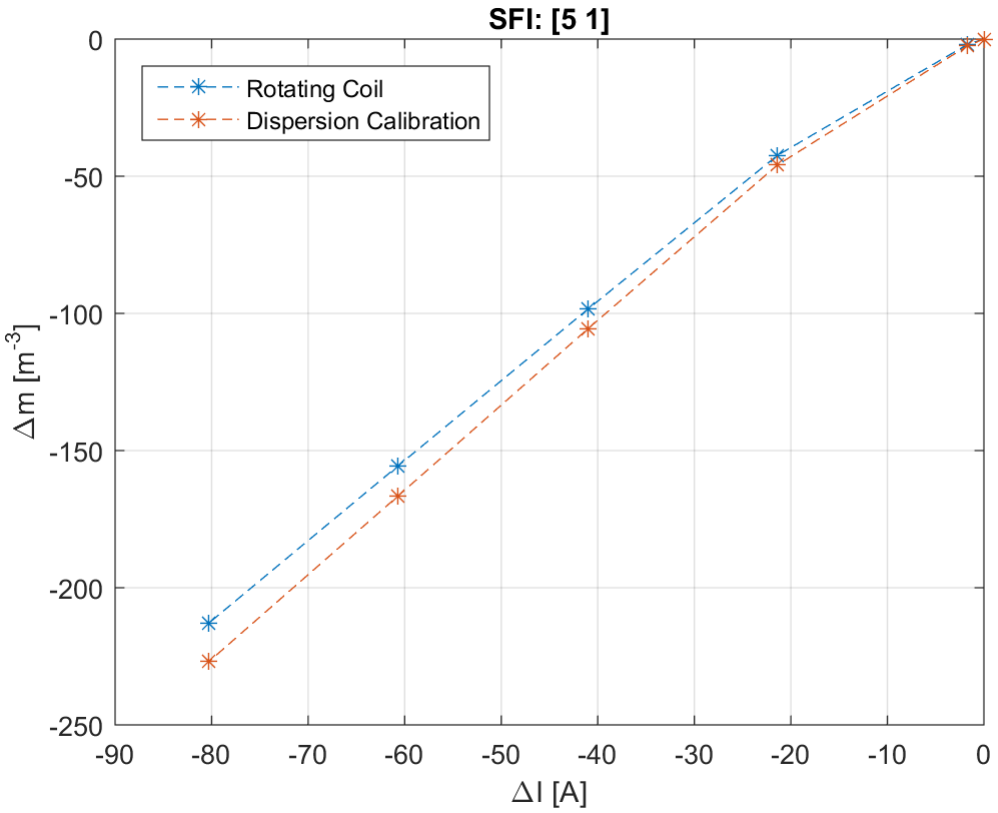
- SDE – Low dispersion/beta sextupole, more noise sensitive.

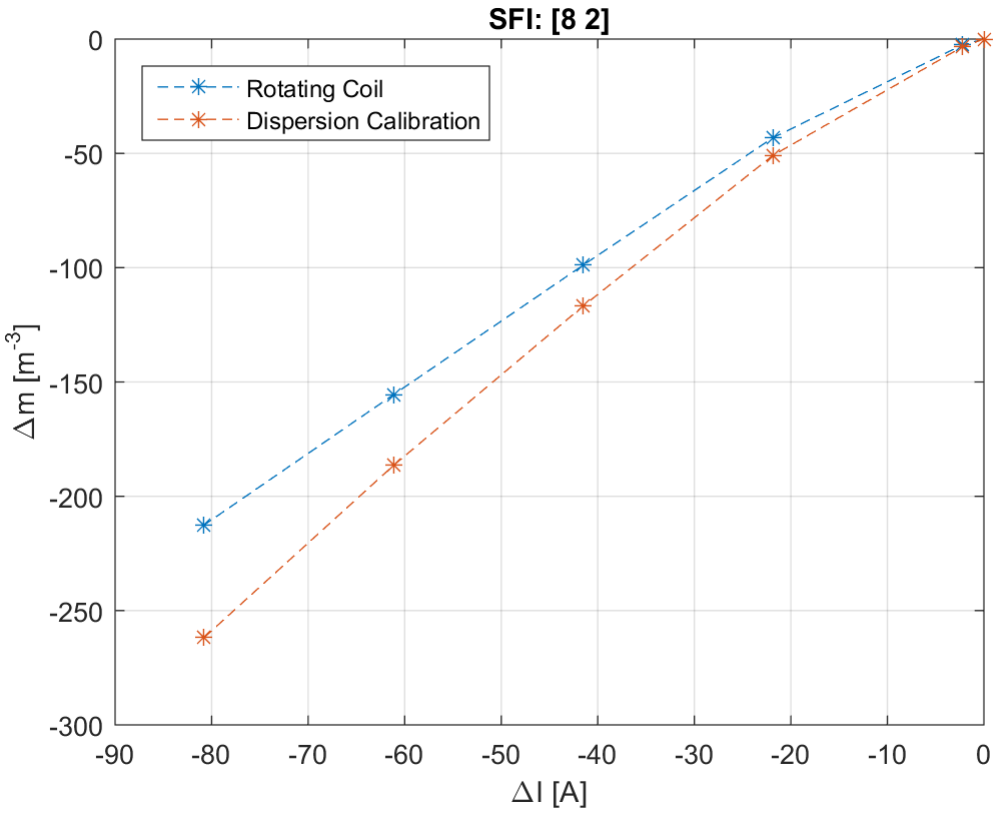




2nd Order Dispersion

- SFI – High dispersion/beta sextupole, less noise sensitive.





Summary

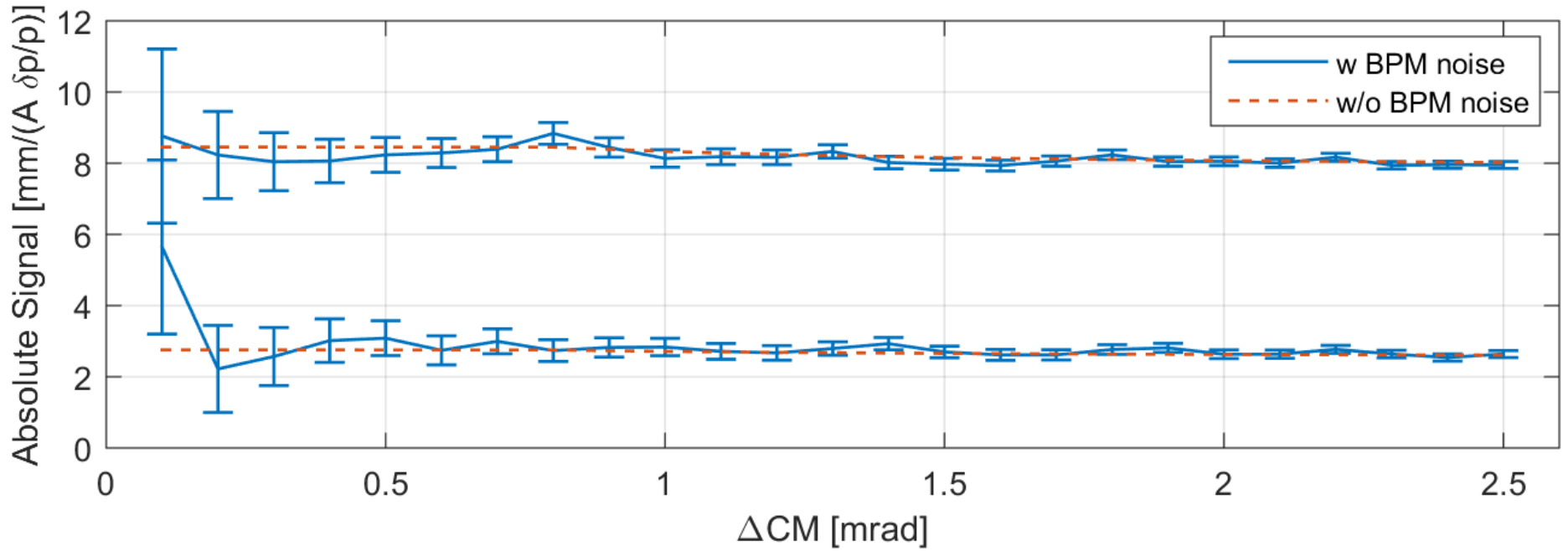
- 2nd order dispersion sextupole calibration has been used to investigate the calibration curve of sextupoles.
- Resulting lifetime and DA when symmetrizing sextupole families is still to be evaluated.
- Goal is to fully symmetrize each sextupole magnet family.

Thank you for your attention!

Extra Slides

OEORM

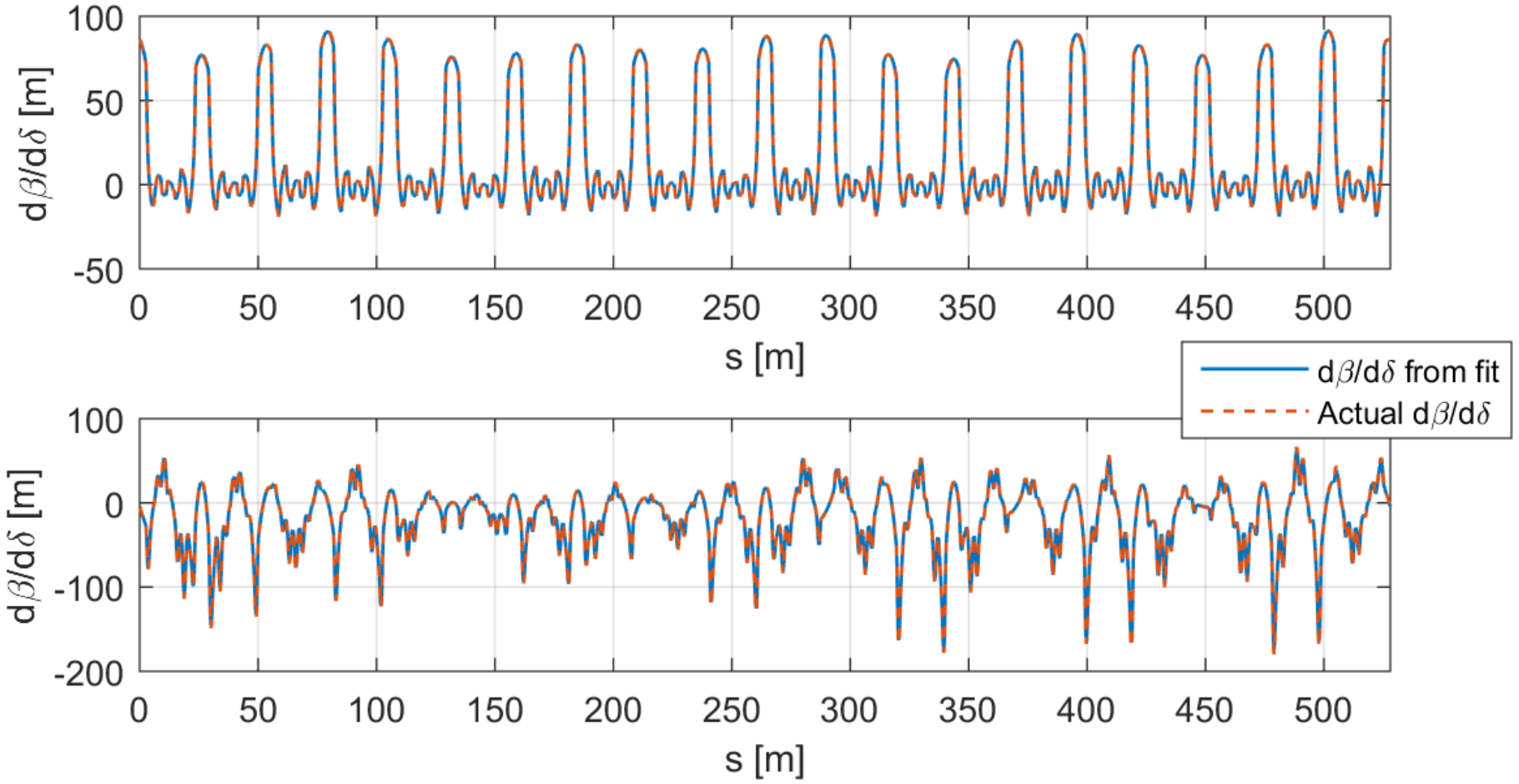
- The OEOR was simulated with different corrector magnet changes as energy offsets corresponding to 50 Hz
- Simulations were done with and without BPM noise
- Real measurements are also limited by power supply limits



For high and low signal BPMs

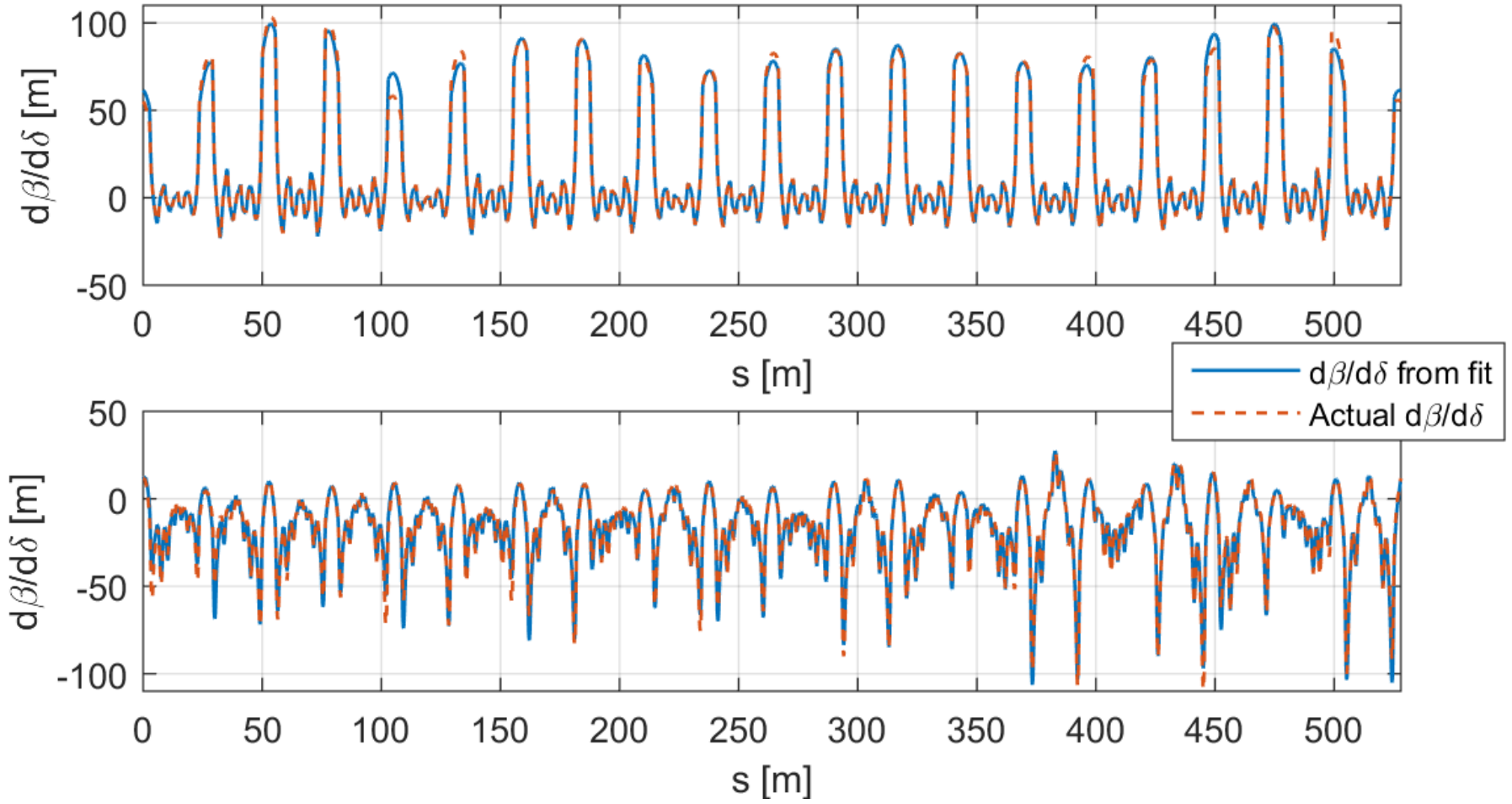
Chromatic Functions

- Chromatic functions when fitting to simulations with circuit errors.



Chromatic Functions

- Chromatic functions when fitting to simulations with magnet errors.



Chromatic Functions

- Chromatic functions when fitting to simulations with magnet and alignment errors.