Error Studies for Low-Emittance Rings with Application to APS-U

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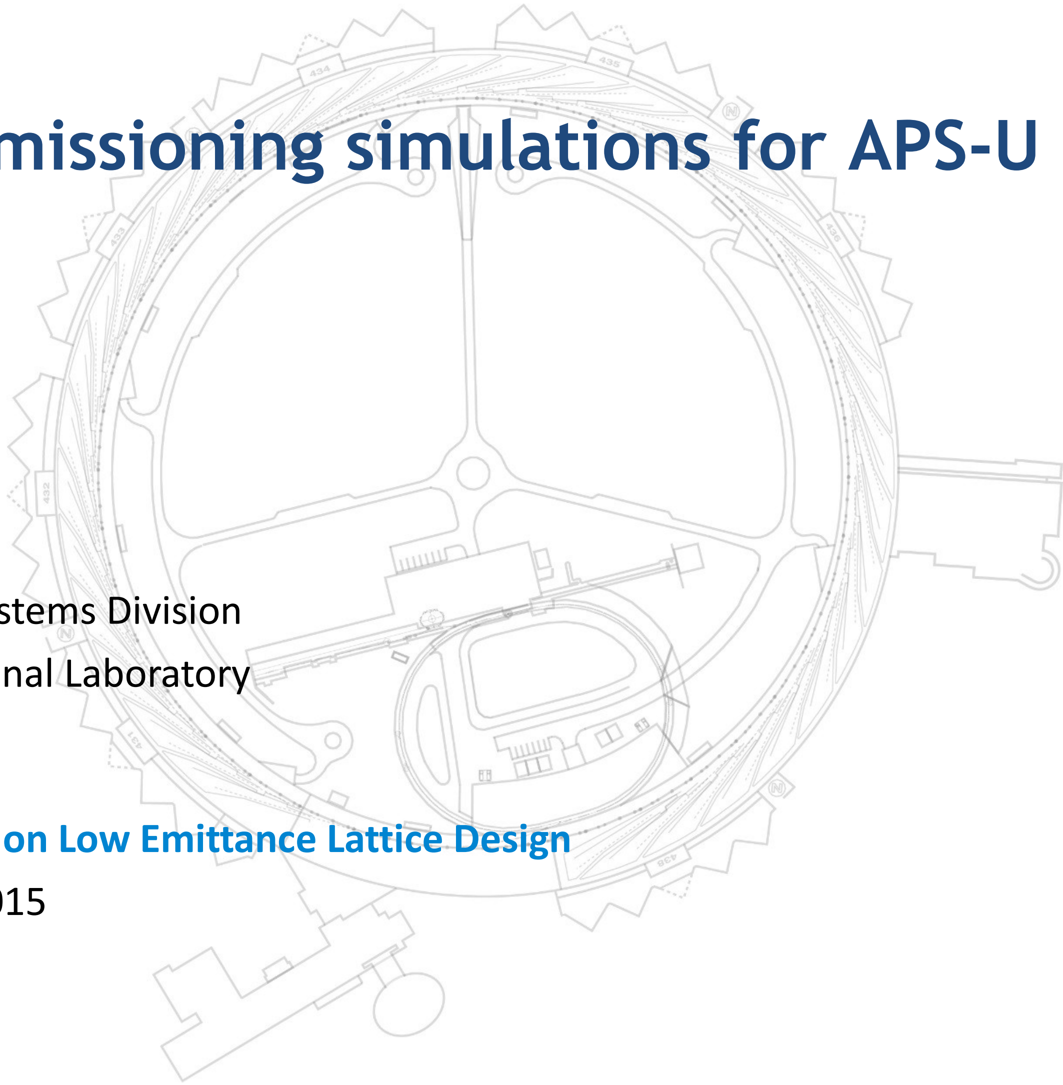
1st Workshop on Low Emittance Lattice Design
April, 23-24 2015

Commissioning simulations for APS-U lattice



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Motivation

- Several important questions are being asked from the beginning of the project:
  - With such strongly-focusing lattice and such small-gap vacuum chamber, will you be able to commission the ring (in a short amount of time)?
  - What are the right errors to use for lattice evaluation
  - Will you be able to keep the orbit stable down to a fraction of the beam size with such small emittances?
- In addition, we needed to make a decision on maximum strength of dipole and coupling correctors
  - Minimize corrector strength

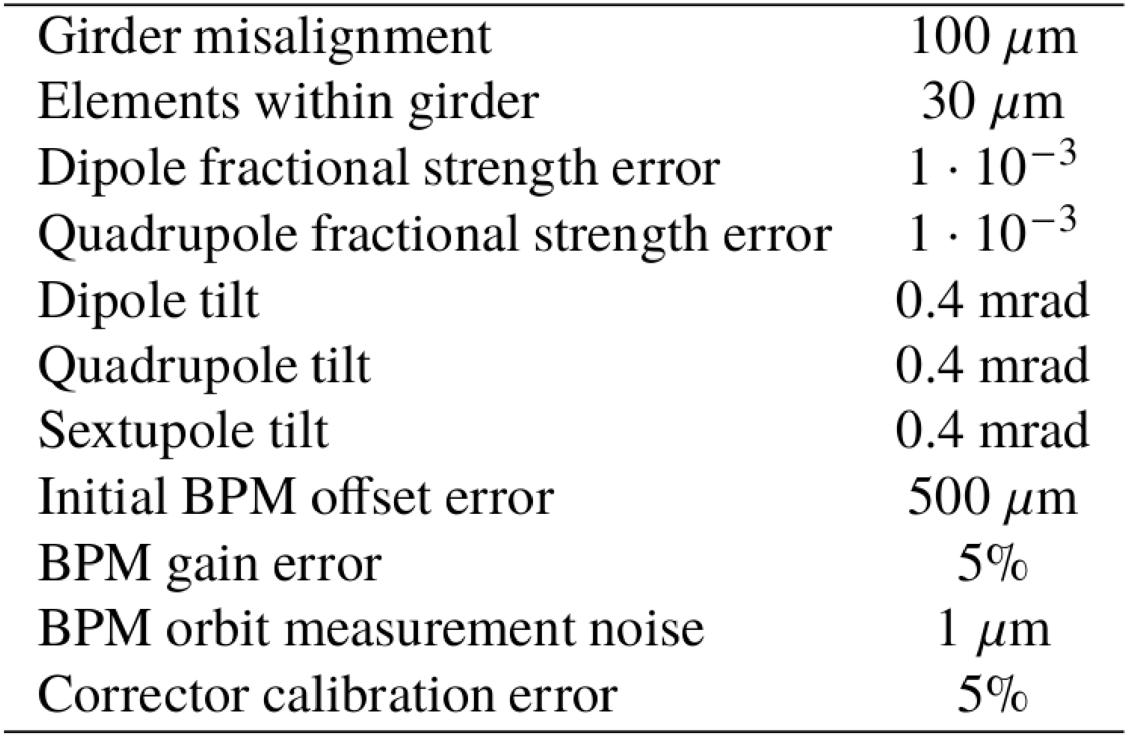
- Commissioning simulation is the best way to answer these questions (though not the orbit stability)
  - Automated commissioning procedure

Automated Commissioning Procedure

- The procedure closely follows steps that will be made during commissioning
  - The intent is to develop a real automated commissioning program
- First, the lattice is detuned to move tunes away from integer and coupling resonances
  - The original fractional tunes are 0.12, moved to 0.18 and 0.24
- The commissioning simulation consists of 4 main steps
  - Error generation
  - Trajectory correction until closed orbit is found
  - Orbit correction down to an acceptable level
  - Lattice and coupling correction
- All simulations are done with elegant

Error values

- The following errors were simulated (all rms, distribution is limited at 2σ):



Girder misalignment	100 μm
Elements within girder	30 μm
Dipole fractional strength error	$1 \cdot 10^{-3}$
Quadrupole fractional strength error	$1 \cdot 10^{-3}$
Dipole tilt	0.4 mrad
Quadrupole tilt	0.4 mrad
Sextupole tilt	0.4 mrad
Initial BPM offset error	500 μm
BPM gain error	5%
BPM orbit measurement noise	1 μm
Corrector calibration error	5%

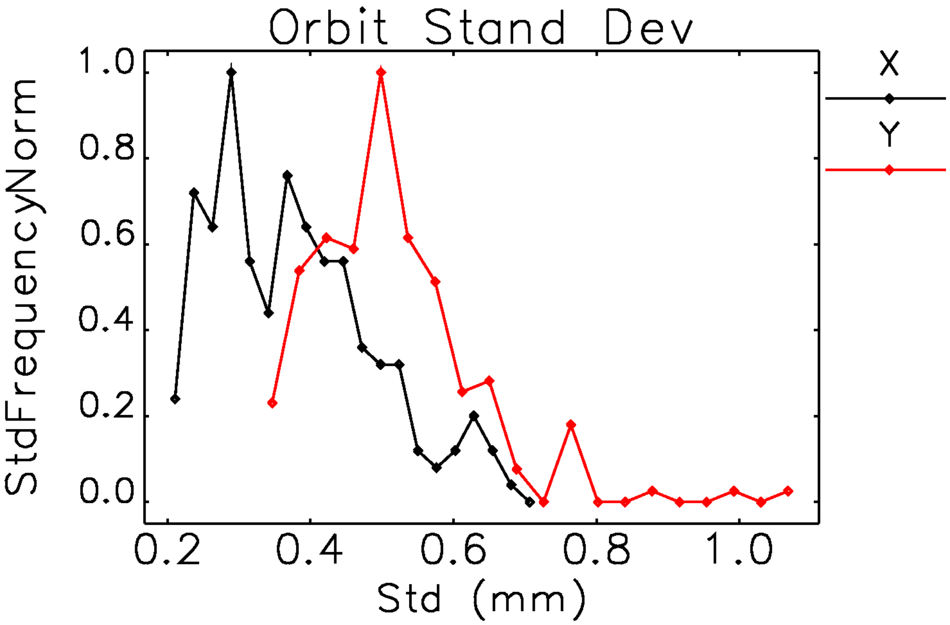
- The correction procedure described below is the result of extensive experimentation with various correction approaches

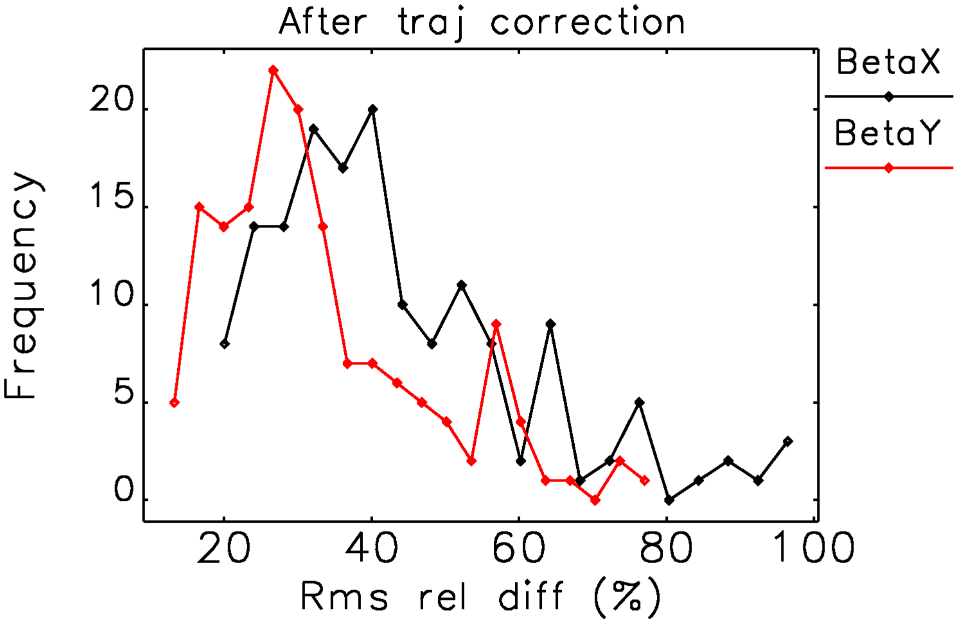
Trajectory correction procedure

- If we want to expect the closed orbit to be inside the vacuum chamber, the alignment should be at least 3 times better than assumed
  - Too expensive
  - Trajectory correction is required
- First step of trajectory correction is to make the beam complete the first full turn
  - Uses elegant’s one-to-best method and only 4 correctors per sector (out of 12) per plane
  - Works well but tends to drive some correctors quickly to their limit
  - To reduce corrector strength, first limit correctors to 1/4 of their maximum strength
  - If first-turn transmission is not achieved, the correction is repeated with increased limits
- Then, global trajectory correction is performed using ideal response matrix
  - Goal – to find the closed orbit
  - Start with small number of singular values, slowly increase SV number, if closed orbit exists, record it
  - When SV number limit is achieved, return to the best orbit
  - If any corrector reaches a limit, reduce it by a certain fraction

Trajectory correction results

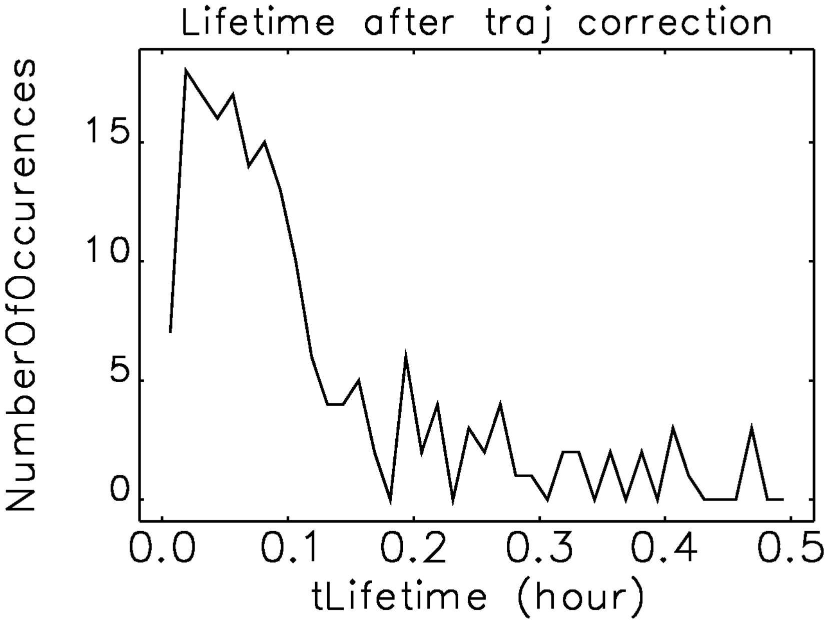
- The procedure finds closed orbit in 100% of cases
- Beta function errors (right plot) are quite large





Lifetime after trajectory correction

- Lifetime is calculated based on Local Momentum Aperture for 1-mA bunch
- We have found that many cases have zero lifetime (even with closed orbit)
- To get non-zero lifetime, run transmission optimization
  - Simplex optimization varies betatron tunes and lowest beta function correction harmonics using predefined quadrupole knobs
  - In real life, we will be maximizing the number of completed turns, here we maximize transmission of 5 particles with 0, ±0.5%, and ±1% momentum errors
- With 90% certainty, lifetime is longer than 1 minute; median lifetime is 5 minutes
- Lifetime is adequate to start orbit correction



Orbit correction

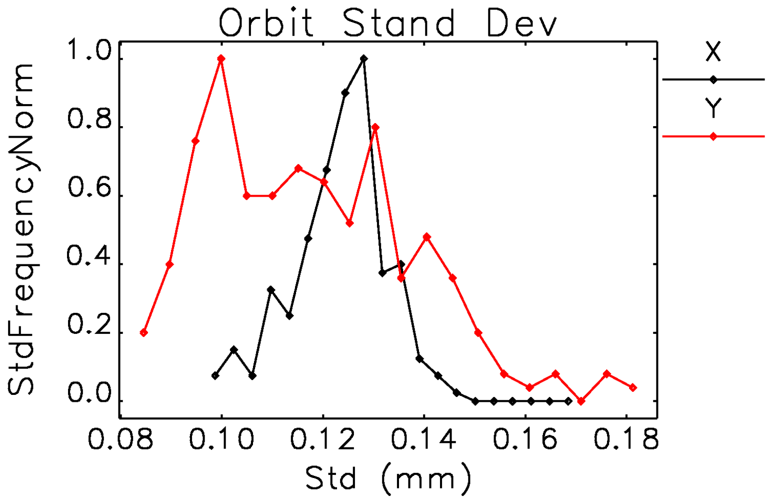
- The orbit correction starts with small number of correctors per sector and small SV number and consists of 2 loops
- The inner loop increases SV number
  - If at any iteration a corrector gets close to its limit, it is reduced by a certain fraction and the iteration is repeated until all correctors are away from limits
  - Tunes are adjusted after every iteration to keep them away from integer resonances
  - The loop is interrupted if the orbit target or SV number limit is reached
- The outer loop increases the number of correctors per sector
  - Correction starts with 2 correctors, increases to 10 correctors in five steps
  - After two iterations, it is assumed the BPM offset measurement is performed
    - Offset measurement is not simulated, offsets are simply reduced by a factor of 10
  - The loop is interrupted if the orbit target or SV number limit is reached

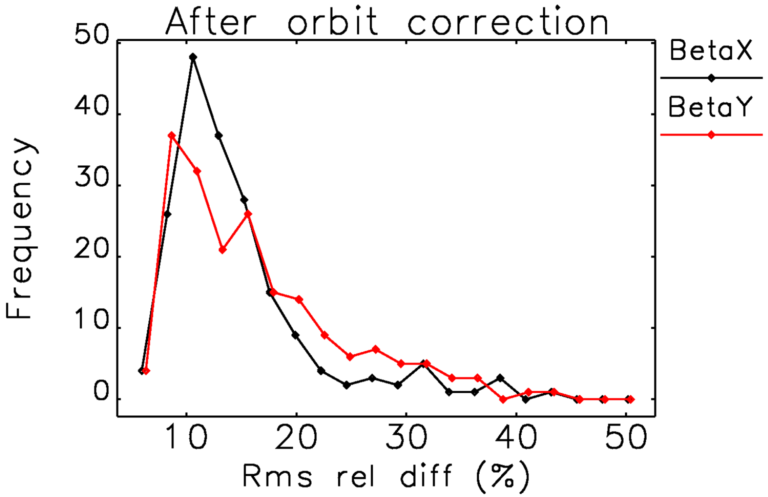
Orbit correction (2)

- If any iteration fails to improve orbit, a coarse fast kick-based optics correction is performed
  - A 0.1 mrad kick in horizontal plane is used
  - Coupling is so strong, the motion couples into vertical plane immediately
  - Fast enough even for 1-minute-long lifetime
- Ignore BPM gain errors since we are trying to correct ~100% modulation of beta functions
  - Only interested in BPM-to-BPM oscillation amplitude modulation
  - A few tens of turns is enough, decoherence should not be a problem
  - Simulated as a single particle tracking for 50 turns
- Oscillation is proportional to $\sqrt{\beta}$, but proportionality coefficient is unknown
  - Since the tunes are close to ideal, it is assumed that average inverse beta functions are equal to those of the ideal lattice
- Only used one BPM and one quadrupole per sector for simplicity
- Works nicely
  - Will try to apply it during transmission optimization

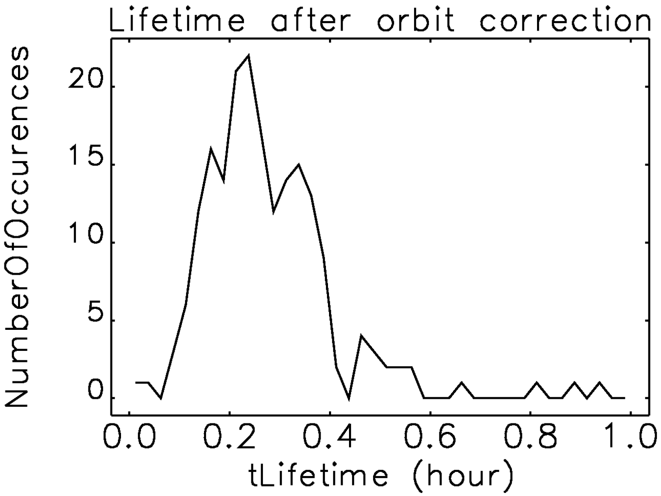
Orbit correction results

- Target of 0.5mm maximum orbit error is achieved in 98% of cases
- Orbit rms is about 100 µm





- With 90% certainty, lifetime is above 8 minutes, median lifetime is 15 minutes

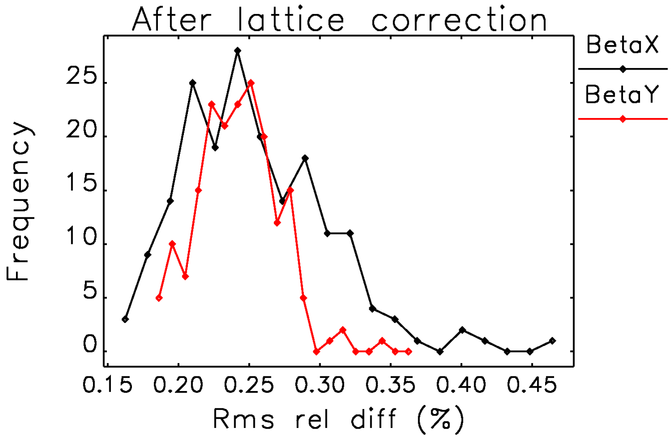


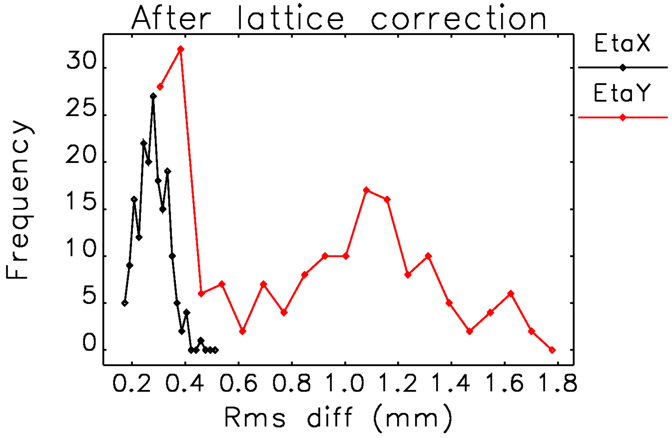
Lattice correction

- Now the lifetime is considered long enough to start lattice correction
- A standard correction procedure that uses response matrix (RM) fit and was developed for APS operations is used
- "Measured" response matrix is generated with BPM noise, BPM gain, and correction calibration errors
  - For measurement speed, only 8 correctors per plane are used (measurement time should be below 5 minutes)
- After response matrix fit is run, the beta functions and horizontal dispersion are corrected using ideal beta function response matrix
- Coupling is corrected by minimizing cross-plane orbit response together with vertical dispersion
- Correction is performed in several iterations with increasing SV number
  - All quads and 4 skew quads per sector are used for correction
  - Orbit is corrected after every iteration
- After minimization, coupling is adjusted to the target of 10% by exciting nearest difference resonance using skew quads

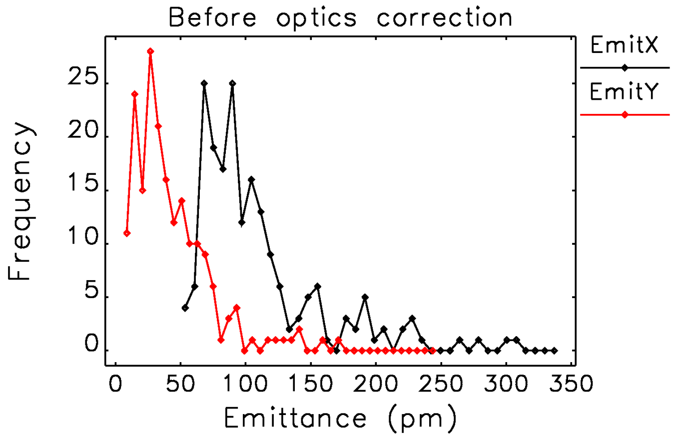
Lattice correction results

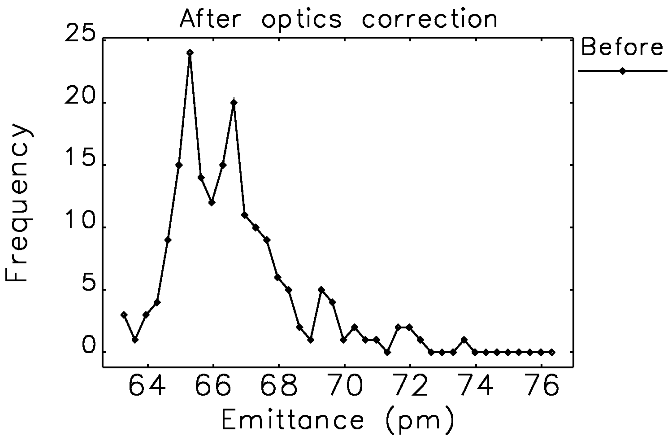
- Beta functions are corrected to below 1% relative rms, dispersion is below 1mm rms





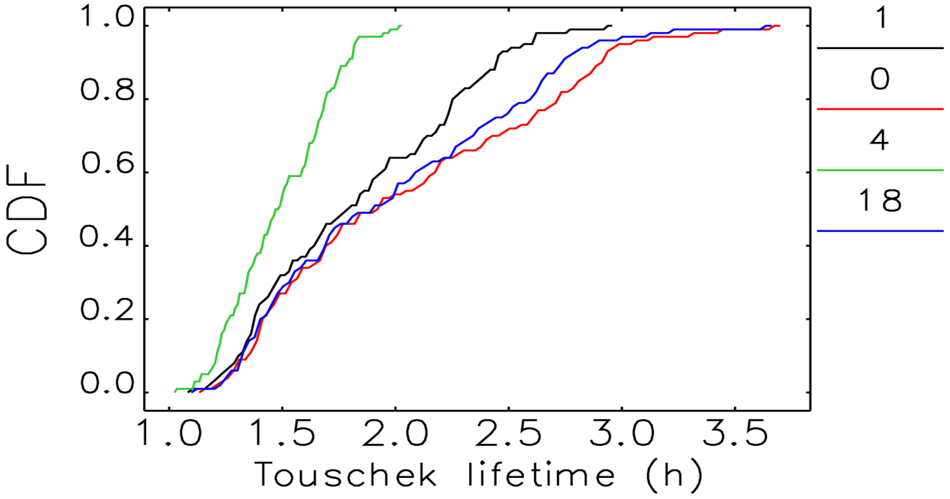
- Emittances before (left) and after (right) lattice correction:





Nonlinear evaluation of the lattice[1]

- Corrected lattice files were used to calculate dynamic and momentum aperture
- Multipole errors were added to all magnets
  - Systematic multipoles were taken from magnetic calculations
  - Random multipoles were generated based on NSLS-II experience
- Many multipole configurations were simulated, random multipoles in quadrupoles were found to have the most effect on lifetime:
  - Case 0: No multipoles
  - Case 1: Nominal multipoles
  - Case 4: Double multipoles in quads
  - Case 18: Half multipoles in quads
- Lifetime was calculated for 48-bunch pattern without high-harmonic cavity



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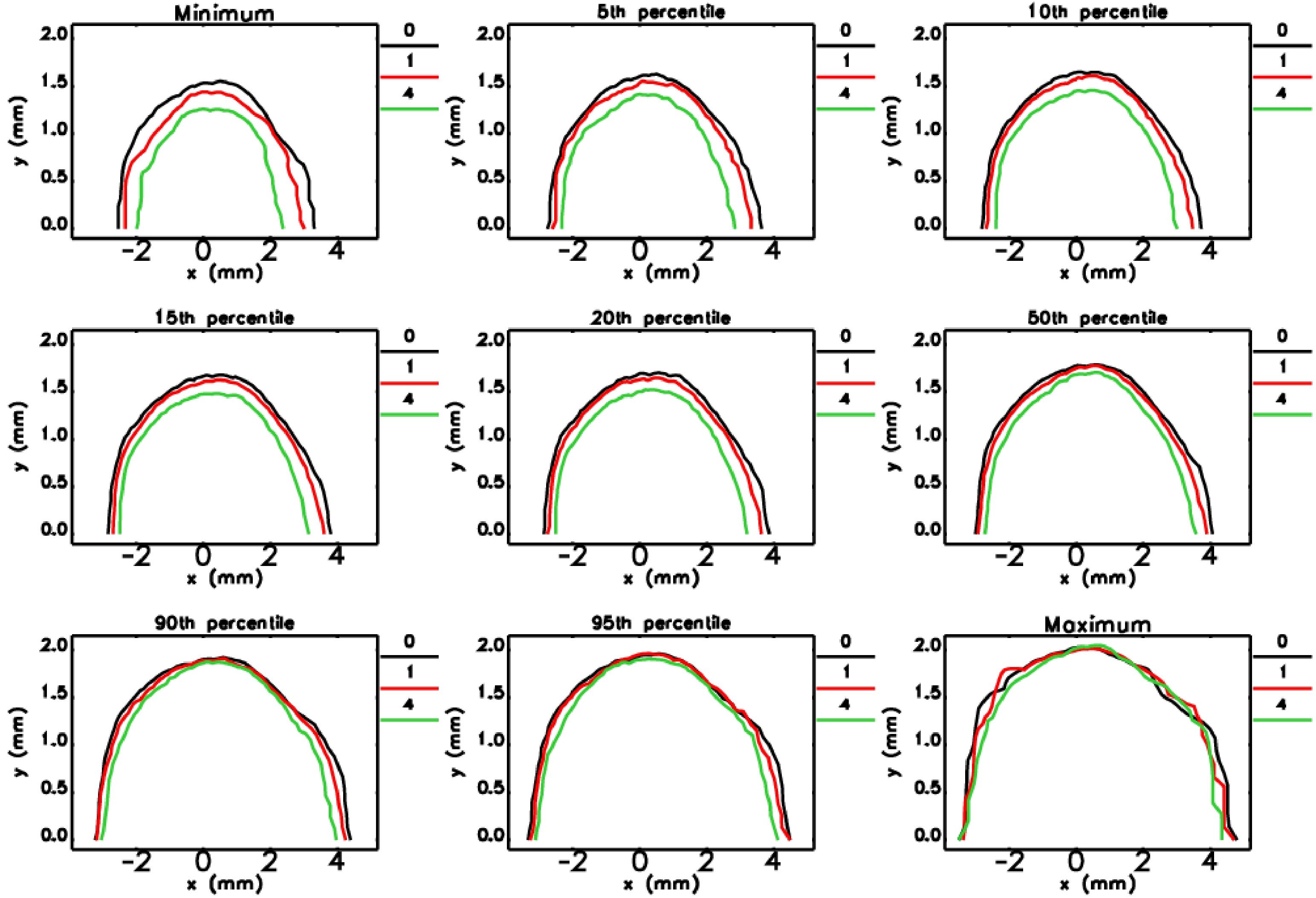
[1] Calculations performed by M. Borland

Nonlinear evaluation of the lattice (2)

- Multipoles have less effect on dynamic aperture

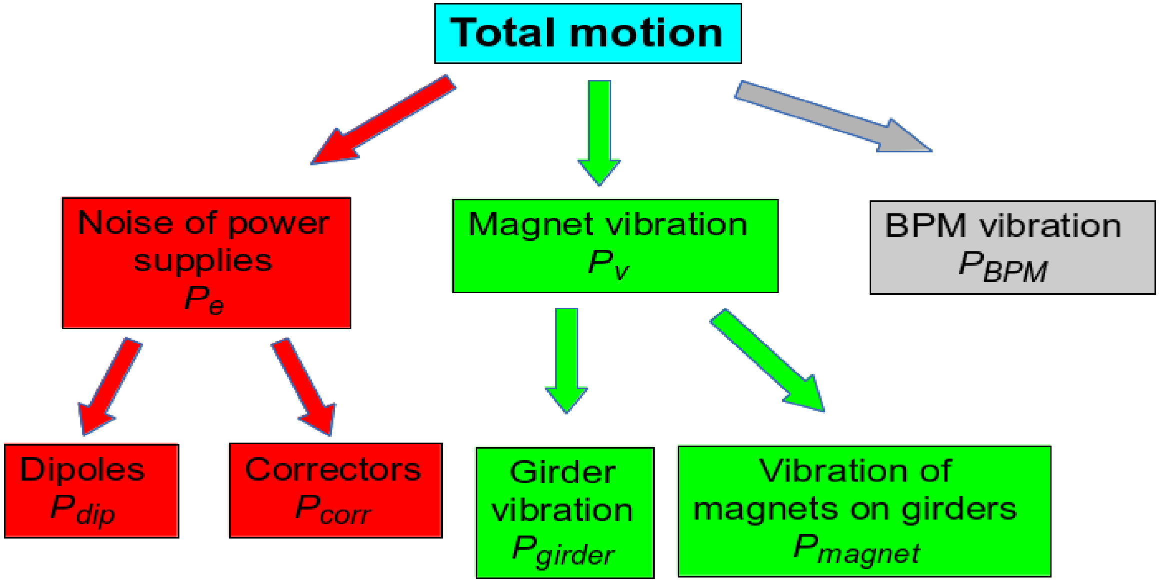


Conclusions

- Automated commissioning simulation procedure was written
- Commissioning was simulated for 200 sets of random errors, succeeded in 98% of cases
- Corrected lattices have lifetime and dynamic aperture that is adequate for on-axis swap-out injection and 7-second topup
- Commissioning simulation gave requirements on maximum dipole and skew quadrupole corrector strength
- High accuracy correction of orbit and lattice is possible, and the design low emittance is achievable
- Commissioning simulation procedure will serve as a guide for real automated commissioning procedure

Orbit stability

- Orbit motion is produced by electrical noise in magnet power supplies and by variable magnetic fields generated by vibrating quadrupoles through frequency-independent amplification factors
- Orbit stability in 0.01Hz-1kHz region is a very stringent requirement (0.4 µm in Y)
  - Cannot be achieved without orbit correction
- Orbit correction reduces orbit motion with frequency-dependent attenuation factor
- Mechanical motion of BPMs affects orbit via orbit feedback
- In some cases, stability without orbit correction is important too



Total motion

Noise of power supplies P_e

Magnet vibration P_v

BPM vibration P_{BPM}

Dipoles P_{dip}

Correctors P_{corr}

Girder vibration P_{girder}

Vibration of magnets on girders P_{magnet}

P is portion of mean square motion

Assumptions about Spectral Characteristics

- Electrical noise PSD is 1/f
- Ground vibrational noise PSD is $1/f^3$, lower frequency is limited to 0.1 Hz (wavelength of 500 m or longer)
  - Girders/supports and individual magnets follow the same spectrum
- BPM motion follows the same vibrational spectrum, orbit correction makes orbit directly follow BPM motion
  - BPM electronic noise of 100 nm is added to this motion
- Orbit correction is an integral controller with bandwidth f_{bw}, its attenuating effect on noise power is f^2/f^2_{bw}
  - Only global orbit correction is considered
- Attenuation of electrical noise due to solid core magnets and vacuum chamber was simulated[1]
- A single orbit measurement (for response matrix) is one-second averaging
  - Only frequencies above 1 Hz contribute to noise

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[1] S. Kim, private communication

Apportioning of motion budget

- Allowable contribution of different motion sources varies depending on whether orbit correction is running or not
- Orbit correction is very efficient at attenuating motion due to vibration, but it emphasizes motion due to BPM vibration
- During beam studies, only frequencies above 1 Hz contribute, where motion due to power supply noise has the most power

		User operation, orbit correction on	Beam studies, orbit correction off
Total motion budget		0.1σ $(1.7\ \mu\text{m}, 0.4\ \mu\text{m})$	$1\ \mu\text{m}$
		0.01 - 1000 Hz	1 - 1000 Hz
Portion of mean square motion due to:			
power supply noise	P_e	0.1	0.89
BPM motion	P_BPM	0.89	0.01
vibrational noise	P_v	0.01	0.1

Summary of tolerances

- Electrical noise tolerances (fractional strength error):

Magnet type	Requirement	Based on
Correctors	$1.9 \cdot 10^{-4}$	Orbit stability w/o orbit correction
Dipoles M3-M4	$2.2 \cdot 10^{-5}$	Orbit stability w/o orbit correction
Dipoles M1-M2	$1.4 \cdot 10^{-5}$	Tune stability
Quadrupoles	$2.3 \cdot 10^{-5}$	Tune stability
Sextupoles	$1.8 \cdot 10^{-3}$	Tune stability

- Vibrational tolerances:

	X (rms) 1-100 Hz	Y (rms) 1-100 Hz	X (rms) 0.1-1000 Hz	Y (rms) 0.1-1000 Hz
u_{girder}	32 nm	40 nm	320 nm	400 nm
u_{quad}	13 nm	9 nm	130 nm	90 nm