(Simulation of) Beam Based Commissioning of Storage Rings

Christoph Steier

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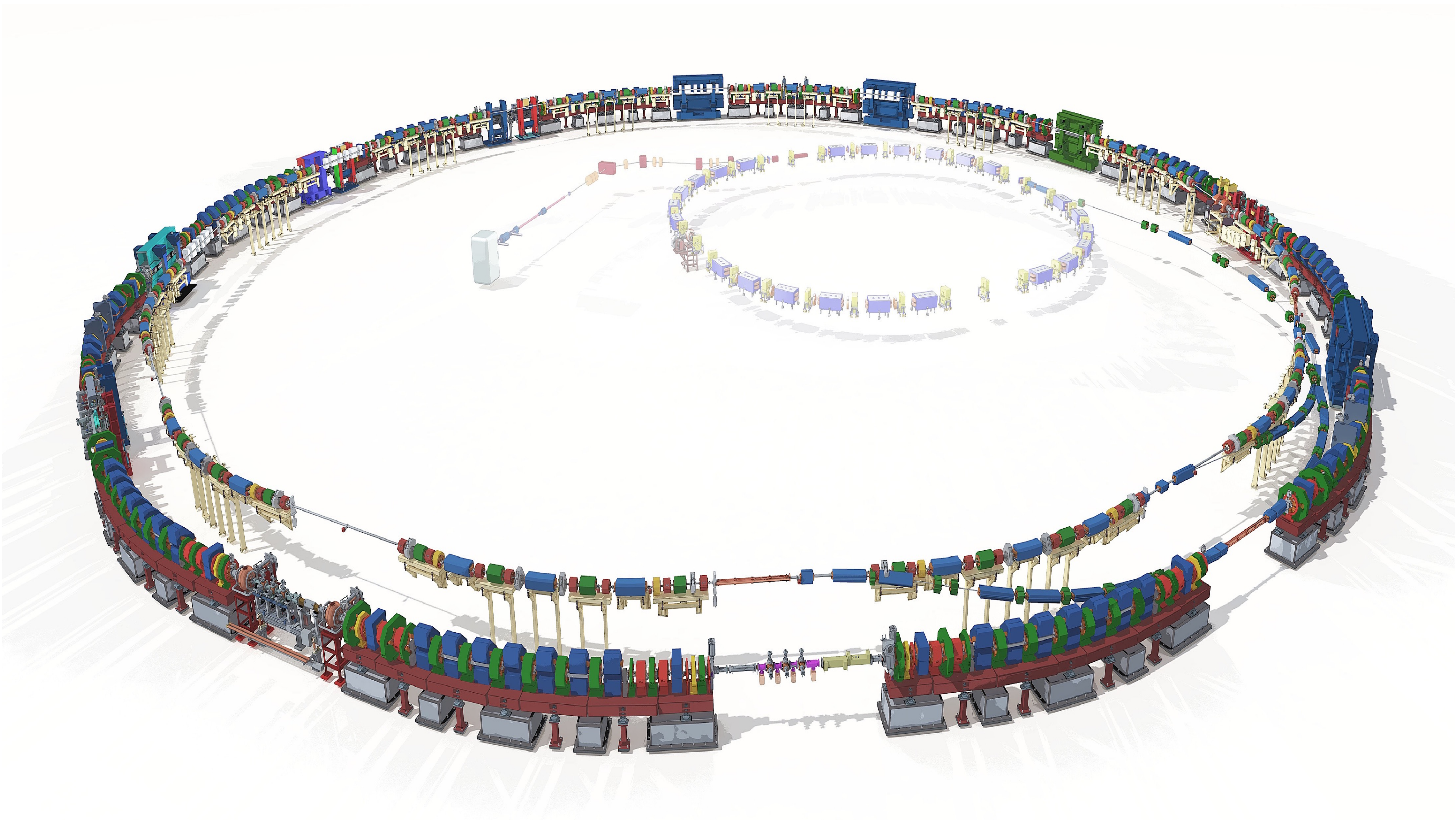
Lecture mostly based on work by
Thorsten Hellert, LBNL
Some results from Vadim Sajaev, ANL

Outline

- Simulated commissioning of light sources
  - Motivation
    - Challenges of multi bend achromat lattices
    - Error / alignment tolerances
  - Development of a toolbox for simulated commissioning
  - Application to the Advanced Light Source Upgrade
  - Other Examples (APS-U)



Recent advances enable ultrabright rings

Storage-ring light sources have not reached their practical limits of brightness and coherence.

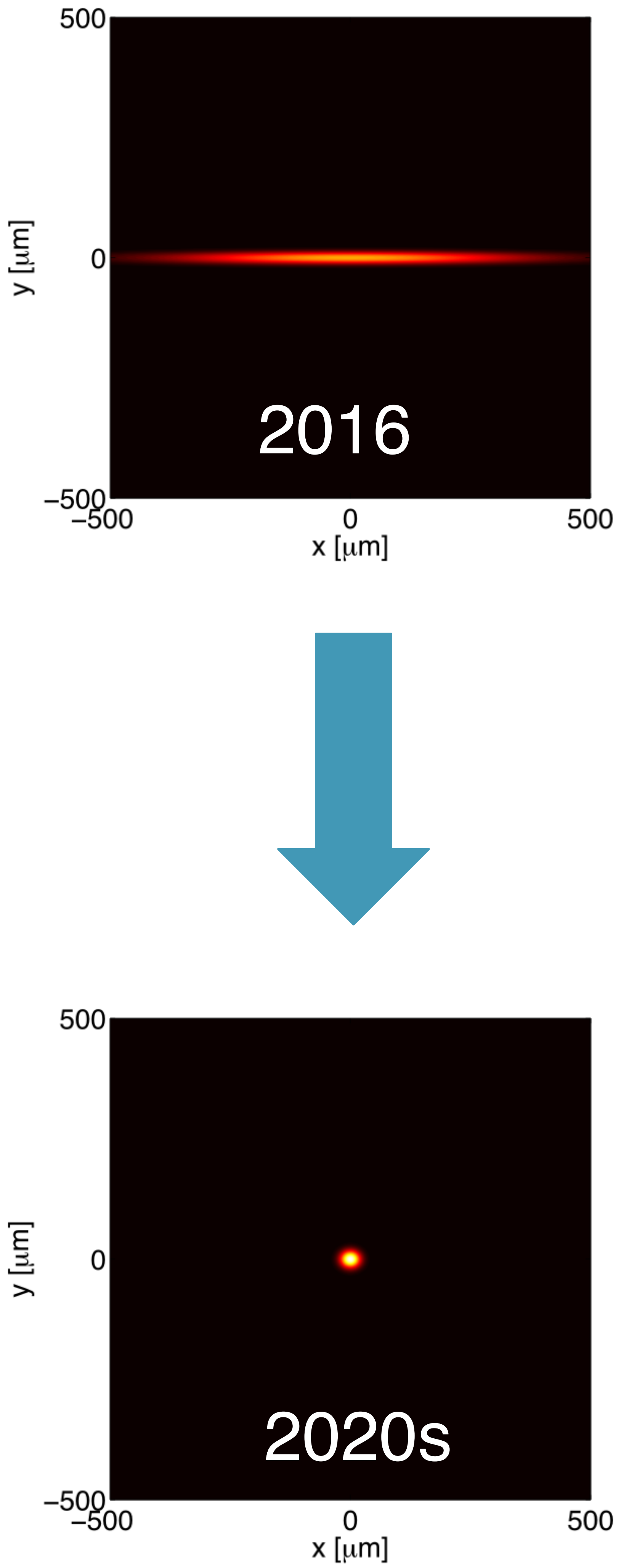
- Dramatic improvements are possible due to transformational advances in accelerator technology.

What has changed:

- Tightly packed, multibend achromat (MBA) lattices via new magnet and vacuum technology.
- Better understanding of storage-ring scaling, advances in simulation, optimization, and alignment.

International community is now upgrading existing facilities and building new facilities using MBA designs

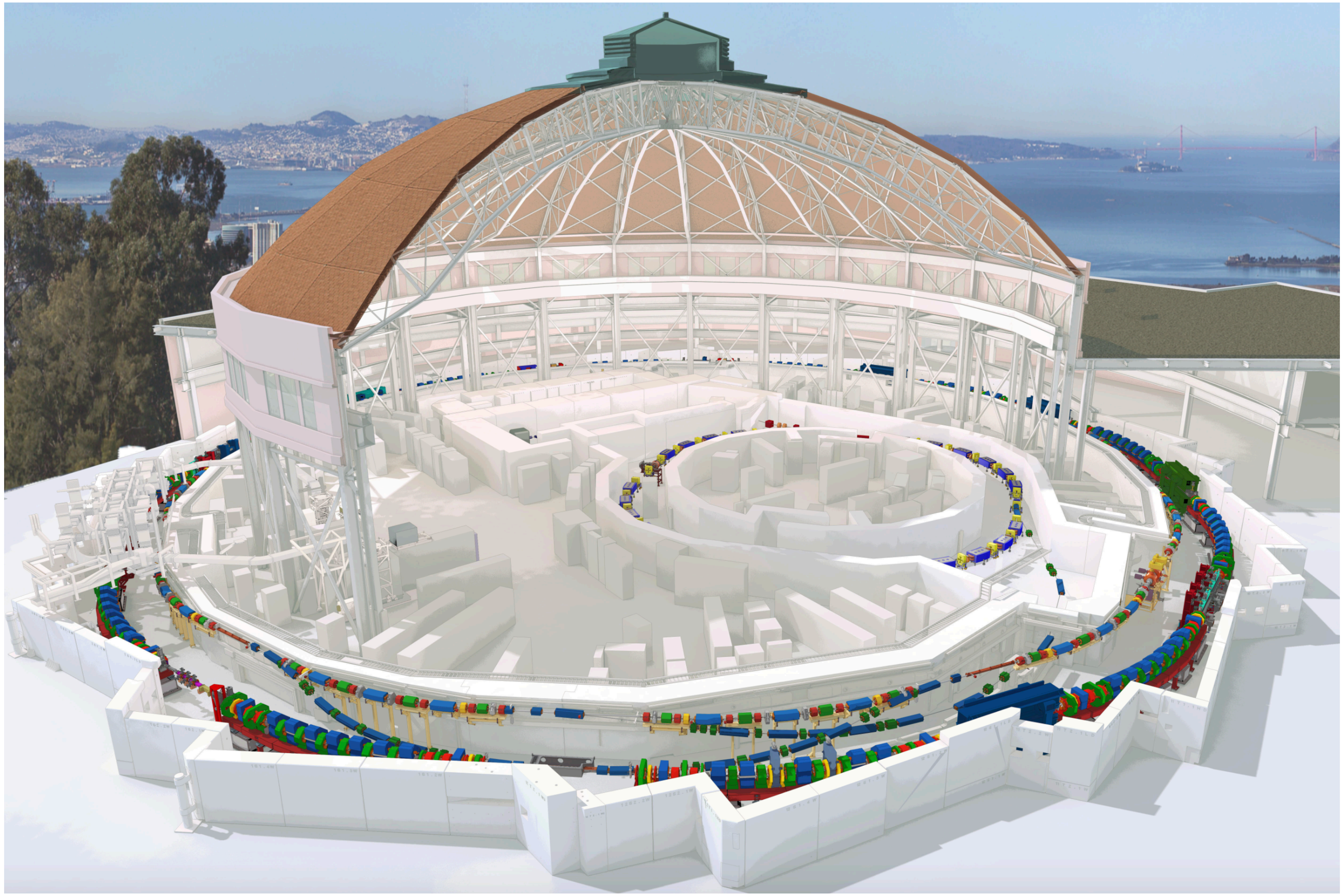
- Producing much higher coherent flux.

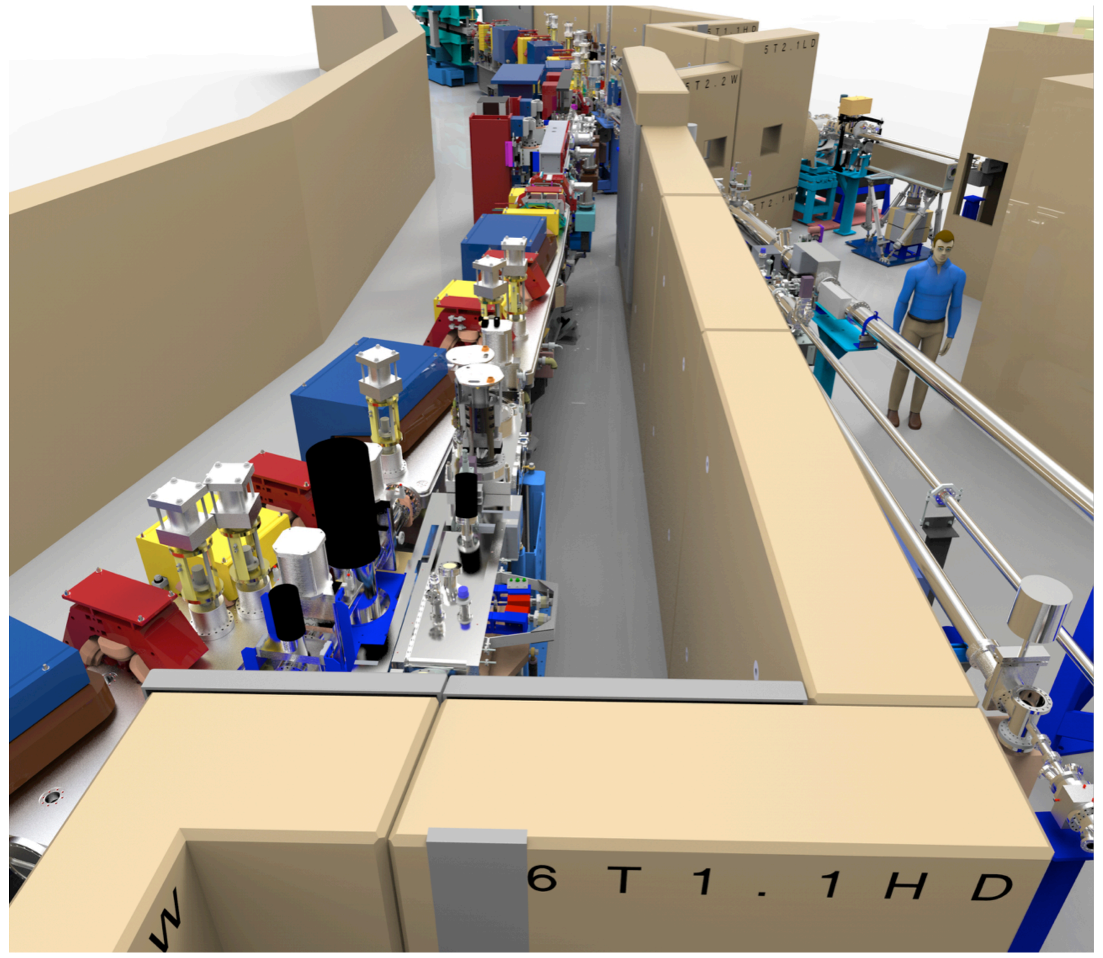


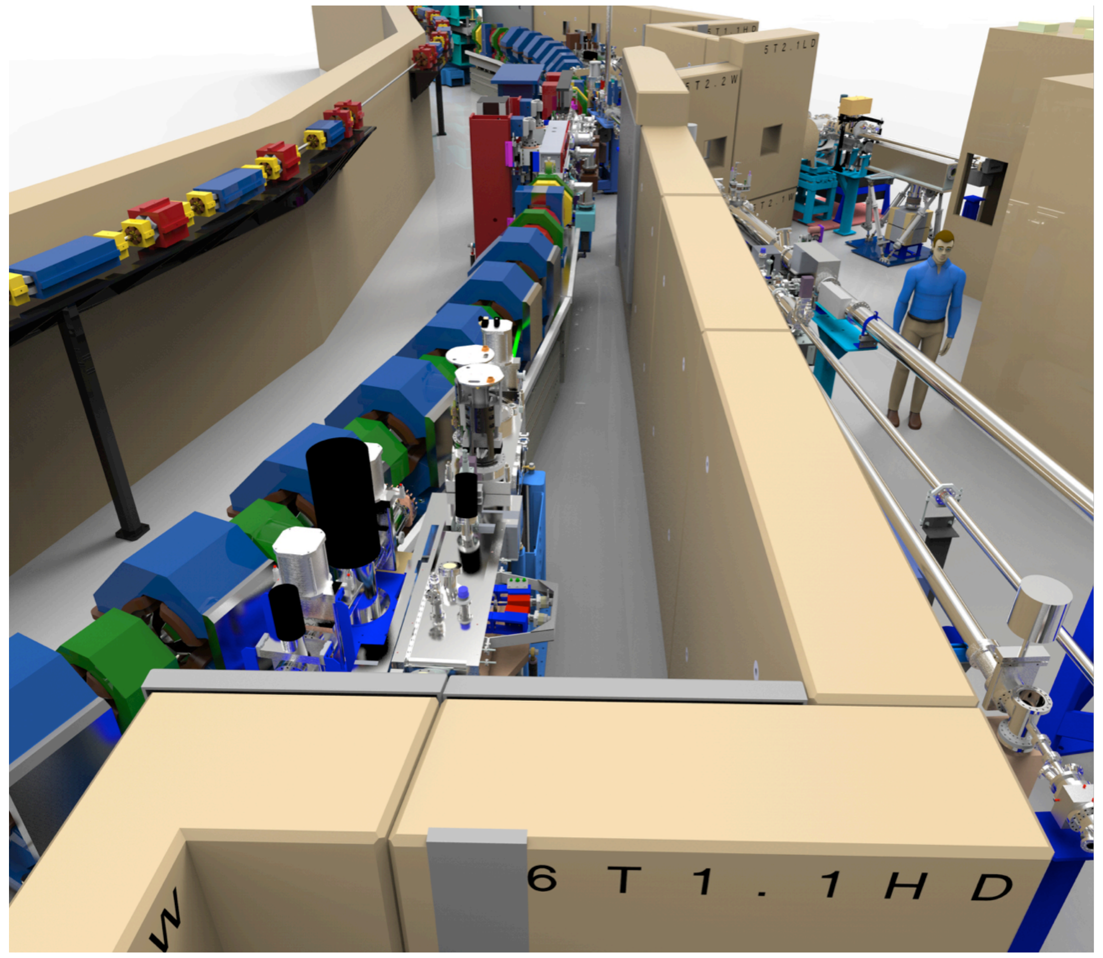
The successful commissioning of MAX IV is a proof of principle and provides a solid technical basis for ALS-U

MBA project at LBNL: ALS-U - 9 bend achromat

Advanced Light Source Upgrade (ALS-U)







Diffraction Limit, Brightness, Coherent Fraction

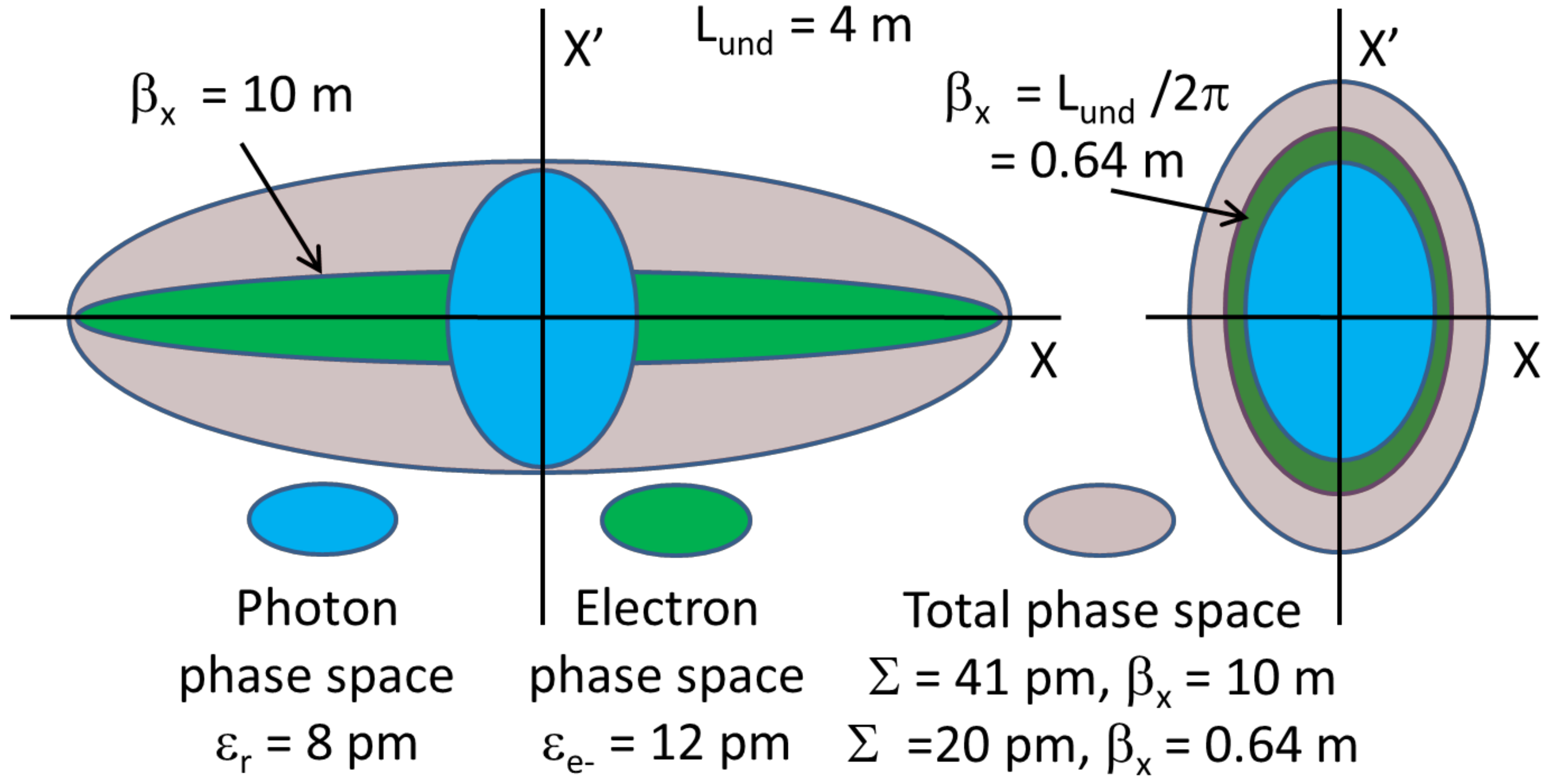
$$\varepsilon_r = \text{diffraction limited emittance} = \sigma_\gamma \sigma'_\gamma = \frac{\lambda}{4\pi} = \begin{cases} \text{80 pm rad @ 1 keV} \\ \text{8 pm rad @ 10 keV} \end{cases}$$

Brightness is inversely proportional to convolution of electron beam sizes and divergences and diffraction emittance

$$\text{Brightness} = \frac{\text{Spectral Flux}}{(2\pi)^2 \sigma_{Tx}\sigma_{Tx'}\sigma_{Ty}\sigma_{Ty'}}$$

$$\sigma_{Tx} = \sqrt{\sigma_x^2 + \sigma_\gamma^2}$$

Electron Photon



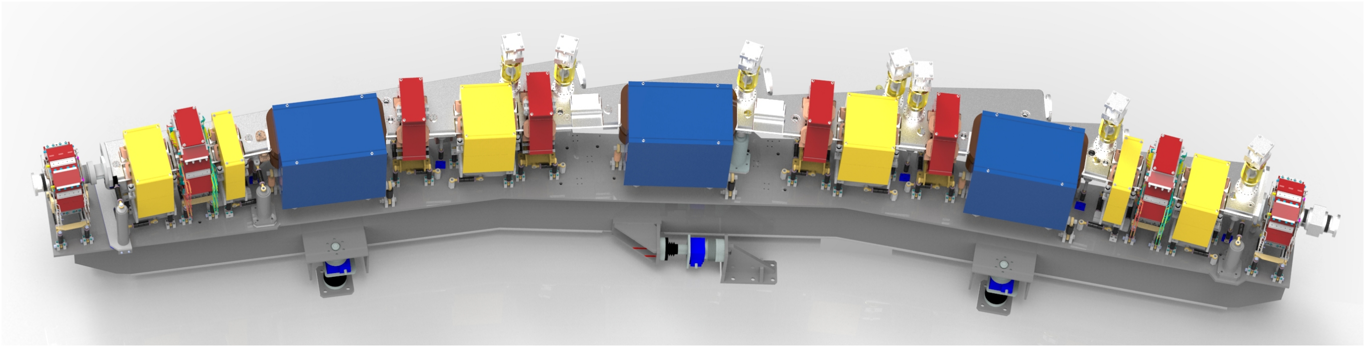
Coherent fraction = ratio of diffraction-limited emittance to total emittance

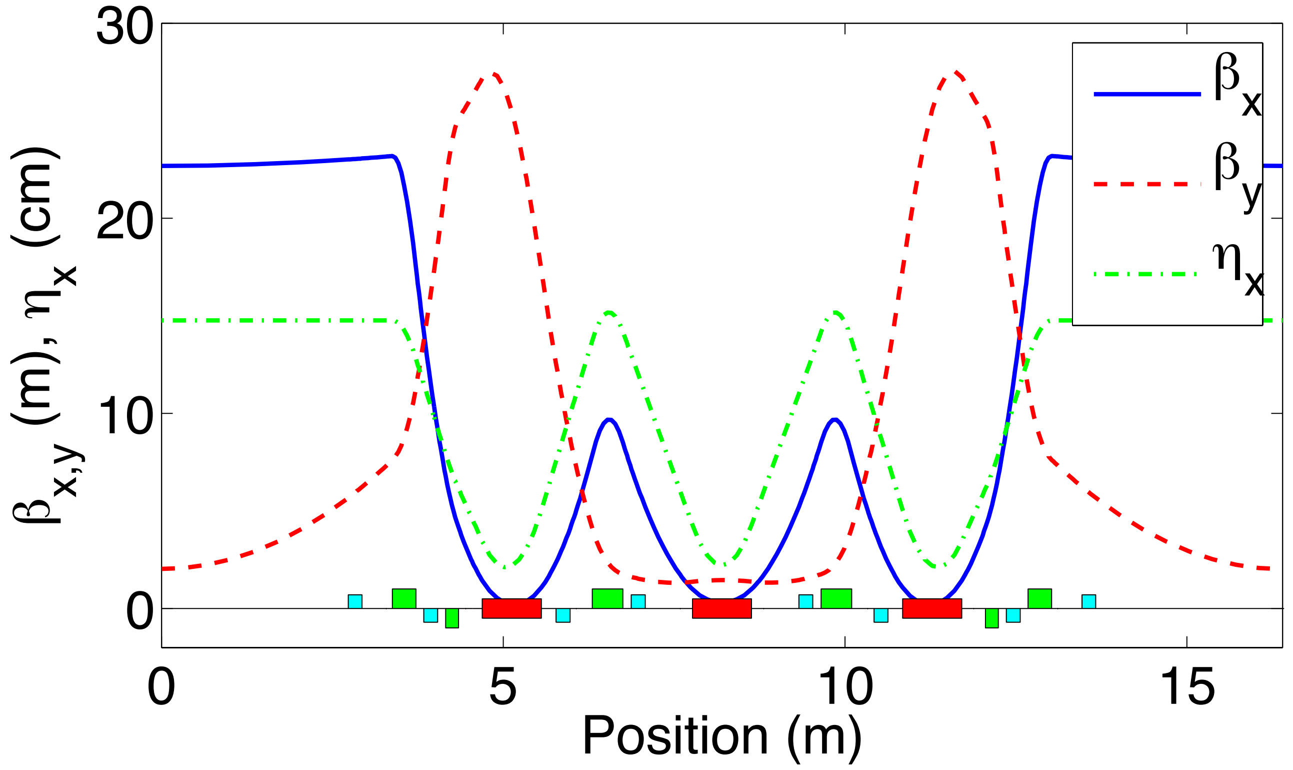
$$f_{coh} = \frac{F_{\mathrm{coh,T}}(\lambda)}{F(\lambda)} = \frac{\sigma_\gamma \sigma'_\gamma}{\underbrace{\sigma_{\mathrm{Tx}}\sigma_{\mathrm{Tx'}}}} \frac{\sigma_\gamma \sigma'_\gamma}{\sigma_{\mathrm{Ty}}\sigma_{\mathrm{Ty'}}}$$

DLSRs produce photon beams with dramatically larger coherent fraction due to reduced horizontal emittance

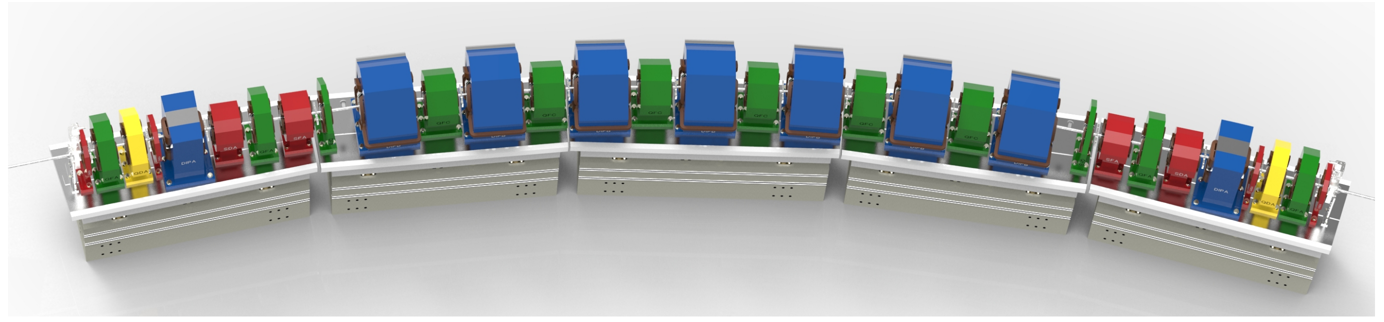
ALS-U example: Nine-bend achromat lattice reaches the soft x-ray diffraction limit up to 1.5 keV

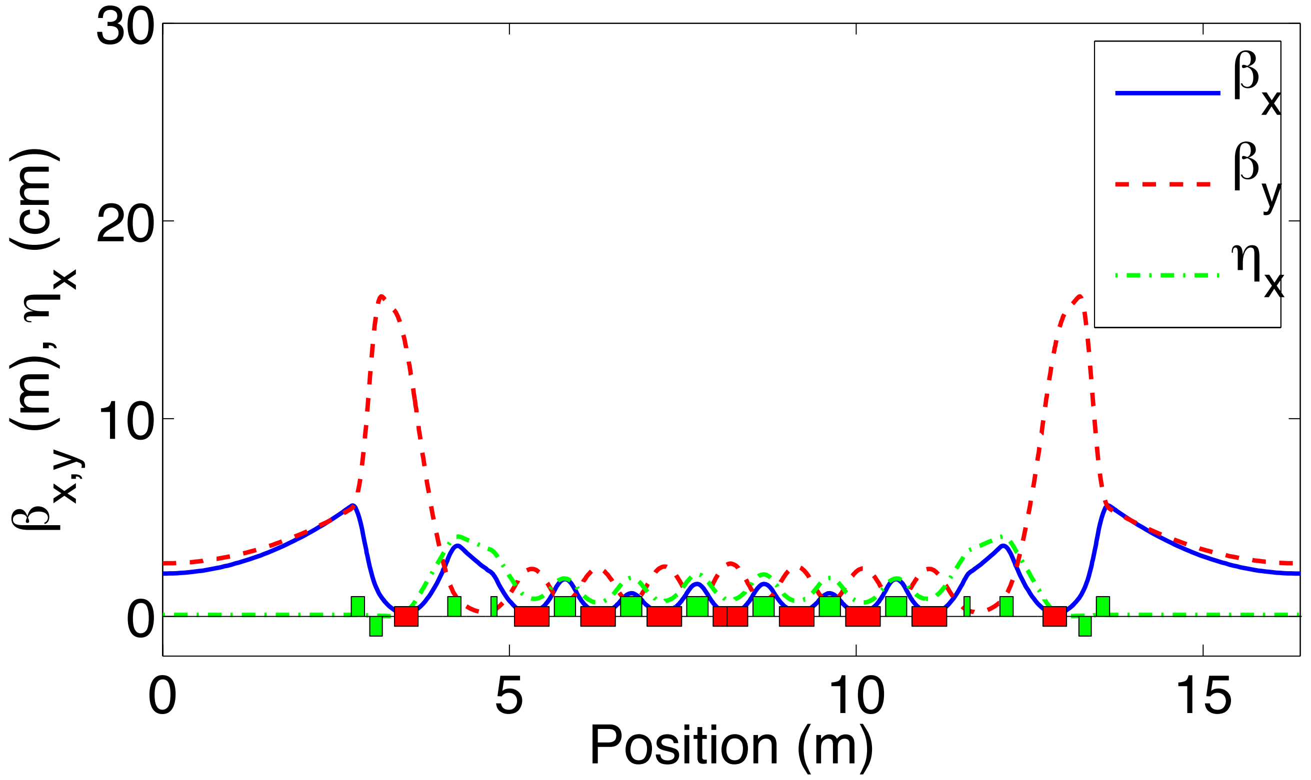
ALS today : triple-bend achromat





ALS-U: nine-bend achromat with reverse bends





$\varepsilon_x \approx 2000$ pm rad at $1.9\,GeV$

$$\varepsilon_x \approx \sigma_x \sigma_\theta \propto \frac{E^2}{N_D^3}$$

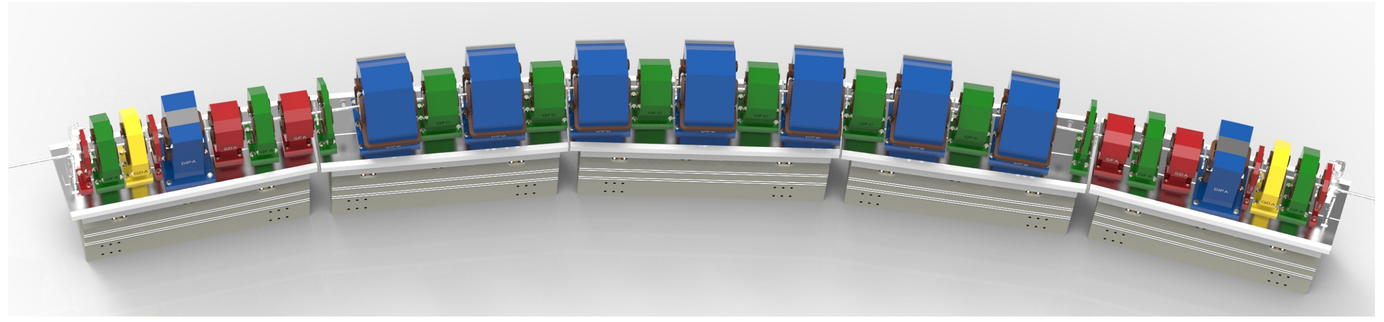
$\varepsilon_x < 70$ pm rad at $2.0\,GeV$

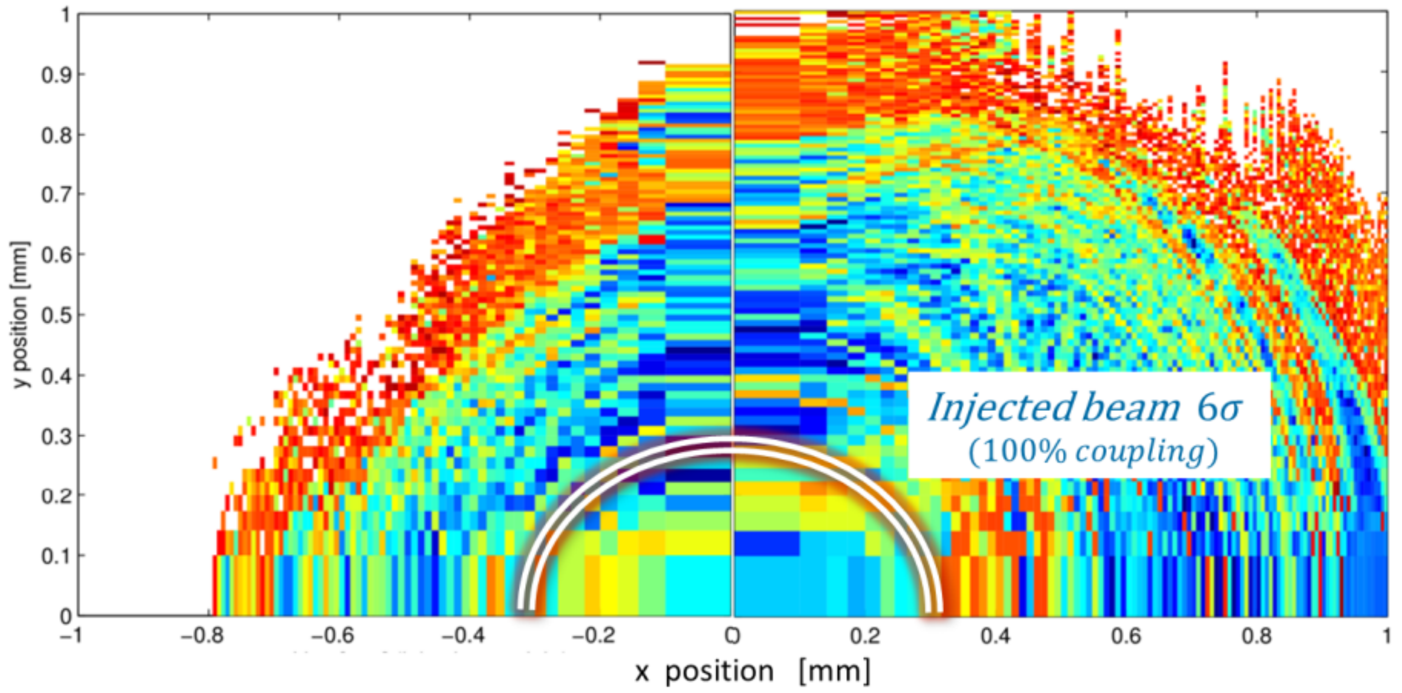
Challenges: Small emittance requires very strong quadrupoles and very strong sextupoles - very tight alignment tolerances and nonlinear beam response already at small (<= 1 mm amplitude)

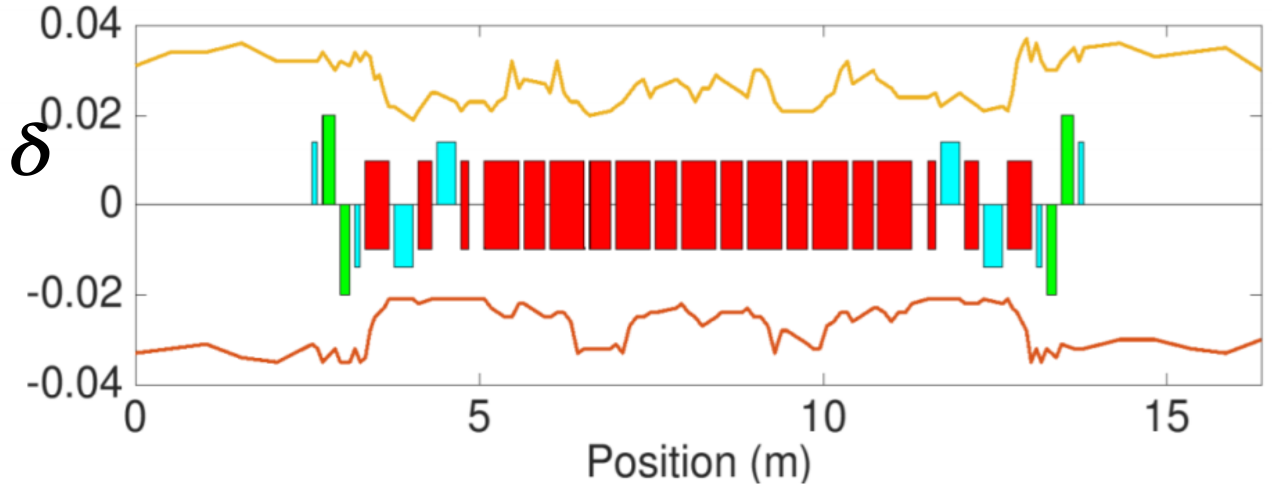
Large increase in coherent fraction due to lower emittance and smaller β-functions

Motivation for the development of new method

- Challenging lattice of future light sources
  - Strong focussing & small aperture - High sensitivity to alignment errors
  - Getting to stored beam with realistic alignment tolerances is not straight forward
  - **Standard approach of setting error tolerances would lead to results that would not be feasible / cost effective**
  - Enabling technology: high resolution turn-by-turn BPMs
- Realistic simulation of commissioning process required
  - Realistic error model
  - Efficient trajectory/orbit/linear optics correction strategies
  - Set (cost effective) requirements
  - Evaluate robustness of lattice and set tolerances for errors
  - Speed up machine commissioning
- Choice of implementation
  - ALS-U will be operated with *Matlab Middle Layer* (MML)
  - Easy communication between MML and *Accelerator Toolbox* (AT)
  - AT implementation of ALS-U commissioning allows for experiments at ALS



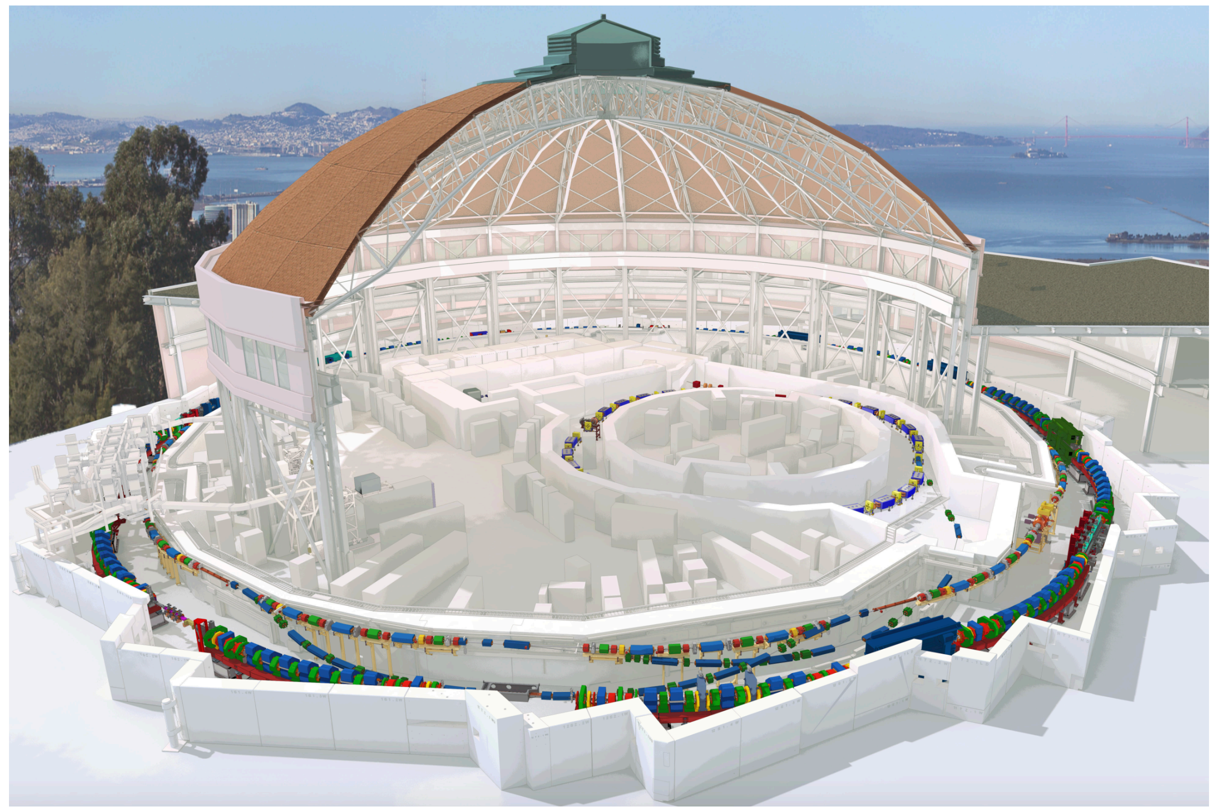




Limited accessibility of machine properties

Power supplies

Operating machine



Diagnostic devices

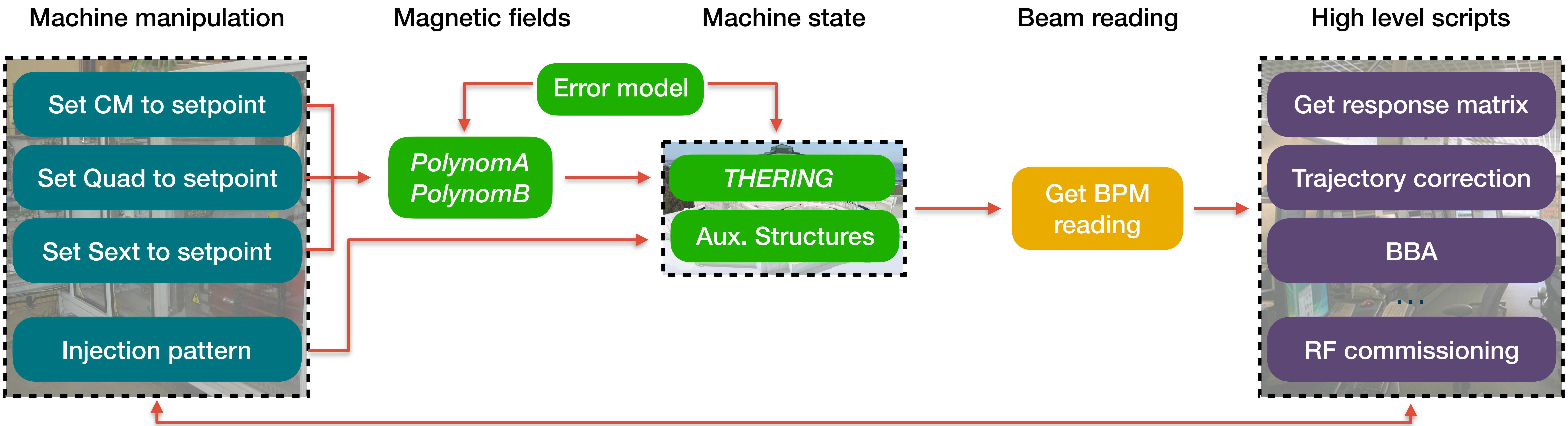
High level controls

Magnetic fields
Particle trajectories
…

No direct access!

Setpoints and read back values

Realistic workflow of toolbox important



Machine manipulation

- Set CM to setpoint
- Set Quad to setpoint
- Set Sext to setpoint
- Injection pattern

Magnetic fields

- Error model
- *PolynomA*
  PolynomB

Machine state

- *THERING*
- Aux. Structures

Beam reading

- Get BPM reading

High level scripts

- Get response matrix
- Trajectory correction
- BBA
- …
- RF commissioning

Set Quad to setpoint

- Compensates bending angle difference by setting horizontal CM
- Checks for CM range (clipping)

Calculate fields

- Calibration errors of all components
- Includes dipole kick from bending angle (set-point & roll)

Auxiliary structures

- Diagnostic errors
- Injected beam trajectory
- Injection pattern
- Current CM limits

Get BPM reading

- Performs tracking including aperture
- Gets BPM signal from ensemble of particle trajectories

High level

- High level functions use only BPM and setpoints as input
- High level functions write only setpoints

Large number of error sources (values rms)

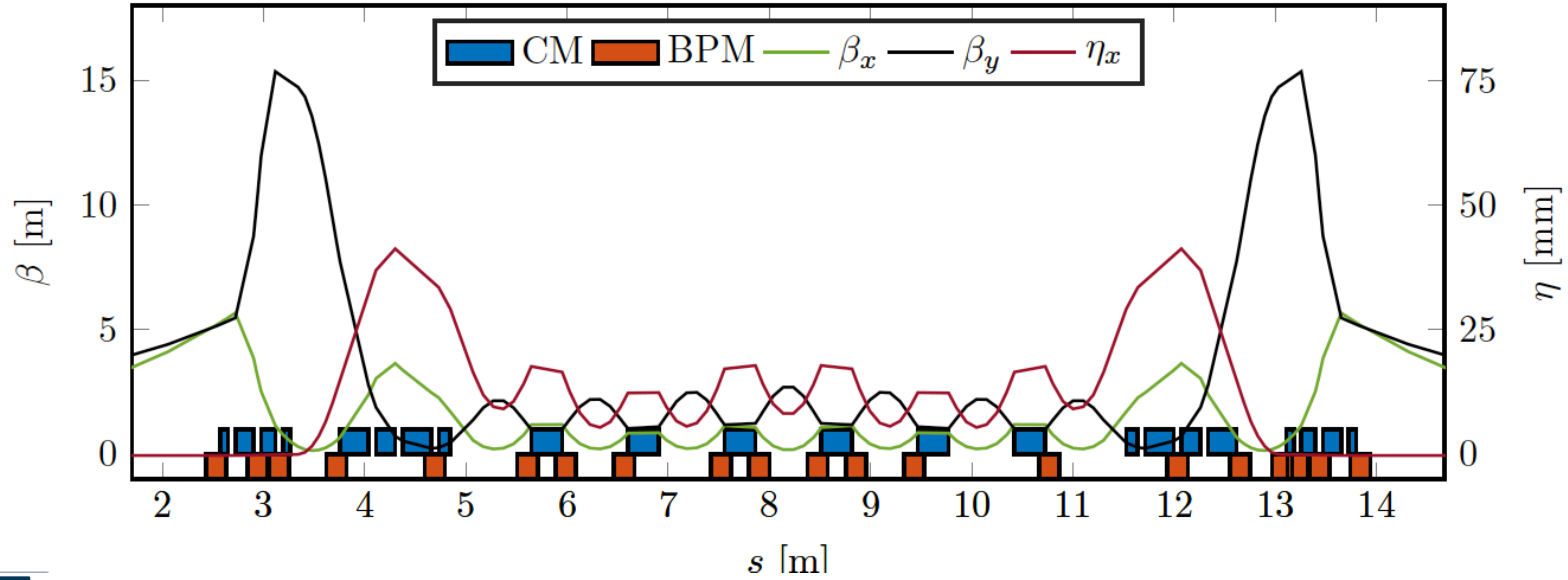
- Magnet errors
  - Magnet offset = 30 μm
  - Magnet roll = 0.2 mrad
  - Magnet strength = 0.1%
  - Girder offset = 100 μm
  - Plinth offset = 100 μm
  - Arc offset = 100 μm
  - Sys. dipole error = 0.5 %
- Diagnostic errors
  - BPM offset = 500 μm
  - BPM cal. error = 5%
  - BPM noise = 3 μm
  - BPM roll = 0.4 mrad
  - CM cal. error = 5%
  - CM roll = 0.4 mrad

- Static injection errors
  - Δx = 500 μm
  - $\Delta x'$ = 200 μrad
  - Δy = 500 μm
  - $\Delta y'$ = 200 μrad
  - ∂E = 0.1 %
  - Δs = 0
- Injected beam size
  - Δx = 64 μm
  - $\Delta x'$ = 32 μrad
  - Δy = 8 μm
  - $\Delta y'$ = 3 μrad
  - ∂E = 0.1 %
  - Δt = 15 ps

- Injection jitter
  - Δx = 10 μm
  - $\Delta x'$ = 6 μrad
  - Δy = 1 μm
  - $\Delta y'$ = 0.5 μrad
  - ∂E = 0.01 %
  - $\Delta \phi$ = 0.1°
- RF errors
  - ΔV = 0.1 %
  - $\Delta \phi$ = $\pi/2$
- Higher order multipoles
  - Static, up to 10th order

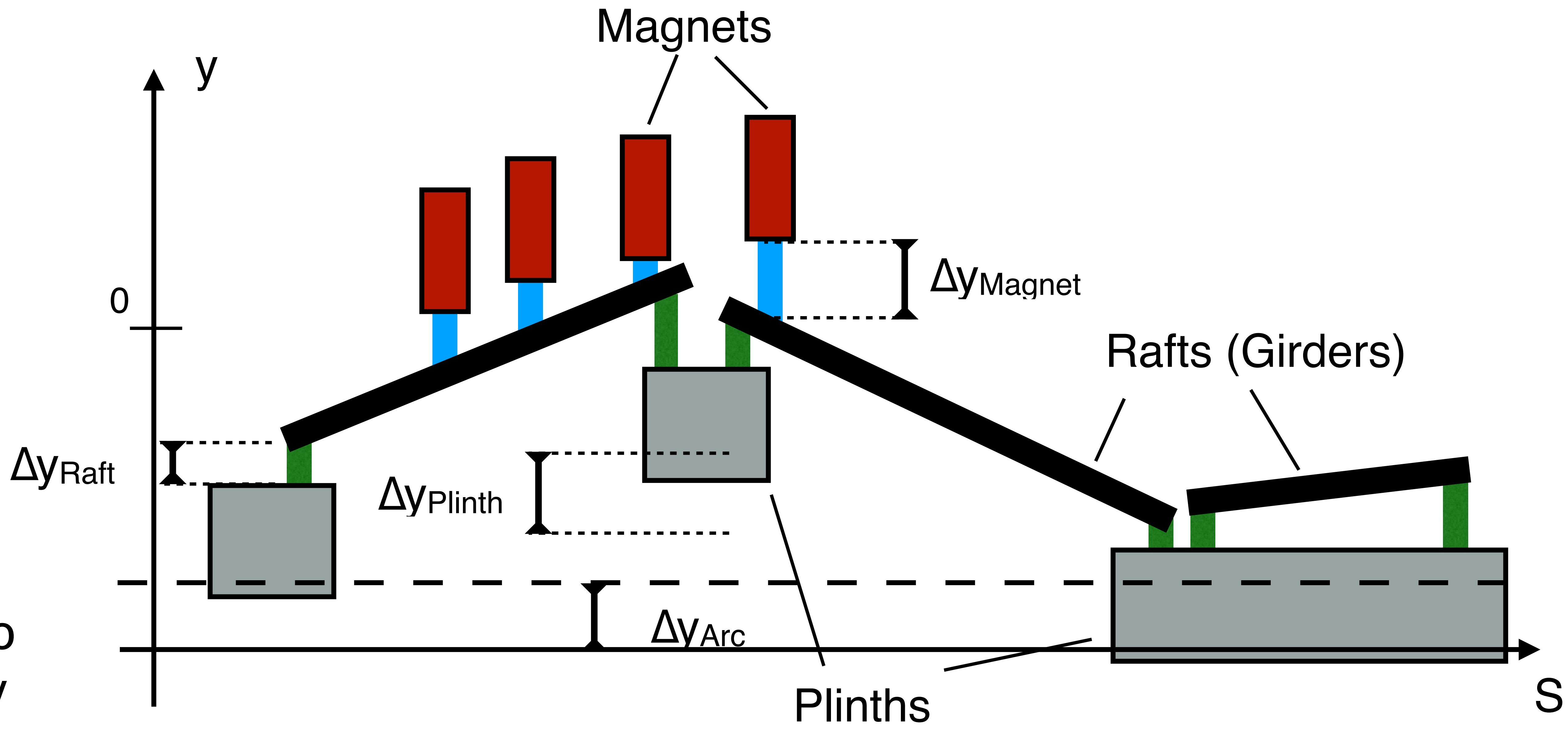
Distribution of BPMs and Correctors

- 12 arcs with each 20 BPMs and 20 corrector magnets (CM)
- All CMs embedded in quadrupole and sextupole magnets
  - All CMs horizontal & vertical
  - CM limits: 0.2 mrad

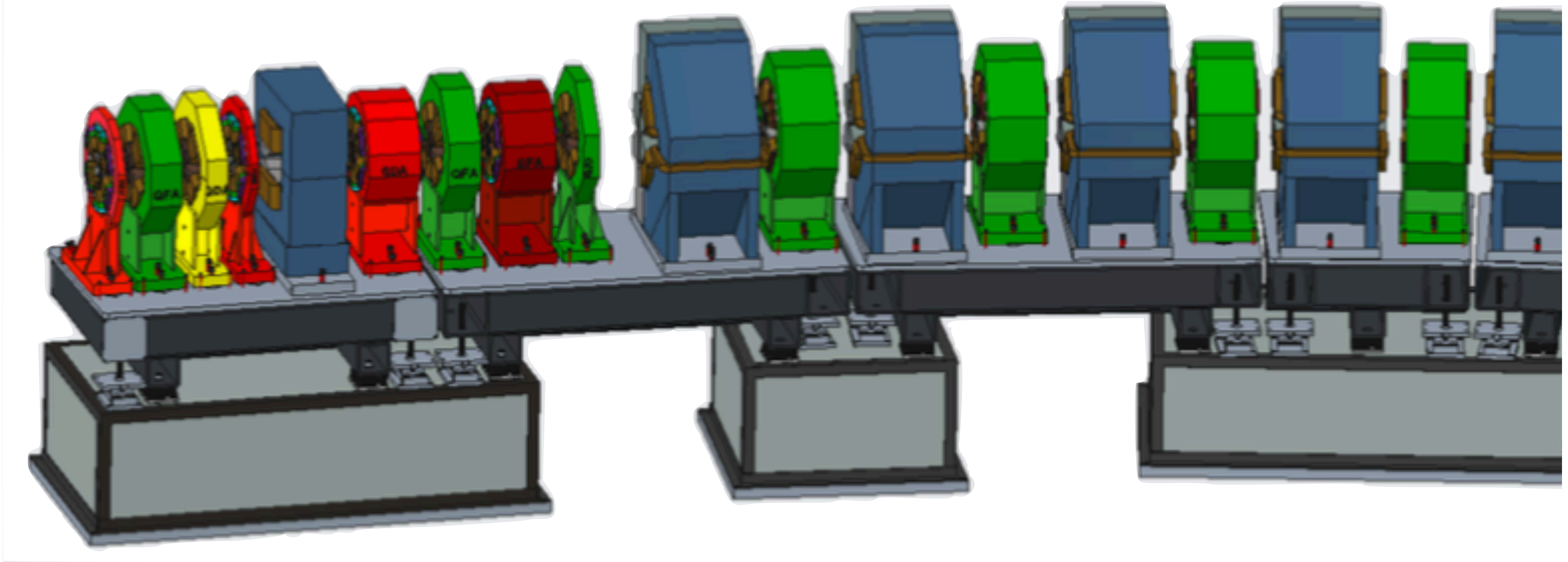


High fidelity misalignment model

- Lateral misalignment model typically used in simulations:
  - Transverse magnet offsets
  - Transverse raft offsets
- ALS-U support system with plinths and rafts
  - Adjacent rafts do not move freely due to ground settlement but in correlated way
- Realistic error model follows magnet support system
  - Magnets
  - Rafts & Plinths
  - Entire arcs

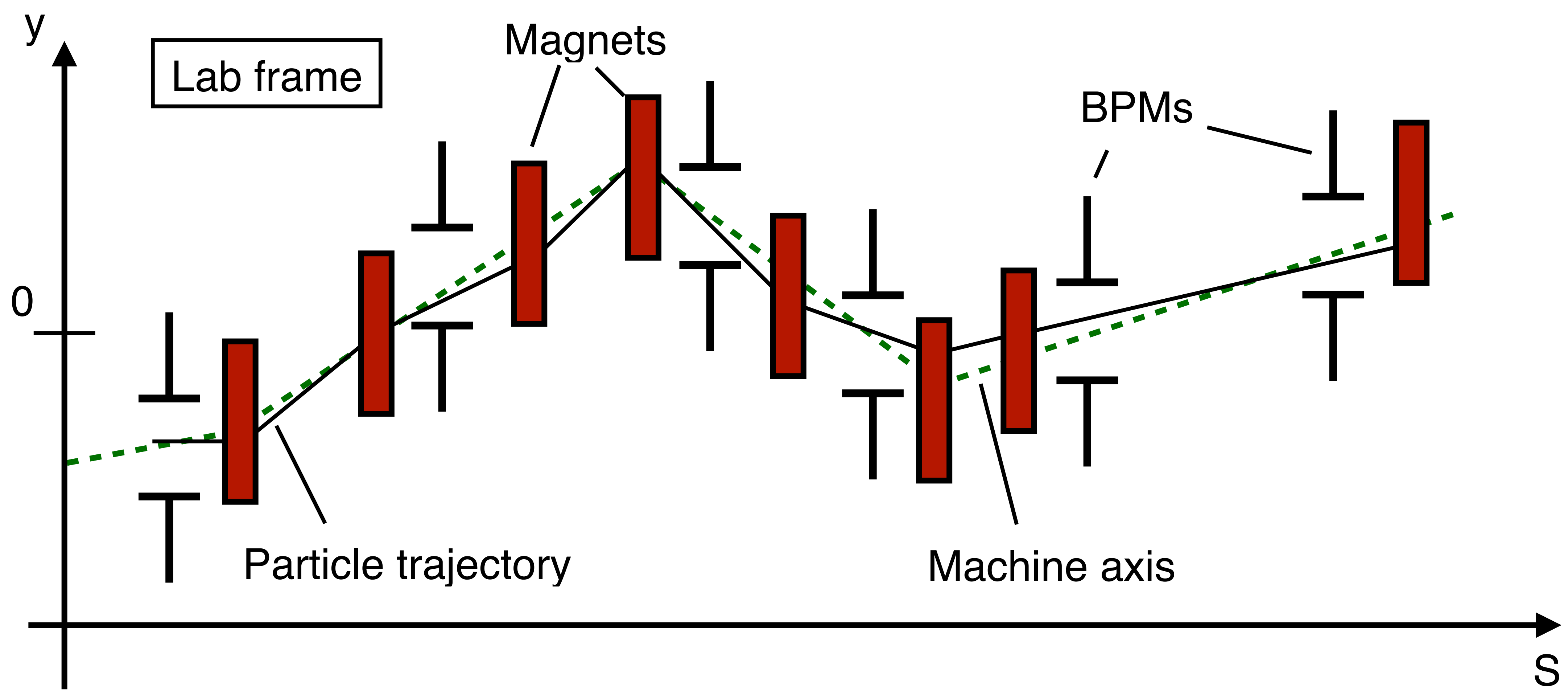


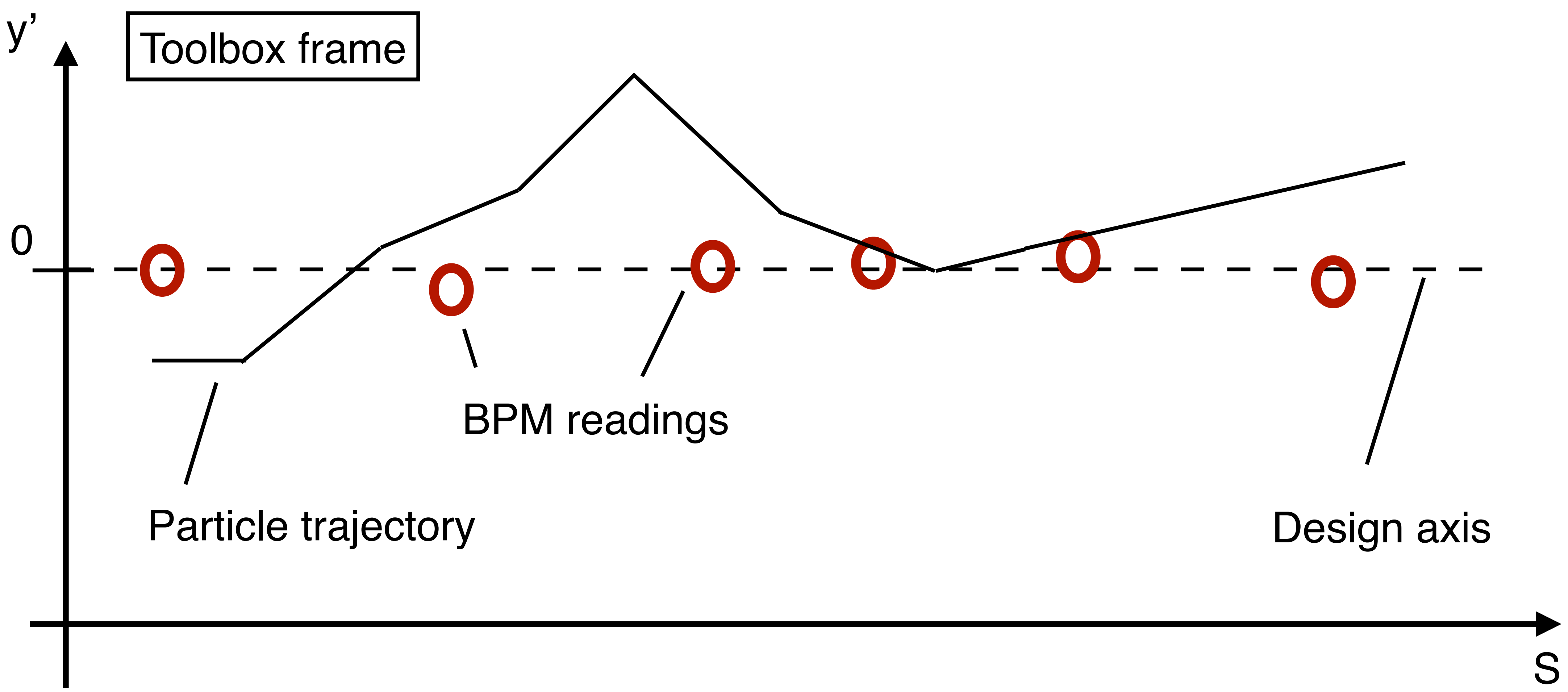
T. Hellert



Choice of reference orbit

- AT uses design coordinate system
  - Tracking performed in ideal co-moving frame
- In reality BPMs mounted on vacuum chamber or raft
  - Vacuum chamber follows magnet/raft alignment
- Reasonable implementation: BPMs follow raft alignment
  - Systematic offset from raft
  - Random offset from BPM imperfections
    => To be reduced with BBA

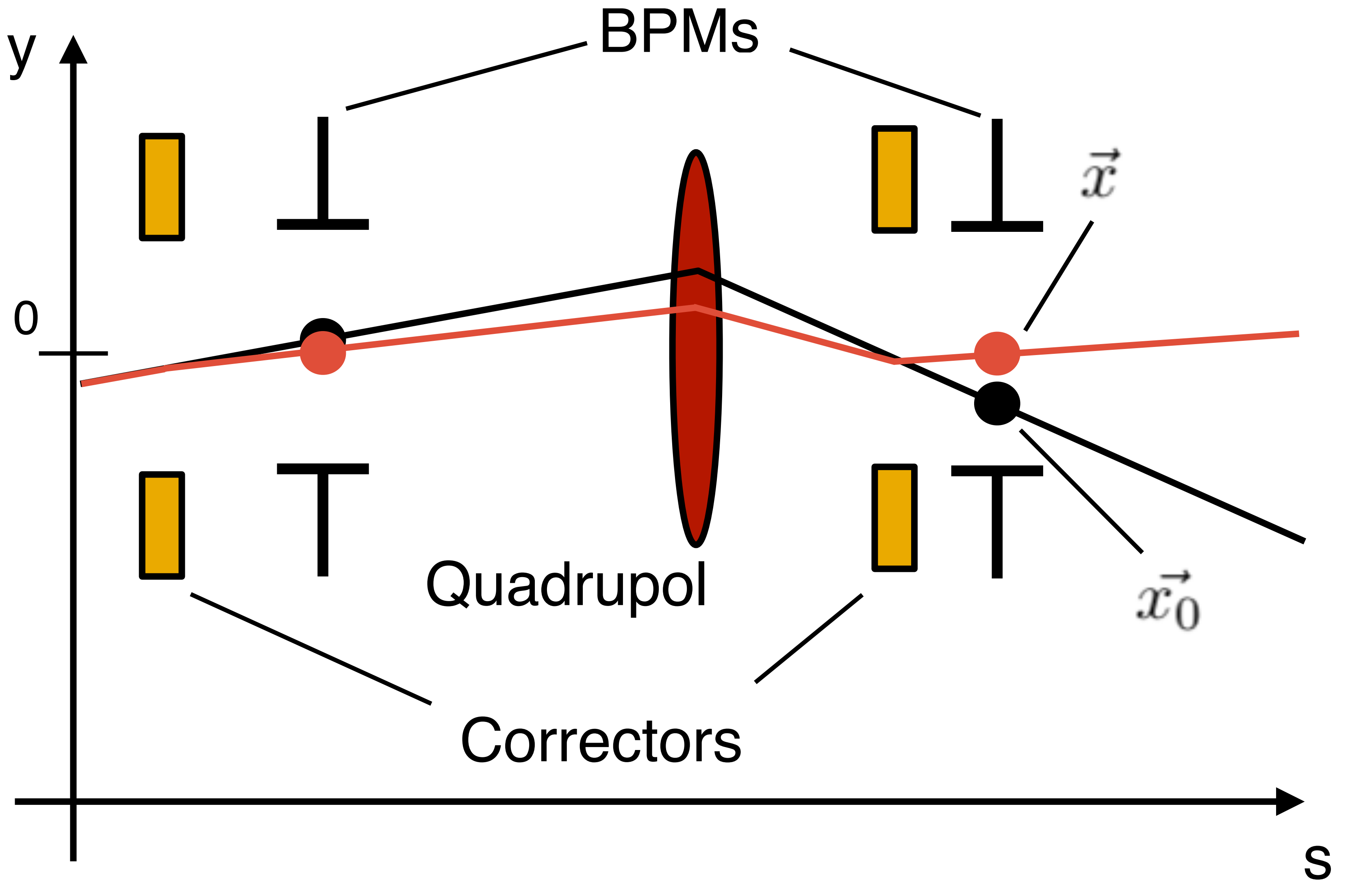




T. Hellert

Principles of trajectory correction

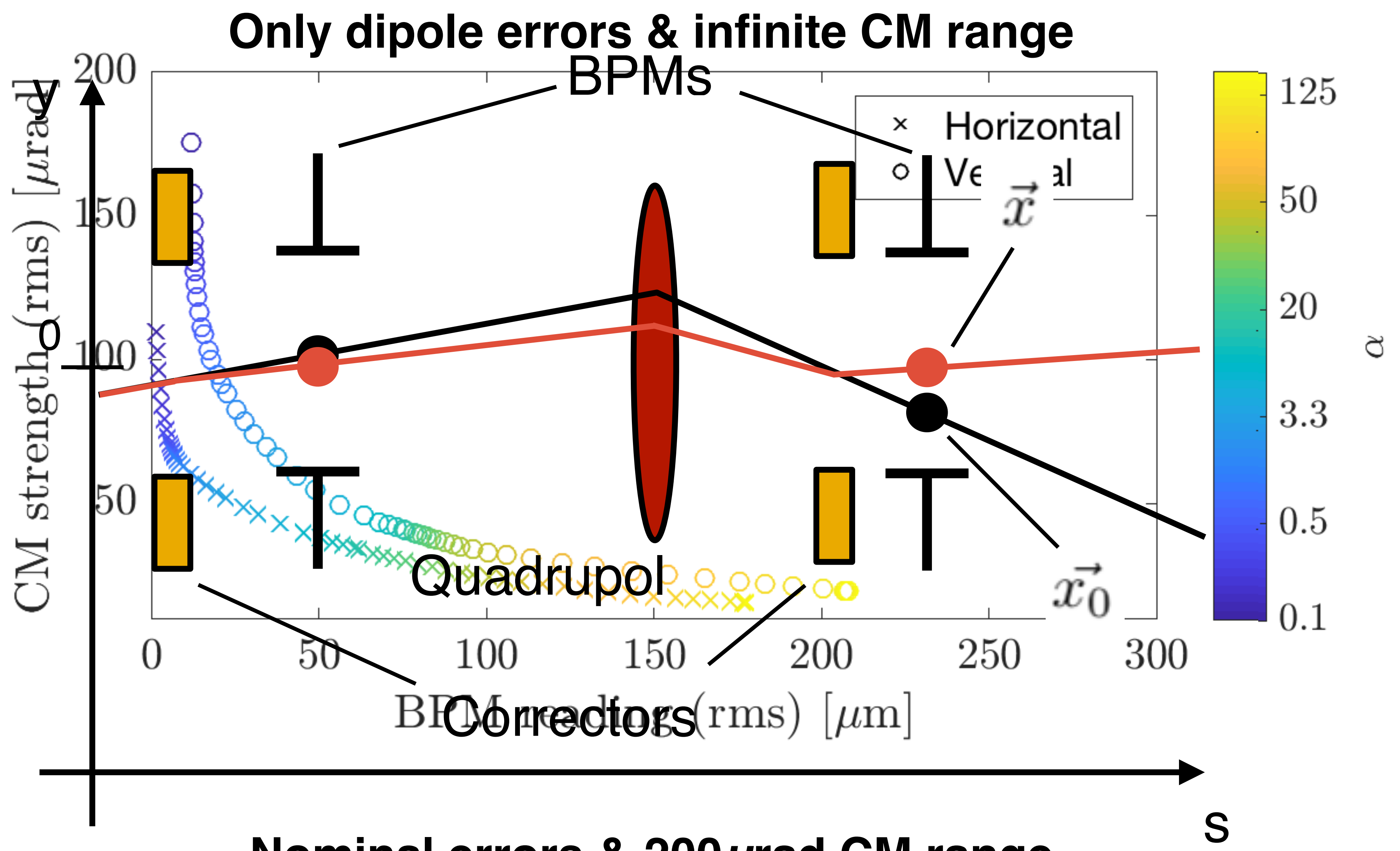
- Trajectory correction
  - Find corrector setting $\vec{\phi}$, that minimizes BPM reading: $\vec{x} = 0$
  - Assuming linear response: $\vec{x} = \vec{x_0} + \underline{M} \cdot \vec{\phi}$
  - Solution requires inverse: $\vec{\phi} = -\underline{M}^+ \cdot \vec{x_0}$
- Singular value decomposition
  - SVD: $\underline{M} = \underline{U} \cdot \mathrm{diag}(\vec{\sigma}) \cdot \underline{V}^T$
  - Pseudo inverse: $\underline{M}^+ = \underline{V} \cdot \mathrm{diag}(\vec{\sigma}^+) \cdot \underline{U}^T$
  - Regularization: $\sigma_i^+ = 1/\sigma_i \text{ (with } \sigma_i^+ = 0 \text{ for } i > n)$
  - Minimizes: $||\underline{M}\underline{M}^+ \cdot \vec{x_0} - \vec{x_0}||_2$
- Problems:
  - Actual response $\underline{M}$ differs from design ← Particular in early commissioning
  - $\underline{M}^+ \cdot \vec{x_0}$ can be exceedingly large ← Particular with small CM range
- Standard approach:
  - Use only limited amount of singular values (SV)
  - And/or try different combinations of CMs and SVs

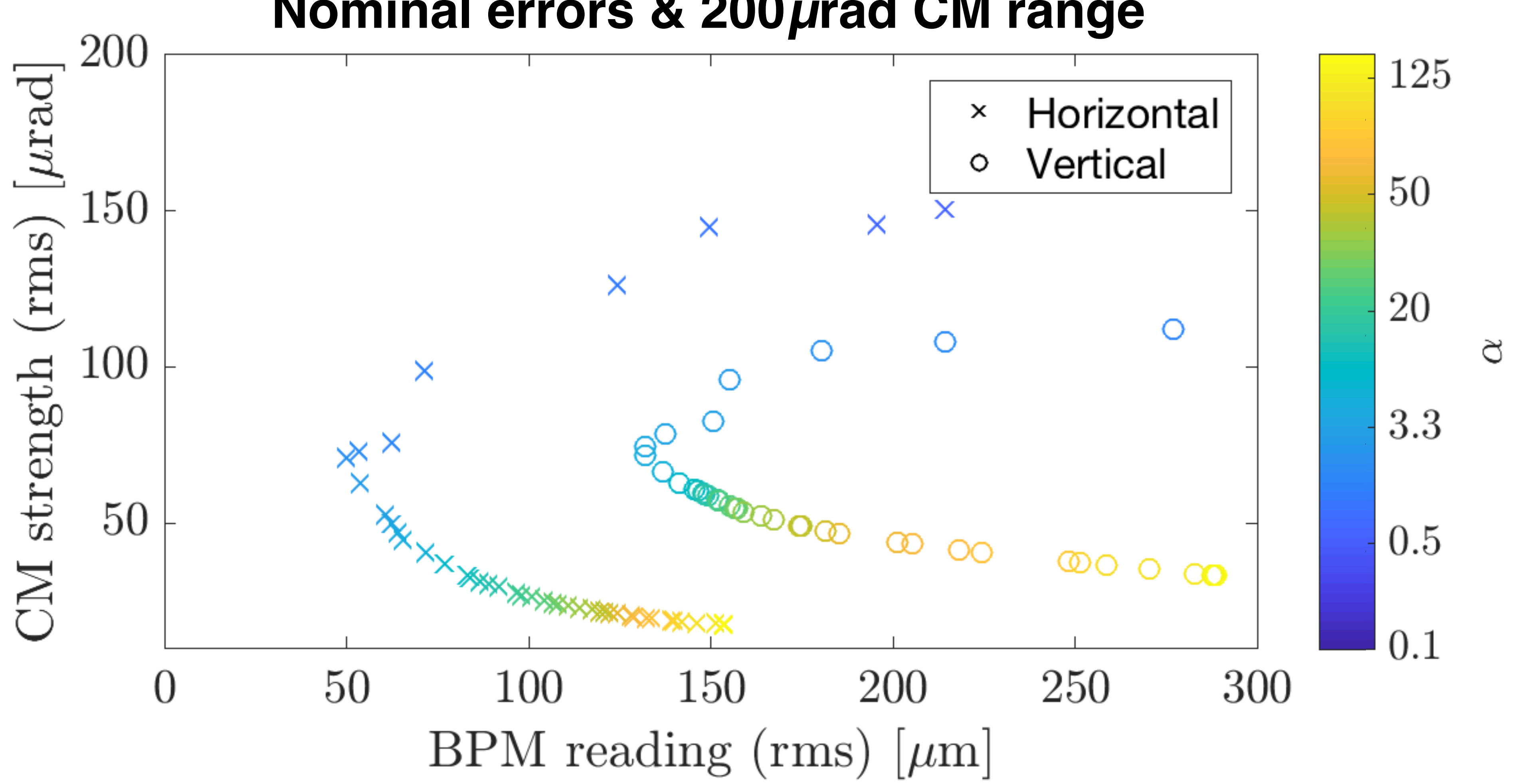


T. Hellert, P. Amstutz

Feedback based trajectory correction

- Trajectory correction
  - Find corrector setting $\vec{\phi}$, that minimizes BPM reading: $\vec{x} = 0$
  - Assuming linear response: $\vec{x} = \vec{x_0} + \underline{M} \cdot \vec{\phi}$
  - Solution requires inverse: $\vec{\phi} = -\underline{M}^+ \cdot \vec{x_0}$
- Singular value decomposition
  - Using all CMs and a Tikhonov regularization of inverse of response matrix
  - SVD: $\underline{M} = \underline{U} \cdot \mathrm{diag}(\vec{\sigma}) \cdot \underline{V}^T$
  - Pseudo inverse: $\underline{M}^+ = \underline{V} \cdot \mathrm{diag}(\vec{\sigma}^+) \cdot \underline{U}^T$
  - Tikhonov: $\sigma_i^+ = \sigma_i / (\sigma_i^2 + \alpha^2)$
  - Minimizes: $\underbrace{||\underline{M}\underline{M}^+ \cdot \vec{x} - \vec{x}||_2}_{\text{BPMs}} + |\alpha| \, \underbrace{||\underline{M}^+ \cdot \vec{x}||_2}_{\text{CMs}}$
- Advantages:
  - Very efficient
  - Useful handle: CM strength vs BPM readings



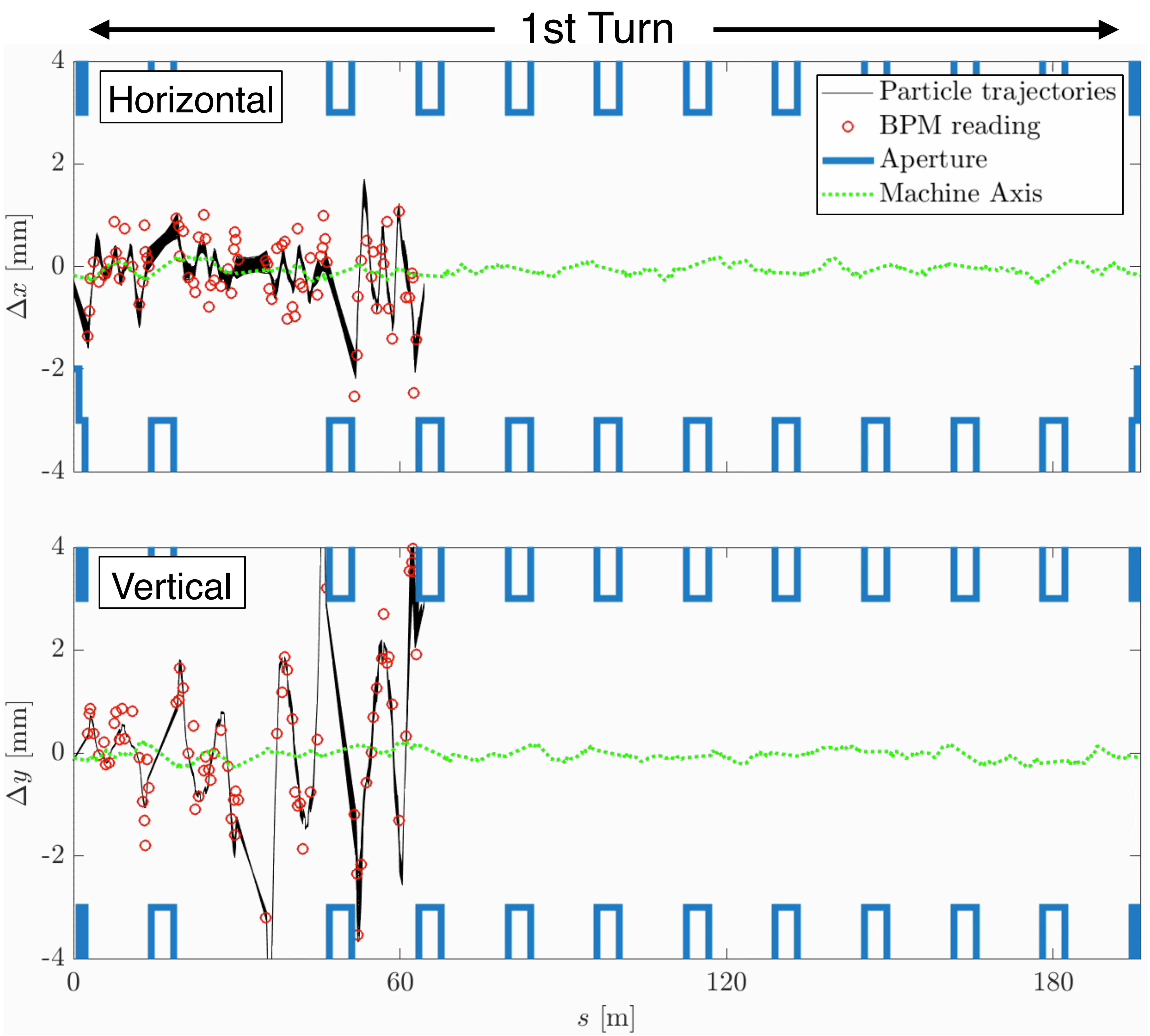


Correction chain for commissioning ALS-U

- Initial transmission
  - Achieve first turn transmission
  - Trajectory correction for multi-turn transmission
- Improving multi-turn transmission
  - Perform beam based alignment
  - Correct injected trajectory error
- Closed orbit correction
  - Match injection trajectory
  - Commissioning of RF cavities
  - Synchronous energy correction
- Achieve beam capture
  - Ramp up sextupoles (chromaticity correction)
  - Trajectory based optics correction
- Achieve design machine parameters (emittance, lifetime, …)
  - LOCO based optics correction
  - ID closing

Improving initial transmission

- First turn threading
  - Feedback on all BPMs with all upstream CMs
  - If beam is stuck for 10 iterations, *wiggle* with increasing number of CMs
  - Run feedback to ensure minimized BPM readings



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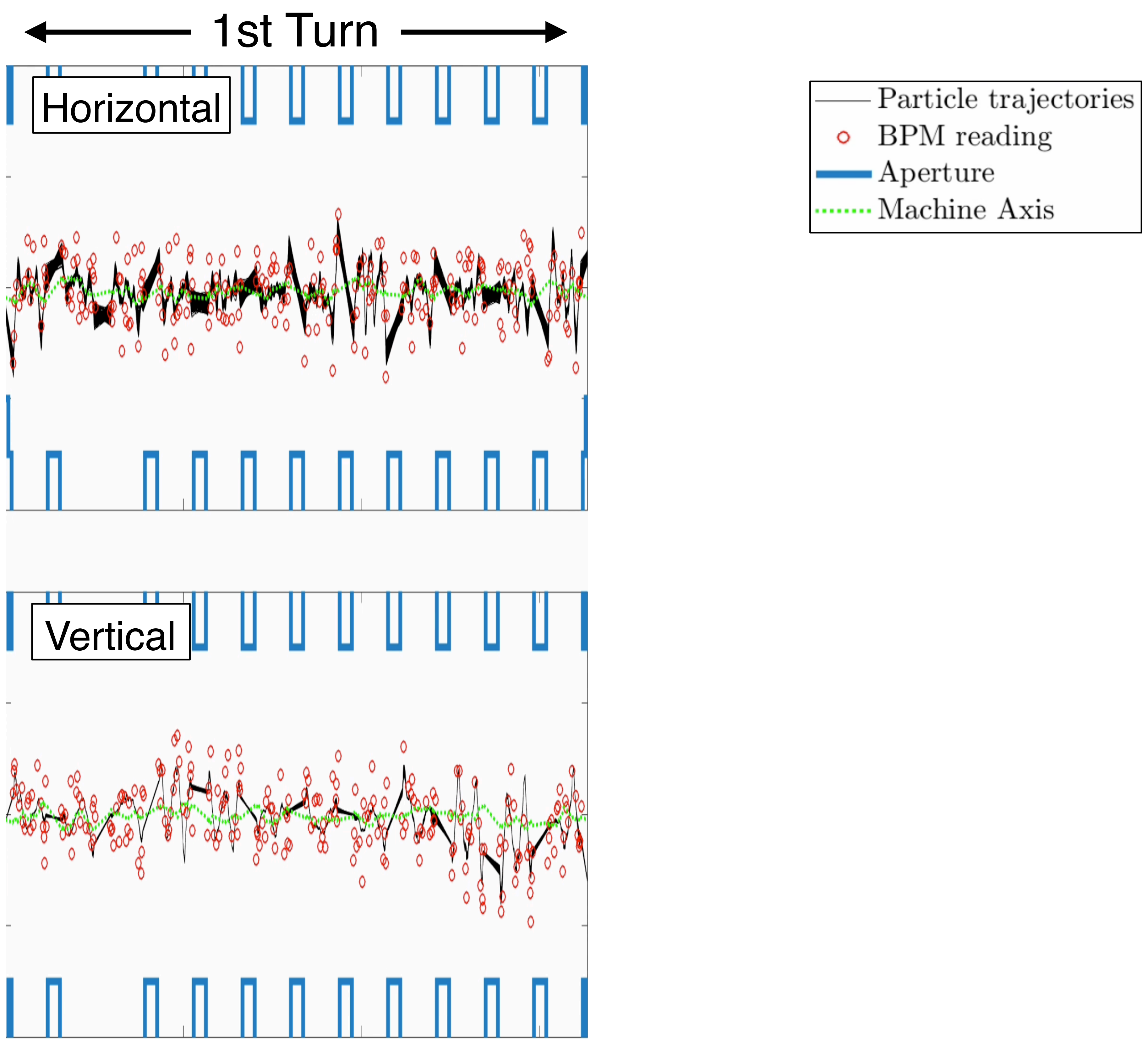

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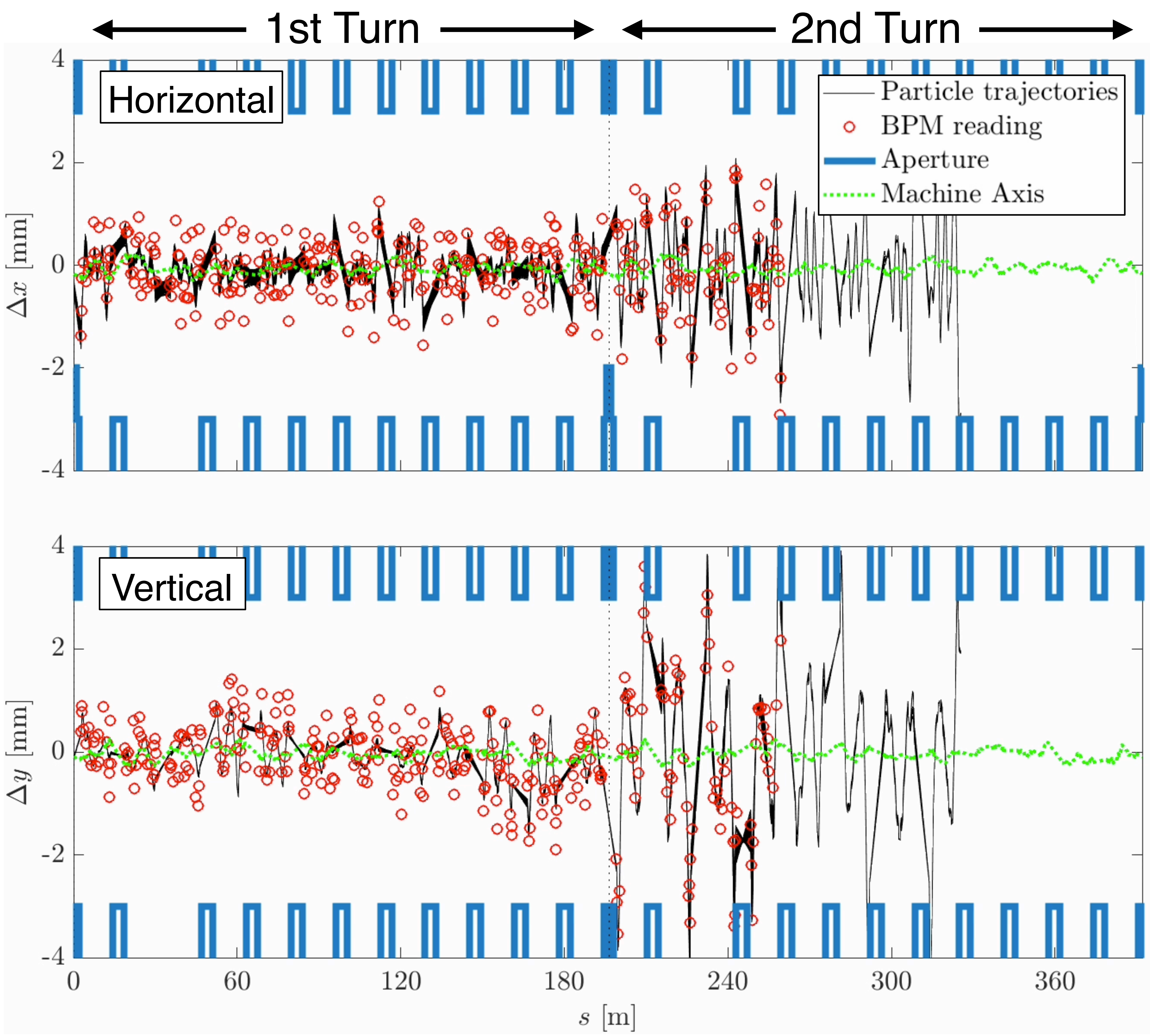
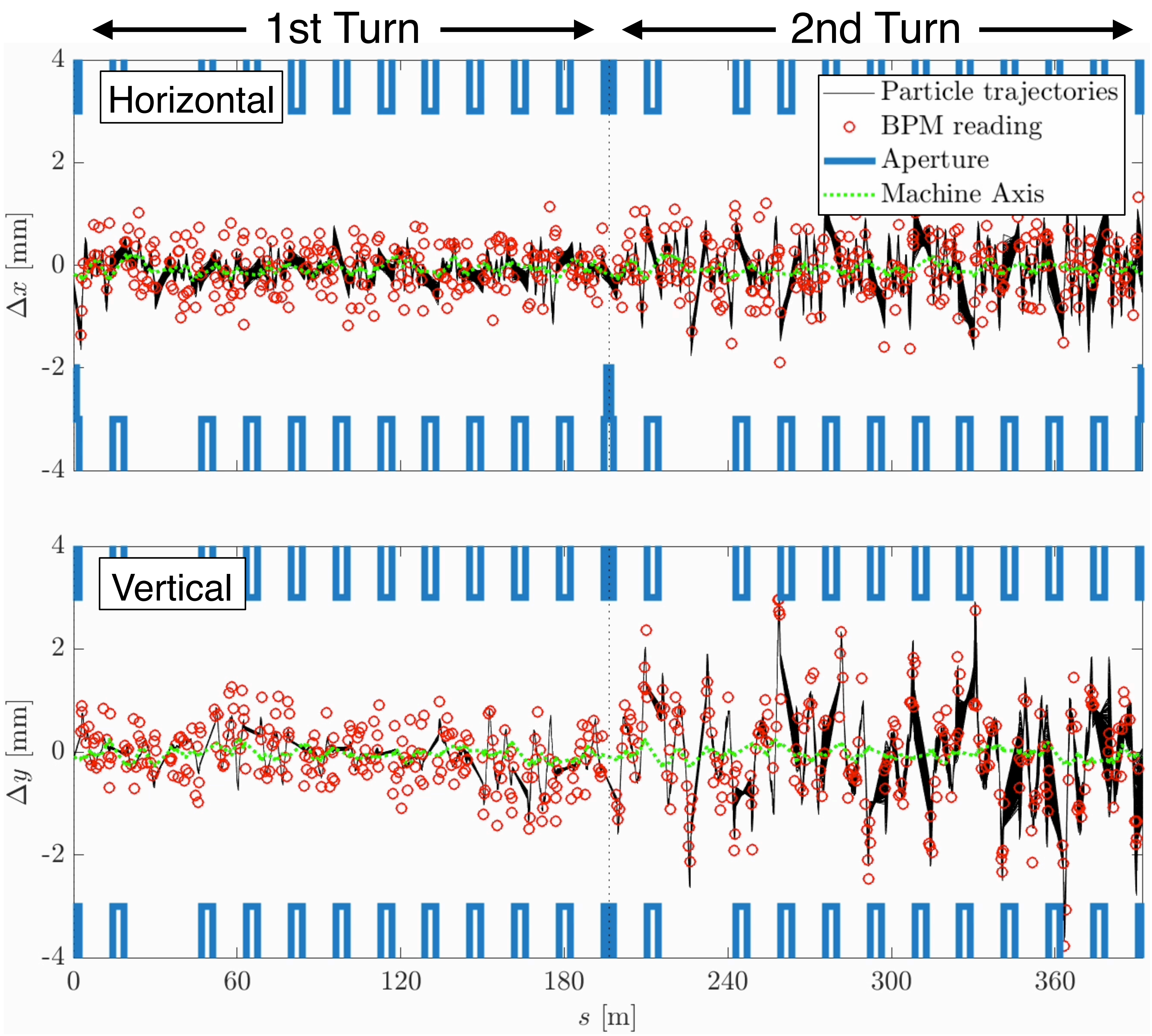


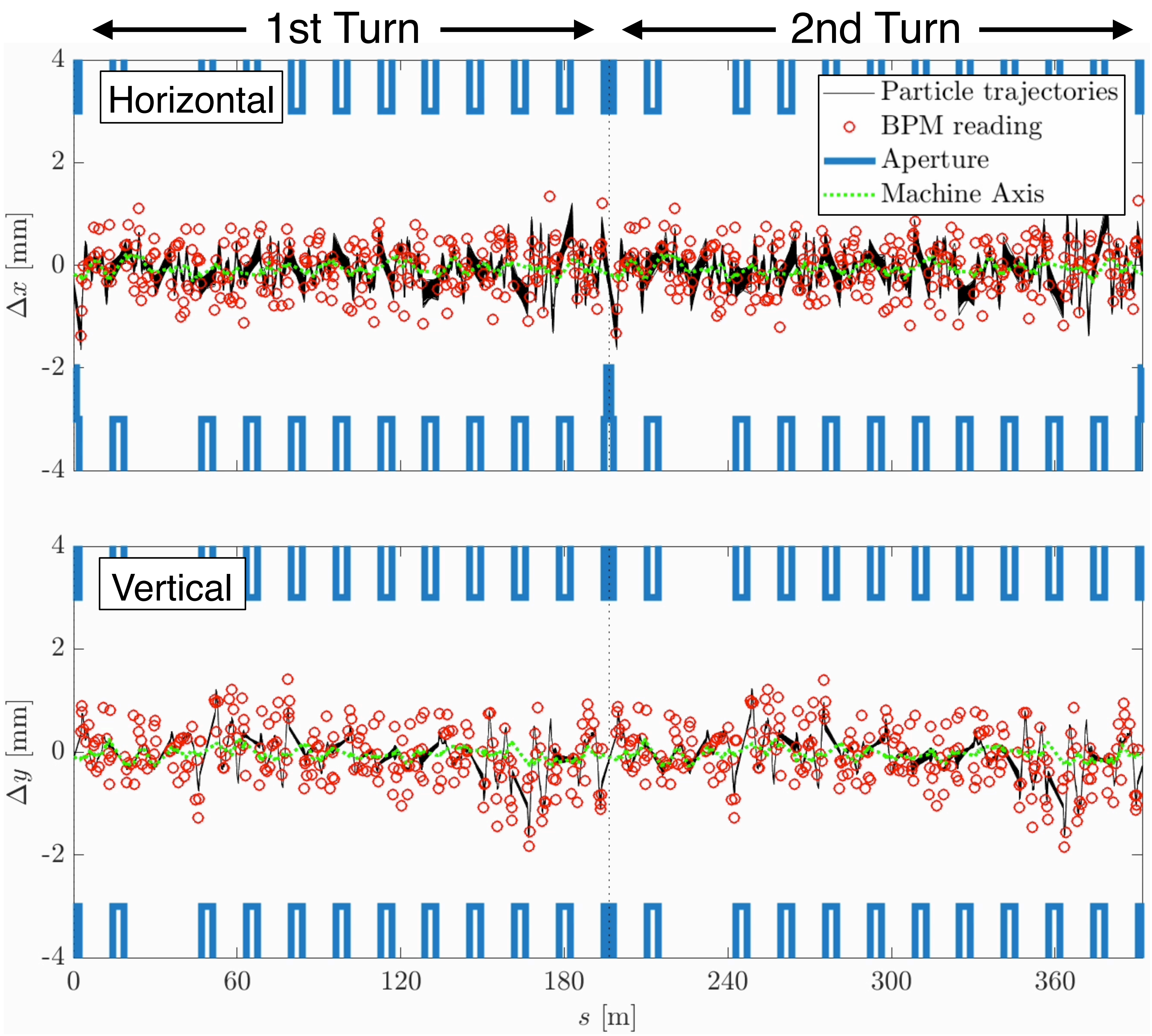
Improving initial transmission

- First turn threading
    - Feedback on all BPMs with all upstream CMs
    - If beam is stuck for 10 iterations, *wiggle* with increasing number of CMs
    - Run feedback to ensure minimized BPM readings
- Stitching first and second turn
    - If no beam in 2nd turn, wiggle with increasing number of last CMs
    - Run feedback on first 3 2nd turn BPM readings with 1st turn BPM readings as reference
- Balancing first and second turn
    - Run feedback on all 2nd turn BPM readings with 1st turn BPM readings as reference



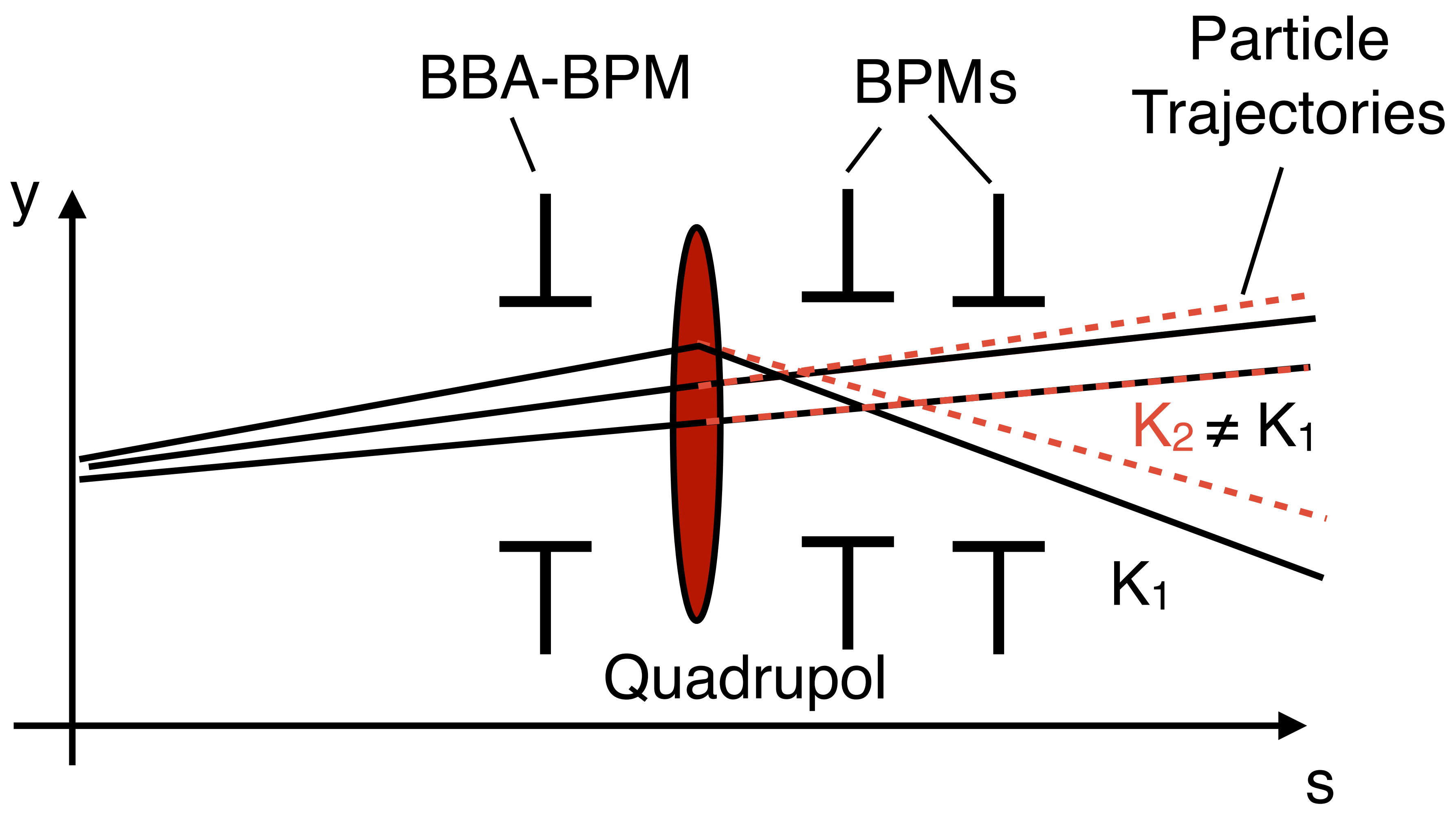
Improving initial transmission

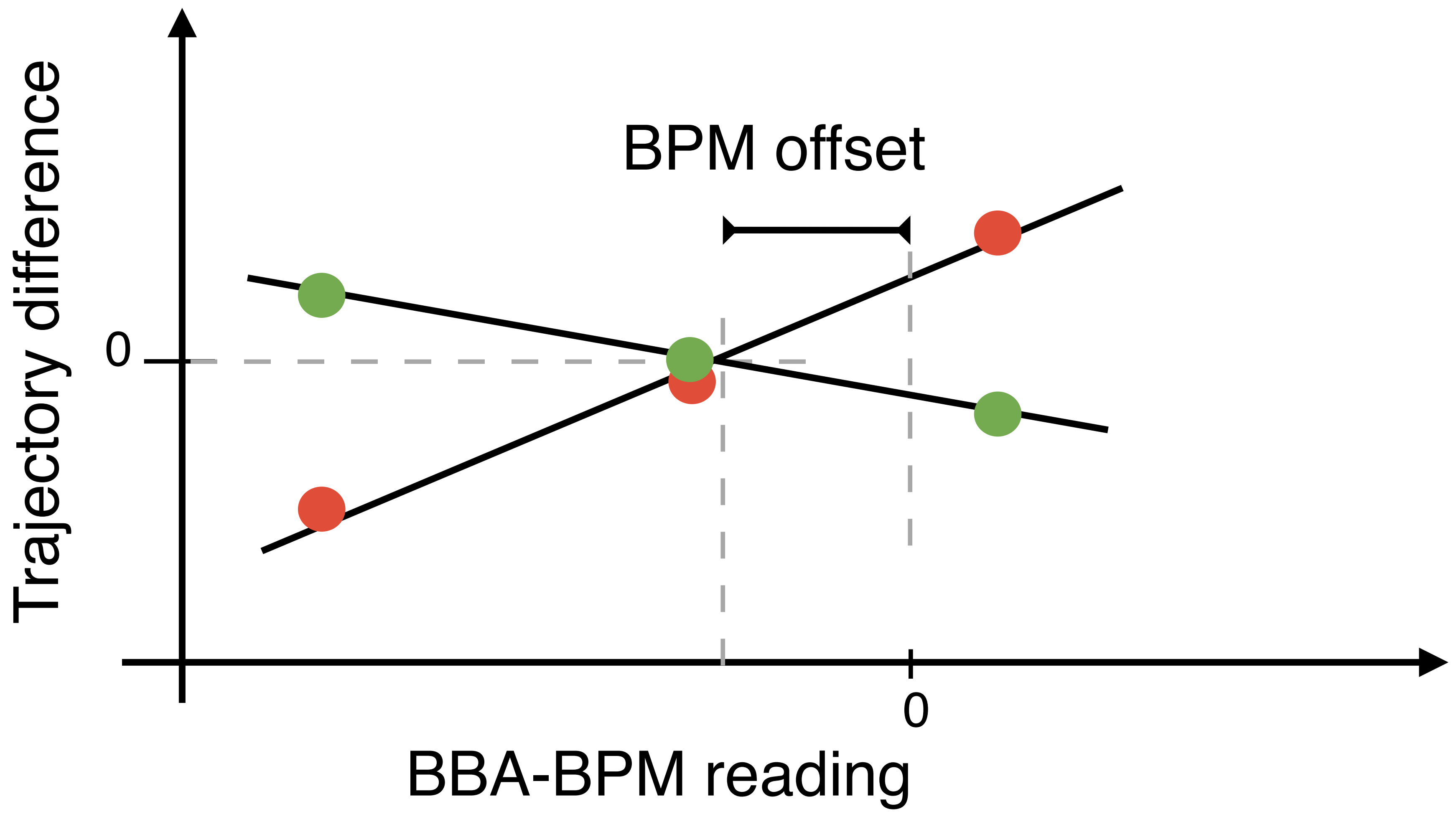
- First turn threading
  - Feedback on all BPMs with all upstream CMs
  - If beam is stuck for 10 iterations, *wiggle* with increasing number of CMs
  - Run feedback to ensure minimized BPM readings
- Stitching first and second turn
  - If no beam in 2nd turn, wiggle with increasing number of last CMs
  - Run feedback on first 3 2nd turn BPM readings with 1st turn BPM readings as reference
- Balancing first and second turn
  - Run feedback on all 2nd turn BPM readings with 1st turn BPM readings as reference
- Minimize 2 turn BPM readings
  - Feedback on all BPMs within 2 turns using all CMs



Beam based alignment in early commissioning

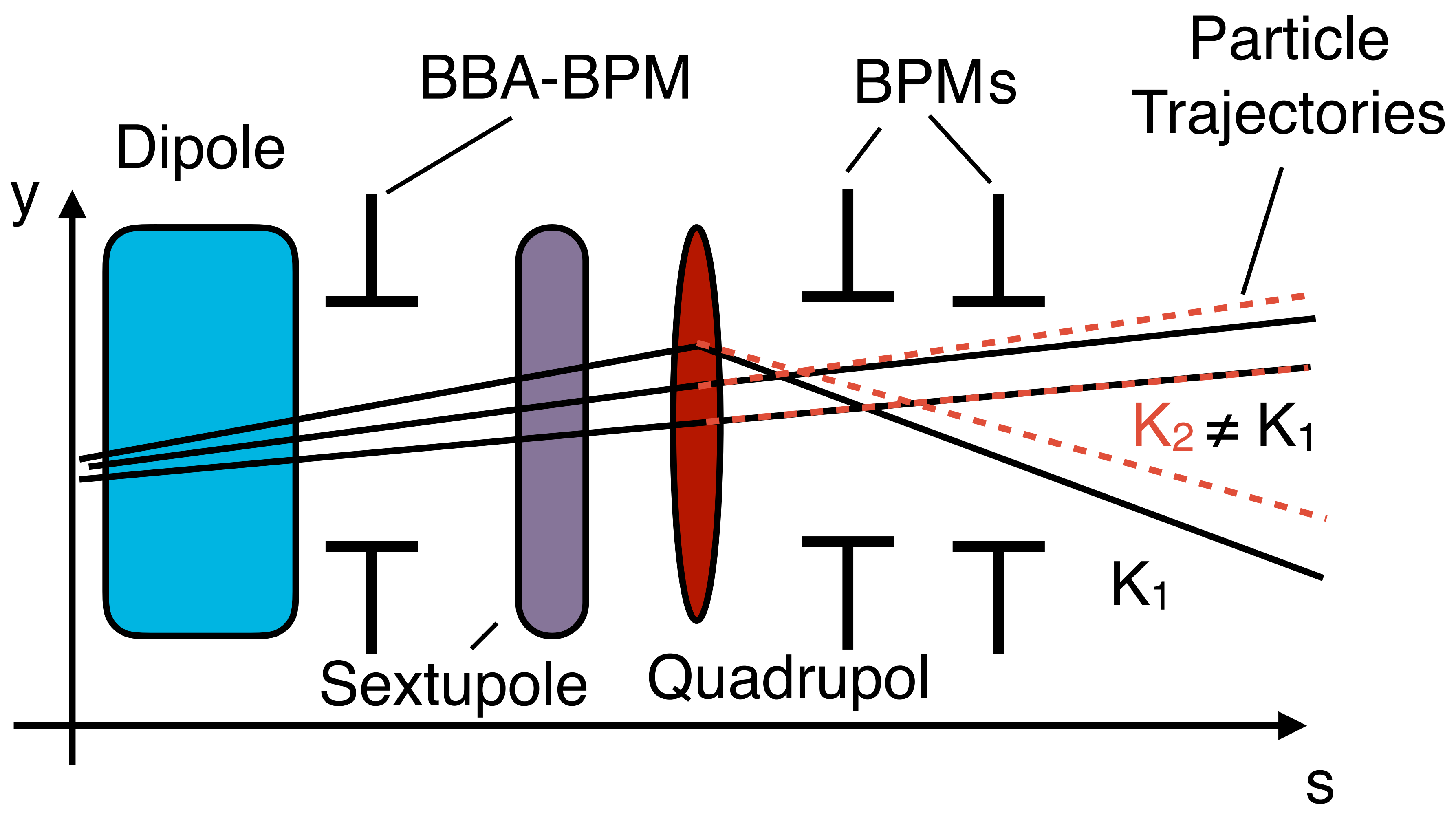
- Initial BPM offsets ~500μm rms
  - Limits capability of trajectory correction
  - Strong sextupole magnets require on axis beam
  - Ideal: align BPMs to magnet centers

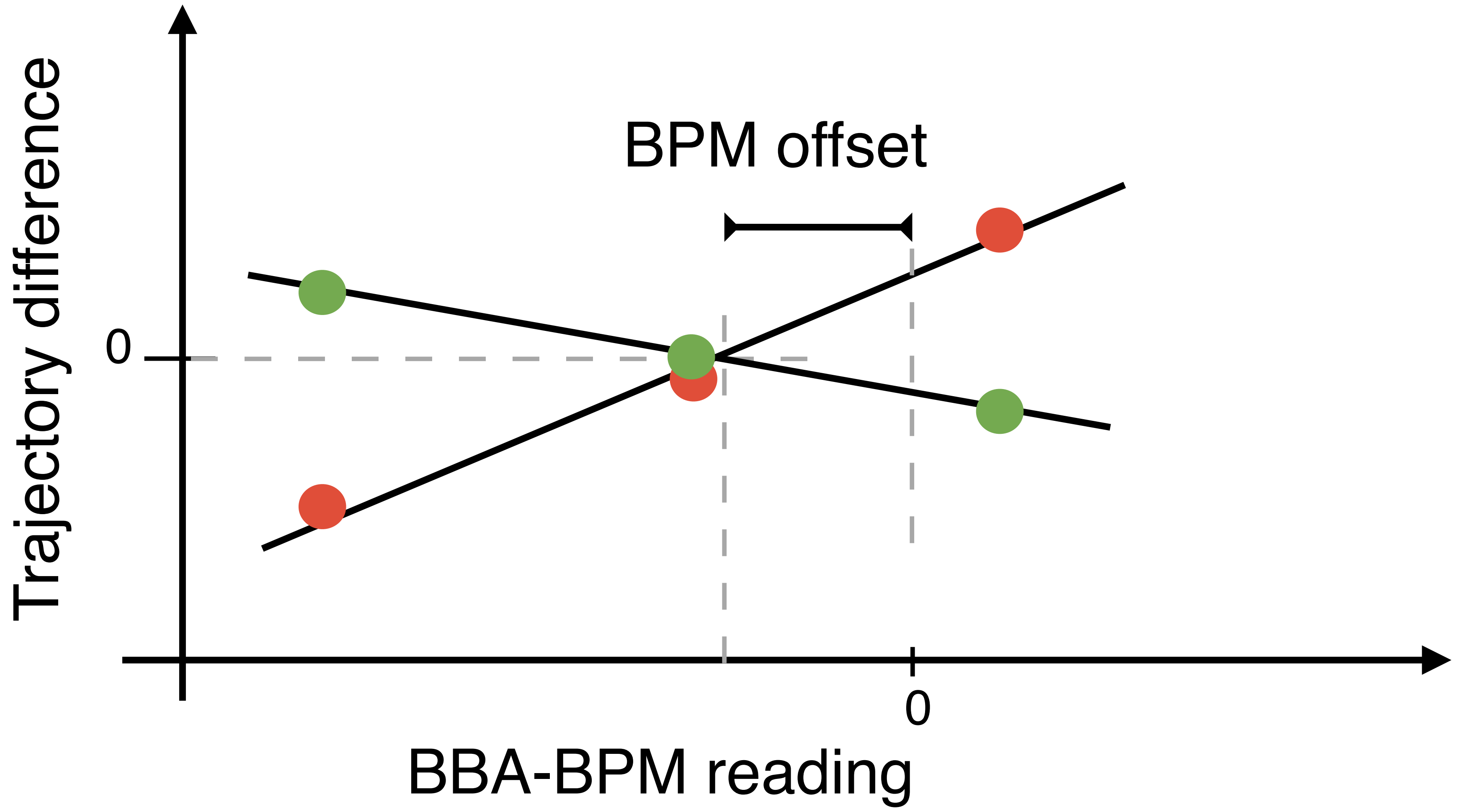




Beam based alignment in early commissioning

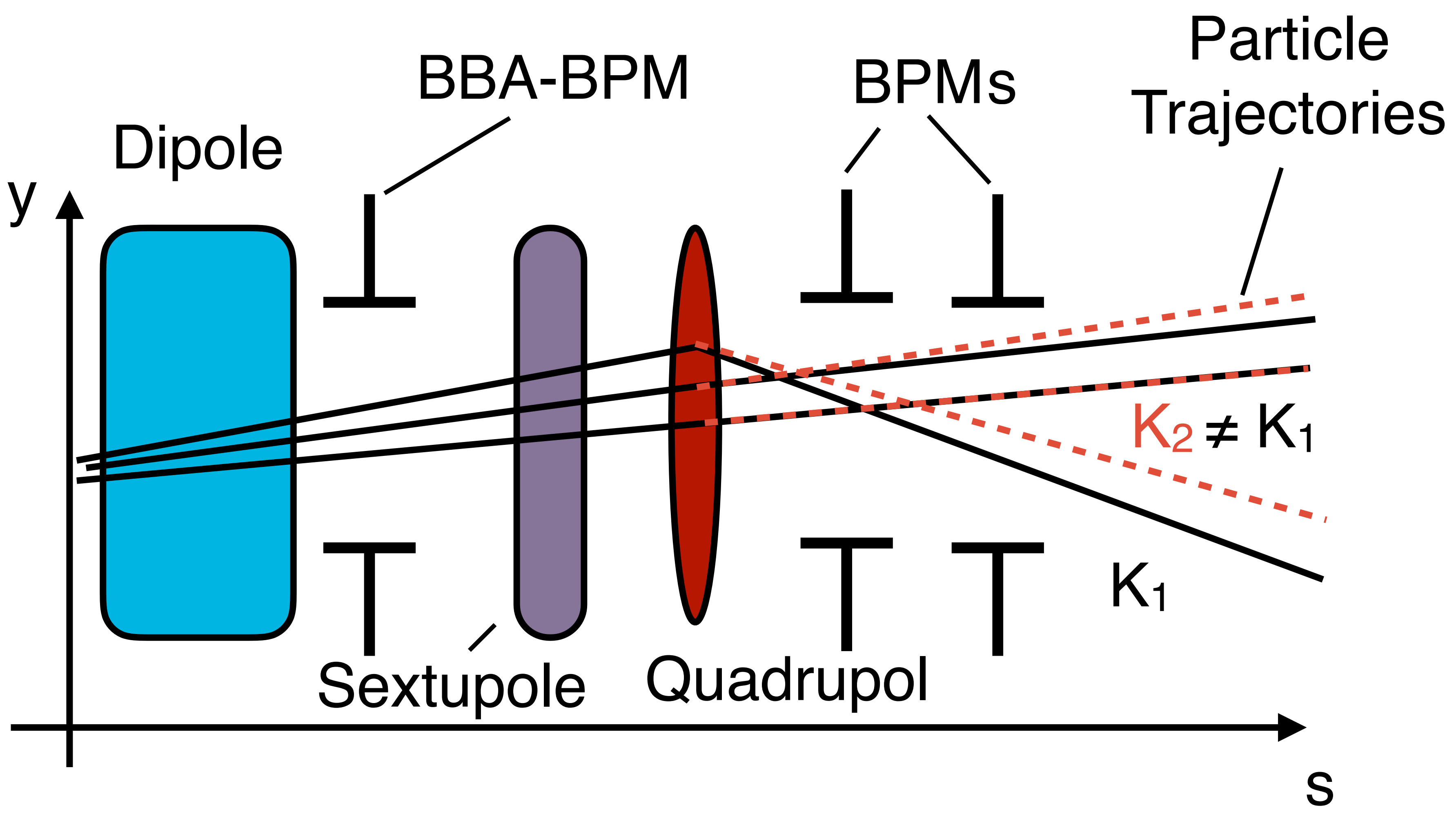
- Initial BPM offsets ~500µm rms
  - Limits capability of trajectory correction
  - Strong sextupole magnets require on axis beam
  - Ideal: align BPMs to magnet centers
- Requirement on adequate BBA routine
  - Significant optics errors during early commissioning **=> *Model independent***
  - Beam survives only limited amount of turns **=> *Single pass***

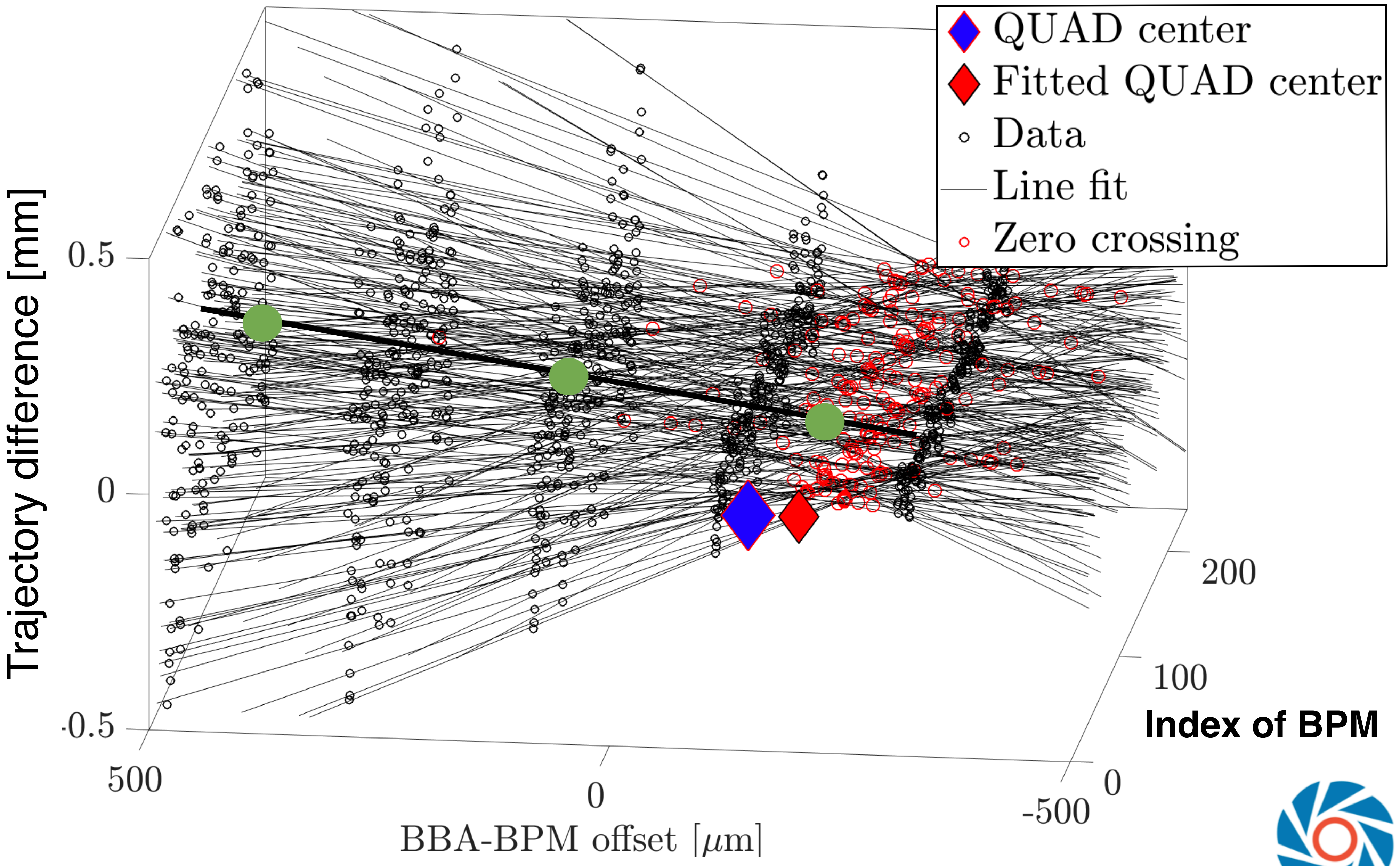




Implementation of BBA procedure

- Change injected beam trajectory
  - Scale for maximum signal
  - Changing phase advance if needed
- Change quadrupole within +/-5%
  - Compensate for bending angle difference
- Calculate trajectory with zero quadrupole dependence
  - Include many downstream BPMs, but:
  - Check for sufficient transmission
  - Check for distribution of fitted quadrupole centers
  - Check for 'feasibility' of result
  - …





Implementation of BBA procedure

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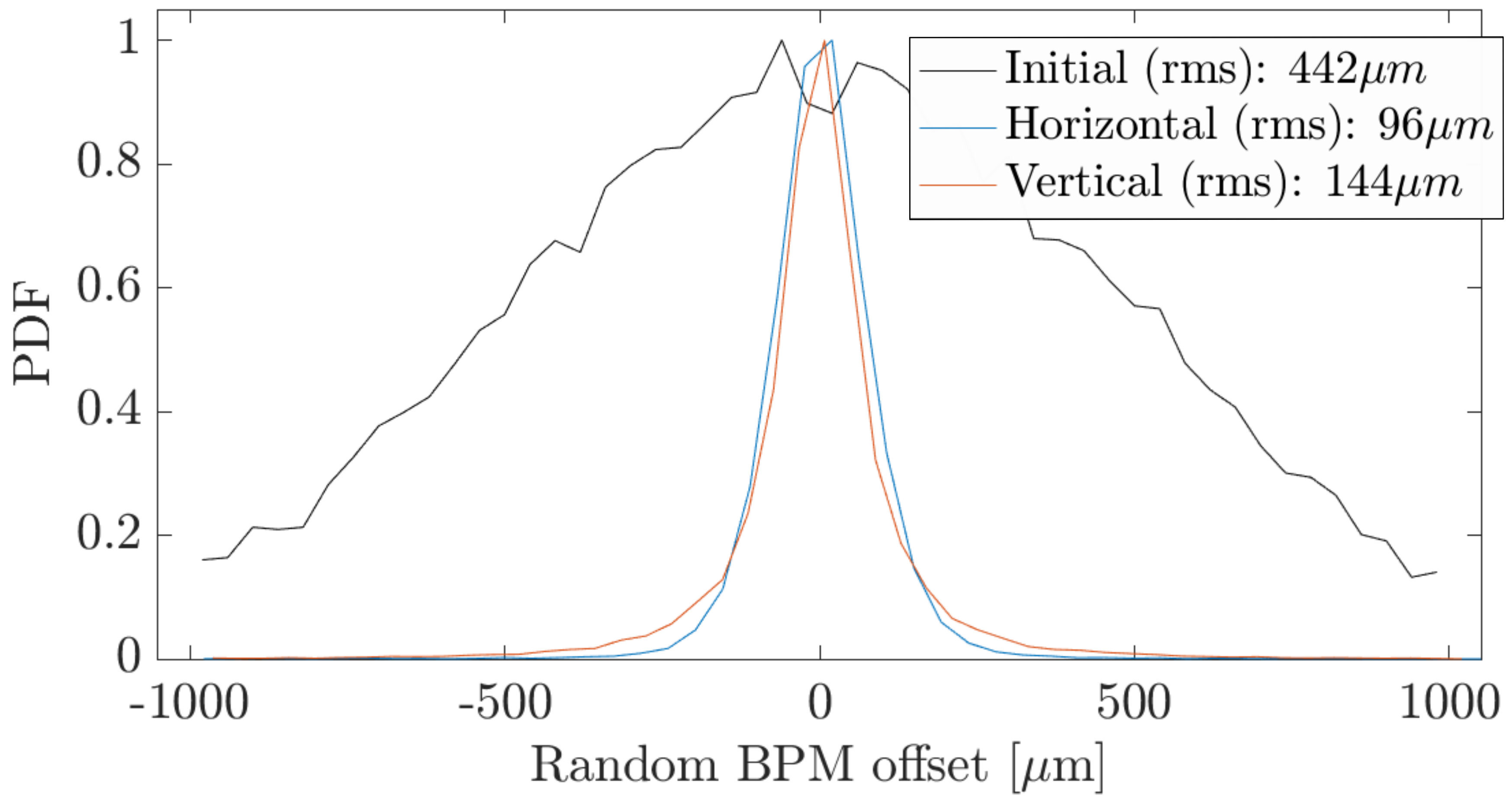
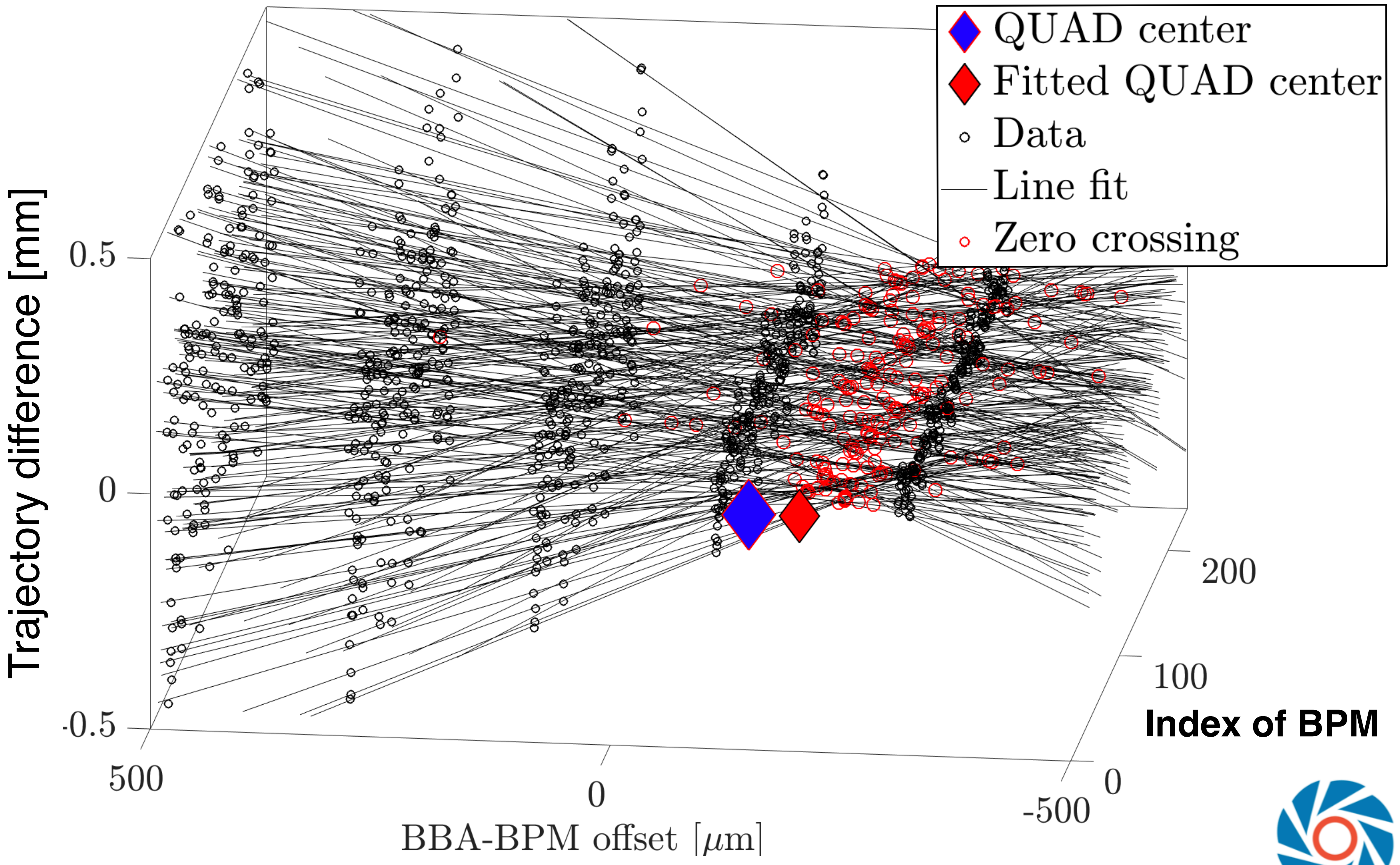
- Change quadrupole within +/-5%
    - Compensate for bending angle difference
- Calculate trajectory with zero quadrupole dependence
    - Include many downstream BPMs, but:
    - Check for sufficient transmission
    - Check for distribution of fitted quadrupole centers
    - Check for 'feasibility' of result
    - …
- Satisfactory performance

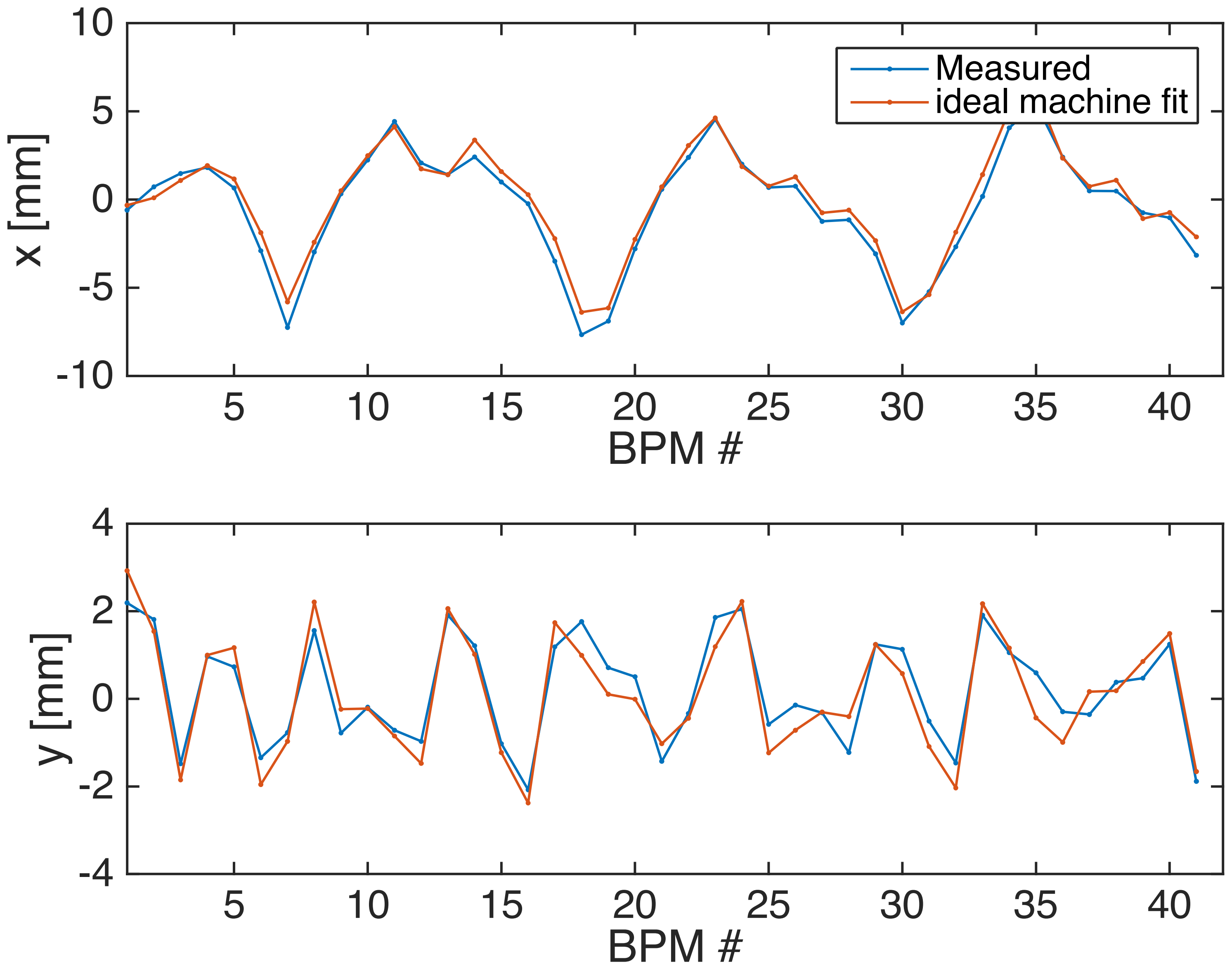
BBA results for 500 seeds



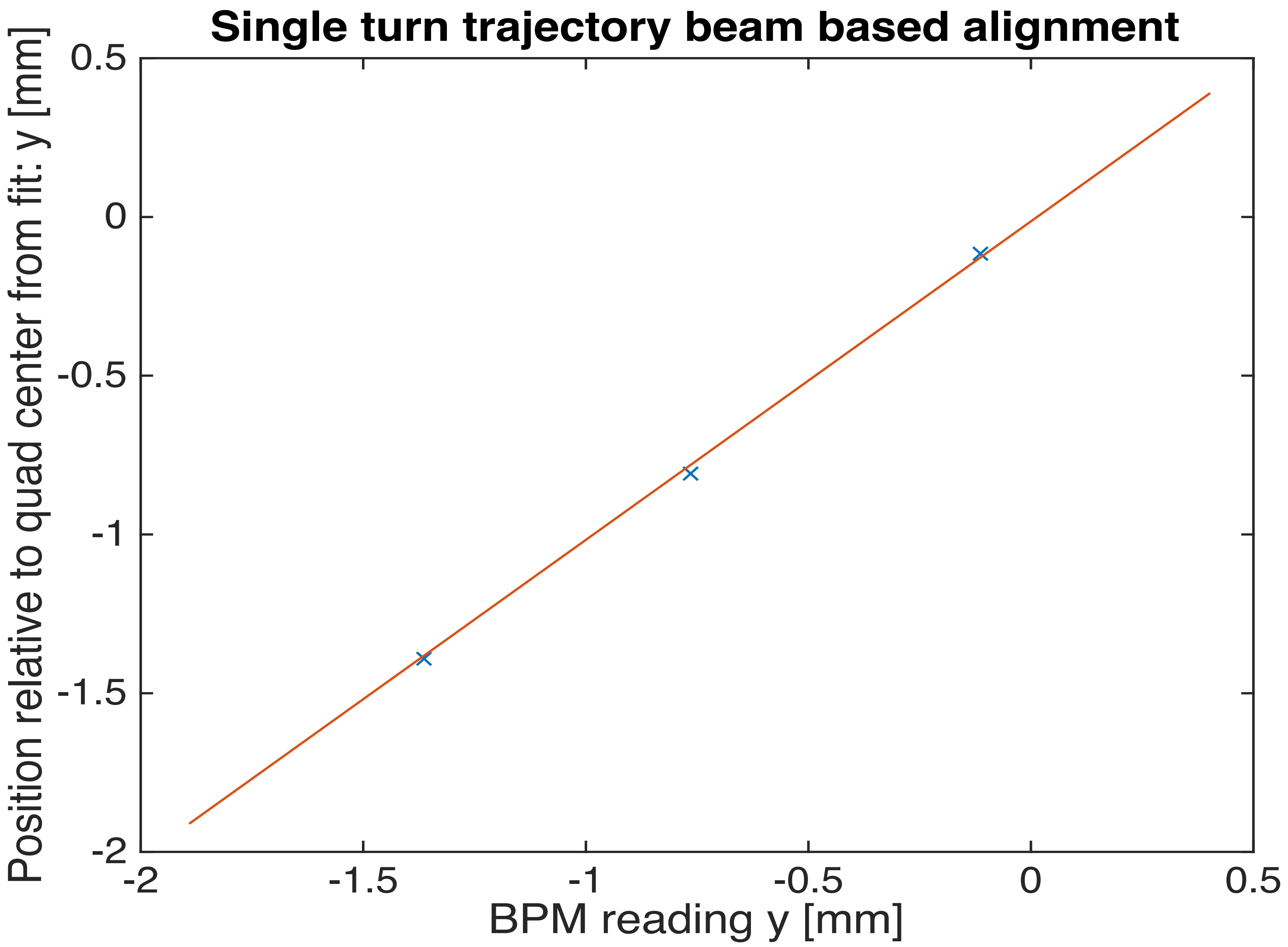


Development example: Beam based alignment using first turn trajectories on ALS

- Demonstrated trajectory correction and ability to do better than 100 micron accuracy beam-based alignment without requiring stored beam.
- Algorithm includes trajectory fit (using ideal lattice) with fitted kick at location of quadrupole to be centered – about 10 injection shots needed per magnet/BPM



Intentionally offset first turn trajectory of injected beam in the ALS and trajectory fits using the ideal machine model.

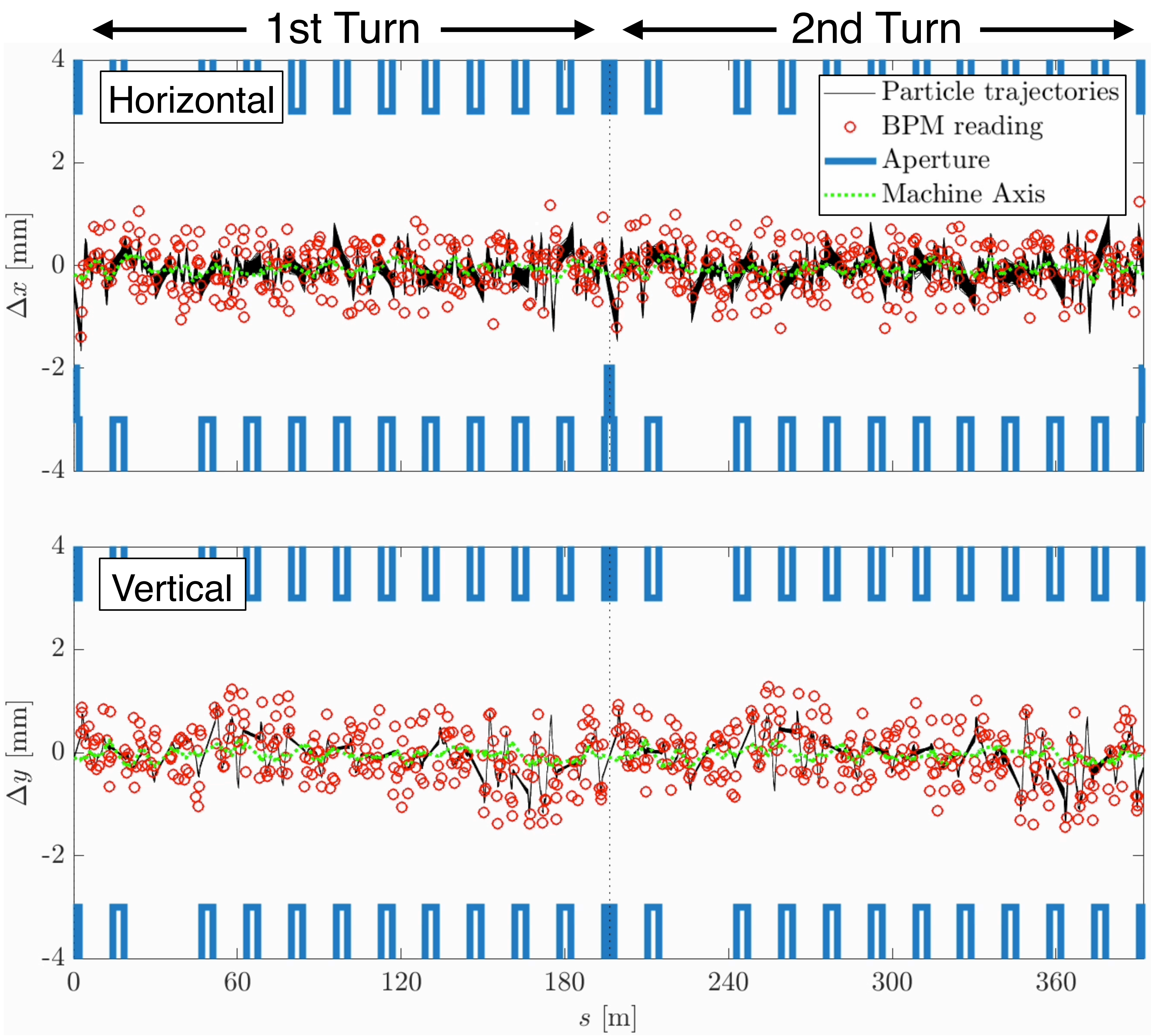


Beam based alignment measurement using only first turn trajectory measurements. Result agrees within 50 microns with stored beam measurements.

Already used after ALS shutdown to recover much faster from complex hardware failure

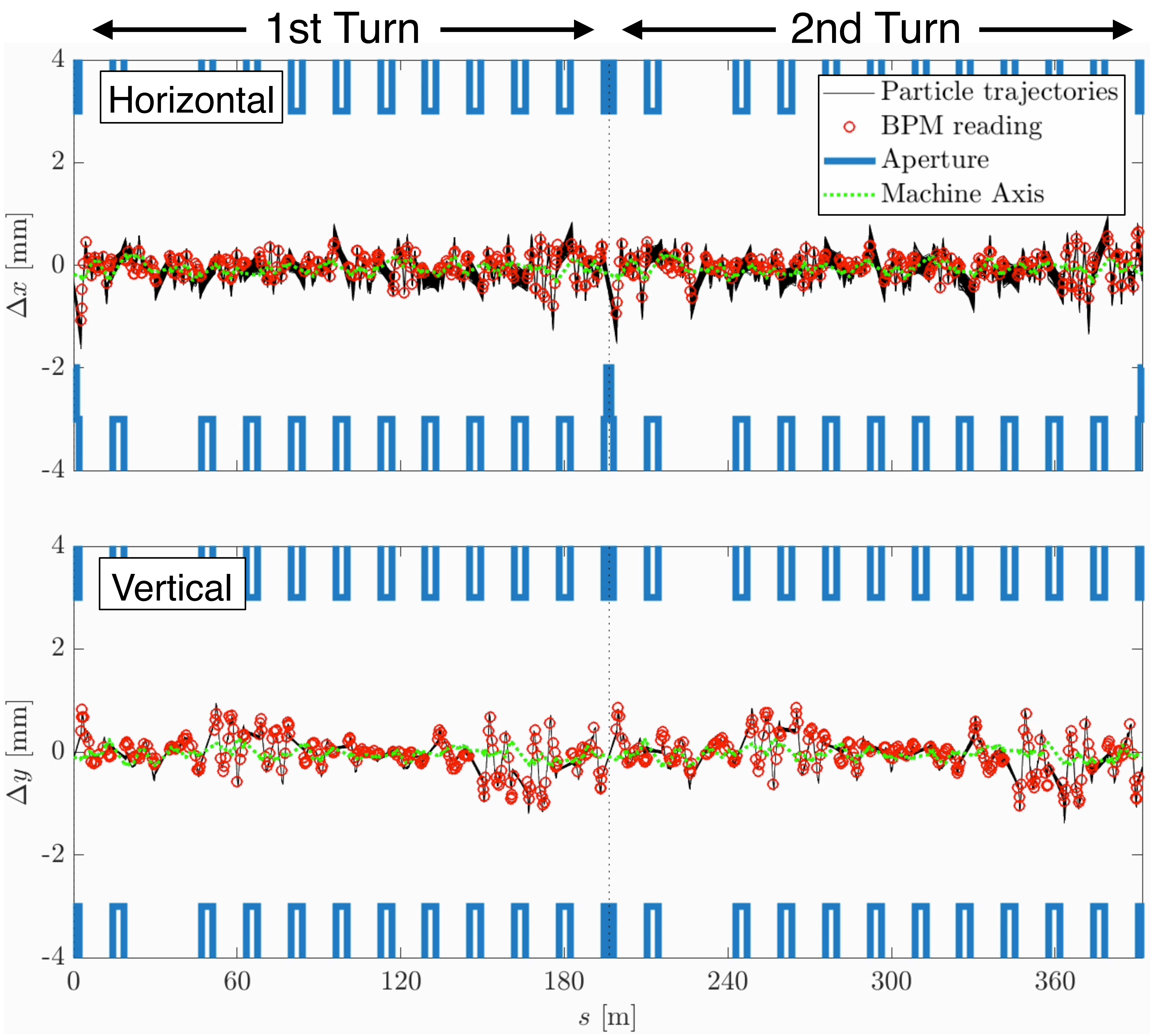
Achieving multi-turn transmission

- Perform beam based alignment
  - Minimize BPM offsets



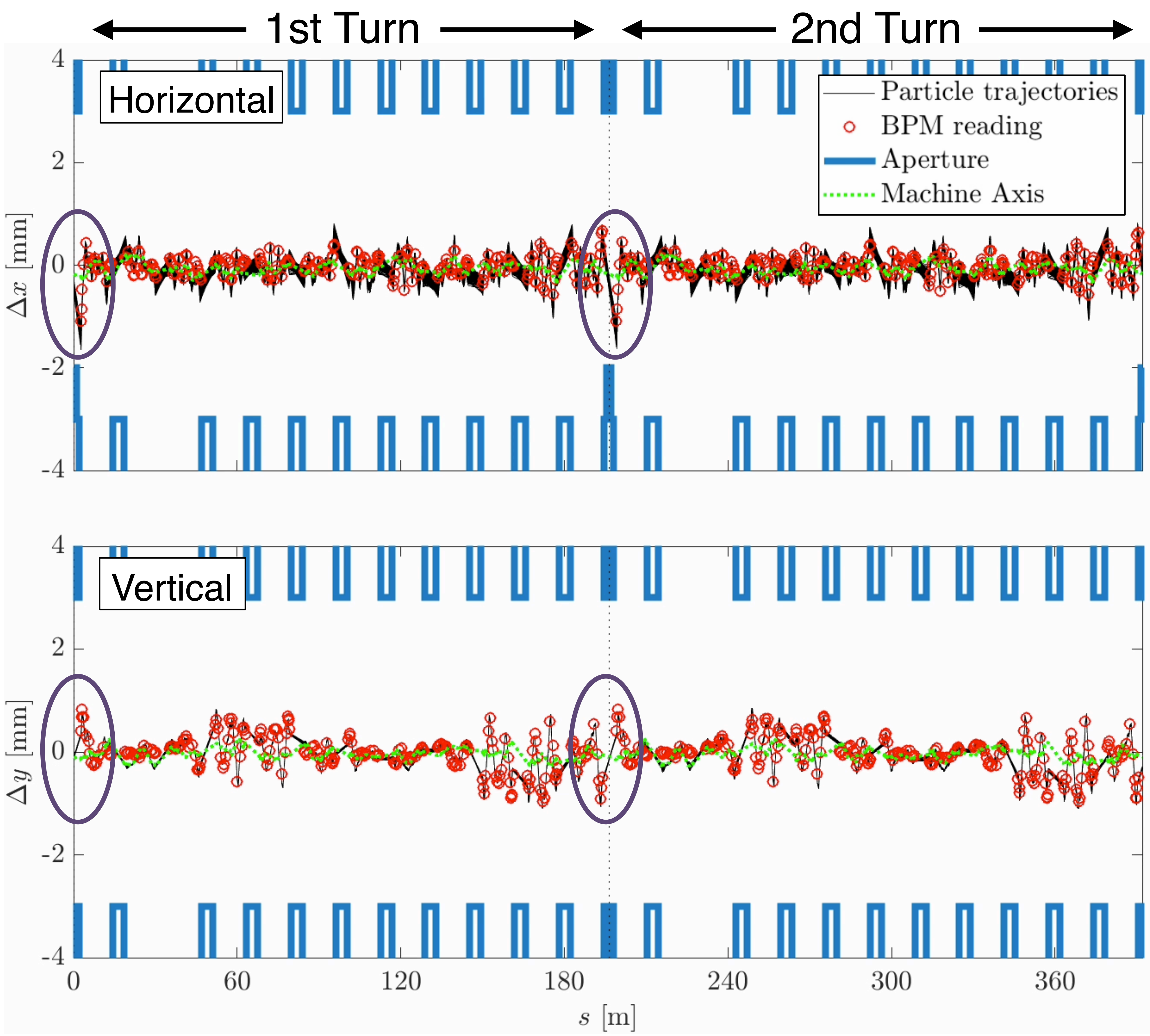
Achieving multi-turn transmission

- Perform beam based alignment
  - Minimize BPM offsets
- Match closed orbit to injection
  - Match 2nd turn to 1st turn BPM readings
    => Creates closed orbit bump at injection point



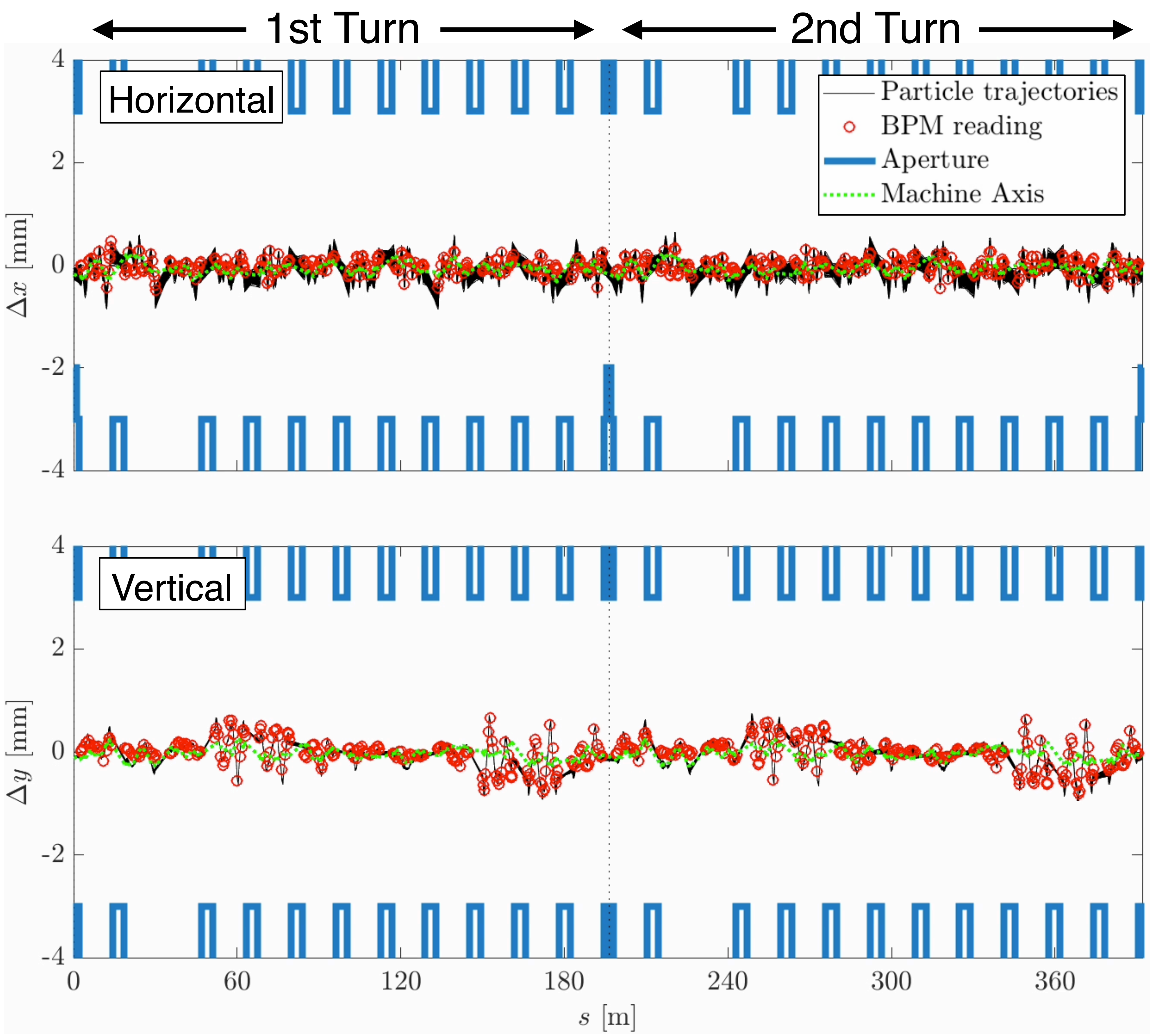
Achieving multi-turn transmission

- Perform beam based alignment
  - Minimize BPM offsets
- Match closed orbit to injection
  - Match 2nd turn to 1st turn BPM readings
    => Creates closed orbit bump at injection point
- Correct injected trajectory error
  - Use drift between last 1st turn BPM and first 2nd turn BPM to determine injection trajectory
- Minimize 2 turn BPM readings
  - Apply static injection correction adiabatically while running 2 turn feedback



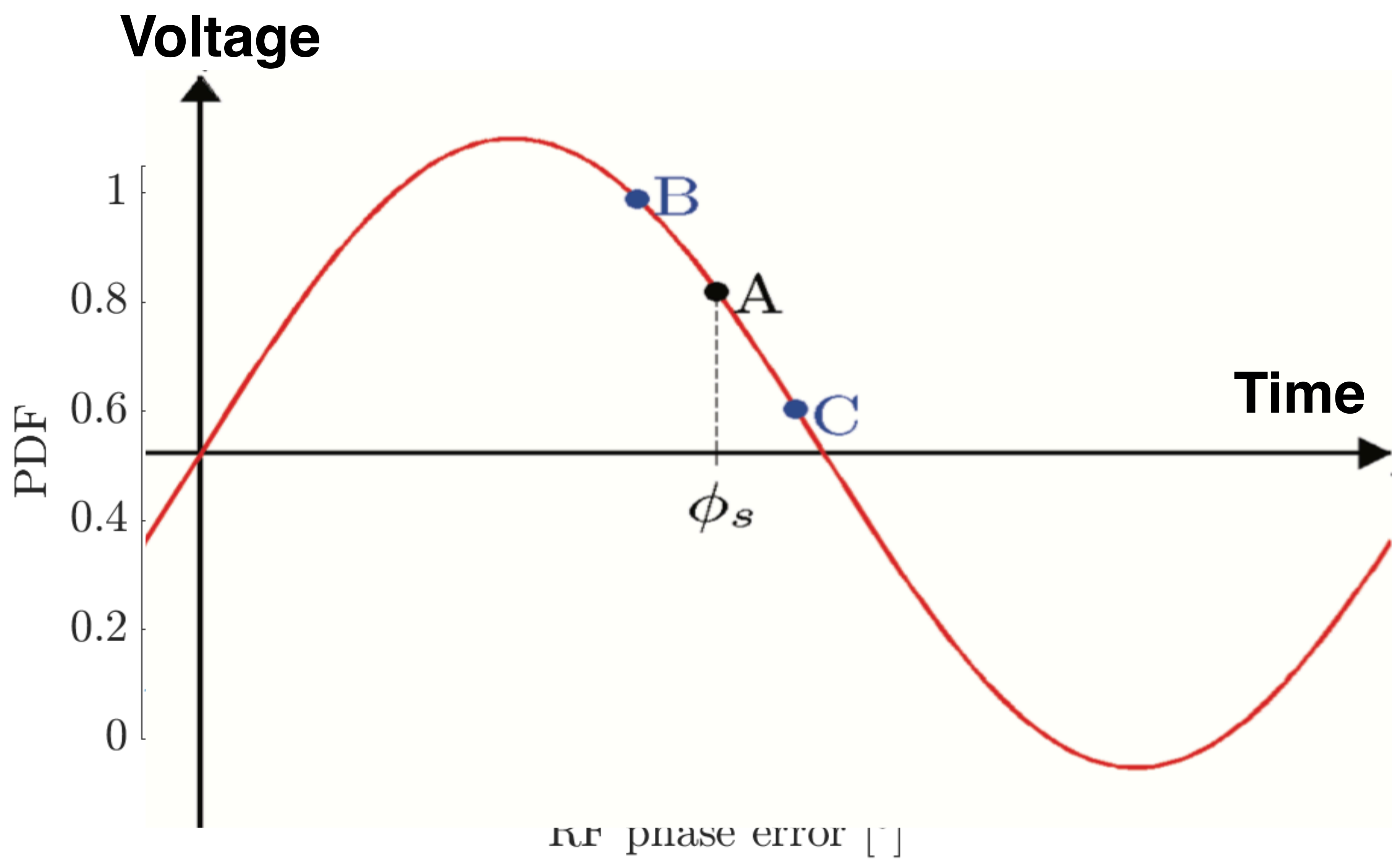
Achieving multi-turn transmission

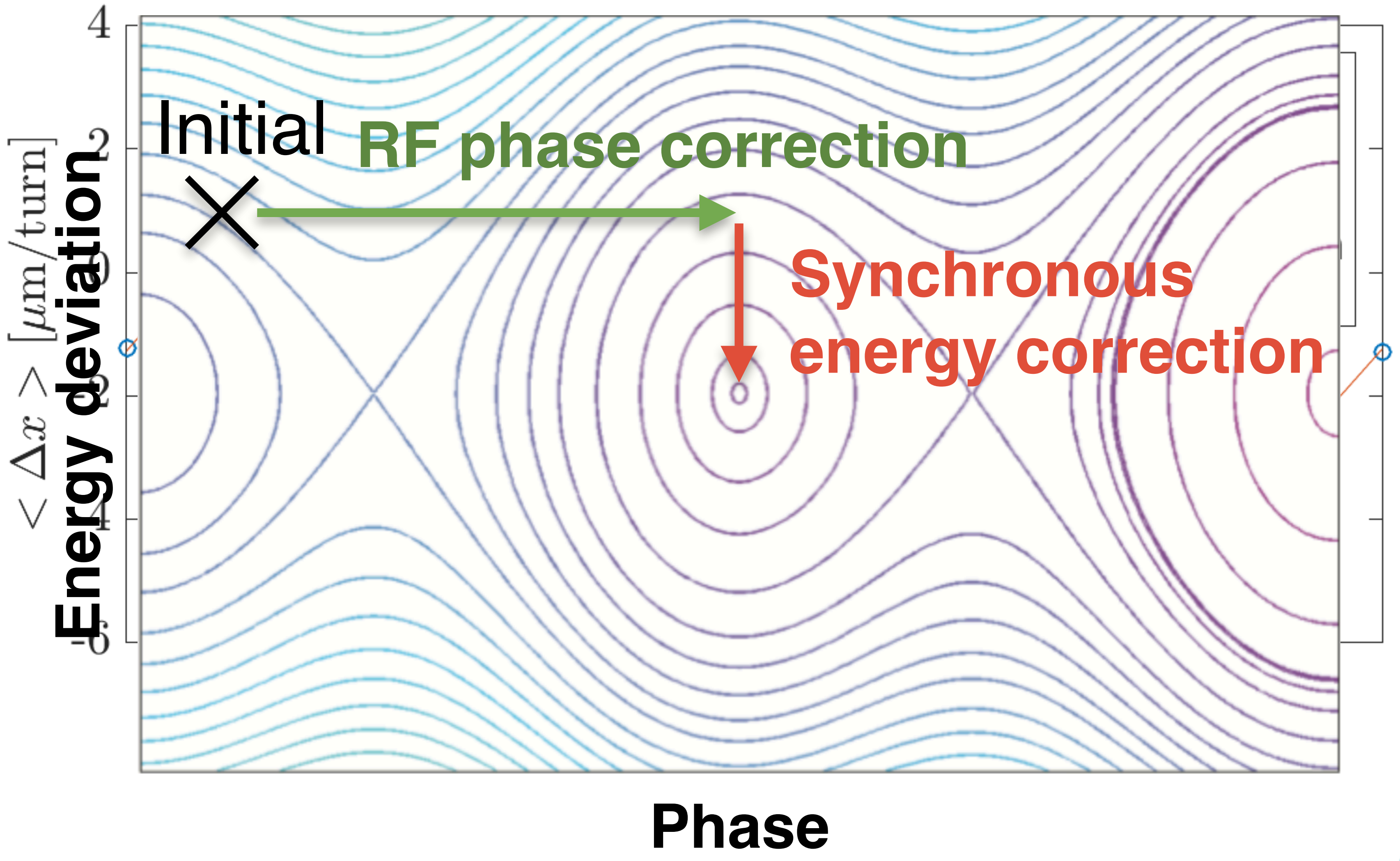
- Perform beam based alignment
  - Minimize BPM offsets
- Match closed orbit to injection
  - Match 2nd turn to 1st turn BPM readings
    => Creates closed orbit bump at injection point
- Correct injected trajectory error
  - Use drift between last 1st turn BPM and first 2nd turn BPM to determine injection trajectory
- Minimize 2 turn BPM readings
  - Apply static injection correction adiabatically while running 2 turn feedback
- Get final closed orbit
  - Match 2nd turn BPM readings to 1st turn BPM readings



RF cavity commissioning

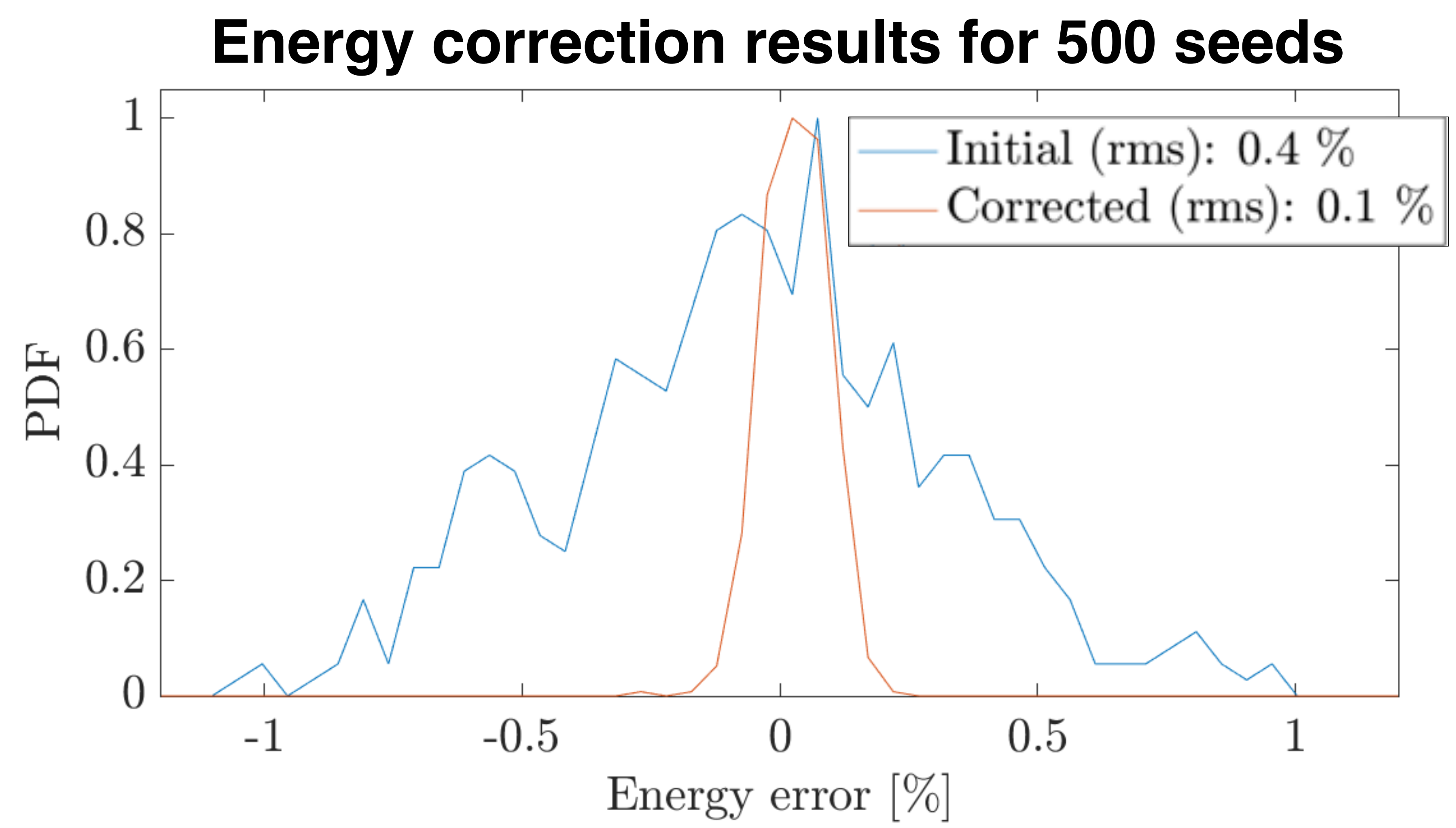
- RF phase critical parameter
  - Frequency error negligible
  - Voltage error small compared to overall voltage
    => Can be adjusted with synchronous phase
- Requirements for RF phase correction:
  - Transmission over 5 turns
- Measurement steps: vary RF phase
  - Evaluate BPM readings over 20 turns
    => Much smaller than synchrotron period
- Calculate mean turn-by-turn horizontal trajectory variation at all BPMs
  - $< \Delta x > /\mathrm{turn} \propto \sin(\phi + \Delta\phi) + c$
- Fit sinusoidal function and identify synchronous phase

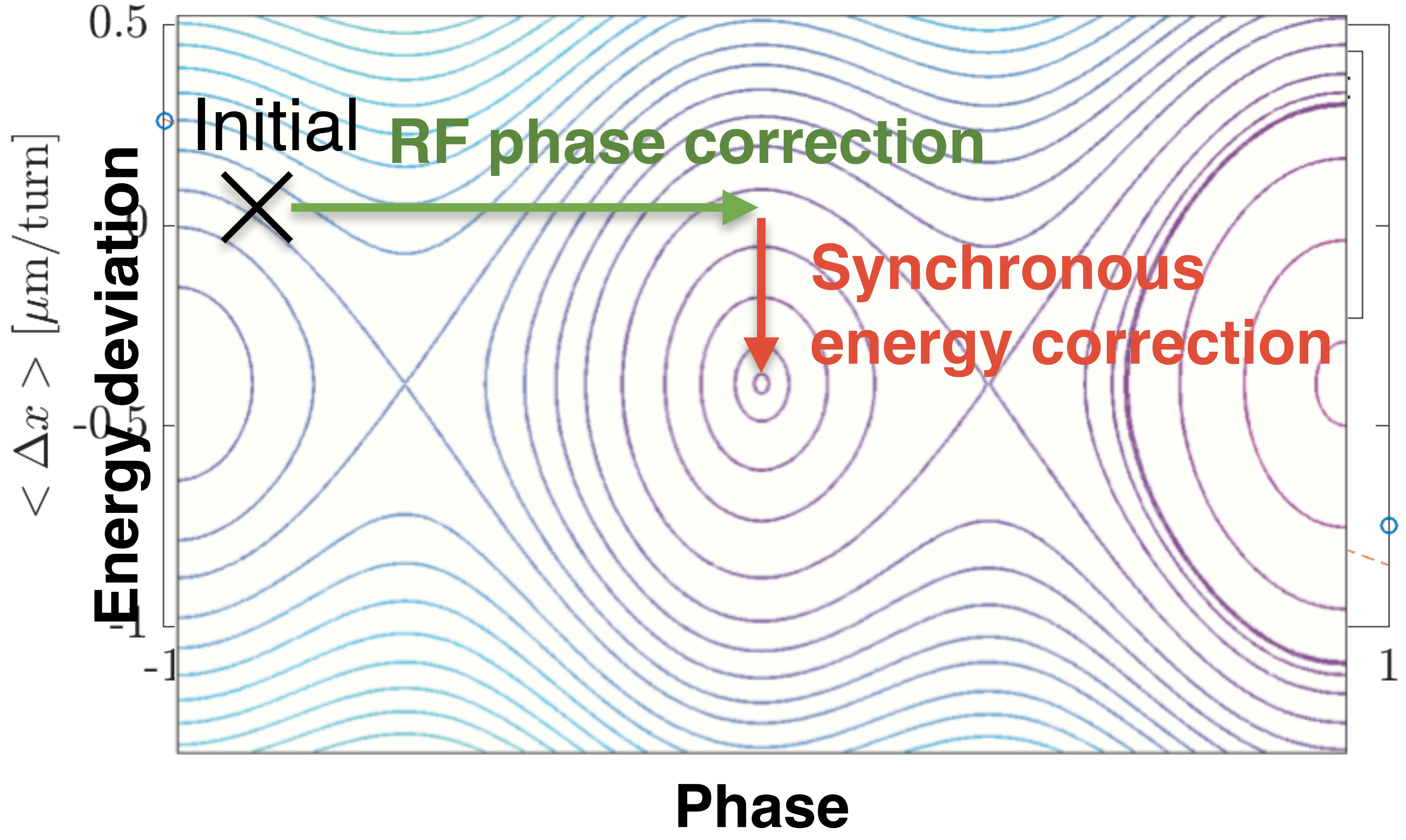




Synchronous energy correction

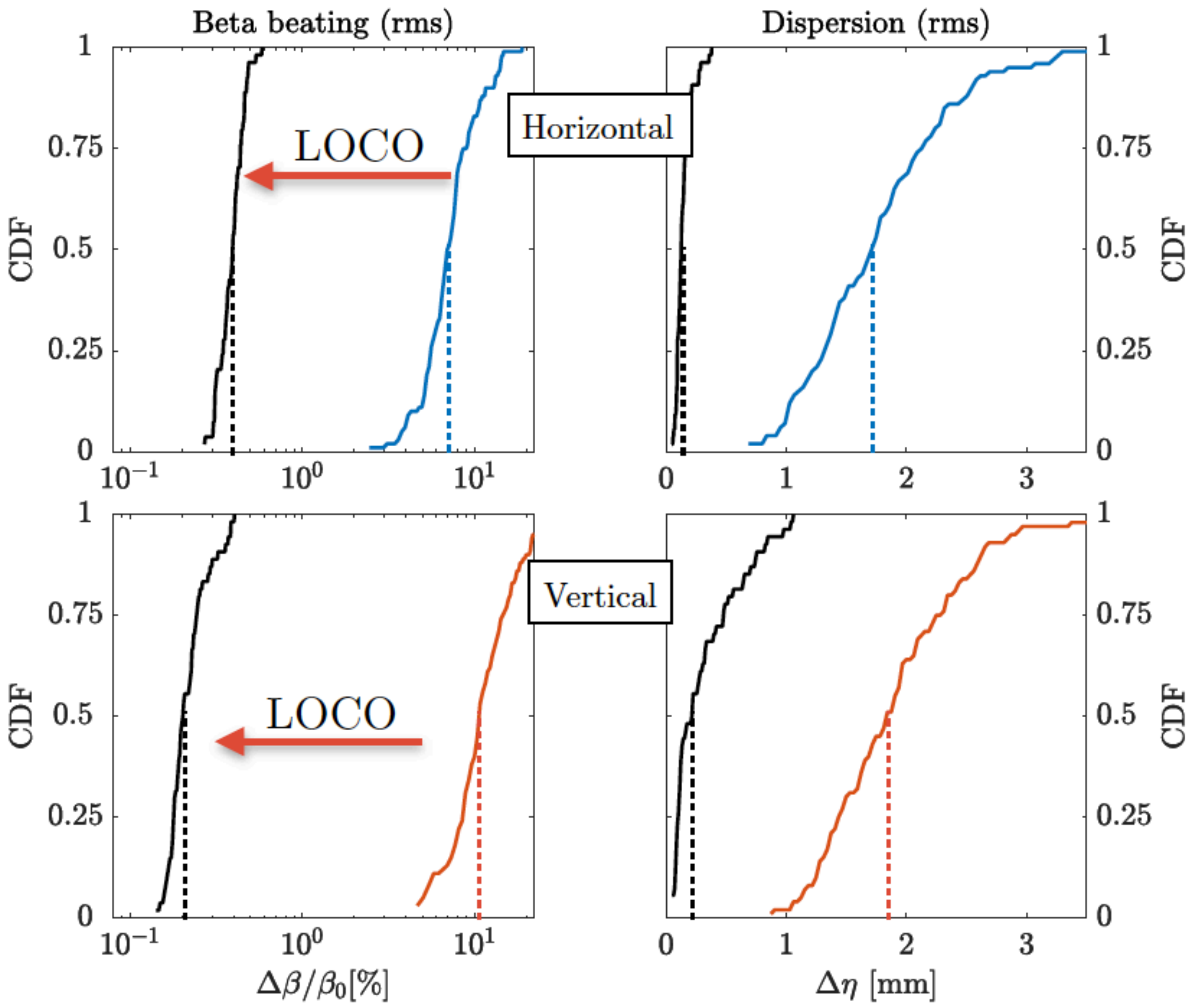
- Momentum aperture in early commissioning
    - Significantly decreased by optics errors
    - Rms bunch energy spread 0.1%
    - Injection at sync. energy critical for beam capture
- Requirements for energy correction:
    - Sufficient multi-turn transmission
    - Well corrected RF phase
- Measurement steps: vary horizontal CMs
    - Evaluate BPM readings over 150 turns
      => Less than half of synchrotron period
- Calculate mean turn-by-turn horizontal trajectory variation at all BPMs
    - $< \Delta x > /\mathrm{turn} \propto \Delta E + c$
- Fit line and identify synchronous energy


Energy correction results for 500 seeds



Last Step: Linear Optics Correction

Beta beat and dispersion errors can be effectively corrected



- Beta beat well below 1 %
  - Horizontal ∈ [0.27 | 0.58] %
  - Vertical ∈ [0.14 | 0.41] %
  - Mean = [0.39 | 0.23] %
- Dispersion below ~1 mm
  - Horizontal ∈ [0.05 | 0.38] mm
  - Vertical ∈ [0.05 | 1.07] mm
  - Mean = [0.14 | 0.32] %
  - Trade off between beta beat and dispersion

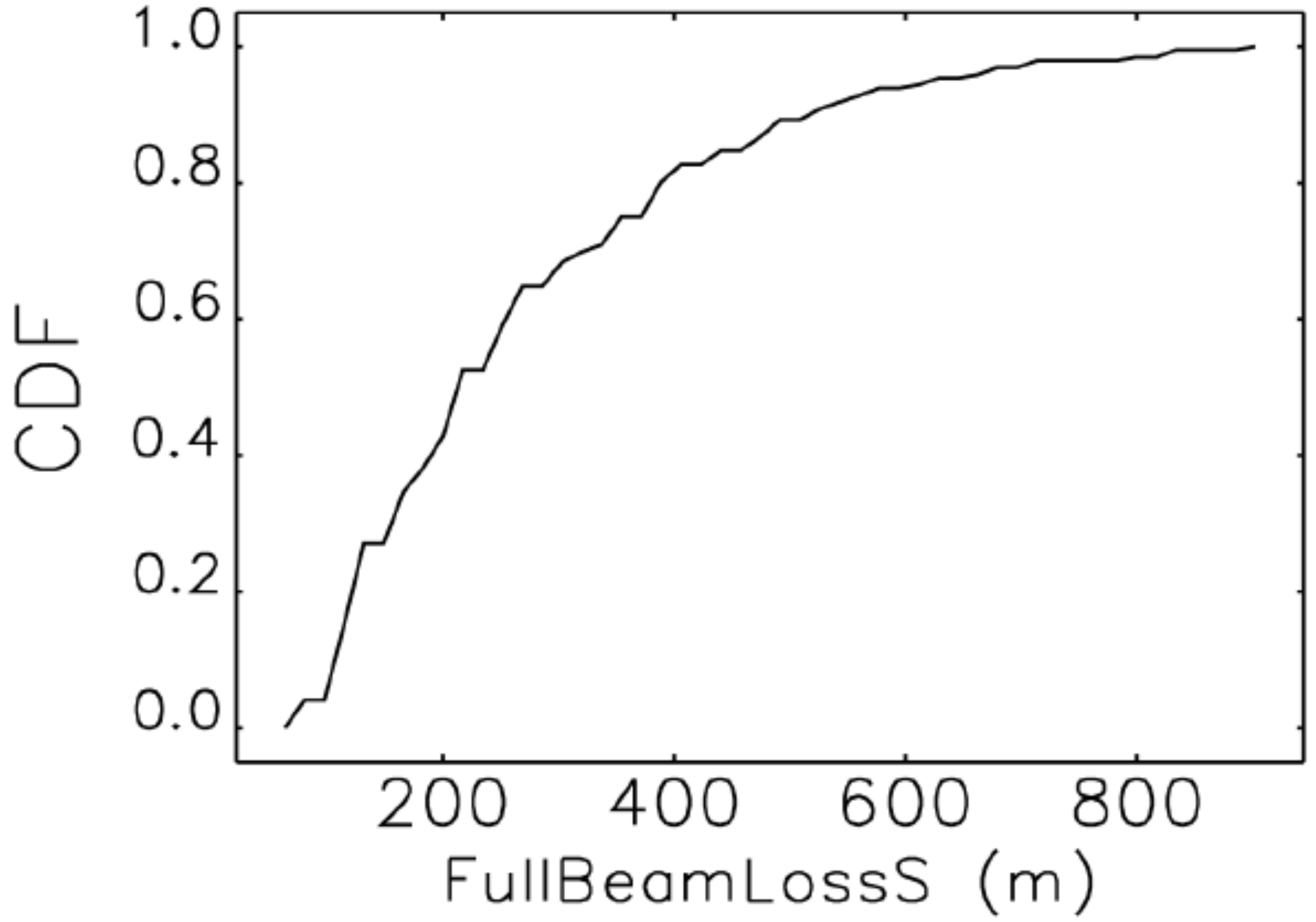
T. Hellert - work in progress, not all error sources are included in this part of simulation, yet.

Other Examples: APS-U

Commissioning simulation ensures fast actual commissioning

- We performed start-to-end simulation of orbit and lattice correction, trying to include as many types of errors as possible, to ensure that fast commissioning is possible

Expected full beam loss position after injection with no trajectory correction



These errors are included in the simulations:

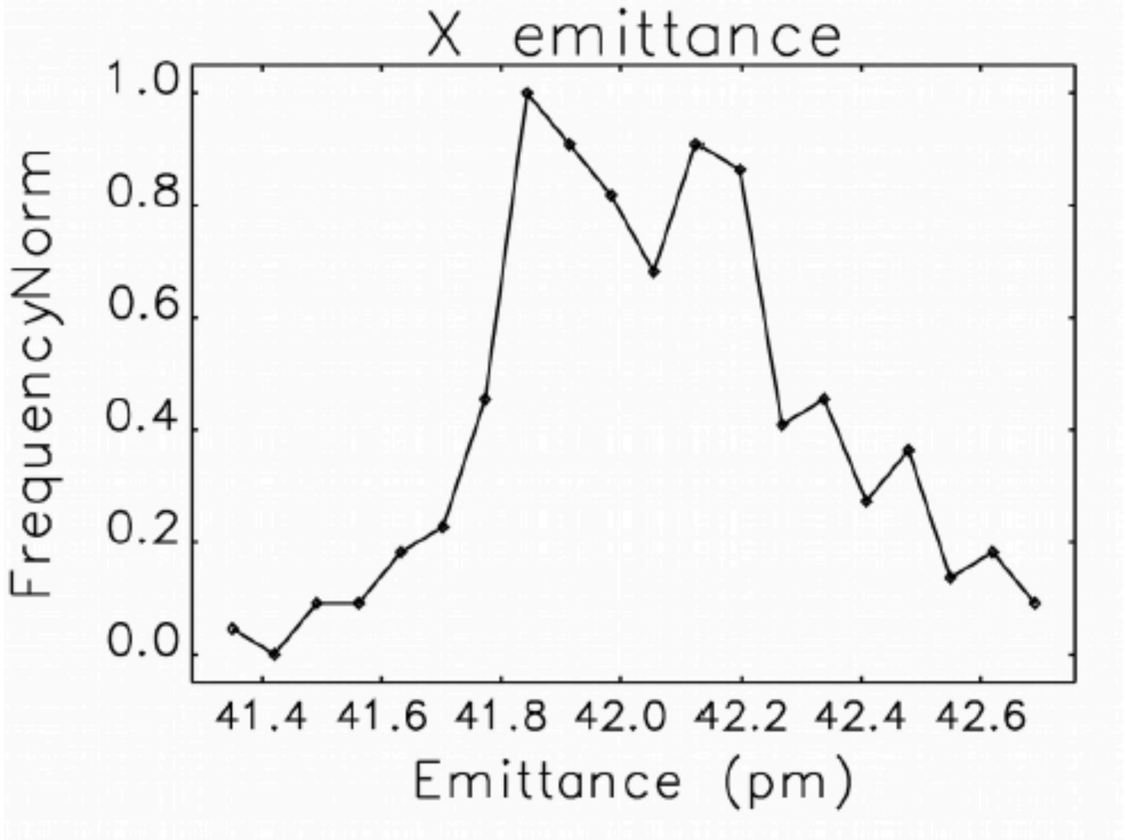
Girder misalignment	100 μm
Elements within girder	30 μm
Dipole fractional strength error	$1 \cdot 10^{-3}$
Quadrupole fractional strength error	$1 \cdot 10^{-3}$
Dipole tilt	0.4 mrad
Quadrupole tilt	0.4 mrad
Sextupole tilt	0.4 mrad
Corrector calibration error	5%
Initial BPM offset error	500 μm
BPM calibration error	5%
BPM single-shot measurement noise	30 μm*
BPM orbit low-current noise	3 μm
BPM orbit high-current noise	0.1 μm
BPM and corrector tilts	1 mrad

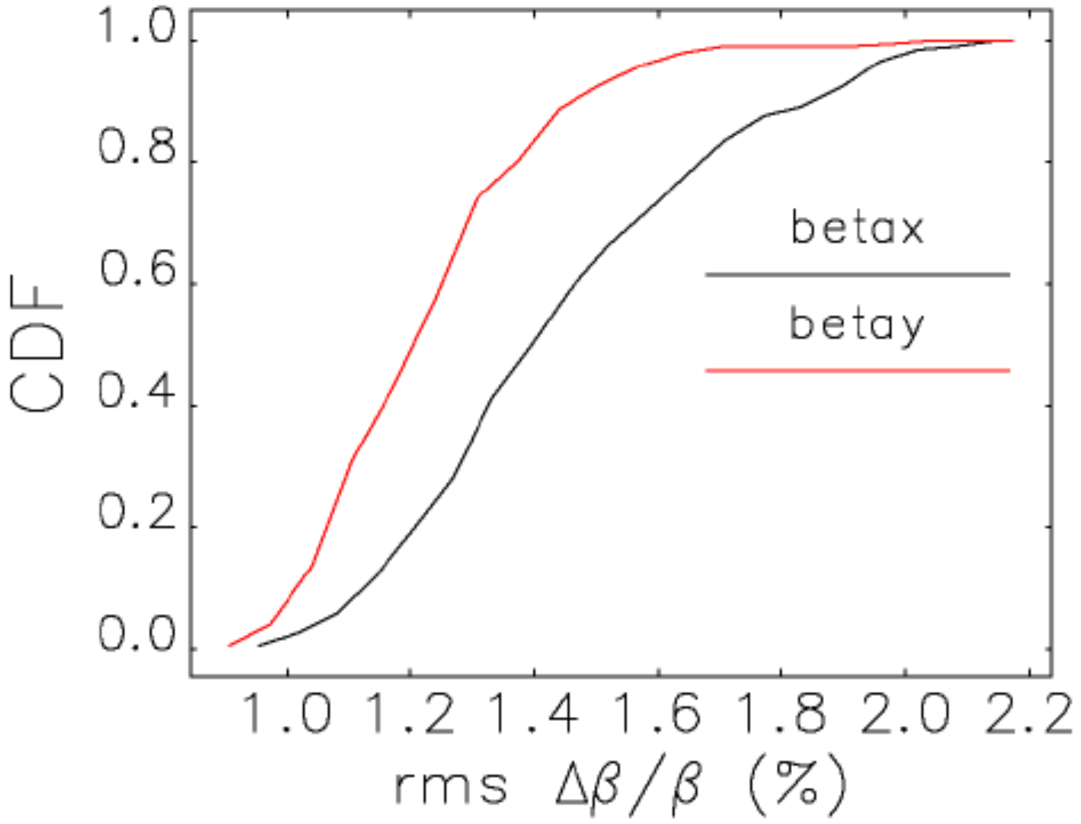
V. Sajaev

APS-U example: procedure / results

Automated procedure performs start-to-end commissioning

- Procedure is made as realistic as reasonably possible by including
  - Error generation
  - First-turn trajectory correction
  - Global trajectory correction until the orbit is established
  - RF frequency and phase set up
  - Orbit correction with sextupole ramp
  - Beta function correction using response matrix fit
  - Coupling correction minimizing cross-plane orbit response
  - Coupling adjustment to 10% at separated tunes
- The simulations are typically run for 200 error seeds
- The procedure is with tunes that are separated and moved away from integer (0.18 and 0.22 instead of 0.10 and 0.10)
  - Tunes are returned back after commissioning is completed





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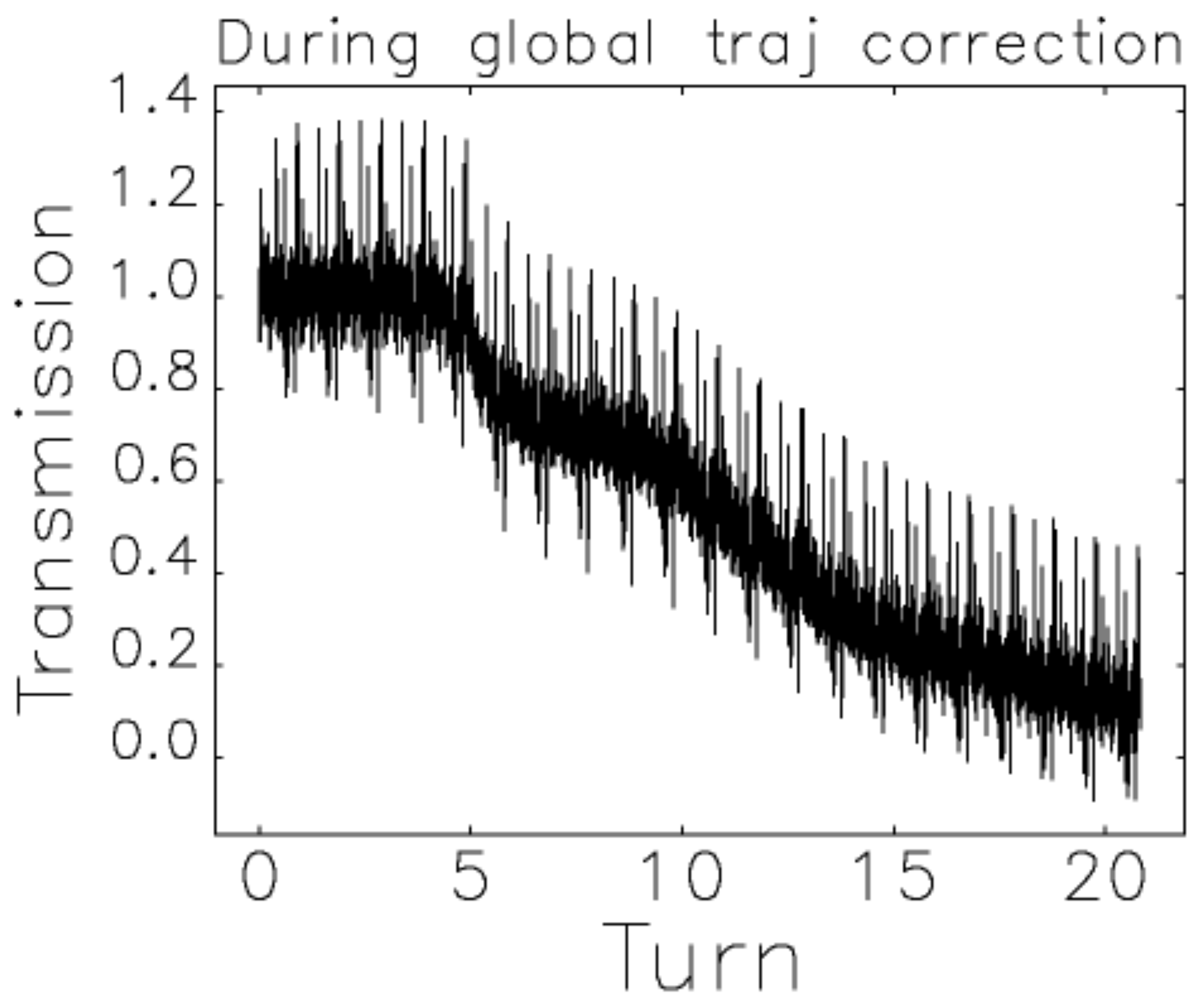
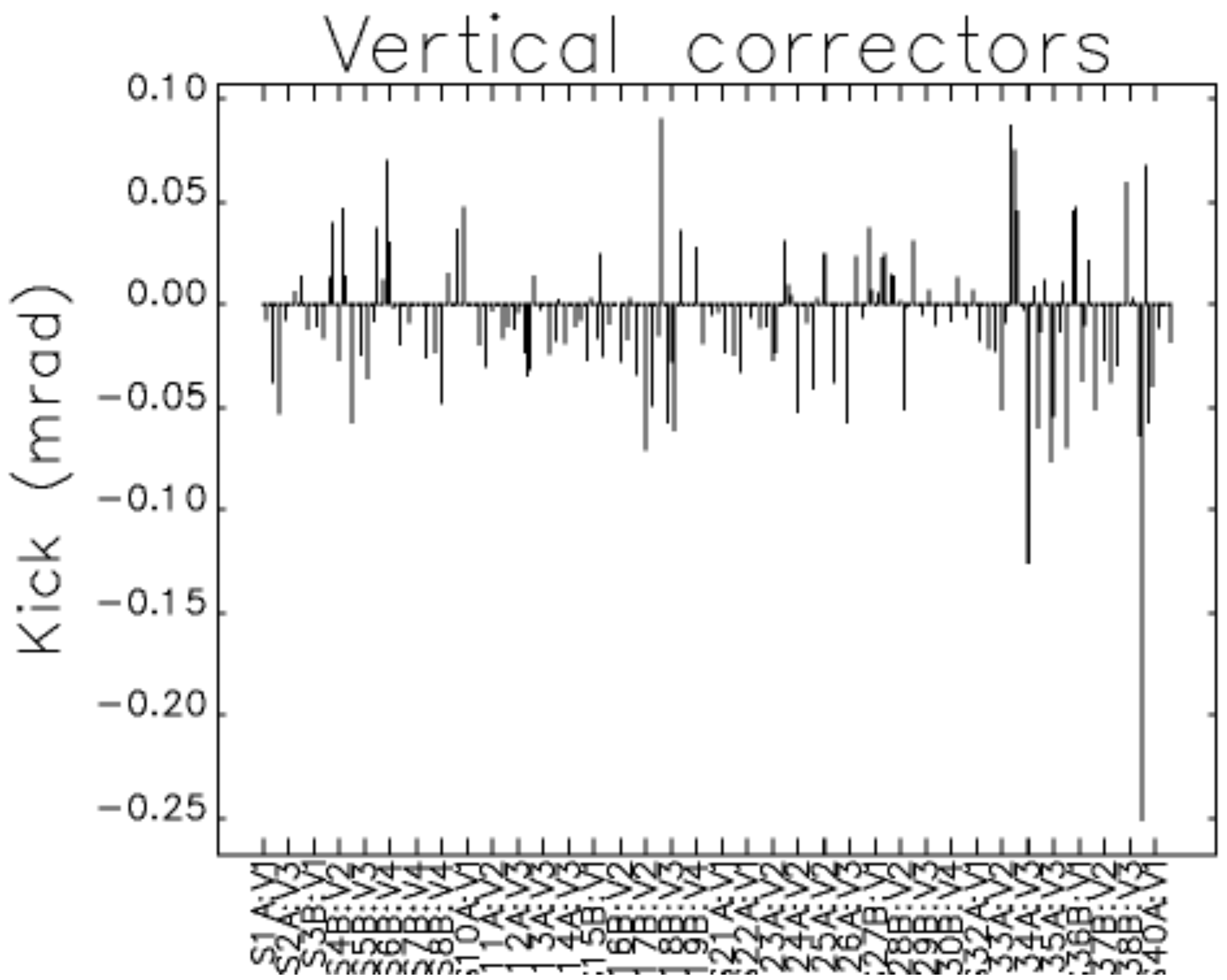
APS-U example: early tests on APS

- Completed steps:
  - Correction of injected beam coordinates
  - First-turn trajectory correction using multi-corrector threading
  - Equalizing end-of-turn coordinates to injected coordinates to create “closed orbit” condition
  - Global trajectory correction
    - Results in ~20 turns
- Used in operations for years:
  - Beta function and coupling correction using response matrix
- Still to complete
  - Orbit correction with low number of turns
  - BPM sanity checks to determine miswired BPM cables
  - RF setup





V. Sajaev

Summary

- Realistic simulation of commissioning process required
    - Challenging lattice of future light sources
    - Standard approach of error tolerance determination not feasible
    - Tolerances studies must include commissioning process
- Development of start-to-end commissioning simulation at multiple places
    - ALS-U / APS-U
    - simulations also in progress at other MBA rings under design, like HEPS, PETRA-IV
- Specific features of ALS-U approach
    - Feedback-like trajectory correction scheme using high resolution turn-by-turn BPMs
    - Reliable multi-turn transmission
    - Model independent single pass BBA procedure
    - 6D closed orbit correction