PETRA IV.
NEW DIMENSIONS

High bandwidth and high precision orbit feedback design for PETRA IV

Sajjad H. Mirza on behalf of Work Package 2.08 (Feedback)
MSK, DESY, Hamburg
Hamburg, 27.06.2023

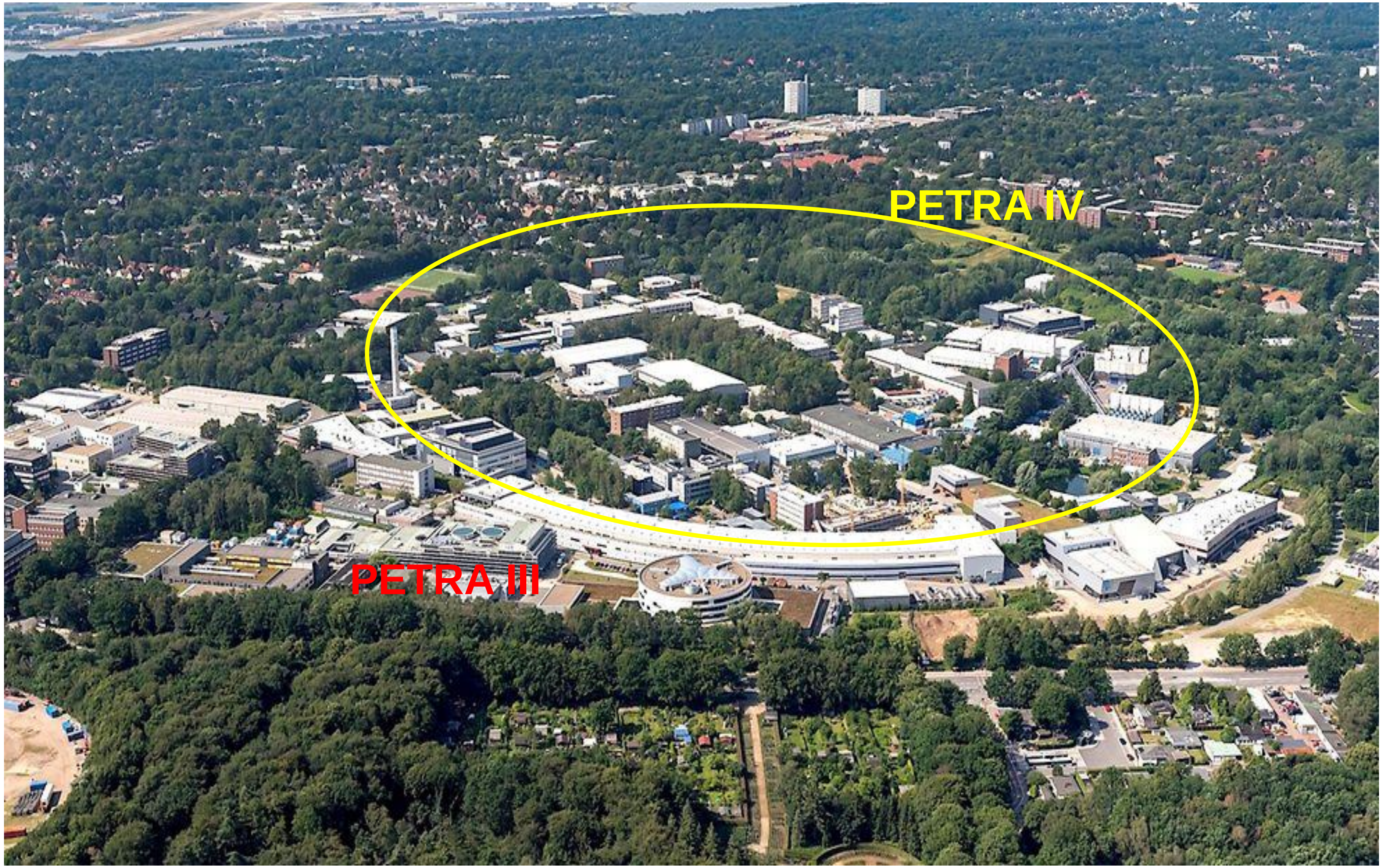
HELMHOLTZ

DESY.

Content

PETRA IV-introduction

PETRA IV. NEW DIMENSIONS



- 6 GeV fourth generation light source under development
- Circumference: 2300 meters.
- Construction of the accelerator within the existing PETRA III tunnel
- Target of highest spatial resolution for all X-ray techniques by focusing the synchrotron radiation on the smallest spot
- Planned beam emittance

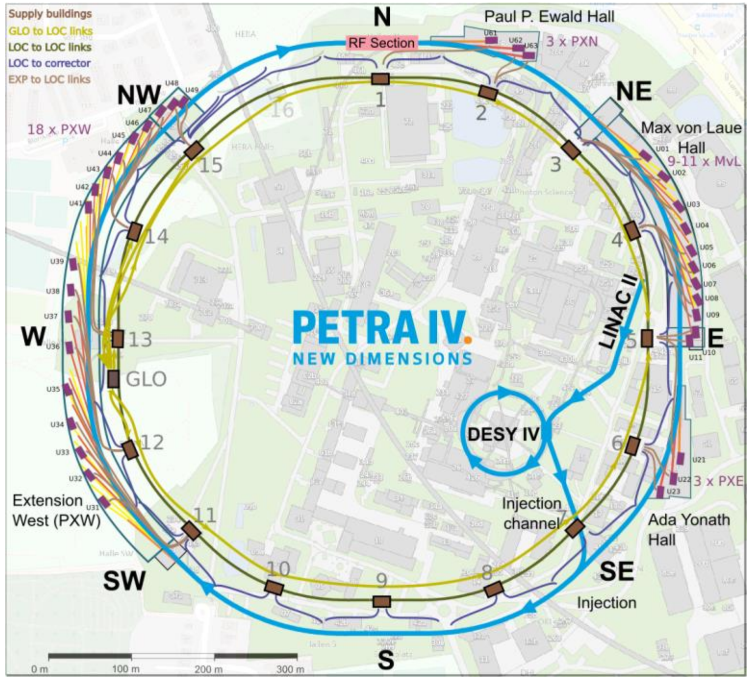
  ε (20 pm.rad (X) and 4 pm.rad (Y))

https://www.hamburg.de/bwfgb/14855792/foederung-petra-iv-tdr/

FOFB parameters

FOFB: Machine Parameters & Beam Stability Requirements

Parameter	**Value**
Circumference	2.3km
Number of BPMs (x/y)	788
Number of fast correctors	560 (244H, 316V)
Betatron freq. (f_x / f_y)	23.4 kHz / 35.2 kHz
Synchrotron oscillation	600 Hz
$\beta_{x,y}$ at ID, standard cell (29)	2.2 m, 2.2 m
$\beta_{x,y}$ at ID, flagship IDs (7)	4 m, 4 m
Natural emittance $\epsilon_{x,y}$	20 pm rad, 4 pm rad
Beam size $\sigma_{x,y}$ at ID, standard cell	6.6 μm, 2.97 μm
Beam size $\sigma_{x,y}$ at ID, flagship IDs	8.9 μm, 3.98 μm
Beam divergence $\sigma'_{x,y}$ at ID, standard cell	3.02 μrad, 1.34 μrad
Beam divergence $\sigma'_{x,y}$ at ID, flagship IDs	2.23 μrad, 1.0 μrad



Beam stability requirements:

Typically 10% of beam size and divergence at the IDs.

$$\sigma_e = \sqrt{\beta\varepsilon + \sigma_E^2\eta^2} \qquad \sigma_e' = \sqrt{\frac{\varepsilon}{\beta}}$$

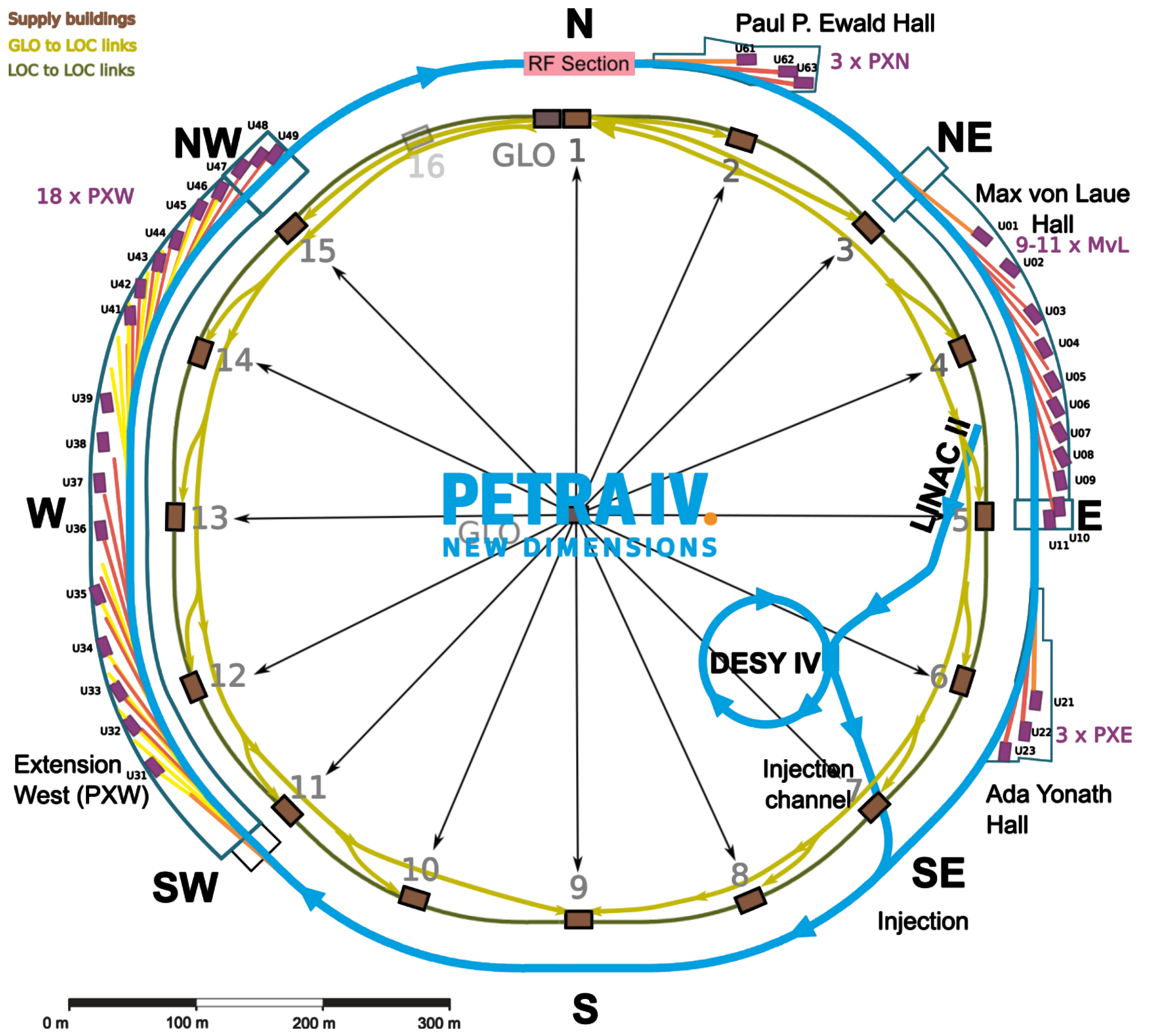
Remark: Some beamlines may require even 5%, 3%, … in future?

FOFB system topology

Latency optimized topology

Task force for radiation damage: e.g. optical connections that have to be routed through tunnels

- **1 central control unit (GLO)**
  - Close to RF system / timing system
  - Short path from GLO to LOC in experimental halls
- **15 distributed local sections (LOC)**
  - BPM collector
  - Transmitter to power supplies
- **Optical fiber communication links**
  - Global to all local systems → classical regulation
  - Local to local system
    - For local control scheme integrating experiments

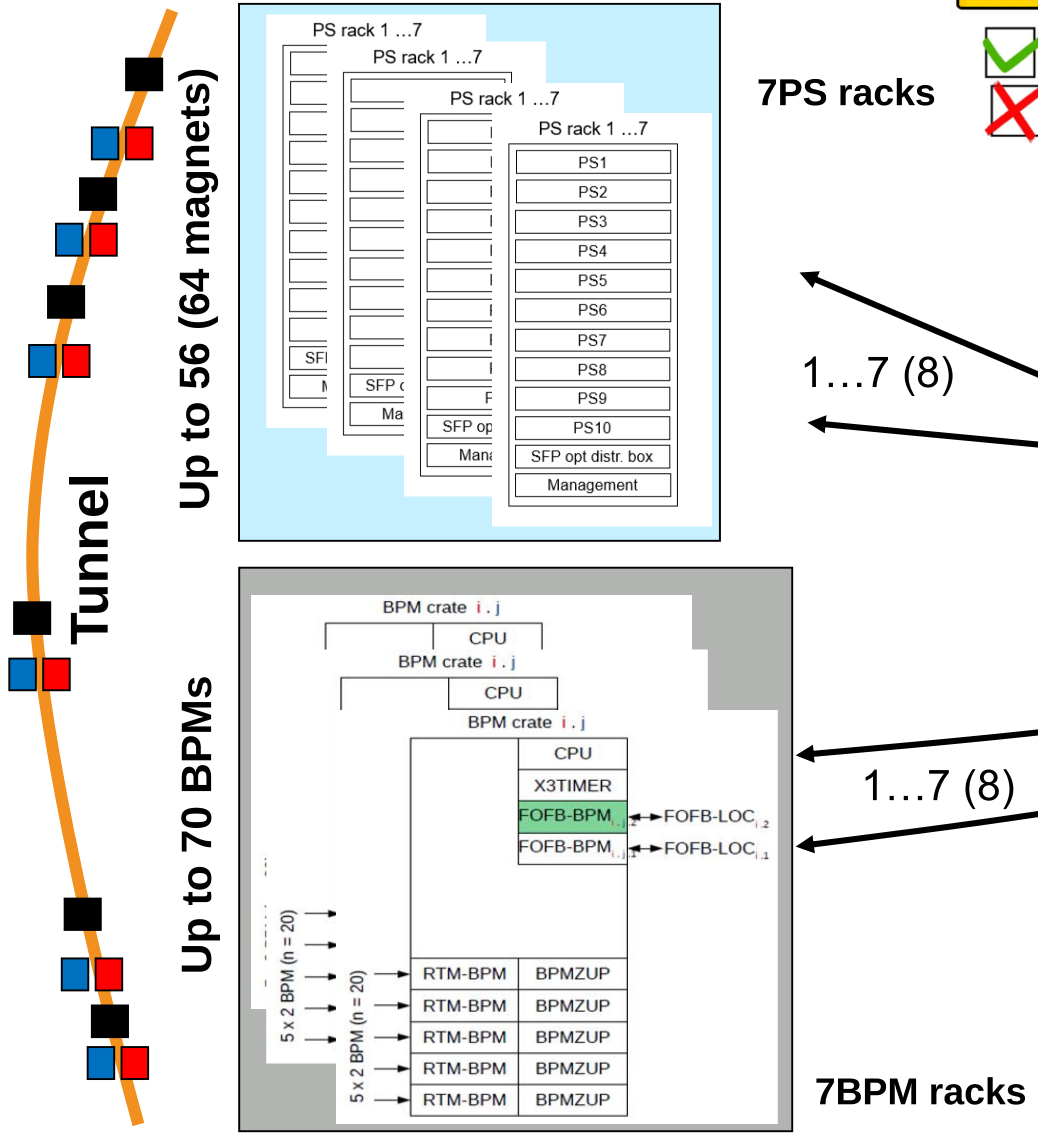


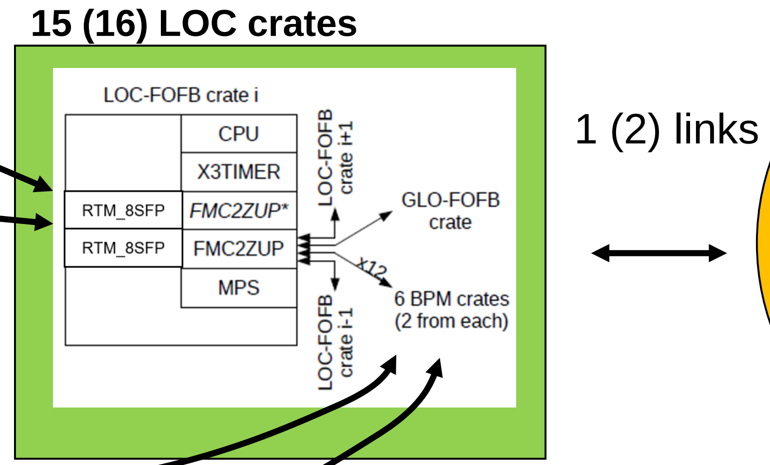
FOFB Infrastructure-local developments

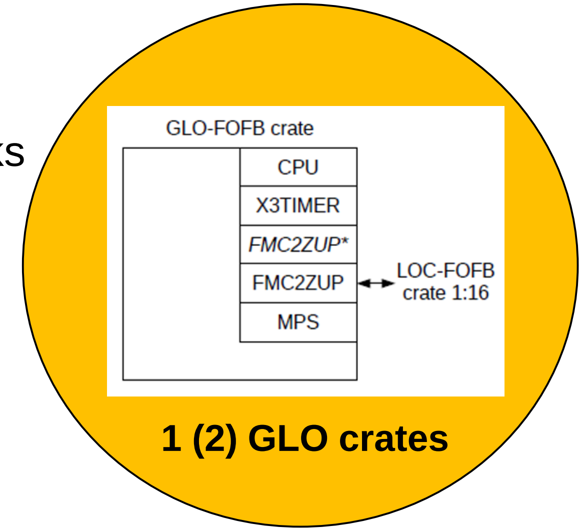
FOFB: Hardware Configuration

FOFB processing boards
- BPM collector board
- FMC2ZUP
- RTM_8SFP

Support boards
- CPU
- X3Timer → WP2.09
- MPS → WP2.05
- Power supplies

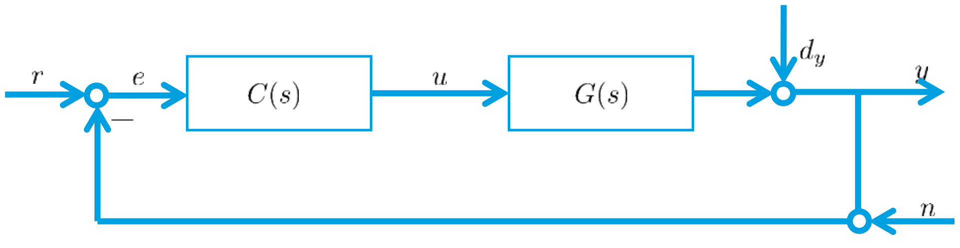




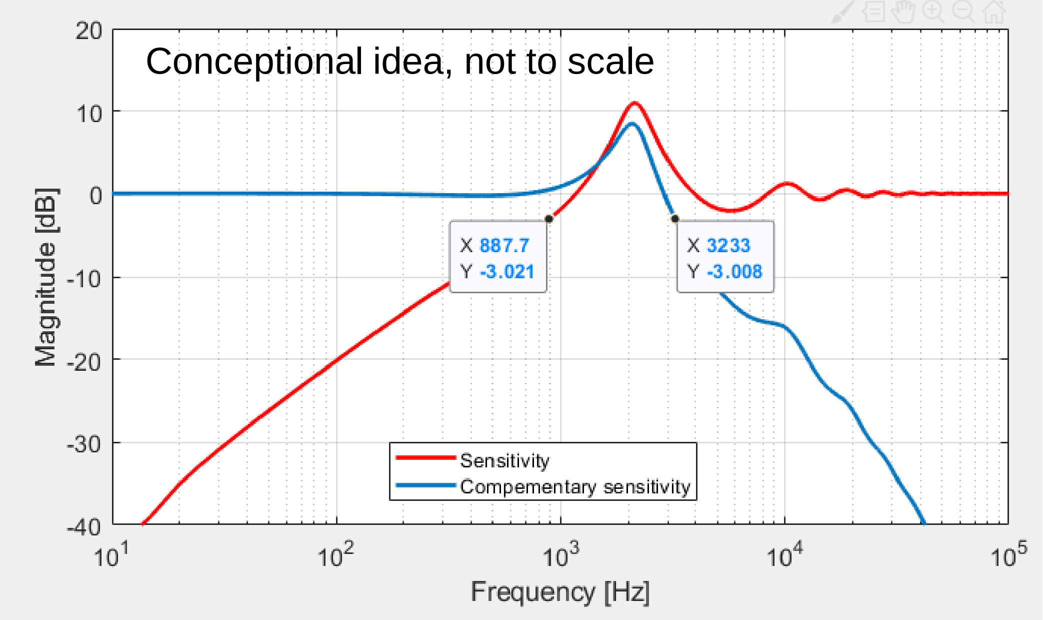


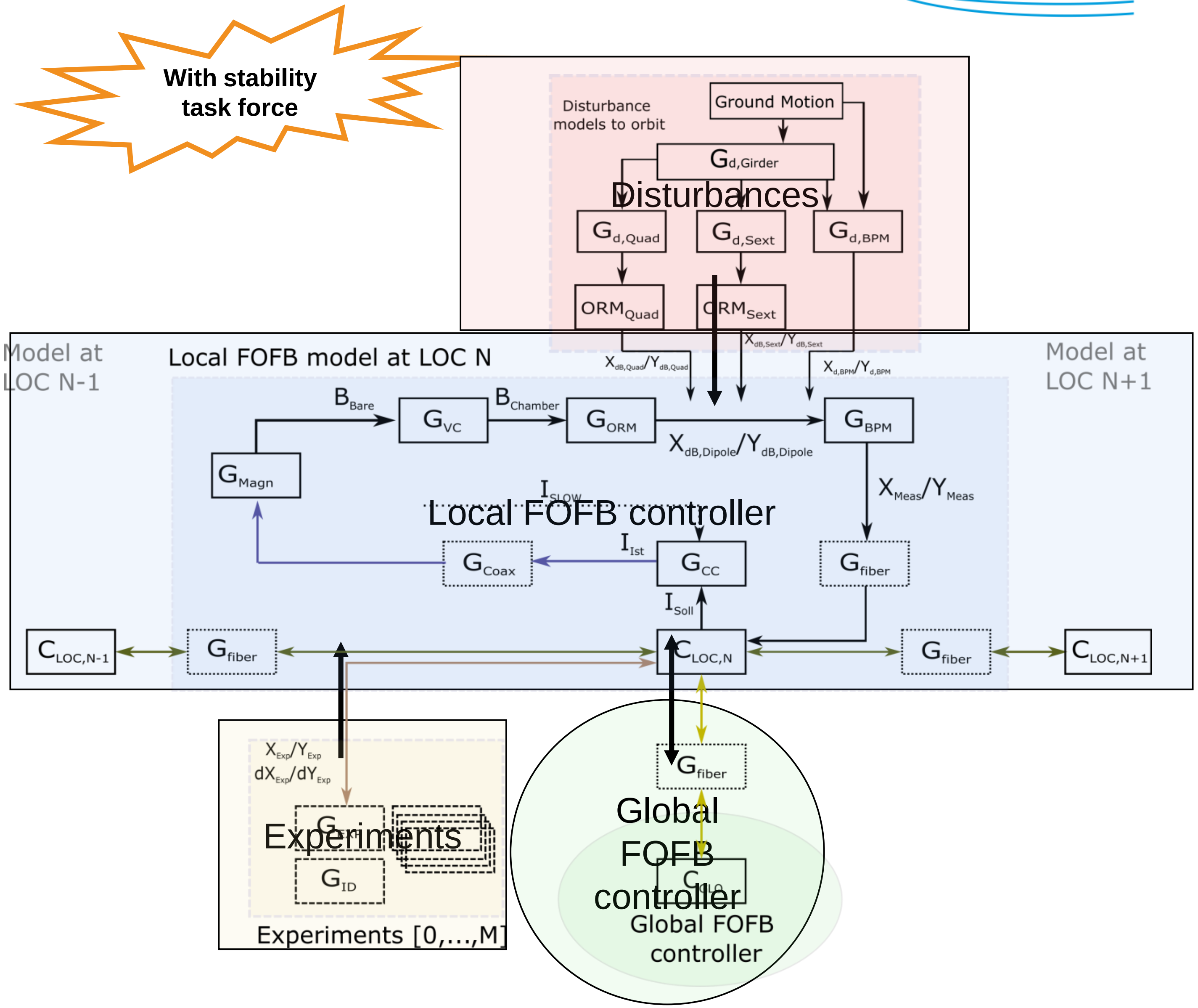
FOFB conceptual design

FOFB: FB Introduction



$$S = \frac{1}{1+GC} \qquad T = \frac{GC}{1+GC}$$





Disturbances

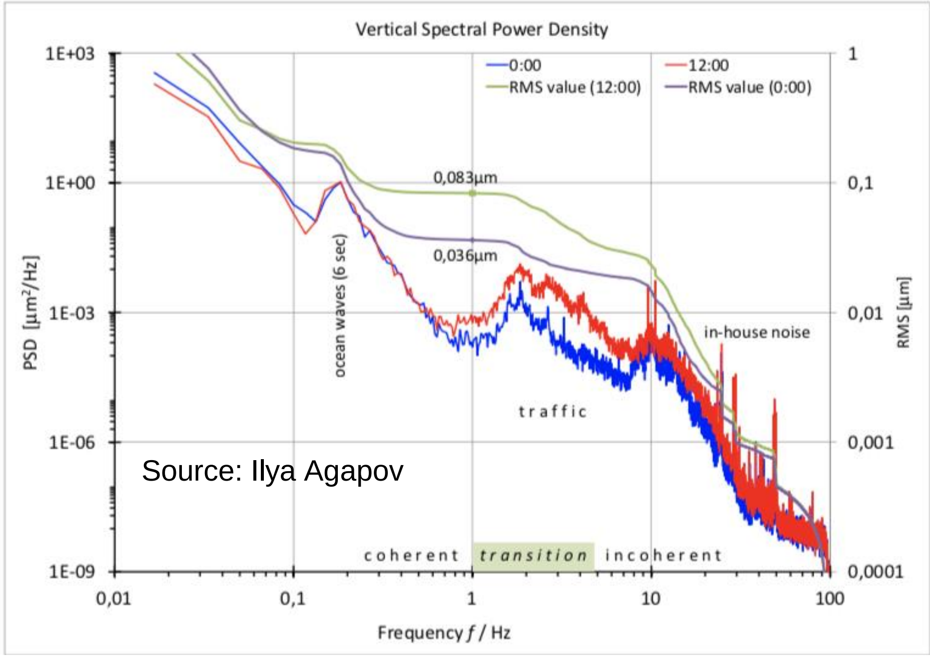
FOFB: Stability task force @ PETRA III

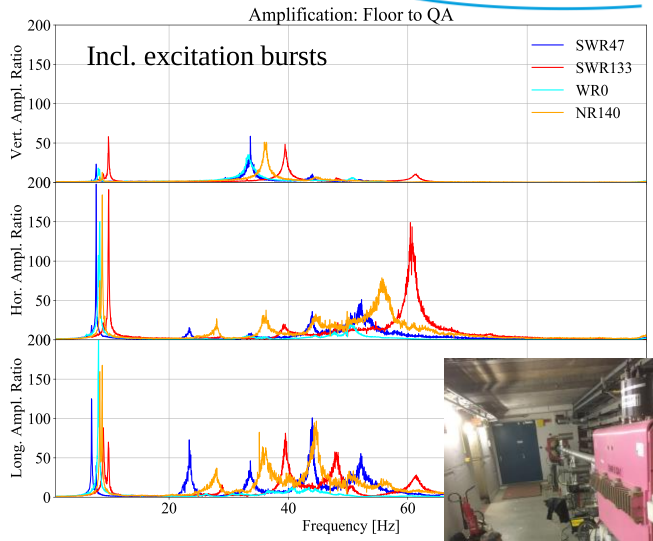
Ground motions

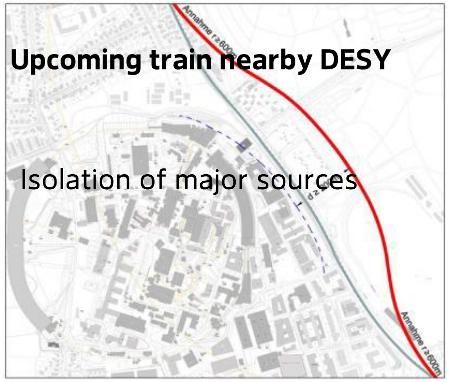
- Ocean waves (<1Hz)
- Traffic (1…10Hz)
- In-house noise (10…100Hz)
- Girder and amplification factor (< 48 Hz)

Additional sources / sinks

- ID gap movements (Hz – depending on speed)
- Asynchronous motors (<50Hz)
- Controlled motors/pumps (25Hz)
- Power supply output ripple (12.5 kHz)
- Harmonics of DESY II (~30Hz)



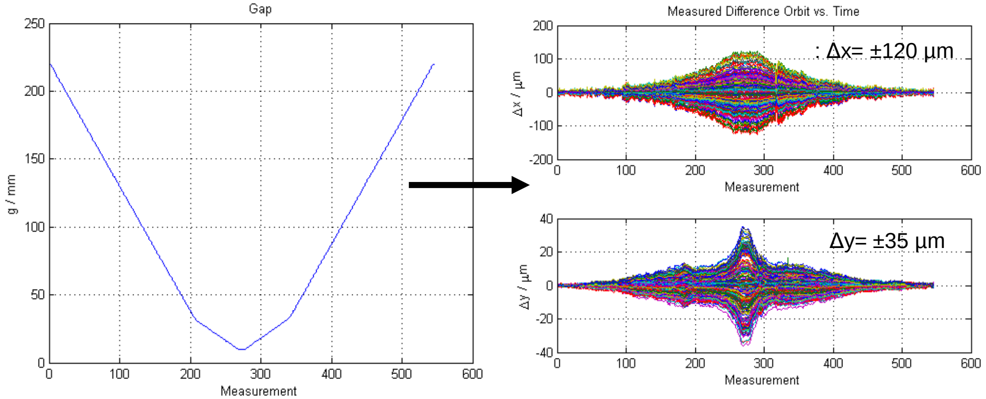




Upcoming train nearby DESY

Isolation of major sources

Orbit perturbation due to gap movements at PETRA III



FOFB Modelling

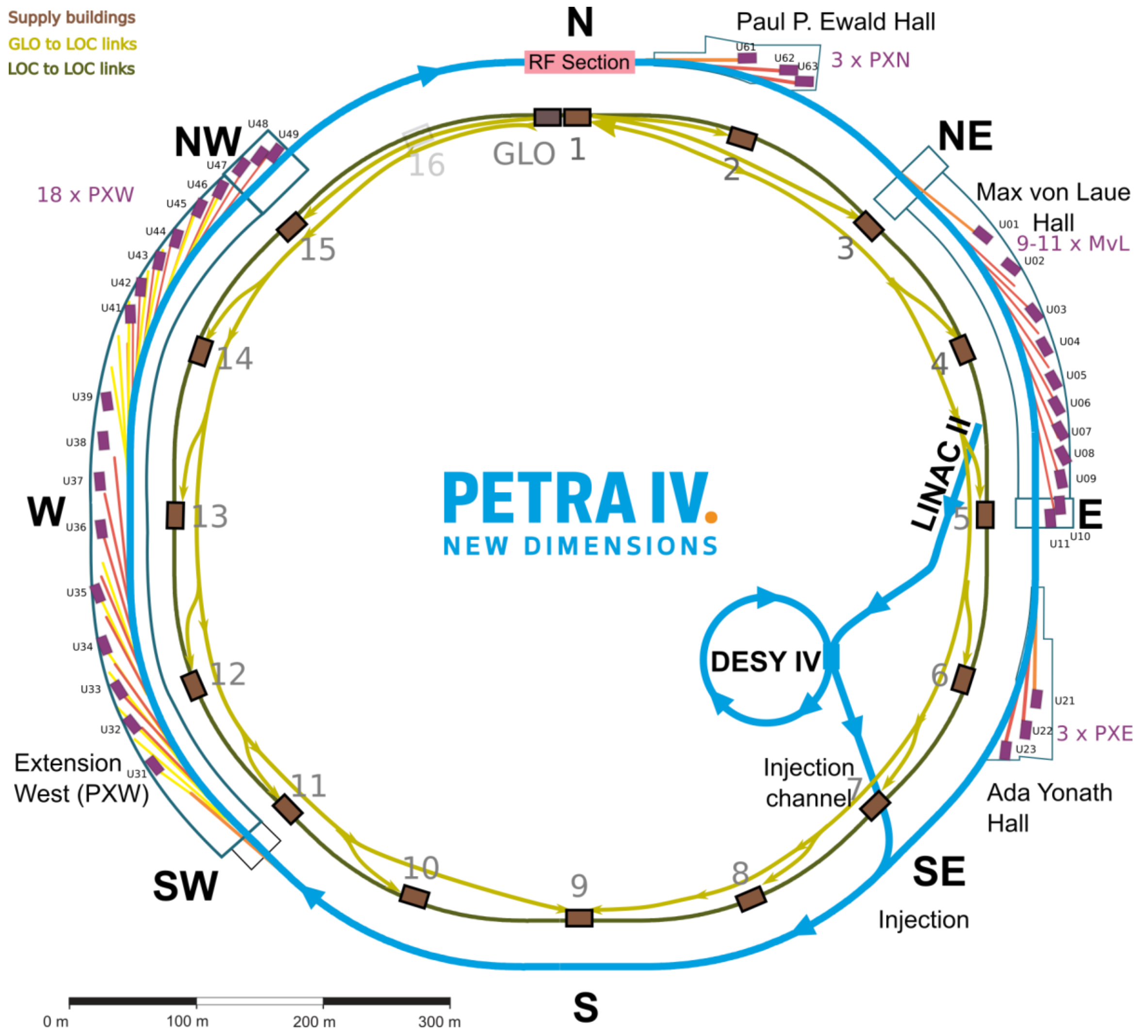
FOFB simulations - Introduction

Single-Input Single-Output (SISO)

- Locally – 1 position
- Dynamic responses of subsystems
- SISO worst case scenario → MIMO best case scenario

Multiple-Input Multiple-Output (MIMO)

- Globally – all locations (spatial distribution)
- Stable SISO system ≢ stable MIMO system
  - SVD modes can get unstable
- Currently static errors



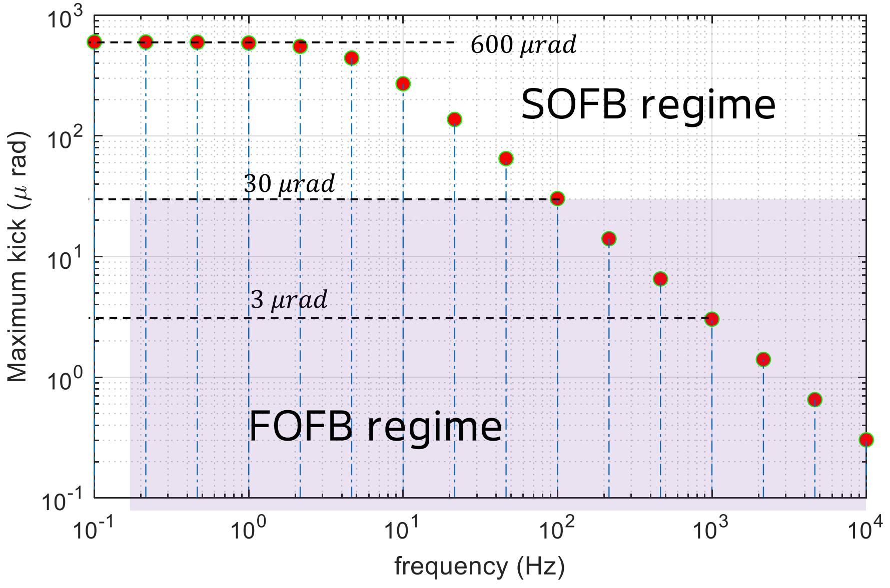
Corrector magnets and Power supply

Slow and fast correctors in lattice

Overlap of slow and fast magnets

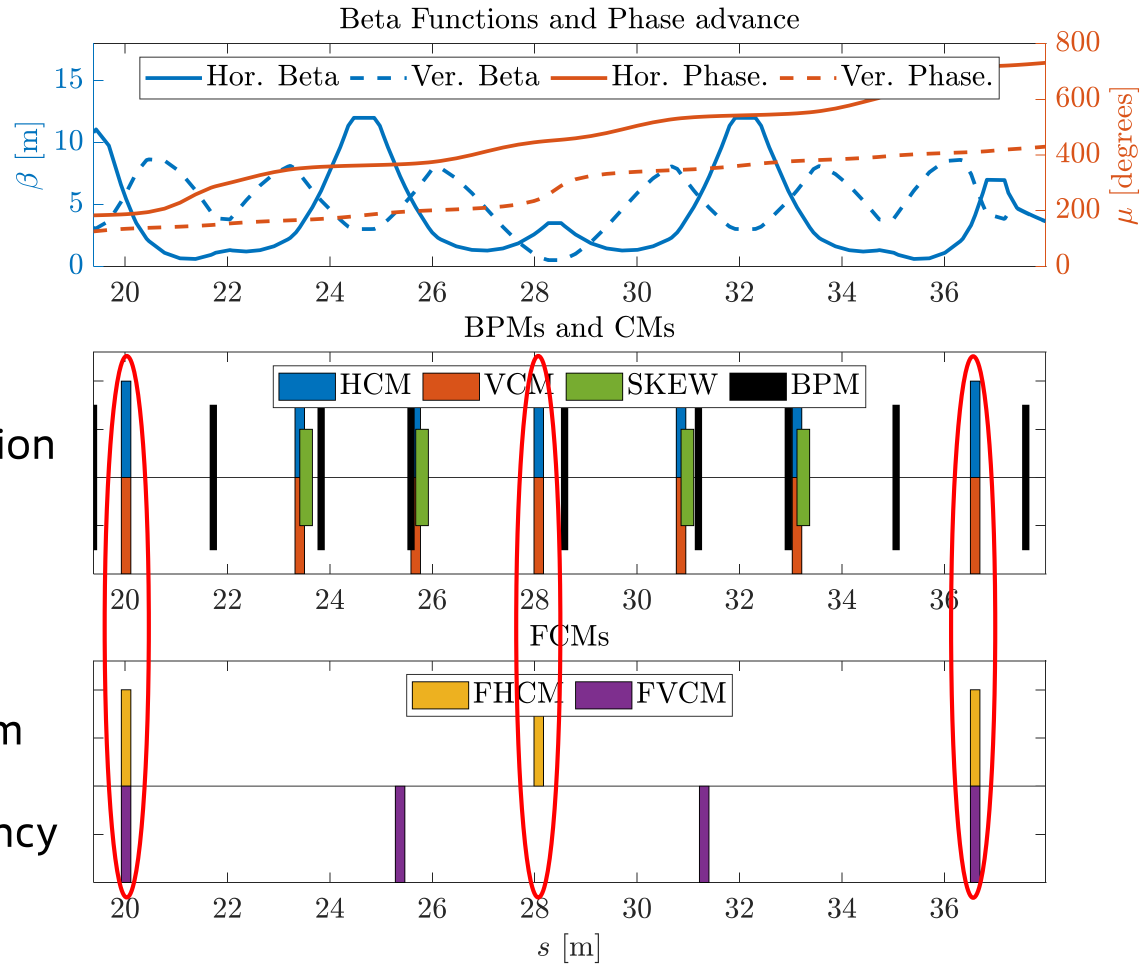
Slow corrector magnets = 618 in X-plane
Slow corrector magnets = 618 in Y-plane
Fast corrector magnets = 244 in X-plane
Fast corrector magnets = 316 in Y-plane

Higher corrector strength of fast magnets due to combined slow/fast action



Slow correction mHz range

FOFB system Quasi-DC to high frequency



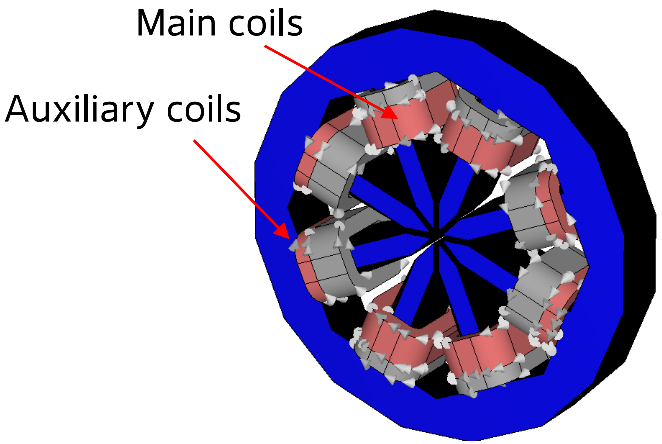
The overlap of slow and fast correctors lead us to interfere in

→Optimization of fast corrector magnet design

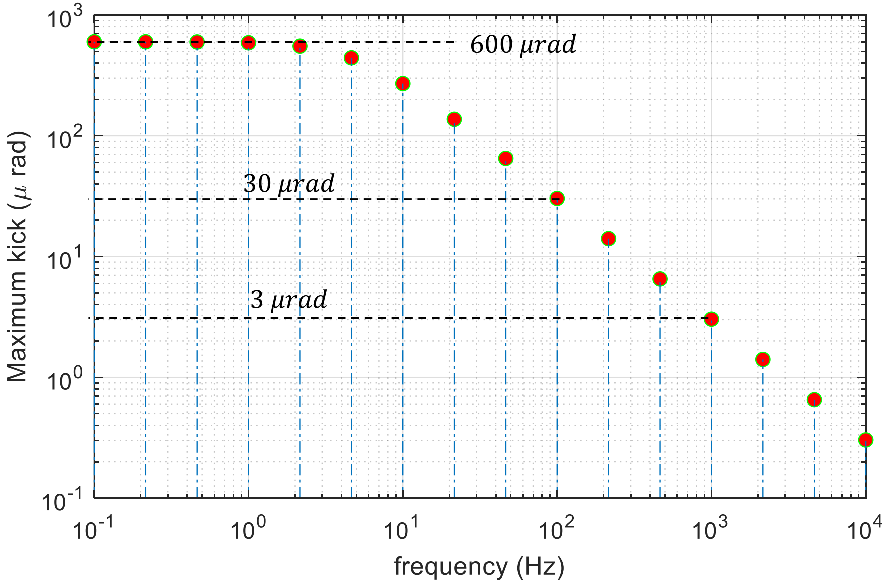
→DC current downloading to slow magnets

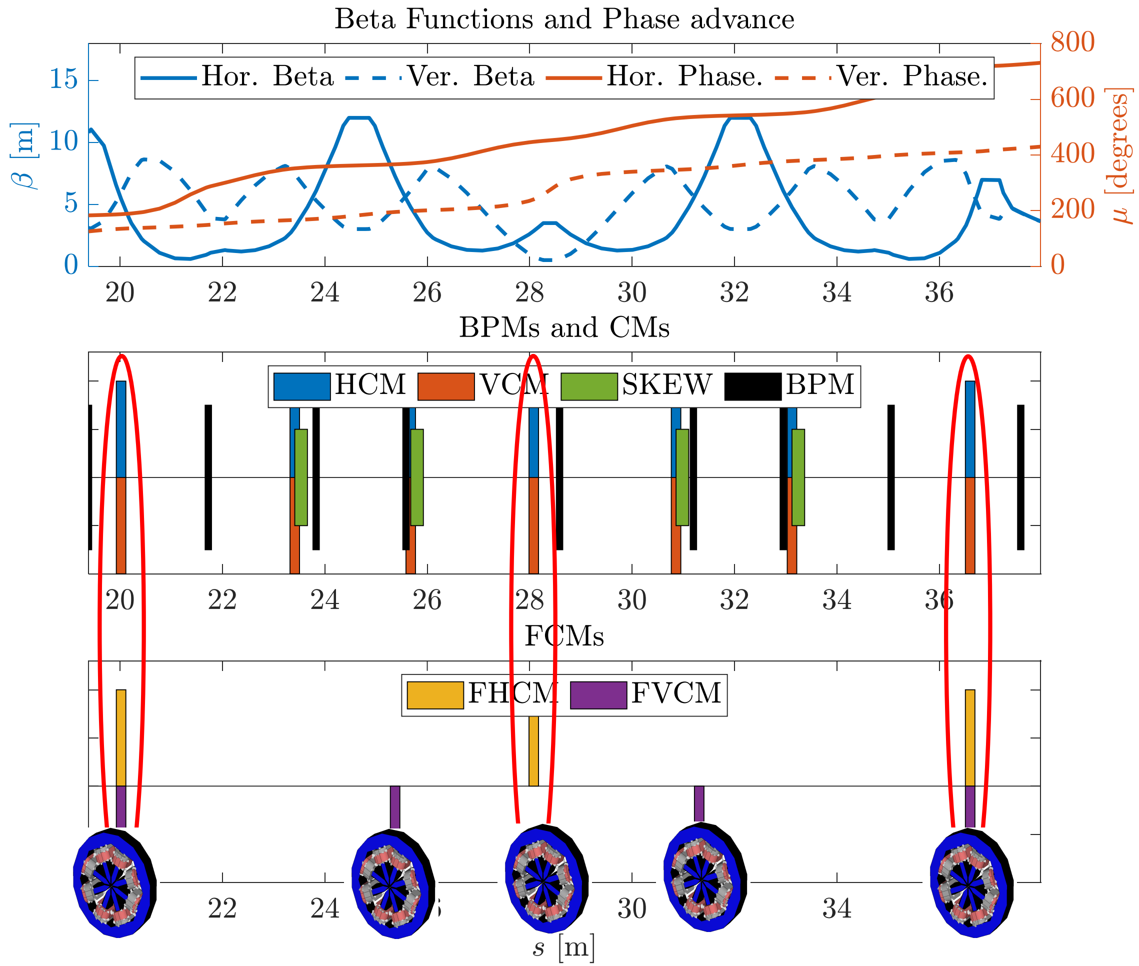
Combined (slow and fast) corrector magnet

Similar to APS-U design



Total / iron length is 150 mm / 90 mm





Baseline parameters: → for current and inductance optimization

- Main/aux coil is 65/27 turns (2.4074)
- Coil current **15 A**
- Self-inductance **23 mH**

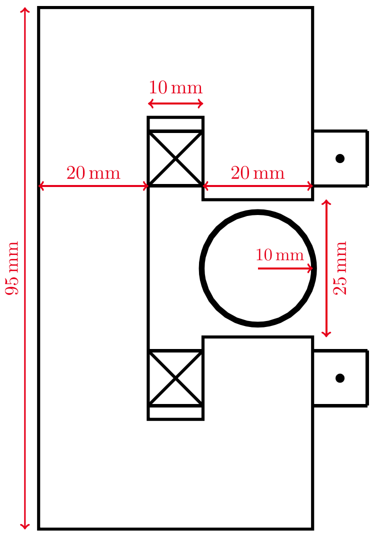
Fast correctors → 3D simulations in CST

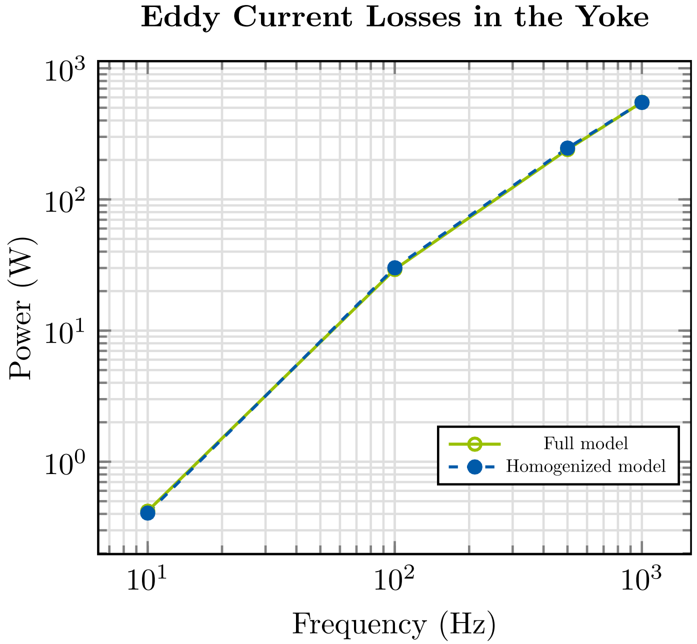
Simulation strategy

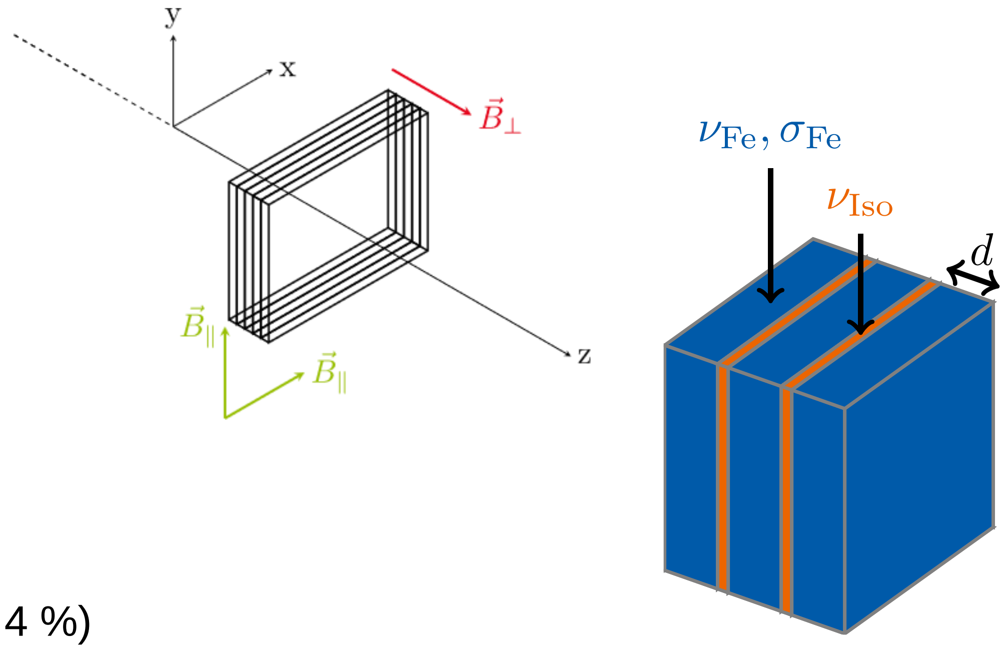
Frequency domain simulations
- ❖ Transfer function (up to 65 kHz)
- ❖ 3D spatial field distribution
  - ▪ Laminated magnet yoke
  - ▪ Vacuum pipe
  - ▪ Nearby quadrupoles

- **Homogenization of the laminated magnet yoke**
- Magnetoquasistatic PDE: $\nabla \times (\nu \nabla \times \vec{\underline{A}}) + j\omega\sigma\vec{\underline{A}} = \vec{\underline{J}}_s$
- Adapt reluctivity ν and conductivity σ in the laminated yoke

P. Dular et al., 2003
L. Krählenbühl et al., 2004







- Good approximation of losses in yoke & beam pipe (max. relative error 4 %)
- Simulation time reduced from several hours to 4 min

Simulations by Jan-Magnus at TEMF TU Darmstadt

Transfer function of vacuum chamber

Theory vs. Simulation

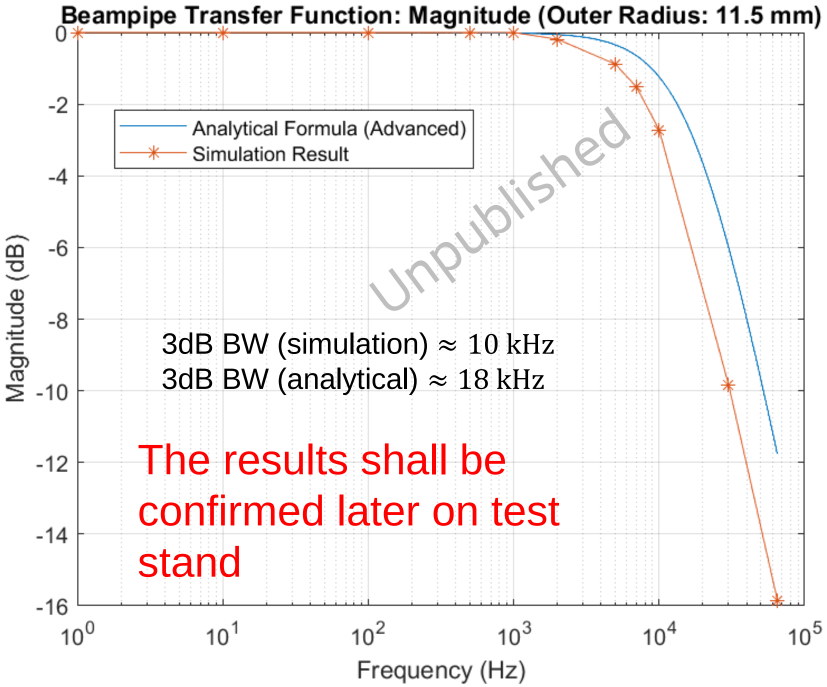
$$\frac{\widetilde{B}_{\text{int}}}{\widetilde{B}_{ext}} = \frac{2/q^2}{I_0(q+qd/b)K_2(q) - I_2(q)K_0(q+qd/b)}$$

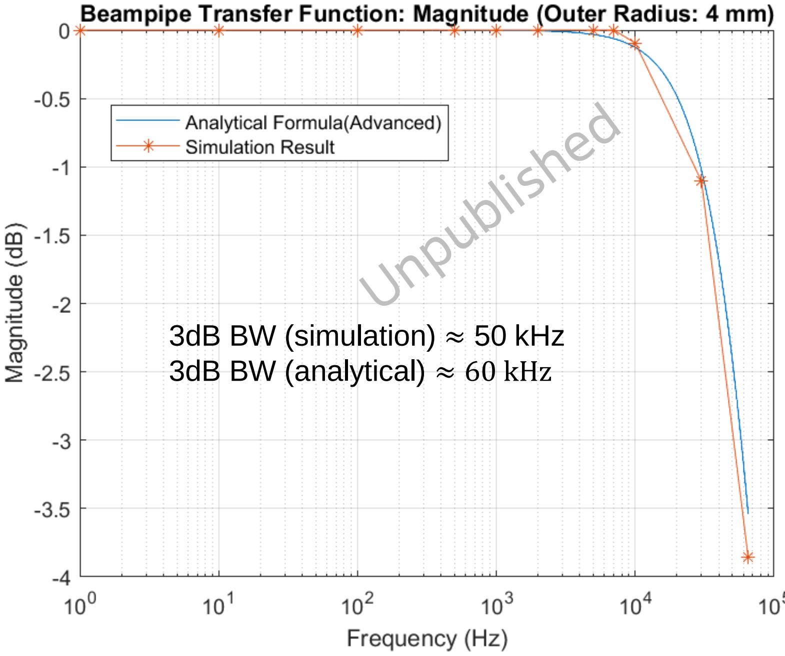
$$q \equiv \sqrt{2p\tau b/d}$$

b stands for the inner radius.

$$\tau = \tfrac{1}{2}\mu_0\sigma_c bd$$

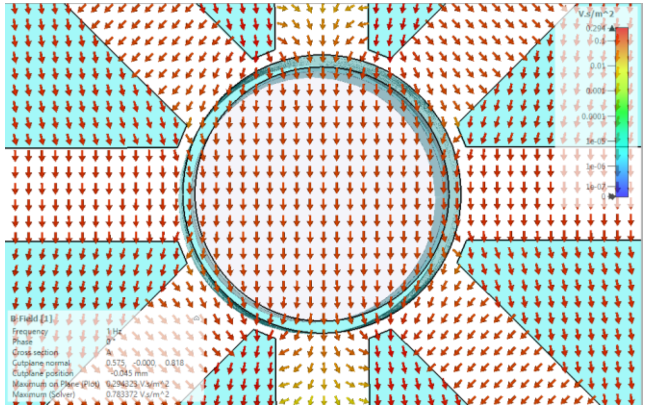
Boris Podobedov, TH5PFP083, Proceedings of PAC09, Vancouver, BC, Canada

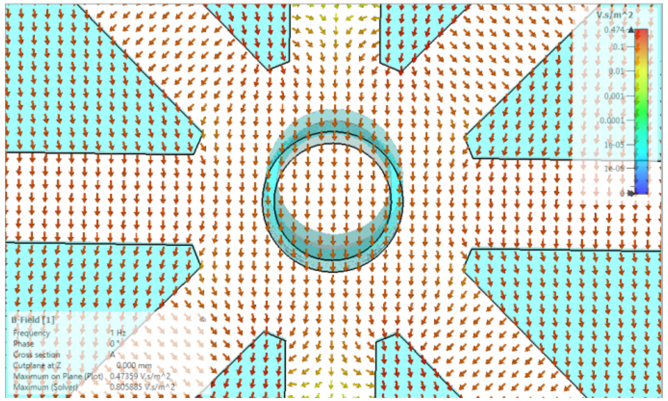




For the beam pipe close to the magnet poles the transfer function deviates from first-order analytical value.

→ The exact deviation is given by simulation

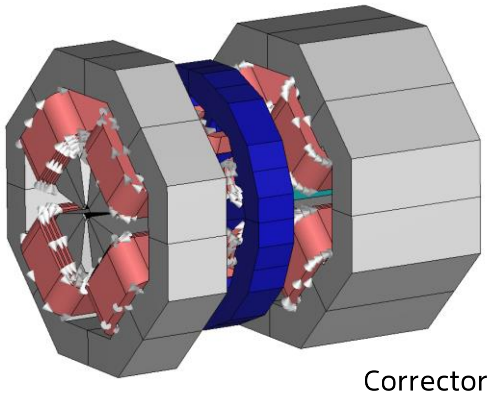




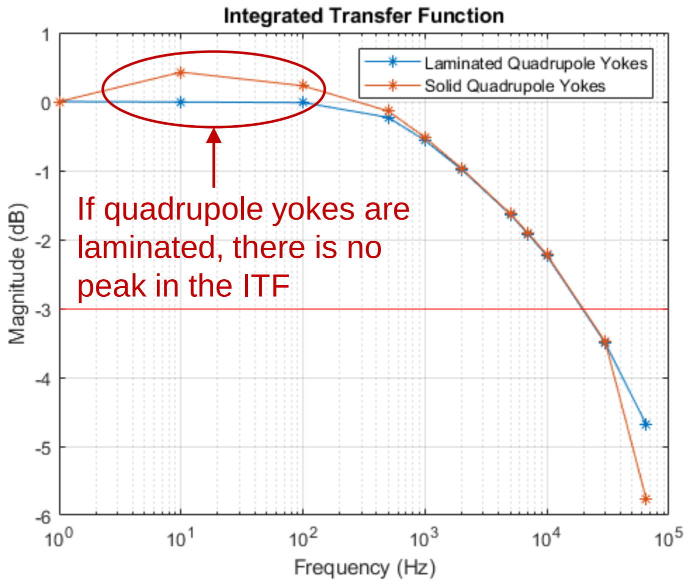
Simulations by Jan-Magnus at TEMF TU Darmstadt

Adding Quadrupoles around correctors

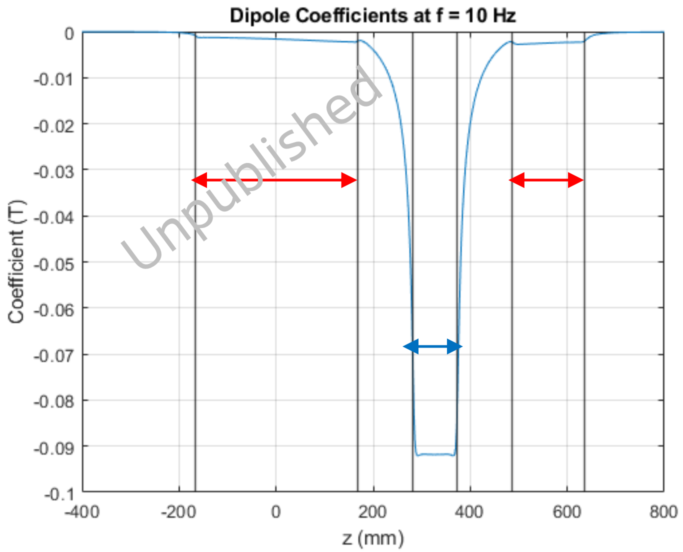
Combined fast/slow corrector magnet



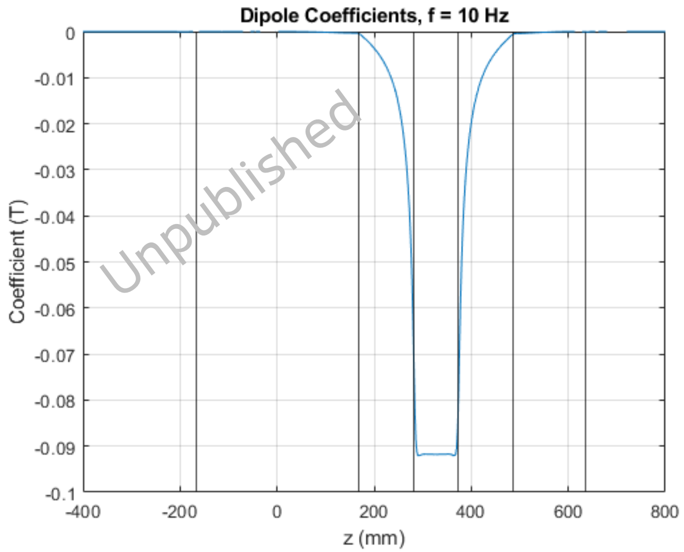
Corrector magnet yoke of 1010 steel
Yoke lamination thickness 0.5 mm



Solid Quadrupole Yokes



Laminated Quadrupole Yokes

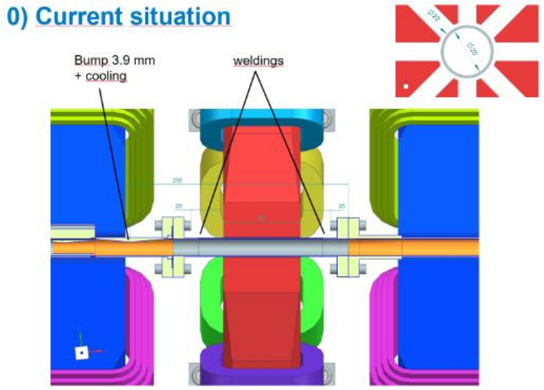


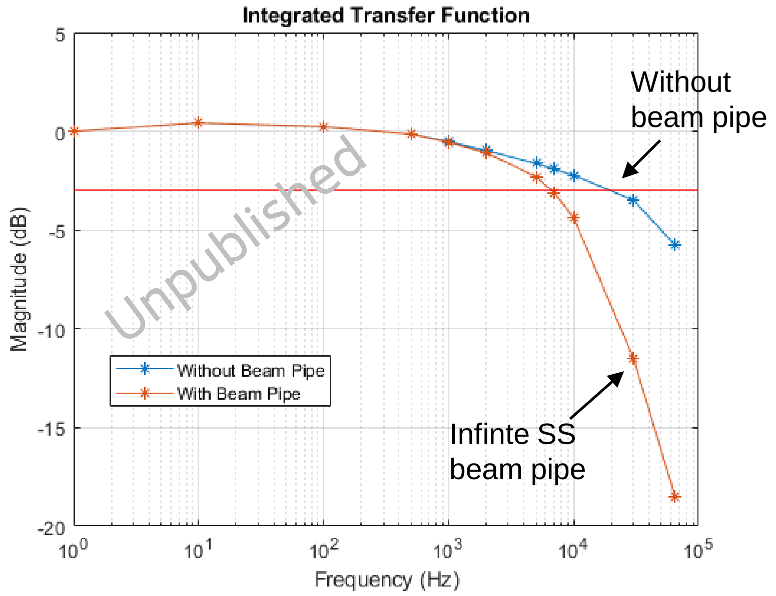
- Parasitic dipole component in the quadrupole for a solid yoke
- Asymmetry in the parasitic field can change the effective position of the corrector magnet.
- Lamination suppresses eddy currents in quadrupole yokes at low frequencies (*high-frequency case not shown*)
- The transfer function has a bump at low frequency in the case of solid quadrupole yoke

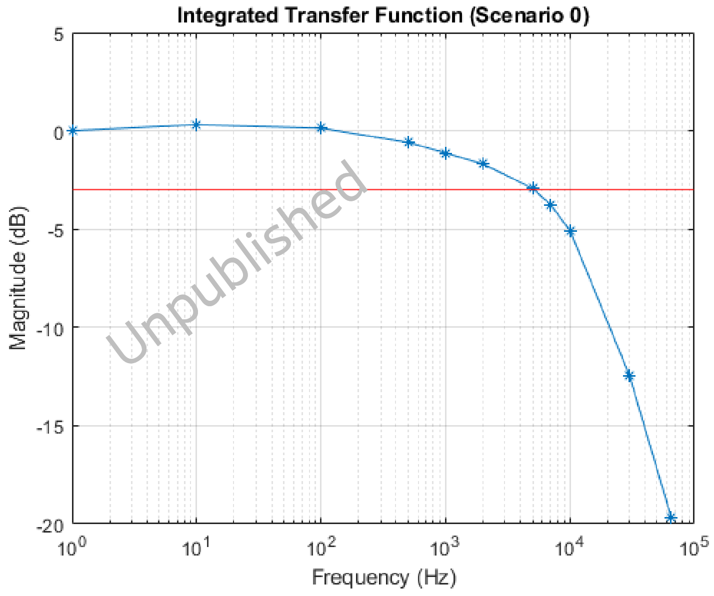
The observations are conveyed to the magnet group

Full realistic model → corrector magnet+vacuum pipe+quadrupoles

Infinite long SS vs. 205 mm SS + Cu beam pipe in quadrupoles

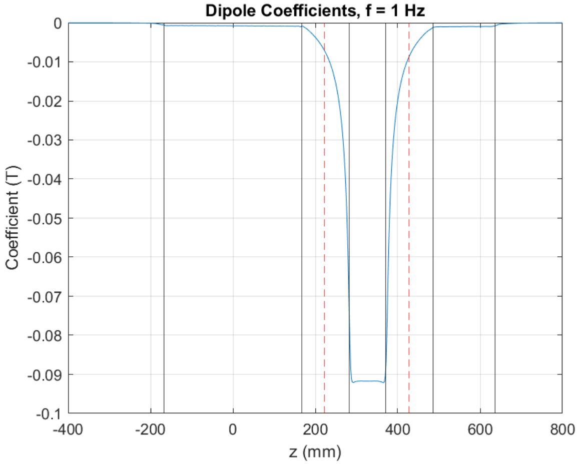


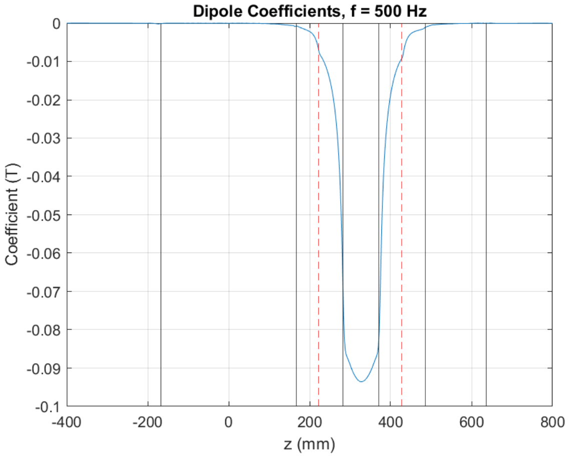


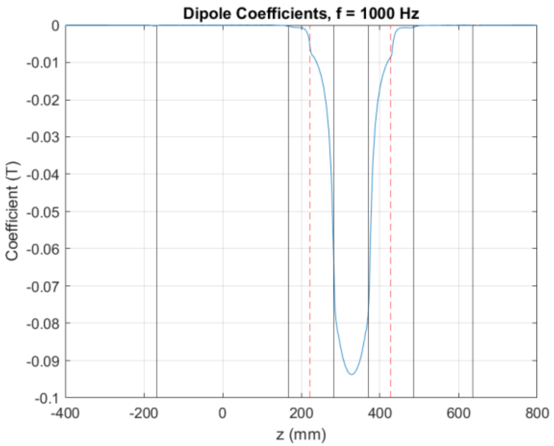


SS pipe outer diameter=11.5 mm
SS pipe thickness= 1 mm

Corrector magnet yoke of 1010 stee
Yoke lamination thickness 0.5 mm
Quadrupole solid yoke



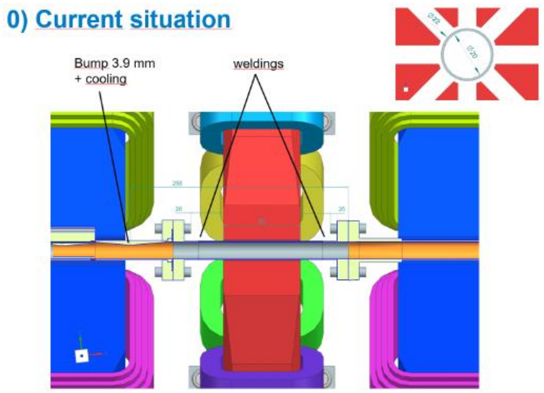




Simulations by Jan-Magnus at TEMF TU Darmstadt

Full realistic model → corrector magnet+vacuum pipe+quadrupoles

Infinite long SS vs. 205 mm SS + Cu beam pipe in quadrupoles



SS pipe outer diameter=11.5 mm
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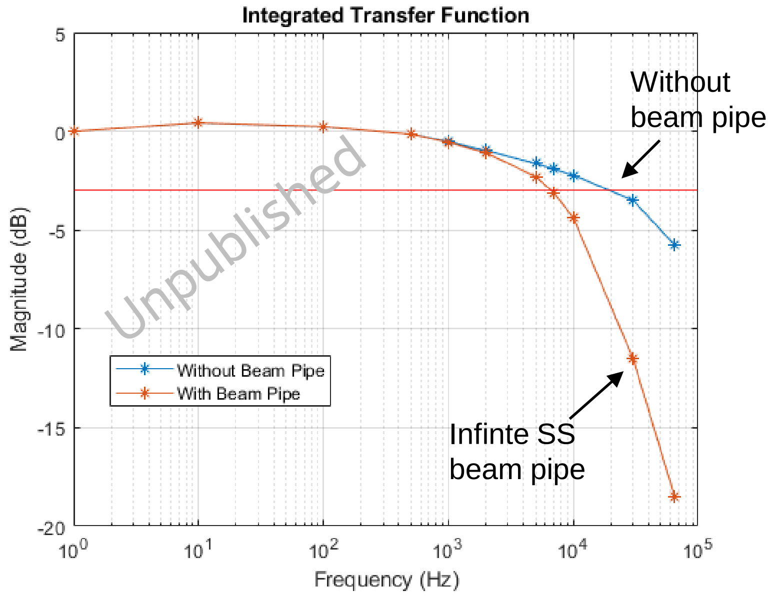
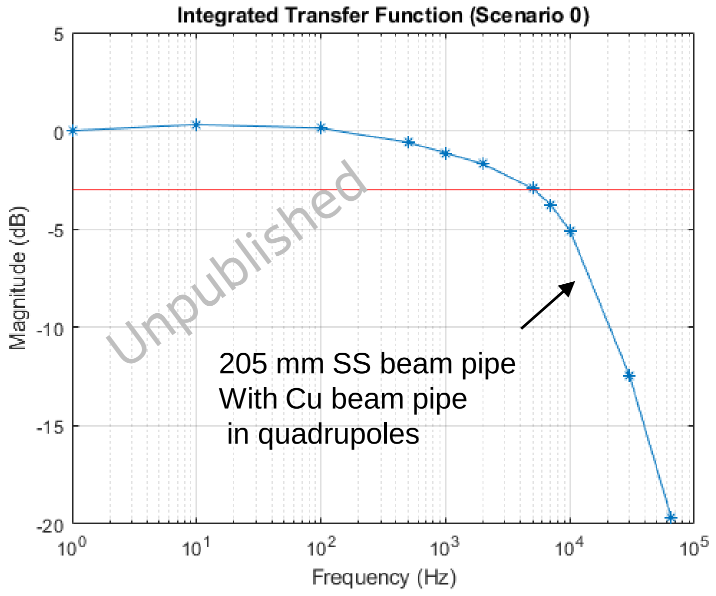
Corrector magnet yoke of 1010 stee
Yoke lamination thickness 0.5 mm
Quadrupole solid yoke



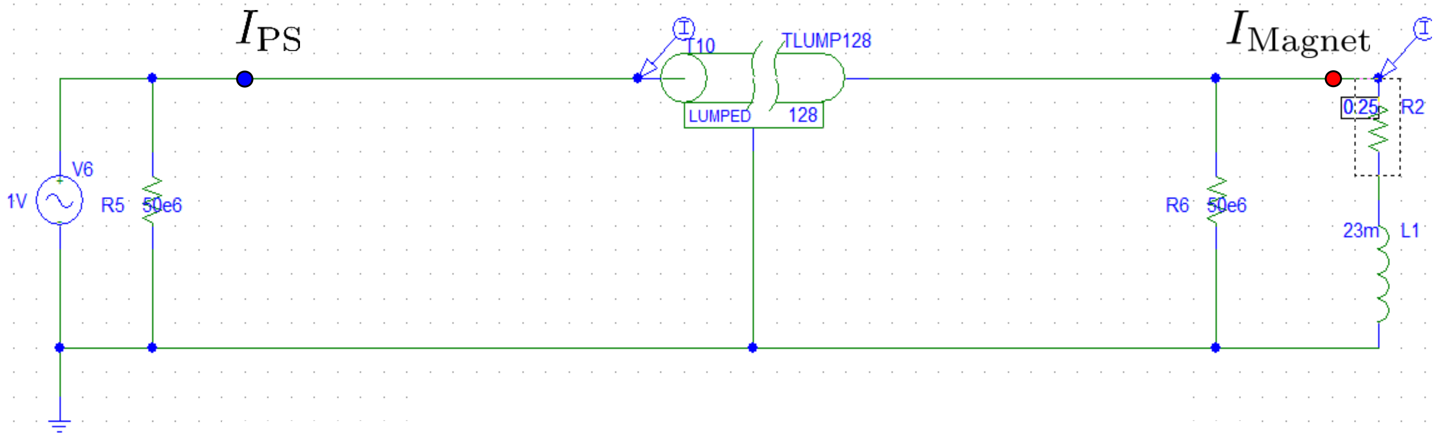


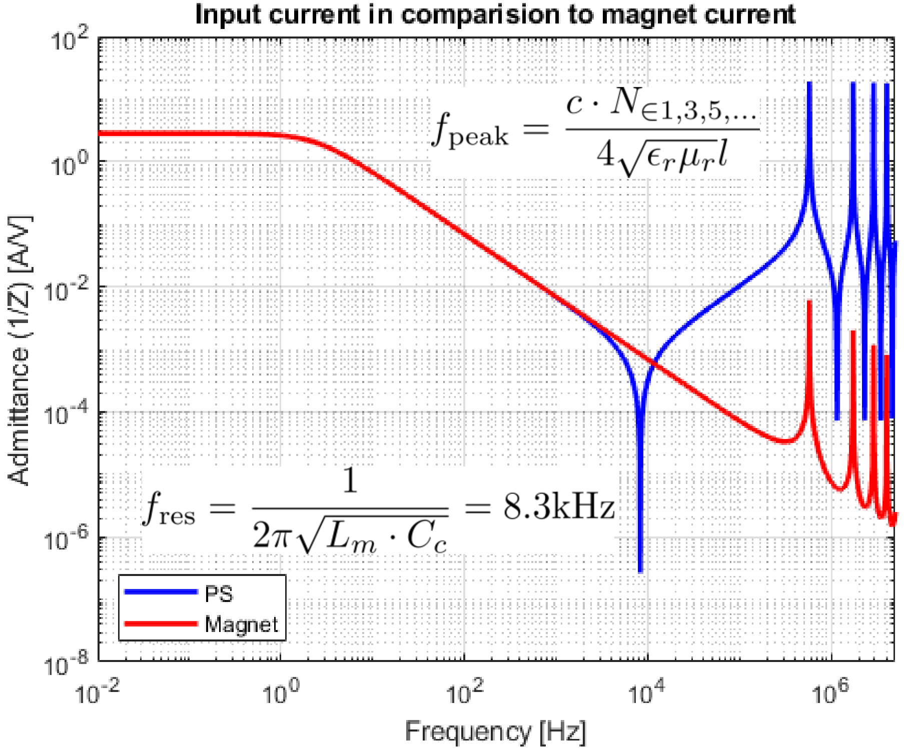
SS beam pipe length	**Without Beam Pipe**	1200 mm	205 mm	148 mm	136 mm	126 mm	102 mm	90 mm
3dB bandwidth	20 kHz	7 kHz	5 kHz	4 kHz	3.5 kHz	3 kHz	2 kHz	1.5 kHz

Corrector-cable response

FOFB: Corrector-cable challenge

- Power Supply as voltage source
- Coaxial cable
  - C′ = 80pF/m, L′ = 57.6nH/m, R′ = 0.52mΩ/km
  - Length = 200m (120nF, 17µH) ; Z0 = 27Ω
- Magnet
  - L = 23mH ; R = 0.25Ω





Magnet and cable

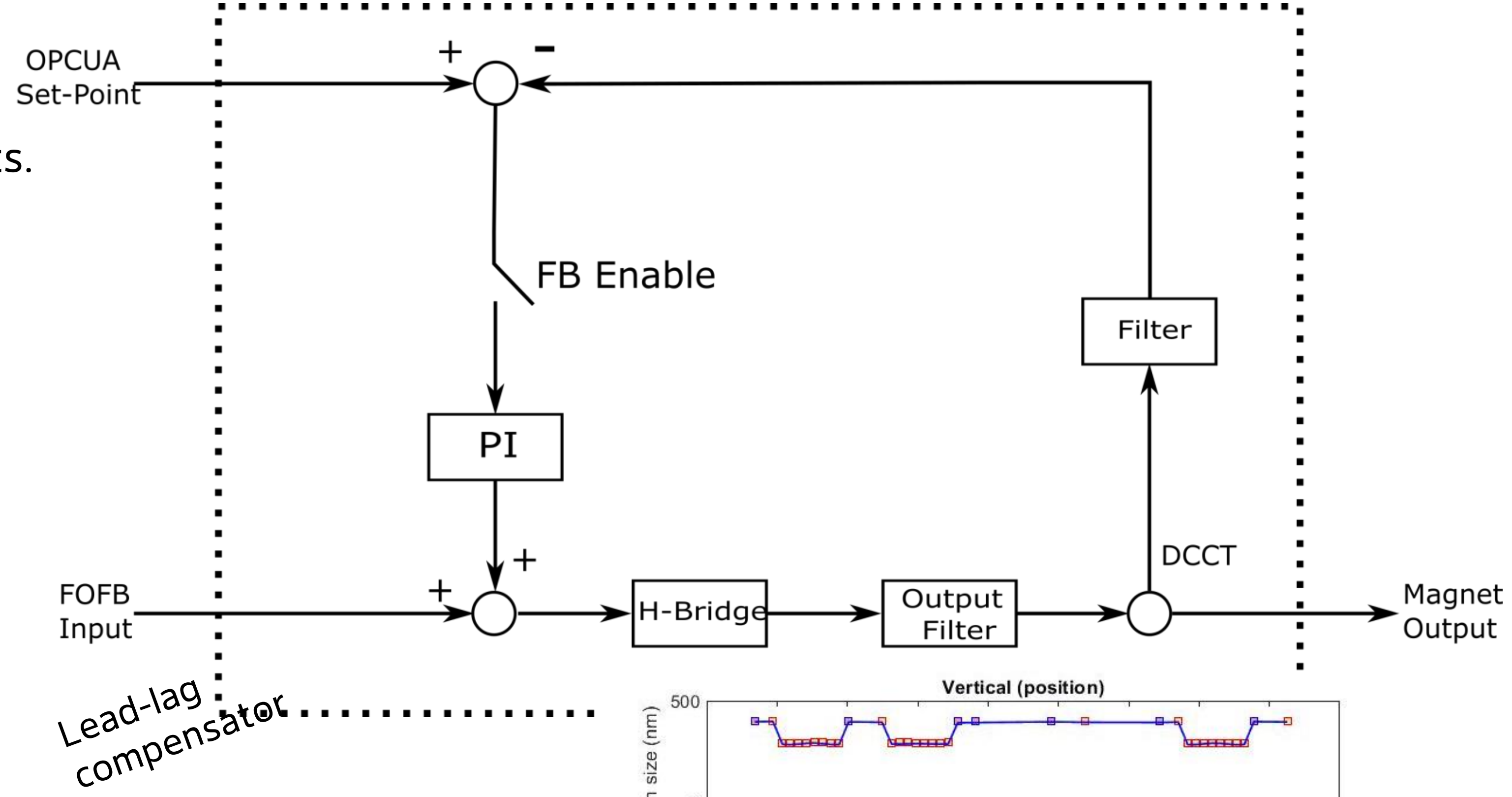
→ **Unobservable currents at power supply**

→ **Dependent on magnet cable length, cable capacitance, magnet inductance**

Preliminary Power Supply Scheme

FOFB: Fast corrector power supply

- OPCUA set point for slow but large currents.
- PI controller for slow current variation
- Fast but small currents from FOFB Input
- No controller for FOFB current inside PS.
- Local lead-lag controller to shift open loop bandwidth to kHz range
    - Mainly limited by BPM noise
- Global FOFB controller to maintain fast current in the magnets



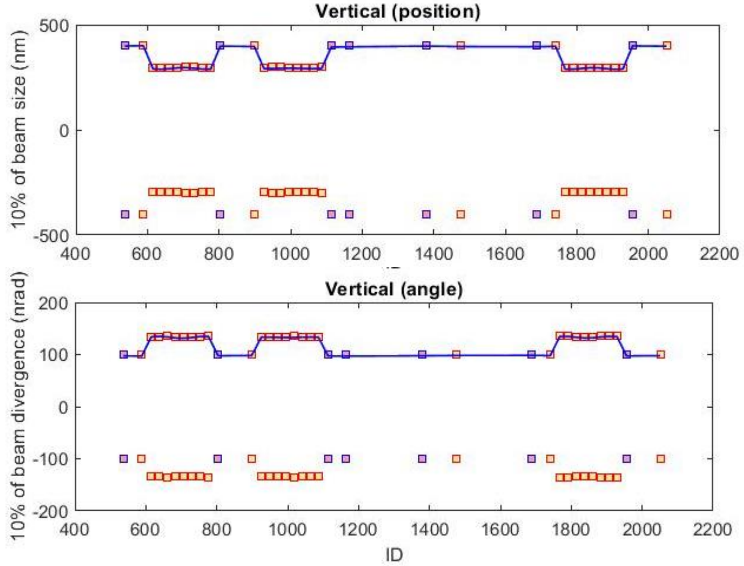
PS allowed RMS noise

Allowed RMS motion in Y-plane

→ 300 nm / 100 nrad

→ $9\ nrad$ (RMS) at all correctors

→ 1.5×10^{-5} of full scale $(600\ \mu rad)$



SISO (single input single output) closed-loop bandwidth

Latency budget

As presented in project proposal

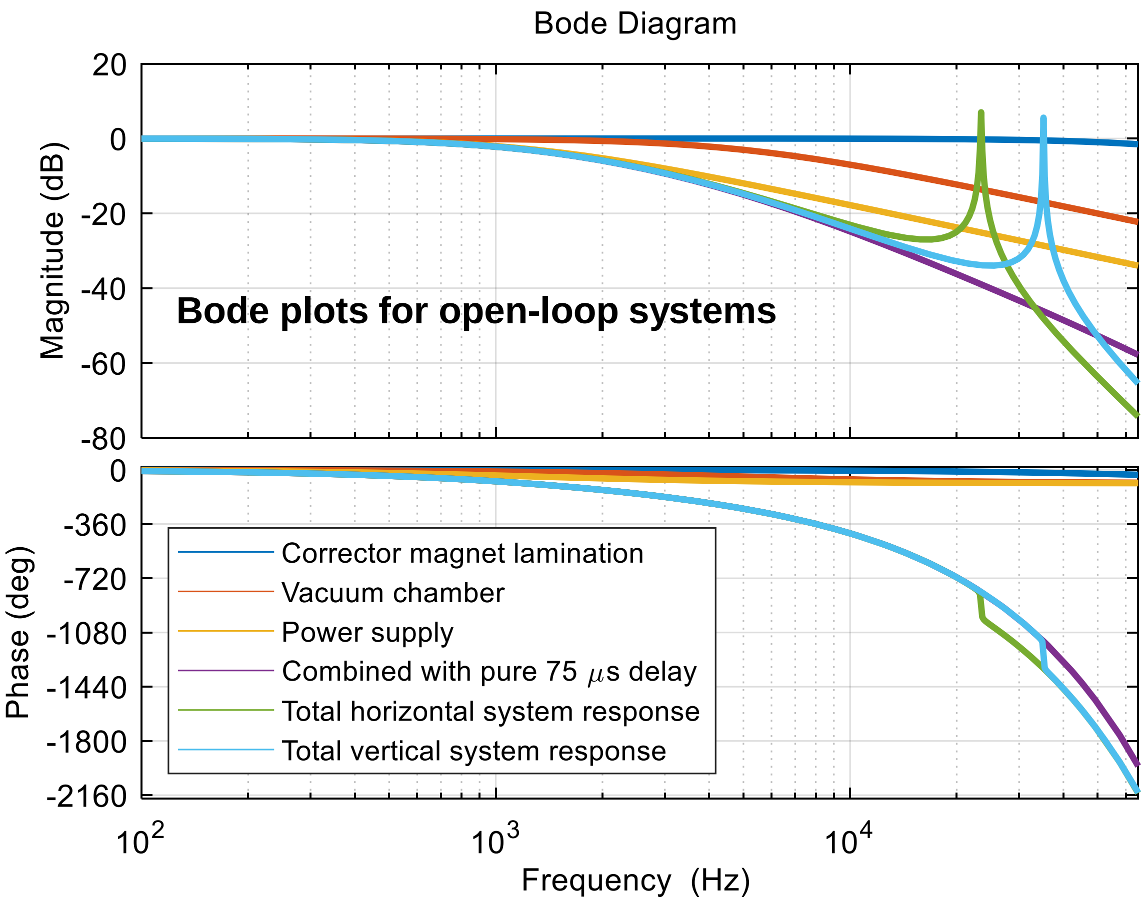
Subsystem/Links	Delay	Comments
Beam position calculation	23 μs	3 turns maximum delay
BPM processor to BPM datahub	<0.5 μs	Backplane link
BPM datahub to LOC	~1 μs	Optical link ~ 10s of meters (10 Gbps)
LOC electronics nodes	<1 μs	Local data processing
LOC to GLO (two ways including encoding/decoding)	12.5 μs	Max of 1250 m (10 Gbps)
GLO controller	20 μs	Global data processing time
LOC to PS	~ 0.5 μs	Optical link ~ 10s of meters (10 Gbps)
Power supply	15 μs	Max input-out delay (estimate)
Corrector magnet power cable	1.5 μs	Max cable length 300m
Total	**75 μs**	Anticipated budget delay

SISO simulations-update

Lead-lag component of PS

System Models for simulation

- An open-loop collective BW of $1.26\ kHz$ and a delay of $75\ \mu s$



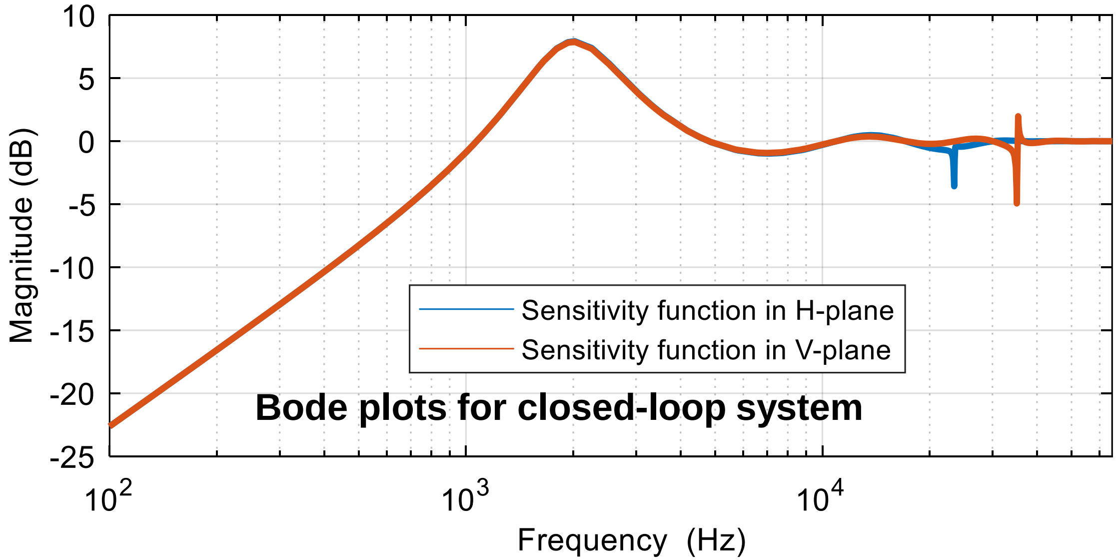
- 1 kHz disturbance-rejection bandwidth (requirement)
- Analytical modelling of subsystems (Update with simulations).
- Frequent system updates with new parameters

Major delay components

- $\tau_{d,BPM} = 23\ \mu s$
- $\tau_{d,controller} = 20\ \mu s$
- $\tau_{d,LOC-GLO} = 12.5\ \mu s$
- $\tau_{d,PS-cable} = 15\ \mu s$

Dominant BWs

- Vac. Chamber = 5 kHz
- Corr. lamination = 20 kHz
- PS+cable+coil = 1.3 kHz (limited by BPM electronics noise using lead-lag for BW shift)



Requirement of 1 kHz disturbance-rejection still achievable

Interaction of FOFB system with DC corrections

Interaction of FOFB system with slow correctors

DC current shift from fast to slow magnets

Philosophy: Only FOFB system → Quasi-DC to high frequency (1 kHz)
→ DC current accumulation on fast magnets

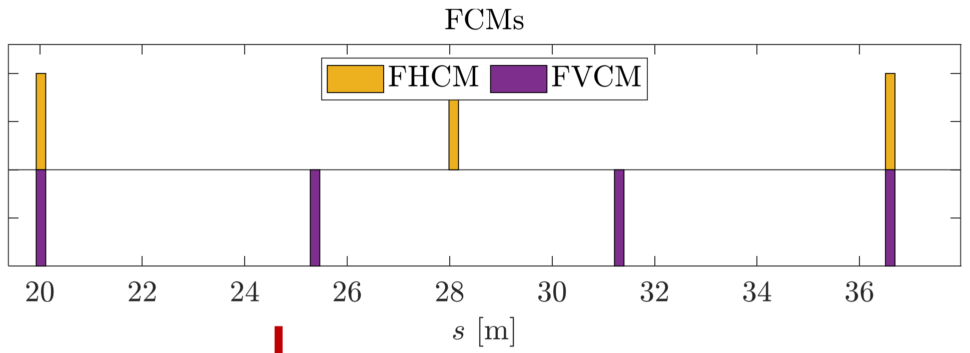
No. of slow corrector magnets > No. of fast corrector magnets
→ Using the larger mode space of all slow corrector magnets

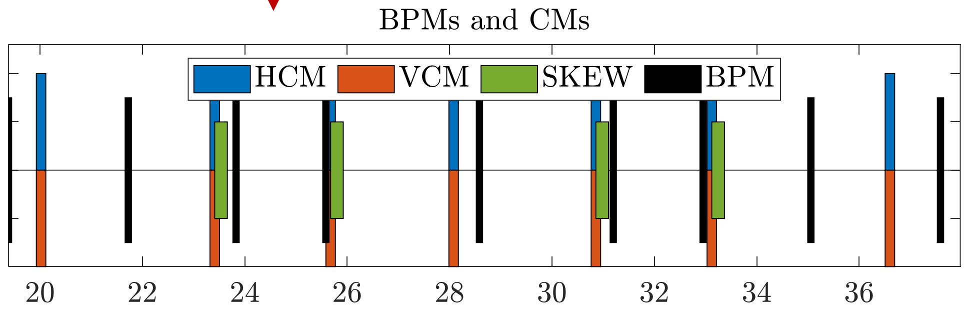
Strategy: Fast corrector strength → ORM (fast) → BPM space

BPM space → ORM^{+} (slow) → Slow corrector strengths

Simulations: Time domain simulations performed in 'cpyMAD' with following approximations:

1- Only quadrupole random oscillations + drift
2- Small amplitude of misalignments and oscillations
→ highly linear machine
3- Update rate of 10 kHz



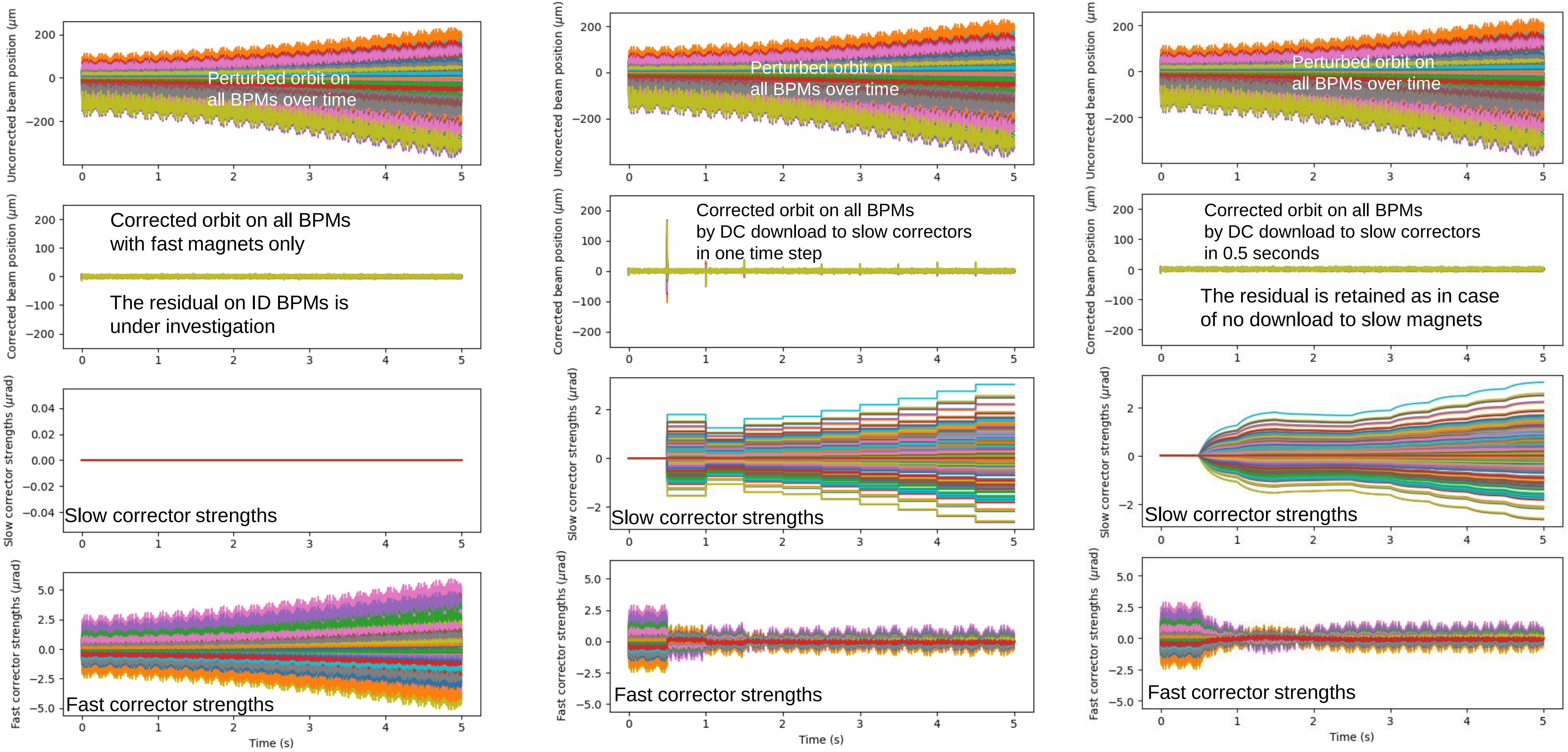


Three scenarios are simulated:
1- Orbit correction with only fast correctors
2- Orbit correction with fast corrector but shifting quasi-DC strength to slow magnets in one time step → non-realistic case
3- Orbit correction with fast corrector but shifting quasi-DC strength to slow magnets in 0.5 seconds → possibly realistic case

The residual on all BPMs is plotted here not on ID BPMs (for stability criteria → a topic for future)

Interaction of FOFB system with slow correctors

DC current shift from fast to slow magnets

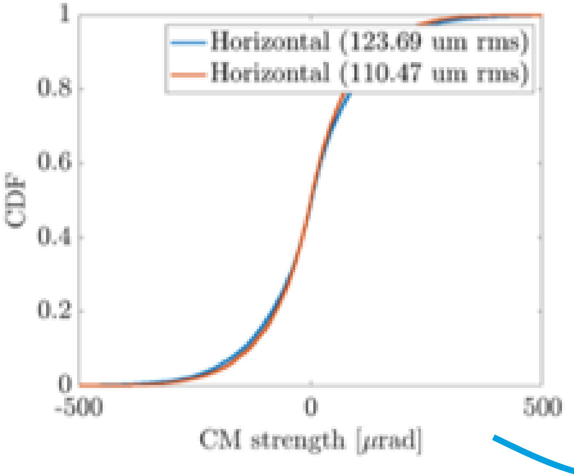


Girder alignment correction

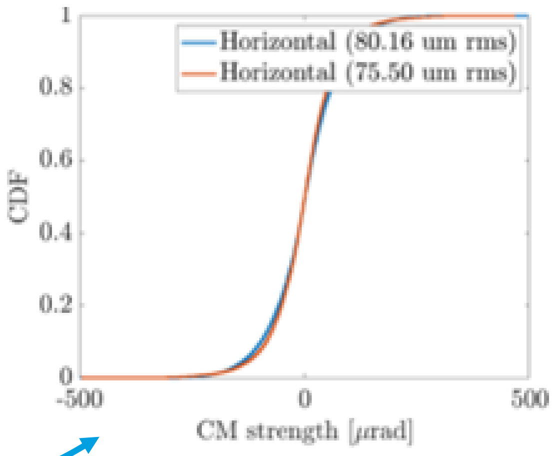
Why we need such a large (600 urad) corrector strength? (APS-U→300 urad)

Girder misalignments → corrector relaxation to Girder movements

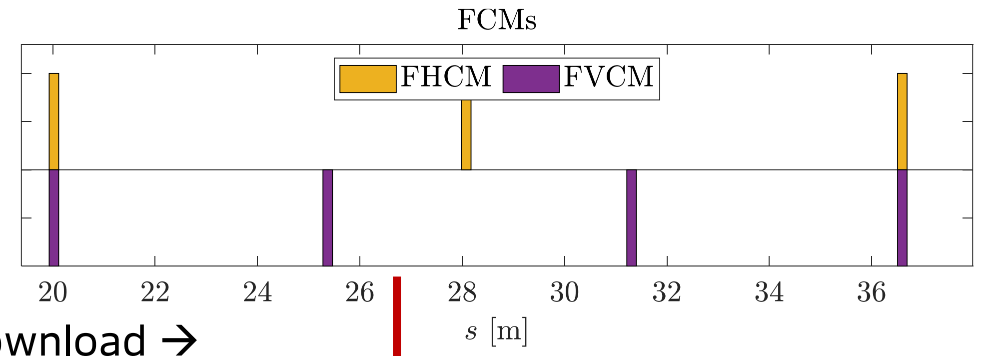
For 150 μm Girder offsets



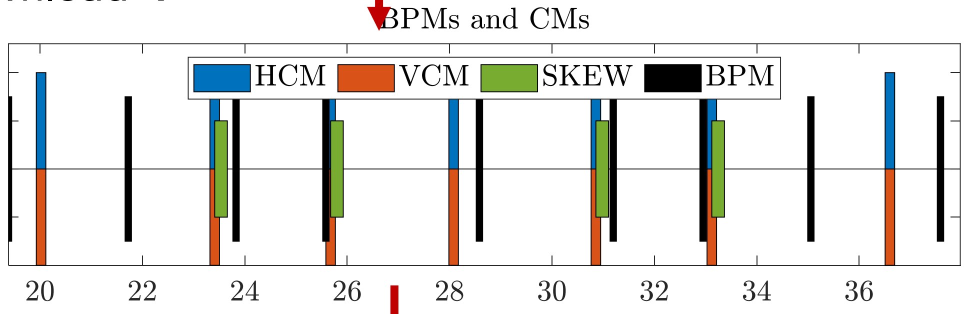
For 0 μm Girder offsets



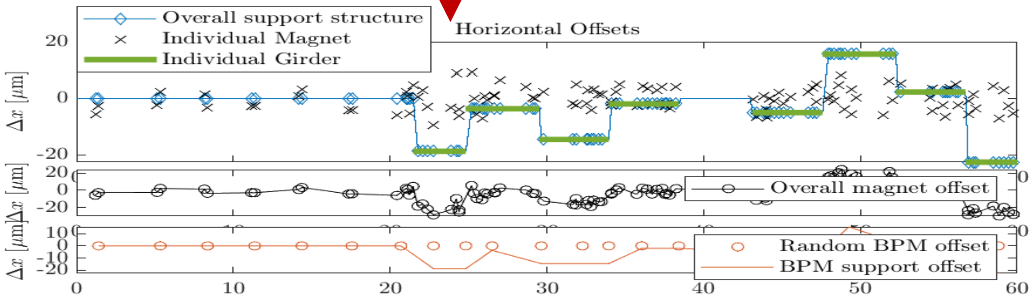
33 % reduction



First download →



Second download →



Consequently, going from perturbed to ideal machine

Correctors strengths →ORM→ BPM space

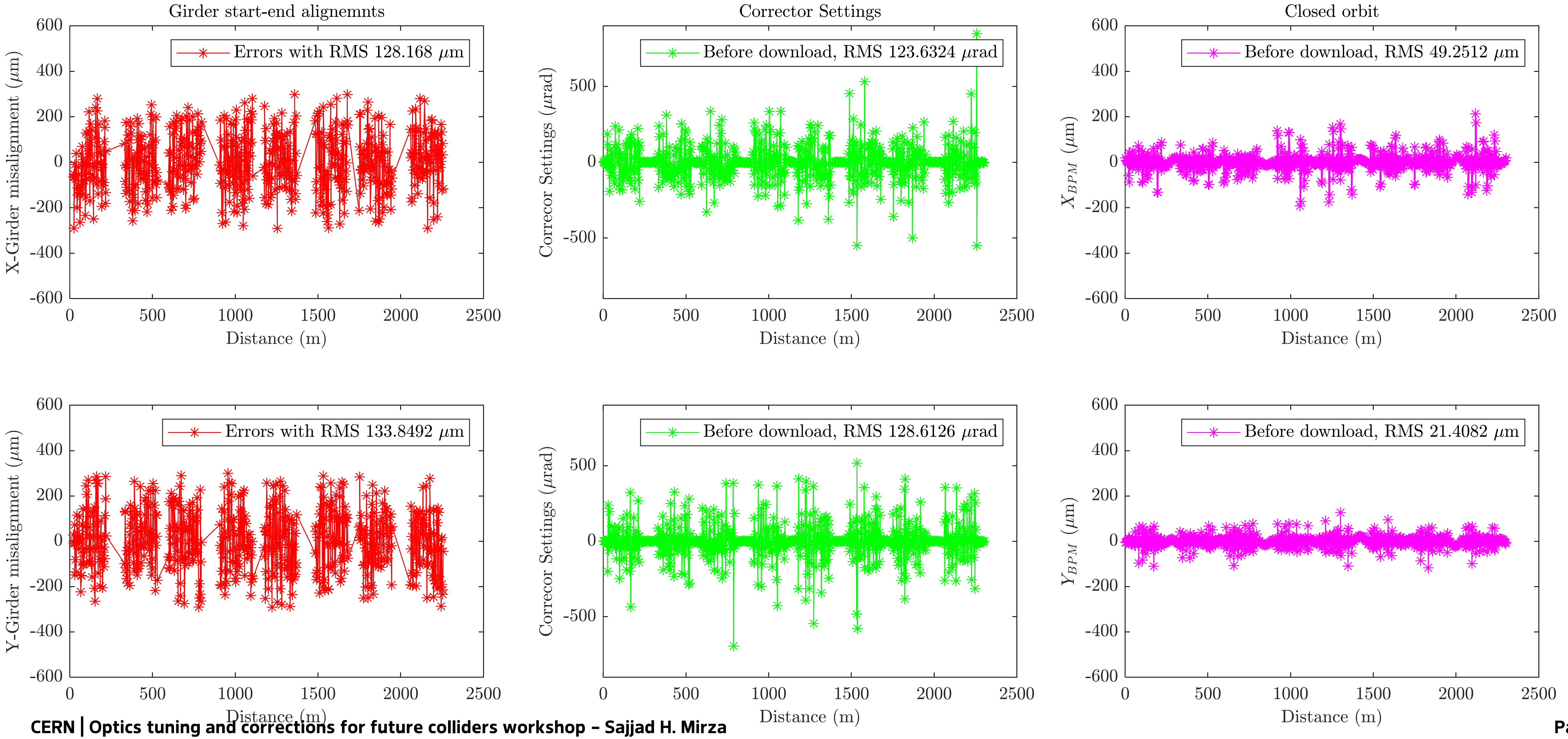
BPM space→ Girder ORM → Girder space

Courtesy to T. Hellert (MPY)

Slow corrector relaxation to Girders

Random Girder misalignments of start and end points = $\sigma = 150\ \mu m$ cut at 2σ Random BPM offset= $\sigma = 20\ \mu m$ Tikhonov regularization for Girder ORM inverse

Random Magnet misalignments = $\sigma = 30\mu m$ cut at 2σ Corrector calibration errors = 0.02% BPM calibration errors = 0.02% $\mu_x = 1, \mu_y = 1$



Slow corrector relaxation to Girders

Random Girder misalignments of start and end points = $\sigma = 150\ \mu m$ cut at 2σ

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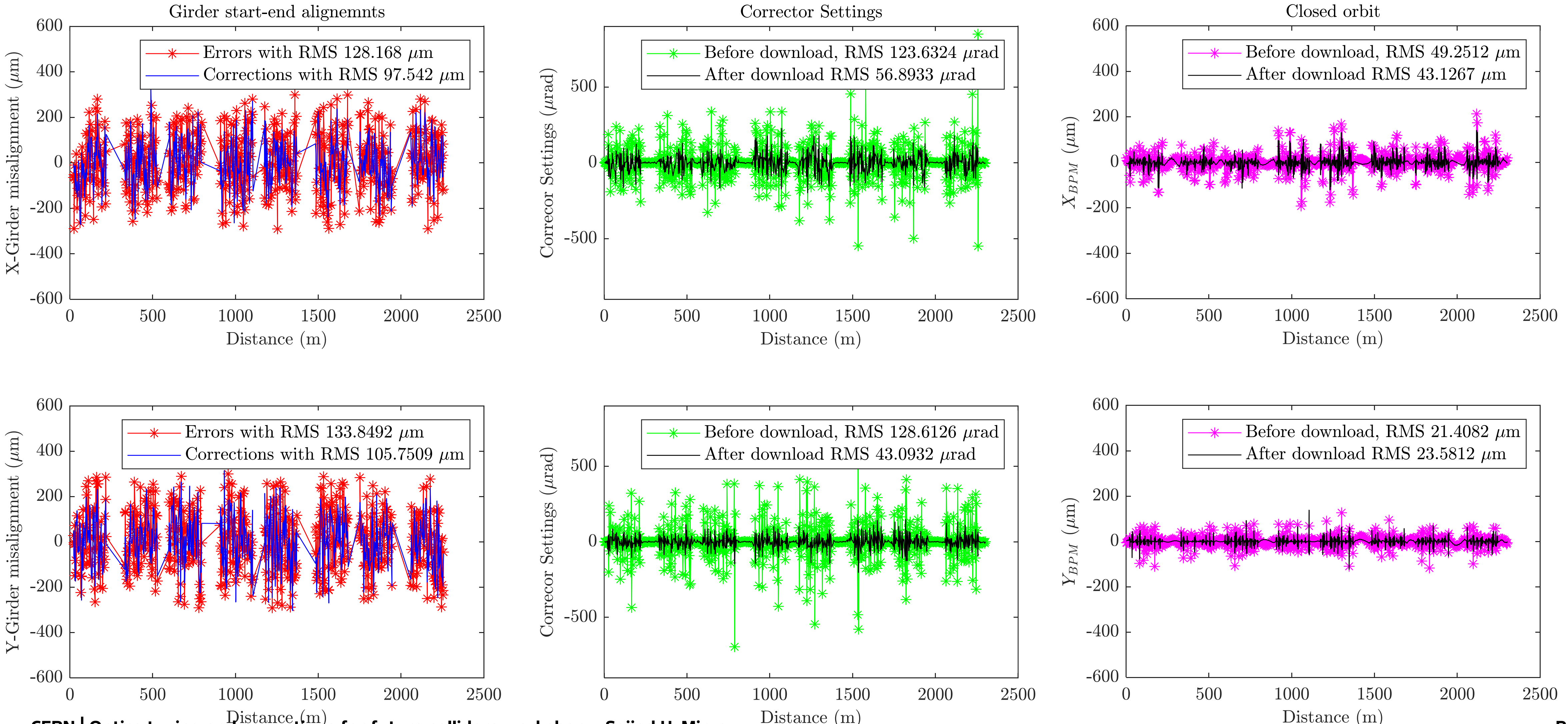
Tikhonov regularization for Girder ORM inverse

Random Magnet misalignments = $\sigma = 30 \mu m$ cut at 2σ

Corrector calibration errors = 0.02%

BPM calibration errors = 0.02%

$\mu_x = 1, \mu_y = 1$



Slow corrector relaxation to Girders → for 72 random machines

Random Girder misalignments of start and end points = $\sigma = 150\ \mu m$ cut at 2σ

Random BPM offset= $\sigma = 20\ \mu m$

Tikhonov regularization for Girder ORM inverse

Random Magnet misalignments = $\sigma = 30\mu m$ cut at 2σ

Corrector calibration errors = 0.02%

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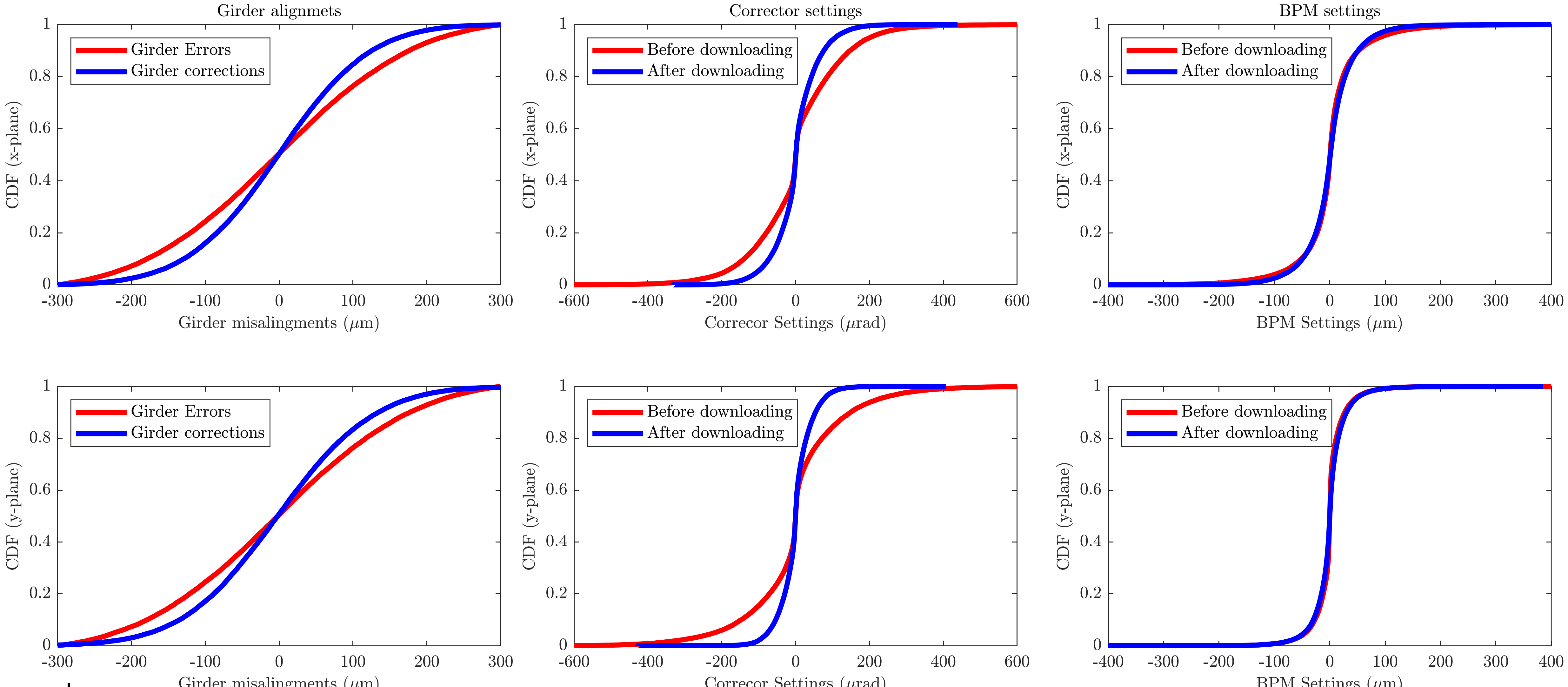
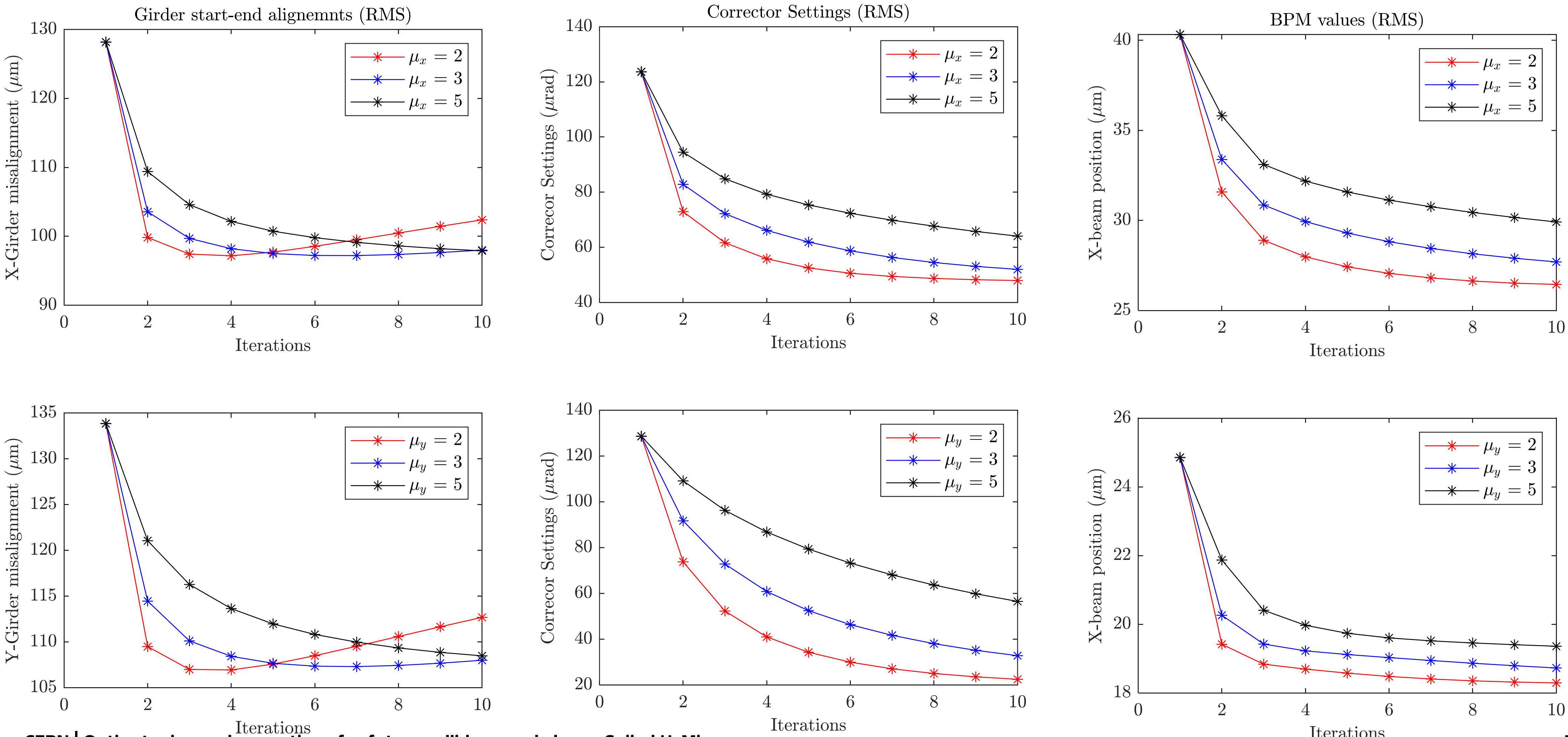


Girders correction feedback →3 FB scheme

Random Girder misalignments of start and end points = $\sigma = 150\ \mu m$ cut at 2σ Random BPM offset= $\sigma = 20\ \mu m$

Random Magnet misalignments = $\sigma = 30\mu m$ cut at 2σ Corrector calibration errors = 0.02% BPM calibration errors = 0.02%



Girders correction feedback →3 FB scheme

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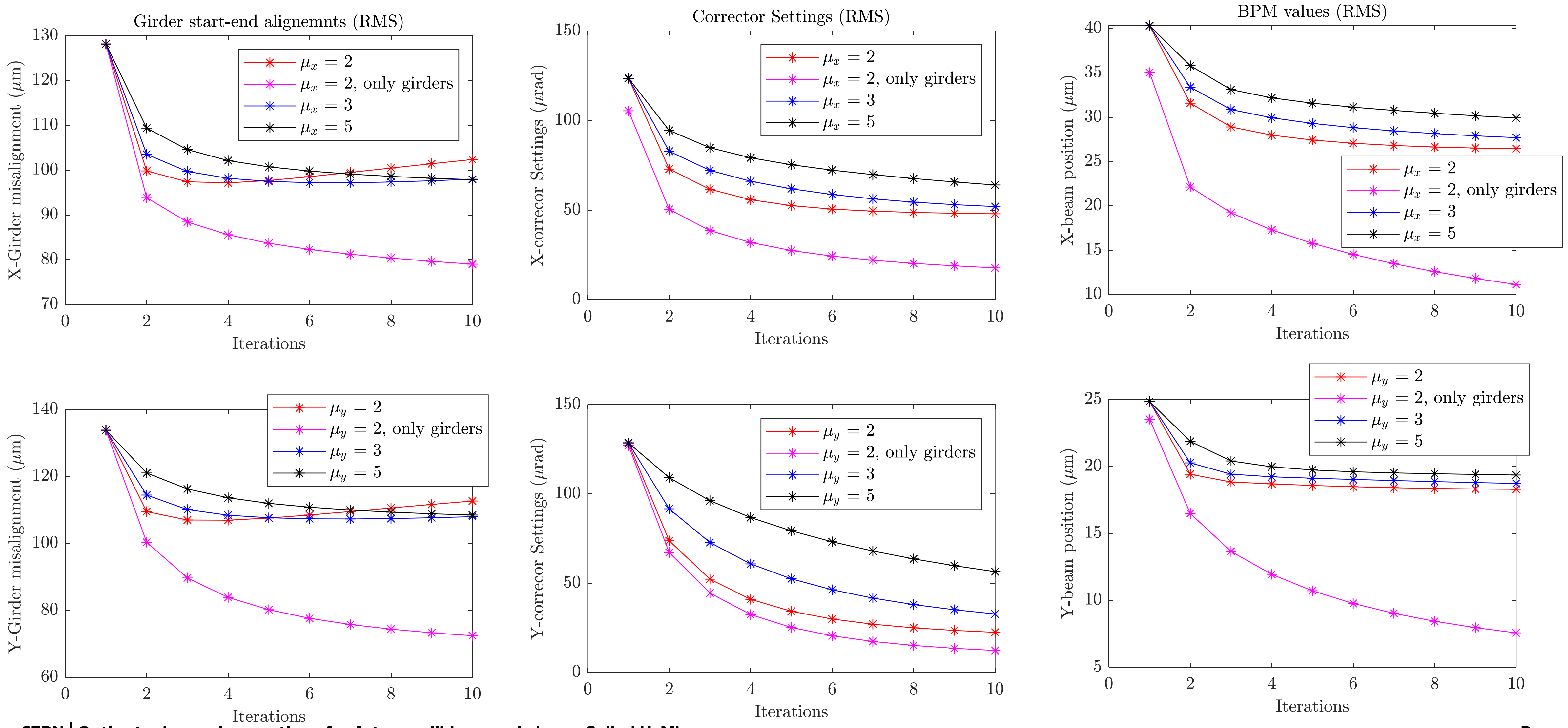

Summary

Subsystem modelling and design is under way for a target of 1 kHz disturbance rejection bandwidth.

Simulations of the corrector magnets reveal that the eddy currents in the nearby magnets and copper pipe cause reduction in the bandwidth of the corrector magnets.

Long cables for PETRA IV corrector power supply put a challenge for current control. The power supply is planned to have a PI controller for slow action. Fast change will be taken care by the global FOFB controller.

Girder alignment is studied as an option to reduce the corrector strengths during operation.

Thank you

Contact

DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

Sajjad Hussain Mirza
WP 2.08
eMail: sajjad.hussain.mirza@desy.de
+49 40 8998 1991