Recent progress in PETRA IV orbit feedback design

11th "Diagnostics Experts of European Light Sources" (DEELS) workshop

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

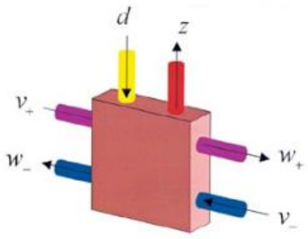
DESY.

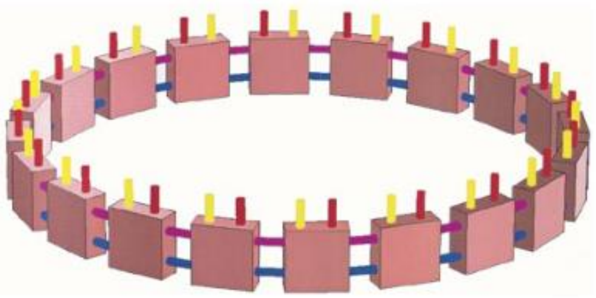
FOFB system topology

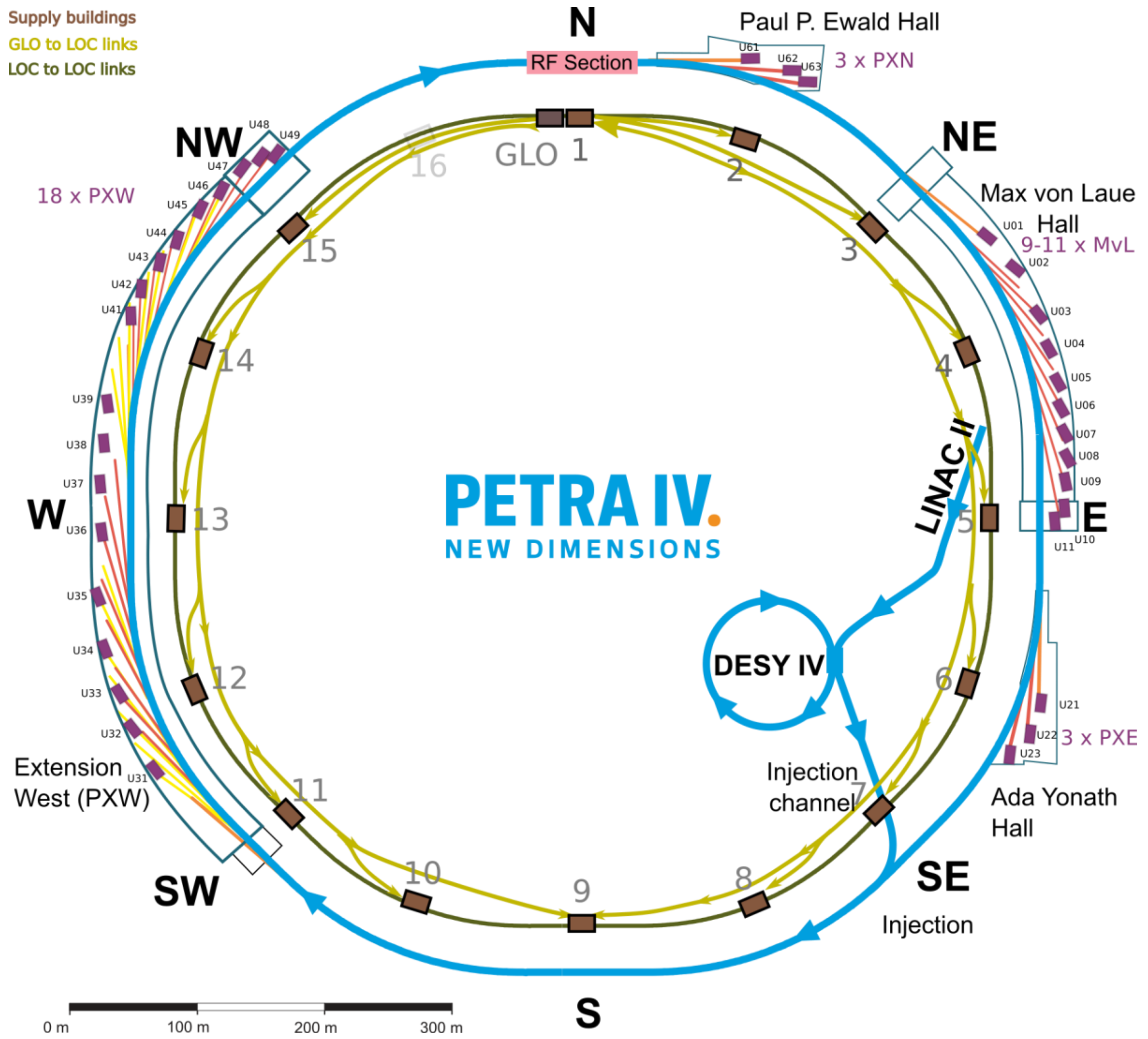
Latency optimized topology

Ring: **2.3km, 789 BPMs, 560 fast correctors,**
FOFB: **10% (5%, 3%) beam stability, DC to 1kHz**

- **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
    - *Redundant system mode as future upgrade*







FOFB System Design

FOFB system: a cross-directional problem

A two dimensional control problem

- The goal is to maintain the beam position **throughout the ring** → Spatial domain
- **Over time** → Temporal domain

$$G(s) = \begin{pmatrix} r_{11}G(s)_{11} & \cdots & r_{1n}G(s)_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1}G(s)_{m1} & \cdots & r_{mn}G(s)_{mn} \end{pmatrix}$$

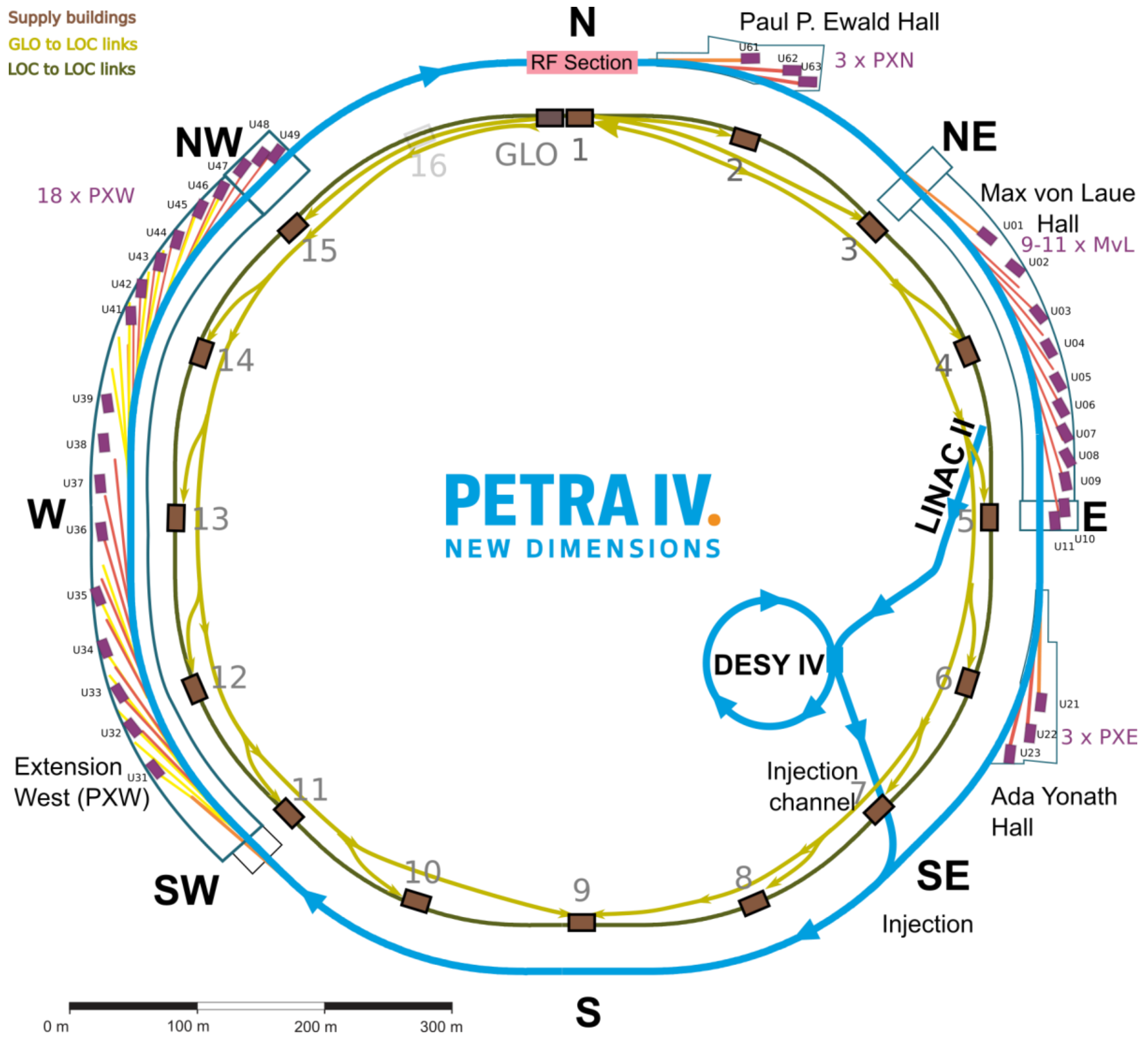
with $$r_{mn} = \frac{\sqrt{\beta_m(z)\beta_n(z)}}{2\pi Q}\cos(\pi Q - |\varphi_m(z) - \varphi_n(z)|)$$

- All corrector channels should have identical temporal response

$$\mathbf{G(s)} = G(s)\mathbf{R} \longrightarrow \mathbf{C(s)} = C(s)\mathbf{R}^+$$

2 step simulation

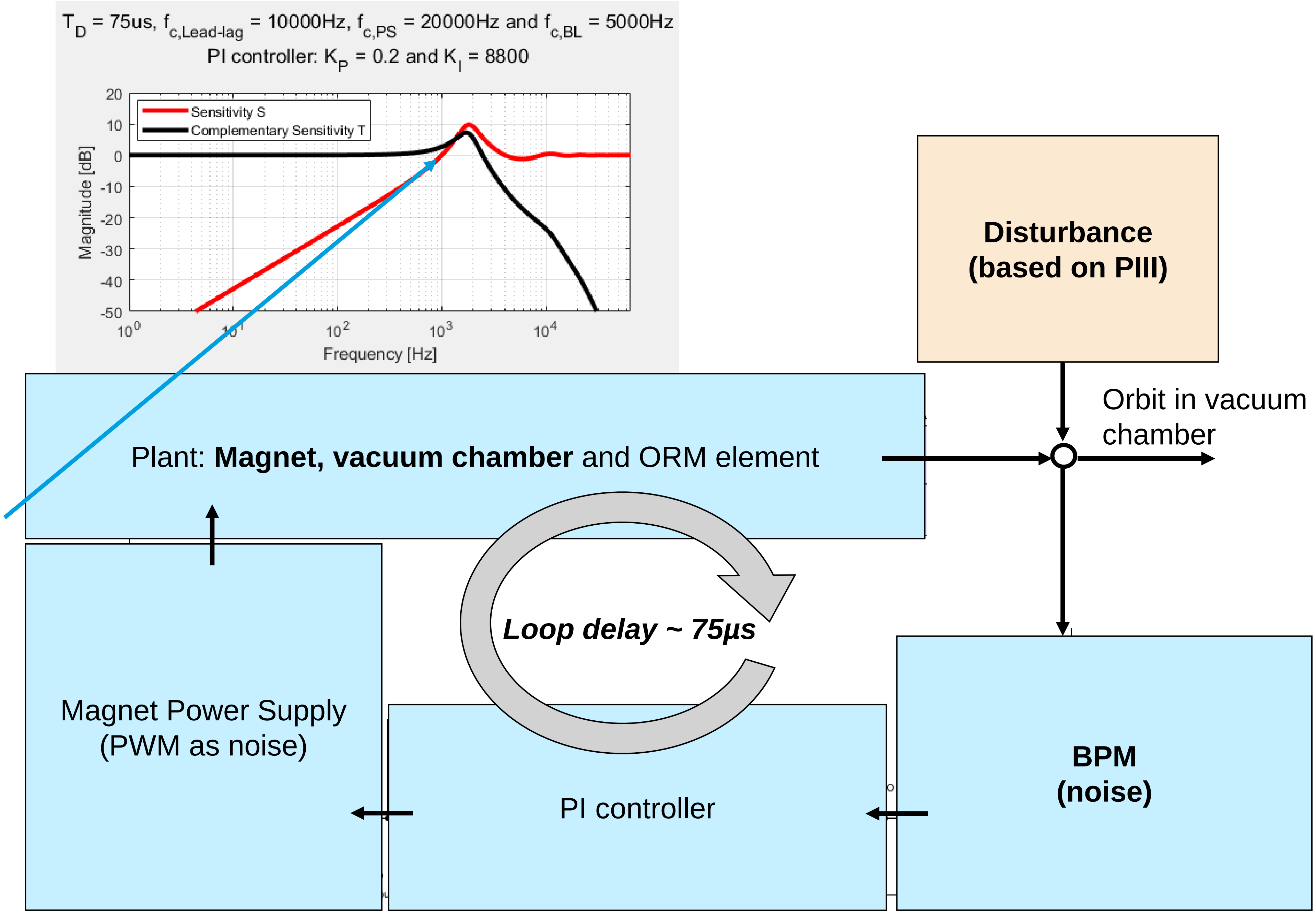
- Dynamical system at 1 location with all TFs
  - *Worst case scenario → best case for MIMO*
- *Spatial (MIMO) system with main dynamics*



FOFB system

SISO simulation

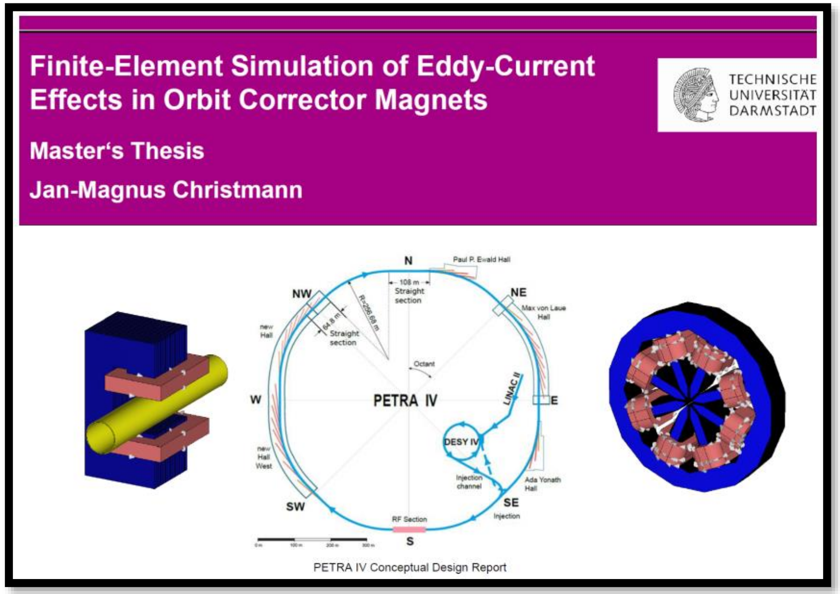
- Subsystems based on PETRA IV design
- Disturbance spectra approximated with measurement at PIII
- PI controller optimized for 1kHz disturbance rejection
- Sensitivity function for disturbance rejection
- Complementary S for reference tracking



PIV - FOFB system

Fast corrector magnet and vacuum chamber

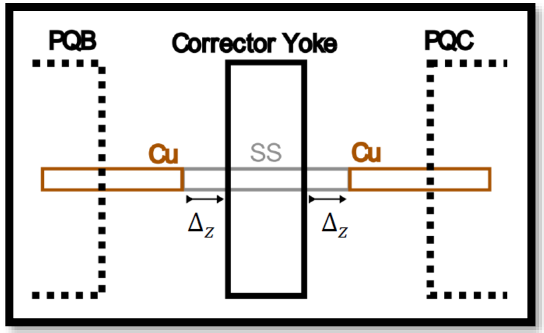
Institute for Accelerator Science and Electromagnetic Fields (TEMF)

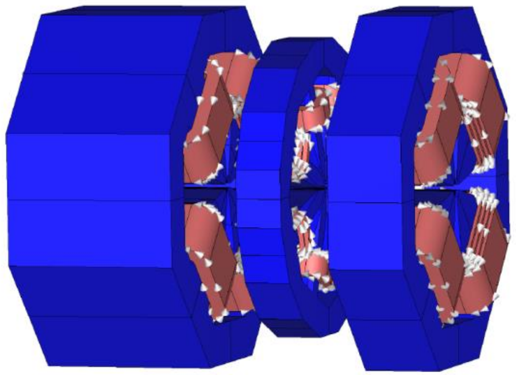


- **Dynamic transfer functions**
  - Fast corrector magnet
    - G = 1/(R + sL) (~Hz BW)
    - Lamination thickness (30kHz - fractional order)
  - Vacuum chamber (7kHz BW)
  - Magnet power supply
    - Output filter (30kHz)
  - BPM electronics
- Delays
  - Processing delay
  - Signal propagation
  - Communication (time between sending and receiving)
- Noise
  - PS Quantization noise
  - Pulse width modulation of the magnet power supply
  - BPM electronic / sensor noise
- Disturbances
  - Incoherent: DC … kHz
- Spatial disturbances
  - Coherent: <1Hz (ocean waves)
  - Transition: 1…10Hz (traffic noise)

2 step procedure

1. Simulation for optimization
   - Started as Master thesis, now PhD thesis
2. Validation on test bench
   - Corrector magnet including VC (and quads)





PIV - FOFB system

BPM electronics

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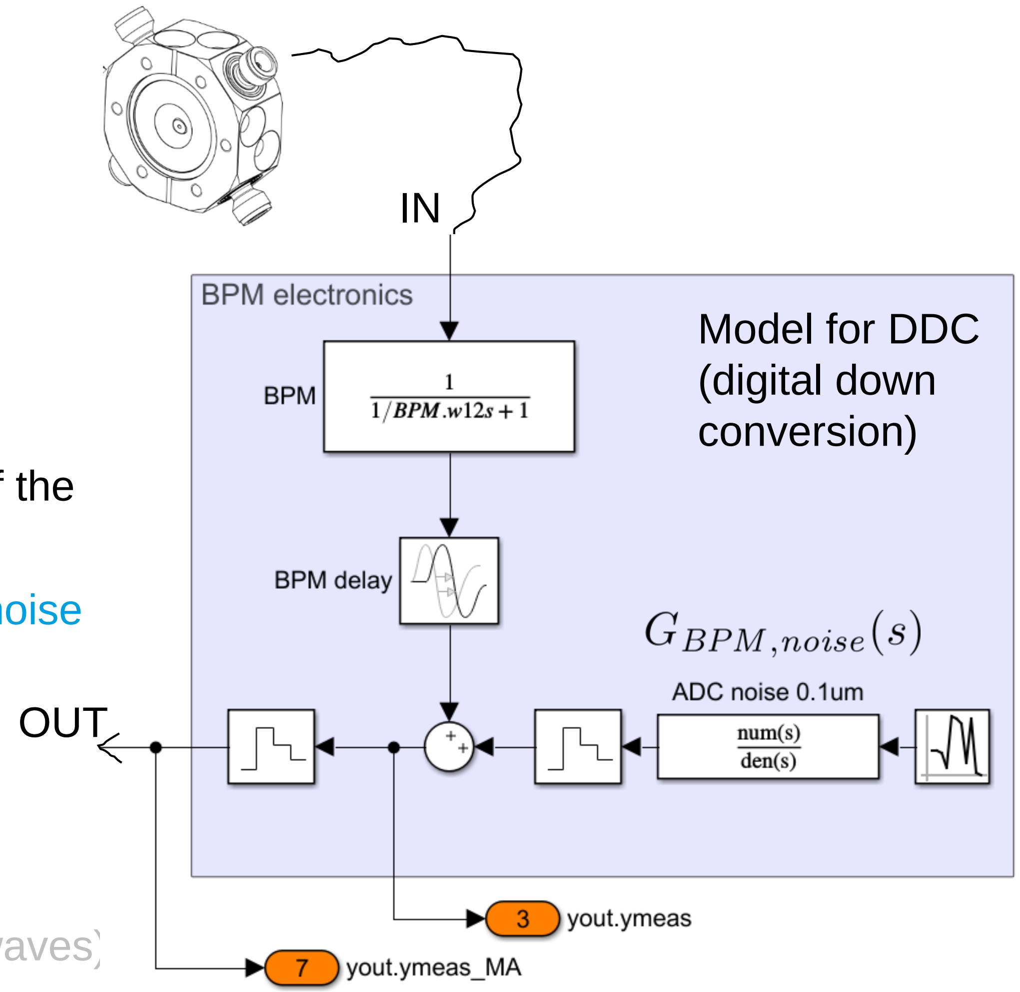
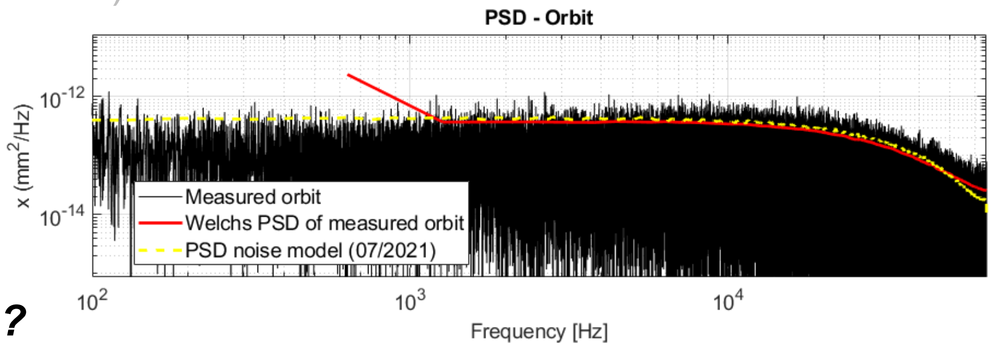


- Noise measured at PIII
- Adapted for PIV simulation



BPM noise as function of bunch pattern, … ?

PIV - FOFB system

Disturbance integration - SISO

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  - Incoherent: DC … kHz
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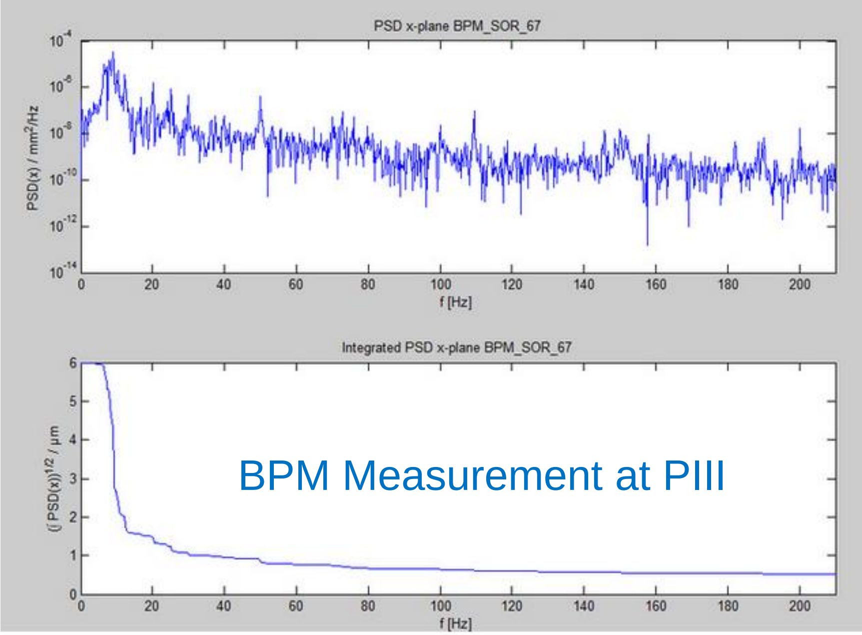
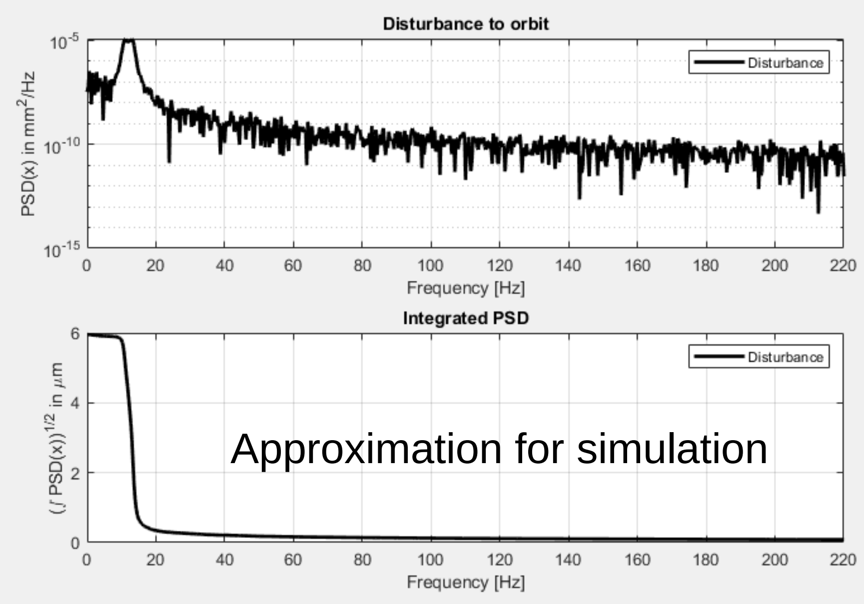
Start with PIII disturbance model to check PIV system simulations
→ Expect reduced distortions at PIV by optimization of girder eigenfrequencies





PIV - FOFB system

Blocks for simulation

- **Dynamic transfer functions**
  - Fast corrector magnet
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MIMO simulation and mode space analysis

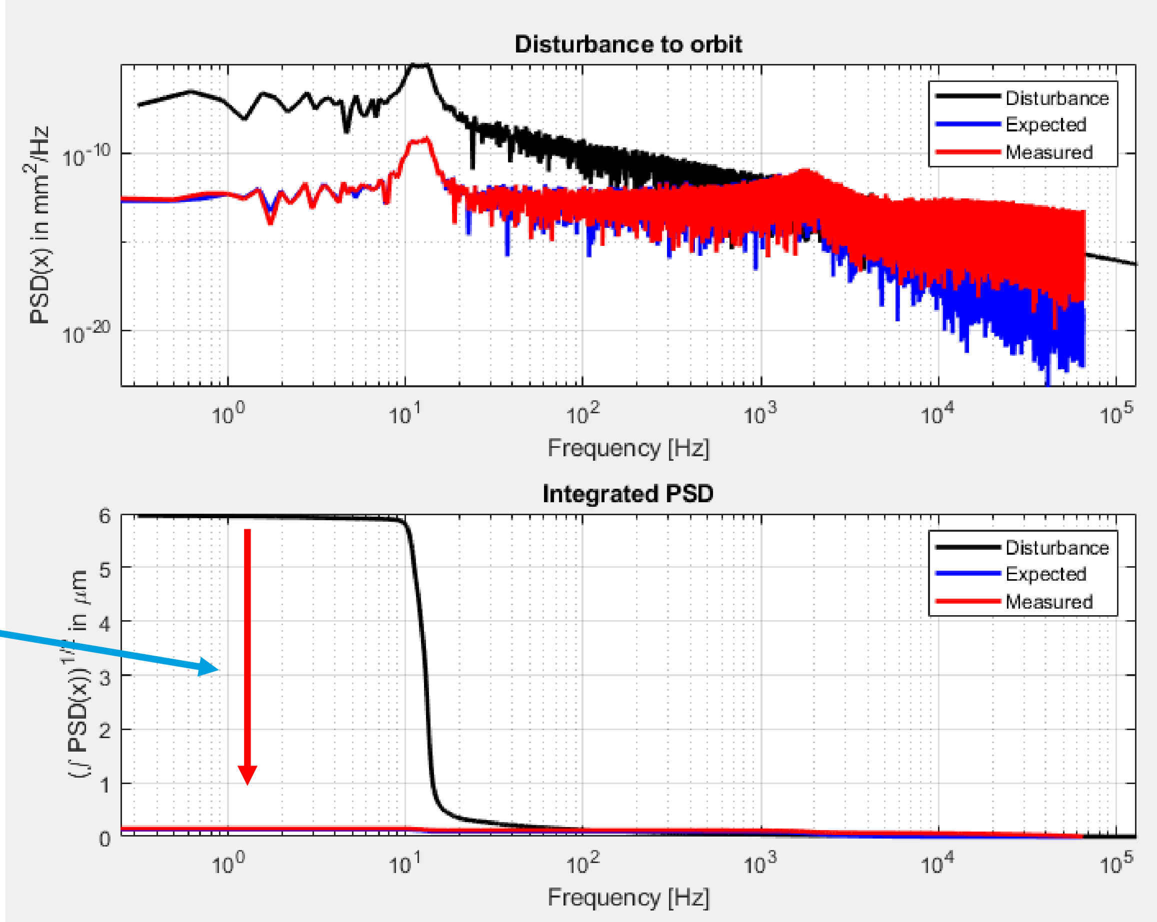
SISO simulation

FOFB system

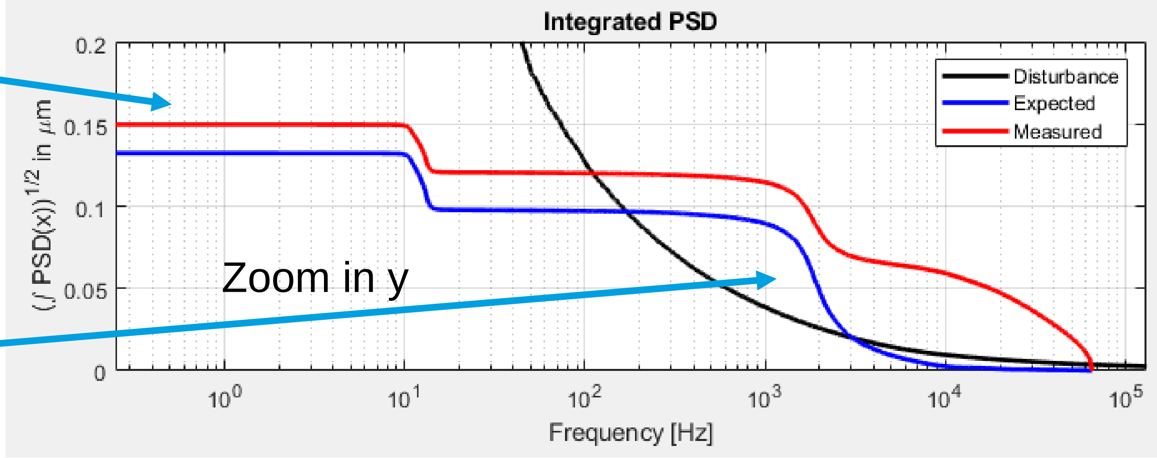
SISO simulation

- Disturbance spectra approximated with measurement at PIII
- Subsystems based on PETRA IV design
- PI controller optimized for 1kHz disturbance rejection

Factor 40 (32dB) reduction by feedback; Limited to FB controller and BPM noise



- 150nm measured → Red: measured with BPM noise
- 132nm expected → Blue: simulated without BPM noise
- **→ 4…5% beam size**



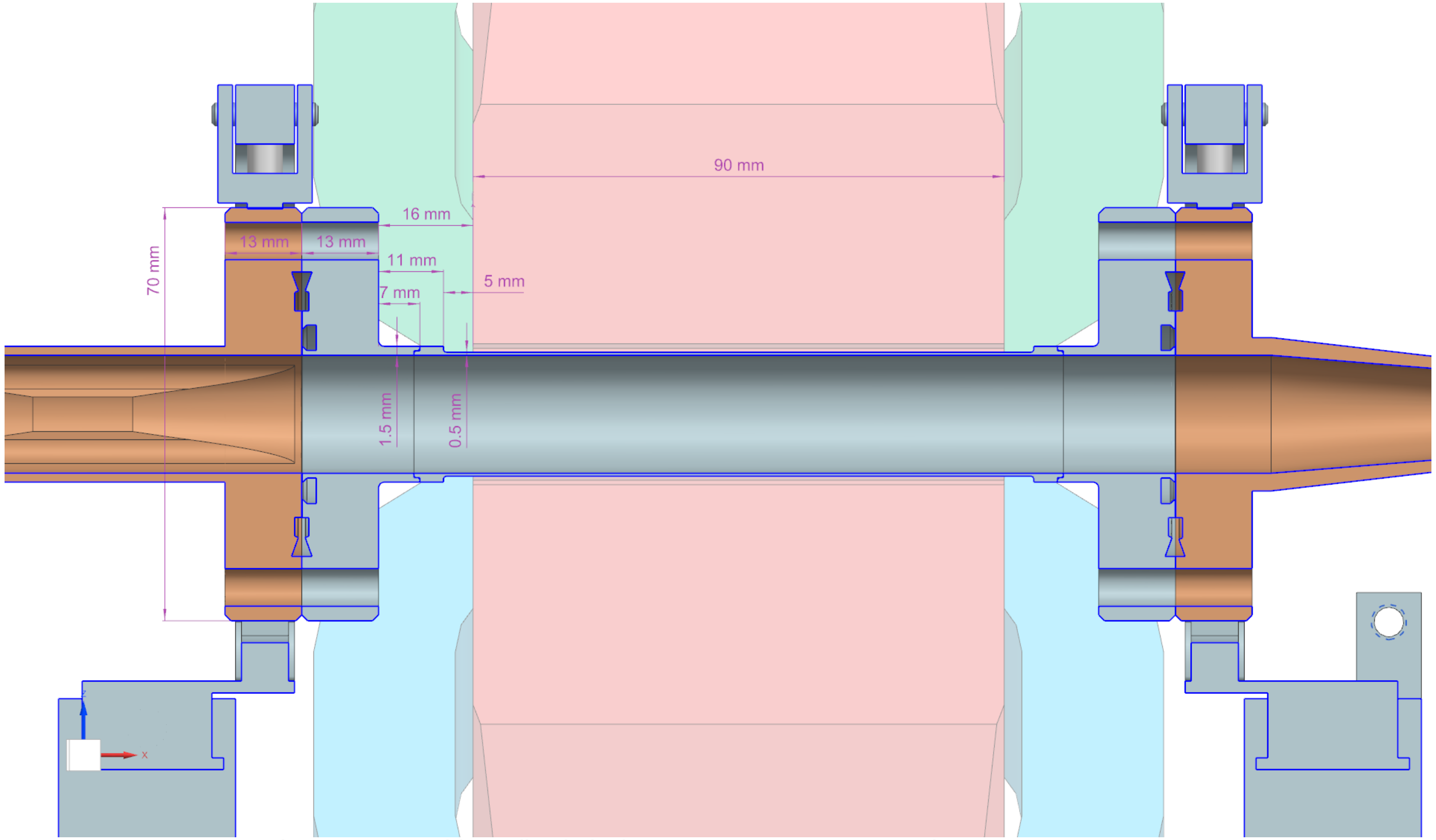
Waterbed effect increasing orbit jitter (latency and dynamics dependent)

Fractional order systems and it’s modelling

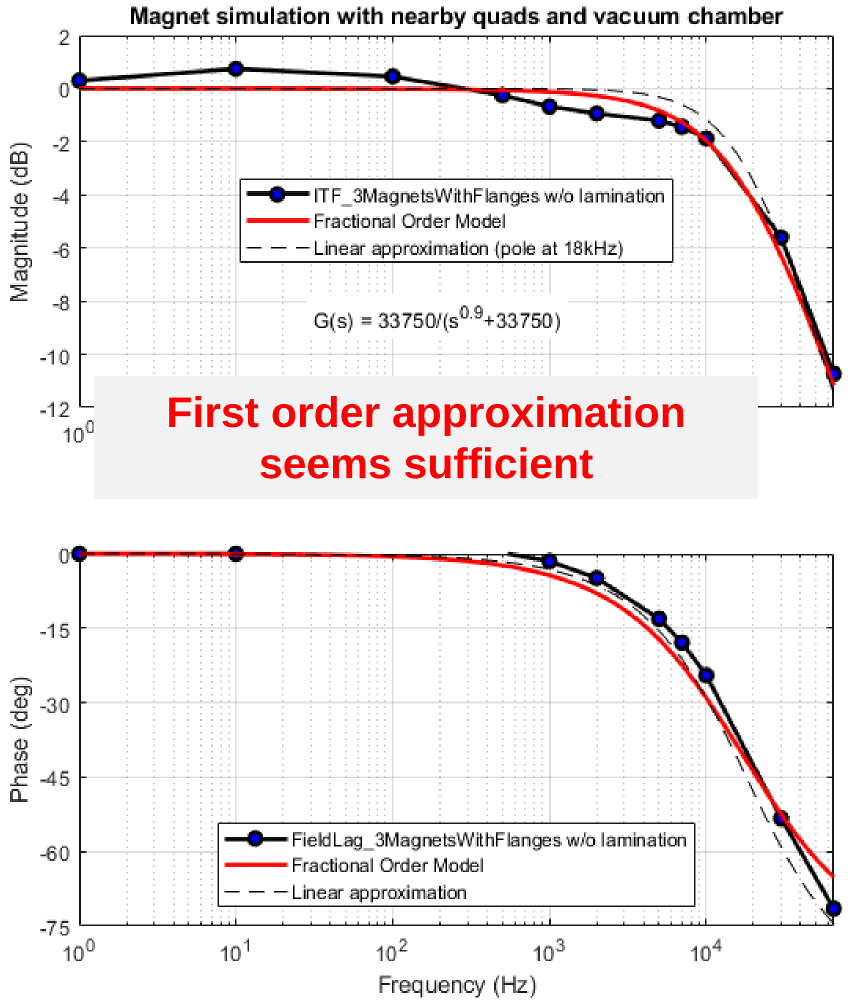
Fractional order systems and it's modelling

Two potential system with fractional order characteristic

1. **Yoke → next slides**
2. SS vacuum chamber with symmetric CU transitions



- SS vacuum chamber with CU transition

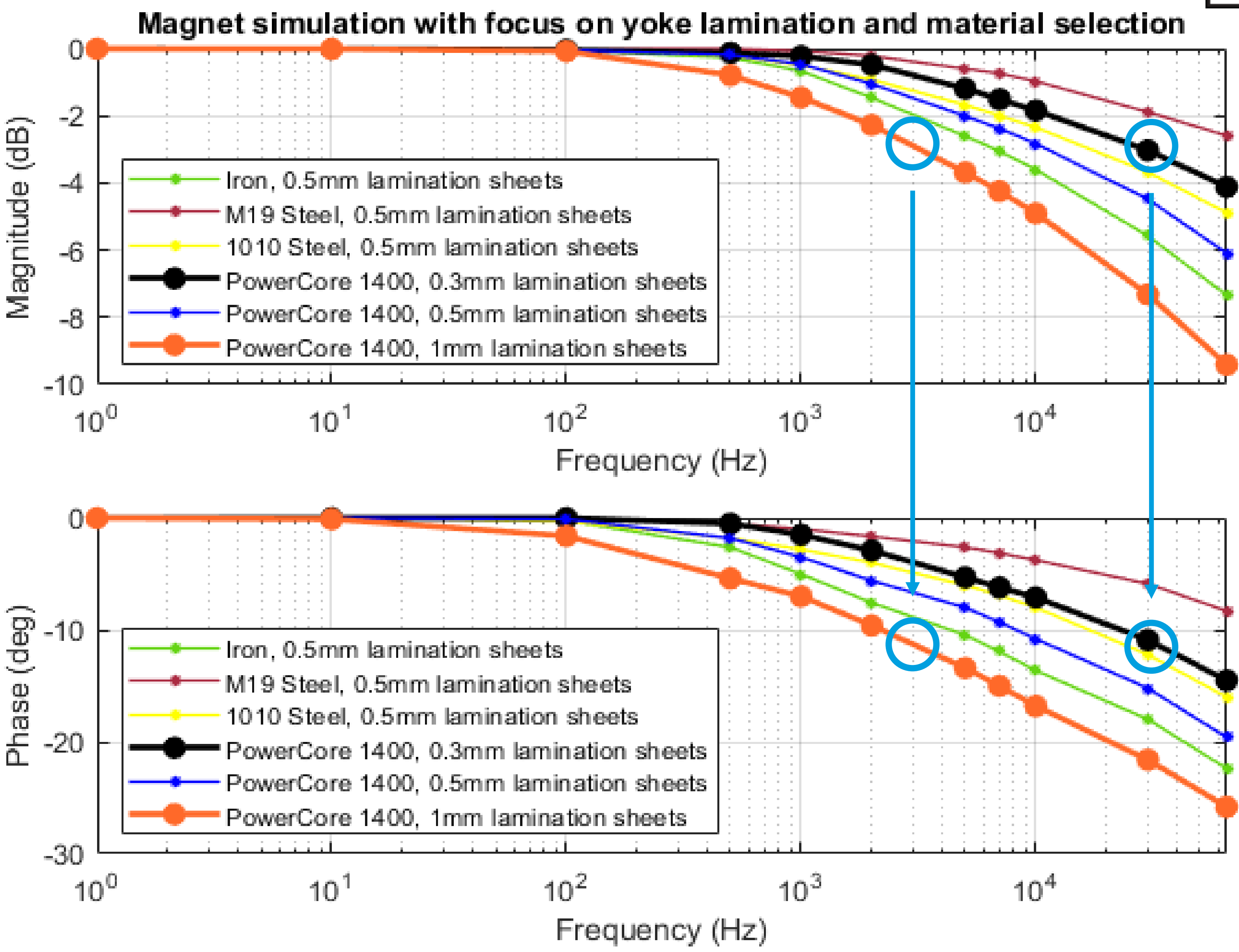


First order approximation seems sufficient

TEMF simulations

Yoke variations

- 1st prototype magnet with PowerCore 1400 and 1mm lamination
  - **3kHz with -10deg.**
- 2nd prototype magnet with PowerCore 1400 and 0.3mm lamination
  - **30kHz with -10deg.**

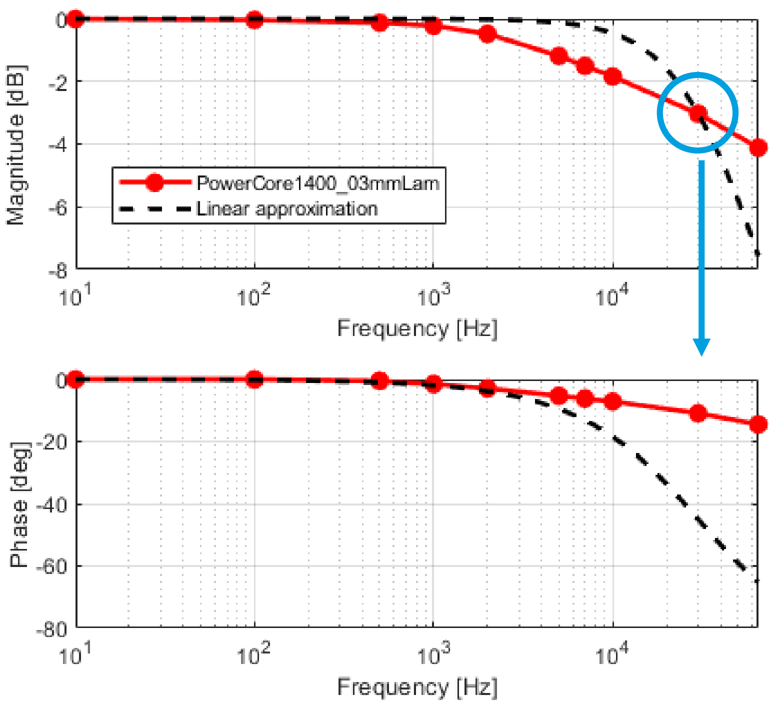


Fractional order characteristics

Modelling

First order system

- All subsystems in full simulation approximated by first or higher order
  - Assumption: worst case scenario with minimum phase margin in feedback



Fractional order systems

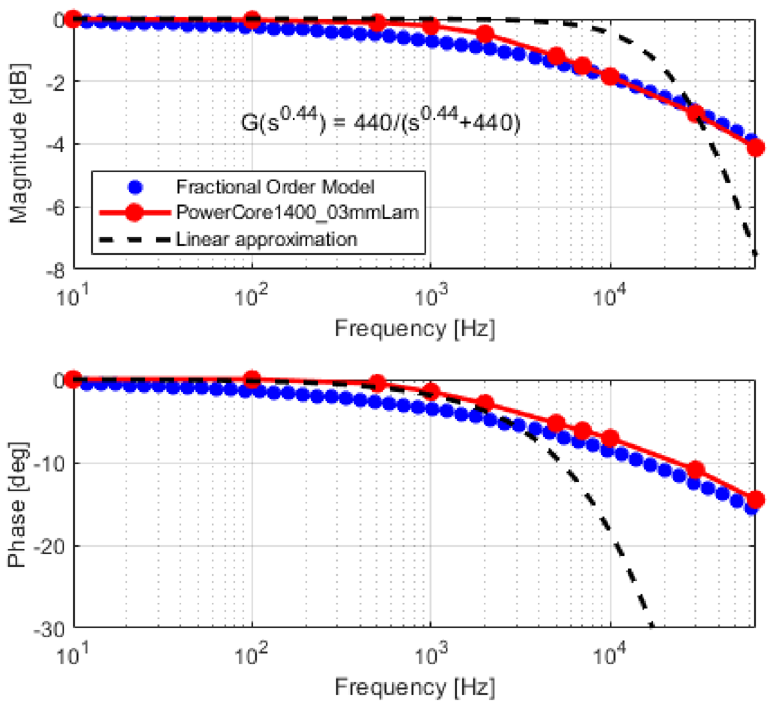
- … is a dynamical system that can be modeled by a fractional differential equation containing derivatives of non-integer order (Wiki).

$$G(s) = \frac{Y(s)}{U(s)} = \frac{\sum_{k=0}^{n} b_k s^{\beta_k}}{\sum_{k=0}^{m} a_k s^{\alpha_k}}$$

Fractional order characteristics

- First order fractional system

$$G(s^{0.44}) = \frac{1}{0.0023 \cdot s^{0.44} + 1}$$



SISO Fractional Order System Simulation

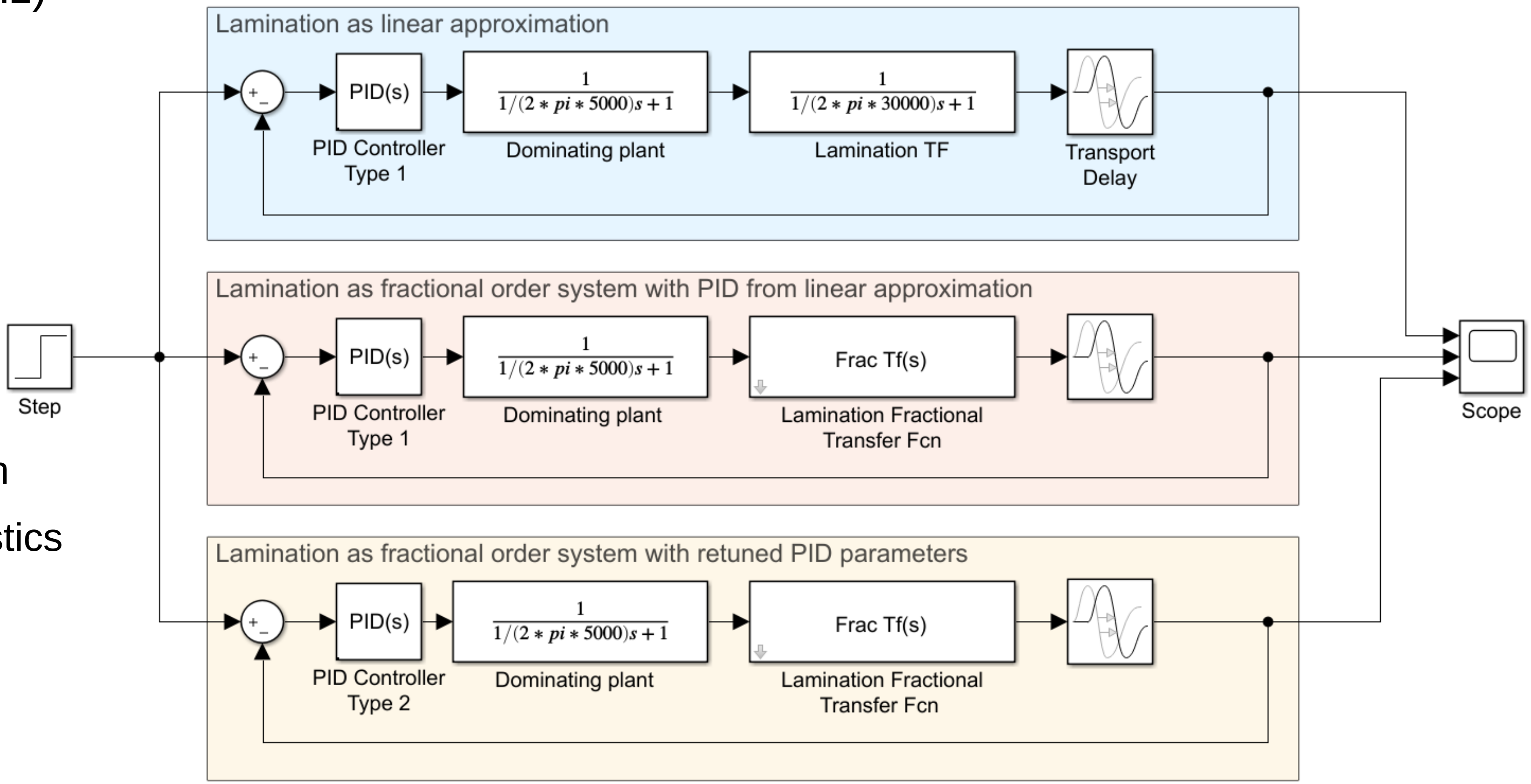
Fractional order characteristics

PI controller for yoke lamination

1. PI controller with linear system → ***1st order modelling***
2. PI controller with fractional order system → **reality**
3. PI controller adapted with fractional order system

Simulation

- Dominating pole as approximation of the main plant characteristics (5kHz)
- Feedback delay ~75us
- Magnet laminations as
  1. Linear approximation
  2. Fractional order system
- PI Feedback controller
  1. Designed with linear approximation
  2. Matched with fractional characteristics



Fractional order characteristics

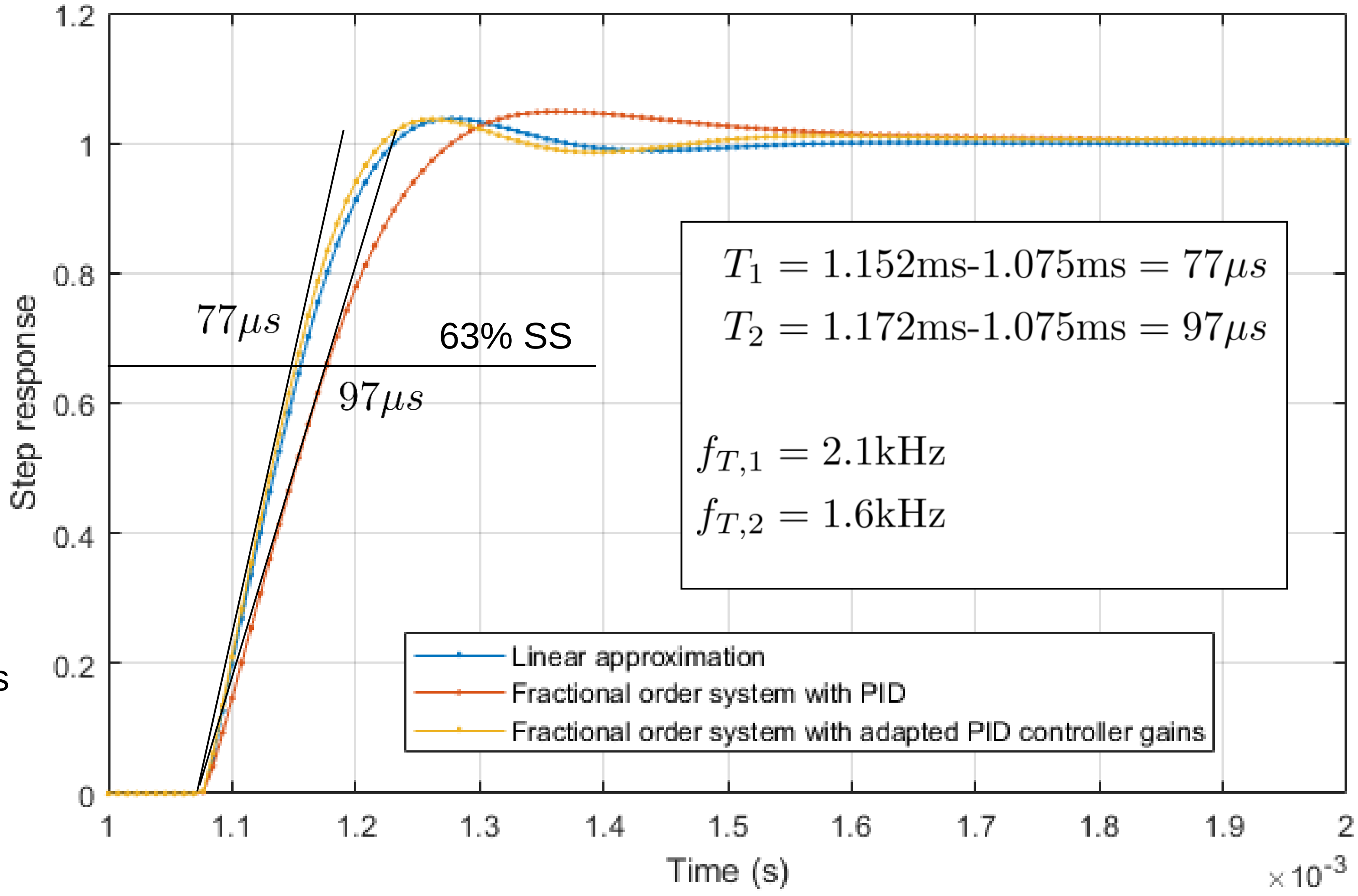
PID controller for yoke lamination

500Hz mismatch in closed loop.
BUT with adopted PID settings similar reference tracking characteristic achieved.

Simulation

- Dominating pole as approximation of the main plant characteristics (5kHz)
- Feedback delay ~75us
- Magnet laminations as
  1. Linear approximation
  2. Fractional order system
- PI Feedback controller
  1. Designed with linear approximation
  2. Matched with fractional characteristics

I gain +10%
P gain +50%



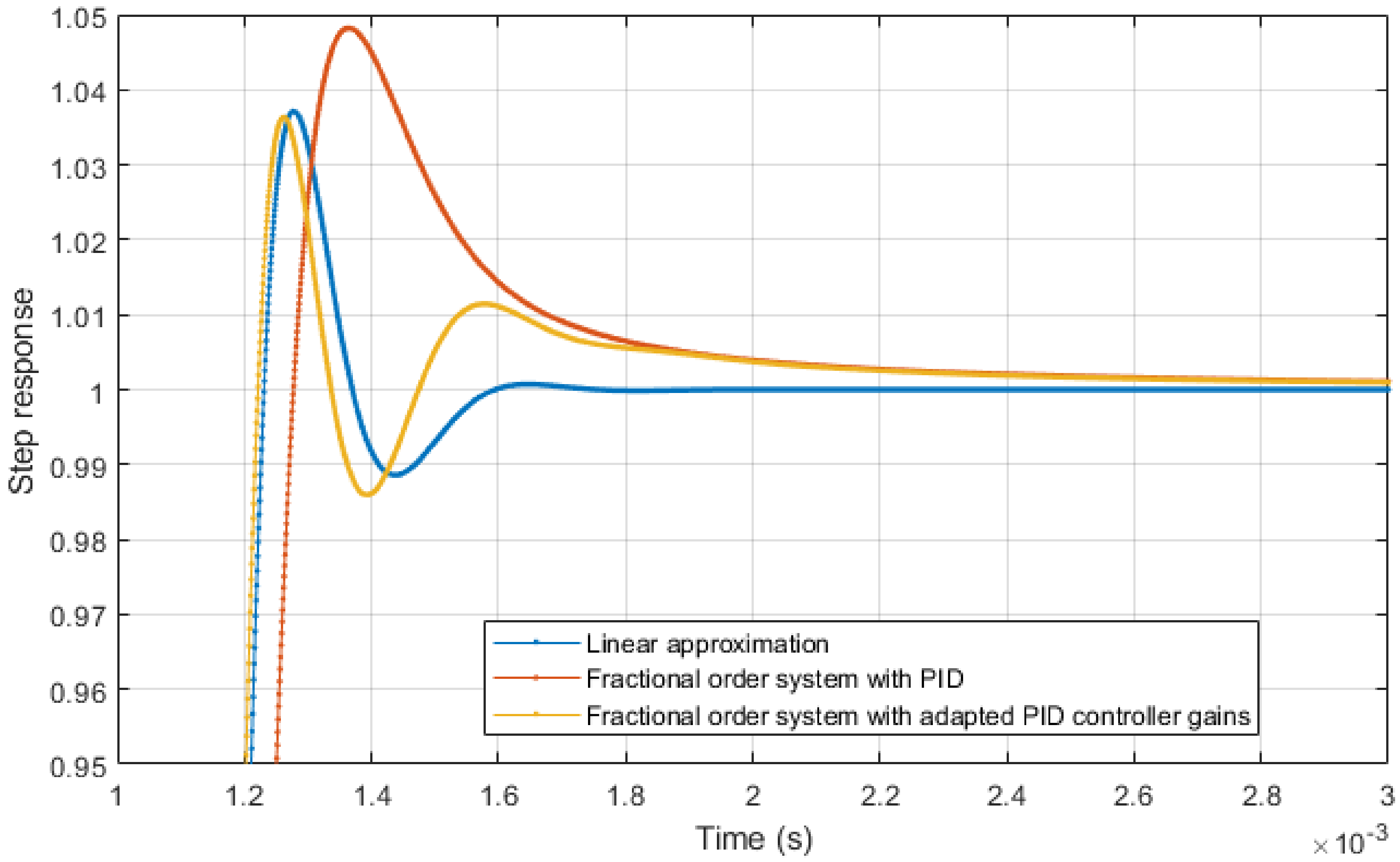
Fractional order characteristics

PID controller for yoke lamination

Linear vs fractional order system:
>1ms to reach convergence

Simulation

- Adapted PID settings for faster reference tracking at the beginning (first 0.1ms)
- **Mismatch of the low frequency tracking**
- Might not be relevant for disturbance suppression feedback
- **BUT**, might be of importance for integration of photon diagnostics using reference tracking → longer settling time



Conclusion & Outlook

- Models (few) derived for (most) PIV systems
- Simulations of fast/slow corrector magnet, vacuum chamber by TEMF
- BPM noise characteristics measured at PETRA III
  - *Partly open for charge/bunch pattern/ … variations*
- Disturbance spectra of PETRA III for PIV simulations
- Fractional order modelling of laminations and effect to feedback regulation with adapted PI settings
  - Observed larger convergence time for reference tracking

Outlook

- Next: Validation of first prototype corrector on magnet test bench
- MIMO simulations with disturbance models
  - Coherence length, PSD, girder transfer characteristic…
- …

Thank you

Contact

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