FOFB system for PETRA IV

"The importance of the simulations and analysis by TEMF"

Sven Pfeiffer for the WP2.08 team

Hamburg, 03.12.2024

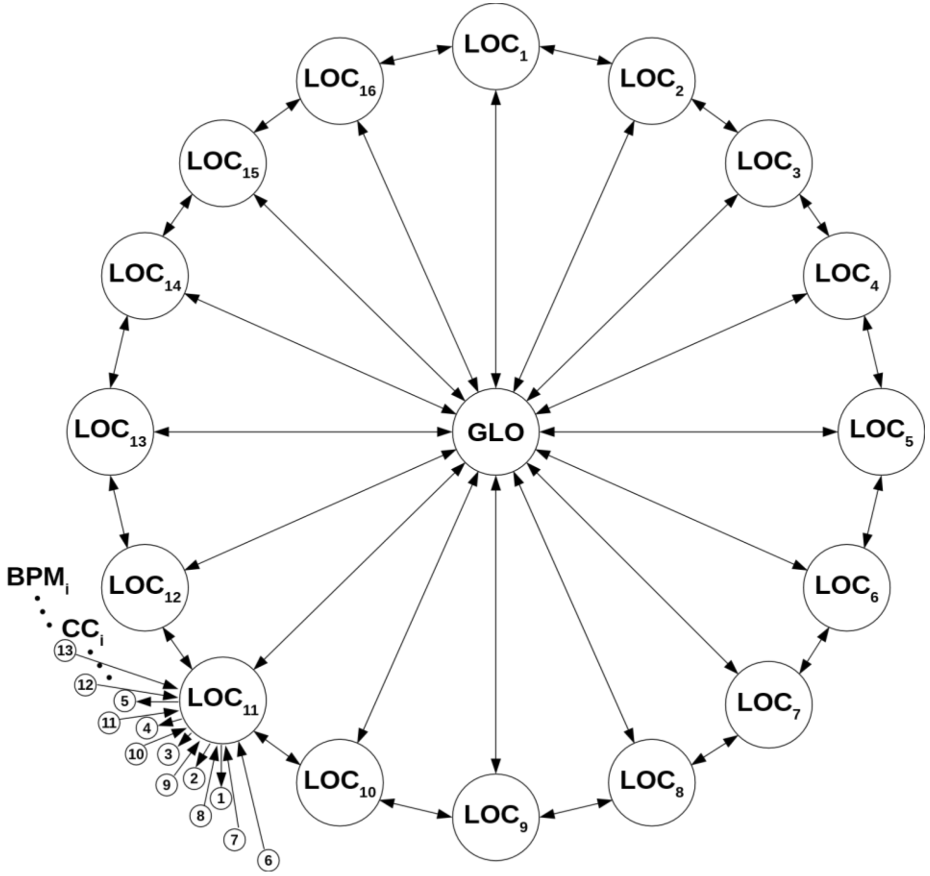
Outline

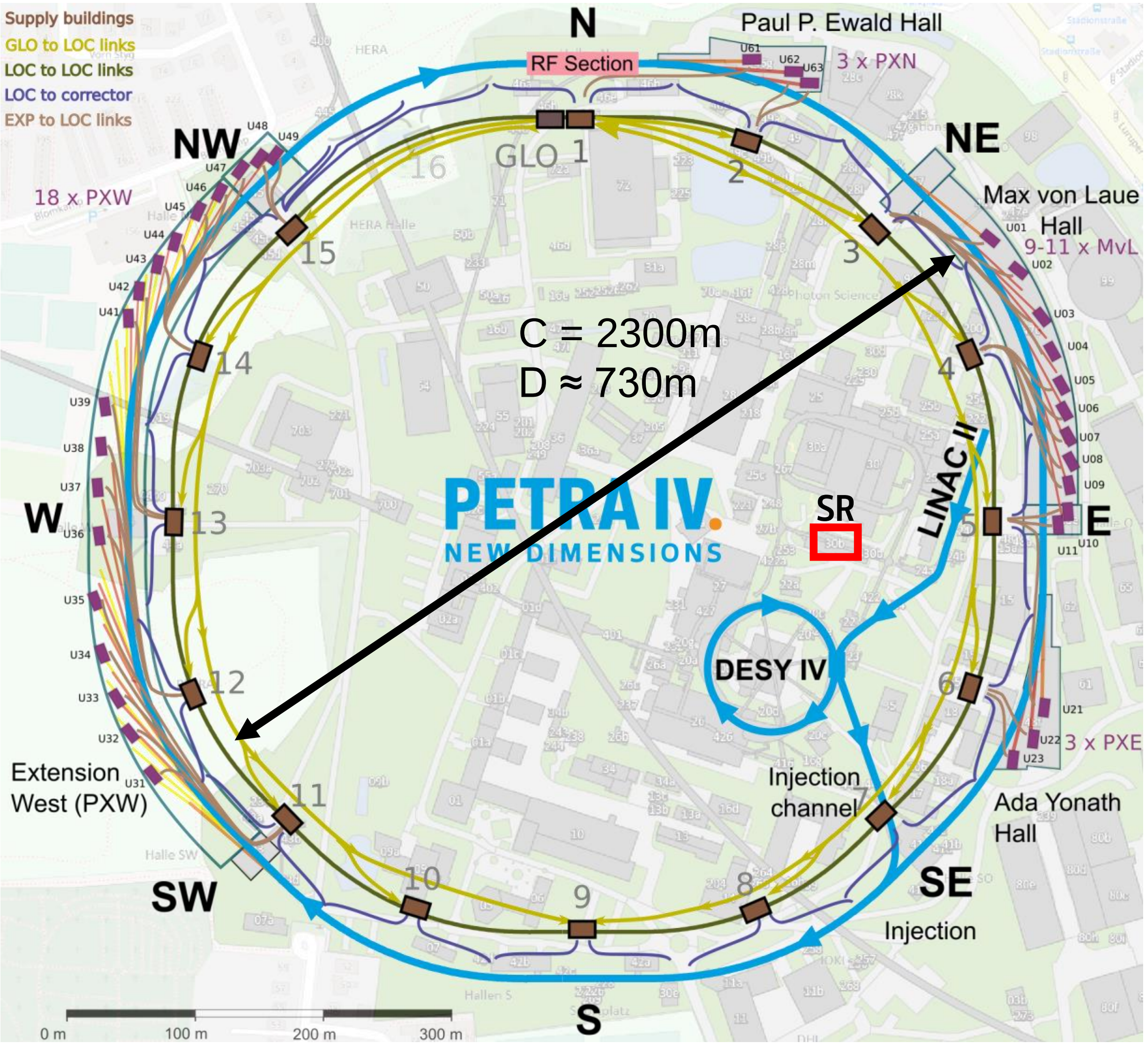
1. Introduction
2. Feedback basics
3. PETRA IV design
4. Next steps
5. Summary

Introduction

FOFB system overview & topology

- GLObal feedback node and LOCal feedback nodes for data processing
- Number of inputs (BPM) ≈ 1576
- Number of fast correctors ≈ 520





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

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

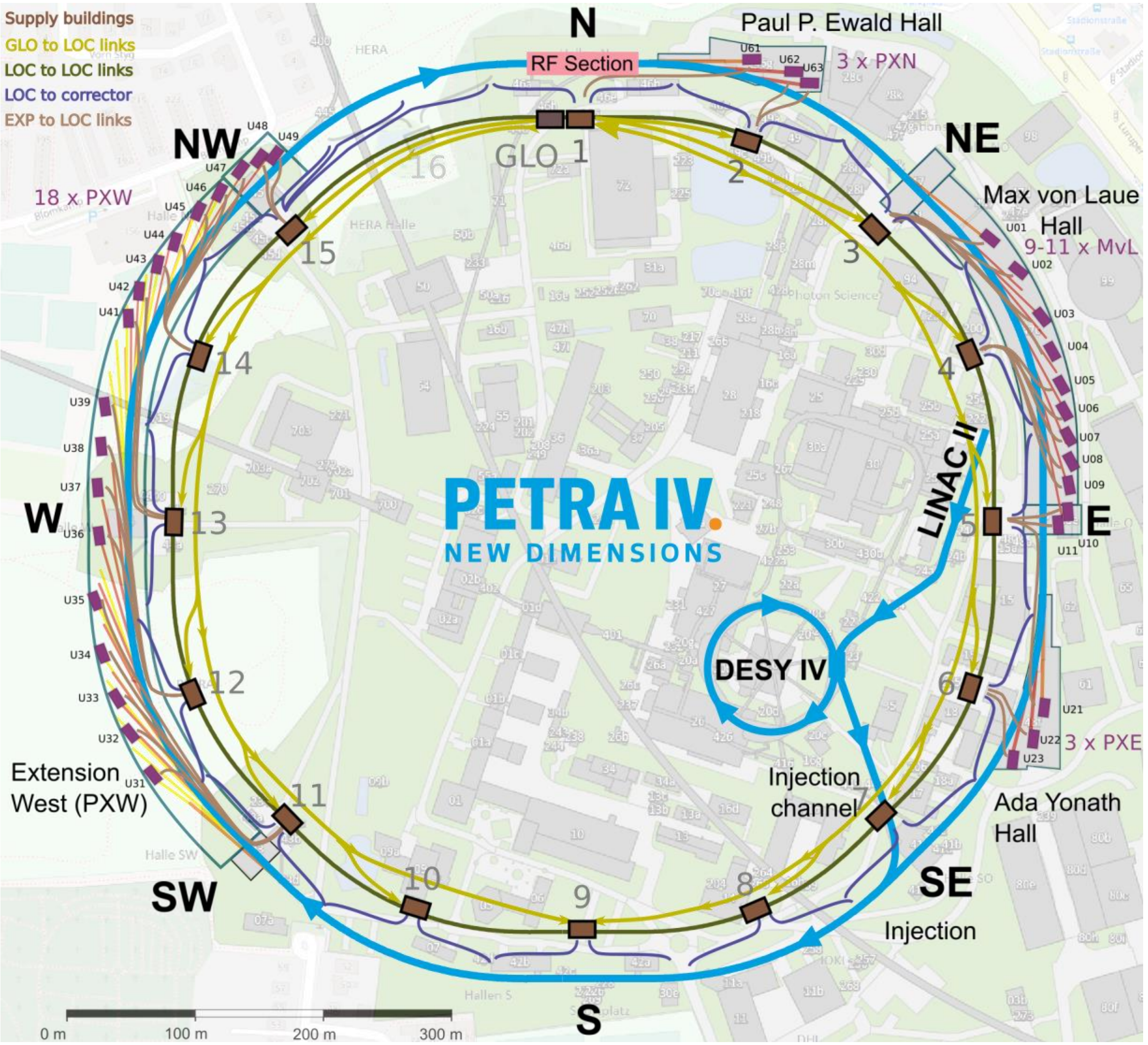
with $$r_{mn} = \frac{\sqrt{\beta_m(z)\beta_n(z)}}{2\pi Q}\cos(\pi Q - |\varphi_m(z) - \varphi_n(z)|)$$

- 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*

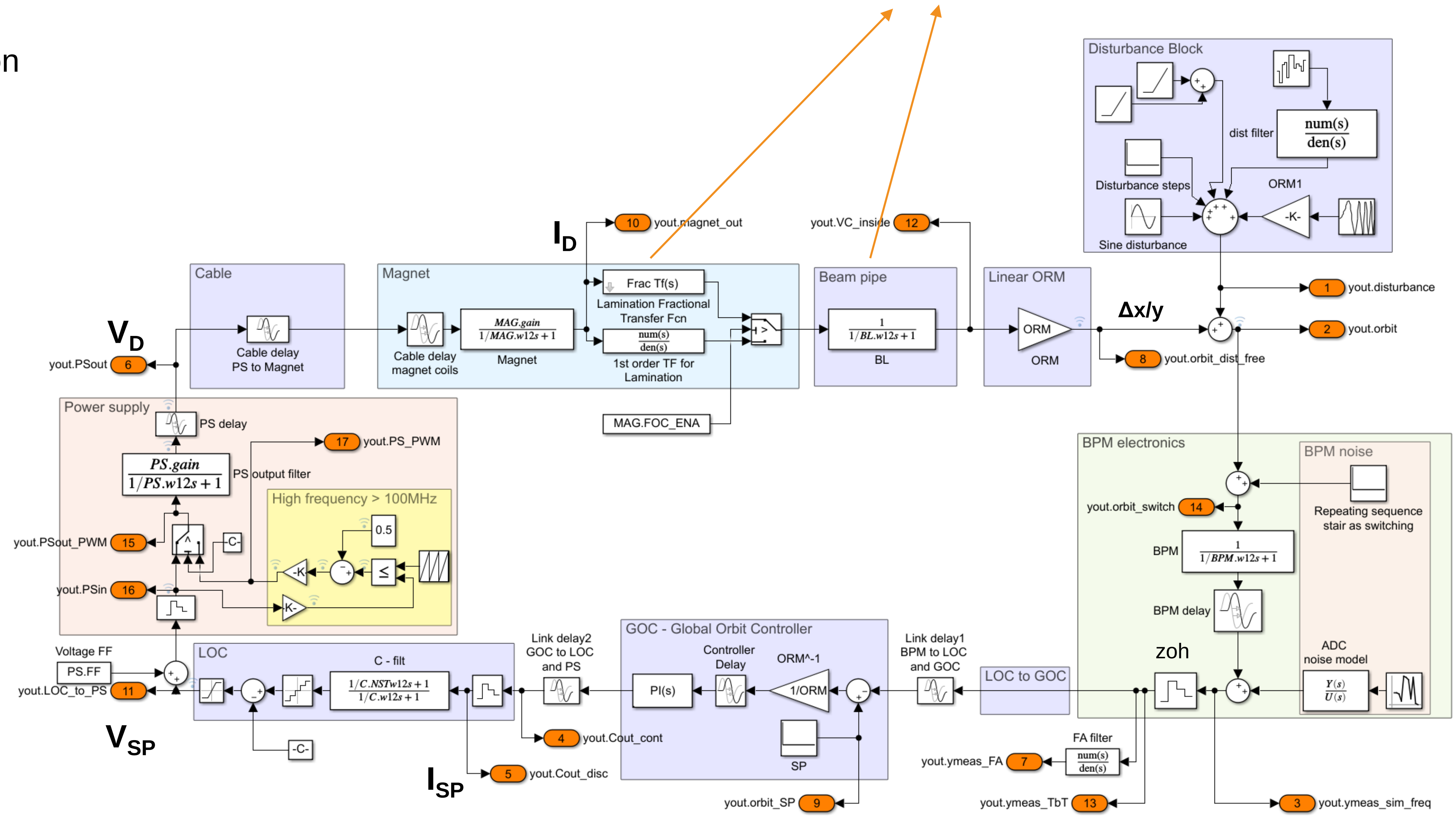


FOFB system

SISO simulation

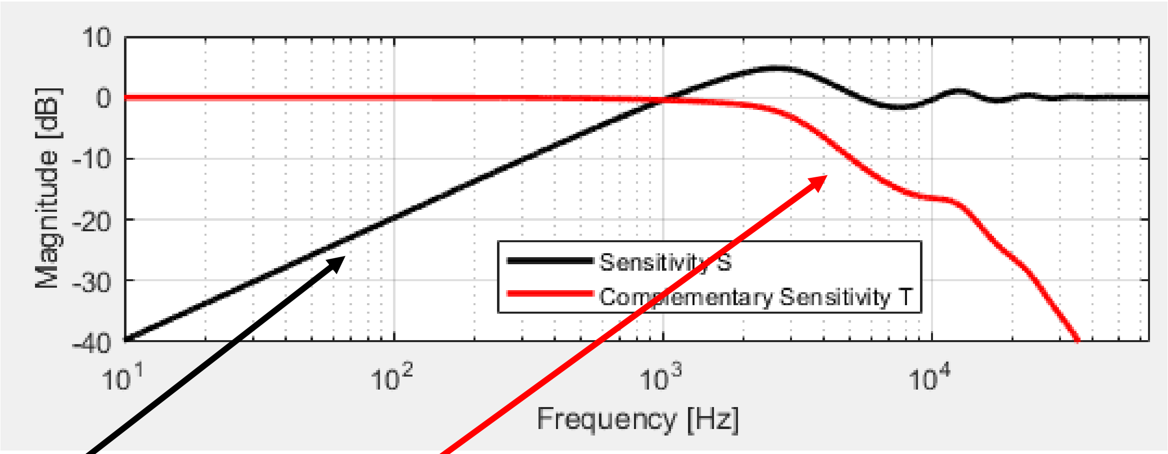
- Subsystems based on PETRA IV design
- Disturbance spectra approximated with measurement at PIII

Simulations by Jan

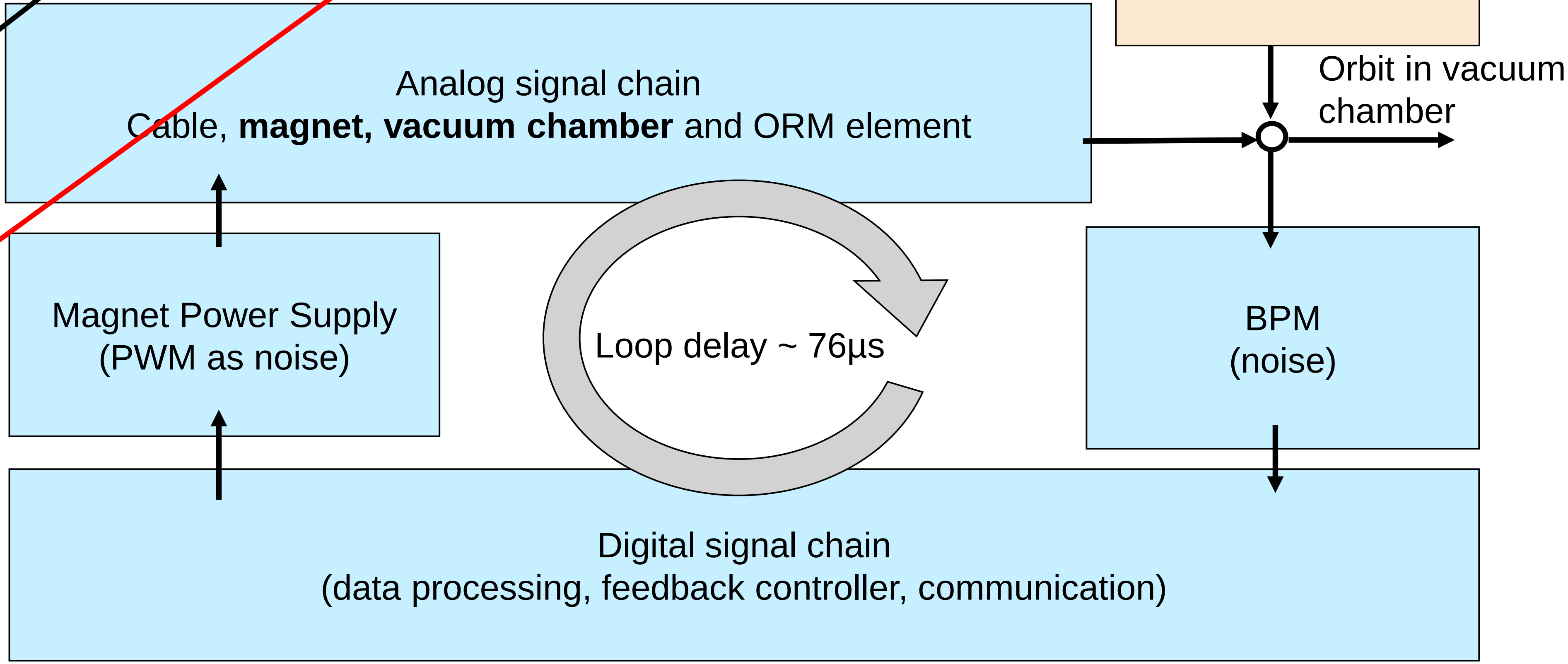


FOFB system

SISO simulation



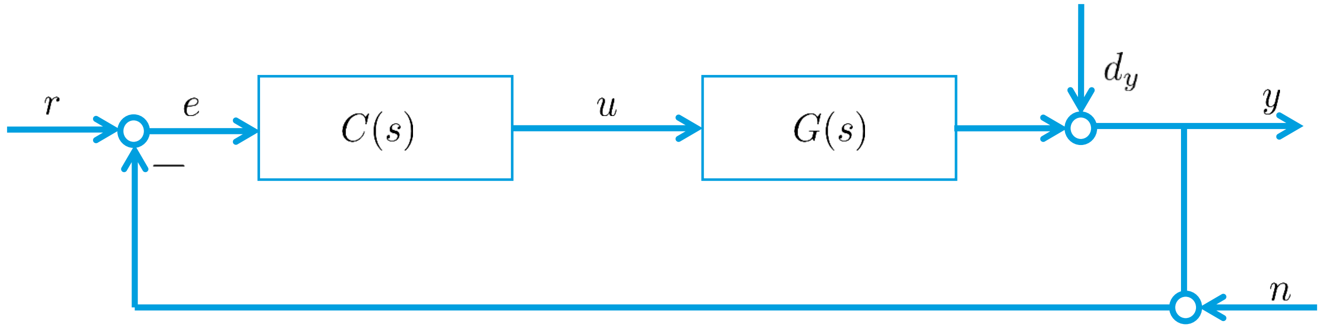
- Subsystems based on PETRA IV design
- Disturbance spectra approximated with measurement at PIII
- PI controller optimized for disturbance rejection
  - Goal: 1kHz
- PI controller optimized for reference tracking
  - Integration of experiments (photon diagnostics)



2. Feedback basics

Feedbacks basics

"One page feedback controls for dynamical systems"



Systems

- G(s) … system model
- C(s) … controller

Signals

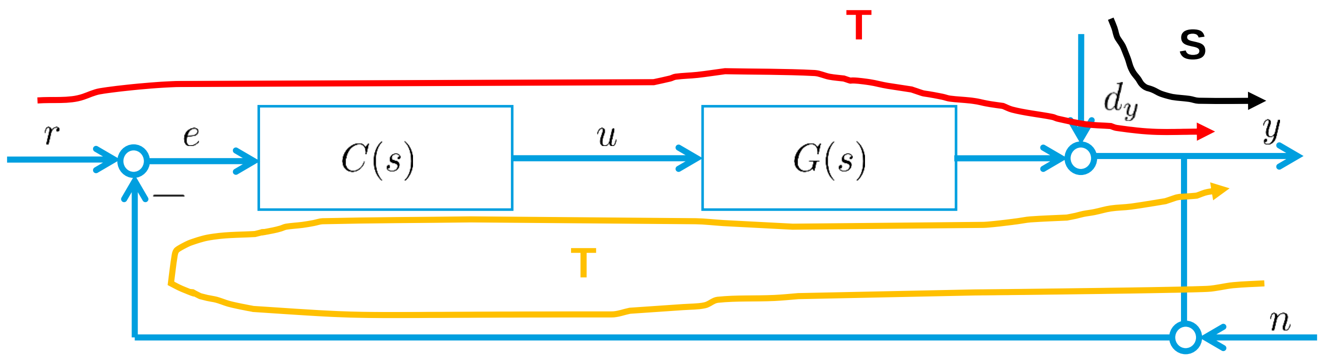
- r … reference
- n … noise (detector)
- d_y … disturbance to y

Inputs

- y … output signal (to be regulated)
- e ... error signal (r-y)

Feedbacks basics

"One page feedback controls for dynamical systems"



Systems

- G(s) … system model
- C(s) … controller

Signals

- r … reference
- n … noise (detector)
- d_y … disturbance to y
- y … output signal (to be regulated)
- e ... error signal (r-y)

Inputs (r, n, d_y)

Closed-loop transfer function

$$y = \frac{GC}{1+GC}(r-n) + \frac{1}{1+GC}d_y$$

Complementary sensitivity function

$$\boxed{T = \frac{GC}{1+GC}}$$

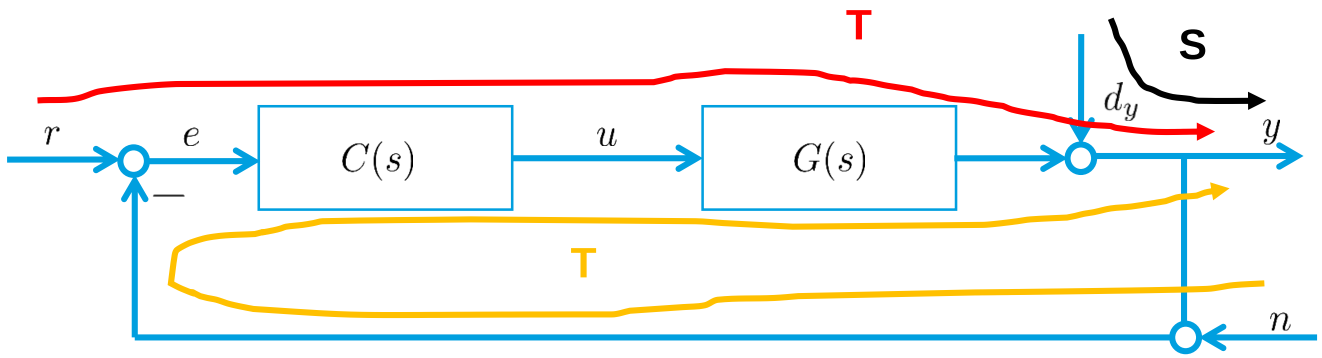
Sensitivity function

$$\boxed{S = \frac{1}{1+GC}}$$

Coupling $S + T = 1$

Feedbacks basics

"One page feedback controls for dynamical systems"



Systems

- G(s) … system model
- C(s) … controller

Signals

- r … reference
- n … noise (detector)
- d_y … disturbance to y

(r, n and d_y: Inputs)

- y … output signal (to be regulated)
- e ... error signal (r-y)

Closed-loop transfer function

$$y = \frac{GC}{1+GC}(r-n) + \frac{1}{1+GC}d_y$$

Complementary sensitivity function

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

Sensitivity function

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

Coupling $\boxed{S + T = 1}$

Conflicting goals:

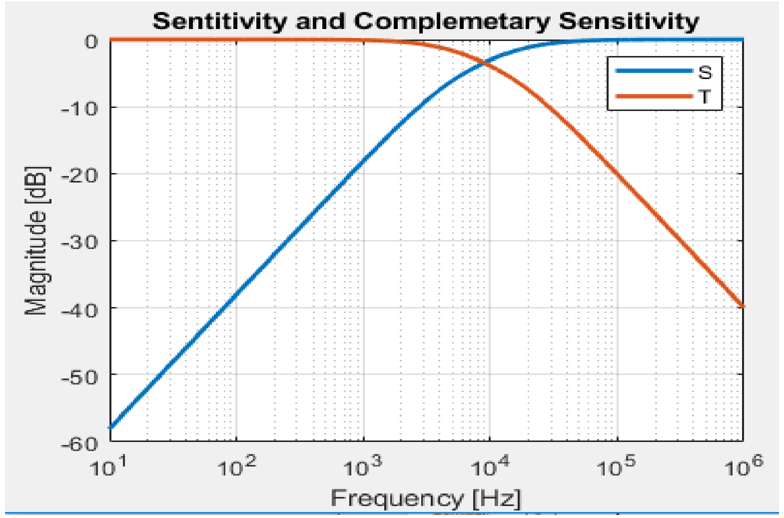
- **S = 0** for disturbance rejection
- **T = 1** for reference tracking
- **T = 0** for noise rejection

Typically:

- High frequency noise signal n
- Low frequency disturbance d
- Low frequency reference signal r

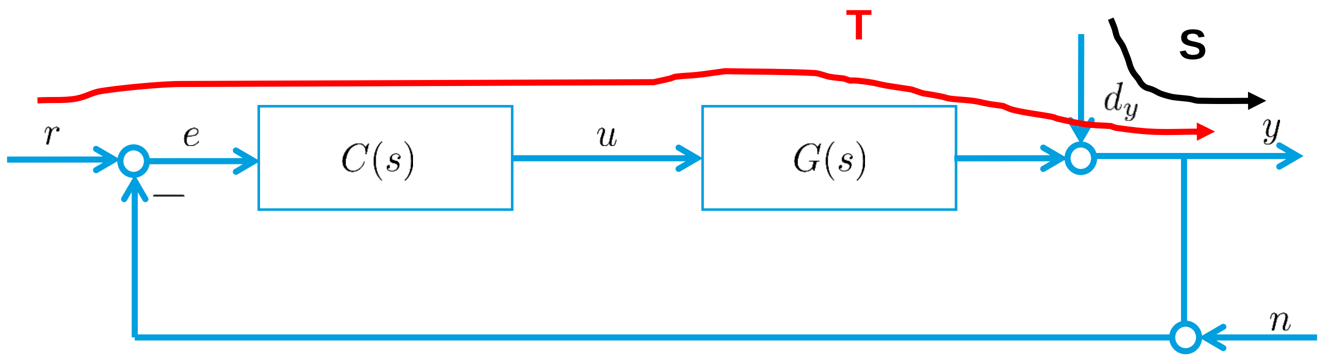
Choose:

$$S(0) = \text{small}; \quad S(\infty) = 1$$
$$T(0) = 1; \quad T(\infty) = \text{small}$$



Feedbacks basics

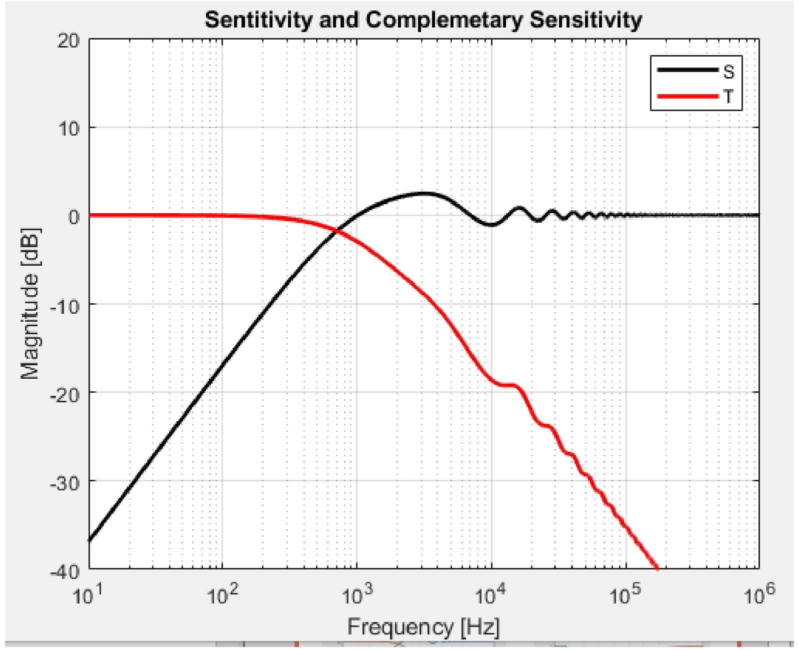
Example global / local control

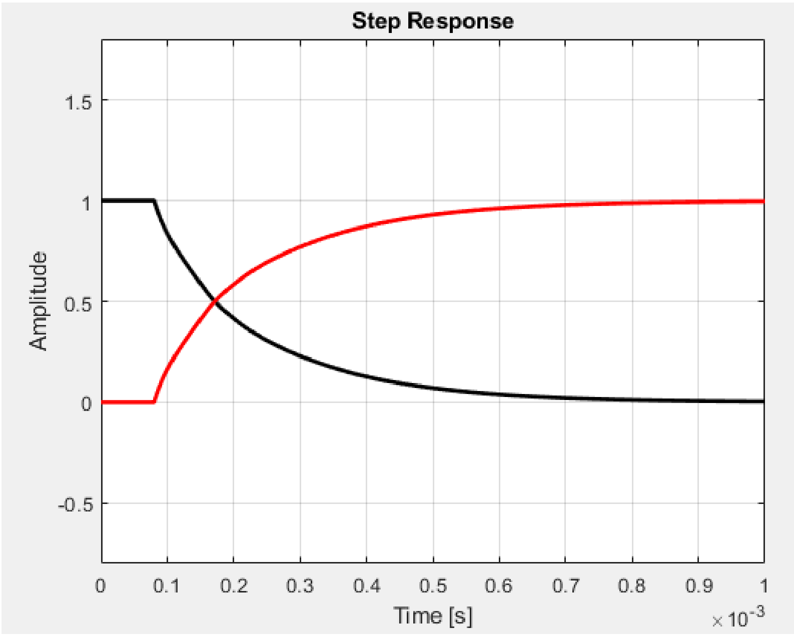


Example system G(s)

- Low-pass characteristic with bandwidth of 10kHz
- Delay of 80µs

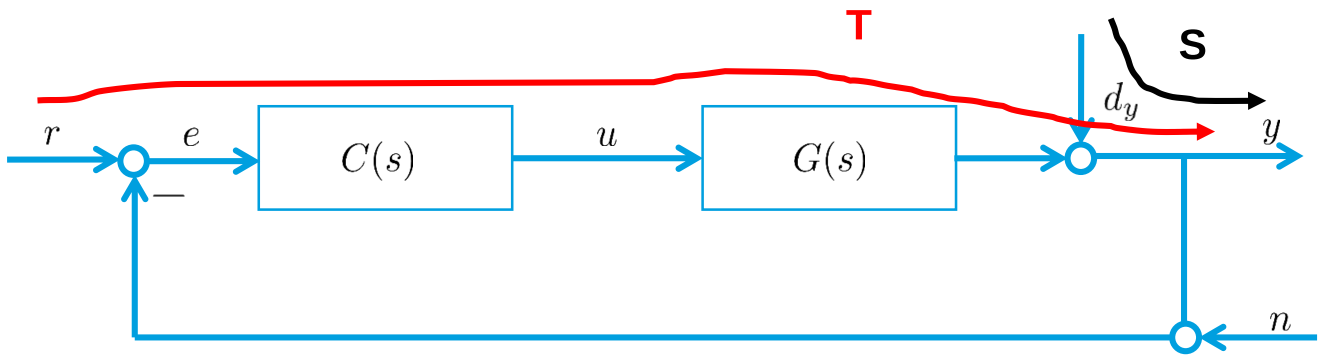
- **PI controller**





Feedbacks basics

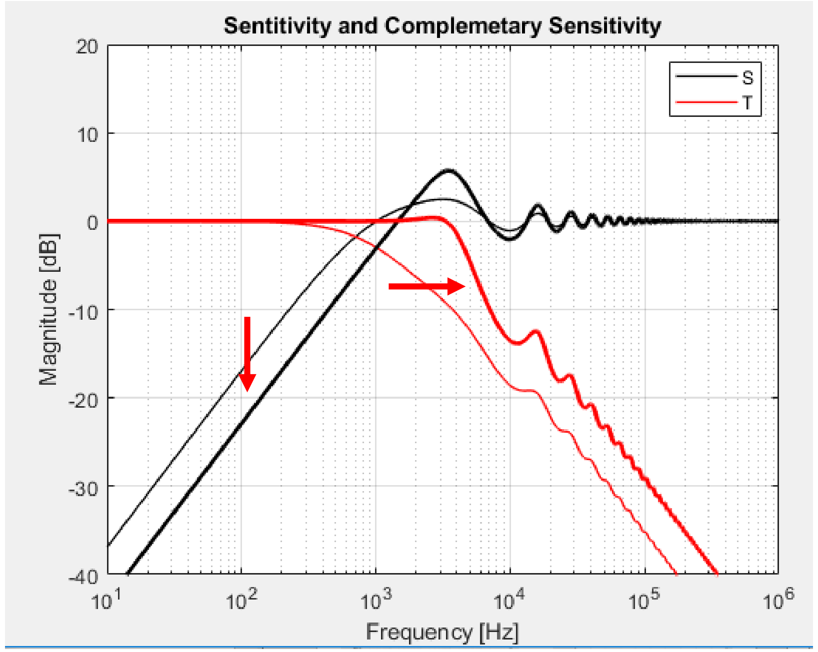
Example global / local control

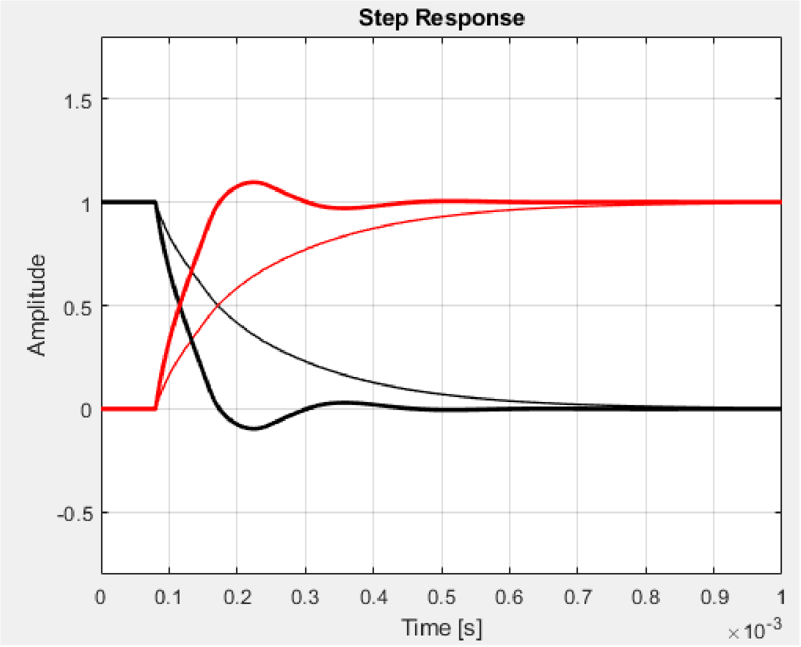


Example system G(s)

- Low-pass characteristic with bandwidth of 10kHz
- Delay of 80µs

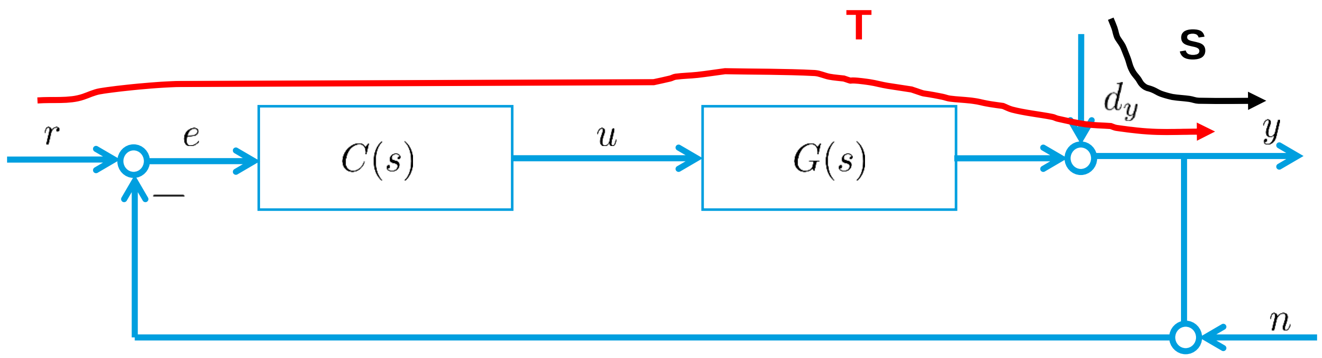
- **PI controller**
  - Increase of FB gain to increase closed loop bandwidth





Feedbacks basics

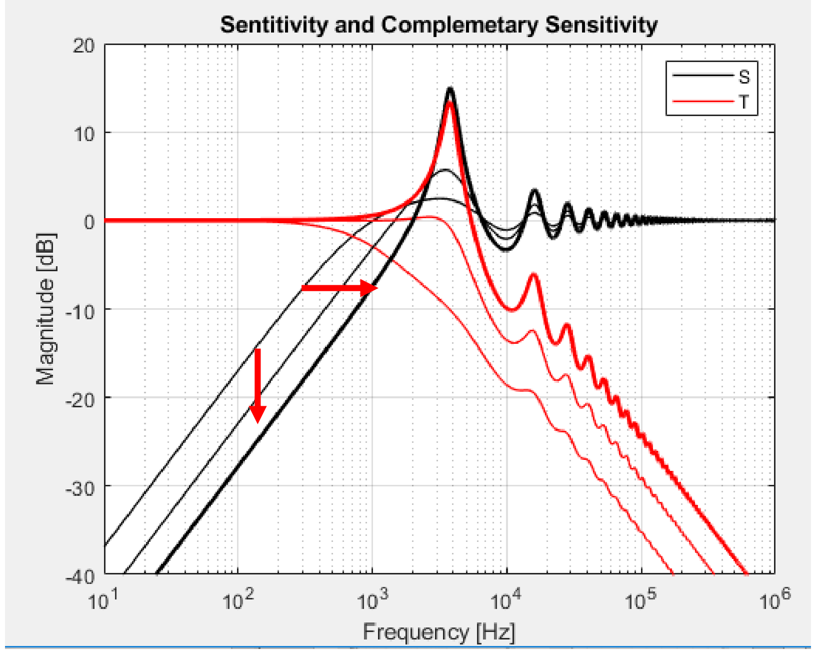
Example global / local control

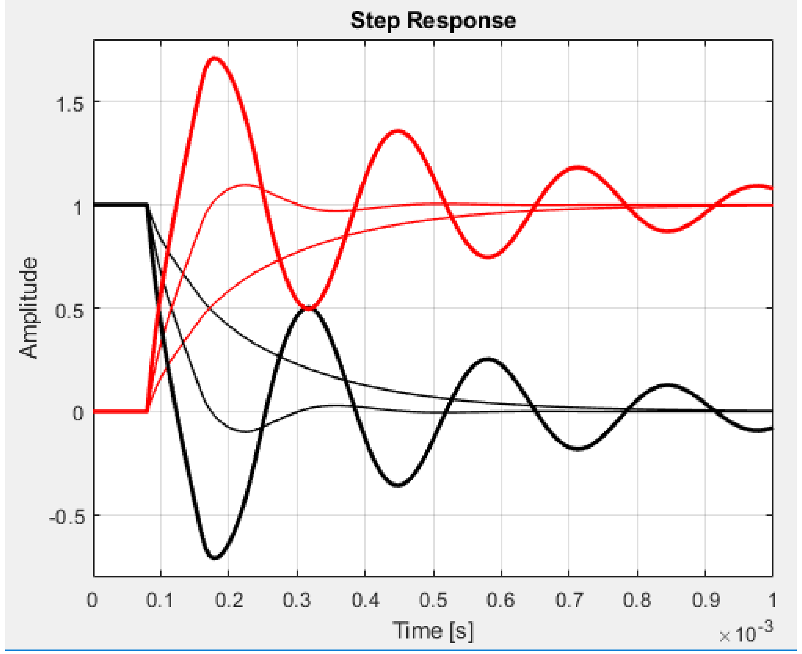


Example system G(s)

- Low-pass characteristic with bandwidth of 10kHz
- Delay of 80µs

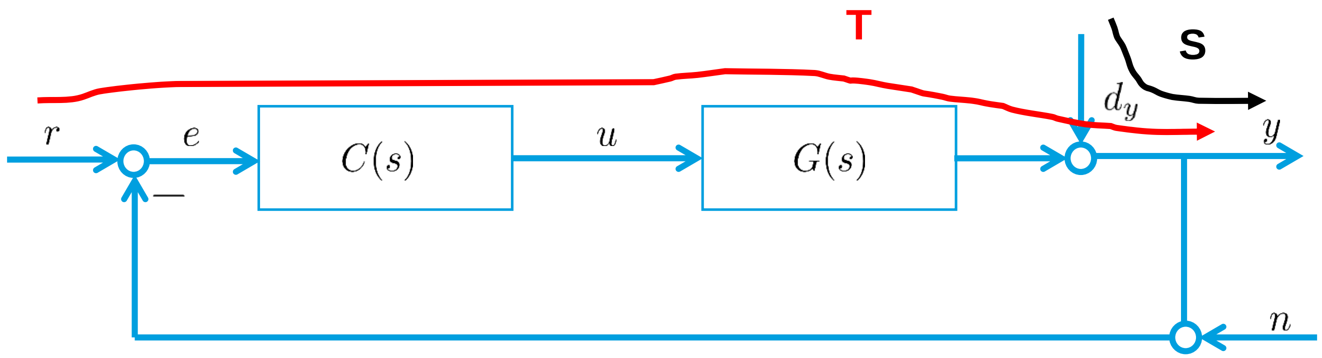
- **PI controller**
  - Increase of FB gain to increase closed loop bandwidth





Feedbacks basics

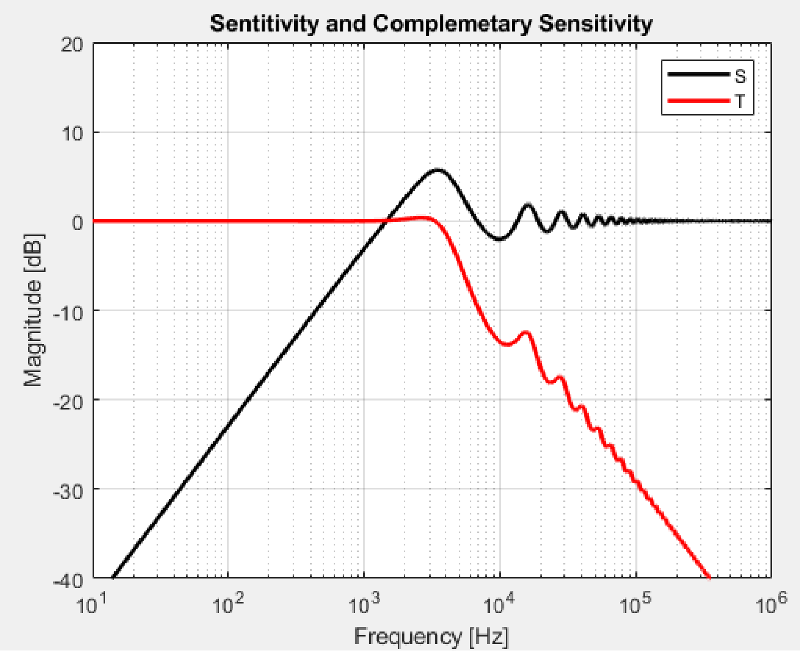
Example global / local control

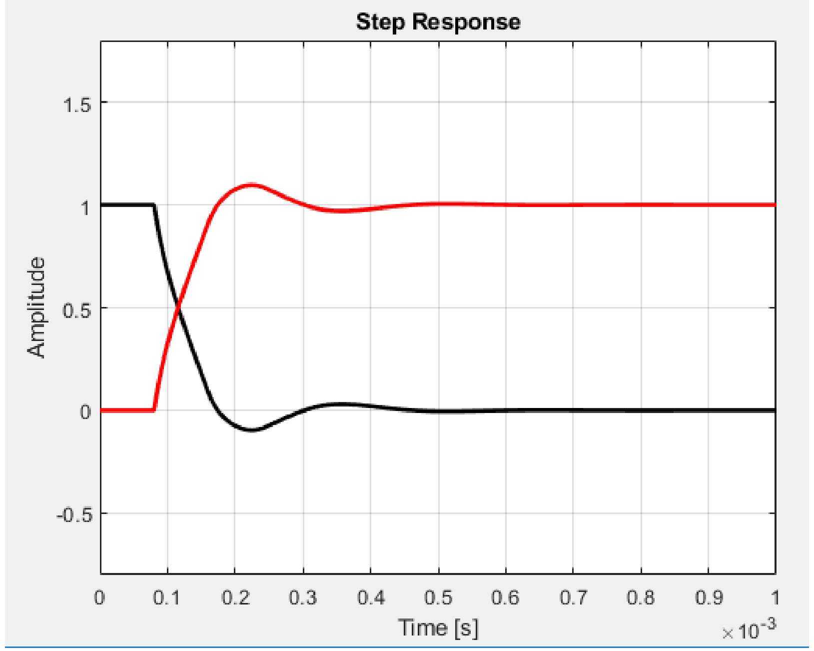


Example system G(s)

- Low-pass characteristic with bandwidth of 10kHz
- Delay of 80µs

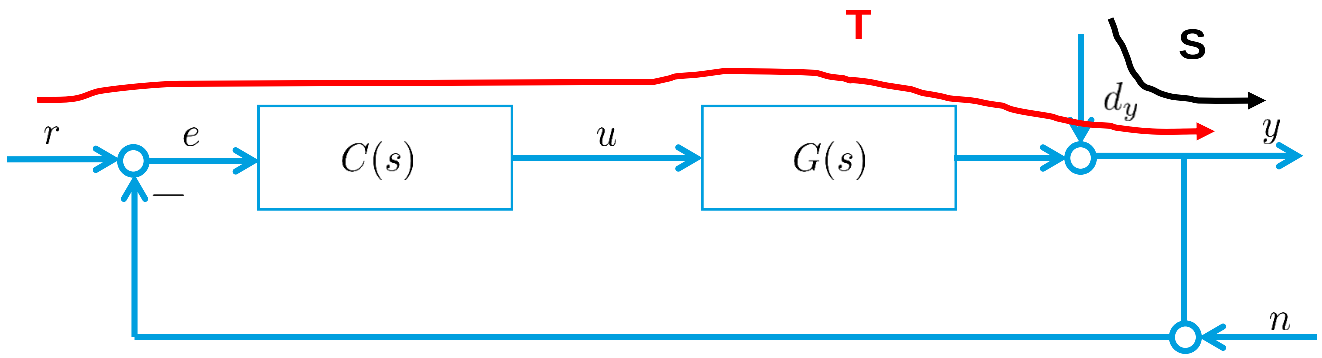
- **PI controller**
- From global to local regulation (loop delay reduction)





Feedbacks basics

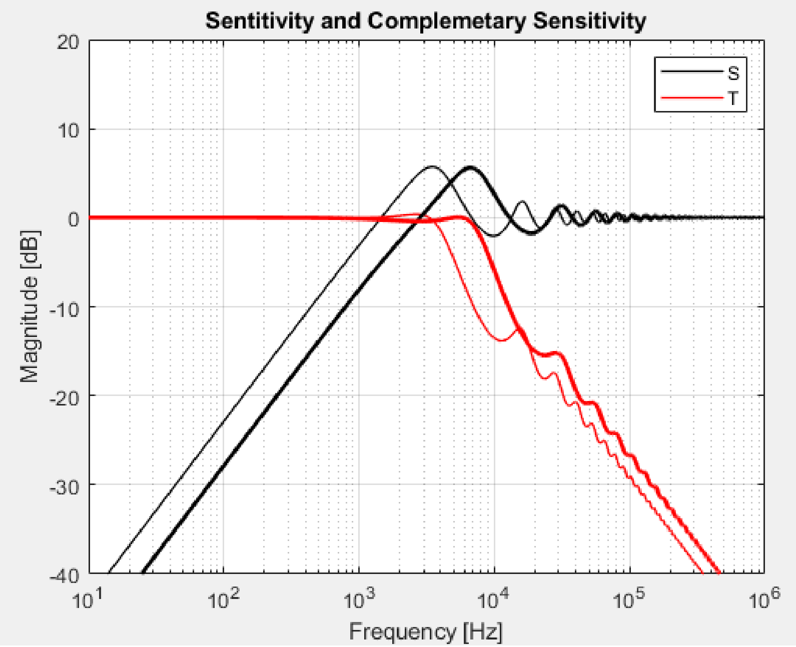
Example global / local control

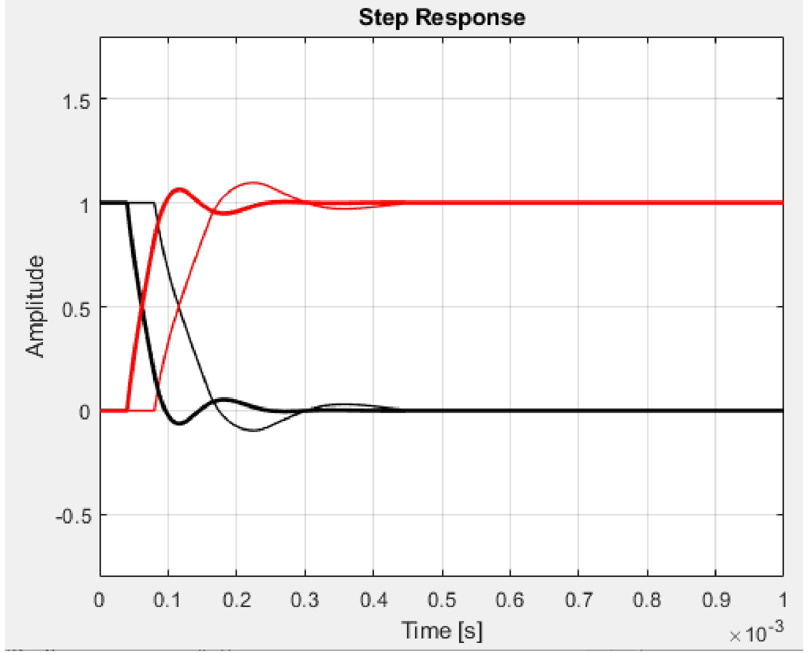


Example system G(s)

- Low-pass characteristic with bandwidth of 10kHz
- Delay of 80µs to 40µs

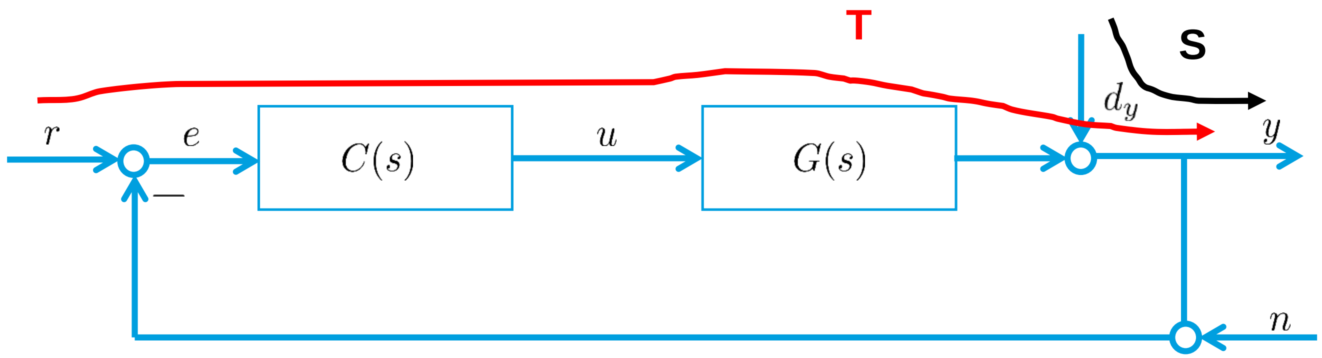
- PI controller
- **From global to local regulation (loop delay reduction)**





Feedbacks basics

Example global / local control



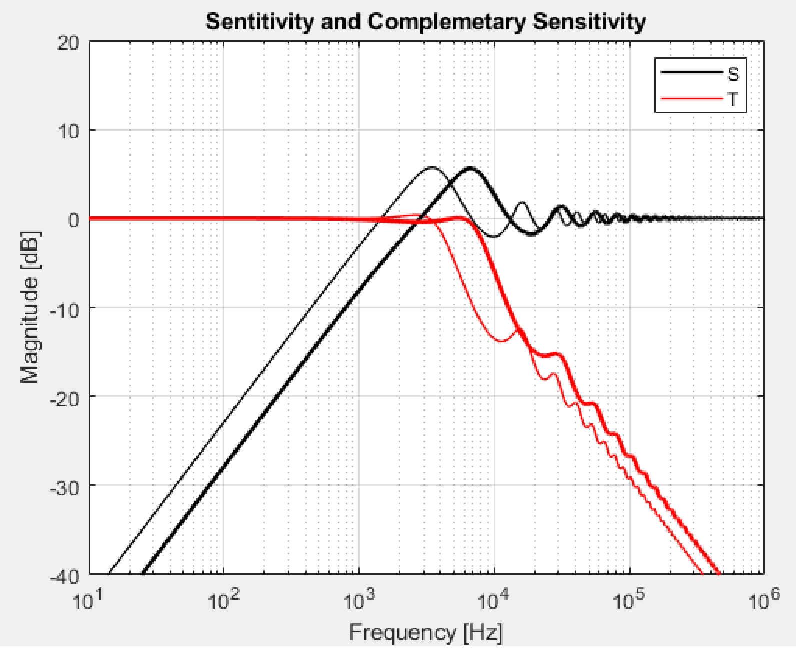
Example system G(s)

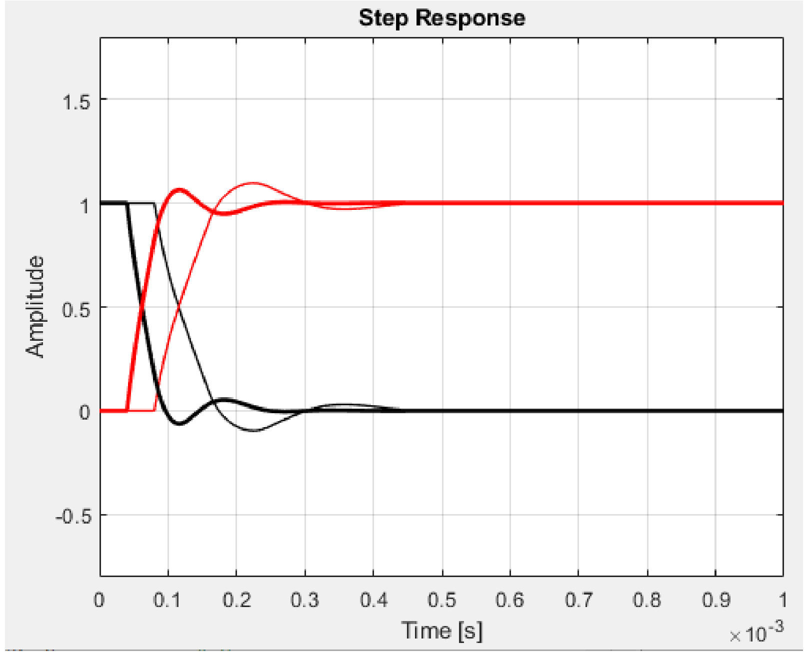
- Low-pass characteristic with bandwidth of 10kHz
- Delay of 80µs to 40µs

- PI controller
- From global to local regulation (loop delay reduction)

Conclusion

- **Frequency characteristic and loop delay are important tuning parameters during the system design!**



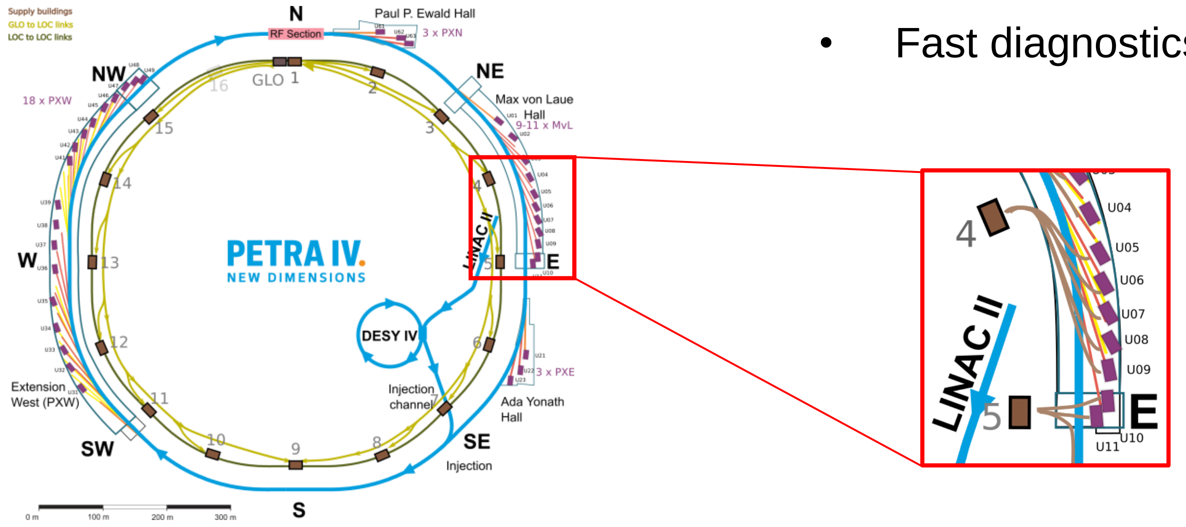


Feedbacks basics

Summary and adding filter functions

Global feedbacks

- Fixed loop delay

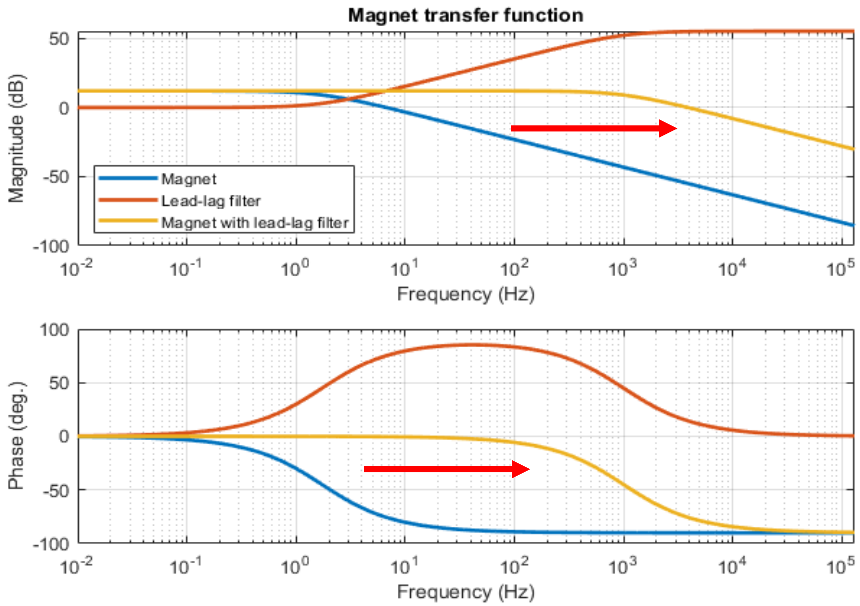


Local feedbacks

- Reduced loop delay
- Fast diagnostics

Frequency domain shaping filters

- Equalize transfer characteristics
  - Extremely important when going to mode space, e.g. multiple correctors to control single BPM
- Example magnet (~ Hz corner frequency)



Both feedbacks share the analog drive part

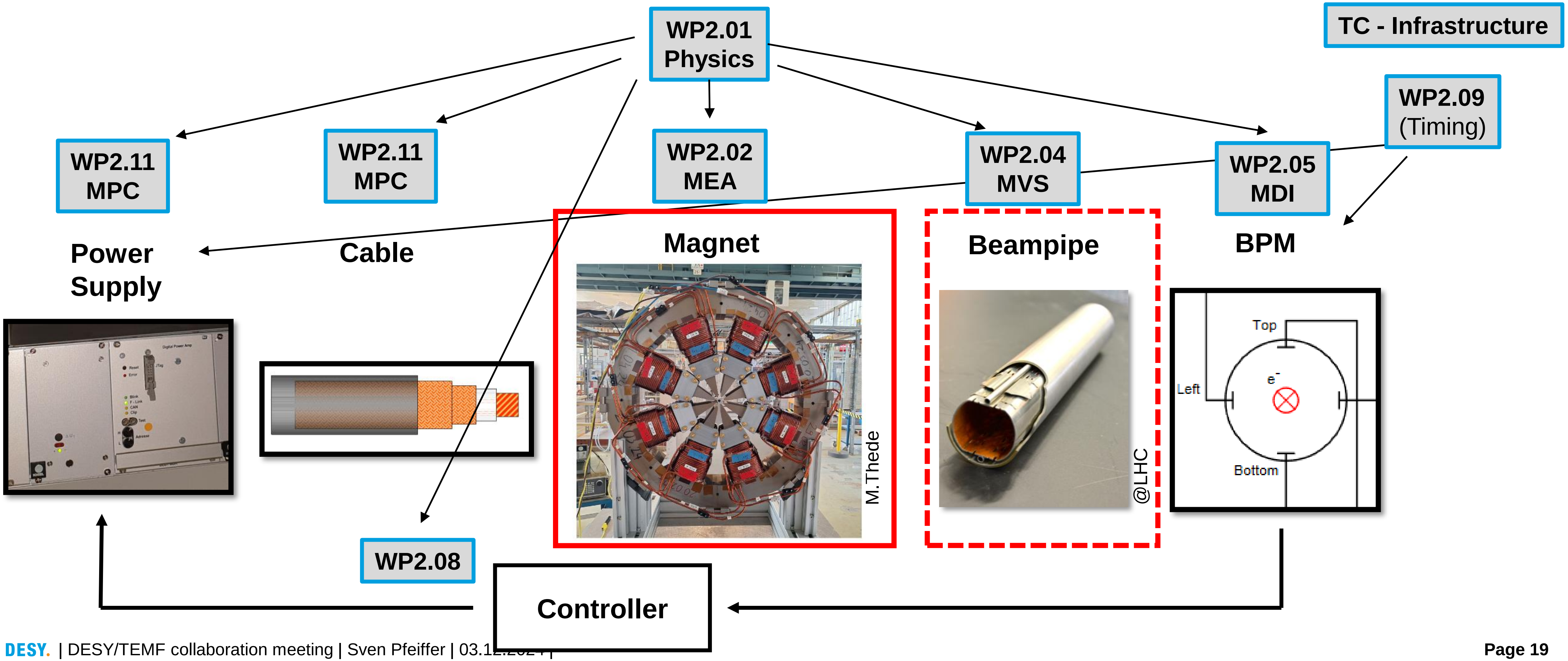
- Requires proper and well understood HW design
- Pushed corner frequencies well above 1kHz for all components
- → Enough margin for faster reactions (>1kHz)

3. PETRA IV design

Design parameters

Goal to study and optimize the fast regulation chain

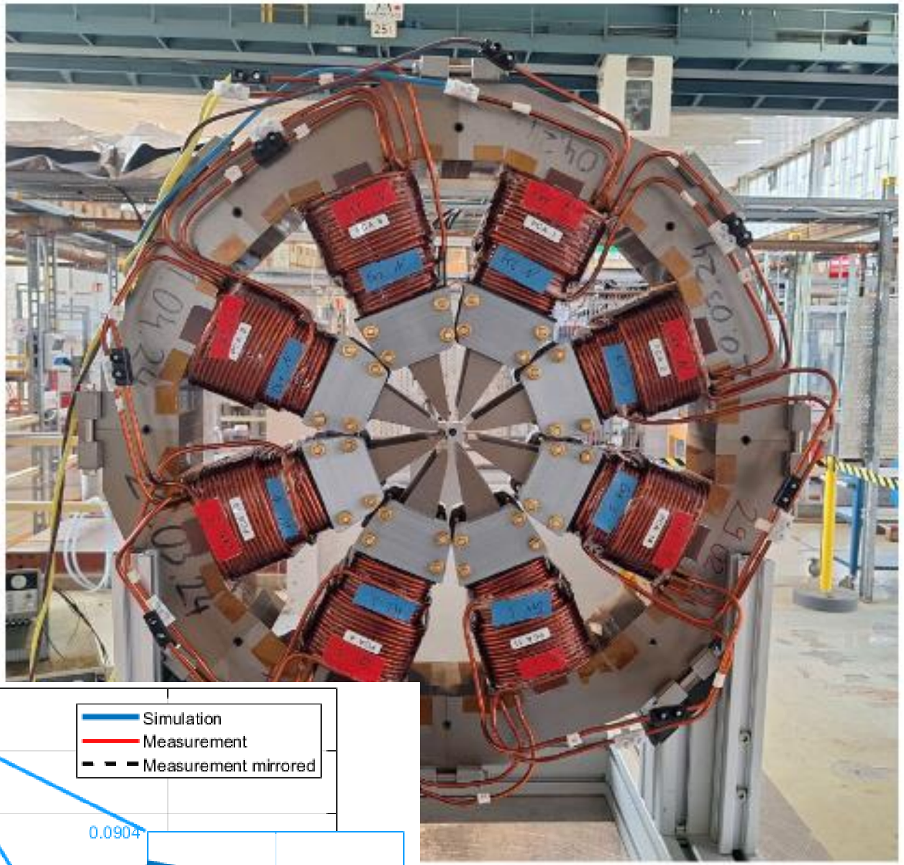
→ Cross-work package (WP) topic for PETRA IV



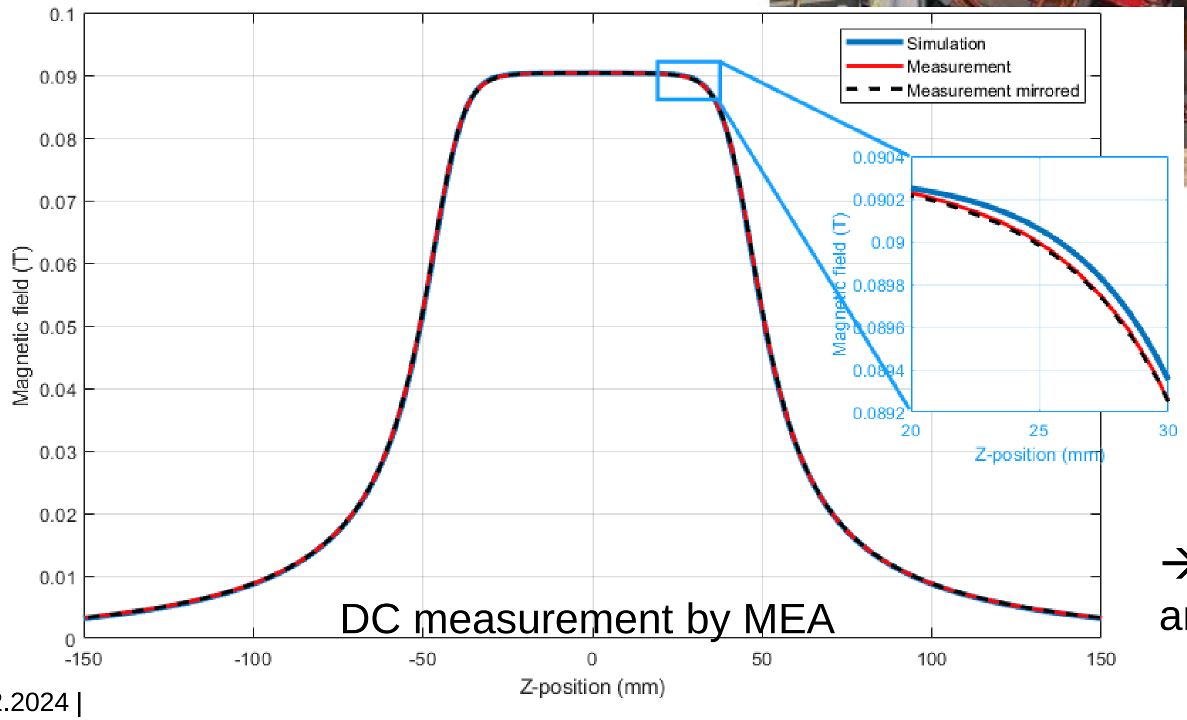
Prototype – PCA (fast corrector)

Slide from last TAC (Matthias Thede)

- Prototype in operation
  - Yoke manufactured in house, coils purchased externally
  - 1 mm lamella thickness steal M1400-100
- First DC measurements done
- Magnet is very short (yoke 86mm)
  - Alignment of the hall sensor is challenging
- Complex mechanical design



Courtesy: M.Thede

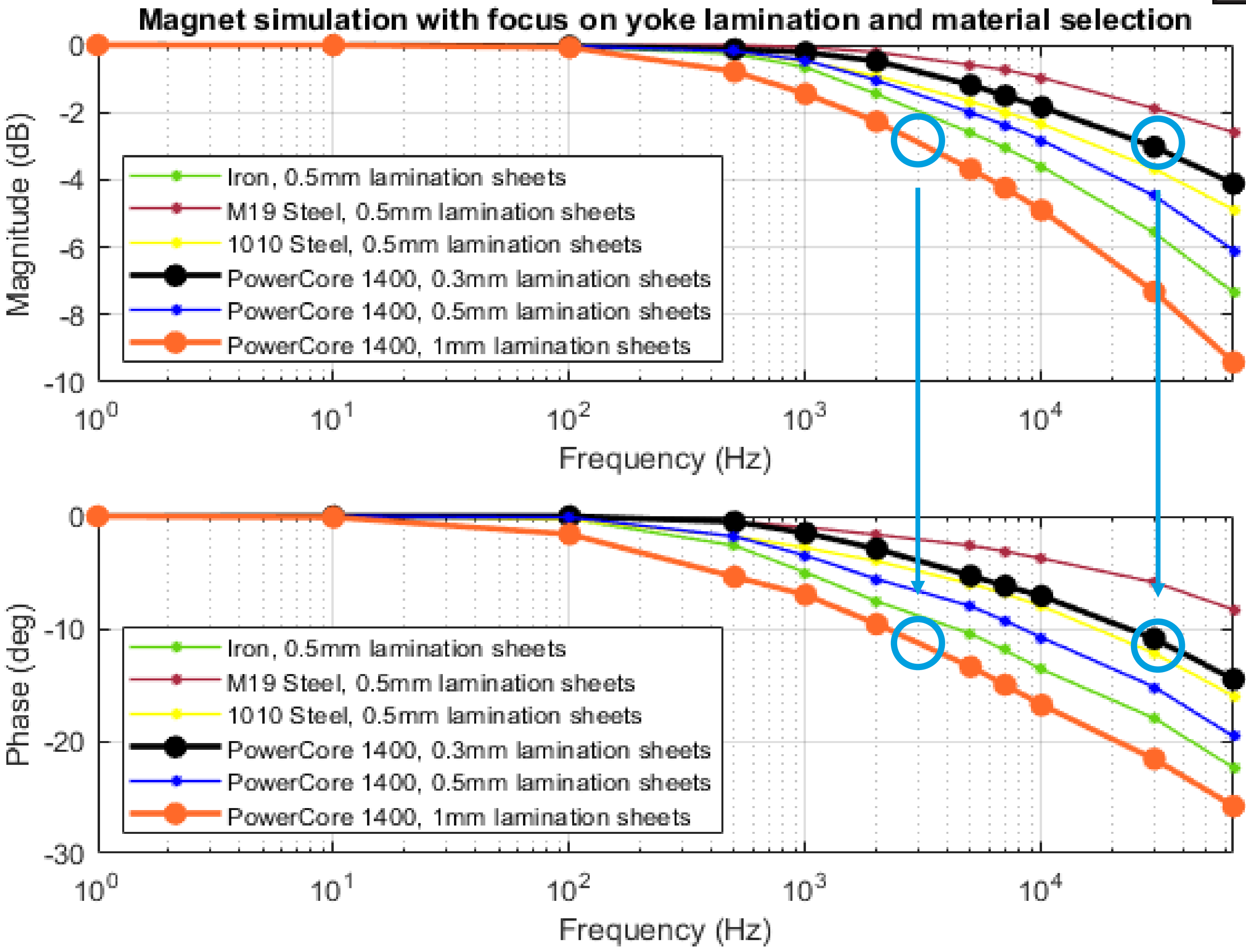


→ Next AC measurements and report

TEMF simulations

Yoke variations

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

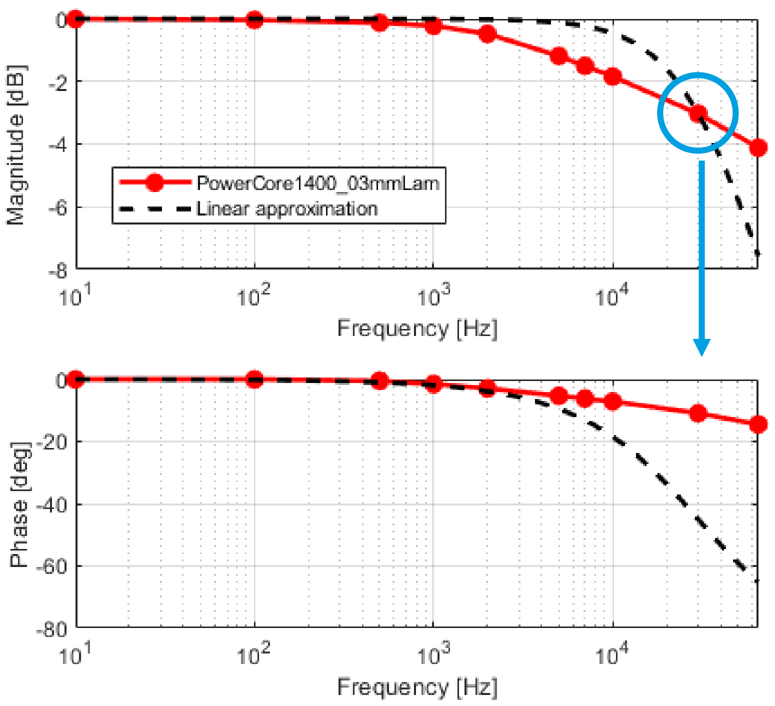


Fractional order characteristics

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 system

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

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

Frequency domain shaping filter

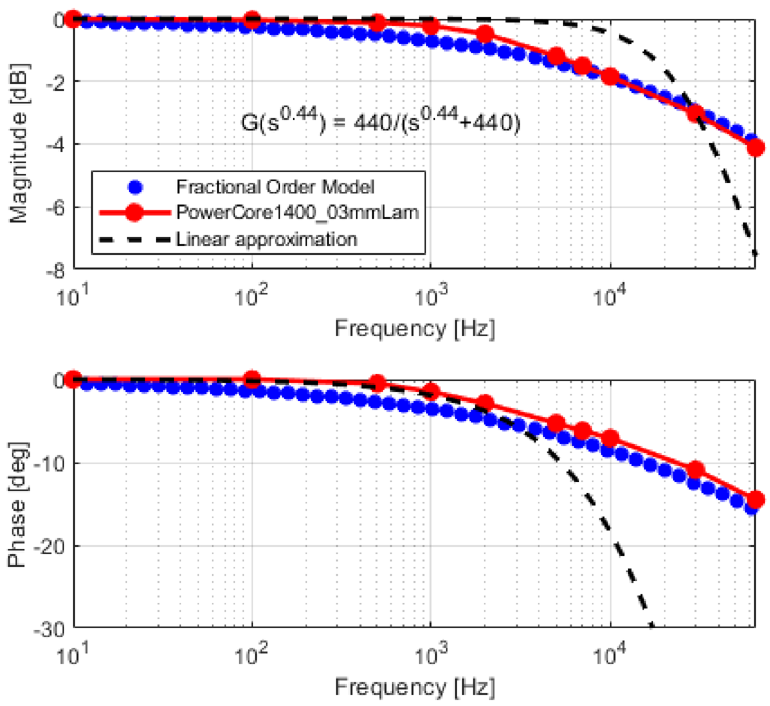
→ Very difficult for fractional order characteristics → Master student (TUHH)

TUHH Hamburg University of Technology

Fractional order characteristics

- First order fractional system

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



4. Next steps

Further simulations by TEMF – side project

As part of master thesis

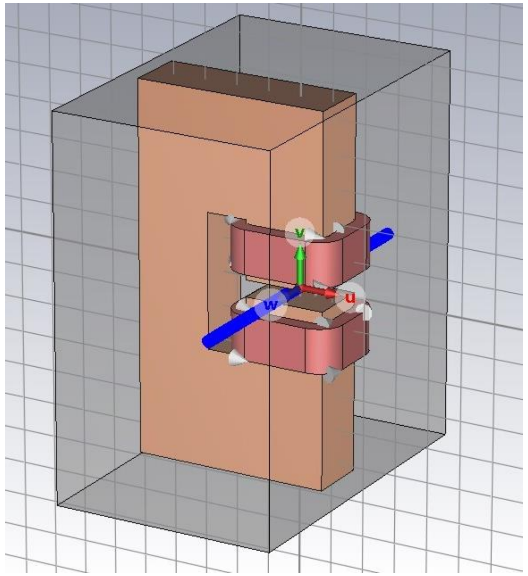
Courtesy: J.M. Christmann

Different shapes as dipoles for standalone AC part

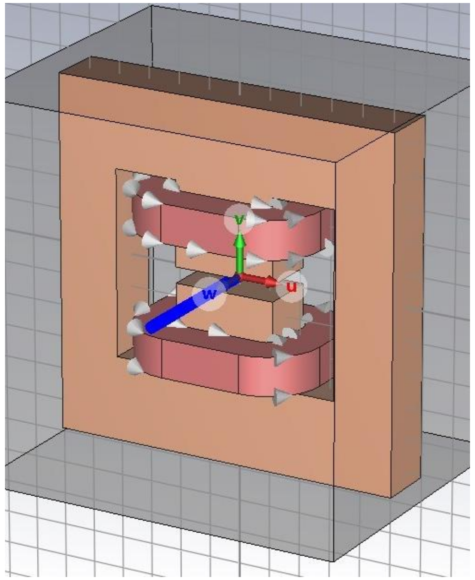
- ***500µrad (combined functioning - AC and DC)***
- 50µrad (AC only)

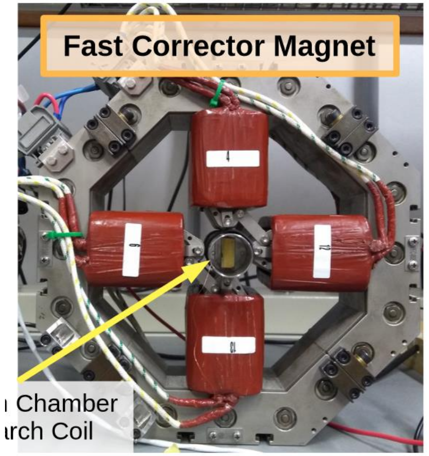
Goal:

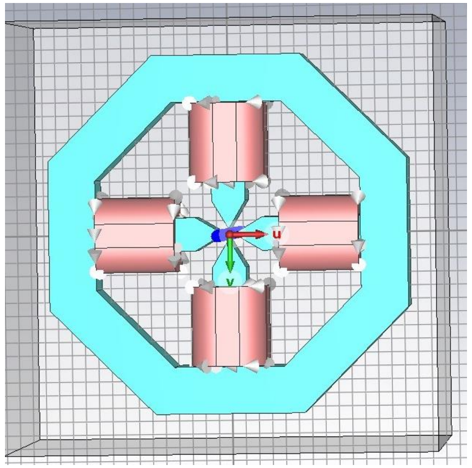
- ***Equalize*** the octupole like ***frequency dependent transfer function*** in magnitude and phase with a dipole magnet
  - Main focus on fractional order characteristics → uncorrectable with low order digital filters
  - Use of standalone AC corrector in the cells (2V correctors) and/or different type of magnets in long straights with larger VC diameter
  - Frequency dependent field quality and coupling computation of quadrupole like design (SIRIUS)



C-shape
H-shape
Quad-shape







Further simulations by TEMF – side project

As part of master thesis

Different shapes as dipoles for standalone AC part

- ***500µrad (combined functioning - AC and DC)***
- 50µrad (AC only)

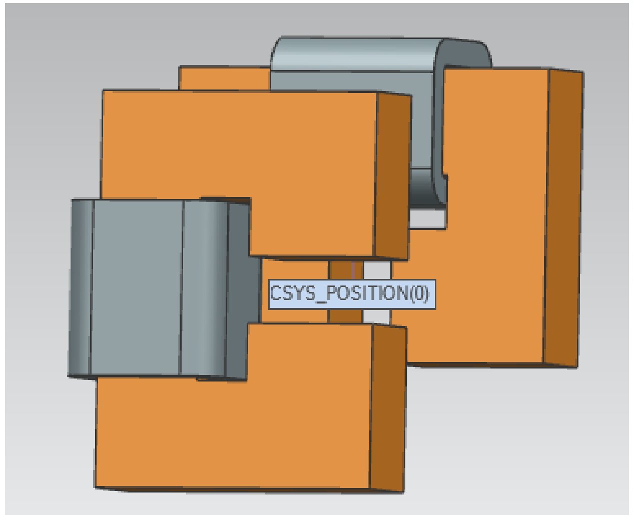
Goal:

- ***Equalize*** the octupole like ***frequency dependent transfer function*** in magnitude and phase with a dipole magnet
  - Main focus on fractional order characteristics → uncorrectable with low order digital filters
  - Use of standalone AC corrector in the cells (2V correctors) and/or different type of magnets in long straights with larger VC diameter
  - Frequency dependent field quality and coupling computation of quadrupole like design (SIRIUS)

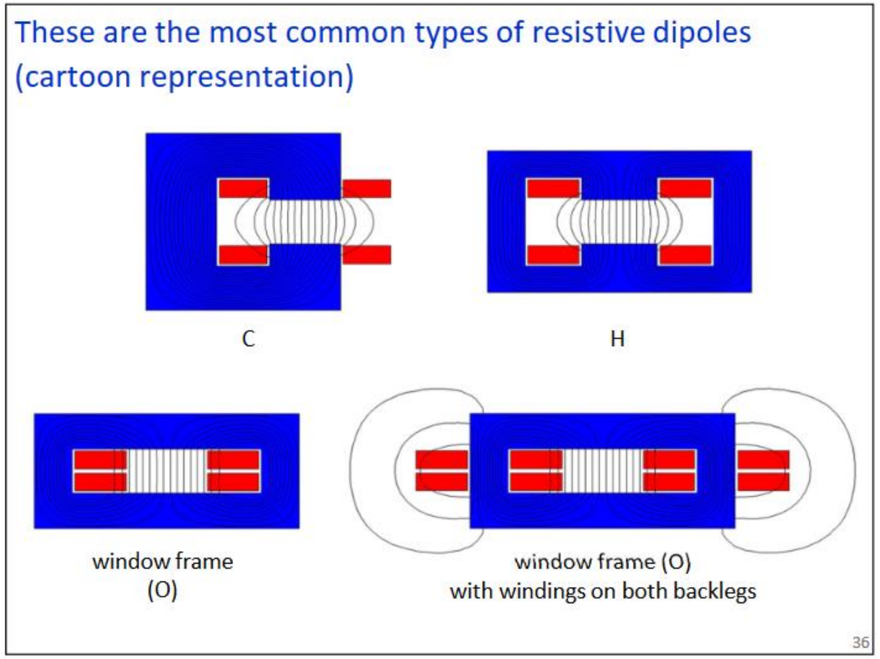
Alternative fast corrector magnet:

- Place 2 dipoles nearby and compute the frequency dependent
  - coupling between H and V field → usable for feedback?
  - field along the longitudinal axis → coupling strength to nearby devices?

Similar scheme as proposed for DESY IV



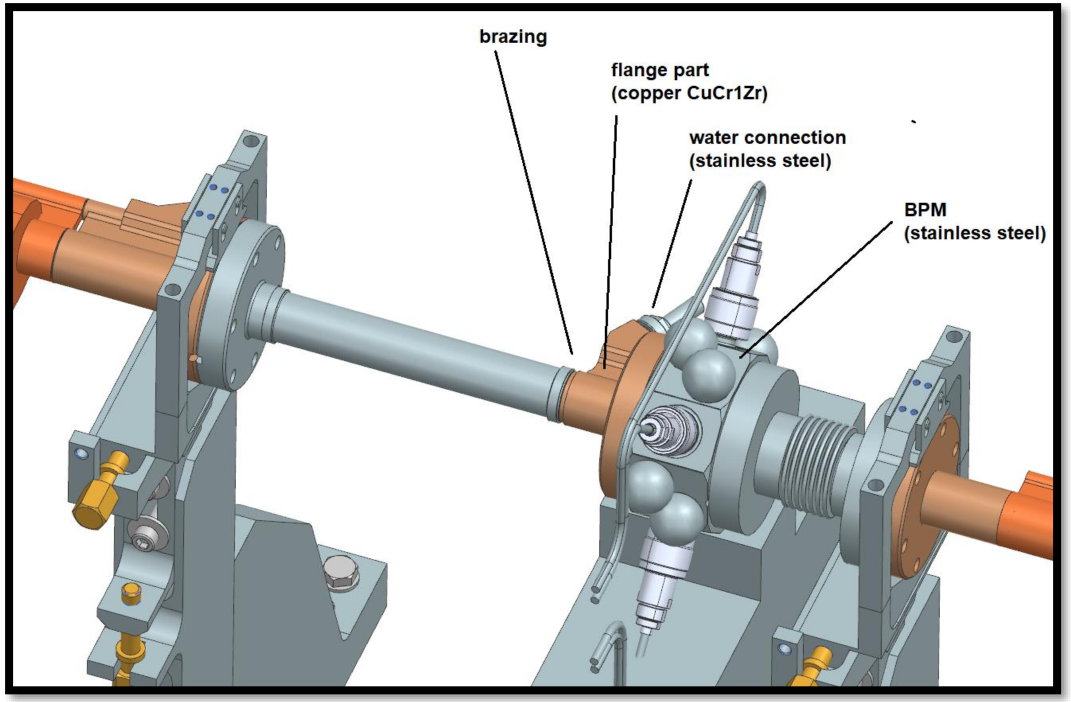
Courtesy: M.Thede



Courtesy: J.M. Christmann

Courtesy: J.Hauser

Summary

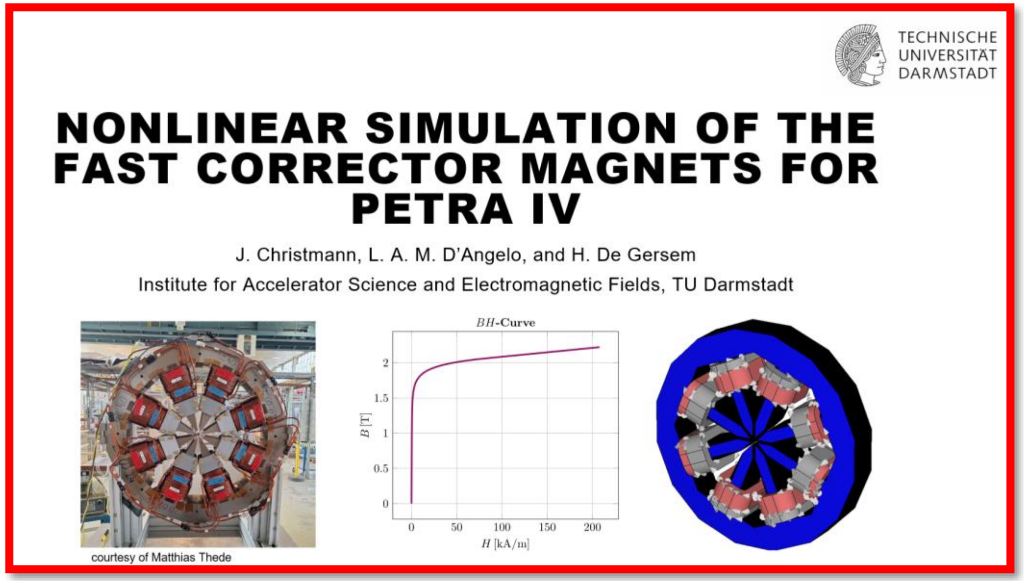


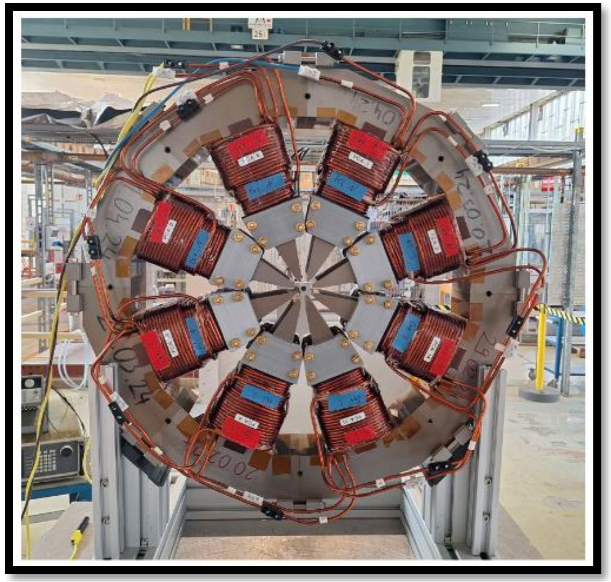
Consideration of the system design right from the start

… cables, magnet PS, BPM (noise), disturbances, …

→ Vacuum chambers (round, elliptical, key-hole, CU-SS transition, thickness, coating, …)

→ Magnet (Integrated field, frequency characteristic. multipoles, laminations, losses, …)





Well recognized at other labs!

Diamond-II (UK) released a decided vacuum system for changes after a presentation of your simulations (DEELS 2023 WS)!

Thank you

Contact

DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

Sven Pfeiffer
DESY - MSK
sven.pfeiffer@desy.de
(+49) 040 8998 2744