Status of the design and simulations for the FOFB of PETRA IV

An brief overview of the activities towards a stable beam orbit

Sven Pfeiffer for the PETRA III & IV team

Karlsruhe, 18.03.2025

Outline

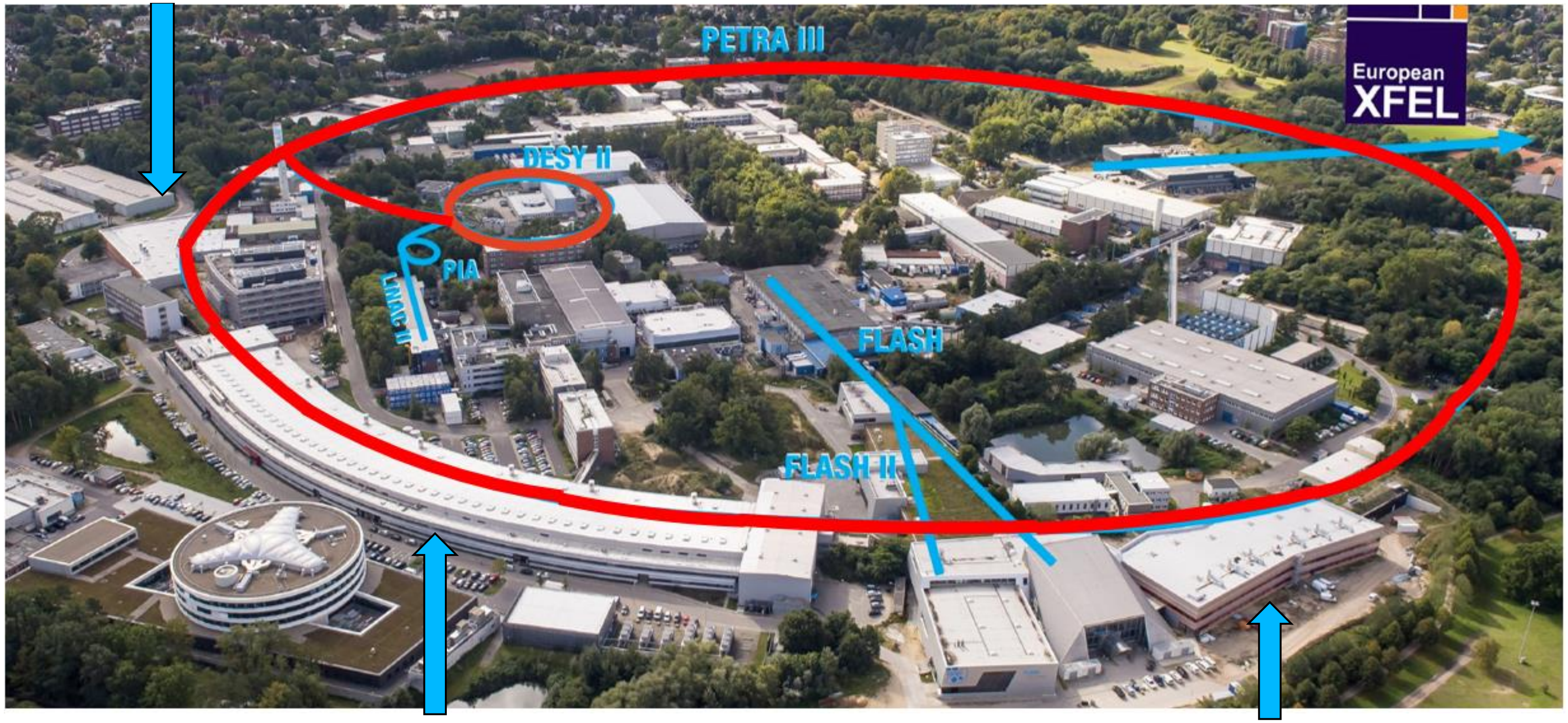
- Introduction PETRA (III / IV)
- Stability task force
- System modelling and HW design
- Disturbance and noise model
- SISO simulation
- Conclusion

Courtesy: R.Bartolini

PETRA III is one of the core facilities at DESY

Each year ~5000h user operation serving more than 2000 users

Ada Yonath Hall
Extension Hall East



Max von Laue Hall

Paul P. Ewald Hall
Extension Hall North

Parameter	PETRA III
Energy [GeV]	6
Circumference [m]	2304
Emittance (hor./vert.) [nm]	1.3 / 0.013
Total current [mA]	100

PETRA III emittance 1300 pm

65 times smaller

PETRA IV emittance 20 pm

enabling 500 times larger X-ray beams brightness

PETRA IV project:

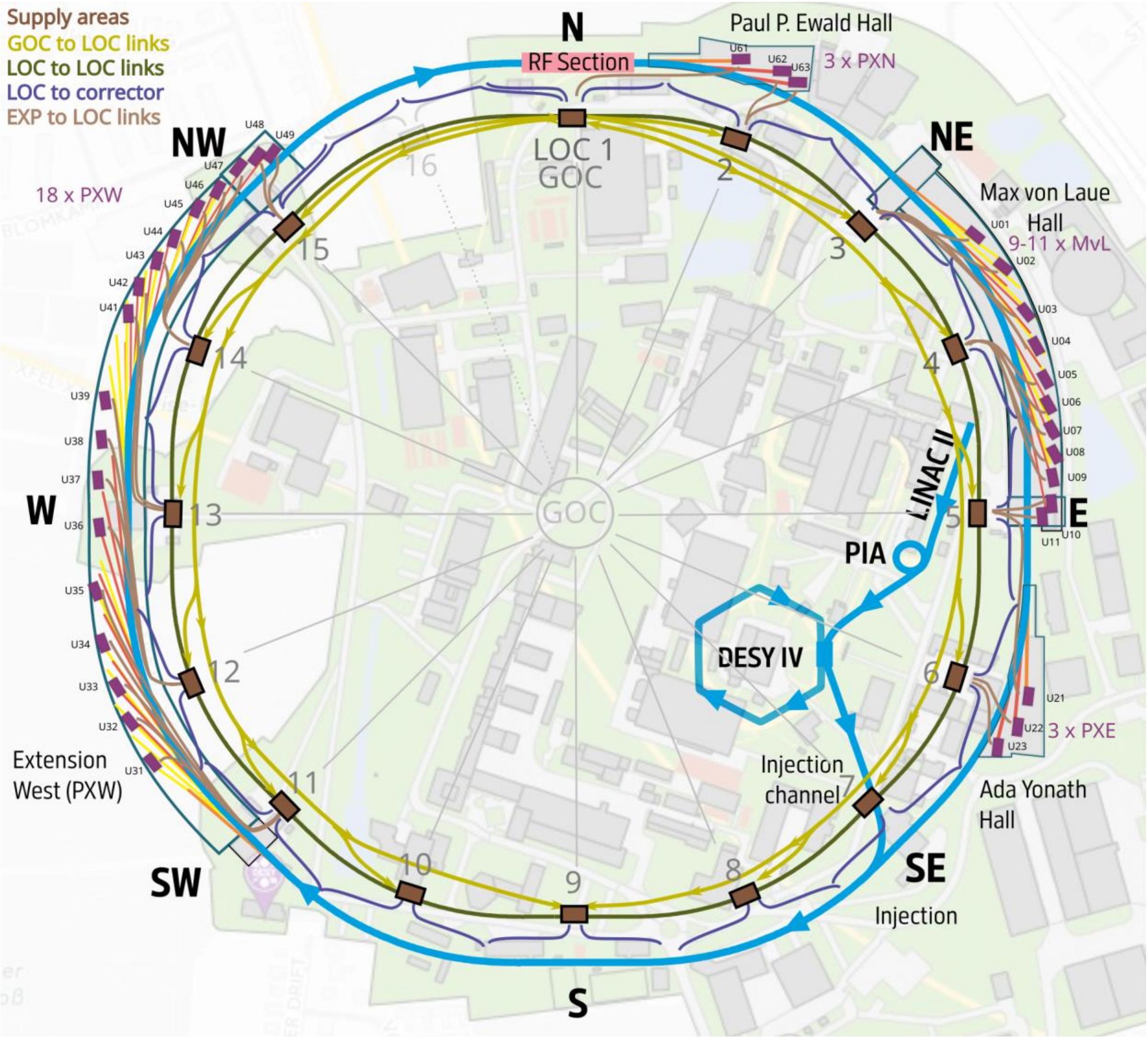
replacing PETRA III with an ultra-low emittance ring (20 pm), adding a new Experimental Hall in two more octants & replacing DESY II with a new low emittance booster

FOFB system topology

Latency optimized topology

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

- **1 global orbit control unit (GOC)**
  - Close to RF system / timing system
  - Short path from GOC to LOC in experimental halls
- **16 (15) distributed local controllers (LOC)**
  - Collection of BPM information
  - Transmission of updated magnet current to power supplies
- **Optical fiber communication links**
  - Global to all local systems → classical regulation (star topology)
  - Local to local system links
    - Integrating experiments based on photon diagnostics



Stability task force

FOFB concept

GOC, LOC, EXP blocks

Initial MIMO and SISO simulations

- Incoherent disturbances
- Focus on main system dynamics

Goal: Full implementation of the dynamic MIMO simulation

- PETRA III as benchmark facility
- Including coherence length
- Realistic dynamic errors and disturbances

Stability task force

(I) Ground motion / disturbances

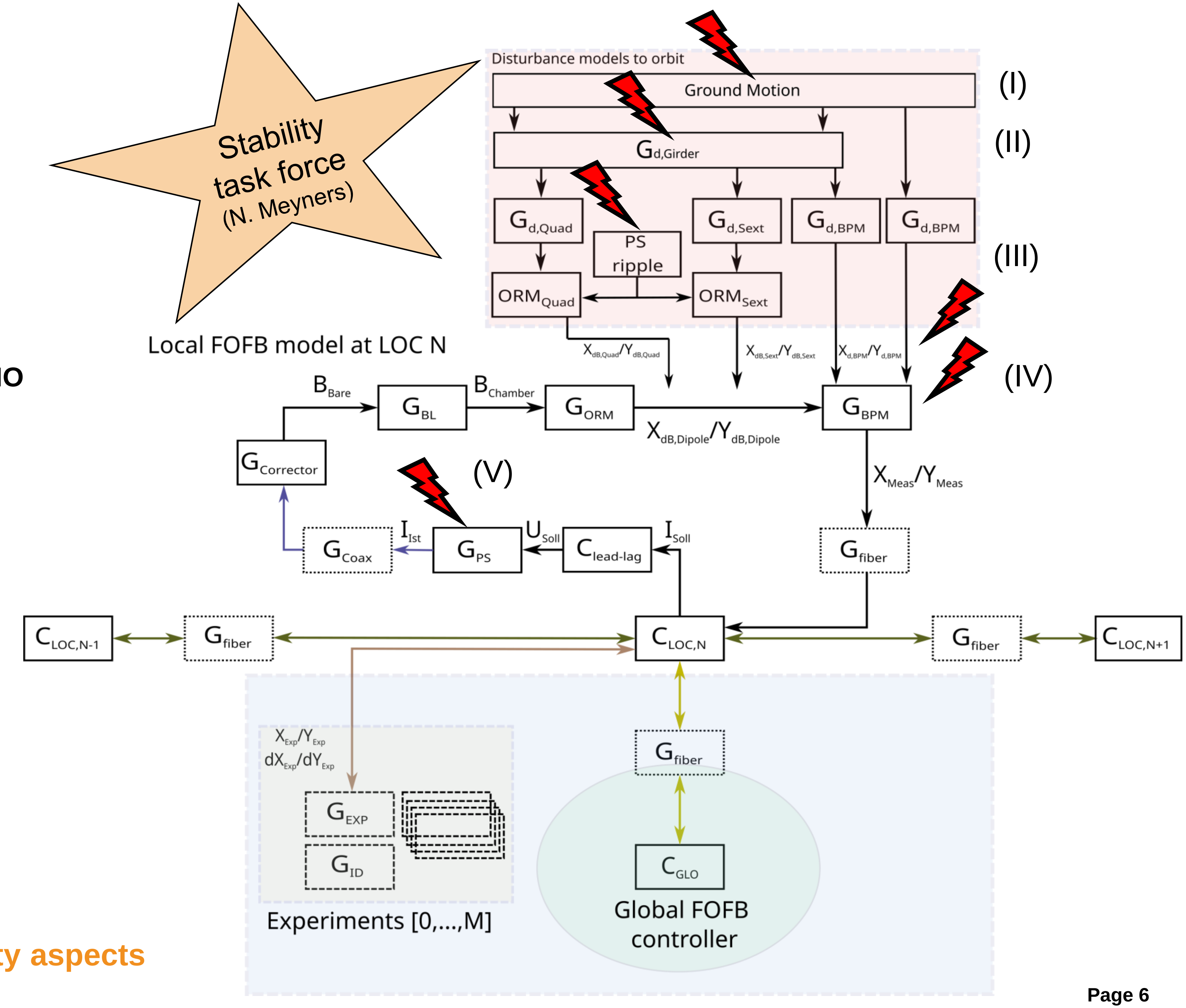
(II) Girder/support amplification/eigenfrequencies

(III) PS ripple, effect on beam

(IV) Orbit measurement noise

(V) Fast corrector power supply ripple

→ **Passive and active orbit stability aspects**



Disturbances

High horz. and long. amplification factor in range 7-10Hz

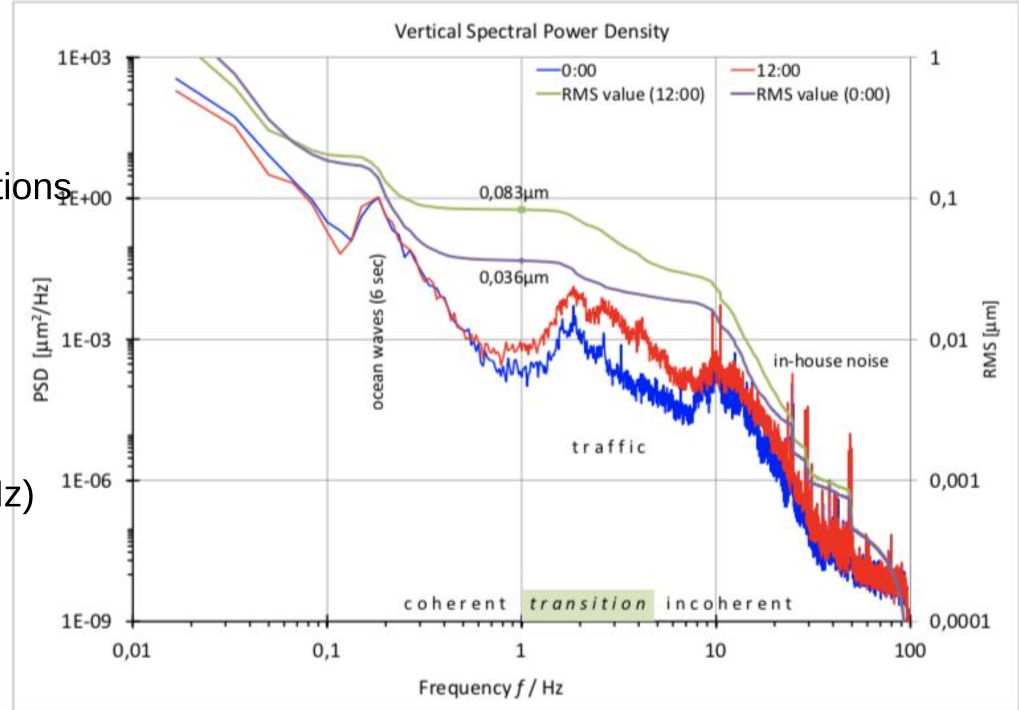
FOFB: Stability task force @ PETRA III (N.Meyners et al.)

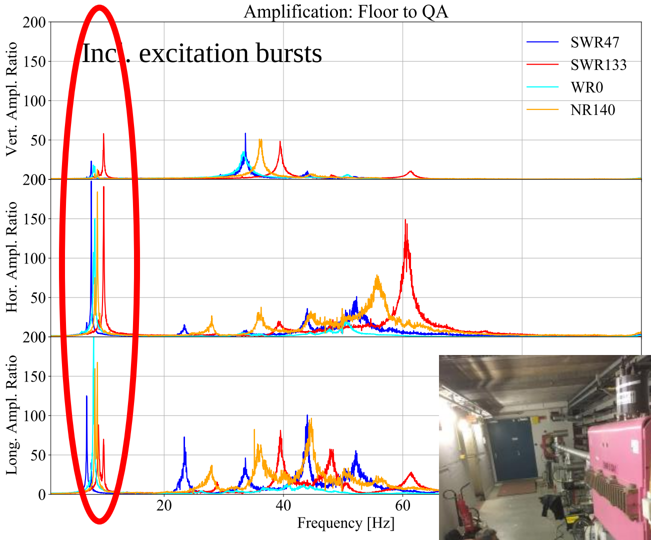
Ground motions

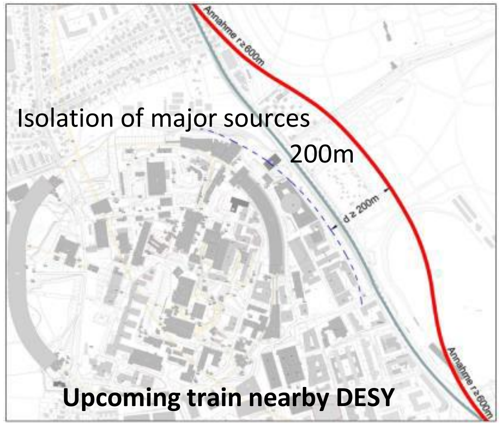
- PETRA I tunnel reused
- Ground settlements and seasonal motions
- Ocean waves (<1Hz)
- Traffic (1…10Hz)
- In-house noise (10…100Hz)
- Girder and amplification factor (< 48 Hz)

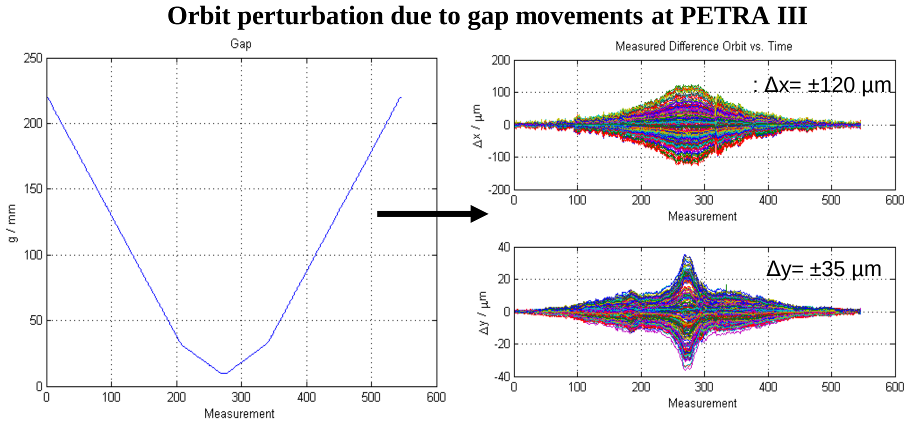
Additional sources / sinks

- Asynchronous motors (<50Hz)
- Controlled motors/pumps (25Hz)
- Power supply output ripple (k · 12.5Hz)
- Harmonics of DESY II (~30Hz)
- ID gap movements (Hz – depending on speed)
- *Injection process (injection FF)*







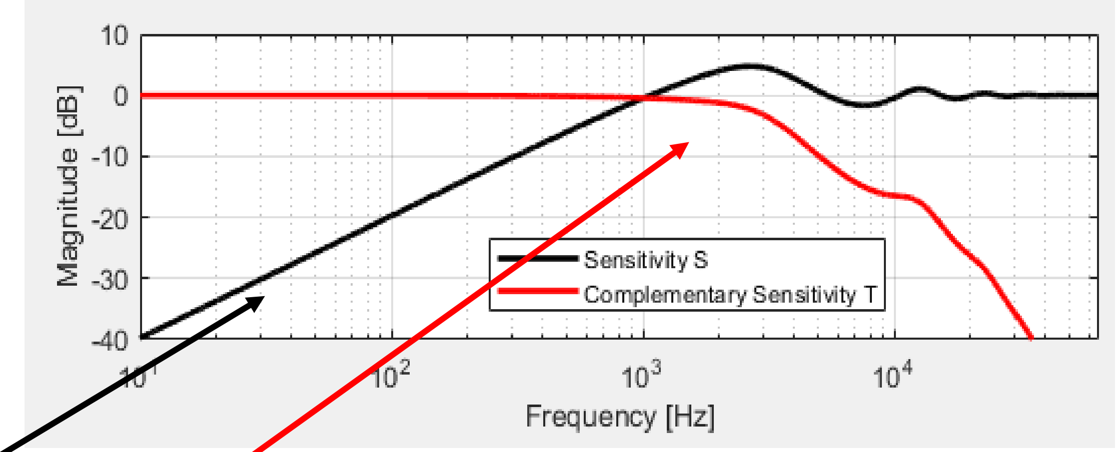


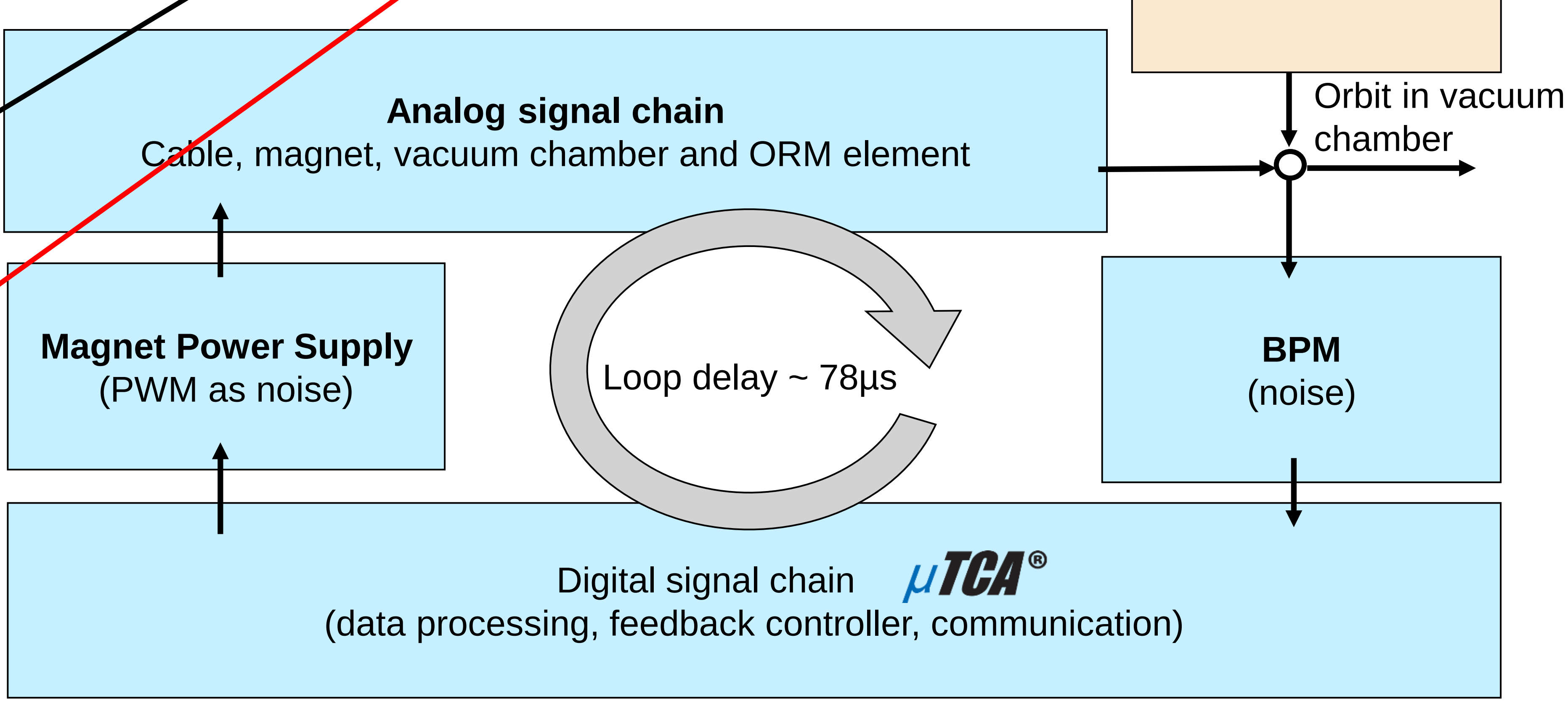
System modelling and design

FOFB sub-systems

SISO modelling and 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)





FOFB Simulations

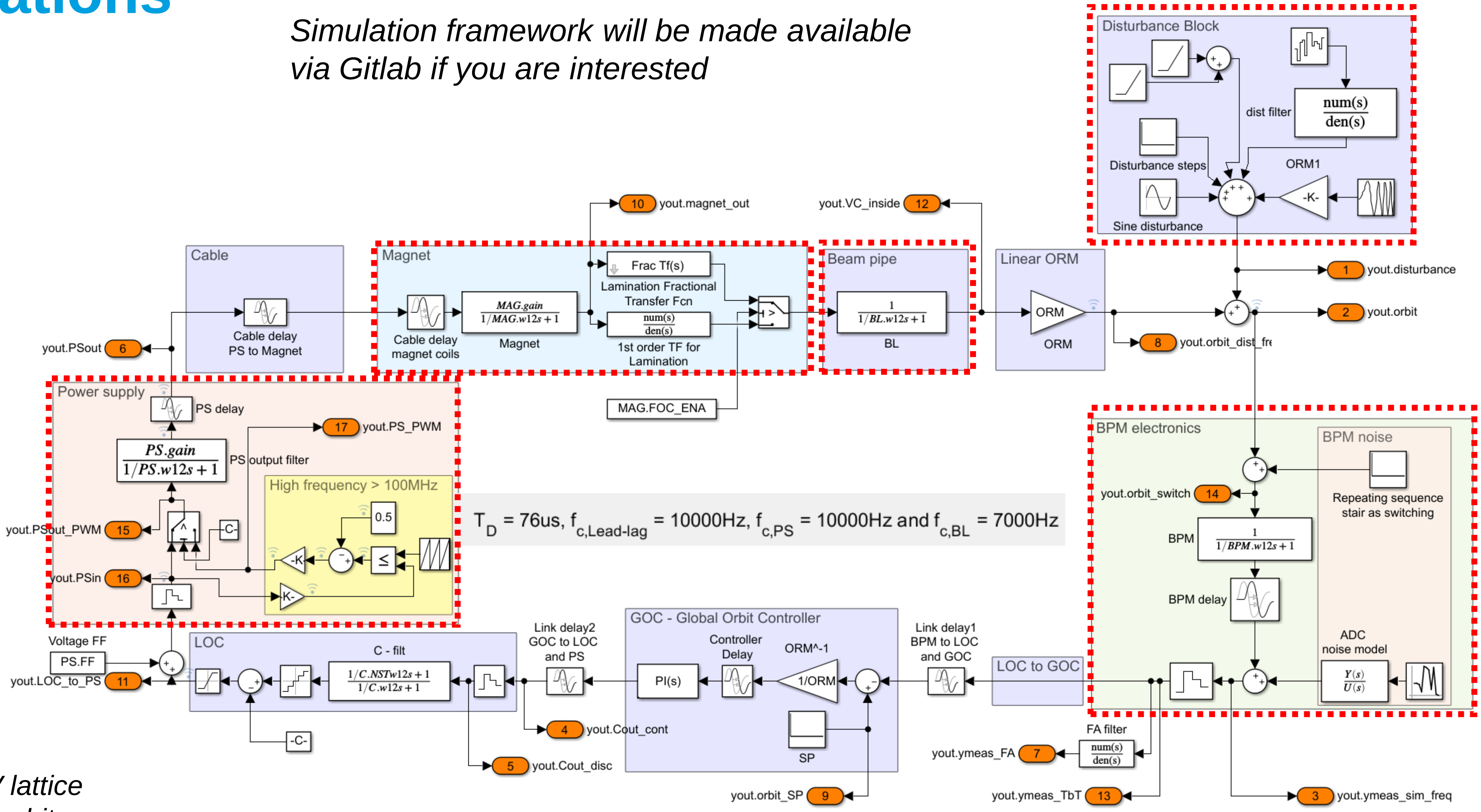
Overall signal chain

Simulation framework will be made available via Gitlab if you are interested

SISO feedback loop

- **Magnet**
- **Vacuum chamber**
- **Disturbance block**
- **BPM electronics**
- **Power supply**
- Cable
- Digital signal chain
- ORM element (PIV lattice)

ORM element from PIV lattice that maps µrad into an orbit offset at a distance of 1m



PETRA IV FOFB

Corrector requirements from PIII to PIV

PETRA III

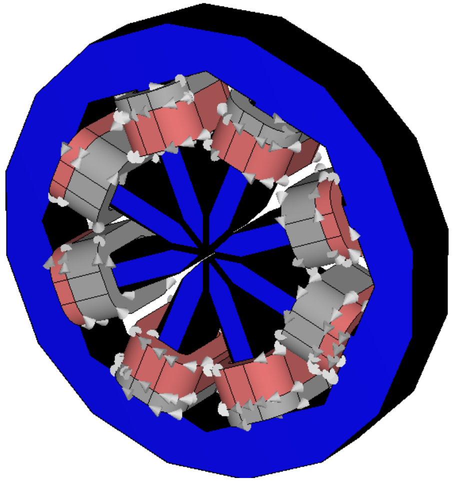
- ***Small corrector magnet*** (0.2mH…0.48mH) as air coil (kHz bandwidth) ***for fast orbit feedback***; max 45µrad
- ***Larger magnet for static*** (DC) corrections
- Stainless steel vacuum chamber (D=94-98mm) with ~1kHz bandwidth as limiting element

PETRA IV → Complete redesign by space constraints

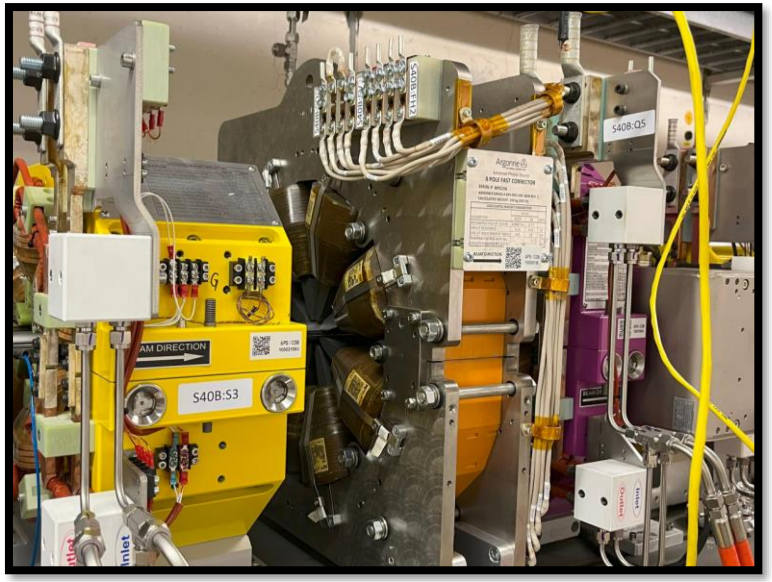
- ***Combined functioning magnet*** (slow and fast corrections) with 23mH; max 560µrad DC, 30µrad AC
  - High field quality (less dependence on orbit fluctuations)
  - Hz bandwidth, pushed digitally into kHz regime → more demands on magnet power supply
  - *(Possibility to integrate skew quad coils)*

PIII: H fast corrector with DC corrector

Courtesy: H.T.Duhme, J.Klute



Slow and fast corrector magnet based on APS-U design

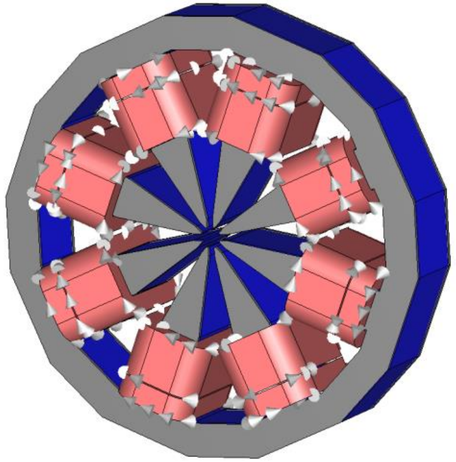


@APS-U (courtesy: John Carwardine, Animesh Jain)

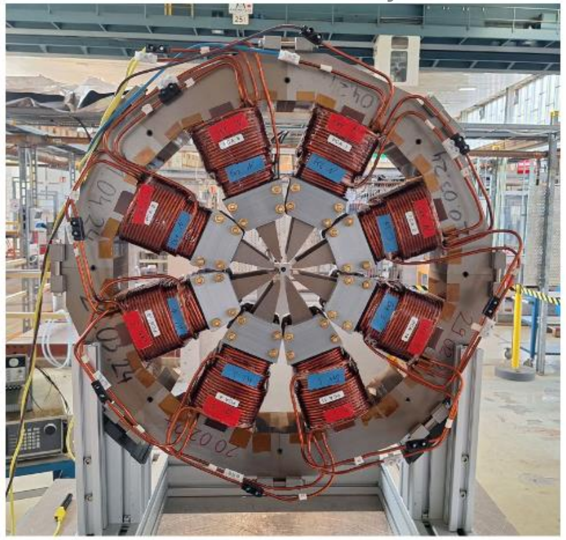
Magnet update

Yoke variations

Courtesy: J.M.Christmann



Courtesy: M.Thede

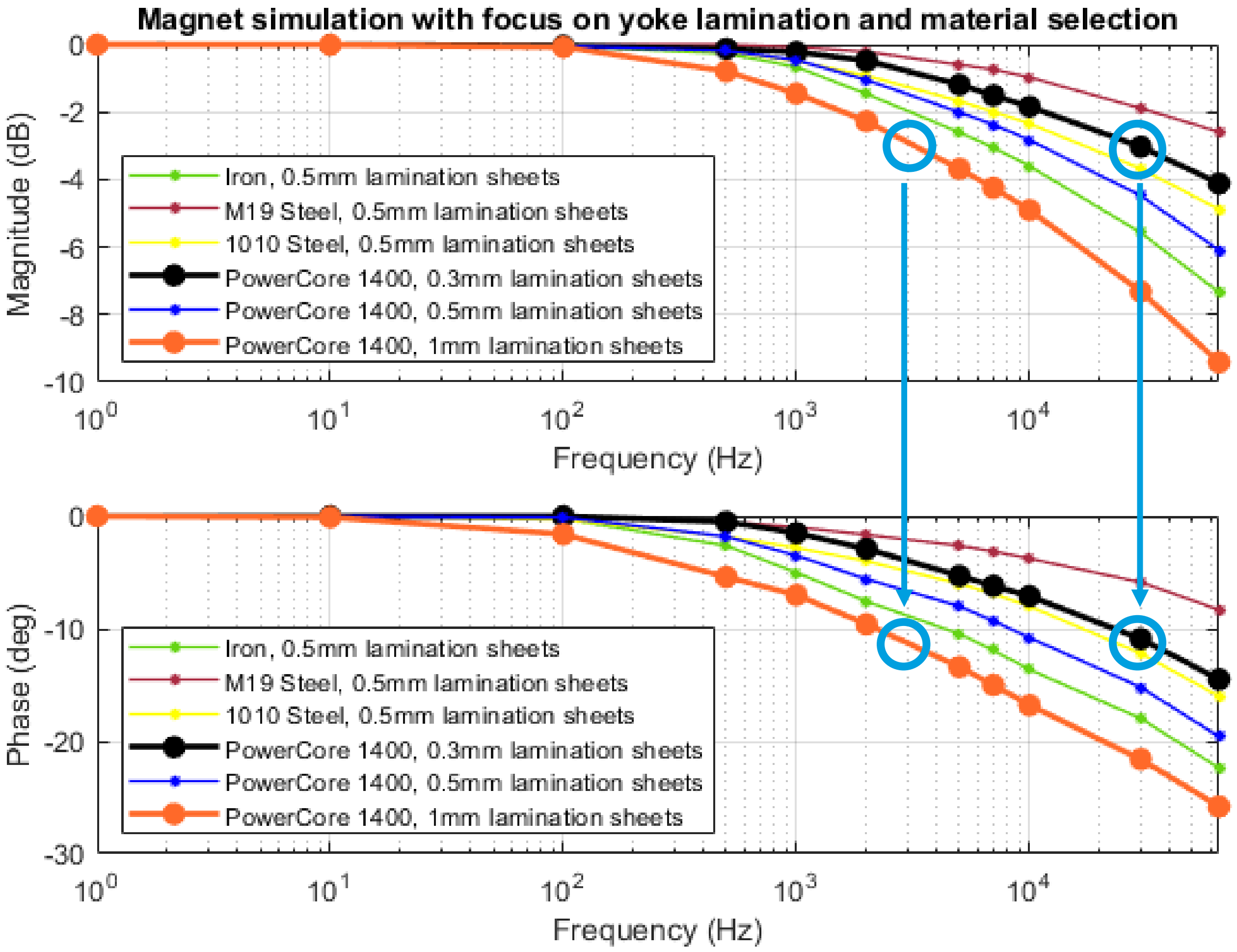


- 1^{st} prototype magnet with PowerCore 1400 and 1mm lamination thickness
  - **3kHz with -10deg.**
- 2^{nd} prototype magnet with PowerCore 1400 and 0.3mm lamination thickness
  - **30kHz with -10deg.**

→ Fractional order system

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

Simulation by TU Darmstadt (TEMF)



First simulations done → shifted in frequency by x10 using 0.3mm laminations → side project for master student

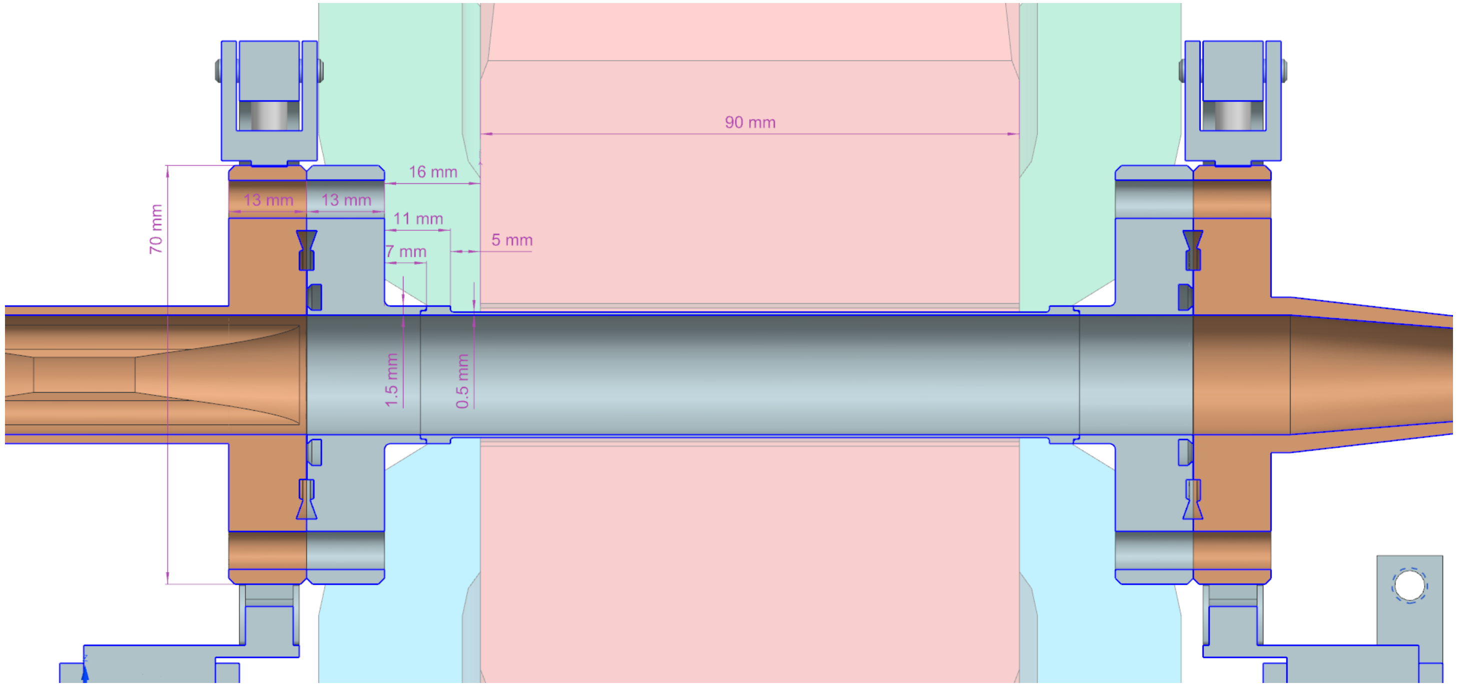
TUHH Hamburg University of Technology

TAL TECH

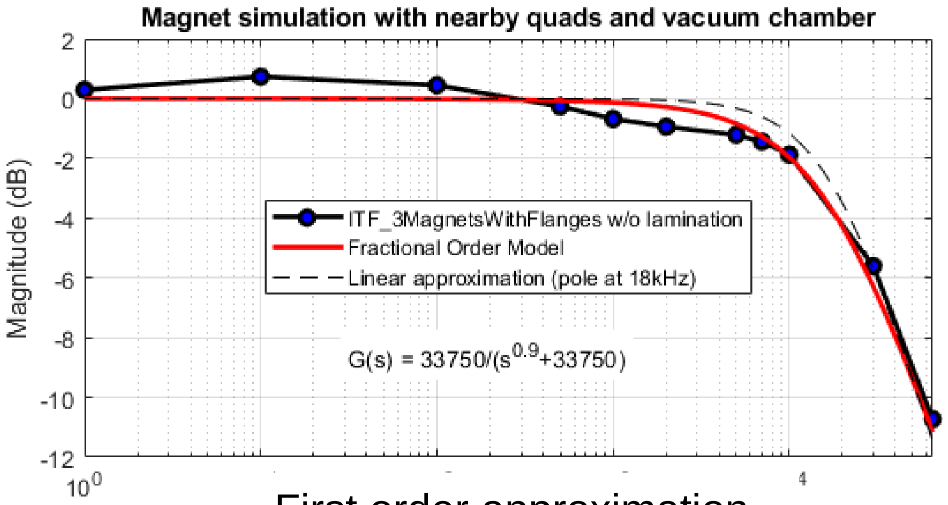
Vacuum chamber design

… for the fast correctors

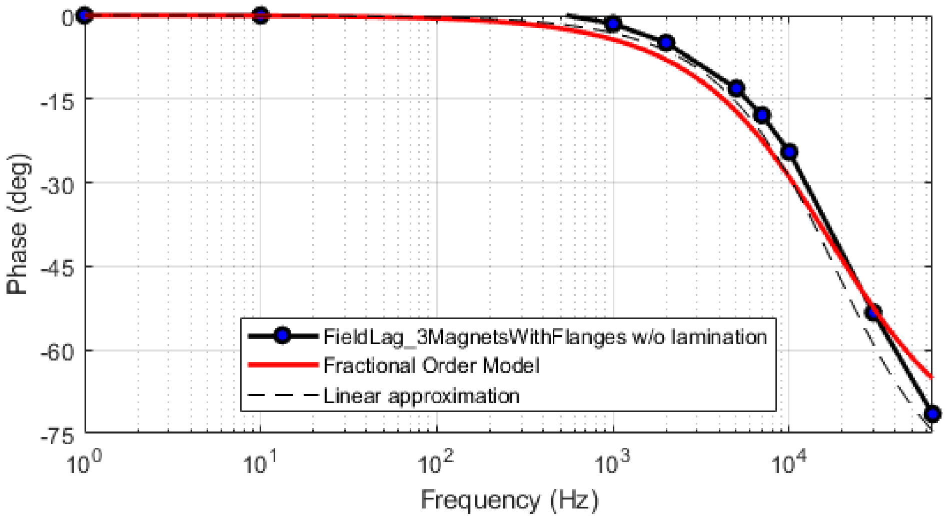
- SS vacuum chamber with symmetric CU transitions
- Thickness 0.5mm
- Yoke-CU distance 29mm



Courtesy: J.Hauser



First order approximation seems sufficient



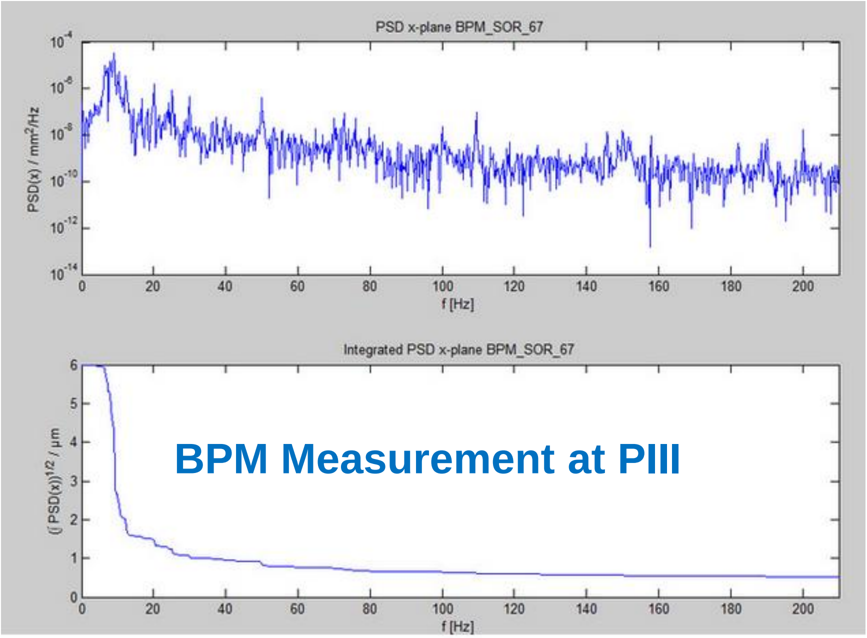
Disturbance and noise models

PIV - FOFB system

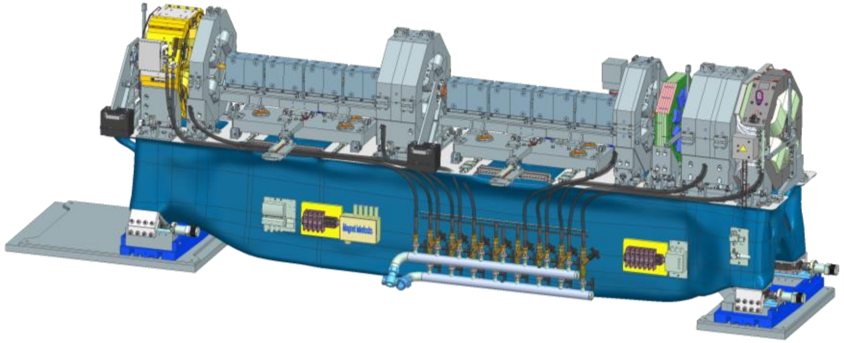
Disturbance integration - SISO

Disturbance

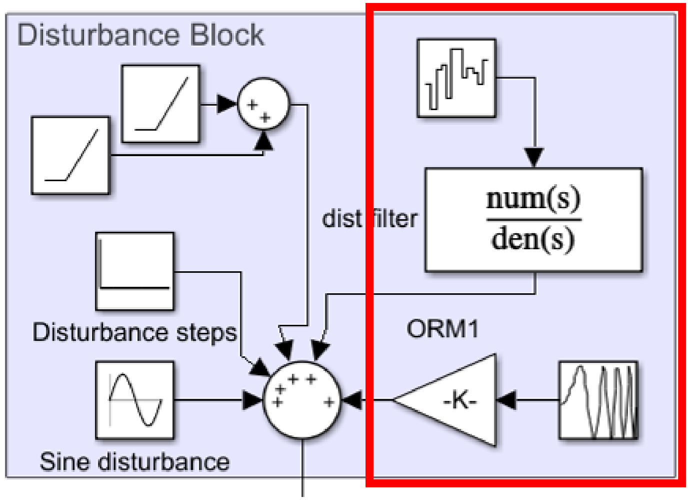
- BPM measurement at PETRA III
- Incoherent: DC … kHz

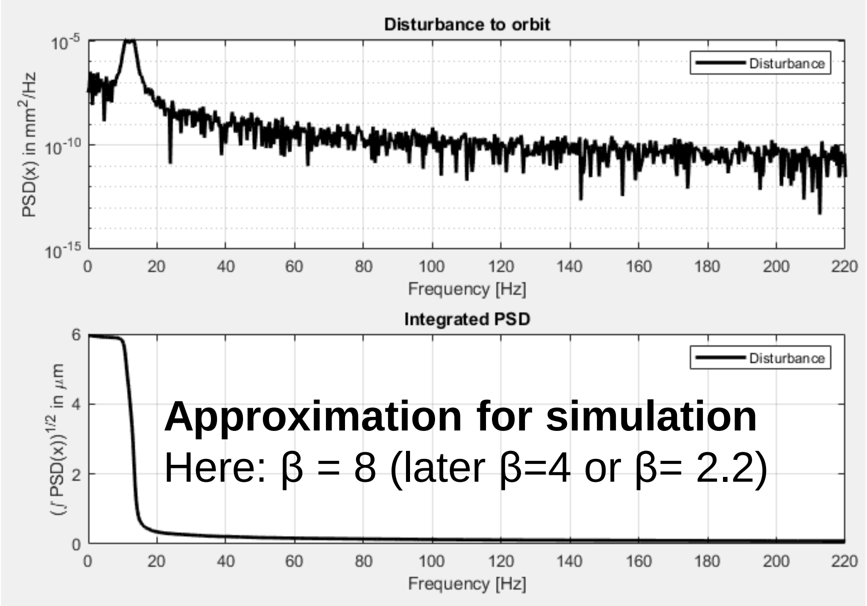


Start with PIII disturbance model to check PIV system simulations
→ Reduced distortions at PIV expected by optimization of girder eigenfrequencies



→Talk: Normann Koldrack





Approximation for simulation
Here: β = 8 (later β=4 or β= 2.2)

Next steps:

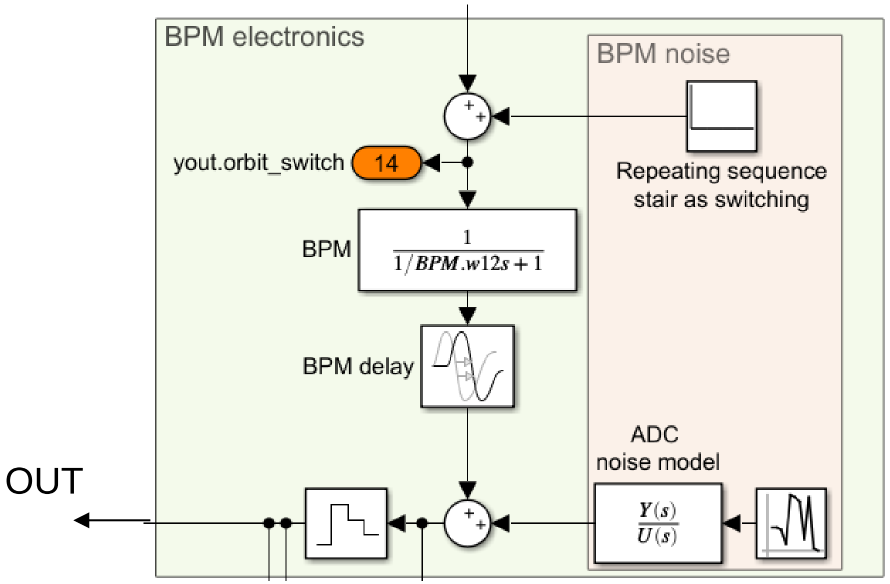
Spatial disturbance integration into full ring simulation including coherence length and transition

- Coherent: < 1Hz (ocean waves)
- Transition: 1…10Hz (traffic noise)

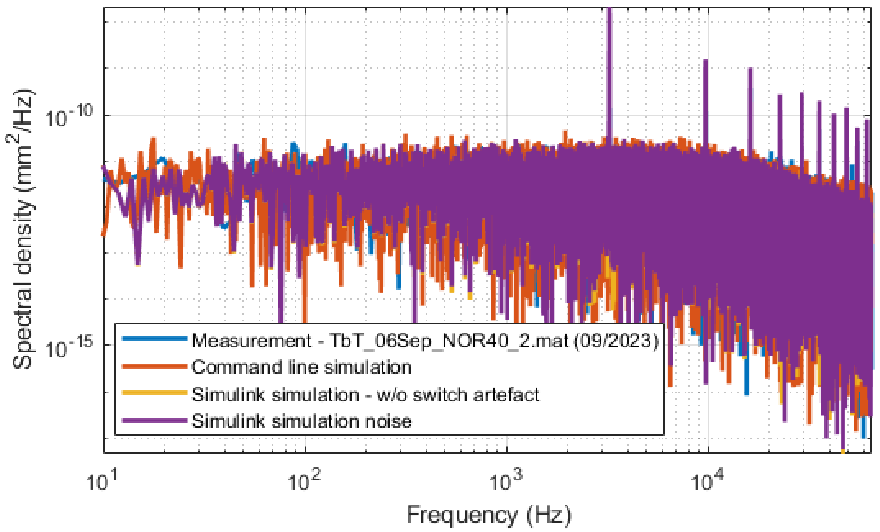
BPM update

BPM electronics model

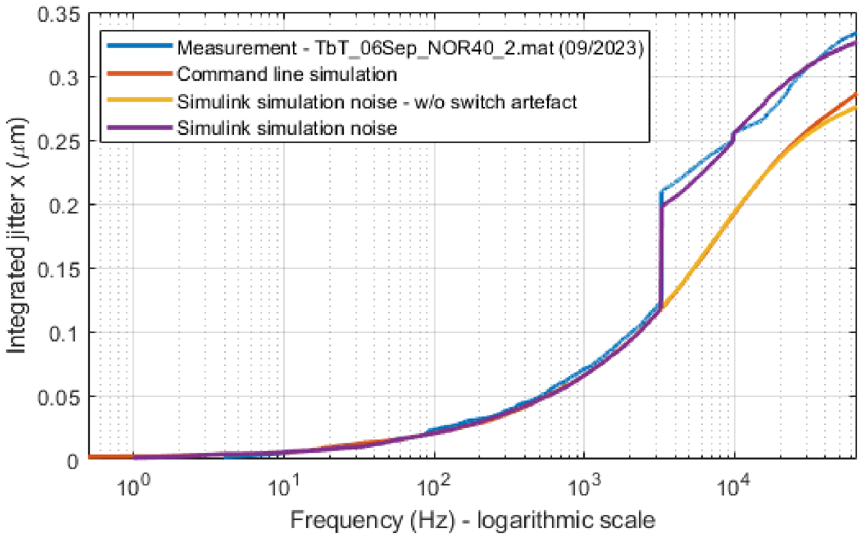
- **BPM electronics**
  - DDC bandwidth and I/O latency
  - Noise including switching sequence
- **Noise characteristic for electronics**
  - Measured at PIII with PIV system (09/2023)



Matching of integrated jitter



Measurement with 480b, 120mA, uniform distribution



Simulations with or without BPM noise and the switching artefact for drift compensation

Working on an advanced noise characteristic, i.e. variation of

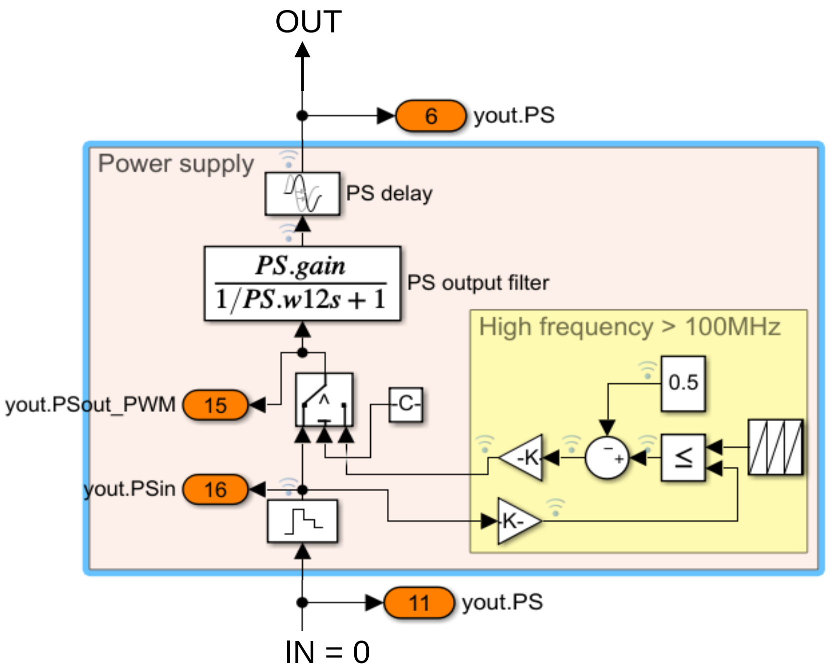
- Number of bunches
- Bunch repetition rate
- Fill pattern (1920b, 80b, 7/8, hybrid mode)
- Bunch charge (hybrid mode)
- …

PS update for fast correctors

Power supply noise using pulse width modulation

- **Power supply**
  - I/O delay (max 15µs)
  - Changeable output filter (10kHz)
- **Noise characteristic**
  - PWM as comparator (implementation on FPGA)
  - Quantization effects/noise (***8***, 10, 11 bit)

Goal to replace analytical model by PSD measurement for first prototype; further checks for 50Hz mains and harmonics contribution and other noise sources.

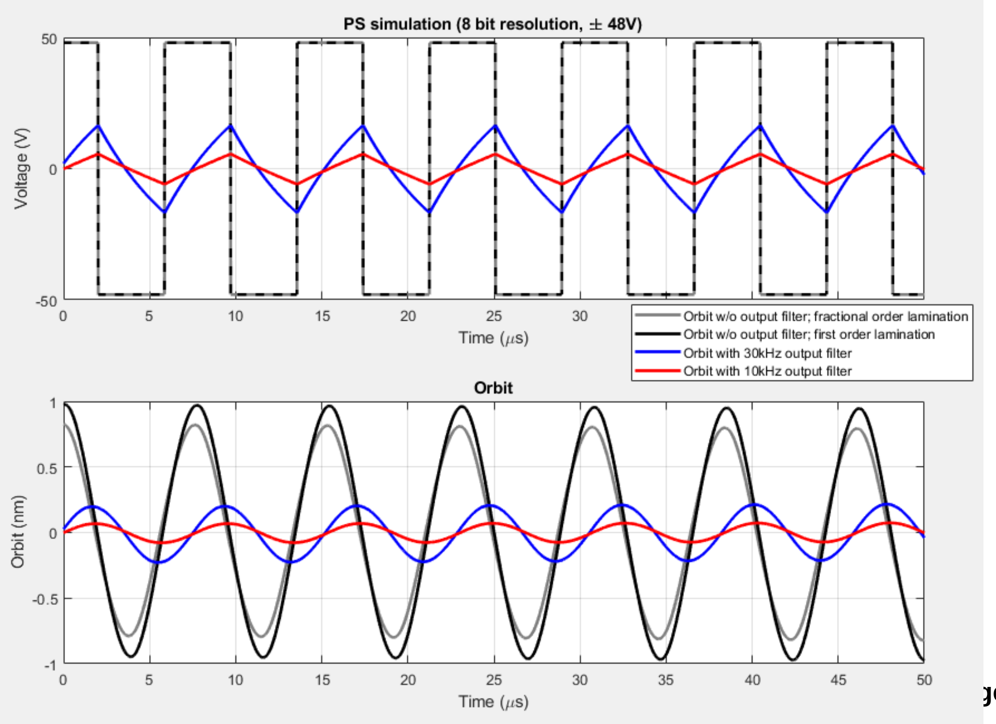


Conclusion from simulation

- PWM switching filtered by the output filter and by bandwidth limiting elements (magnet, yoke lamination and vacuum chamber)

  → ***1nm expected maximum orbit distortion***

- Noise is working point dependent, but well below the BPM resolution



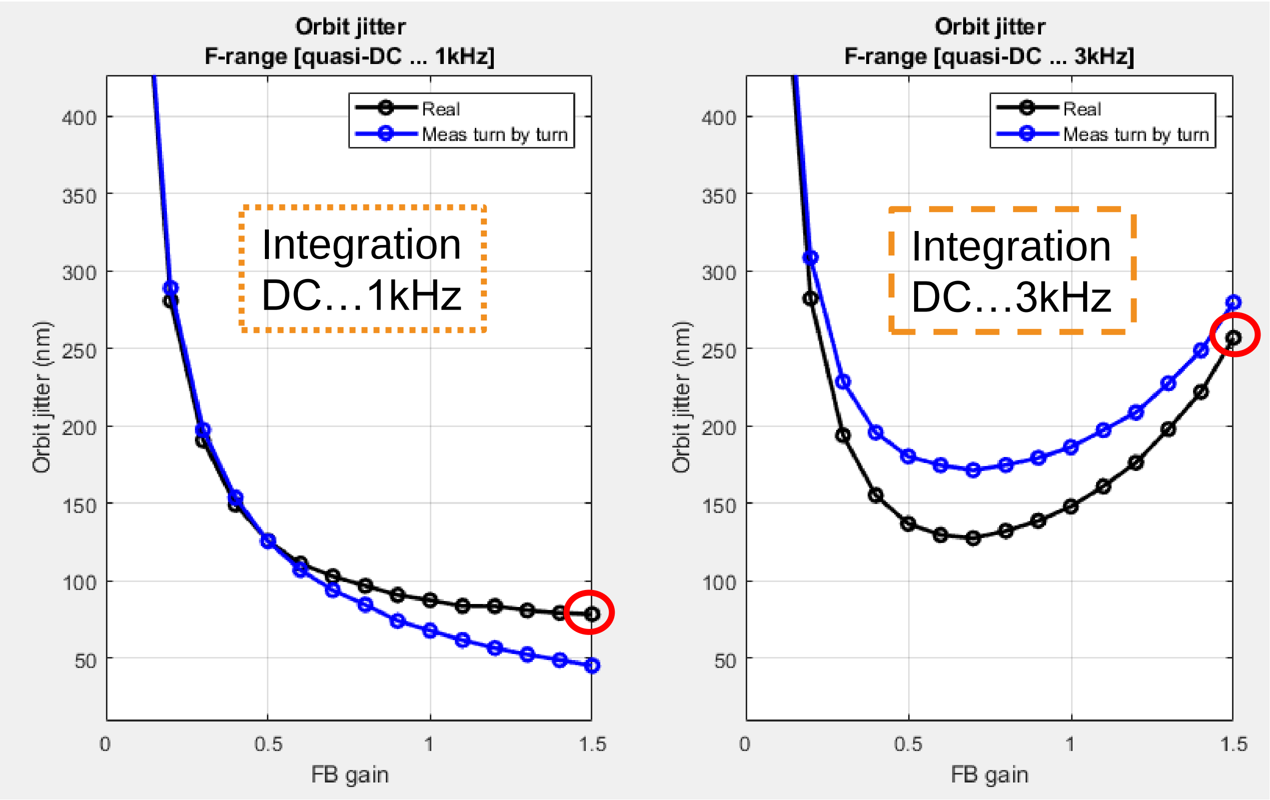
SISO simulation

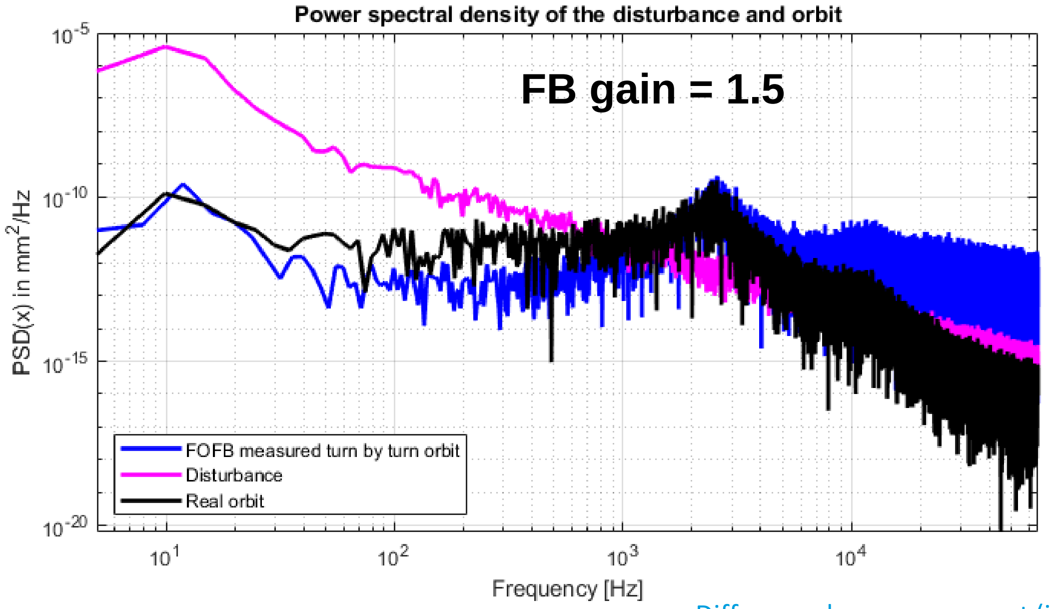
FOFB simulation

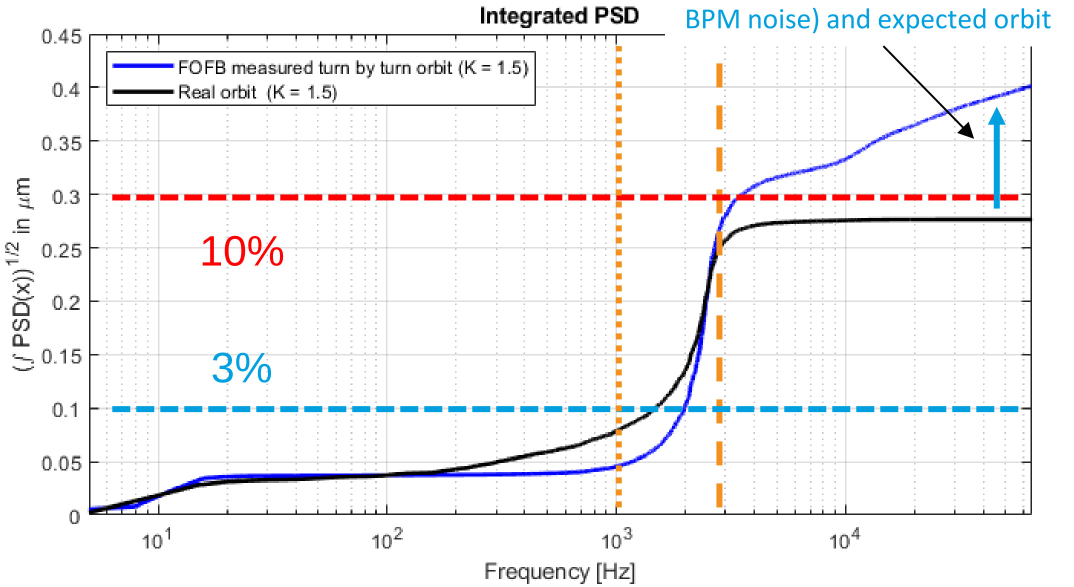
Expected orbit jitter as function of FB gain

SISO closed loop simulation

- Feedback gain scan vs integrated orbit jitter
- Measured in comparison to real orbit jitter







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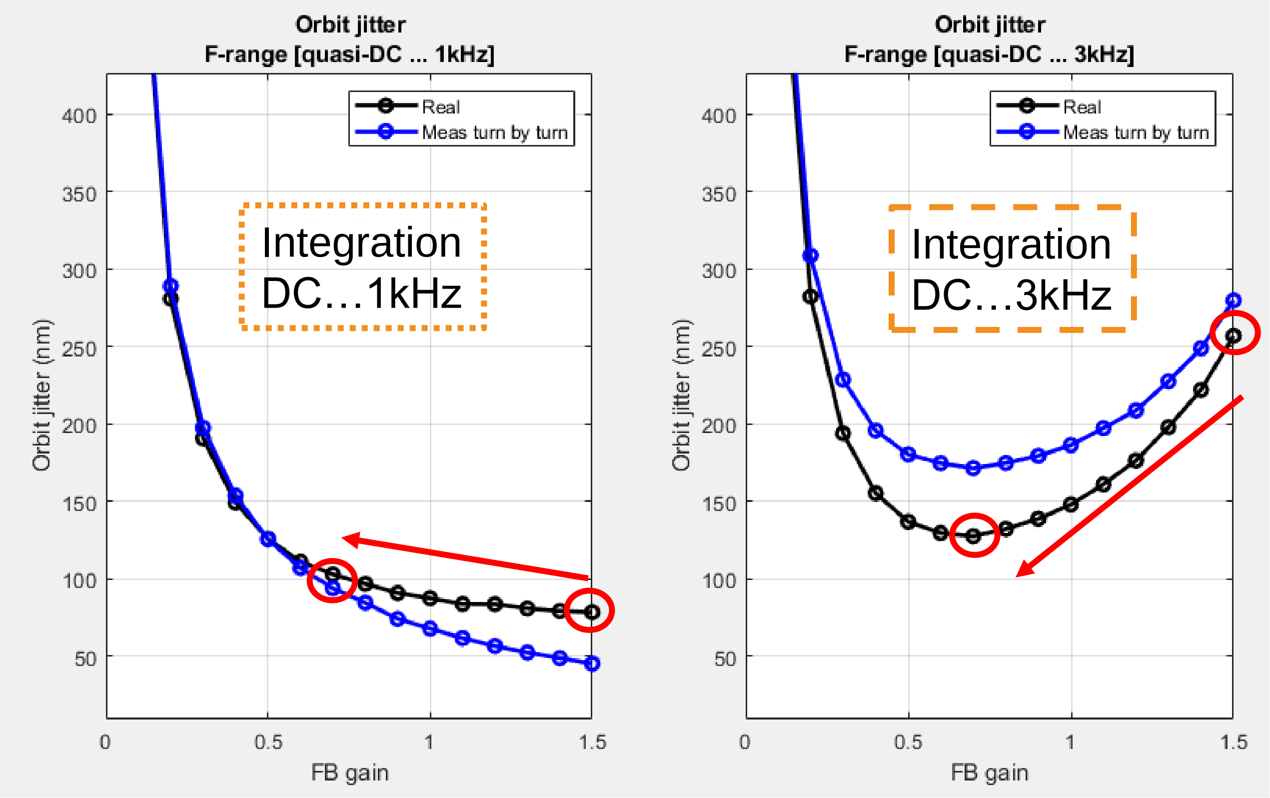

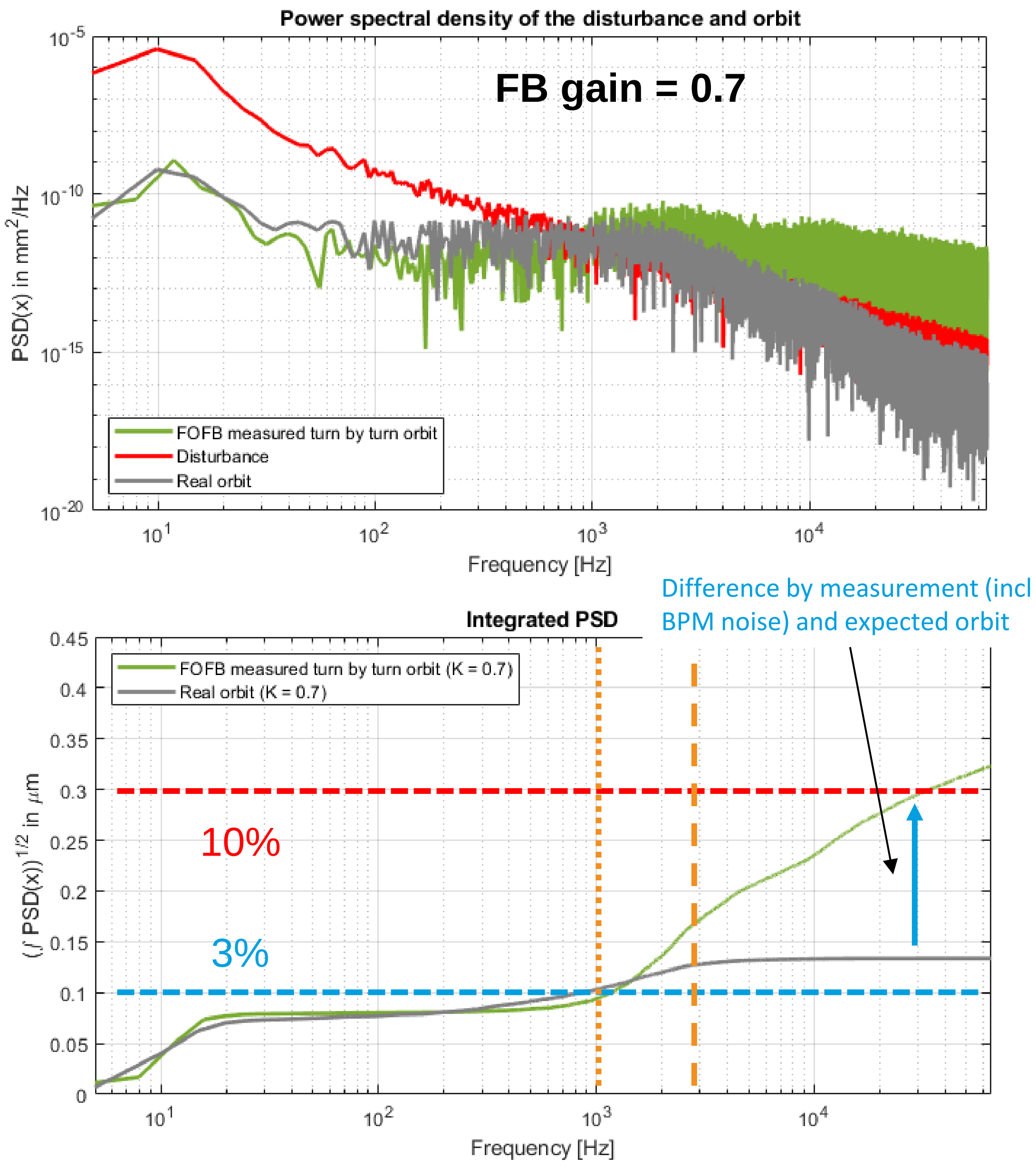

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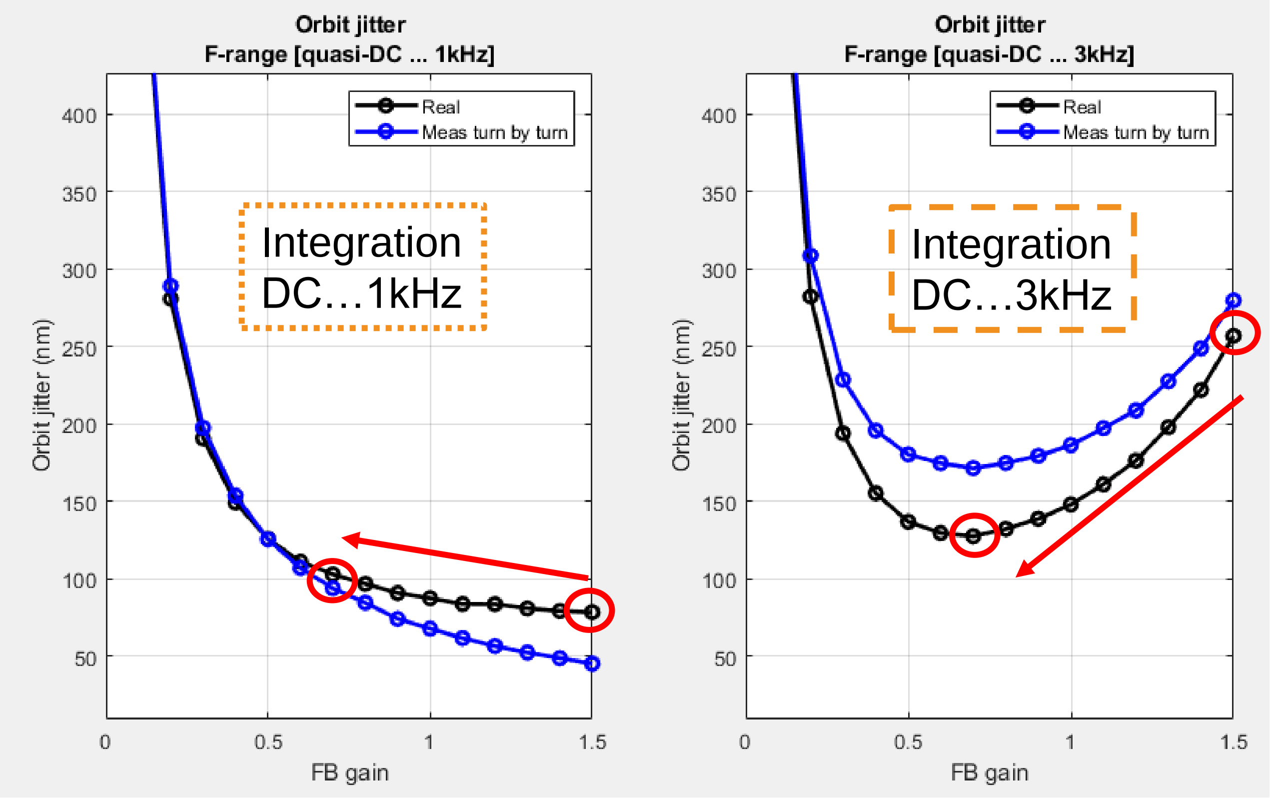
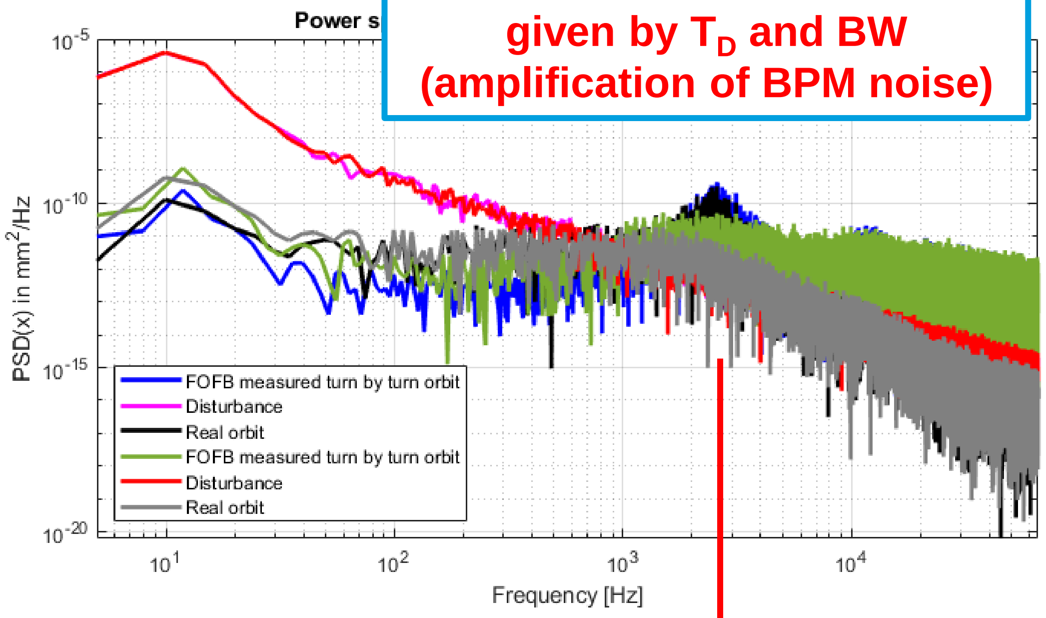
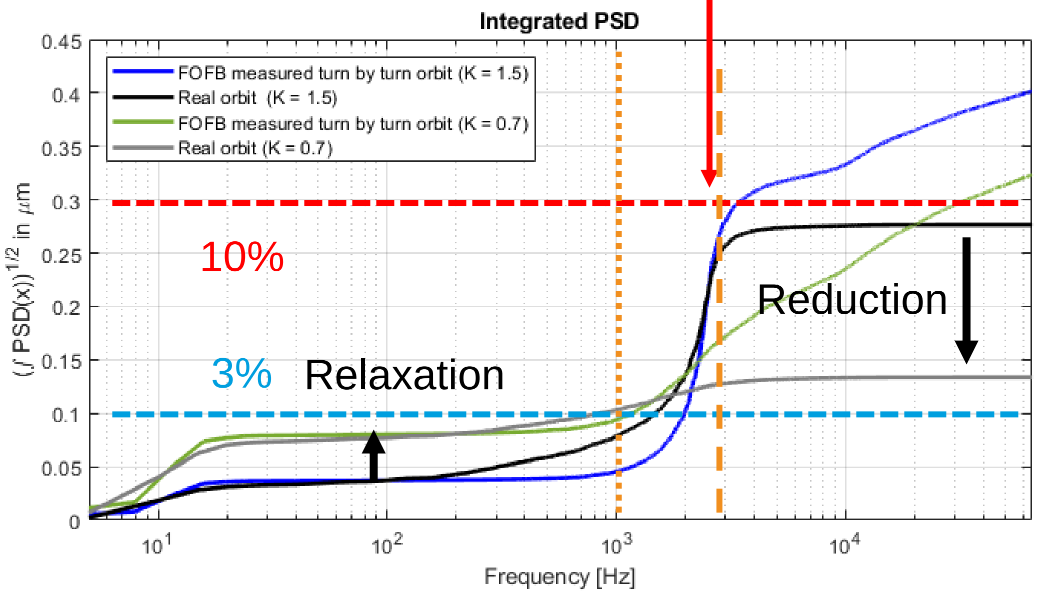


Waterbed effect at 2.5kHz given by T_D and BW (amplification of BPM noise)





→ MIMO mode space simulation to check noise & disturbance suppression ongoing

Conclusion & Outlook

Conclusion

- PETRA IV as the most important project at DESY
- Passive and active orbit stabilization
  - Orbit distortions in stability task force
  - FOFB system design
  - Sub-system modelling and HW specifications
  - Noise and disturbance modelling
- SISO simulations

Next steps

1. PETRA III as benchmark system for MIMO simulations
2. Full MIMO simulation with all noise and disturbance sources
3. Spatial disturbance integration including coherence length and transition
4. Different BPM supports (ground, girder)
5. Optimal (& robust) integration of photon diagnostics into (F)OFB

Thank you for your attention!

Thank you

Contact

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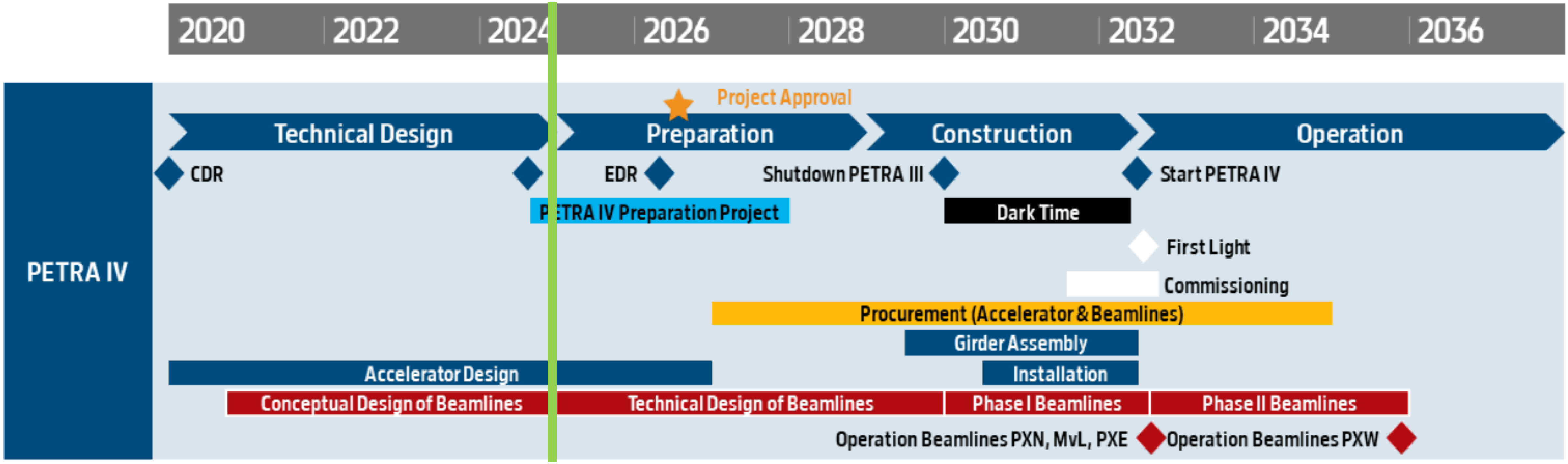
The PETRA IV project timeline hinges on project approval by mid-2026



The draft breakdown below hinges on

- Project approval in mid 2026
- Call for tender start in mid 2027
- **PIII shutdown end 2029**

- Procurement for the accelerator estimated to 3 years
- **Dark period 30 months**
- Three months commissioning time
- **First light in Jul 2032**