PETRA IV.
NEW DIMENSIONS

PETRA IV:
alignment, stability, and optics correction

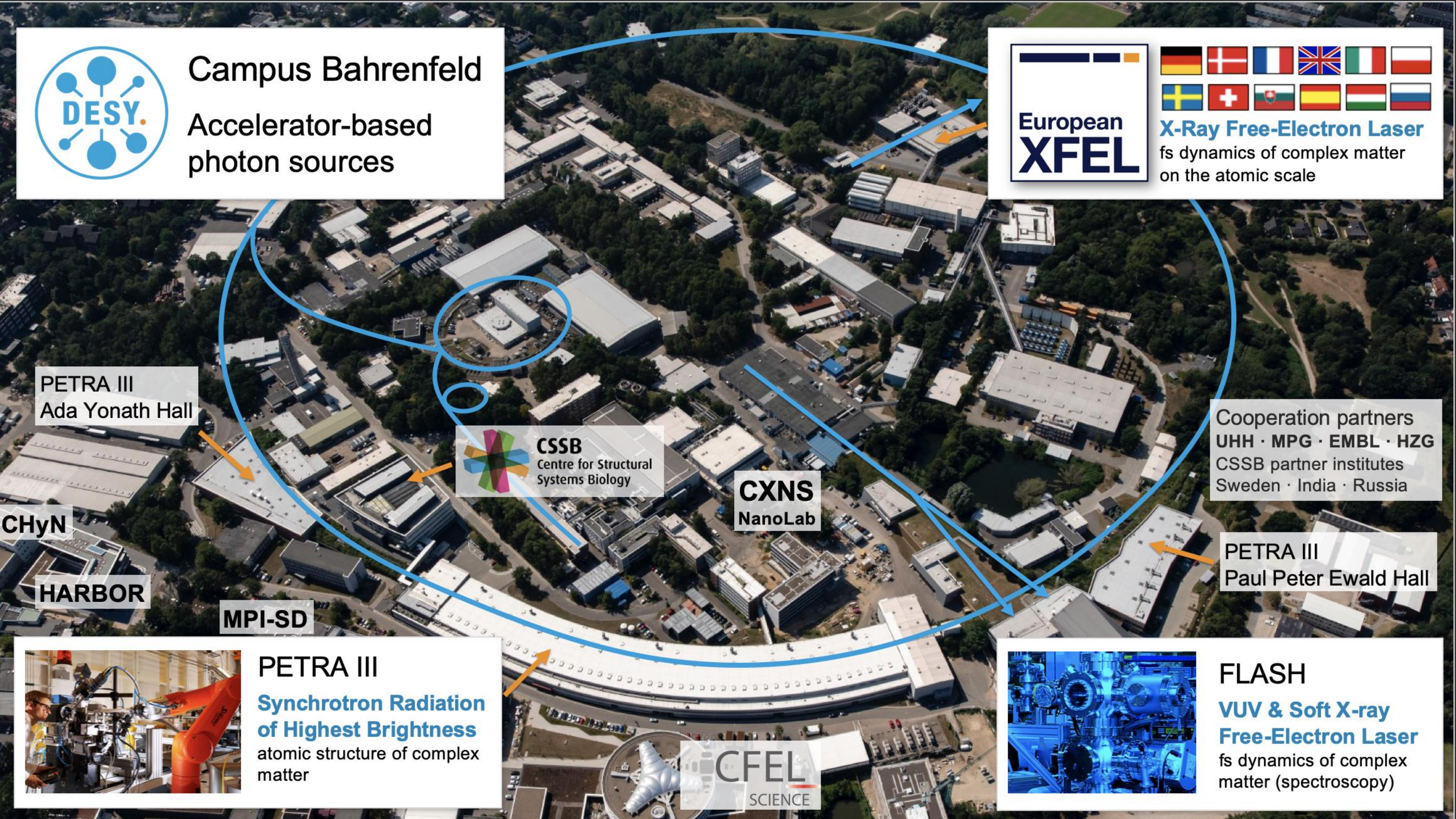
Ilya Agapov, DESY

Geneva, May 11th, 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754

DESY.



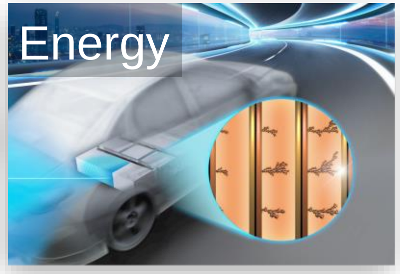
DESY.
Campus Bahrenfeld
Accelerator-based photon sources
European XFEL
X-Ray Free-Electron Laser
fs dynamics of complex matter on the atomic scale
PETRA III
Ada Yonath Hall
CSSB
Centre for Structural Systems Biology
CXNS
NanoLab
Cooperation partners
UHH · MPG · EMBL · HZG
CSSB partner institutes
Sweden · India · Russia
CHyN
HARBOR
MPI-SD
PETRA III
Paul Peter Ewald Hall
PETRA III
Synchrotron Radiation of Highest Brightness
atomic structure of complex matter
CFEL
SCIENCE
FLASH
VUV & Soft X-ray Free-Electron Laser
fs dynamics of complex matter (spectroscopy)

PETRA IV.

Christian Schroer

X-Ray Microscope for Chemical, Biological, and Physical Processes

Cross-scale view of structure and function of complex systems in nature and technology:

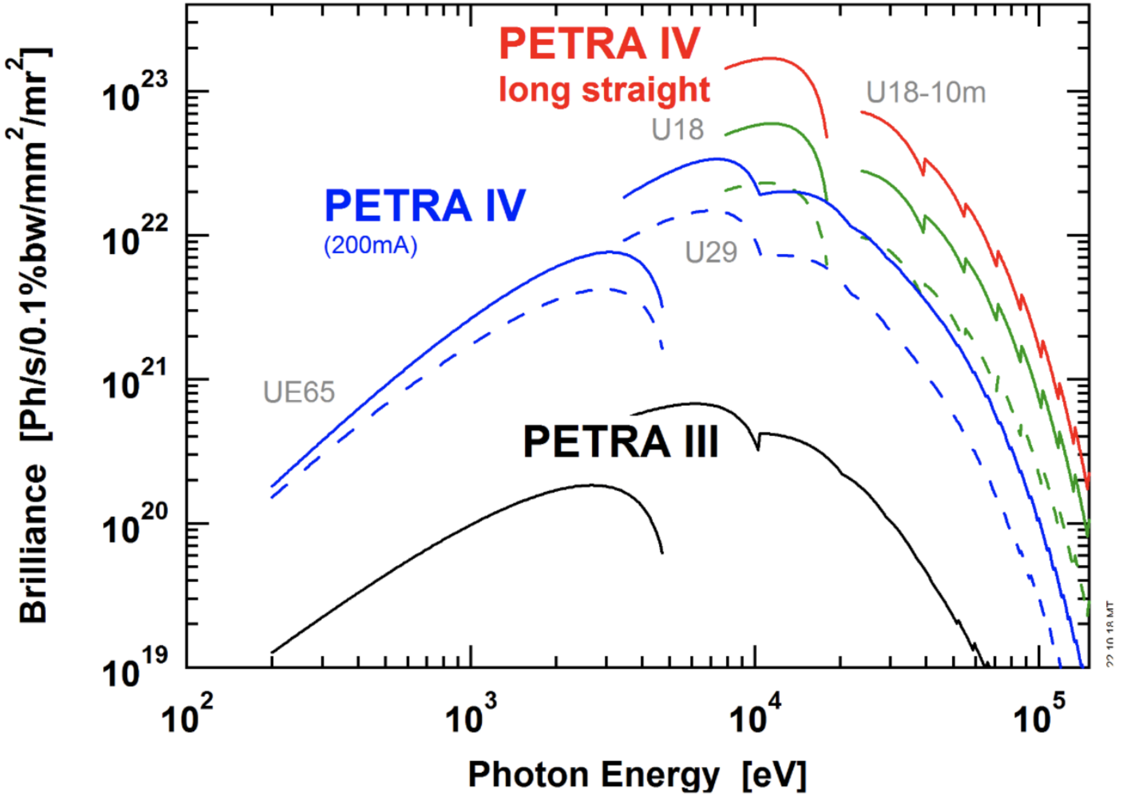


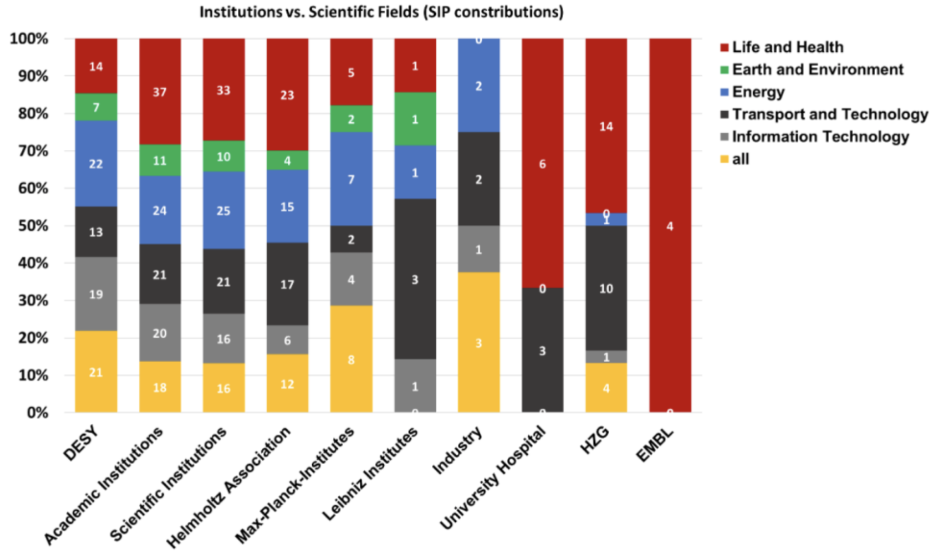
> contributions to grand challenges
> all fields of science
> academia and industry

PETRA IV unprecedented beam parameters enable a diverse experimental portfolio

$$\mathcal{B} \propto \frac{F}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \qquad \Sigma_{x,y}^2 = \sigma_{x,y}^2 + \sigma_R^2 \qquad \Sigma_{x',y'}^2 = \sigma_{x',y'}^2 + \sigma_{R'}^2$$

Parameter	Brightness mode	Timing mode
total current (mA)	200	80
bunch current I_b (mA)	0.125	1.0
arc ID β_x/β_y(m)	3.6/2.2	3.6/2.2
flagship ID β_x/β_y(m)	4.0/4.0	4.0/4.0
hor. emittance ϵ_x (pm rad)	14.2	22.9
vert. emittance ϵ_y (pm rad)	2.84	4.60
bunch length σ_z (mm)	13.58	19.96
bunch length σ_t (ps)	45.7	64.3
energy spread σ_p (10^{-3})	0.988	1.436
Touschek lifetime τ (h)	8.5	2.1



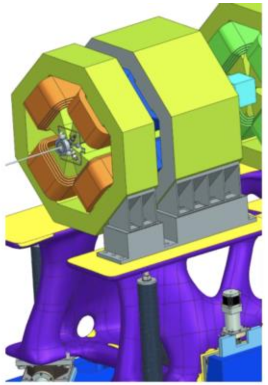


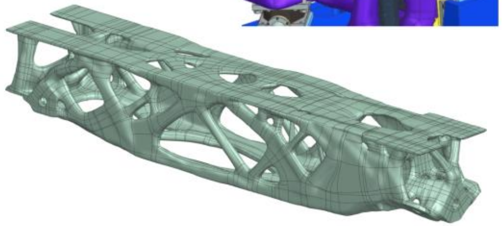
Kai Bagschik, Karo Baev, Stephan Klumpp,
Christian Schroer, Oliver Seeck, Markus Tischer, HC Wille

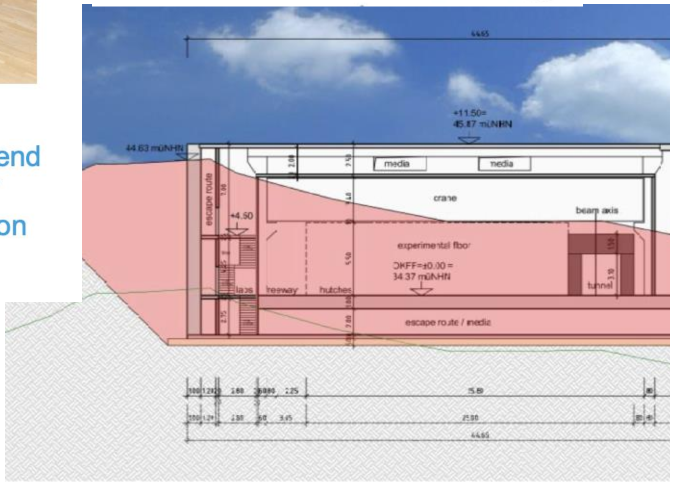
Technical design is transitioning into implementation

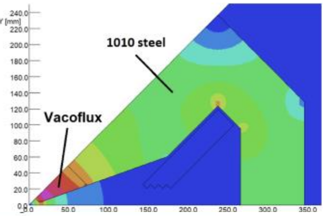
Harald Reichert, Riccardo Bartolini

Harald Reichert was Director for Research in Physical Sciences at ESRF from 2009 until the end of last year. He will now **support the PETRA IV Team in the creation of the TDR** which builds on the Conceptual Design Report (CDR).

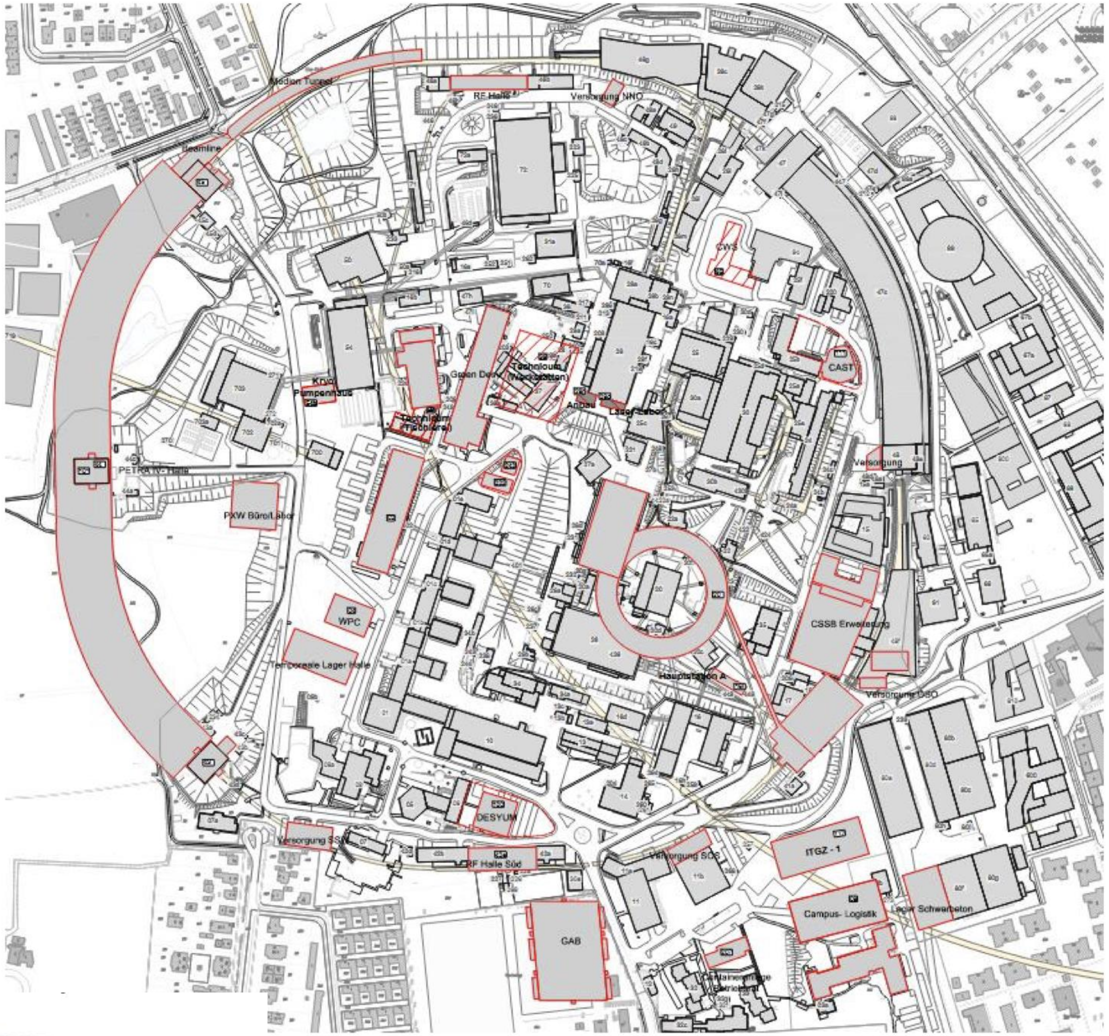


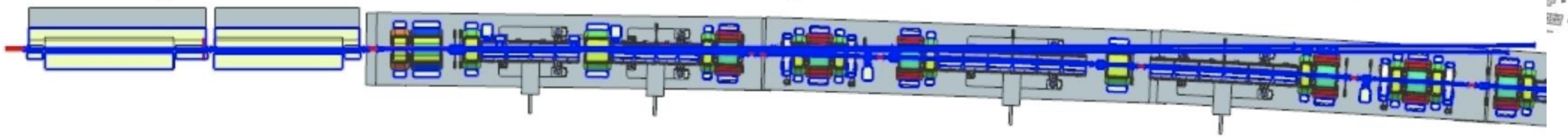




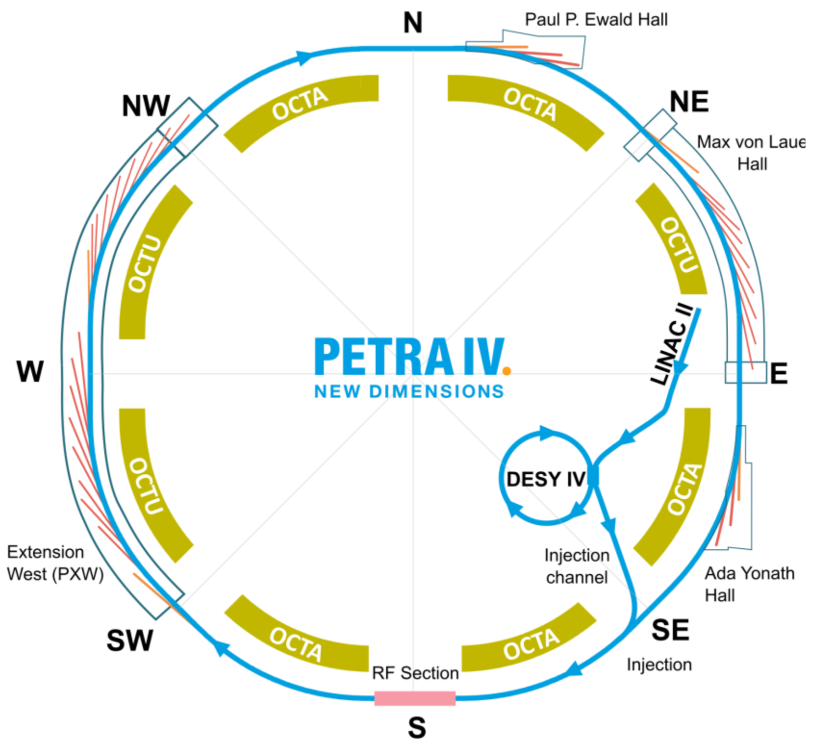


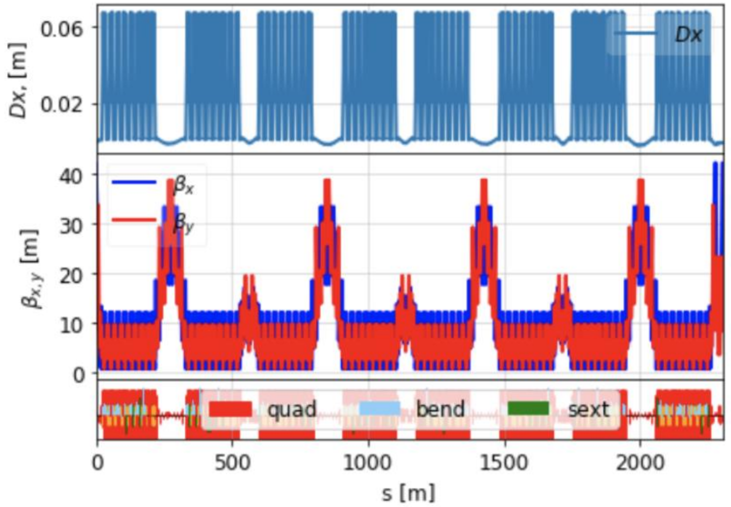
Civil Construction - Summary

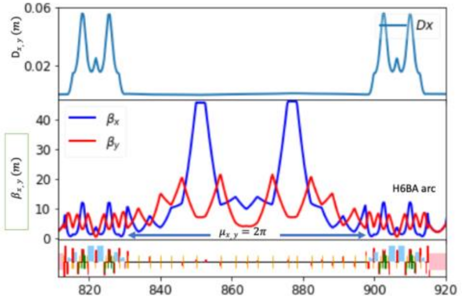


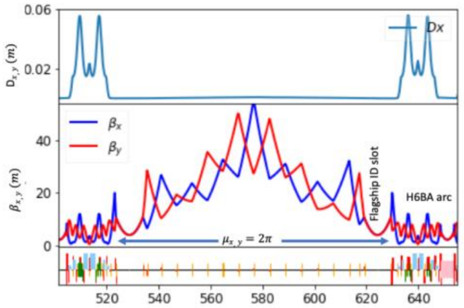


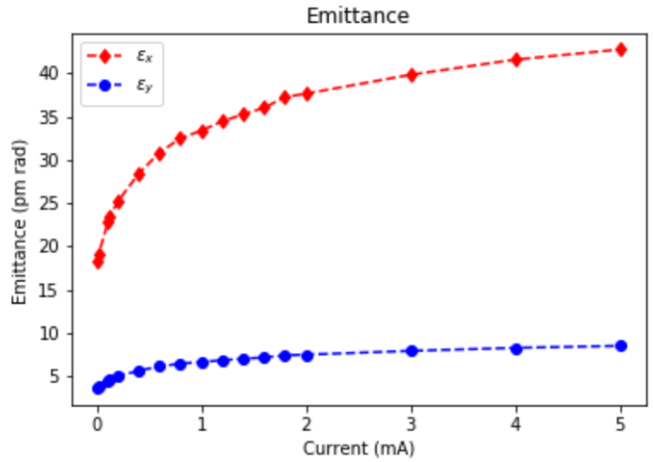
PETRA IV Lattice is based on six-bend achromat arcs

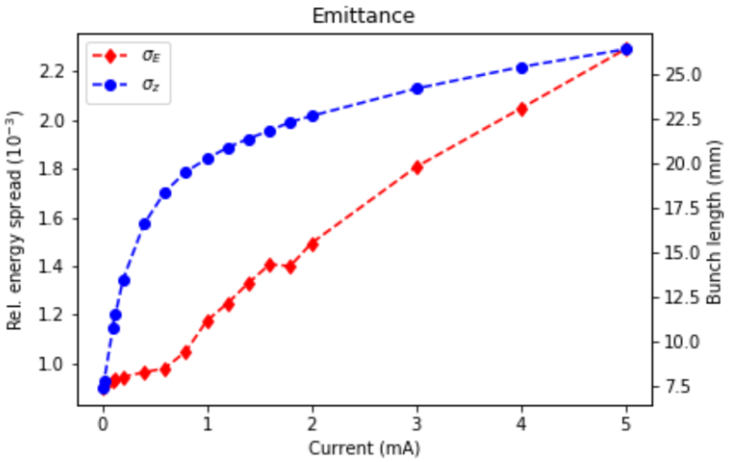






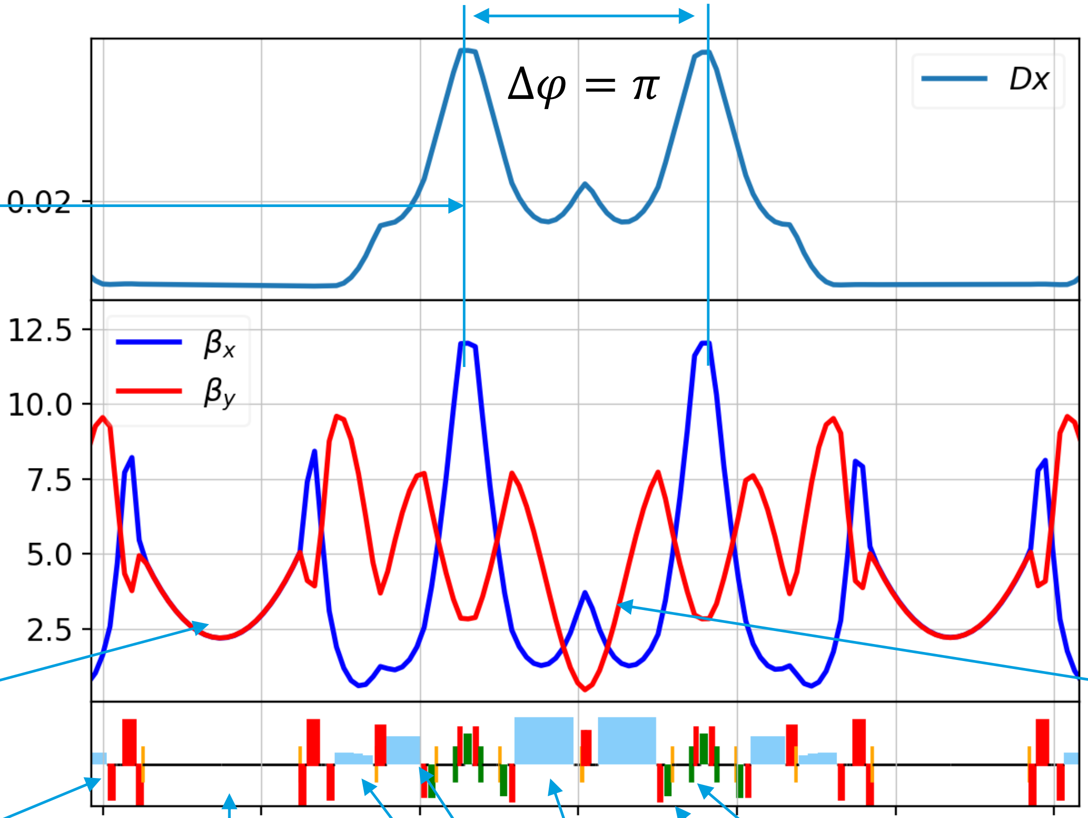






- Challenges: size and low degree of symmetry
- Initially considered H7BA
- Changed to H6BA in 2021
- Lattice frozen in April 2022

Unit cell with 43 pm emittance. 2x damping with wigglers



Large dispersion c.f. H7BA

Low beta 2.2 m

Triplet 115 T/m

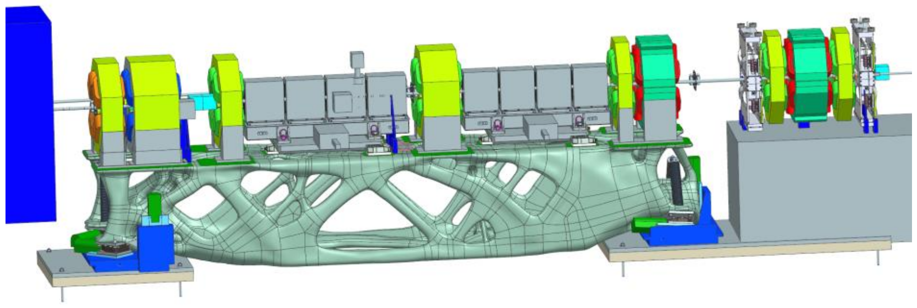
ID space 4.9 (4.7) m User ID or damping wiggler

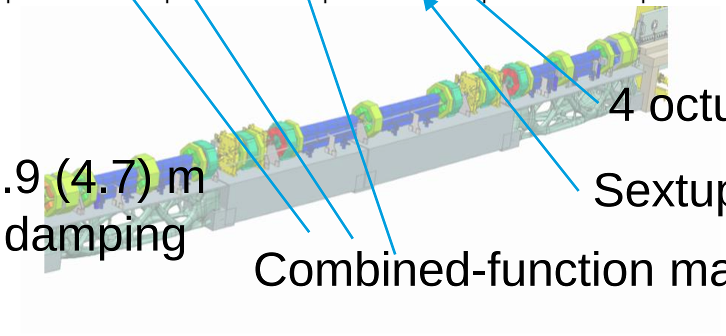
Combined-function magnets

Sextupoles moderately strong

4 octupoles per cell

Shorter sextupole-to-sextupole distance compared to H7BA





Magnet type	Max. strength	bore rad./half-gap
Combined (Dipole/Quad.)	0.2 T	10 mm
Quadrupole	115 T/m	9 mm
Sextupole	2500 T/m^2	10 mm
Octupole	100000 T/m^3	10 mm
Orbit corrector	1 mrad	10 mm
Fast orbit corrector	30 μrad	30 mm

Machine stability is challenging

https://sciencecity.hamburg

MBA lattices are sensitive to errors

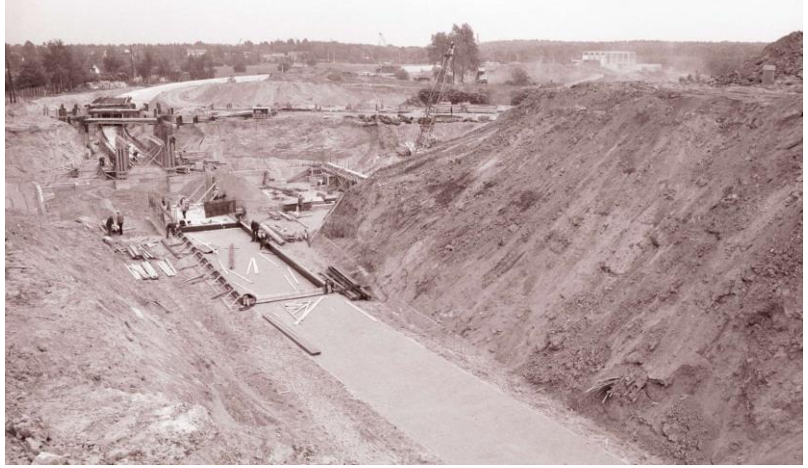
Static errors (alignment errors, multipole errors, long-term tunnel drifts):

- Amplitude in 10s of µm range
- Response to errors nonlinear, up to unstable beam
- Machine bootstrapping required

Dynamic errors (mechanical vibrations, electric noise).

- Smaller amplitude
- Linear behaviour
- No conceptual difference to PETRA III
- But better precision required in PIV due to smaller beams and higher degree of coherence

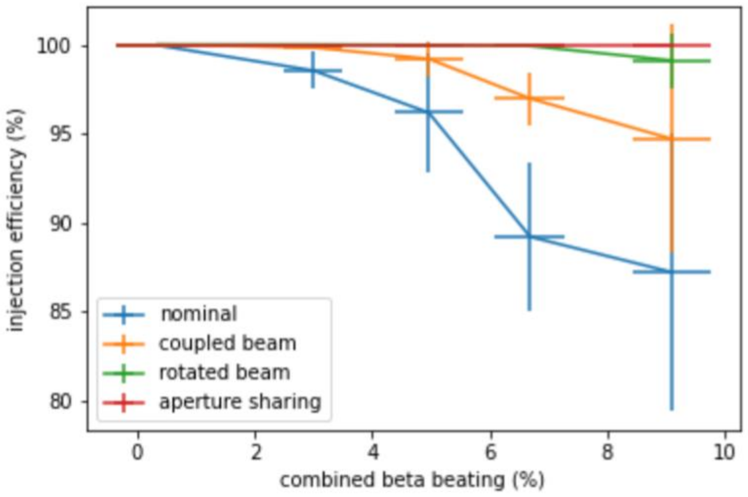
Noisy urban environment, legacy infrastructure

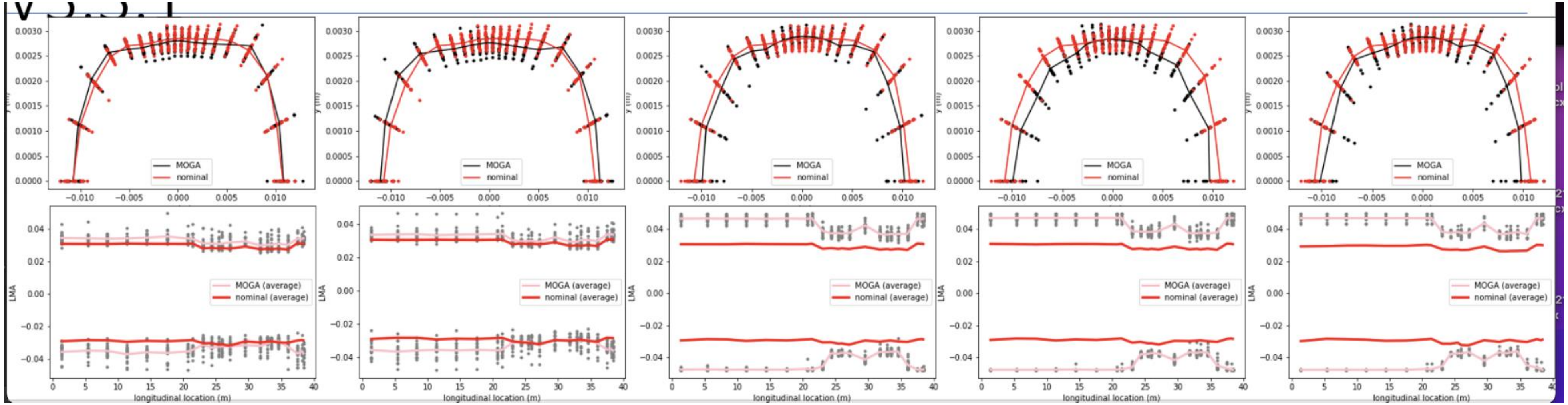


Sensitivity analysis was driving lattice development

- At the early design stages lattice changes happen too often to set up and perform bootstrapping simulations
- Frequency maps give good prediction on DA/LMA with errors
- We use proxy characteristics, such as
    - Probability of closed orbit existence vs. alignment error
    - Closed orbits and vs alignment error
    - Beta beat vs. closed orbit
    - DA and LMA vs. beta beat
- MOGA and several other simulations use simplified error and correction model (smaller errors + only orbit and tune correction). This agrees well with the full bootstrapping simulations

Marc Jebramcik, Joachim Keil, Thorsten Hellert

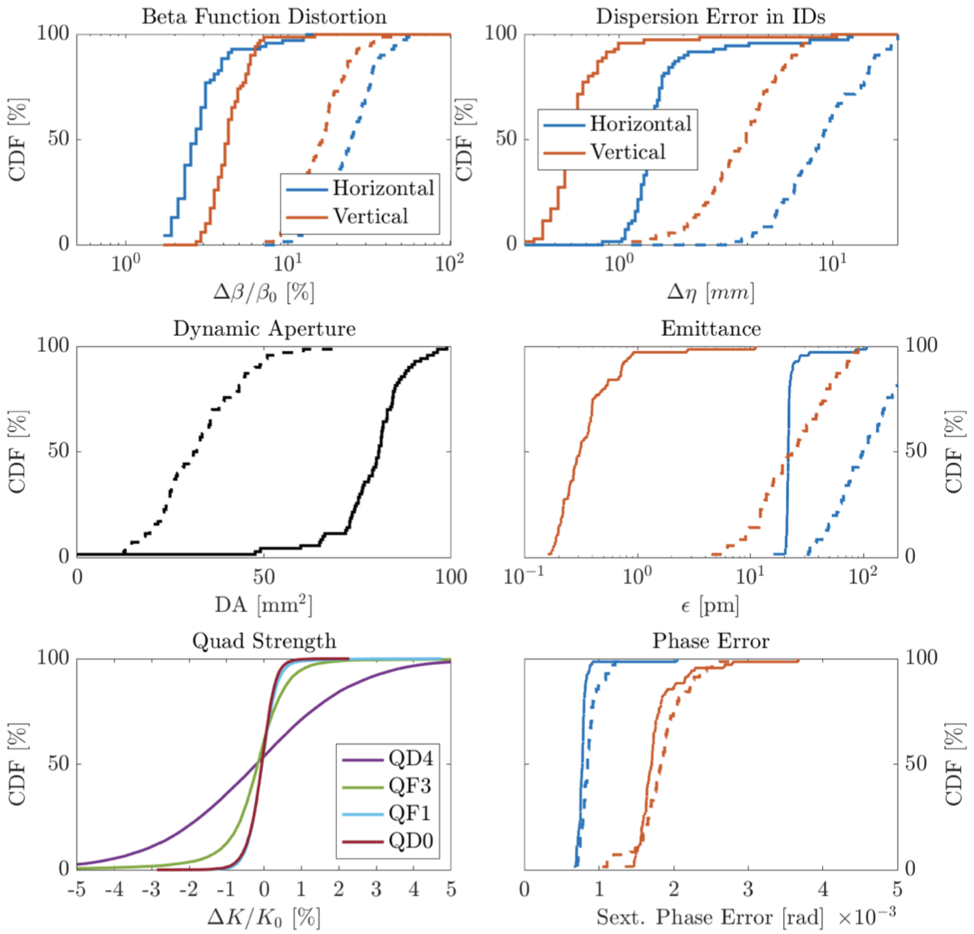




Machine bootstrapping procedure set up and tolerances specified

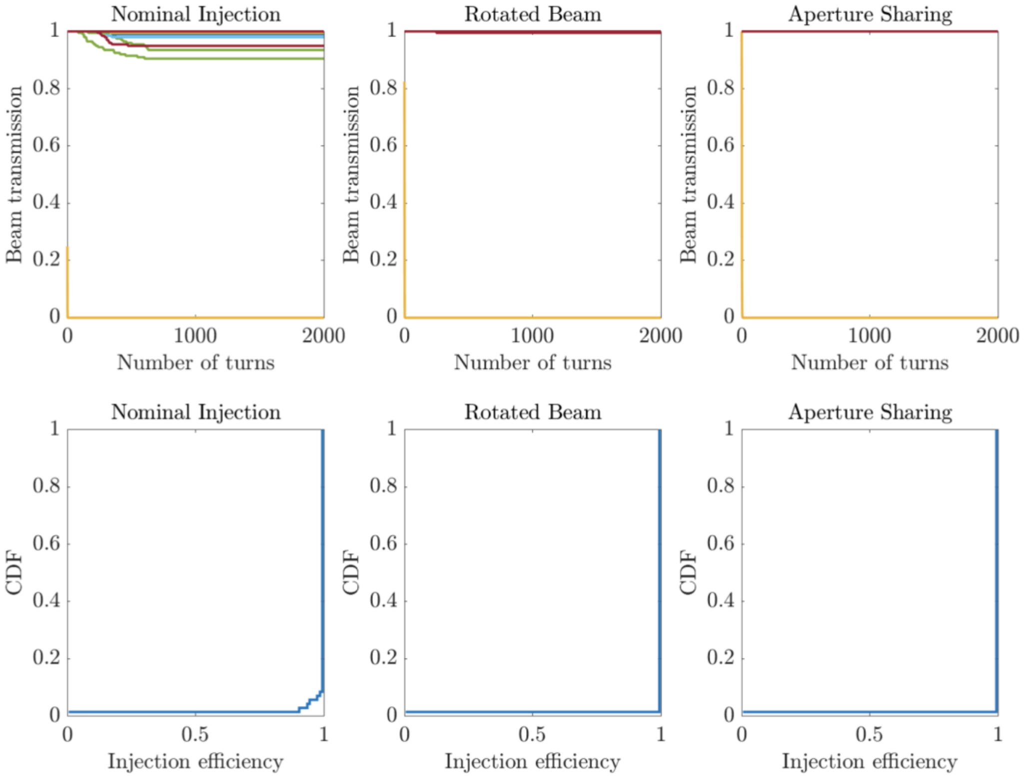
Thorsten Hellert

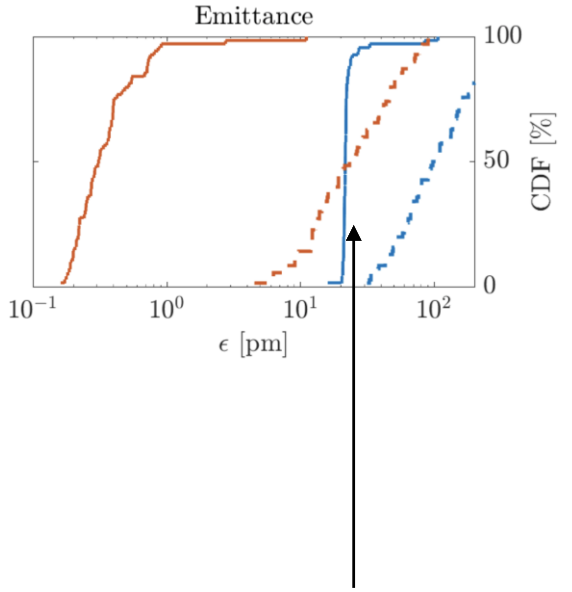
- **Magnet Errors:**
  - Magnet offsets = 30 µm
  - Magnet roll = 200 µrad
  - Magnet calibration = $1\cdot10^{-3}$
  - Quadrupole calibration = $5\cdot10^{-4}$
- **Girder Errors:**
  - Girder offsets = 100 µm
  - Girder rolls = 200 µrad
- **BPM Errors:**
  - BPM offsets = 500 µm (30 µm after BBA)
  - BPM roll = 400 µrad
  - BPM calibration = 2%
  - BPM nose (TBT) = 20 µm
  - BPM noise (CO) = 0.1 µm
- **CM Errors:**
  - CM roll = 200 µrad
  - CM calibration = 2%
- **Simplified correction:**
  - First turn threading
  - Sextupole/octupole ramp
  - Orbit and tune correction
  - Reduced LOCO



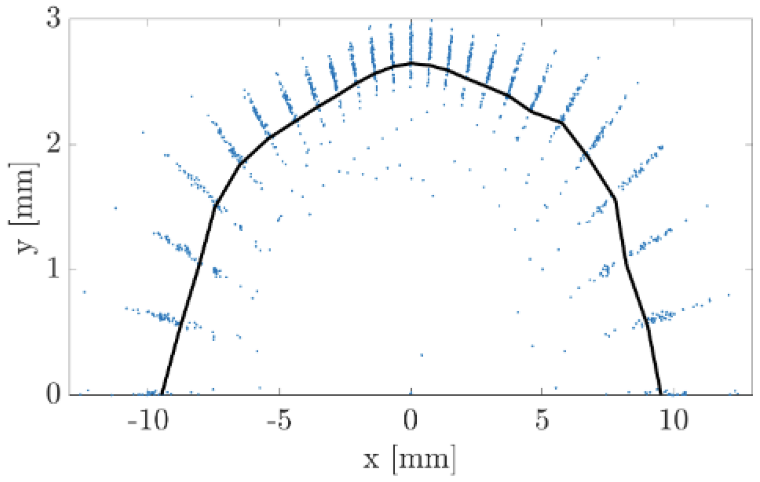
Machine performance parameters reached in simulation

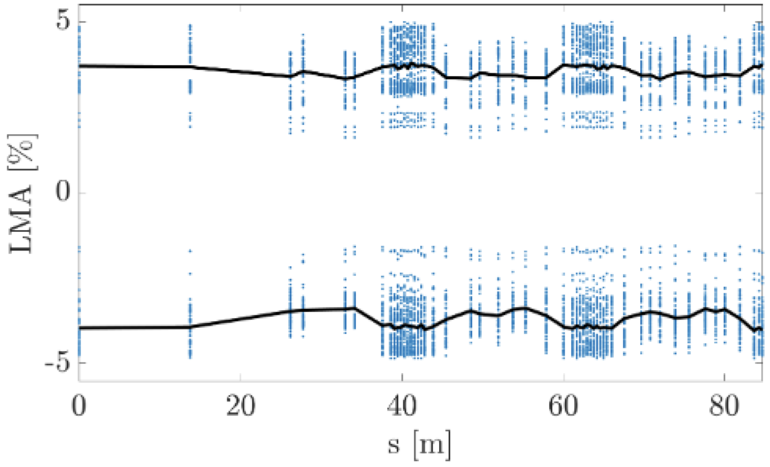
- DA guarantees 100% theoretical injection efficiency with errors
- LMA guarantees theoretical lifetime with errors of > 5 h
- Next steps: optimization of the start-up procedure, implementation of production-level software,





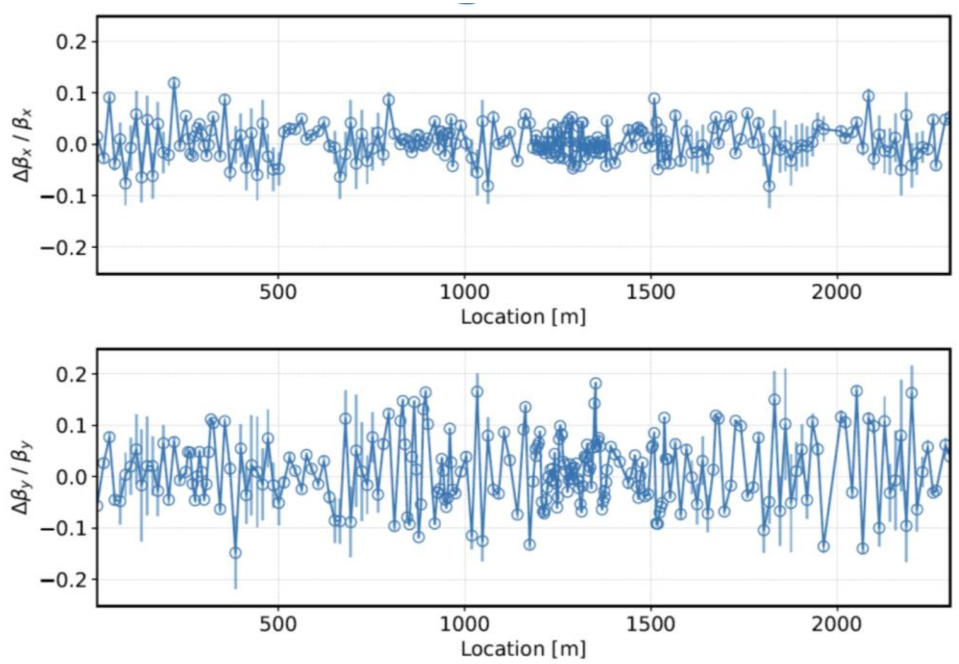
20 pm target





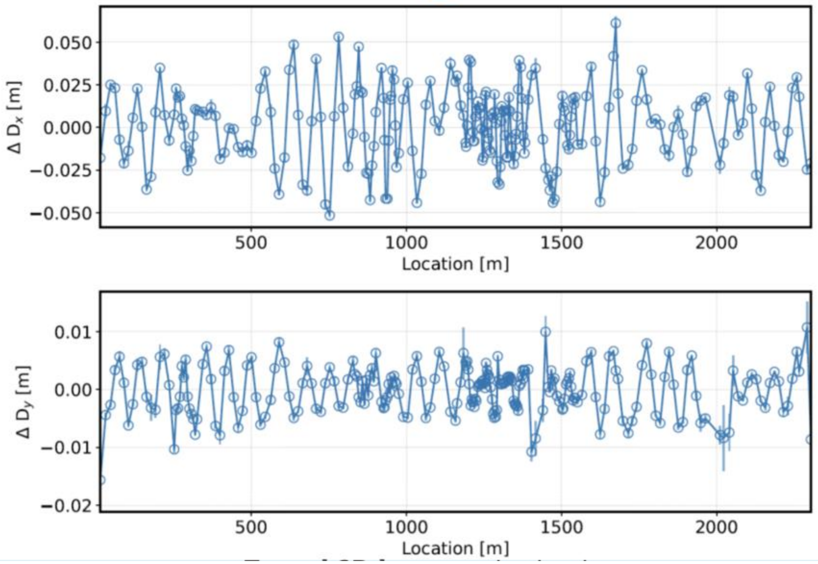
Experimental work on alternative optics correction schemes

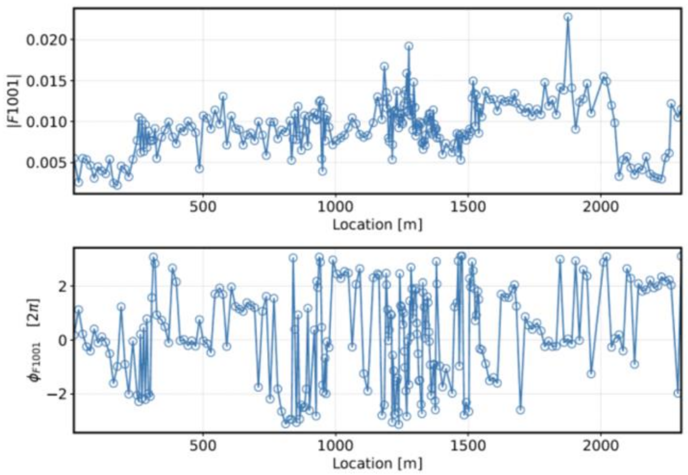
Lukas Malina

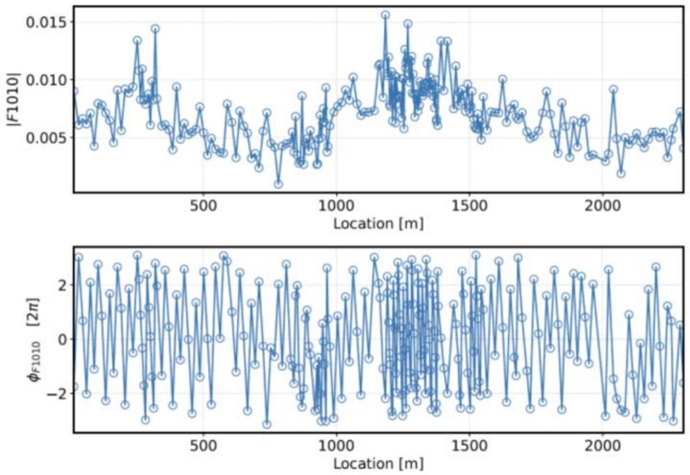


- Standard optics correction at PETRA III based on response matrix https://www.desy.de/xfel-beam/data/talks/talks/keil_-_response_measure_20051212.pdf
- Optics measurements from driven oscillations implemented
- Beta beating, dispersion and RDTs measures
- Putting in operation: facing issues with BPM synchronization, and BPM server overloads

Uncorrected machine





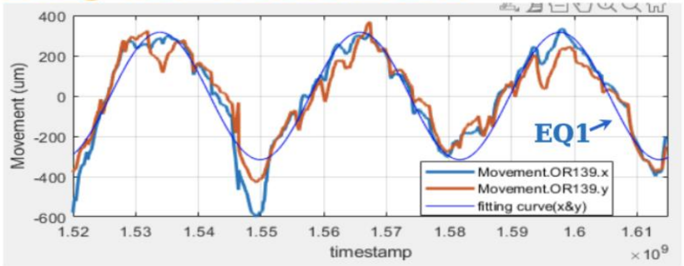


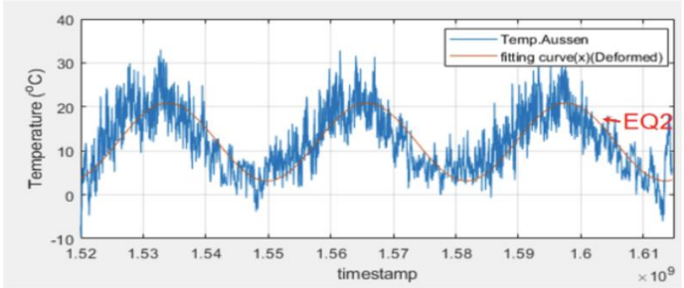
Measures for static correction being taken

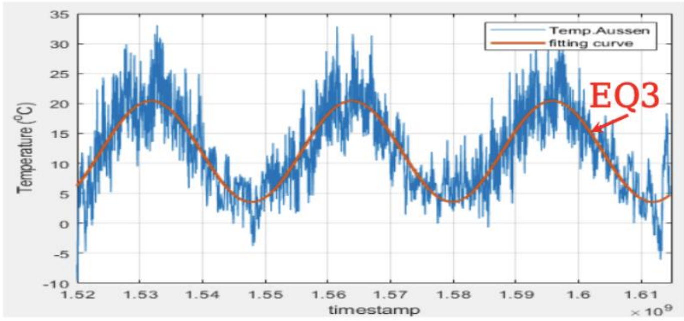
Michael Bieler, Jens Klute, Michaela Schaumann

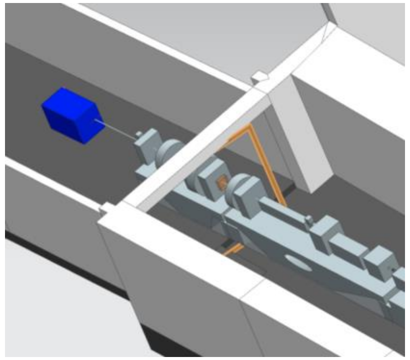
- Several places in the tunnel exhibit strong movements (cracks)
- The cracks are monitored
- Temperature stabilization in the tunnel could not fully eliminate the floor movements
- Evaluated possibilities of tunnel reinforcement, deemed inefficient
- Movable girders and feed-forwards are foreseen
- Heat dissipation in tunnel will be minimized to provide best temperature stability
- Cracks accounted for in CAD model and in beam dynamics calculations

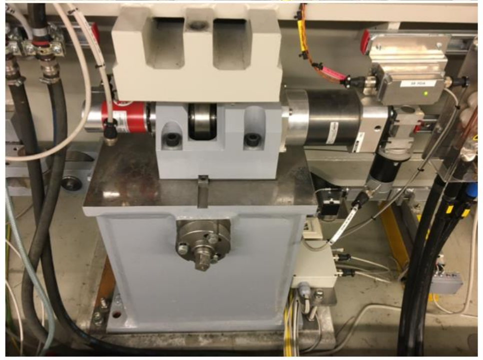
Long term Movements

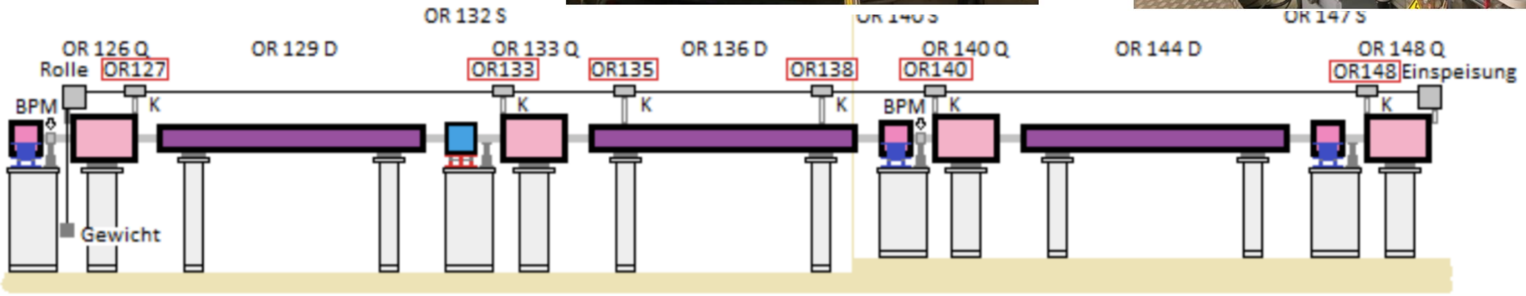








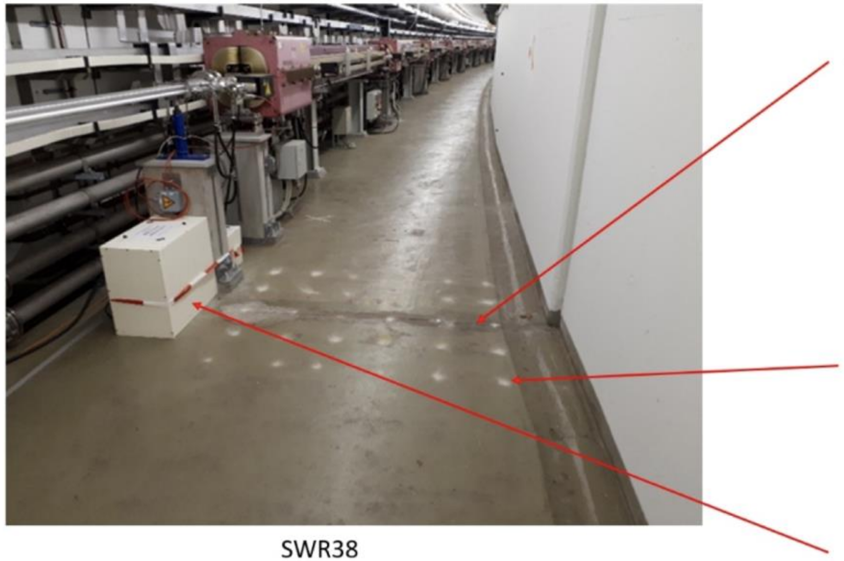




Monitoring in PETRA III

Epoxy fixation of tunnel cracks: minor stability improvement seen

Michael Bieler

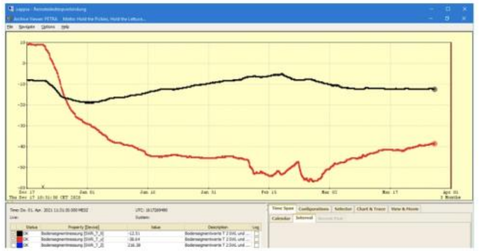


SWR38

SWR long term transverse motion 2021/22

Stabilized

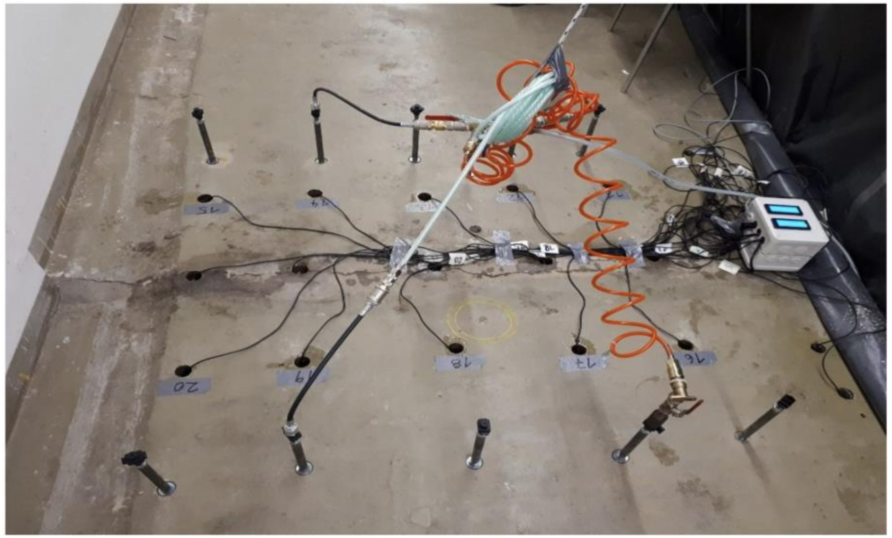
Not Stabilized



SWR long term transverse motion 2020/21

SWR long term longitudinal motion 2021/22

SWL long term longitudinal motion 2020/21

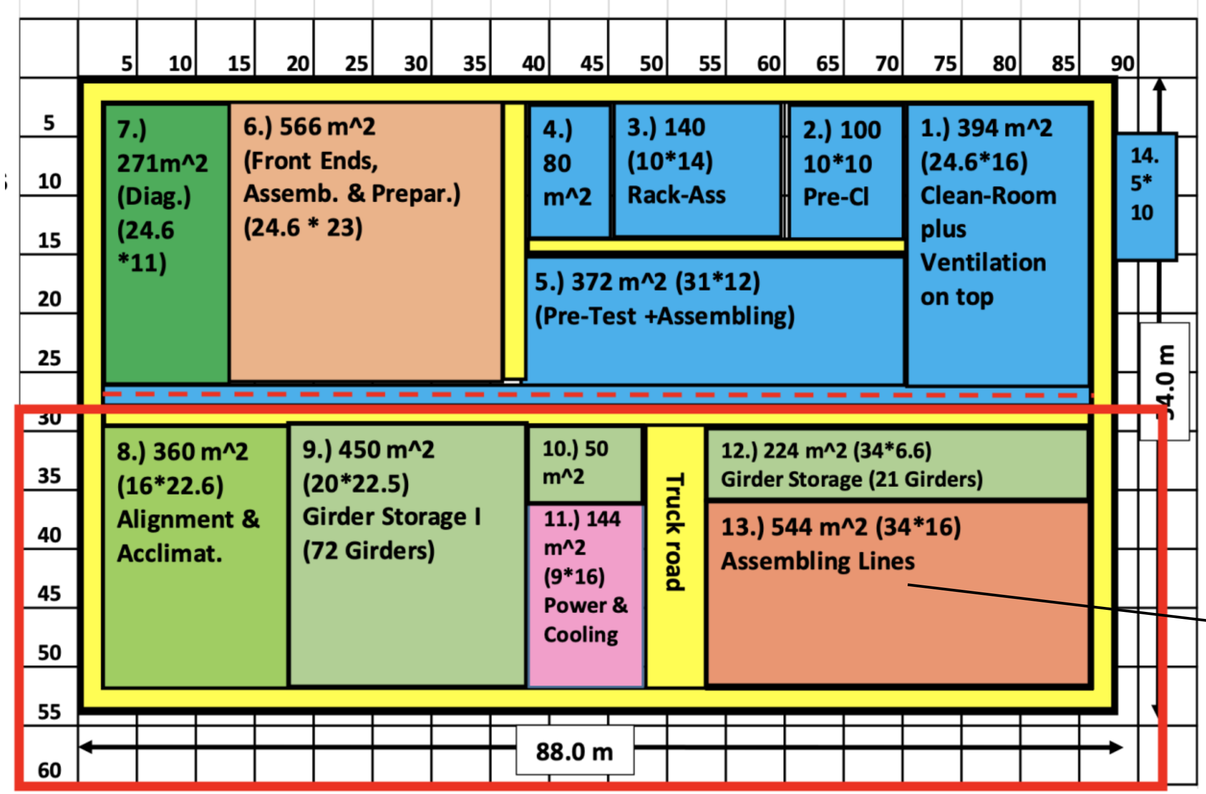


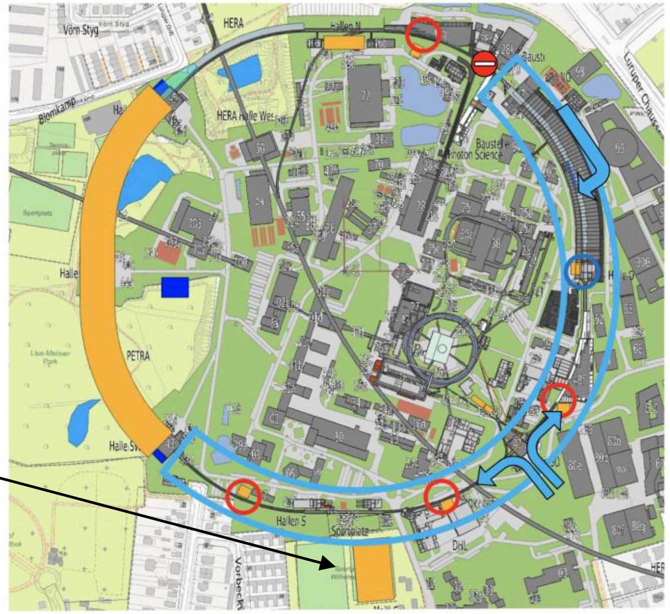
Alignment and logistics concepts being consolidated

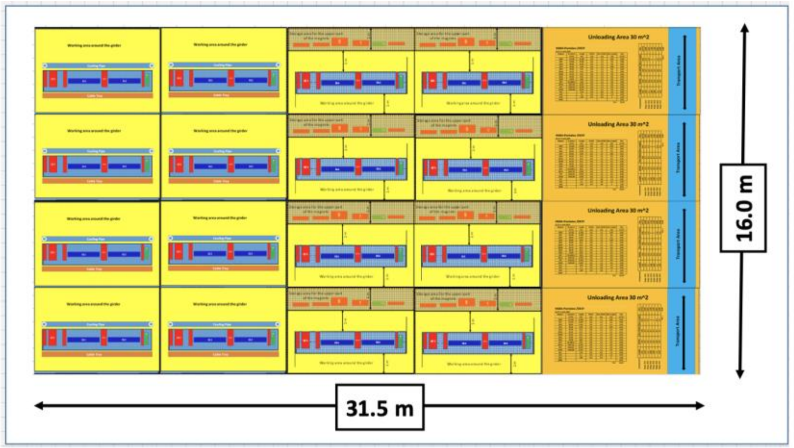
Dieter Einfeld,
Markus Hüning

- 30 µm alignment tolerance relatively easily achievable “in the lab”, under assumption’
  - Sufficient space
  - Constant temperature
  - Reduced transport
- Alignment requirements and the logistics plan strongly coupled

Boundary conditions have been constantly changing
Logistics plan converged







Transport tests being performed

Barker, Prenting, Schloesser

- Tests with PETRA III girder performed
- Will be redone with PETRA IV mock-up girder

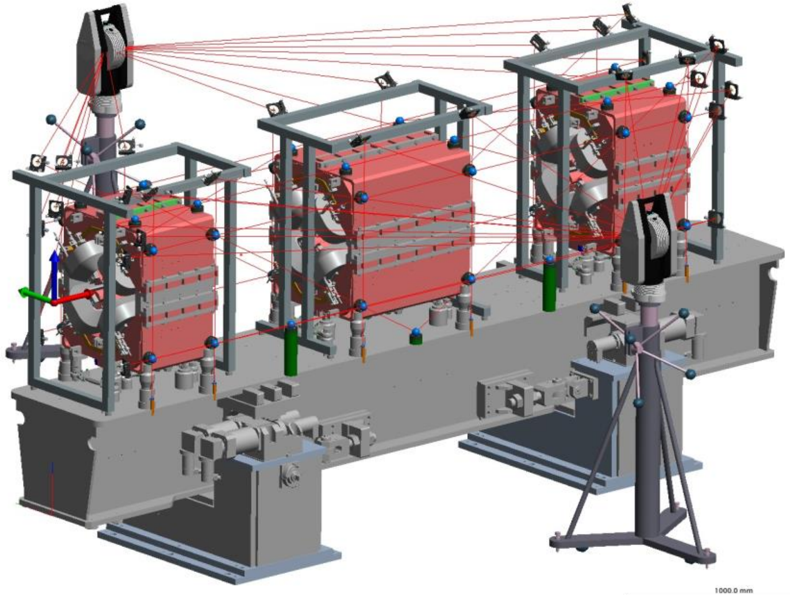


Table 1 Laser Tracker specifications

Measurement	Standard deviation
Hz angle	0.15 mgon
V angle	0.15 mgon
IFM distance	0.4 µm + 0.15 ppm
ADM distance	0.010 mm
Distance combined	10.4 µm + 0.15 ppm

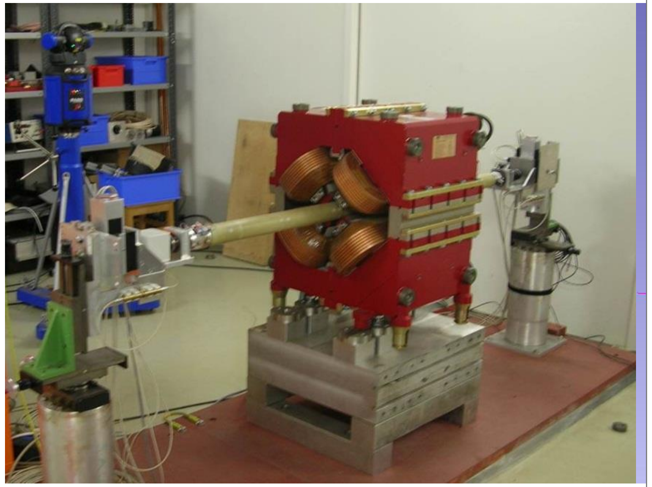
Epoch number	Date	Test before epoch
-1	1.9.2021	-
0	20.9.2021	None
1	22.9.2021	Craning
2	29.9.2021	Truck

Point #	Deformation X / µm	Deformation Y / µm	Deformation Z / µm
PQK36_AUS	4	-5	9
PQK36_EIN	1	7	-11
PQK36_MITTE	2	1	-1
PQK36_OBEN	12	6	-3
PQK62_AUS	10	5	-6
PQK62_EIN	7	7	6
PQK62_MITTE	8	6	0
PQK62_OBEN	2	4	-1
PQL6_AUS	-9	-6	-1
PQL6_EIN	-12	-9	11
PQL6_MITTE	-11	-7	5
PQL6_OBEN	-16	-10	4

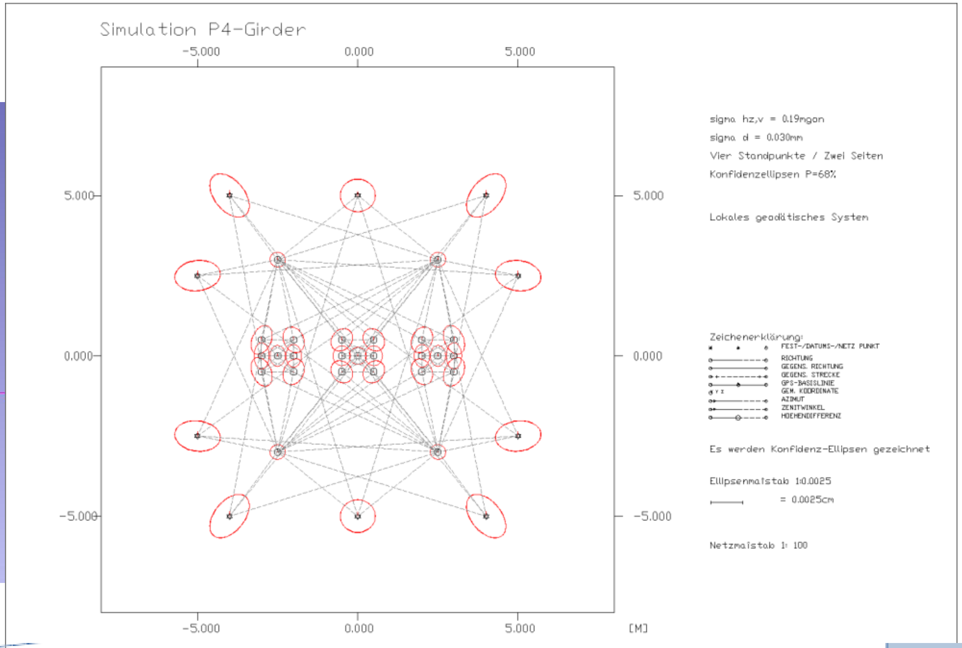
Alignment procedure worked out for 30 µm precision after transport

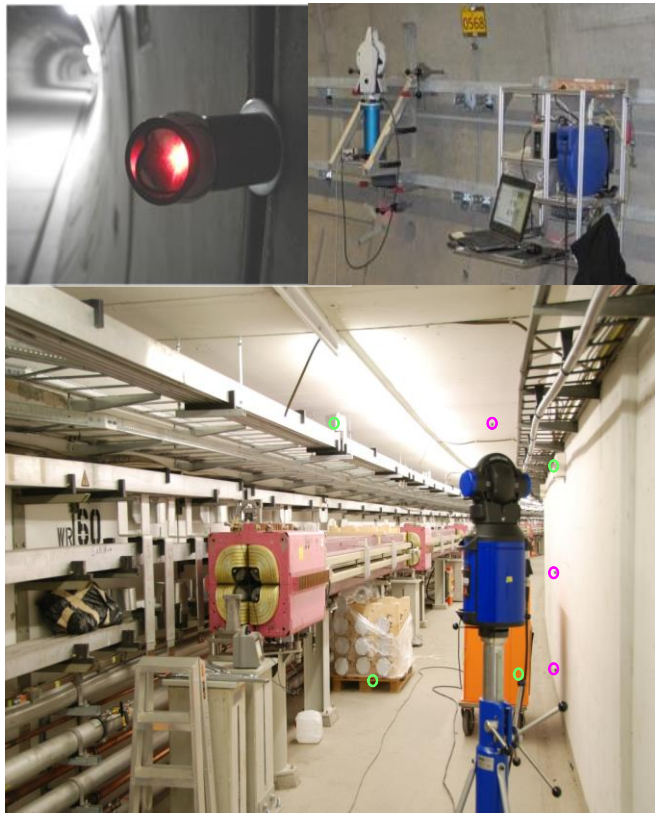
Barker, Prenting, Schloesser

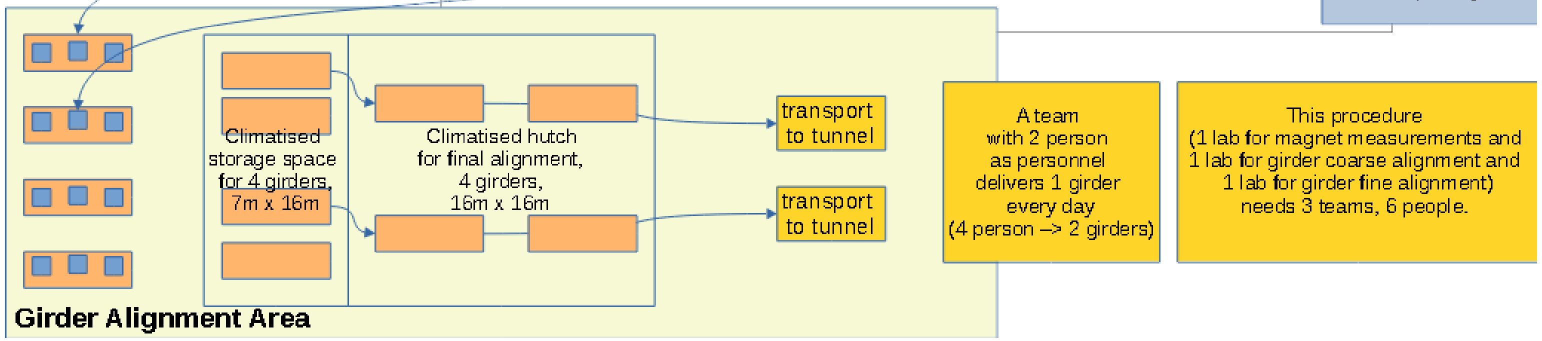
- Alignment in tunnel only possible with 100 µm precision
- Combining alignment with magnetic measurements in a temp. controlled environment



Referencing survey nests to magnetic axis







Vibrations: large orbit amplification factors

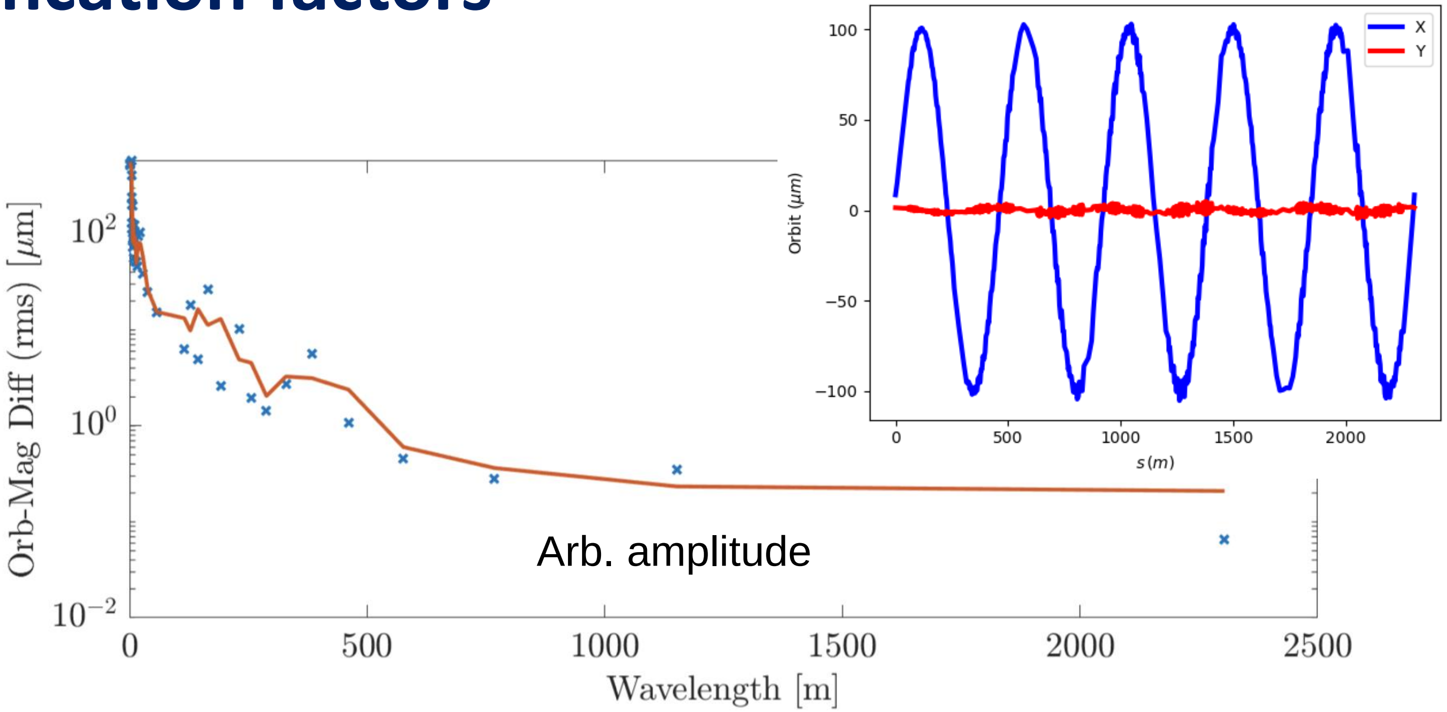
Uncorrelated amplification can be estimated analytically to good precision

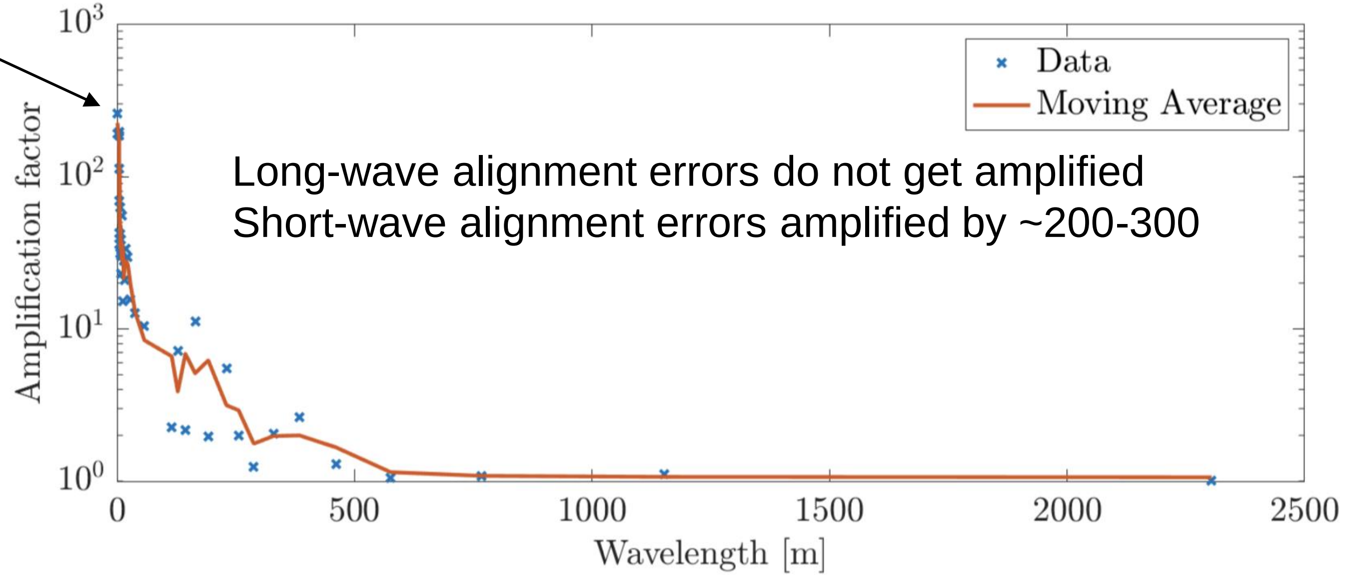
$$\Delta r_{beam,i} = \theta_j \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi Q} \cos(2\pi|\mu_i - \mu_j| - \pi Q).$$

$$\Delta r_{beam} \propto \langle \beta \rangle \sqrt{N_{mag}} \left(\frac{L_{mag} g}{3.33 E} \right) \Delta r_{sup}$$

large   large

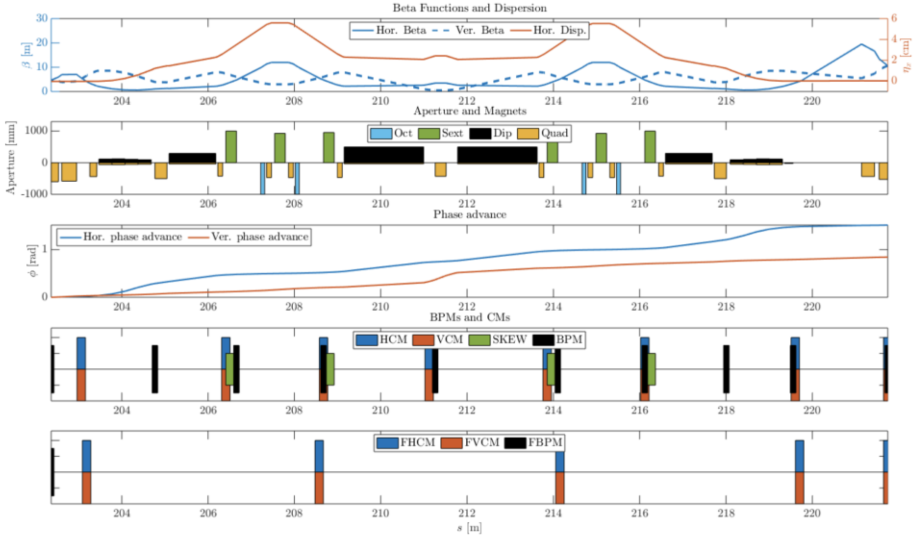
Hellert



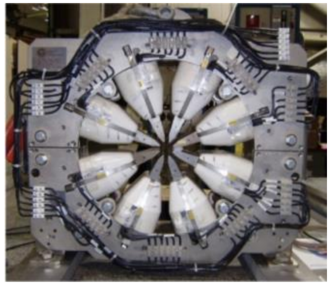


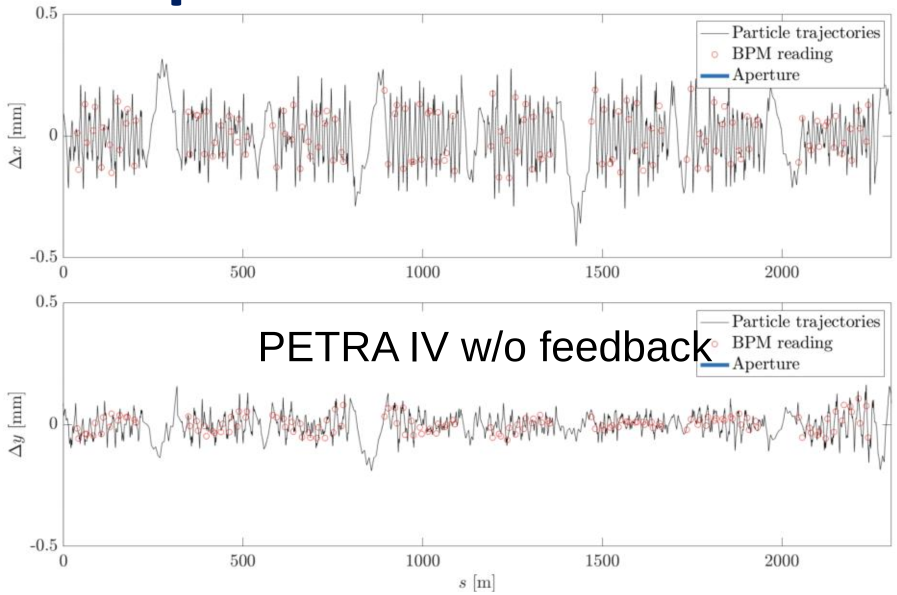
PETRA IV FOFB: necessary corrector strength depends on ambient noise

PETRA IV - fast and slow corrector layout

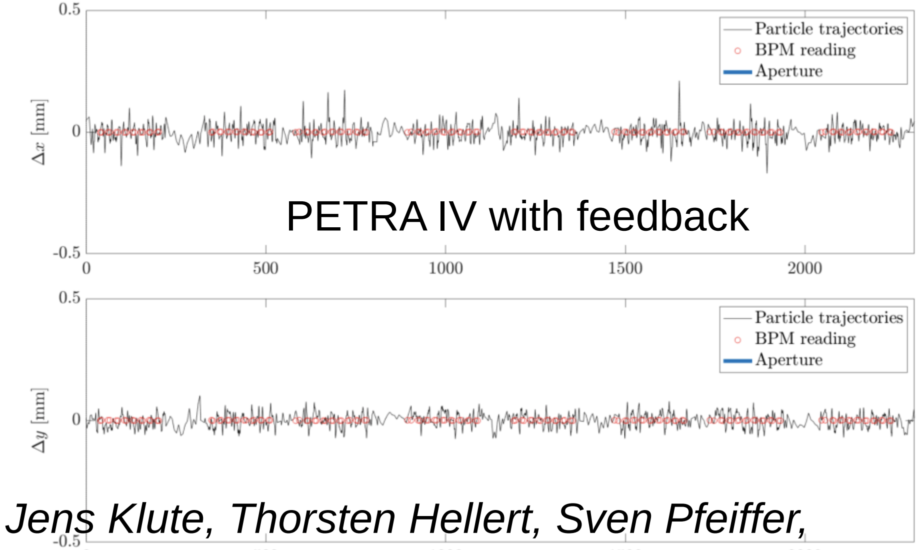


APS-U-type Combined AC/DC corrector



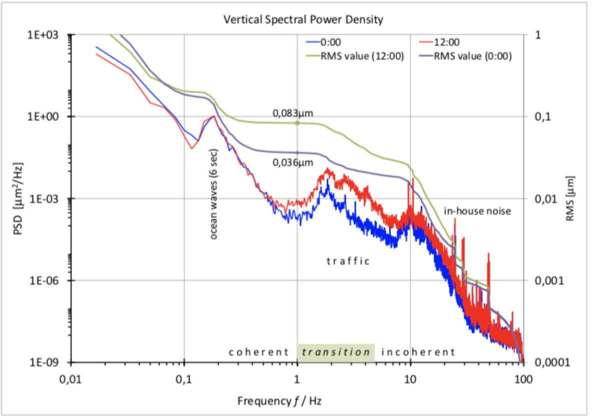


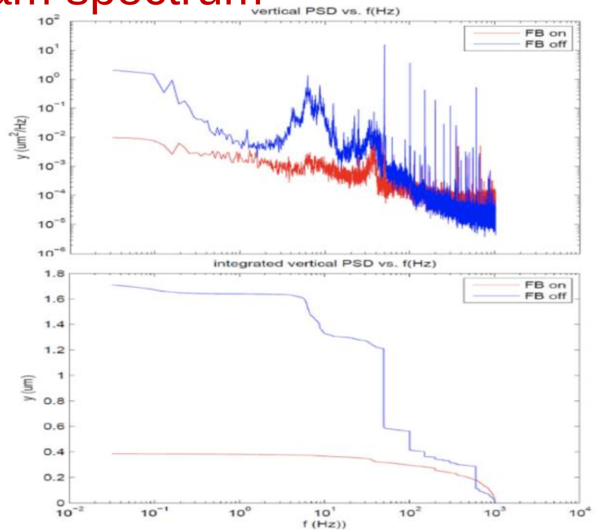
PETRA IV w/o feedback



PETRA IV with feedback

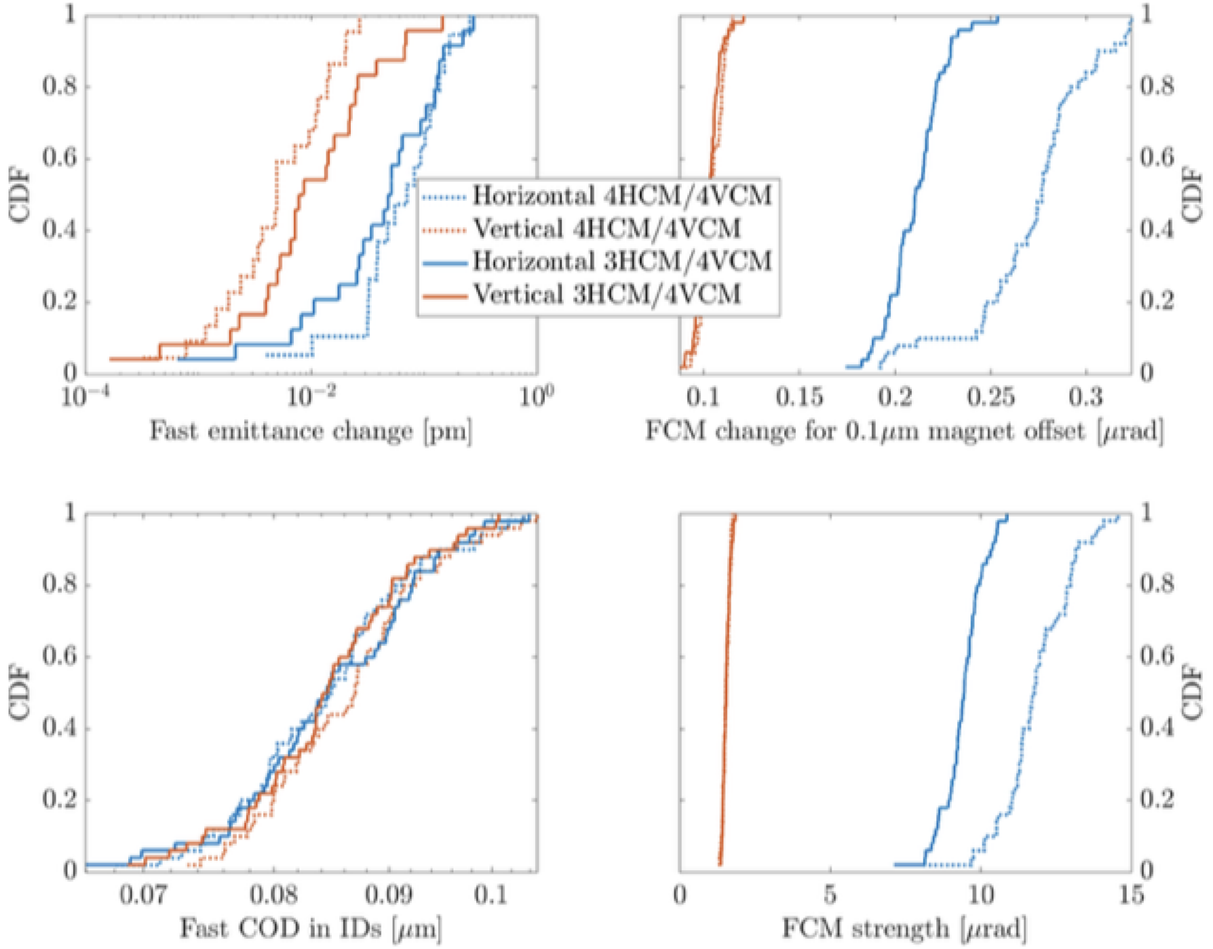
PETRA III - ground motion and beam spectrum

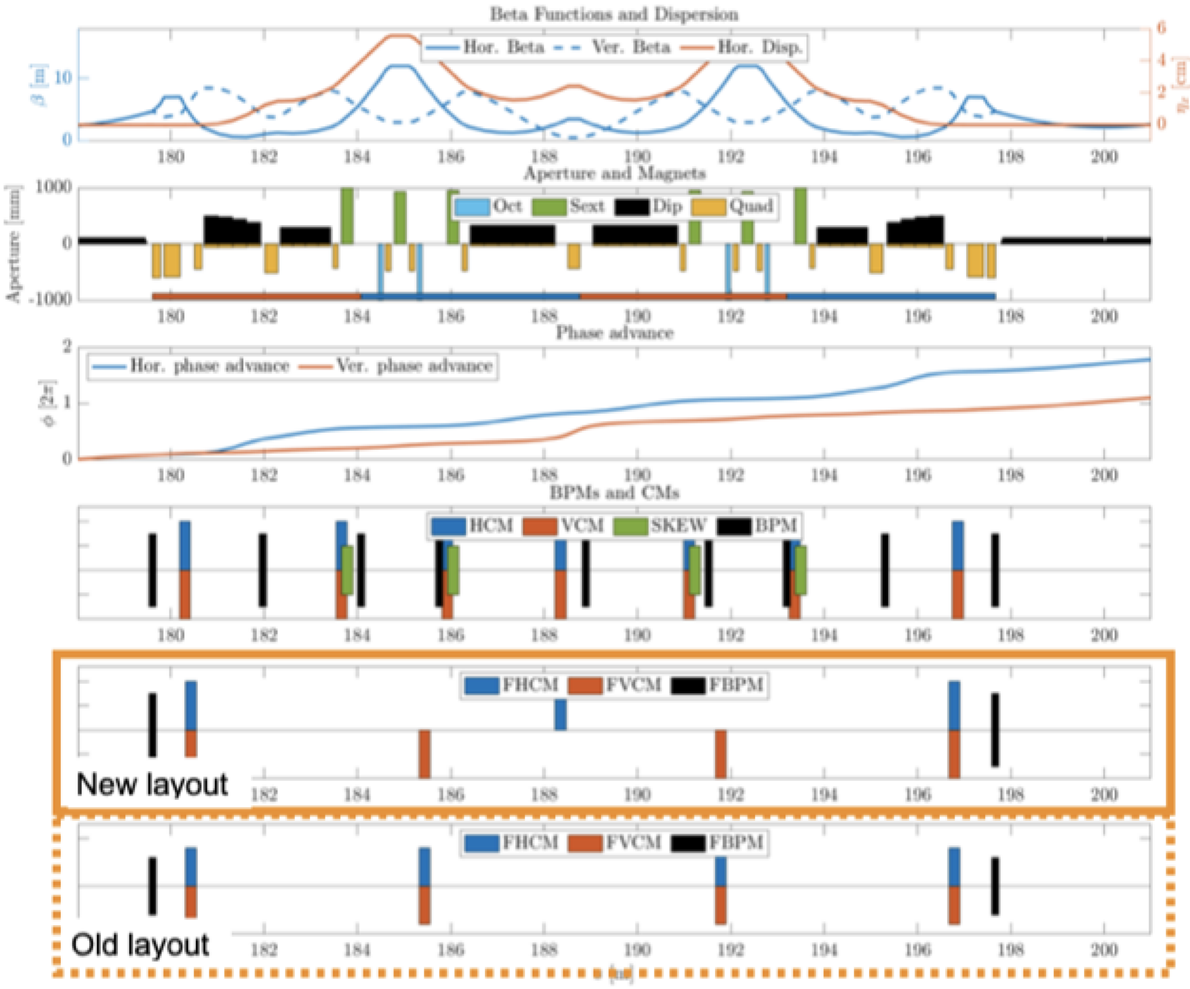




Jens Klute, Thorsten Hellert, Sven Pfeiffer, Sajjad Hussain Mirza, Annika Eichler, Holger Schlarb, Alexander Aloev

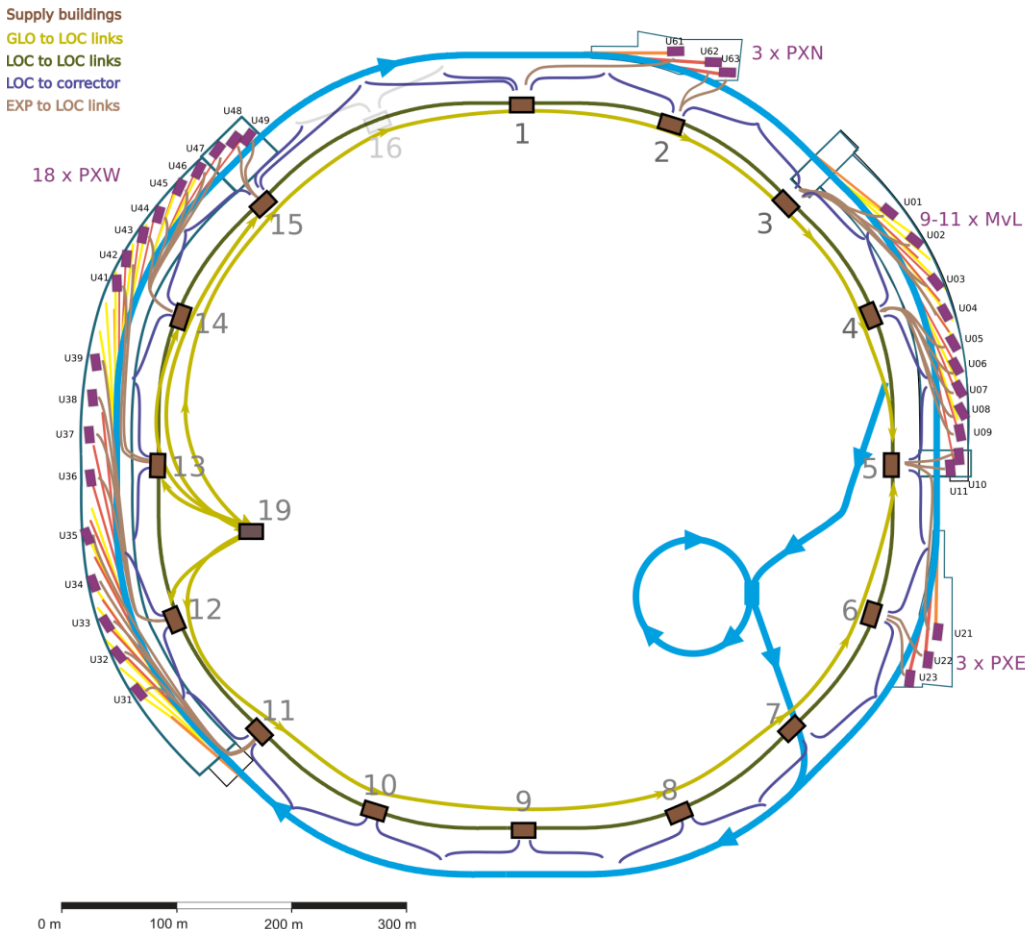
Revisiting the FOFB scheme based on corrector design

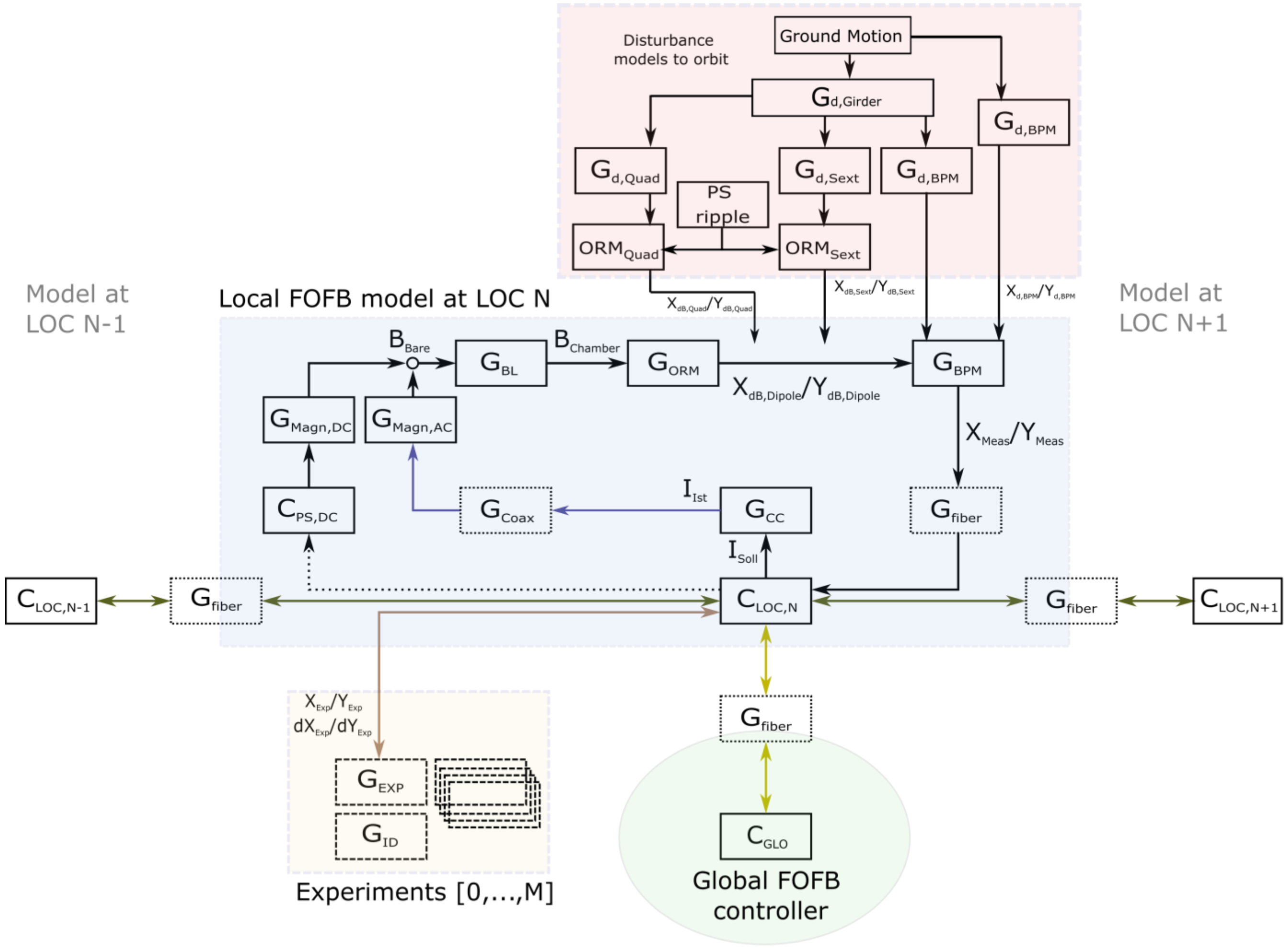




More detailed FOFB simulations and design underway

Sajjad Hussain Mirza, Sven Pfeiffer

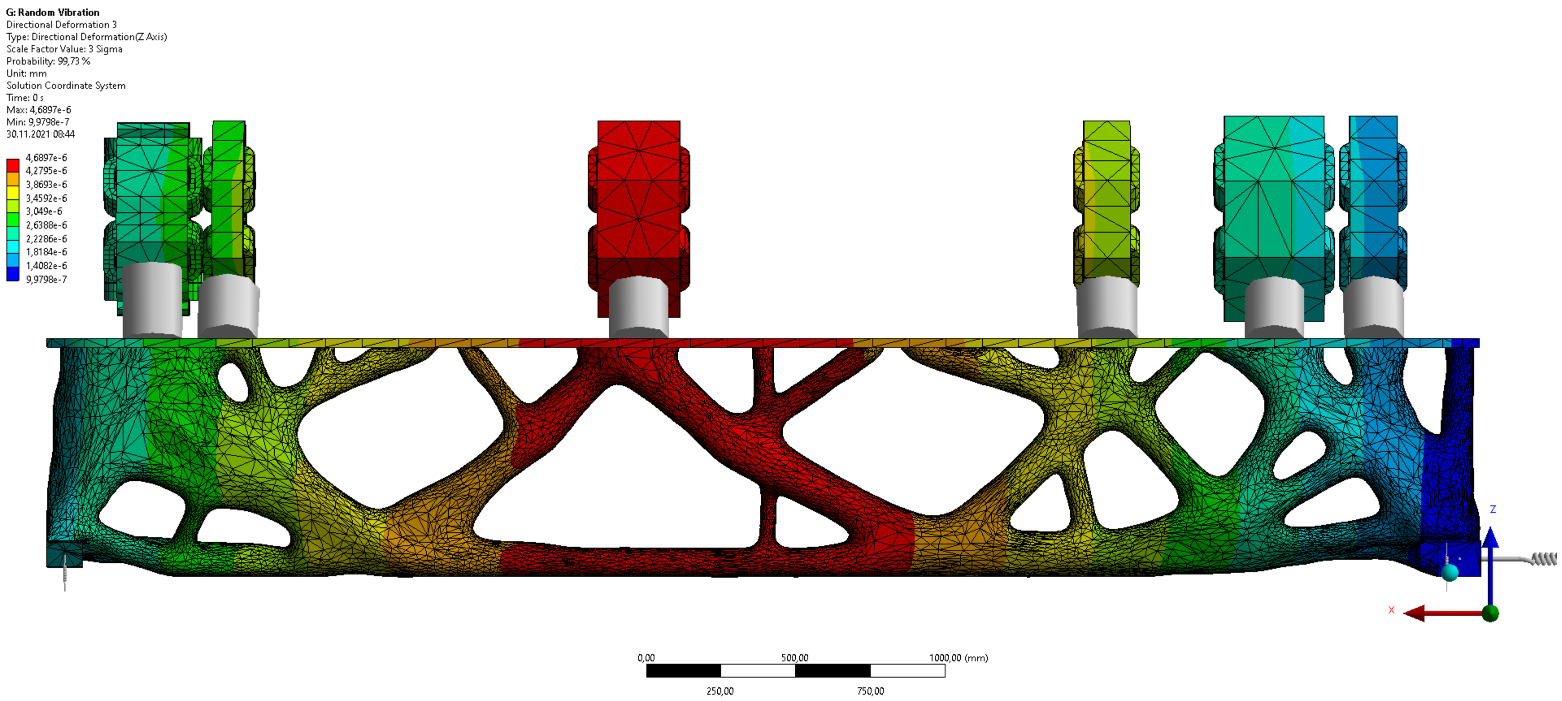




Remarks:
Communication blocks are shared/distributed.
Disturbance models by girder movements.
Local disturbances not added here.

Girder Design is optimized for stability

- R&D on topologically optimized girder performed during the CDR phase
- Mode analysis on preliminary design of a topologically optimized girder performed, sub-10 nm amplitude due to ground motion
- Traditional welded design also in place

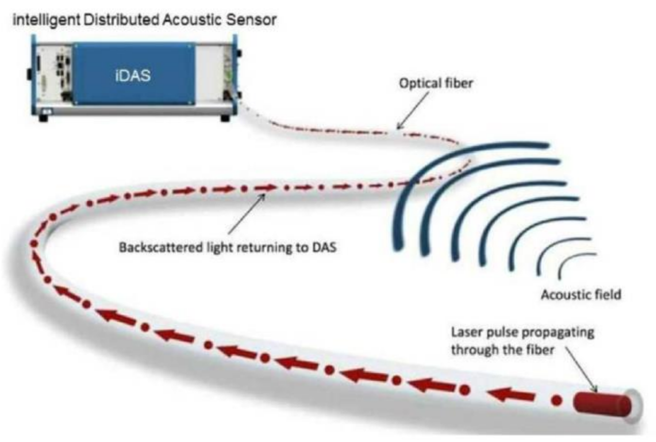


Prize for her work within the collaborative project on the influence of bio-inspired structures on the vibrational properties and the development of the **girder structure for PETRA IV**.

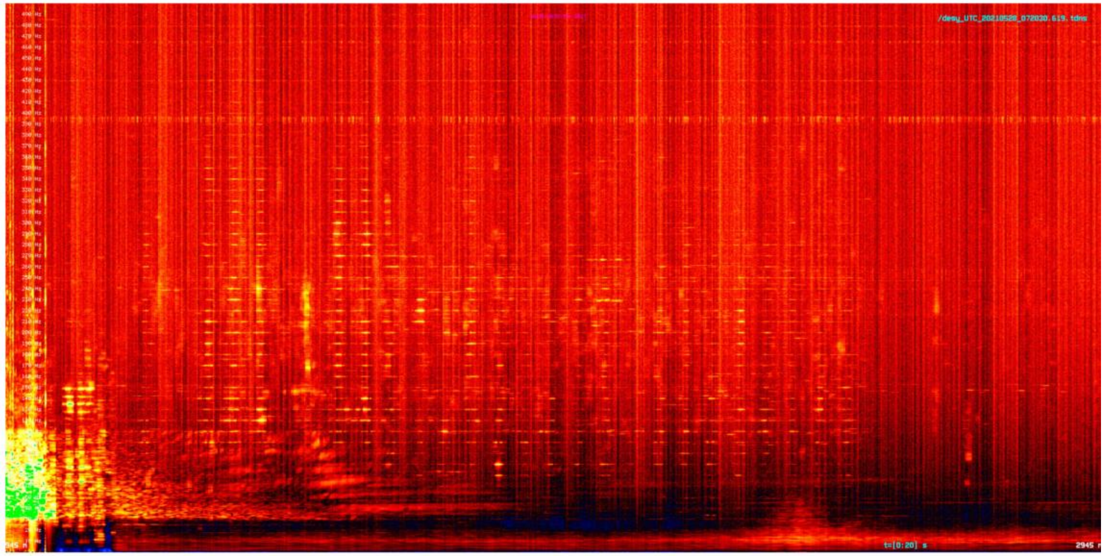
	Simulation	Measurement
f_1	119.6 Hz	116.6 Hz
f_2	189.8 Hz	199.7 Hz
f_3	236.8 Hz	238.7 Hz
f_4	257.1 Hz	250.2 Hz
f_5	290.4 Hz	292.5 Hz

Normann Koldrack, Simone Andresen

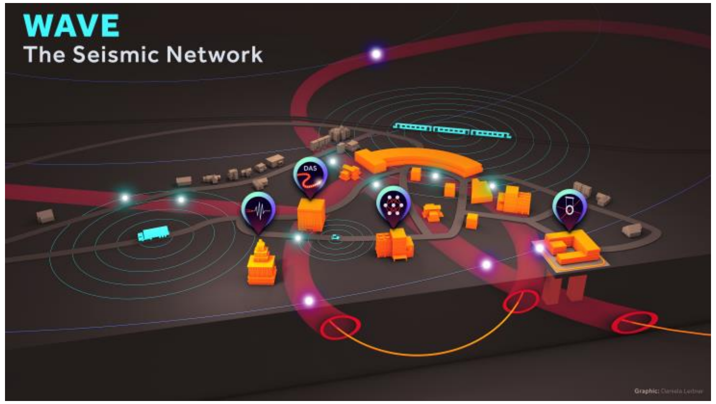
Optical Fiber network being set up for vibration monitoring

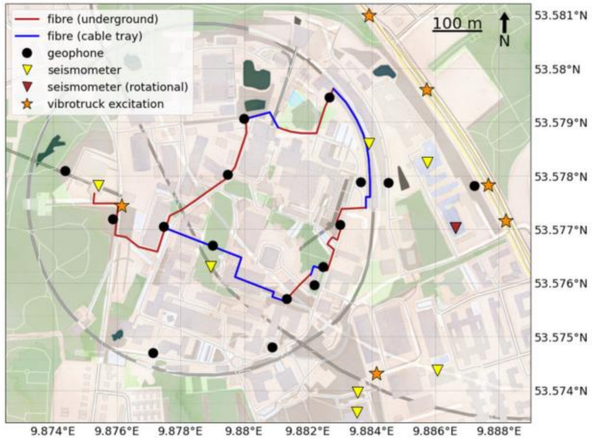


Freq. (Hz)



XFEL tunnel length (m)





Hoffmann, Meyners, Schlarb

http://wave-hamburg.eu

Workshop on May 13 2022
https://indico.desy.de/event/34125/

Conclusion and outlook

- Lattice design for PETRA IV in place, engineering integration ongoing and TDR nearing completion
- Commissioning simulations demonstrate feasibility of machine operation given a number of stability challenges
- Alignment, logistics and operation concept in place for stab le machine operation