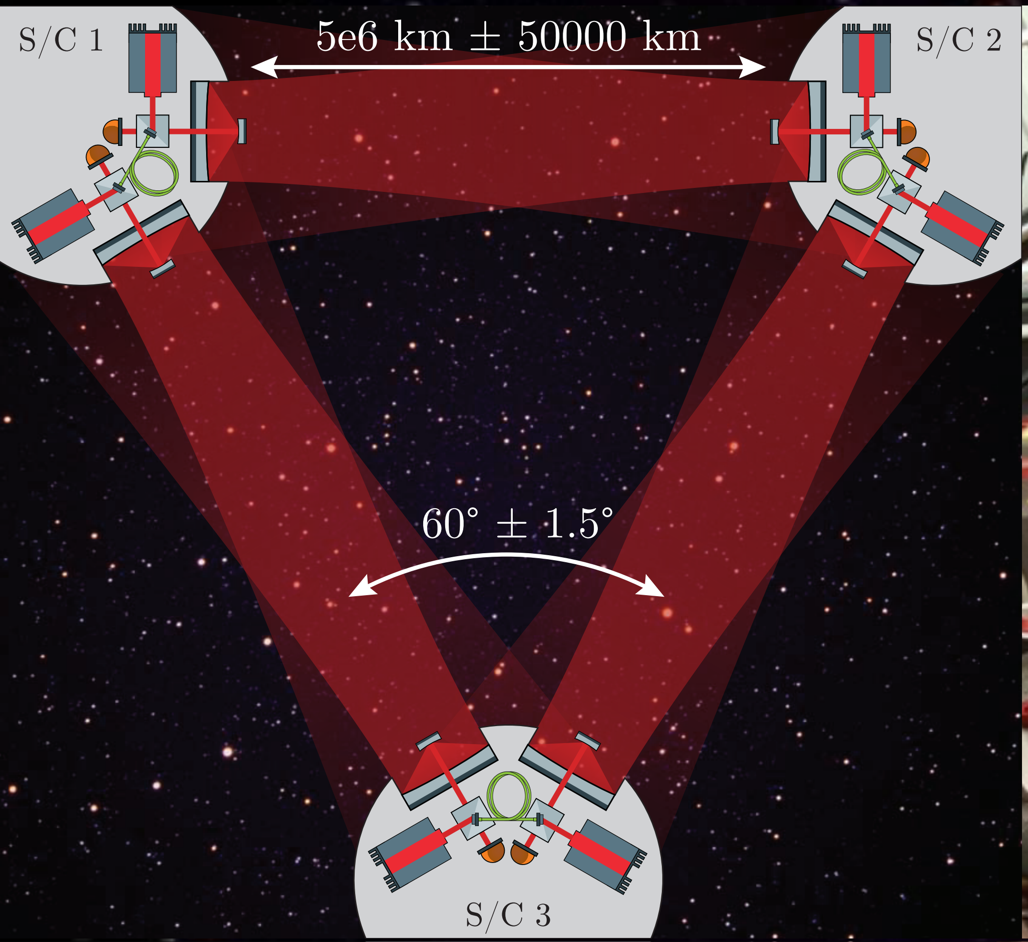
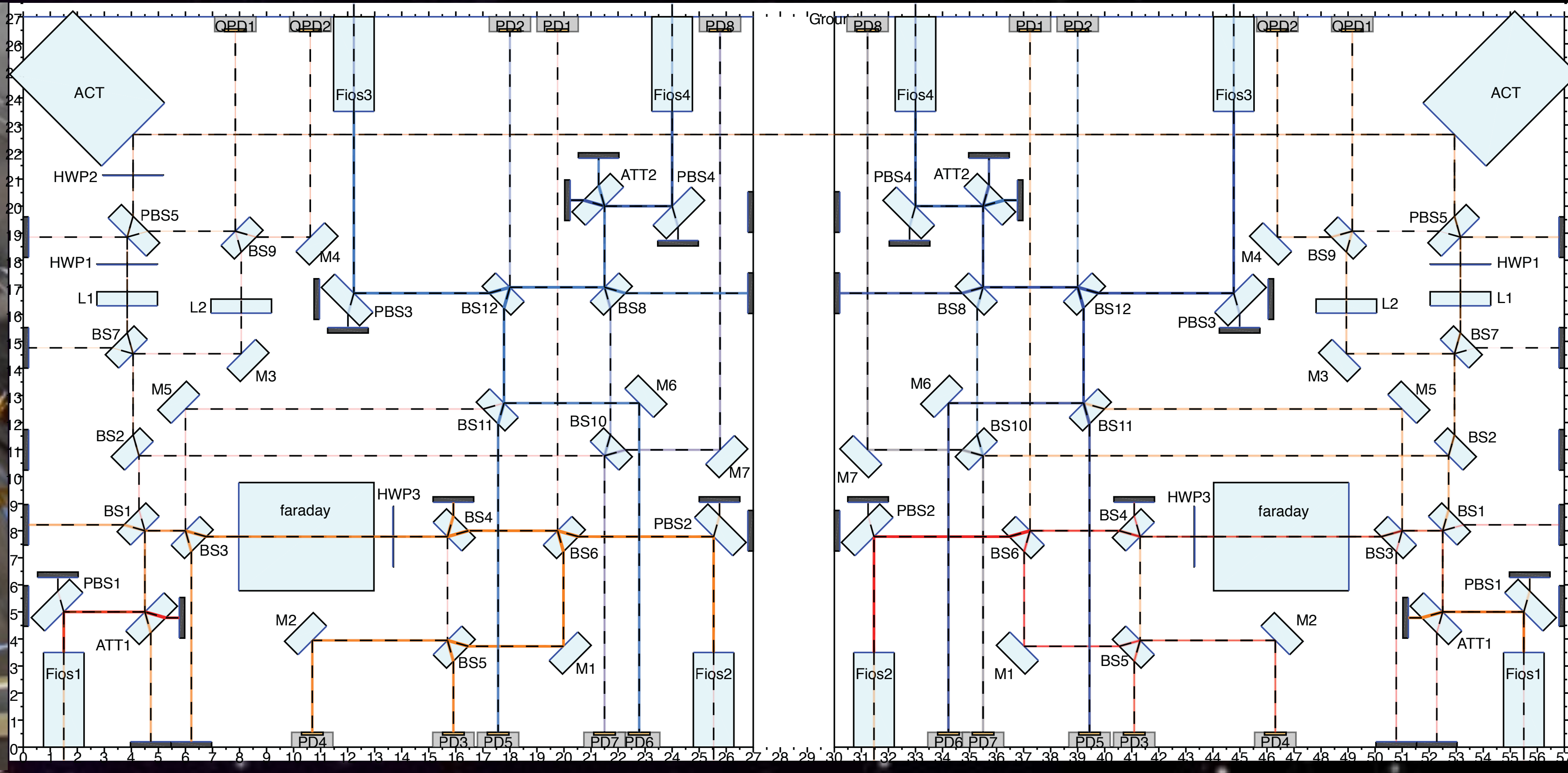




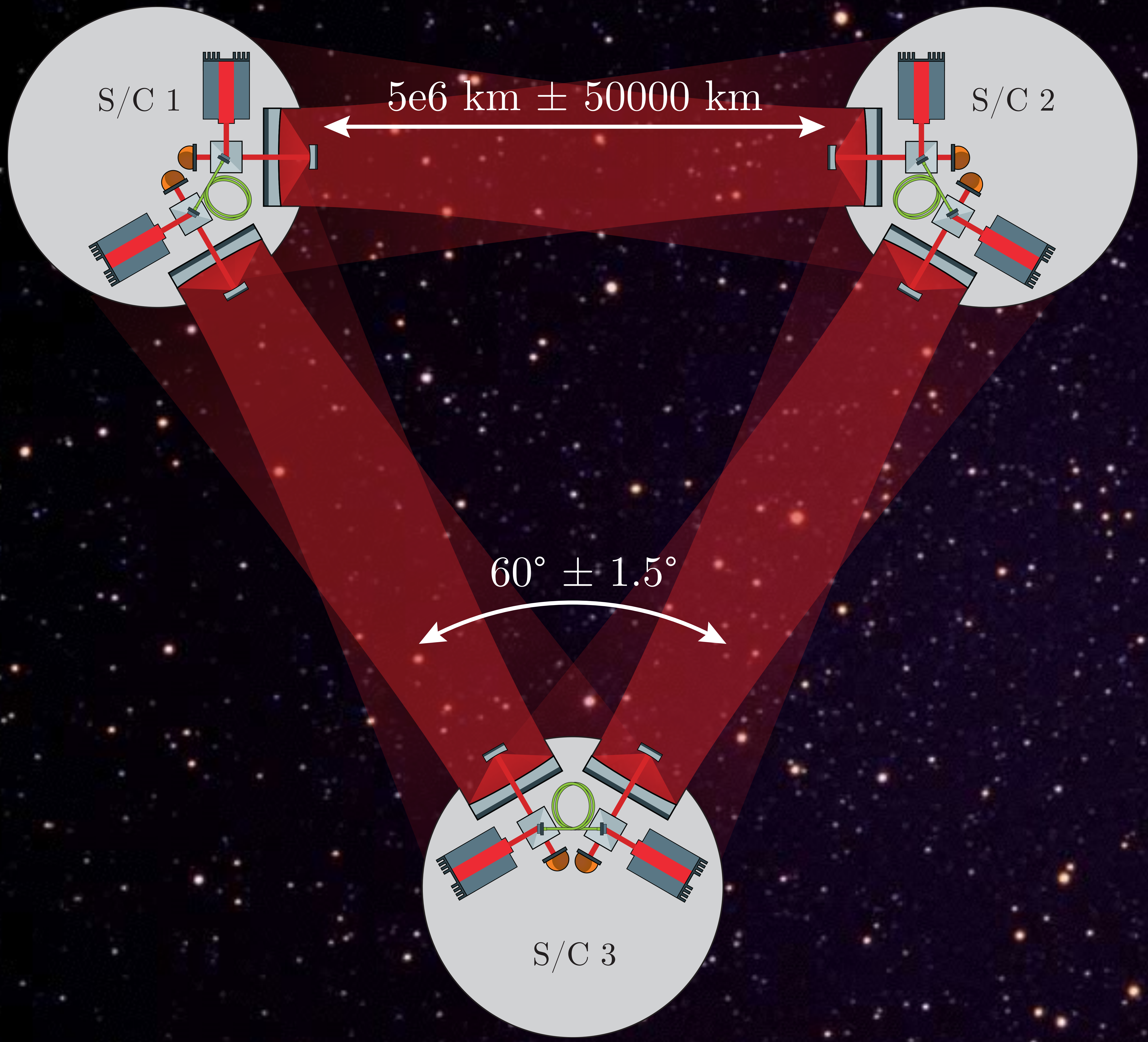


The LISA backlink

Comparing optical phase reference systems

Katharina-Sophie Isleif &
O. Gerberding, L. Bischof, S. Ast, M. Tröbs, M. Winter, M. Zimmermann,
J. Reiche, G. Heinzel, K. Danzmann

Institute for Gravitational Physics, Albert Einstein Institute, Leibniz Universität Hannover and Max Planck Institute for Gravitational Physics



- **two moving optical sub-assemblies** to compensate angular variations

  ➡ two **moving** optical benches per S/C

- **Time Delay Interferometry (TDI)** to compensate arm length differences

  ➡ optical phase reference between the two local lasers (the **backlink**)

$$10^{-20}/\sqrt{\text{Hz}}$$

- **two moving optical sub-assemblies** to compensate angular variations

  ➡ two **moving** optical benches per S/C

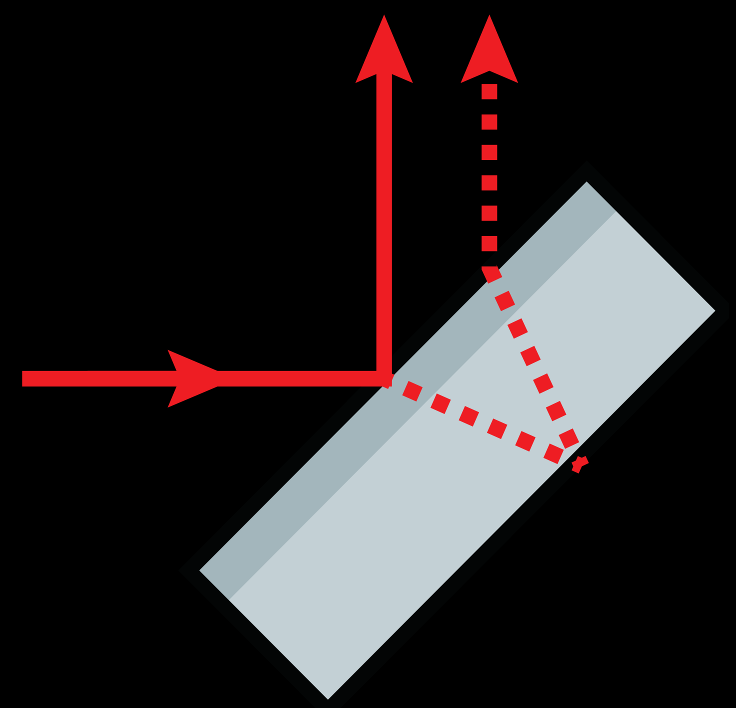
- **Time Delay Interferometry (TDI)** to compensate arm length differences

  ➡ optical phase reference between the two local lasers (the **backlink**)

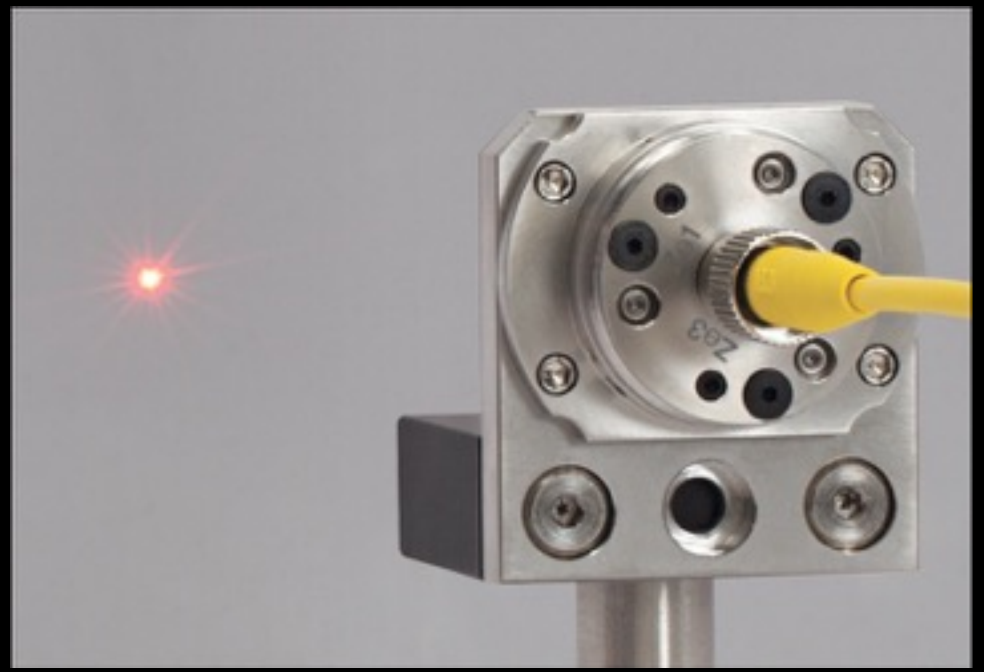
$$10^{-20}/\sqrt{\mathrm{Hz}}$$

Results from the classic Fiber BL

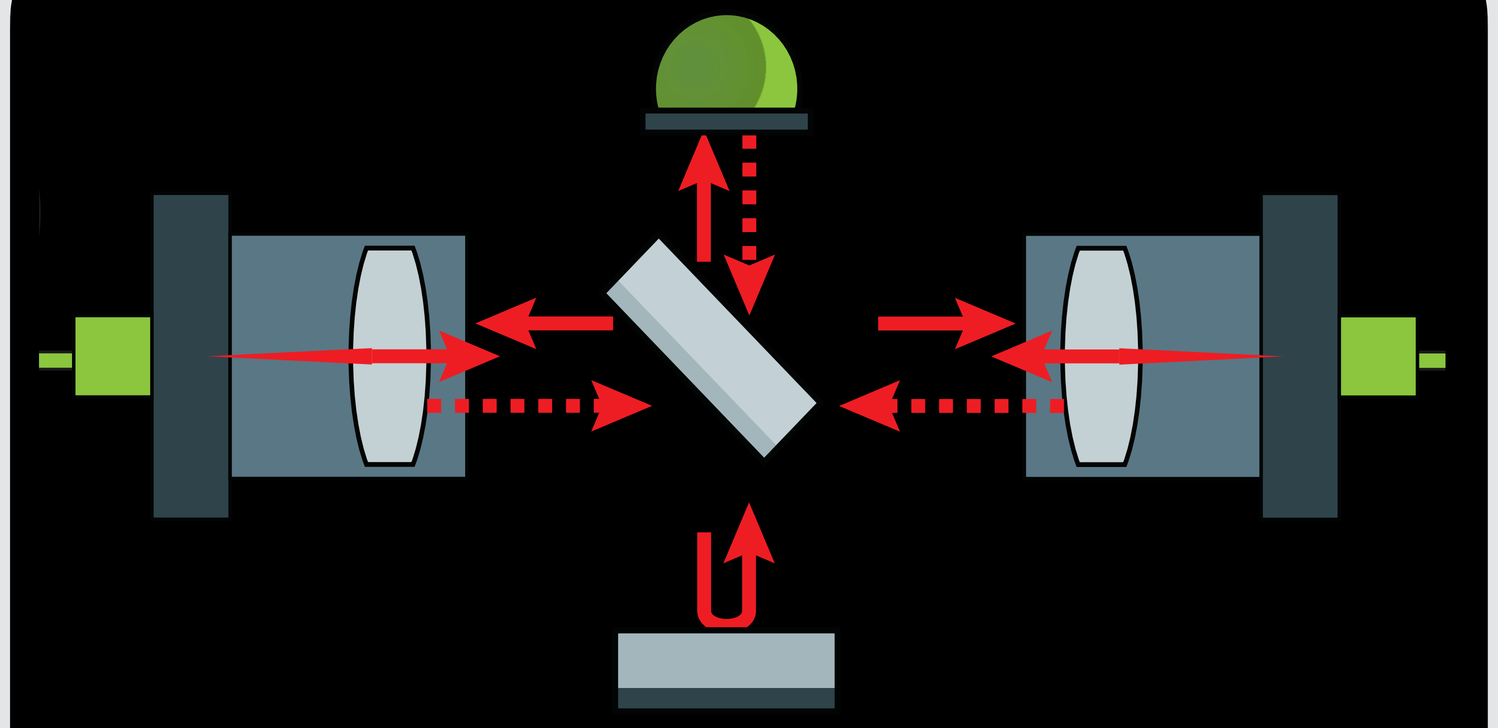
- Origin of stray light:



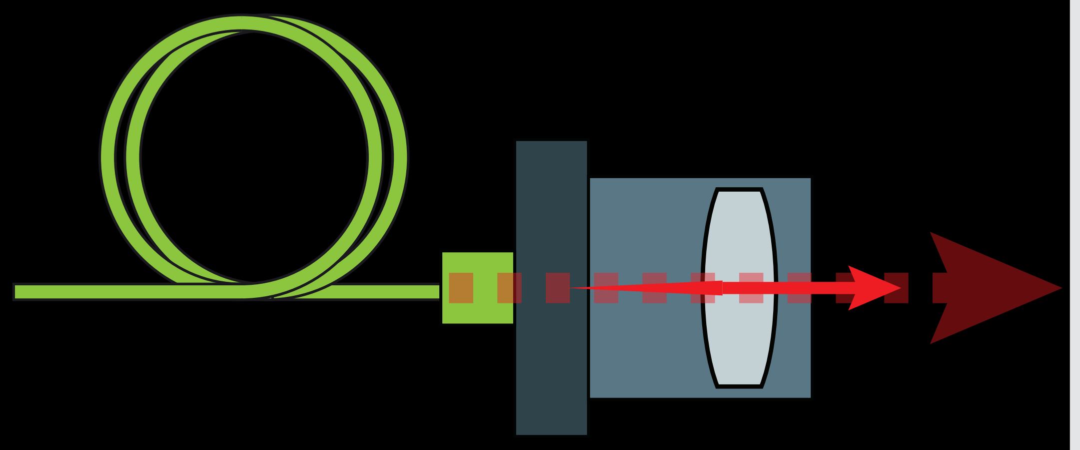
2nd BS and mirror surface (AR)



higher order modes & non-clean polarization

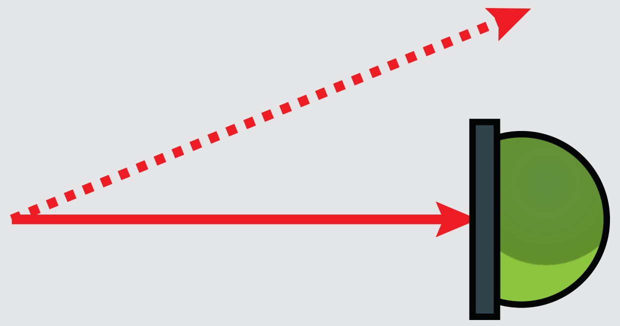


reflection at fiber collimator & at photodiodes/lenses

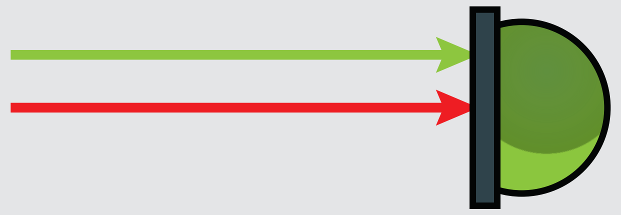


Rayleigh scattering in fiber

- Relevant for pm precision interferometry if...
  - ...the stray light enters the photodiode

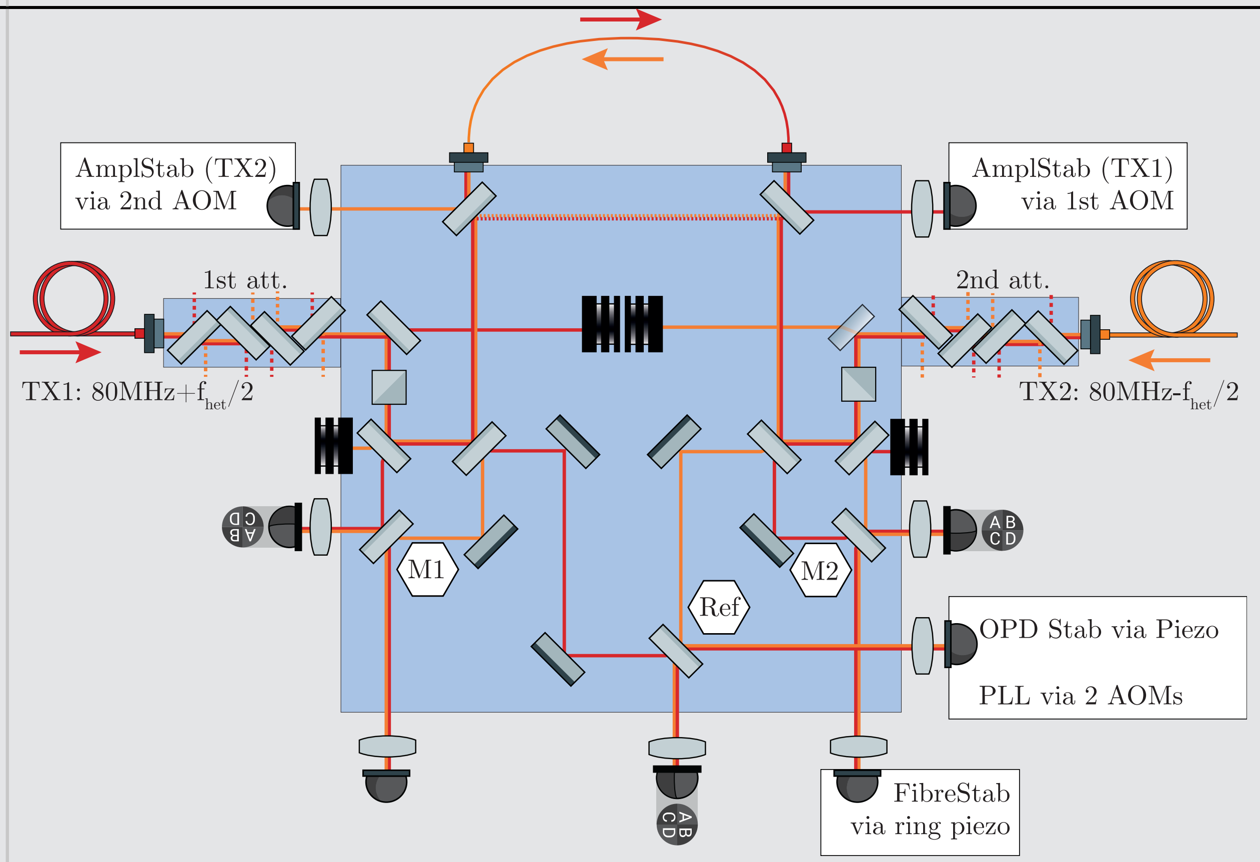


  - ...it interferes with one of the beams at the frequency that is monitored

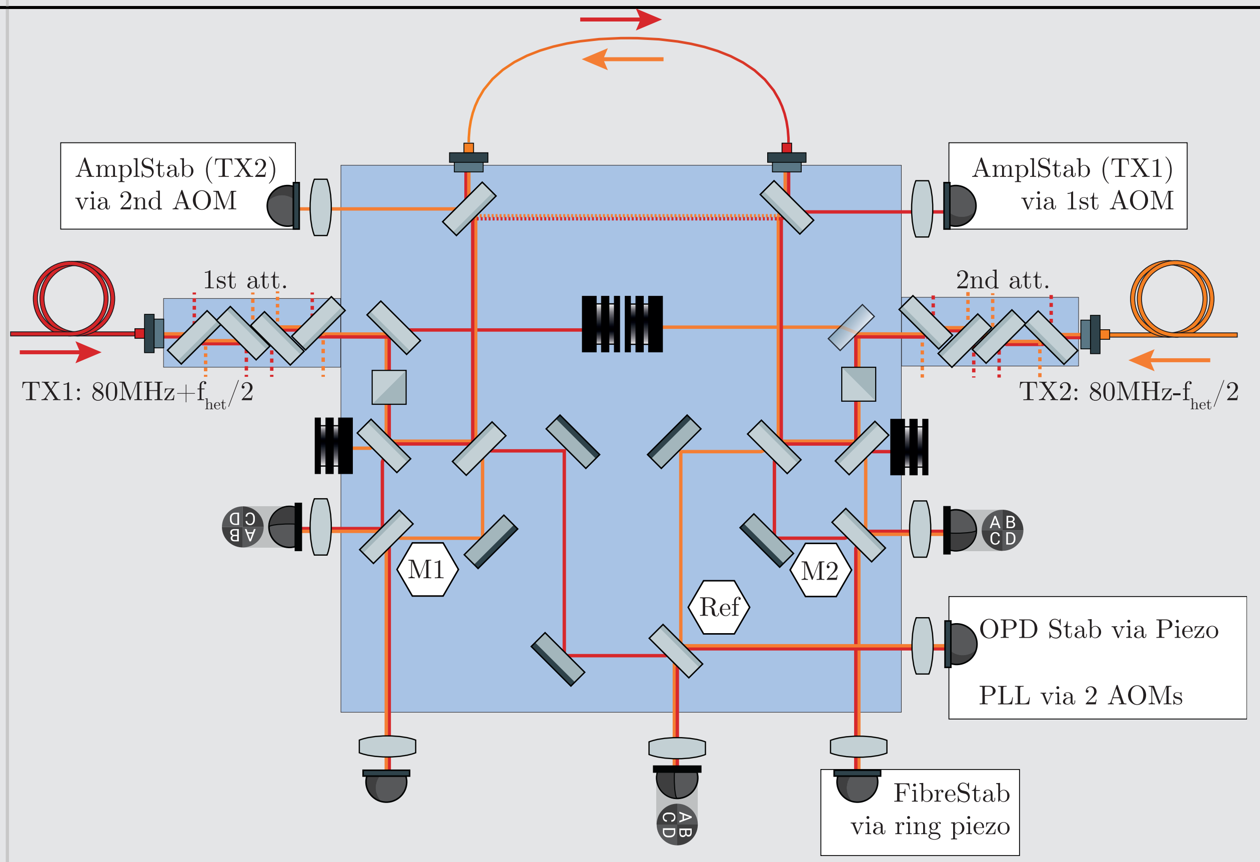


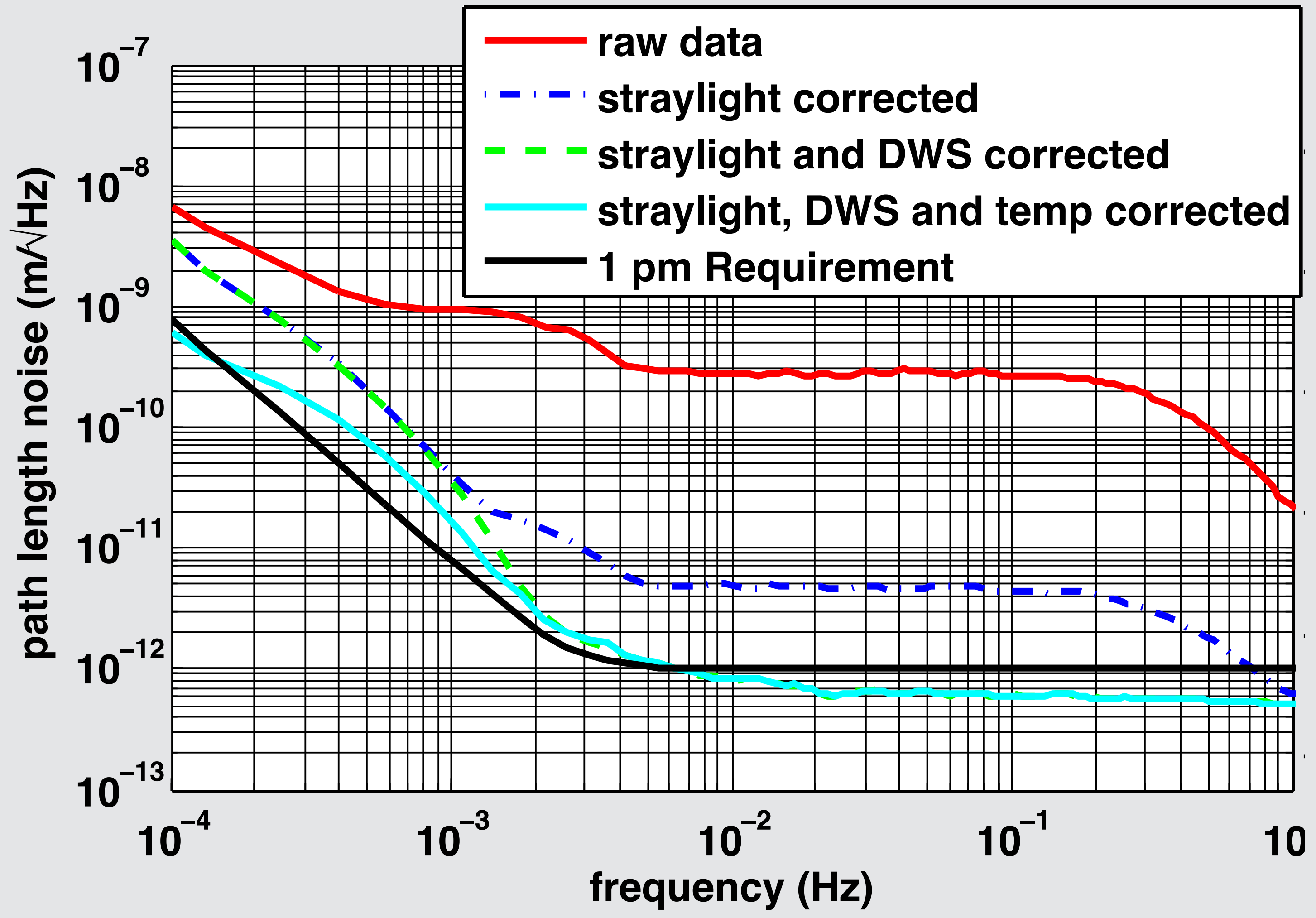
  - ...the stray light amplitude is larger than 10^{-12} of the nominal signal amplitude

The journey to a LISA customized BL

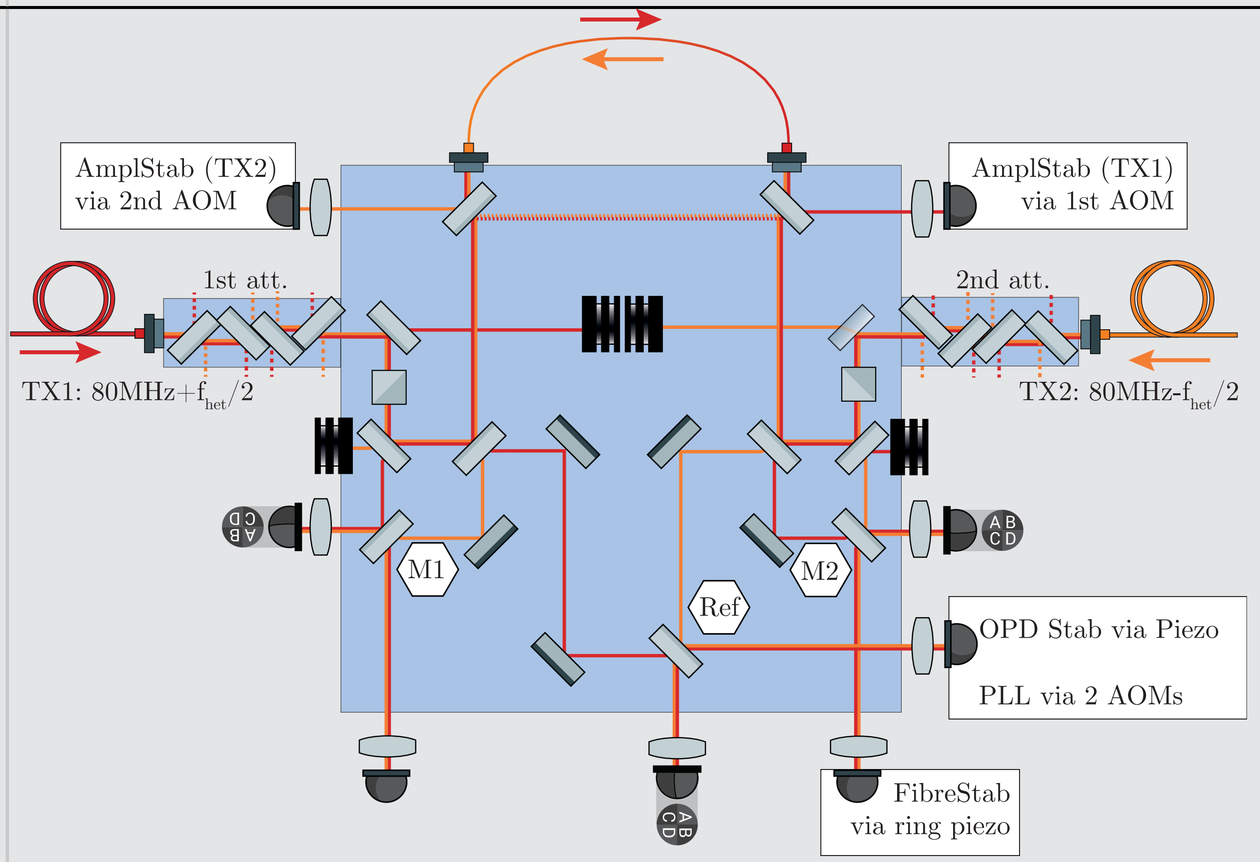
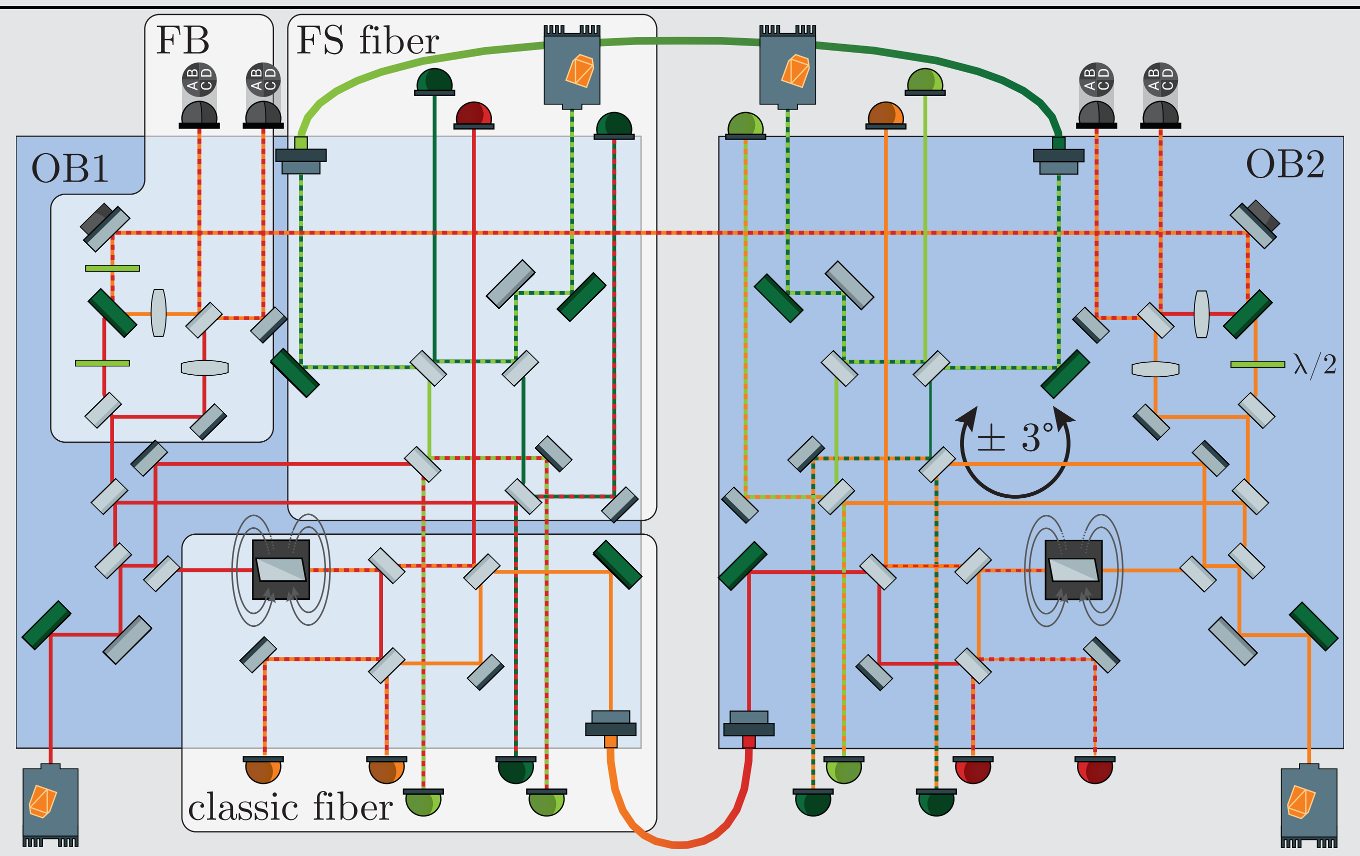
noise	classic fiber Backlink (BL)
set-up	
stray light	balanced detection
	drastic power attenuation
	fiber length stabilization
	-
beam jitter	DWS correction
AOM crosstalk	OPD stabilisation
	fiber length stabilization
temperature fluctuations	operation in vacuum
	data post correction

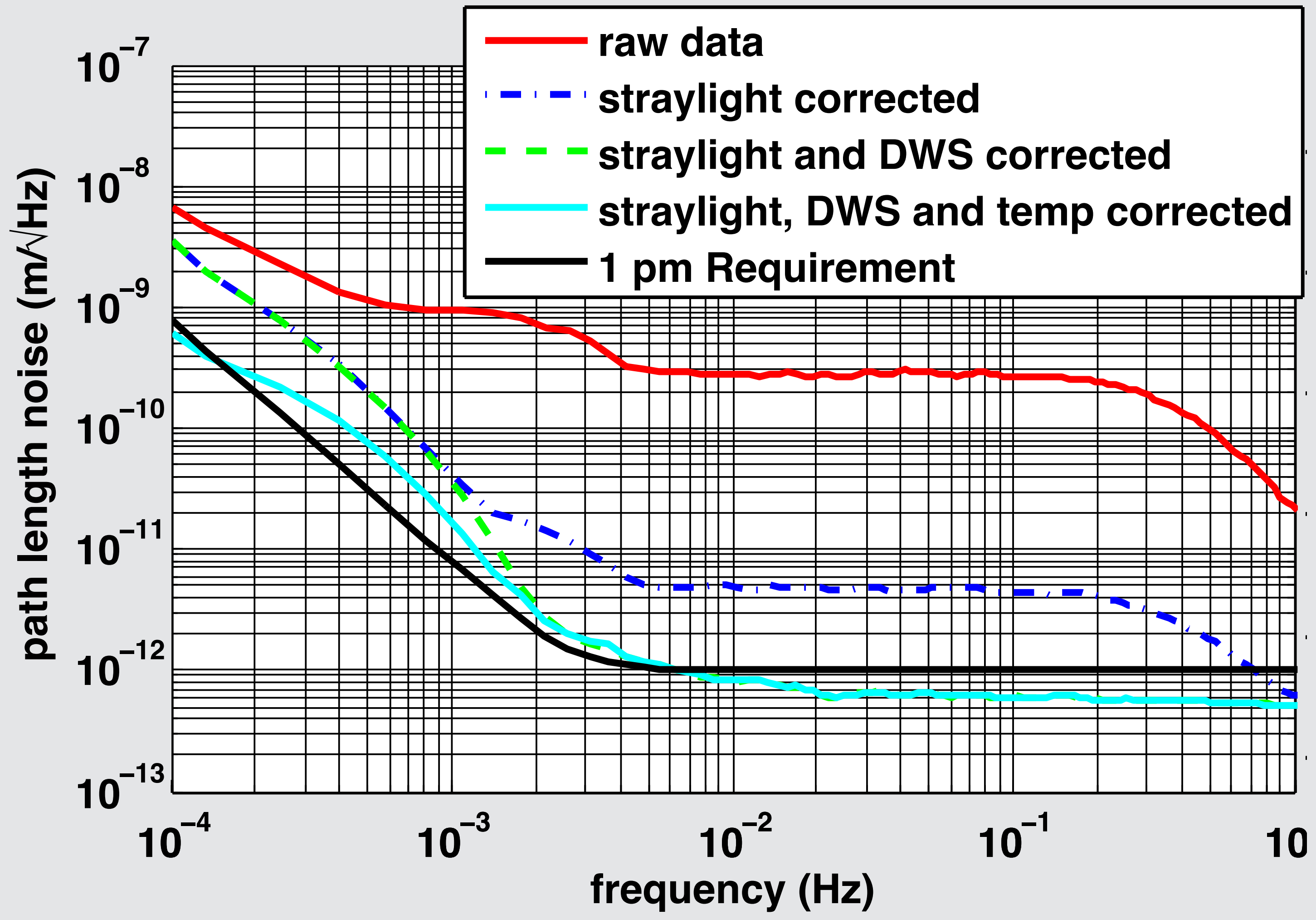
The journey to a LISA customized BL

noise	classic fiber Backlink (BL)
set-up	
stray light	balanced detection
	drastic power attenuation
	fiber length stabilization
	-
beam jitter	DWS correction
AOM crosstalk	OPD stabilisation
	fiber length stabilization
temperature fluctuations	operation in vacuum
	data post correction

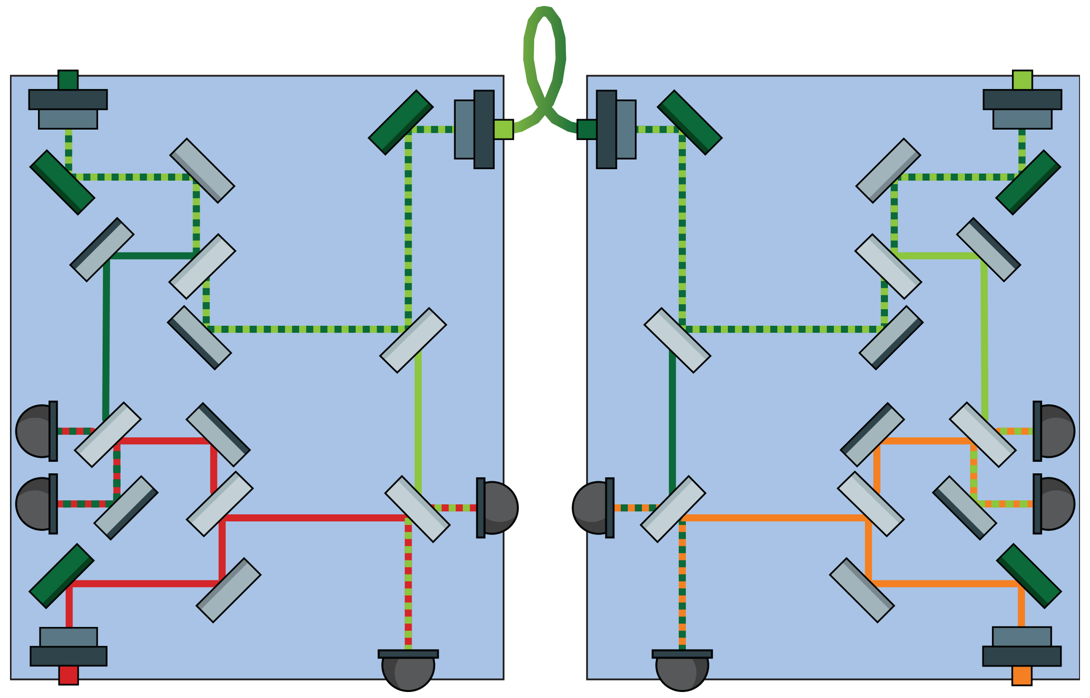


The journey to a LISA customized BL

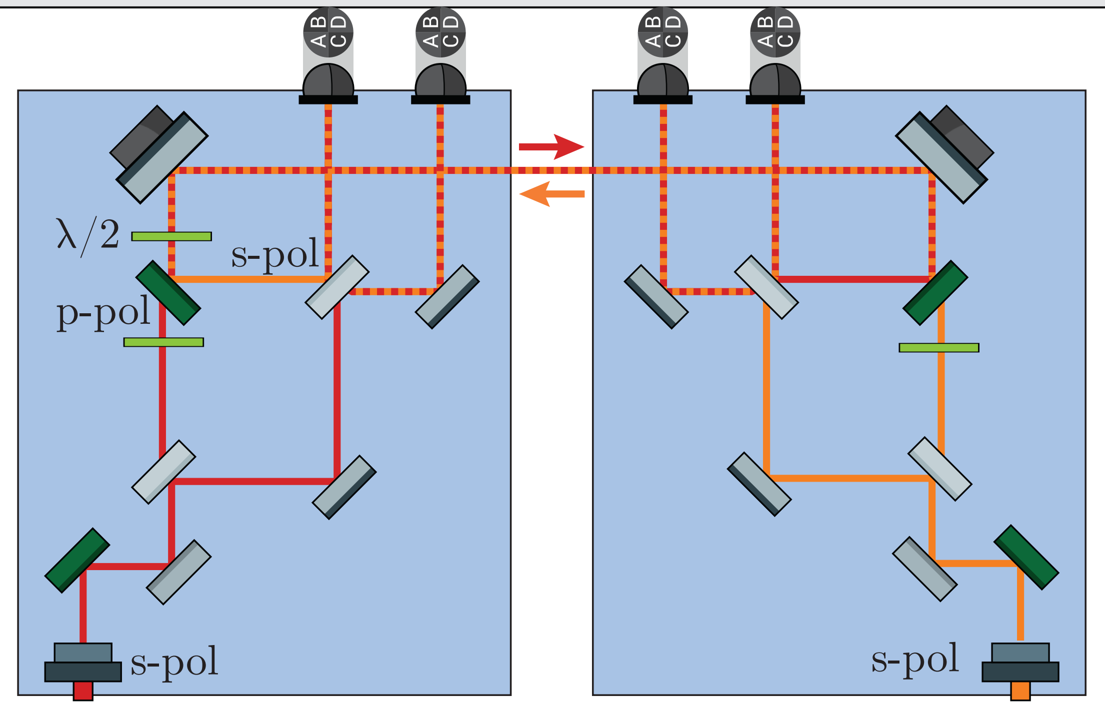
noise	classic fiber Backlink (BL)	Three Backlink (3 BL)
set-up		
stray light	balanced detection	AOMs (optional)
	drastic power attenuation	5/95 beamsplitter
	fiber length stabilization	polarising optics (opt.)
	-	Faraday isolator (opt.)
beam jitter	DWS correction	stable FIOS
AOM crosstalk	OPD stabilisation	-
	fiber length stabilization	
temperature fluctuations	operation in vacuum	
	data post correction	



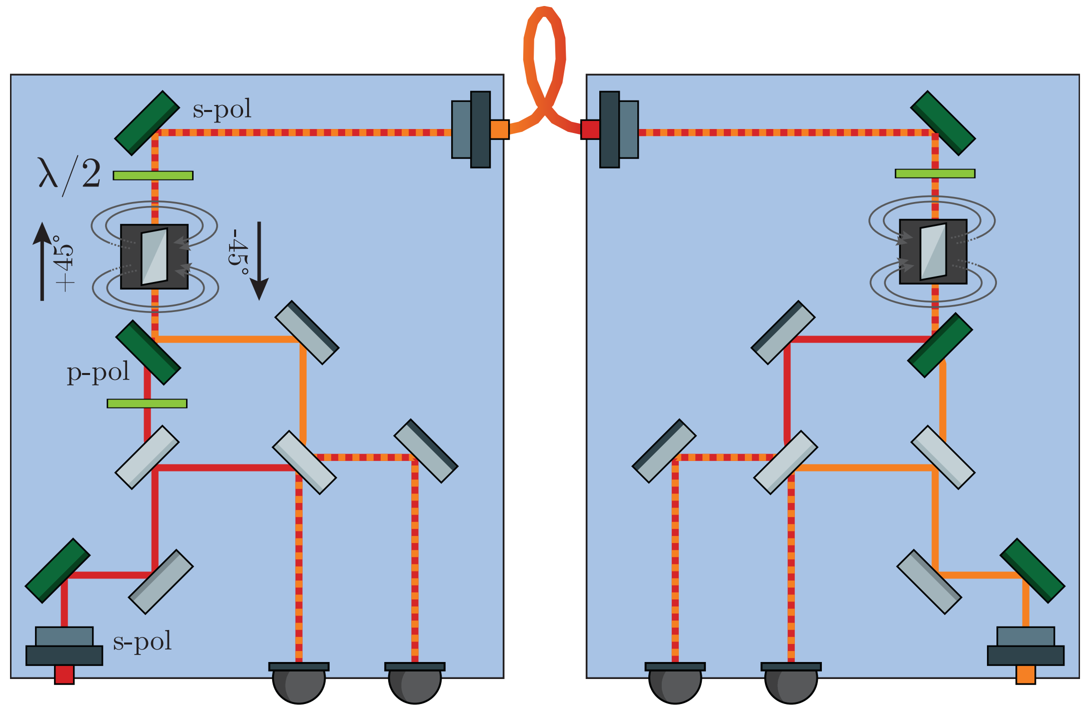
The Three Backlink Experiment Design



Freq. sep. Fiber BL
2 additional lasers
attenuation BS

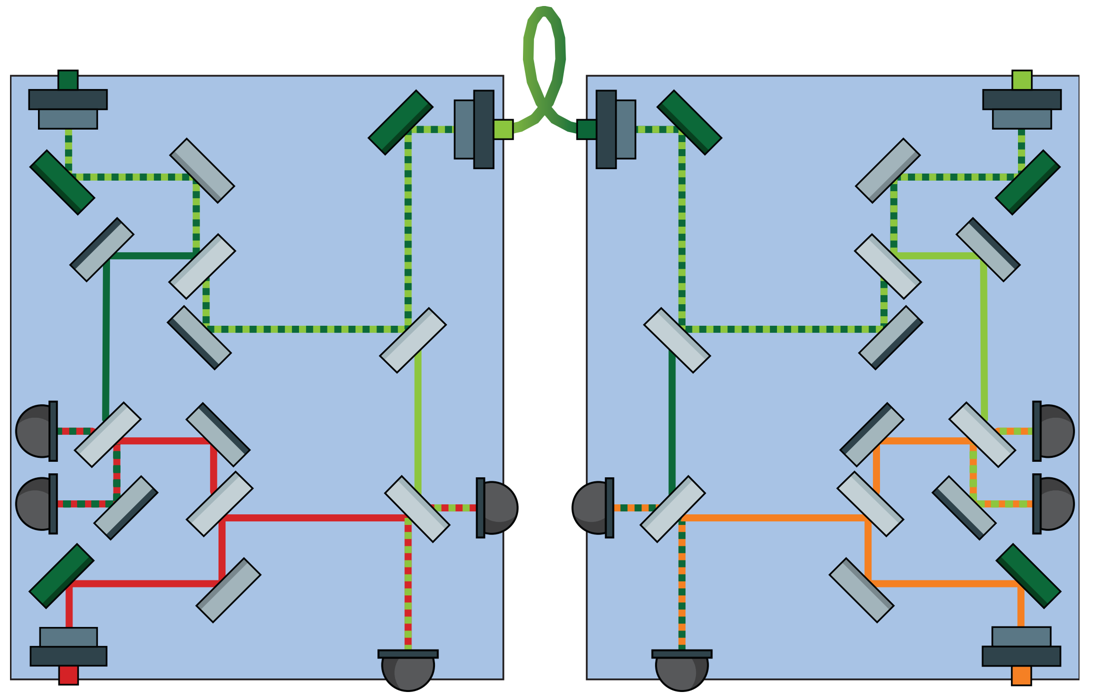


Free Beam BL
act. mirror
imaging optics
polarizing optics

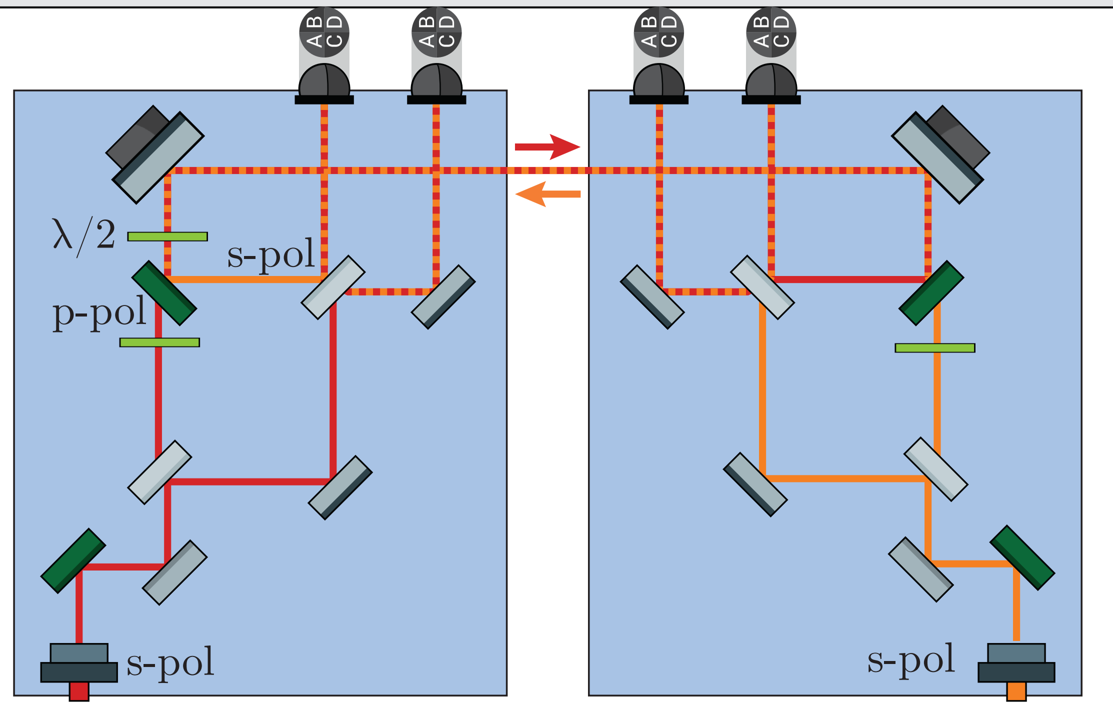


Classic Fiber BL
Faraday isolator
attenuation BS
polarizing optics

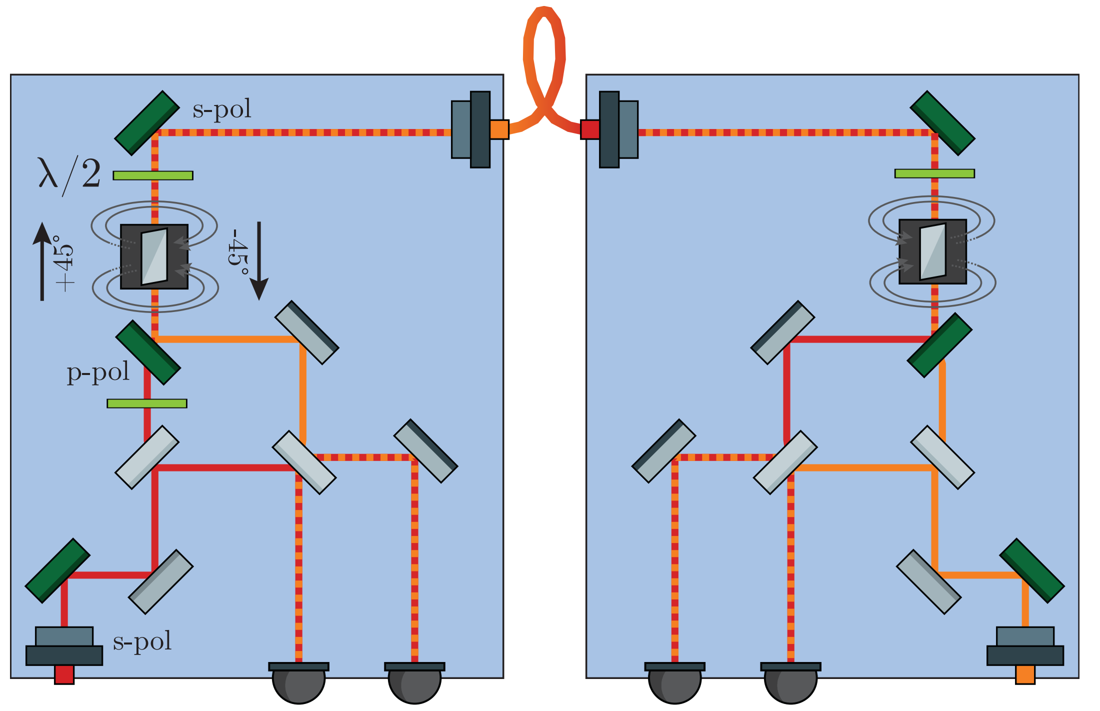
The Three Backlink Experiment Design



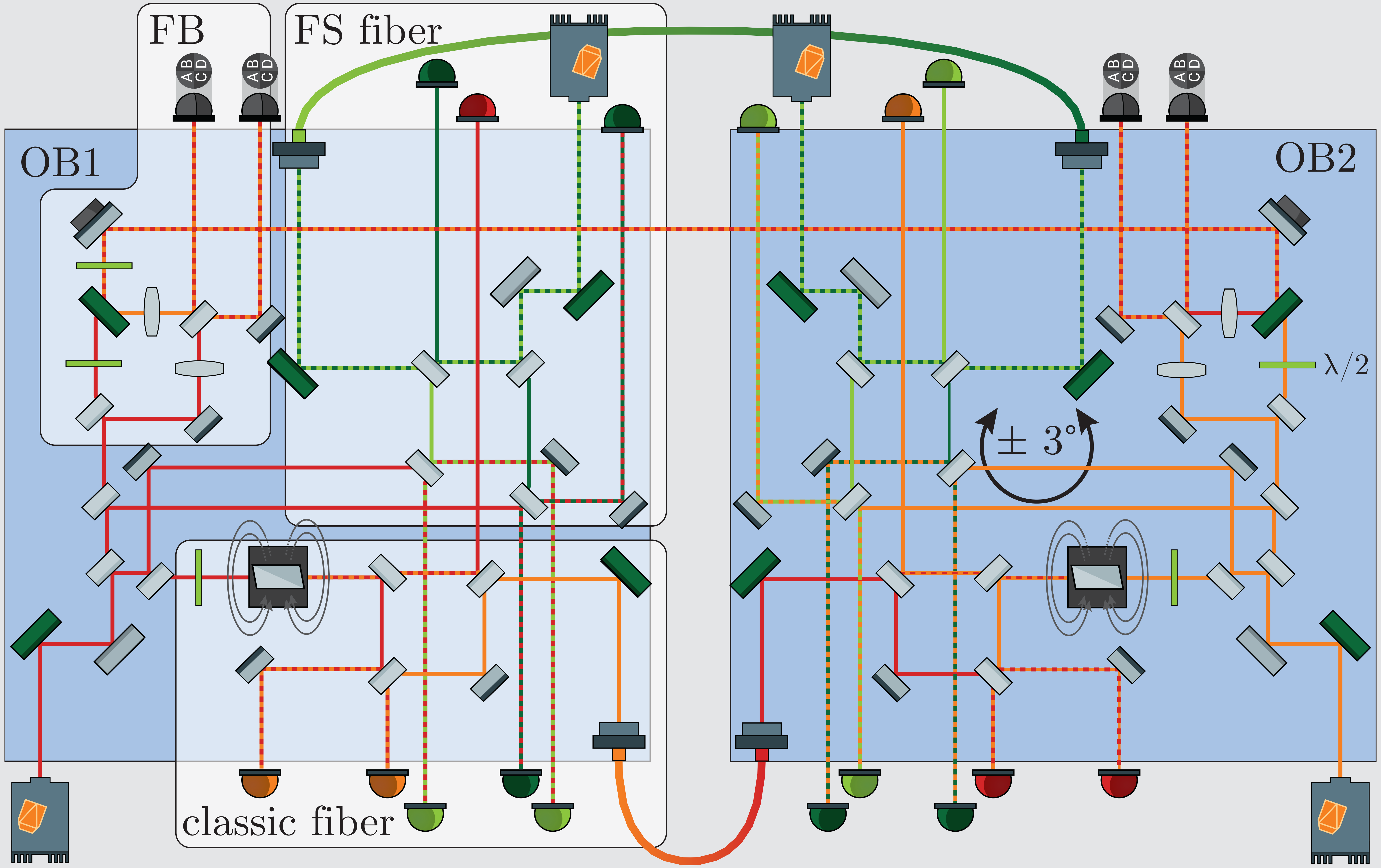
Freq. sep. Fiber BL
2 additional lasers
attenuation BS



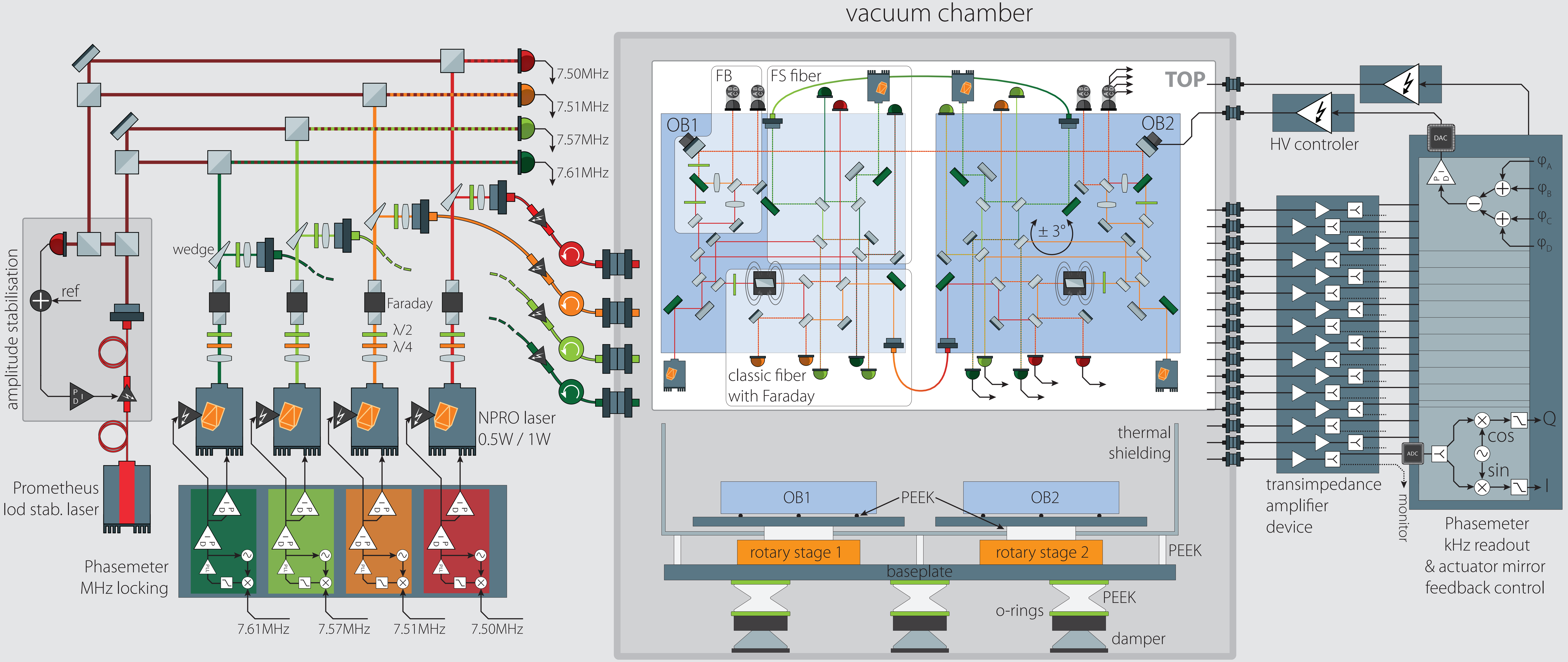
Free Beam BL
act. mirror
imaging optics
polarizing optics



Classic Fiber BL
Faraday isolator
attenuation BS
polarizing optics



The journey to a LISA customized BL



The challenge

I. usage of **4 NPRO lasers** frequency locked to an iodine stabilised reference laser

II. **LISA-like testbed** - two rotating optical benches

III. **2 phasemeters** - for laser locking, free beam BL control and readout

IV. **DWS control loop** for the free beam BL - **decoupling** of two actuator mirrors

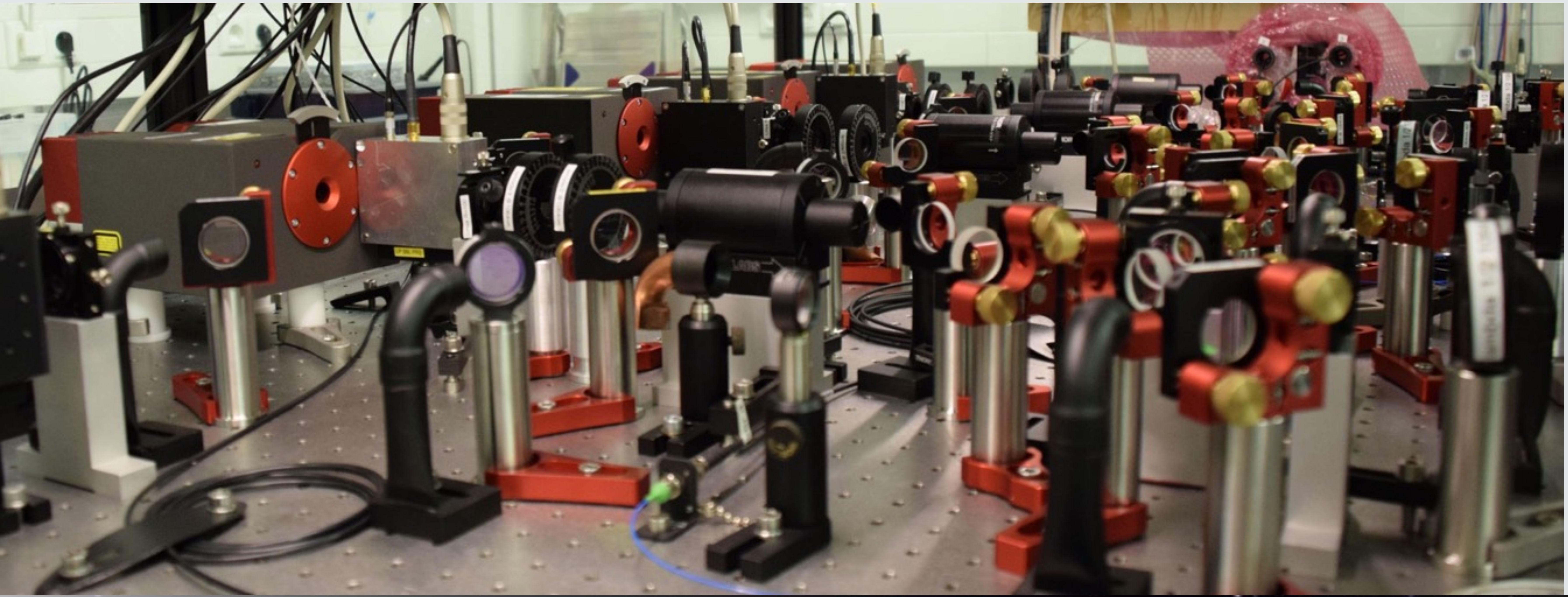
V. **stray light-*free*** designed 3-BL

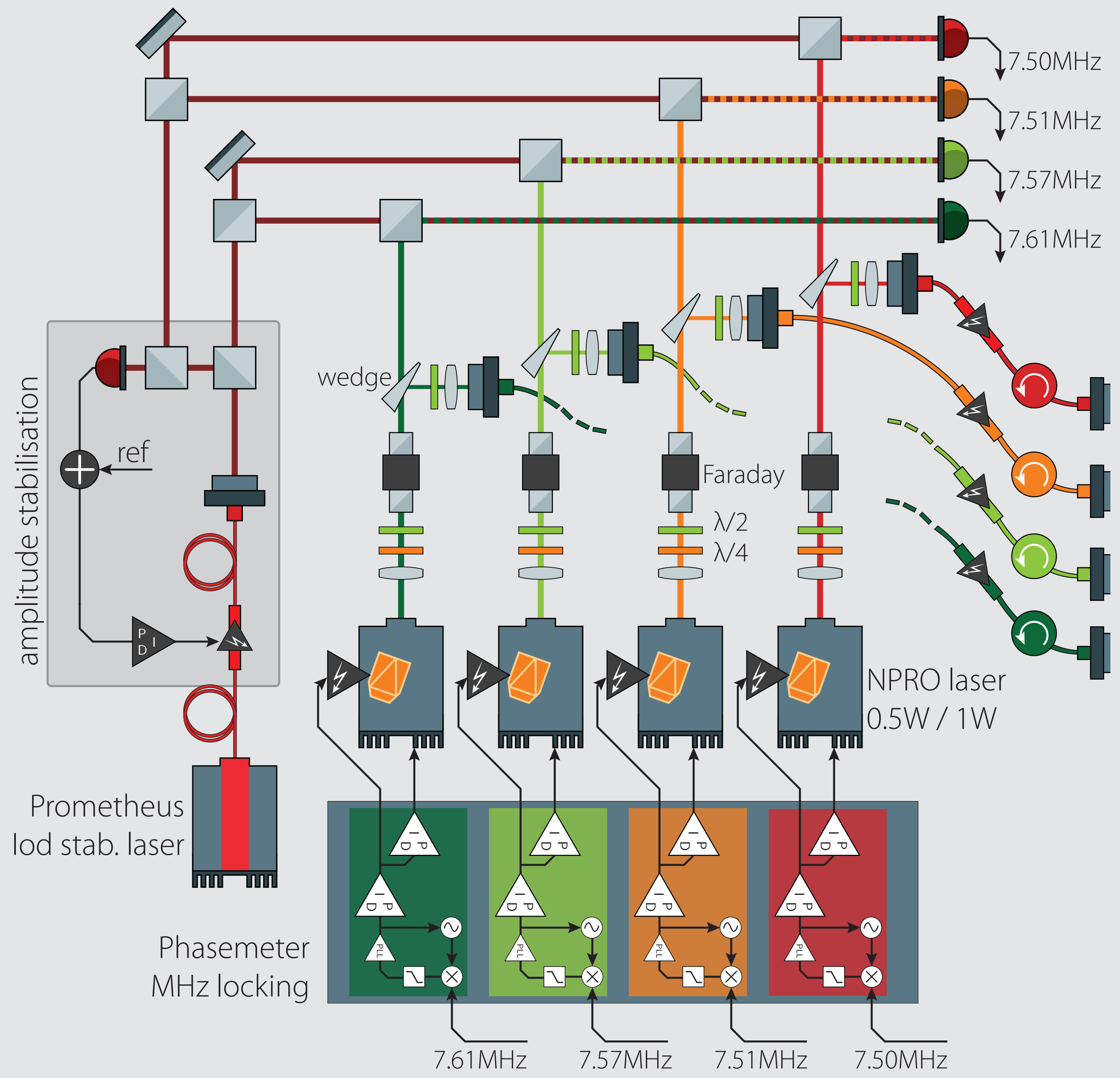
VI. construction of **two antisymmetric quasi-monolithic set-ups**

The journey to a LISA customized BL

Status - The experimental infrastructure

- **laser stabilisation** is running over weeks / months using a dedicated **phasemeter**

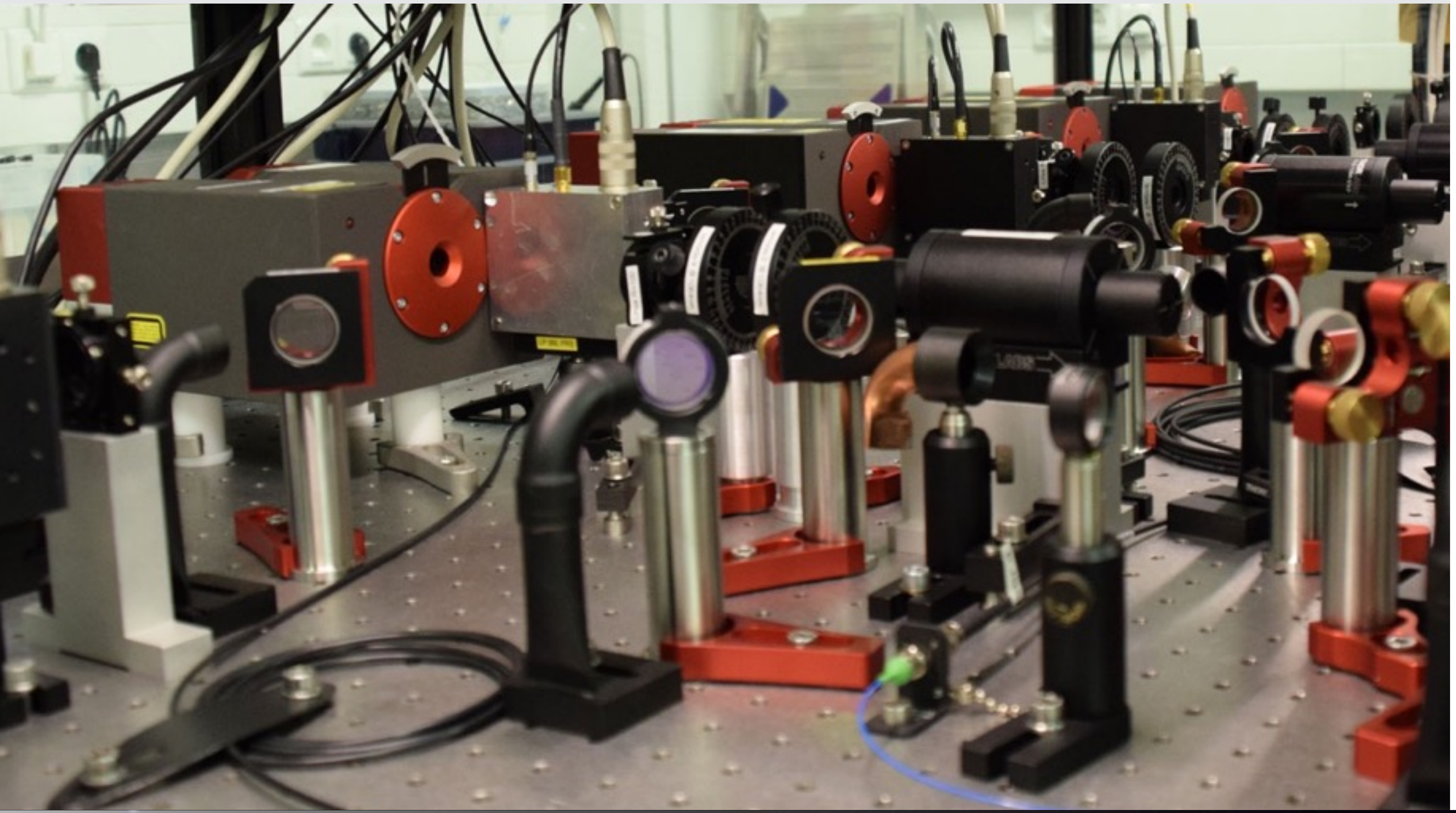


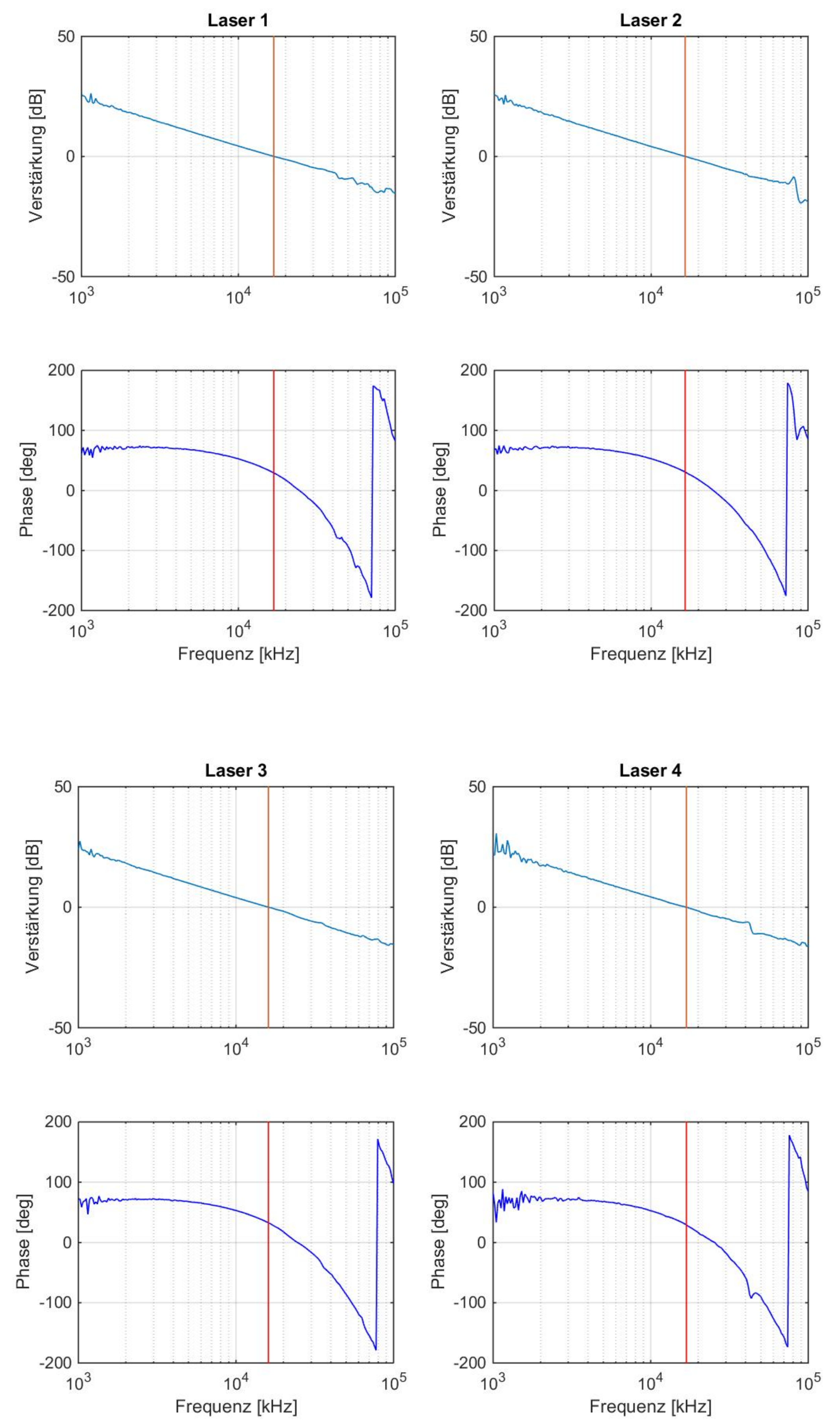


The journey to a LISA customized BL

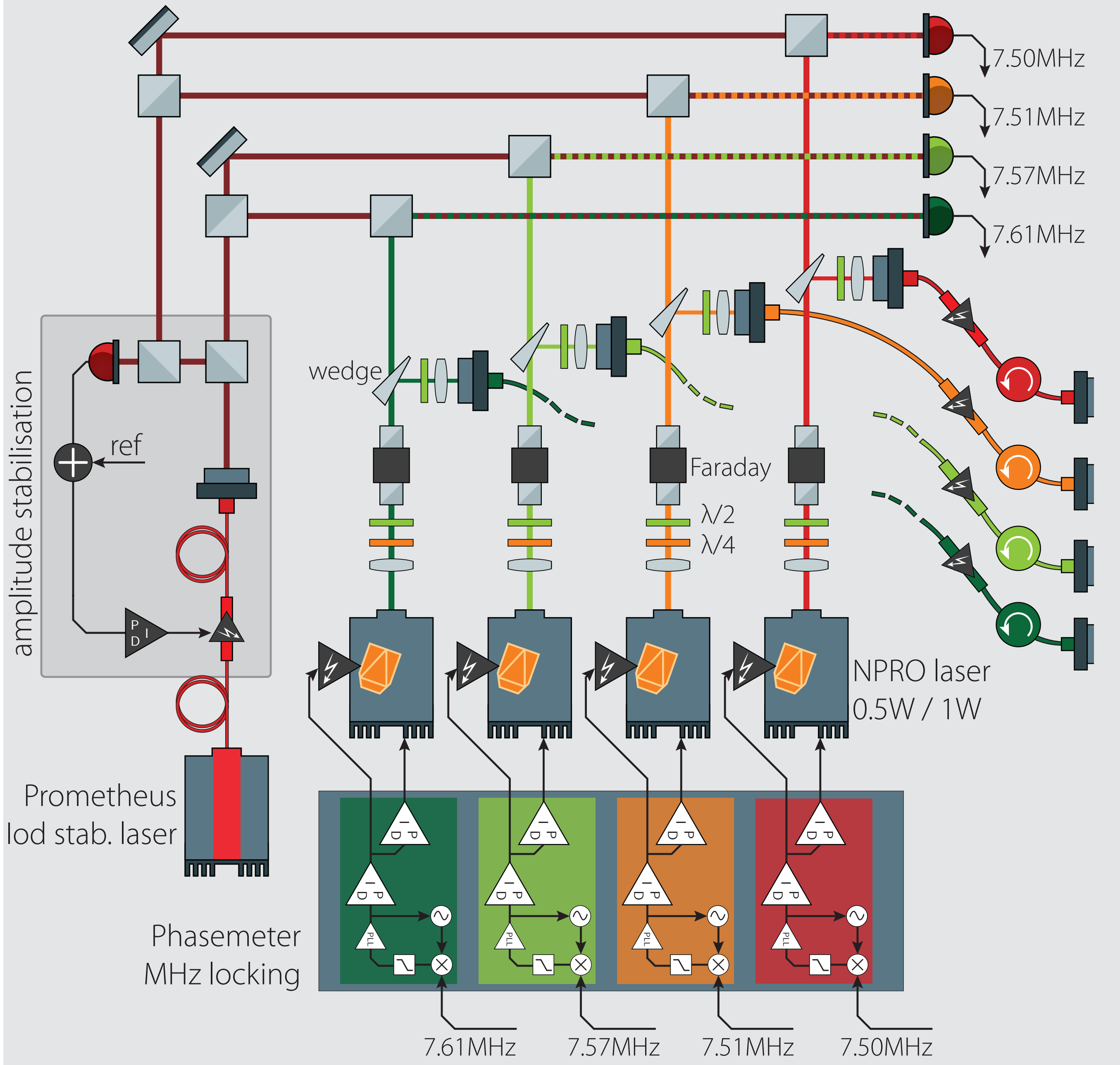
Status - The experimental infrastructure

- **laser stabilisation** is running over weeks / months using a dedicated **phasemeter**



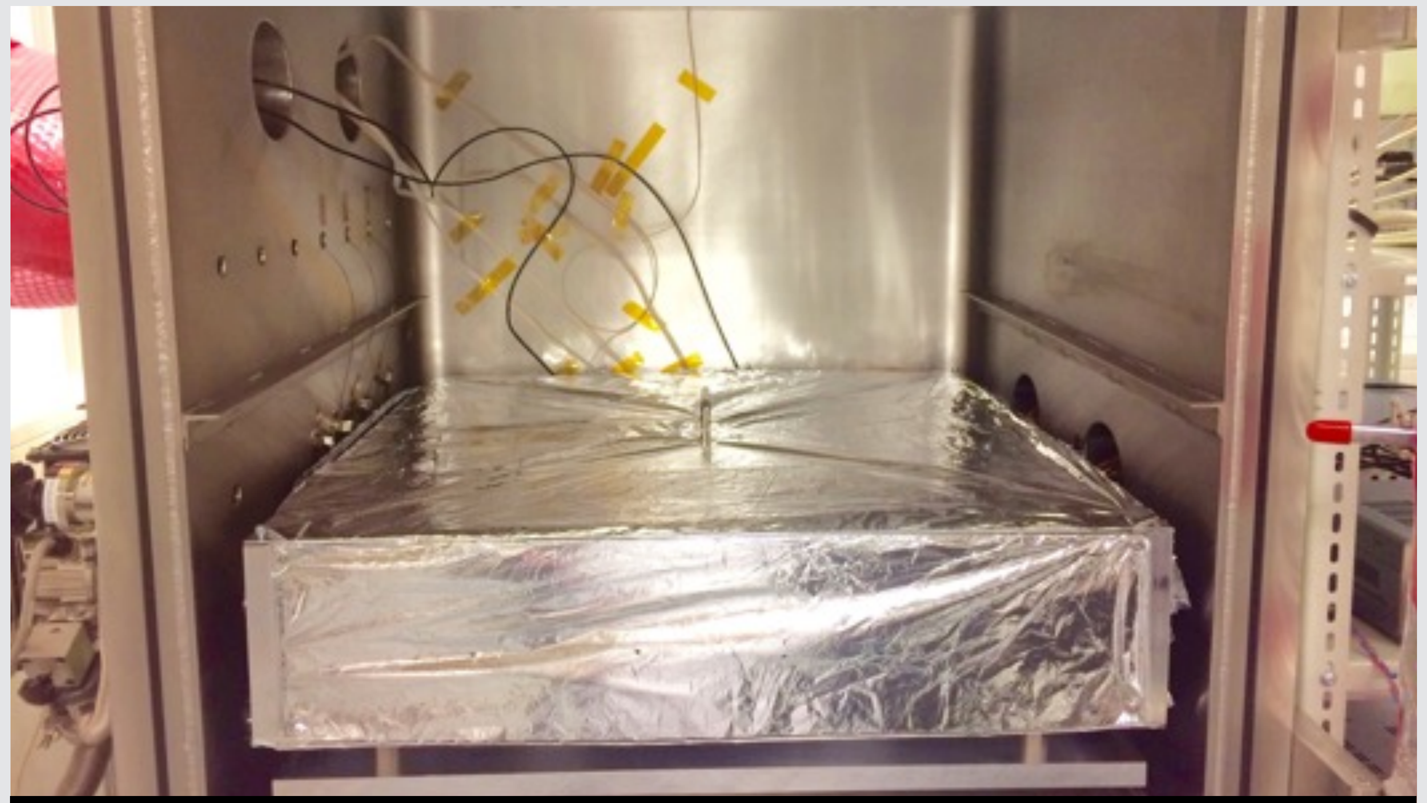


- unity gain frequency > 16kHz
- phase reserve 30°
- amplitude stabilization of the iodine stabilized laser: > 2kHz, 40°

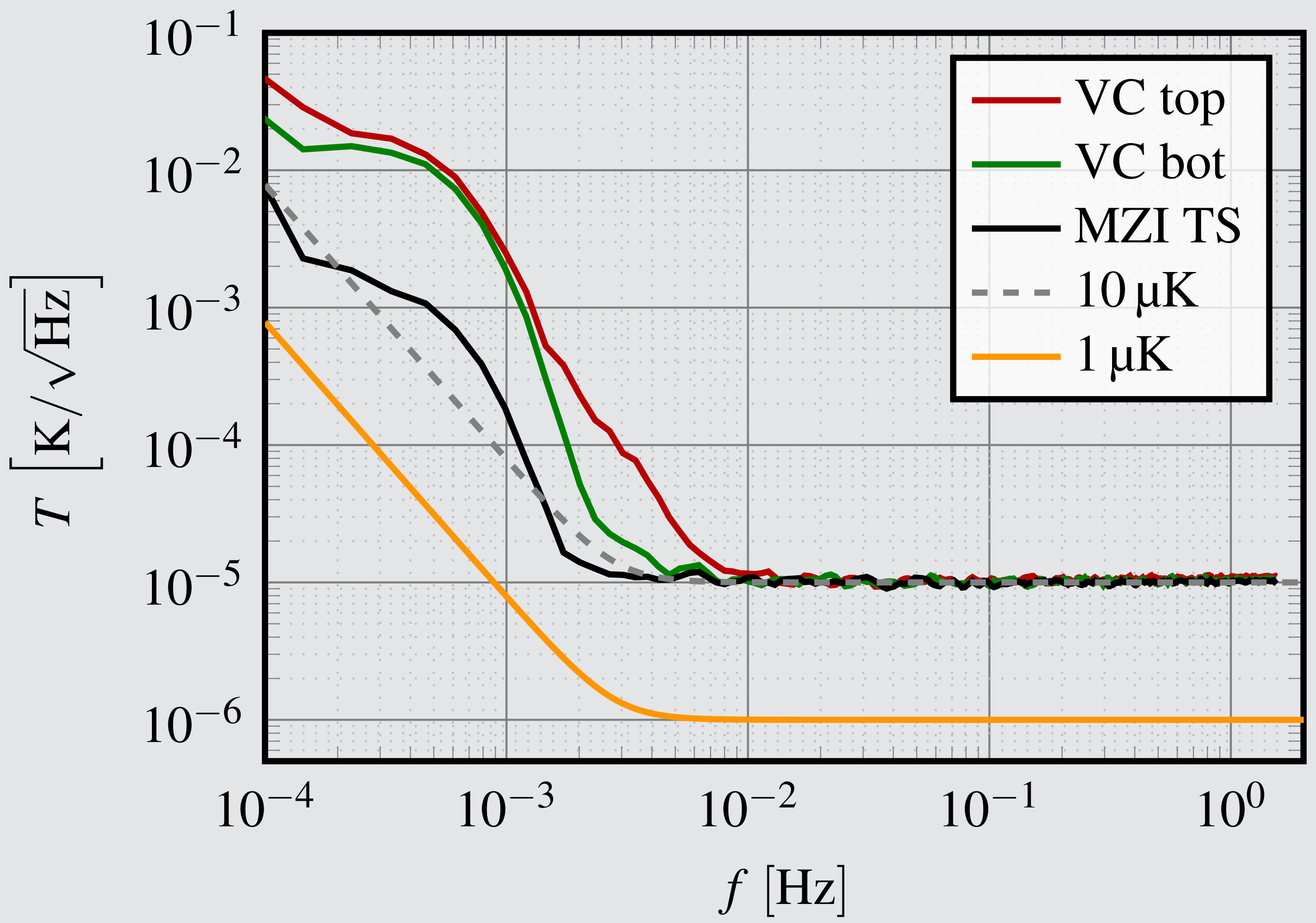


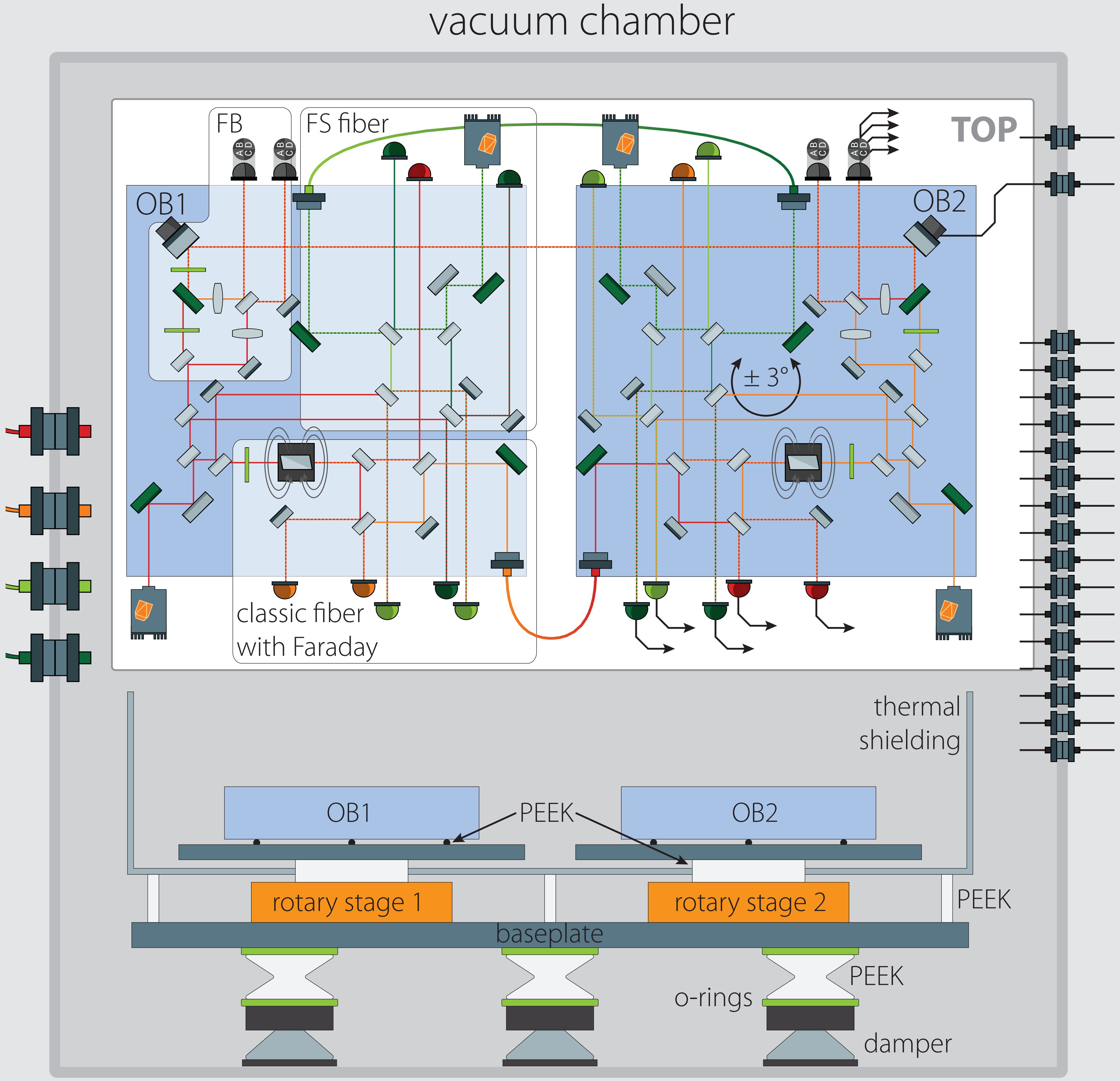
Status - The experimental infrastructure

- **laser stabilisation** is running over weeks / months using a dedicated **phasemeter**
- **thermal shielding** is installed - first thermal stability measurements are running



Thermal shield inside the vacuum tank

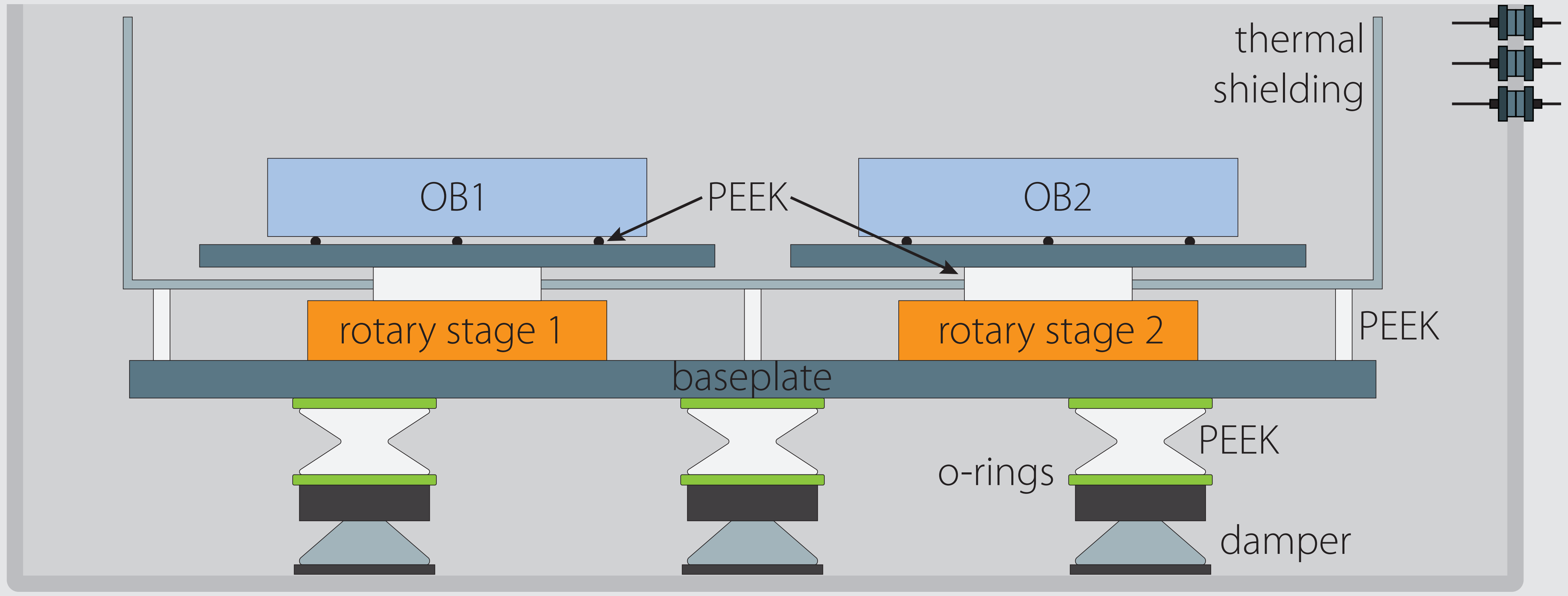




The journey to a LISA customized BL

Status - The experimental infrastructure

- **laser stabilisation** is running over weeks / months using a dedicated **phasemeter**
- **thermal shielding** is installed - first thermal stability measurements are running
- **rotary stages** are working



Newport stage

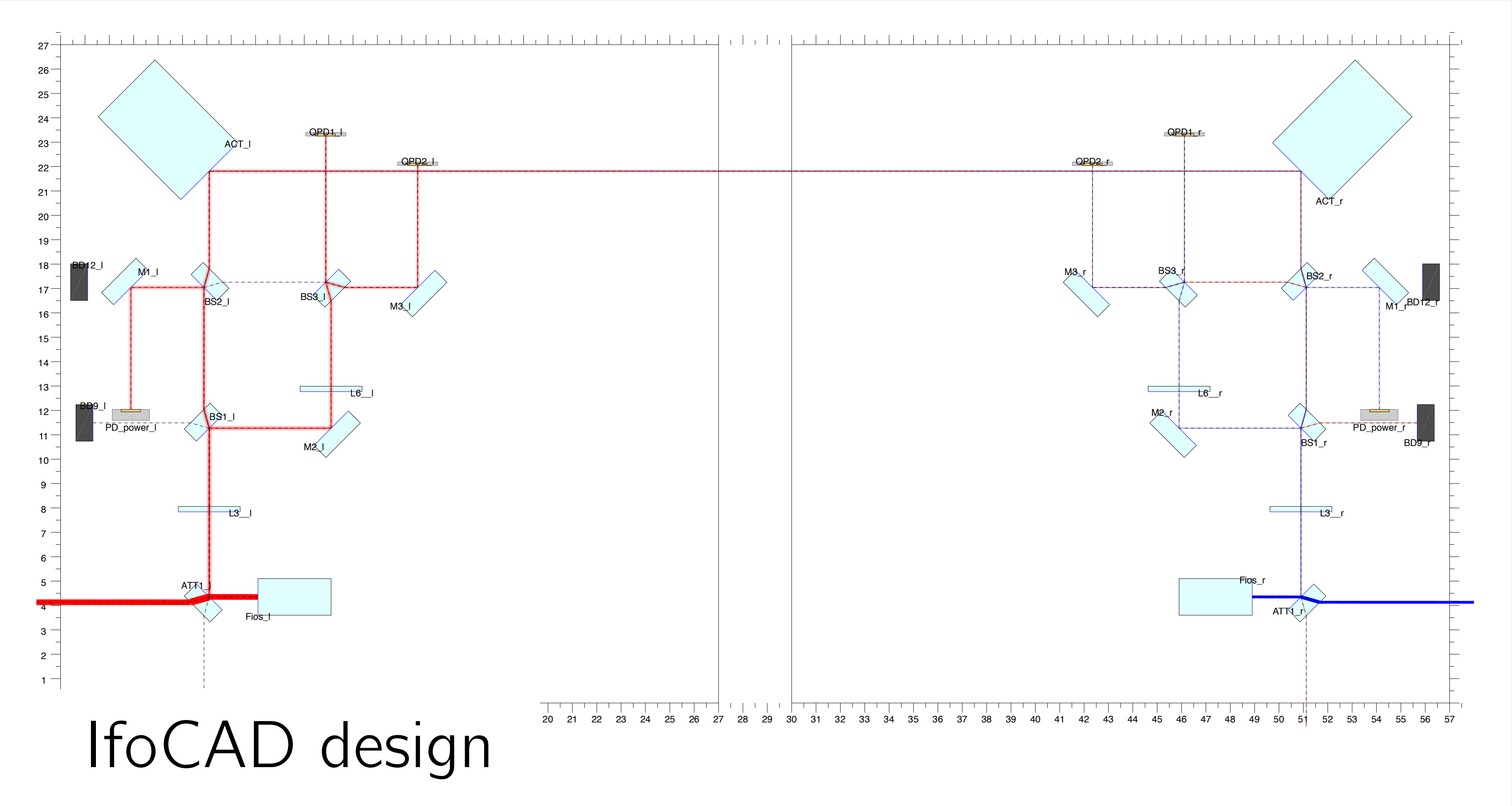
Rotary stages inside the vacuum tank

Driver for the stages - ESP 301

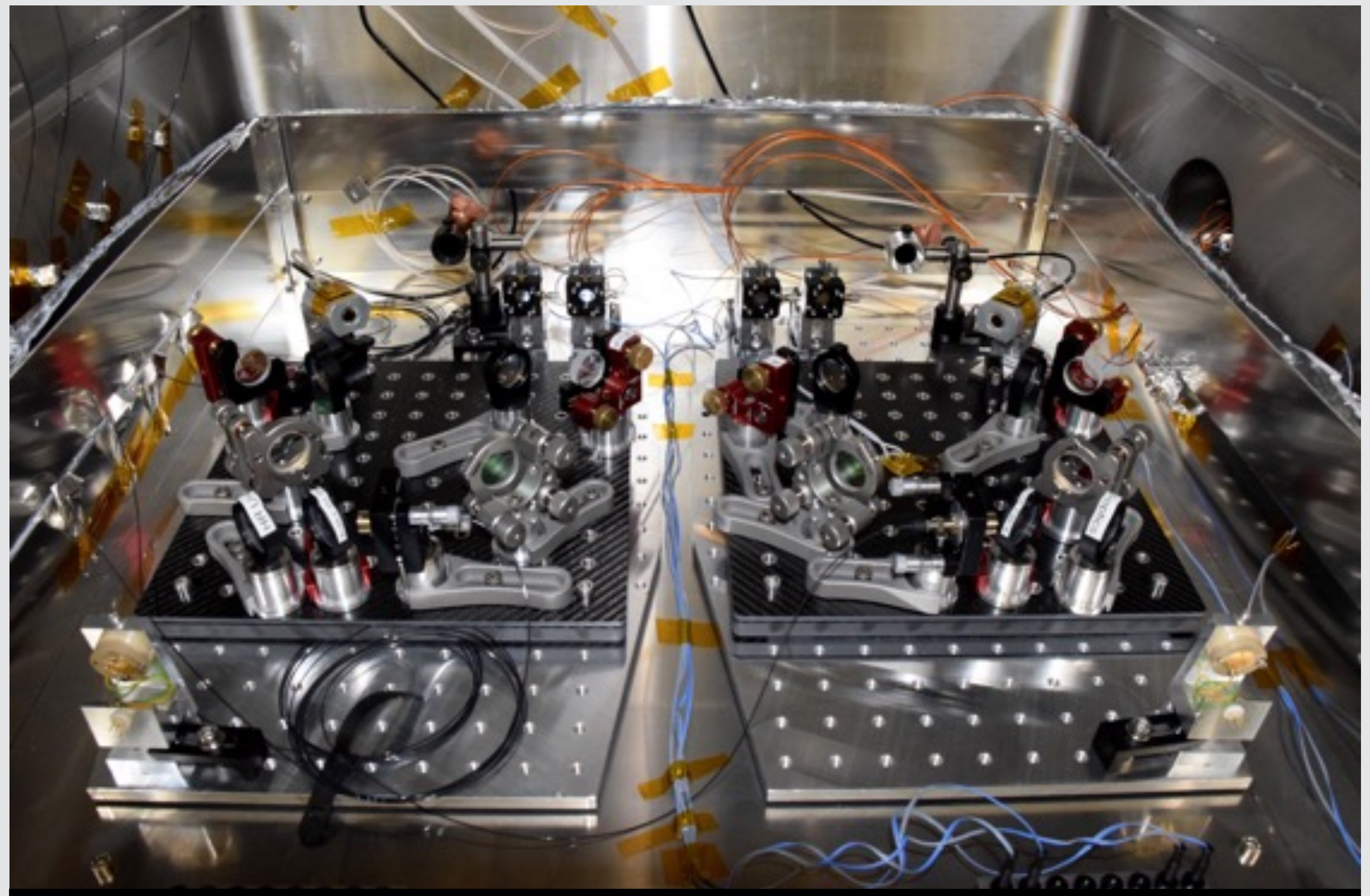
Status - The experimental infrastructure

- **laser stabilisation** is running over weeks / months using a dedicated **phasemeter**
- **thermal shielding** is installed - first thermal stability measurements are running
- **rotary stages** are working
- **pre-experiment for the free beam backlink** is aligned and measures **coupling coefficients** with a **2nd phasemeter**

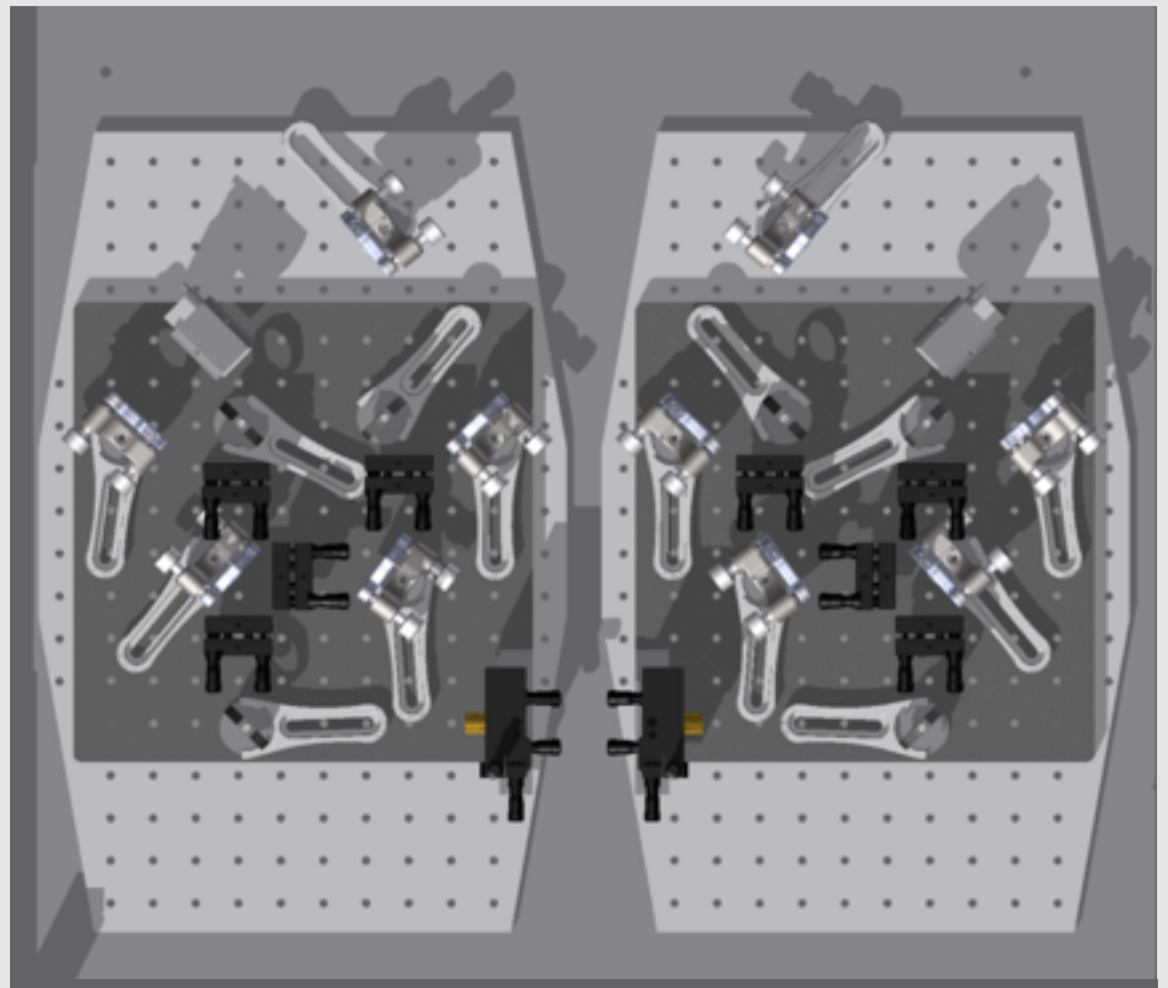
$$\begin{pmatrix} \mathrm{DWS_l} \\ \mathrm{DWS_r} \end{pmatrix} = \begin{pmatrix} K1 & K2 \\ K3 & K4 \end{pmatrix} \cdot \begin{pmatrix} x_\mathrm{l} \\ x_\mathrm{r} \end{pmatrix}$$



IfoCAD design



Free Beam Pre-Experiment in vacuum



Inventor modelling

The journey to a LISA customized BL

Status - The experimental infrastructure

- **laser stabilisation** is running over weeks / months using a dedicated **phasemeter**
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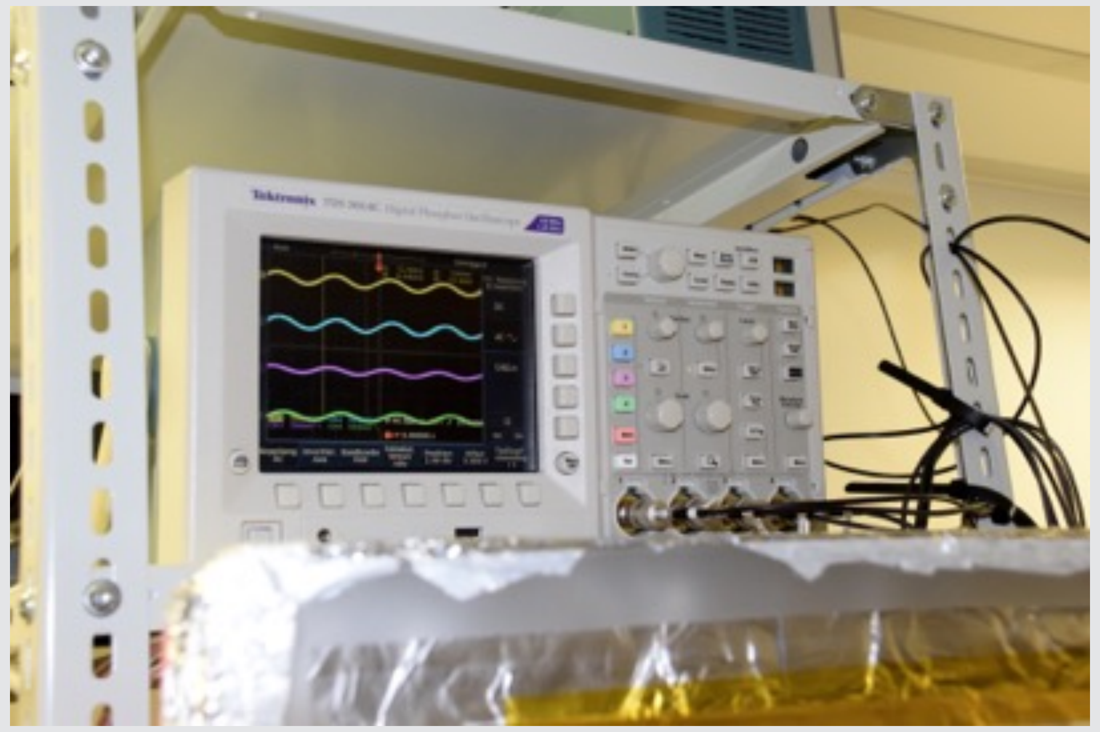
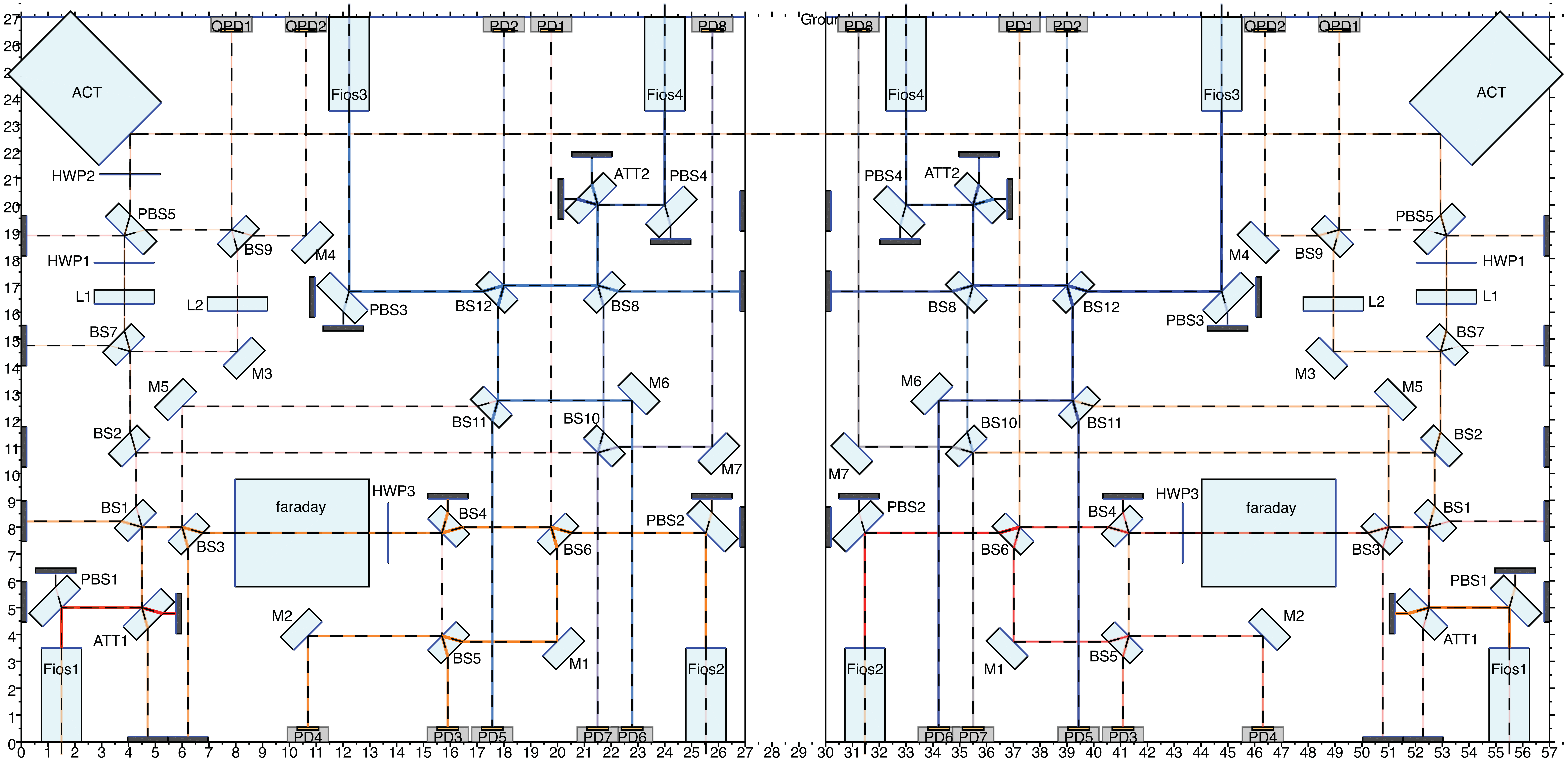


Experiment design



- 2 clearceram benches (27cm x 27cm)
- 8 monolithic fiber injectors
- 20 photodiodes (4 QPDs)
- 5/95 attenuator for TX and ALO beams
- 8 interferometers
- 2 steering mirrors
- 2 Faraday rotators
- assembly via UV gluing

The journey to a LISA customized BL

What is next? - Only a few issues left ...

Finalize the free beam experiment:

- measurement of **coupling coefficients** by rotating mirrors and benches
- first approach to close the actuator mirror loop while rotating the benches
- measure thermal behavior of the actuators

Finalize the design for the 3 Backlink interferometer:

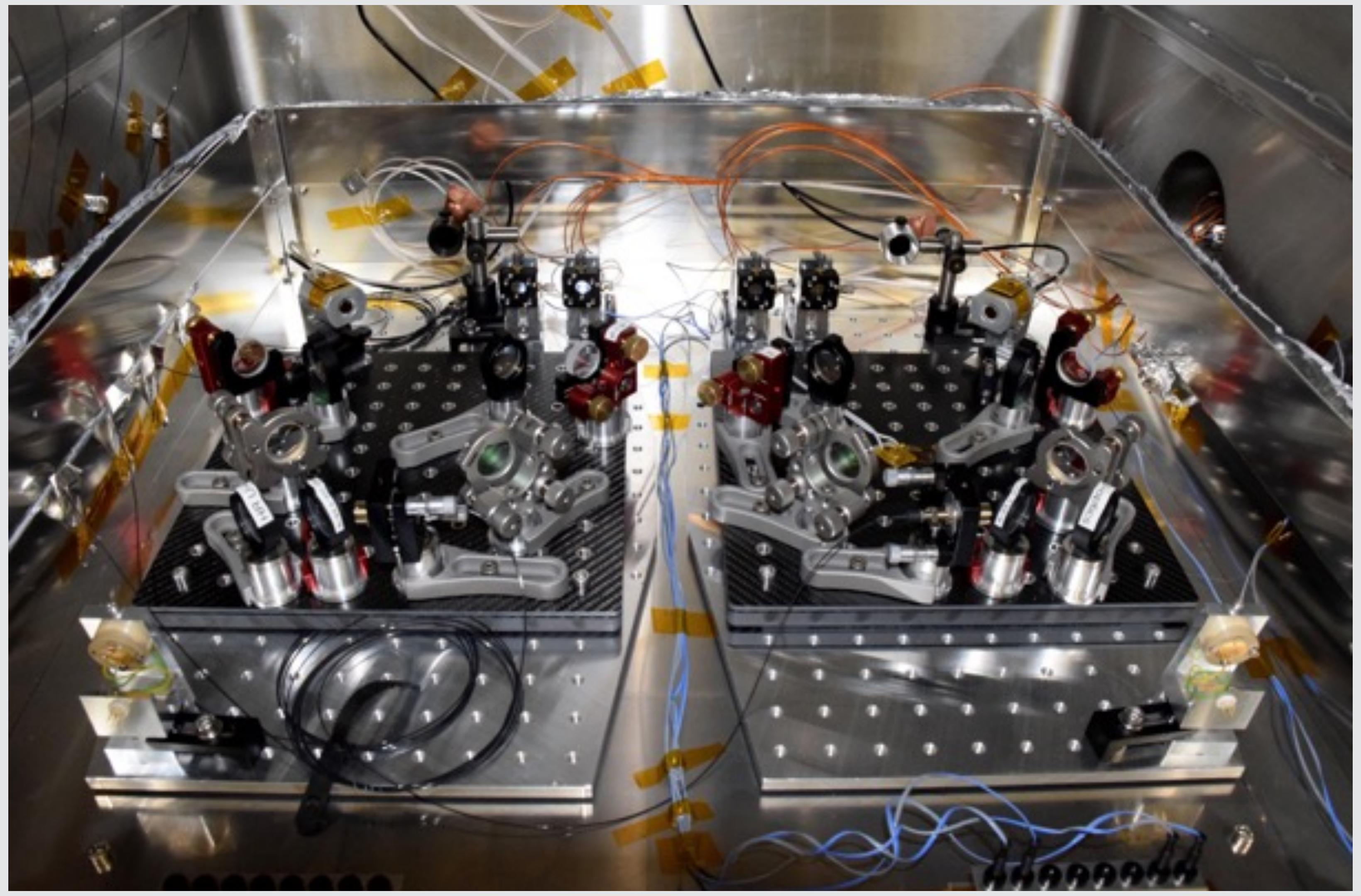
- **adopt the imaging systems** from the free beam BL experiment
- update the 3-BL design

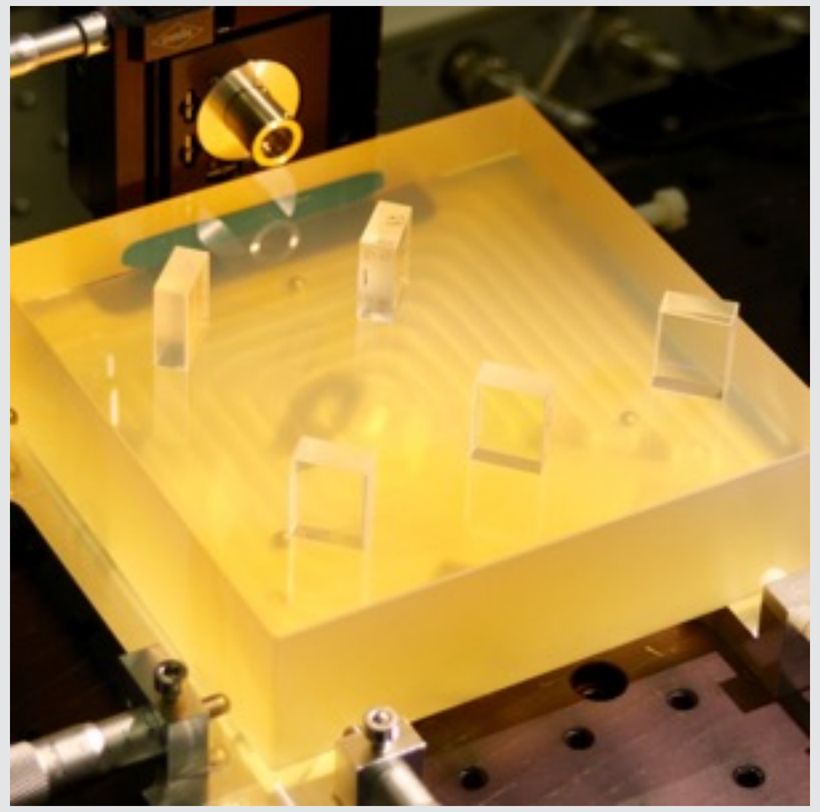
Construction of the 3 Backlink interferometer:

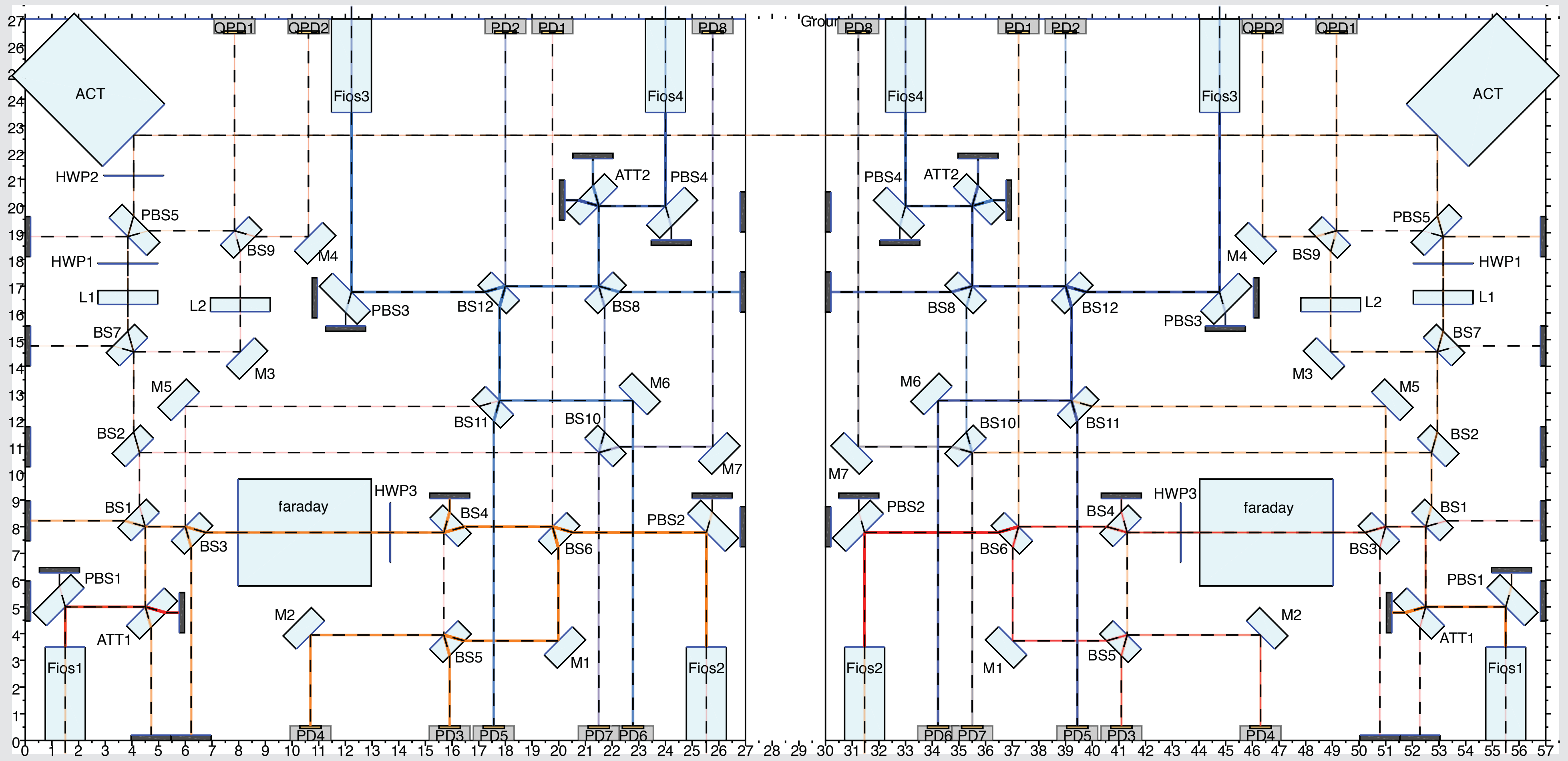
- construct monolithic fiber injectors
- manufacturing of the templates
- gluing the quasi monolithic 3-backlink interferometer in the clean room

Get the 3 Backlink interferometer running in the lab:

- replace the free beam backlink interferometer with the 3 backlink interferometer
- compare the 3 backlink solutions with each other







The LISA backlink

Thank you for your attention!

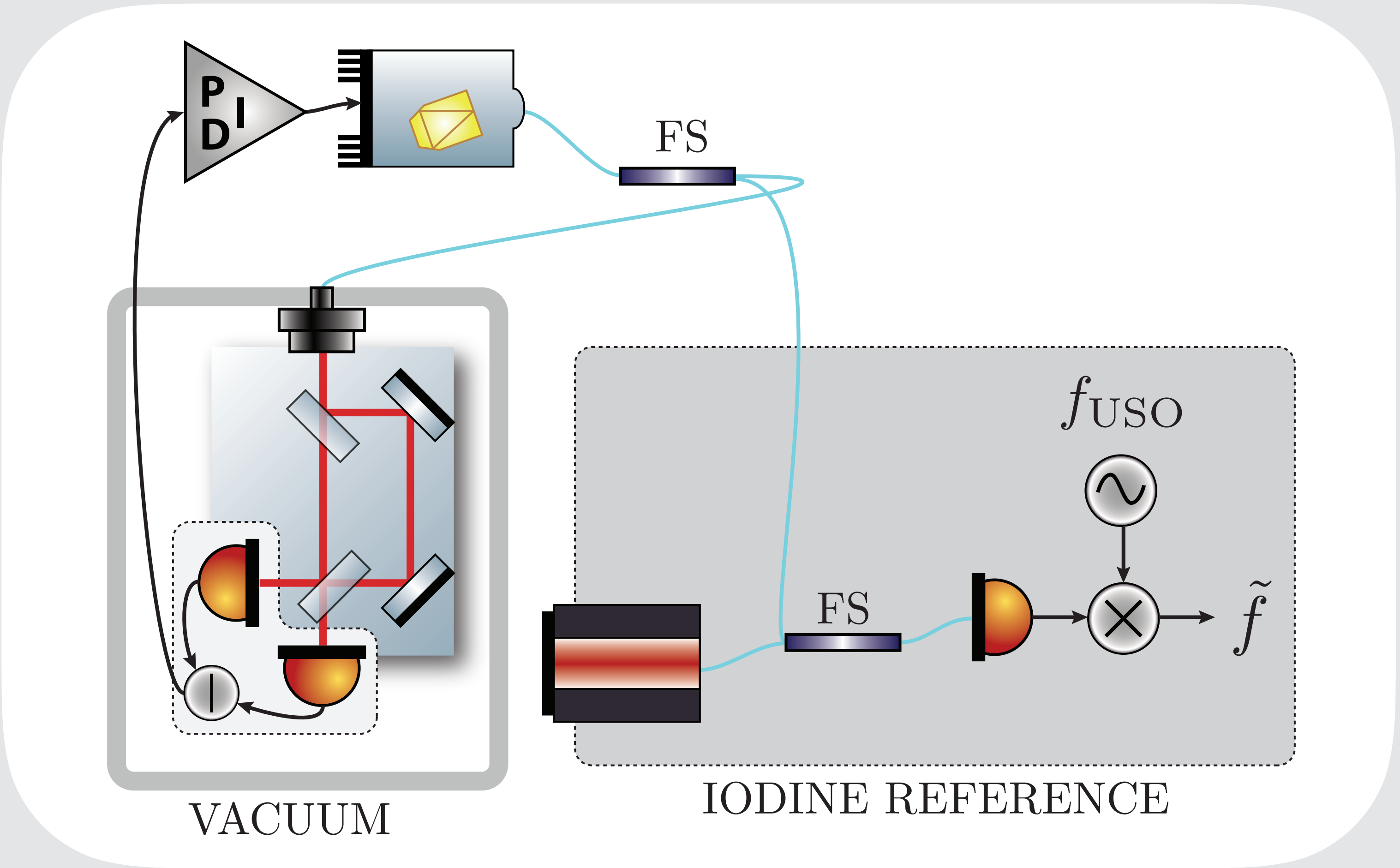
Katharina-Sophie Isleif &

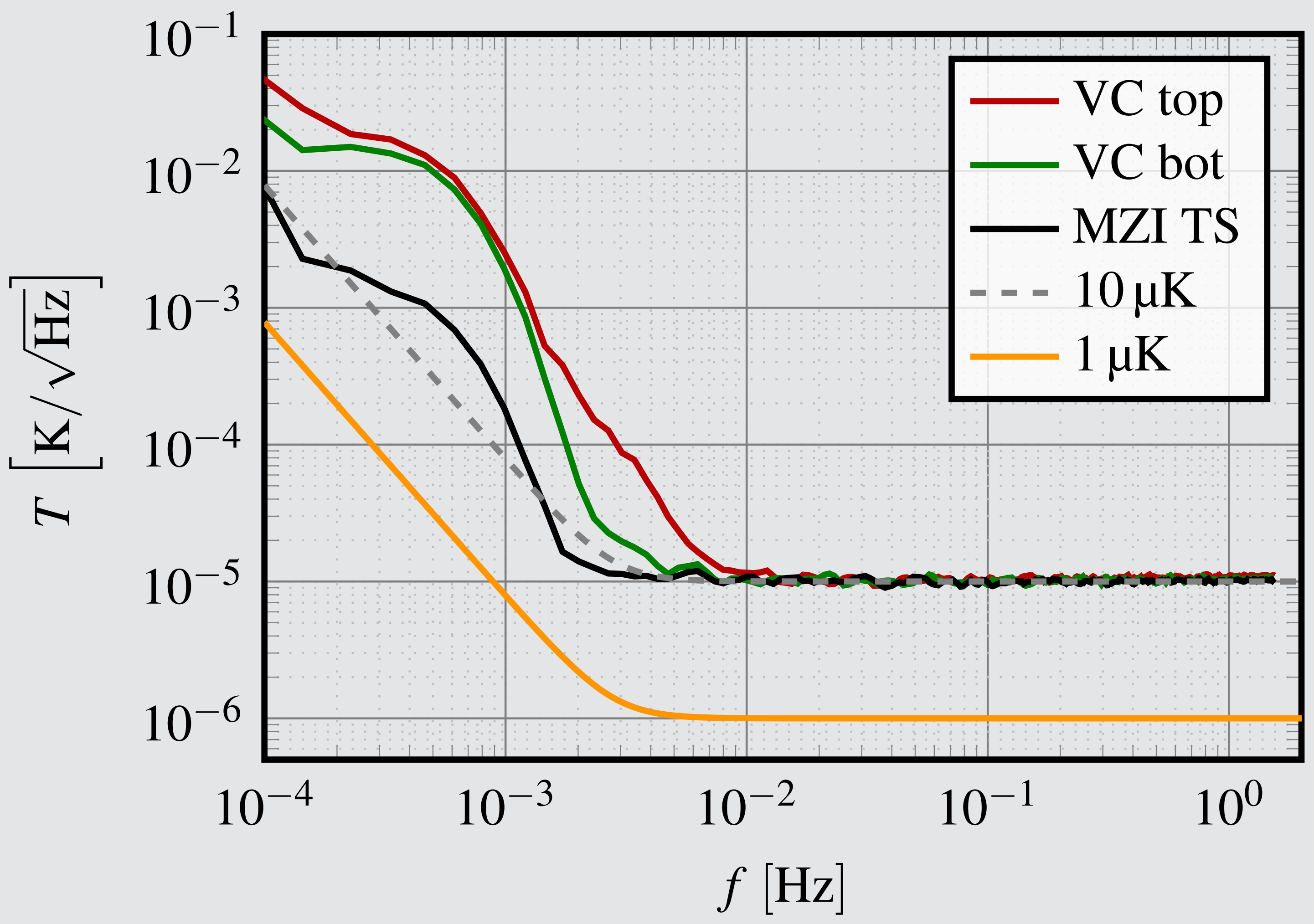
O. Gerberding, L. Bischof, S. Ast, M. Tröbs, M. Winter, M. Zimmermann,
J. Reiche, G. Heinzel, K. Danzmann

Institute for Gravitational Physics, Albert Einstein Institute, Leibniz Universität Hannover and Max Planck Institute for Gravitational Physics

Quasi-monolithic Mach Zehnder - Performance of UV gluing

Set-up:





Temperature dependency:

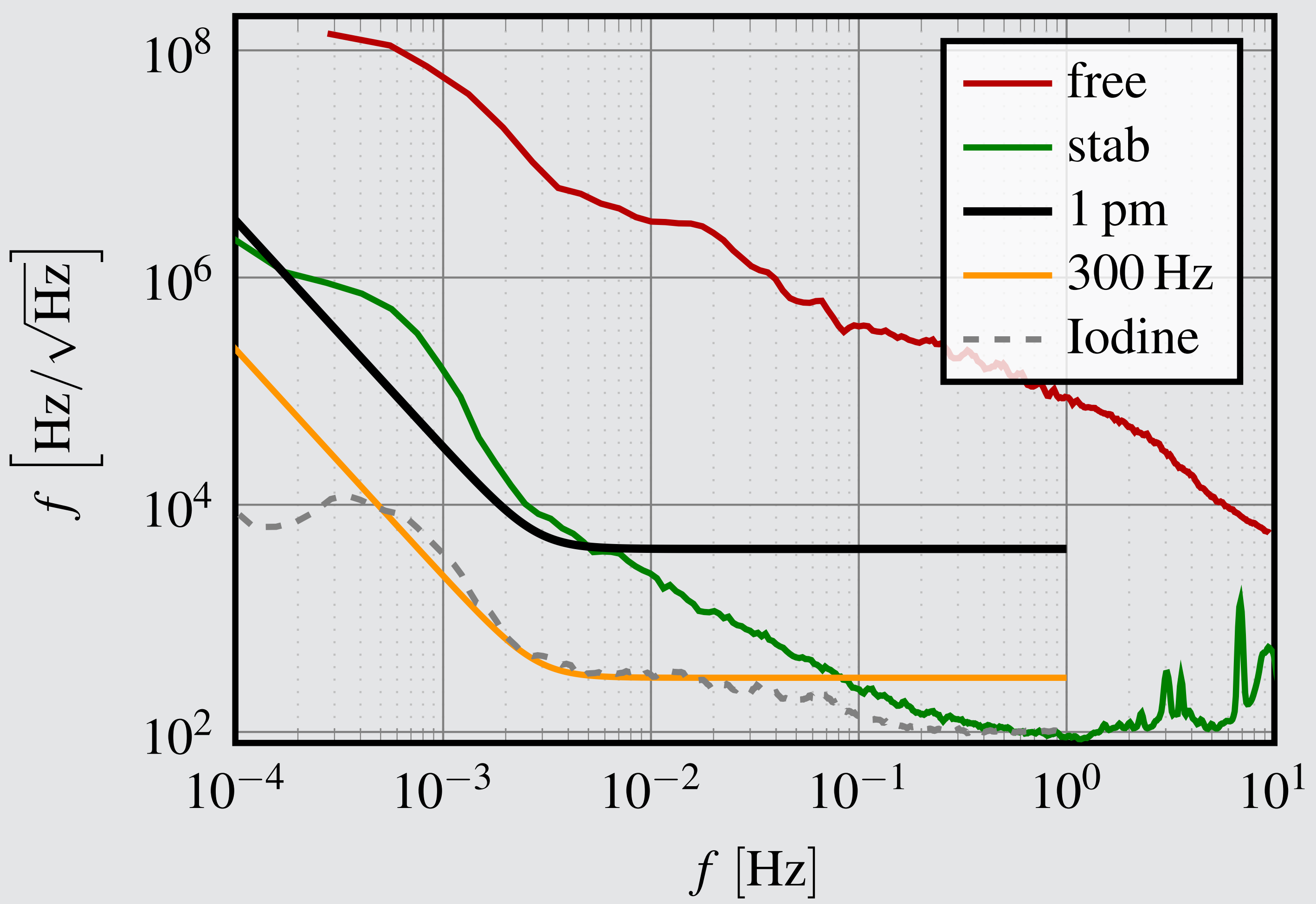
- timeseries of raw temperature and frequency data show oscillation
- oscillation frequency: ca. 1h
- corresponds to the hump in the spectra
- caused by the lab air conditioning

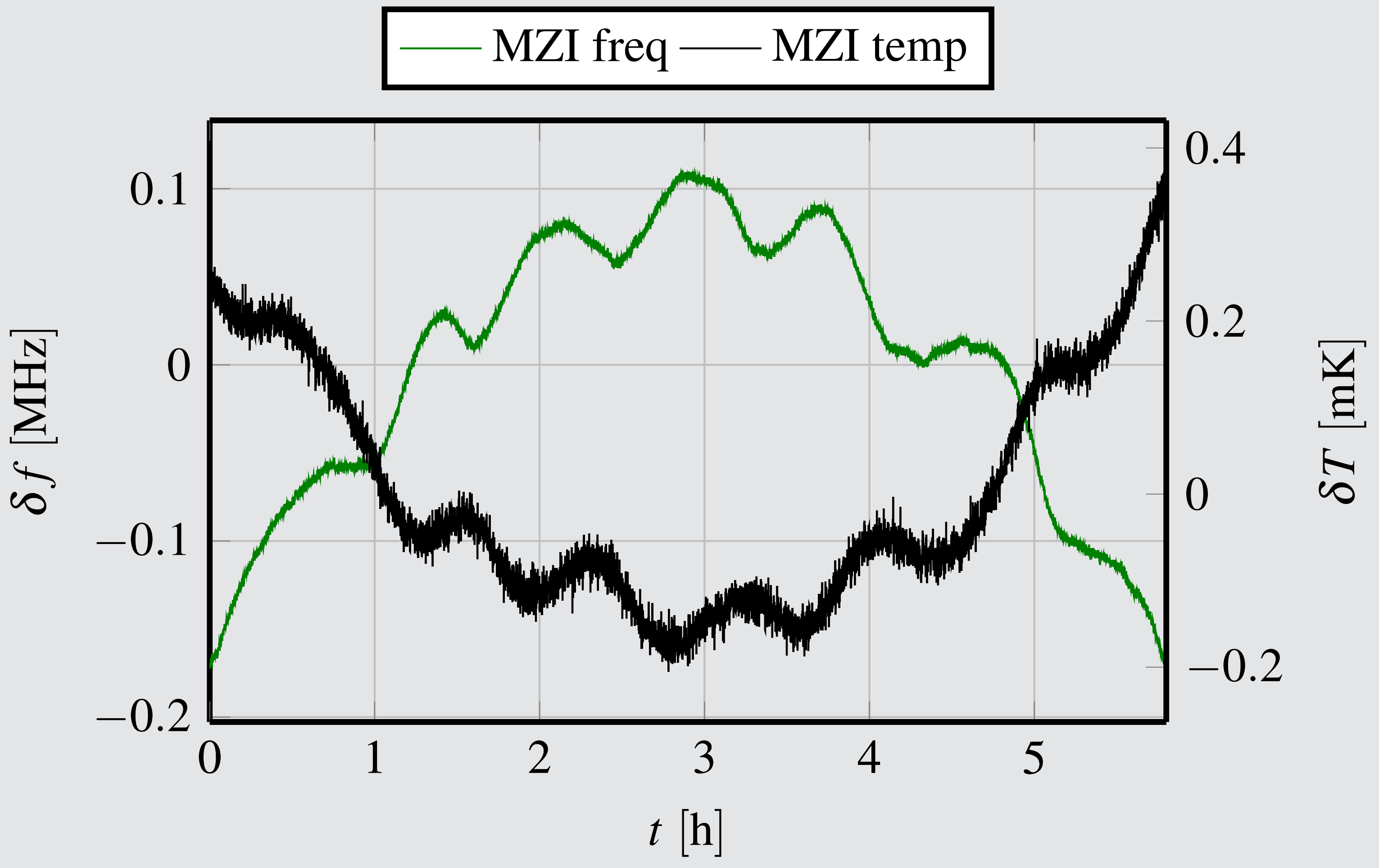
Performance measurement:

- potentially limited by stray light from photodiodes/ polariser/lenses...

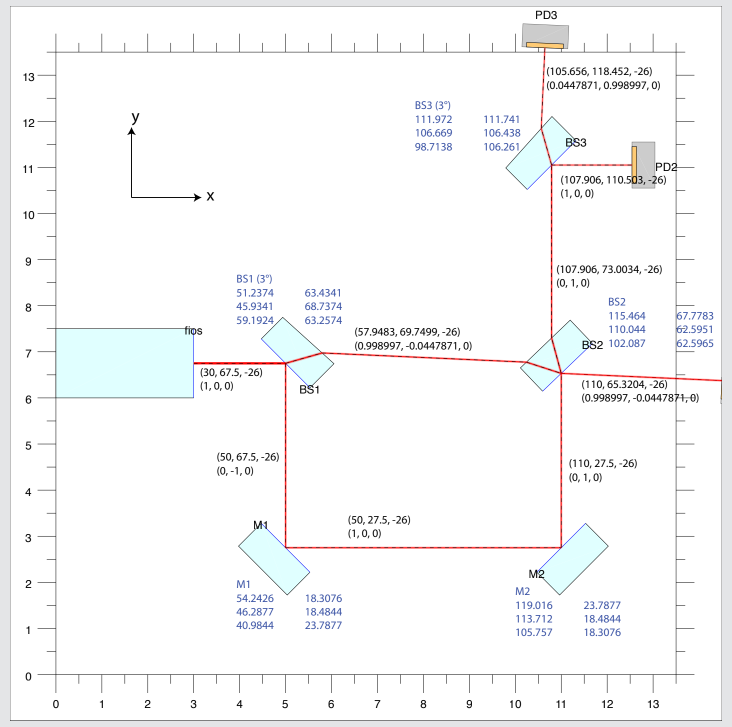
Thermal stability measurement:

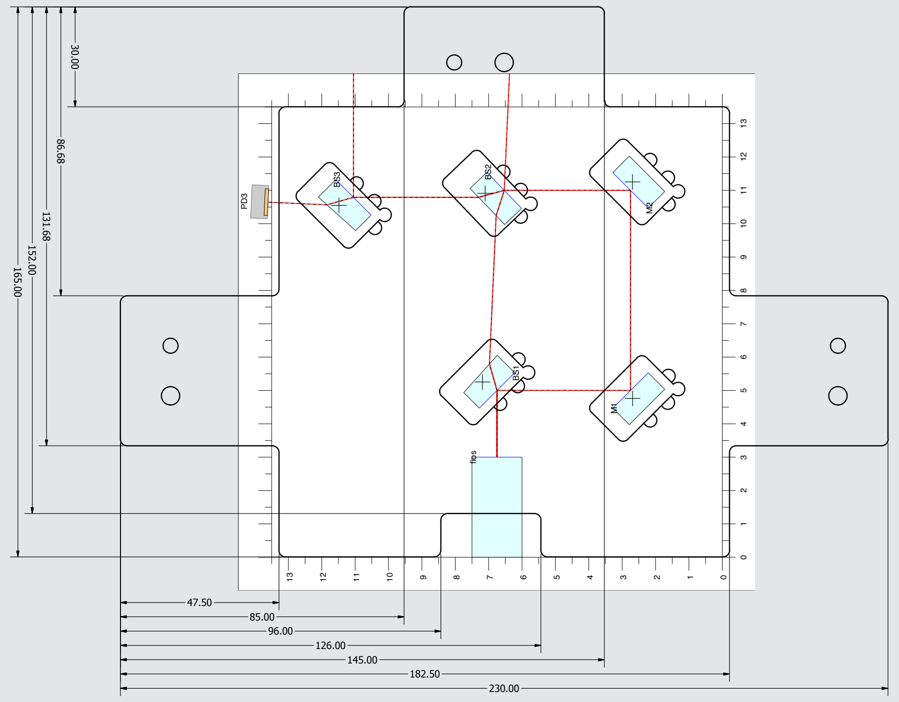
- reference Mach Zehnder shows 1pm stability at 5mHz
- temperature hump below 1mHz also visible in the frequency performance
- dynamic range: 3 orders of magnitude

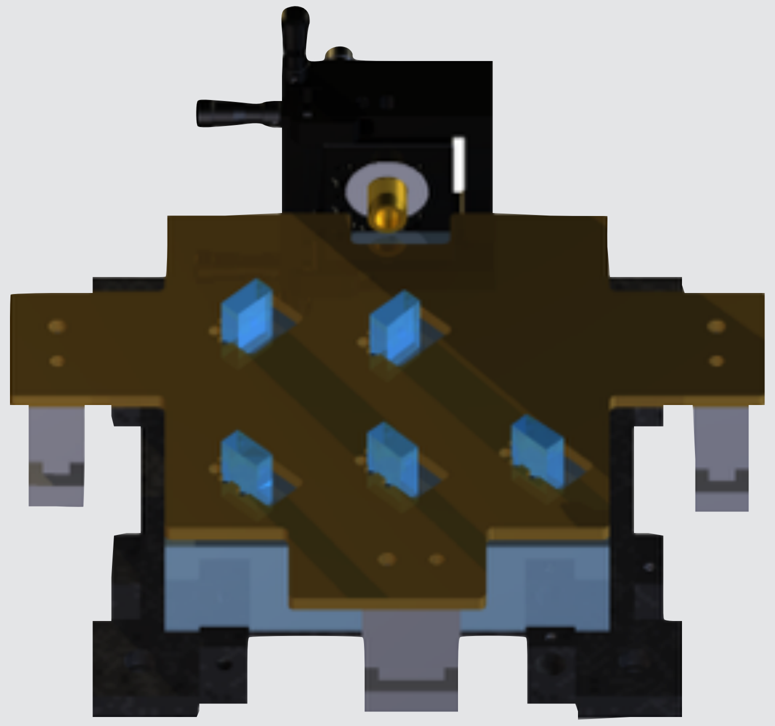


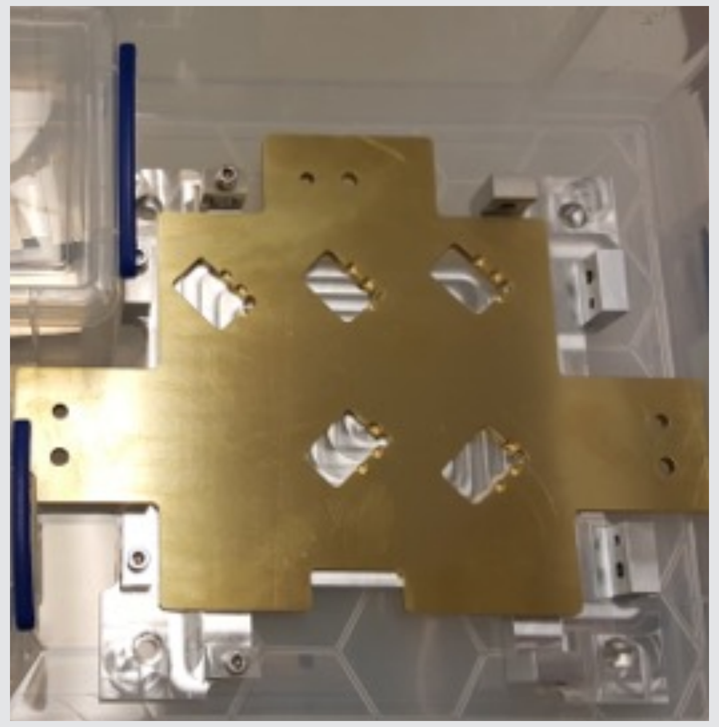


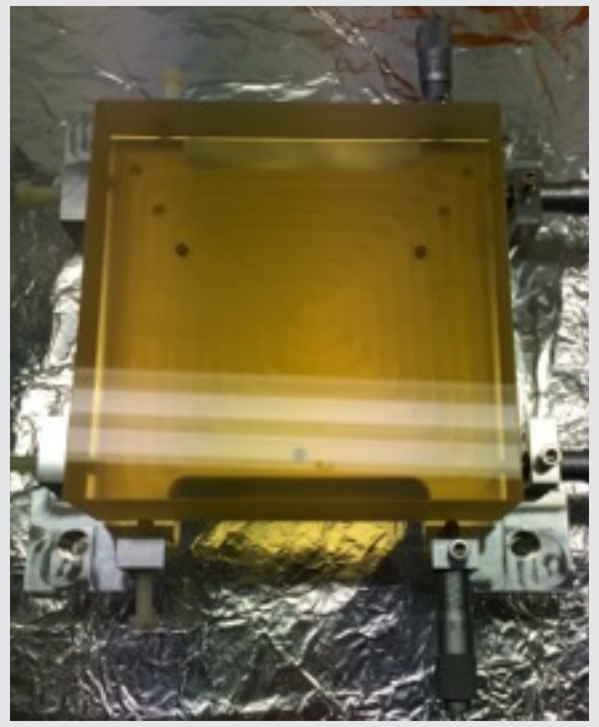
Quasi-monolithic Mach Zehnder - Fabrication

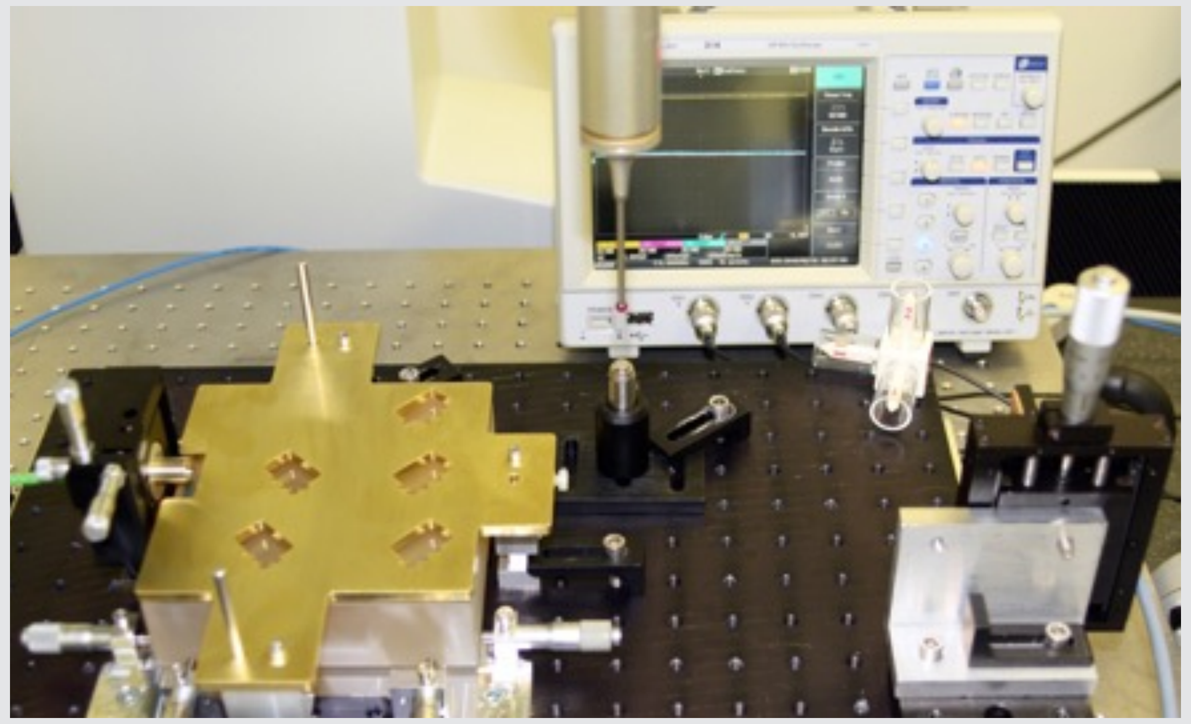


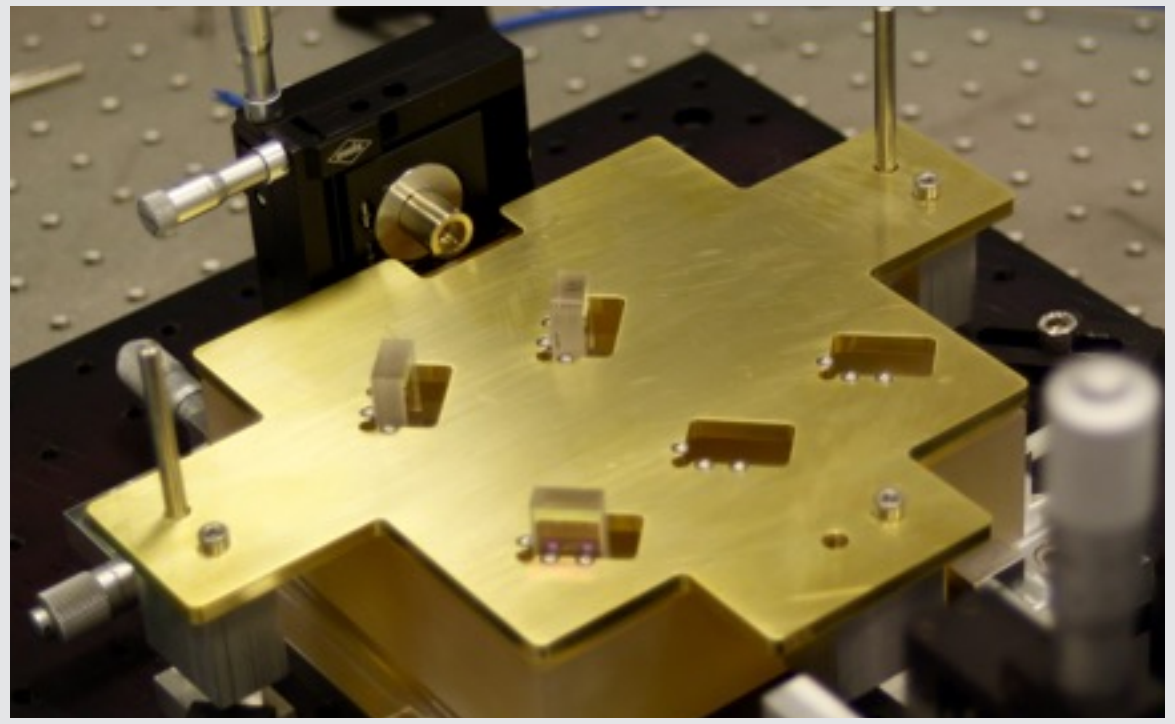


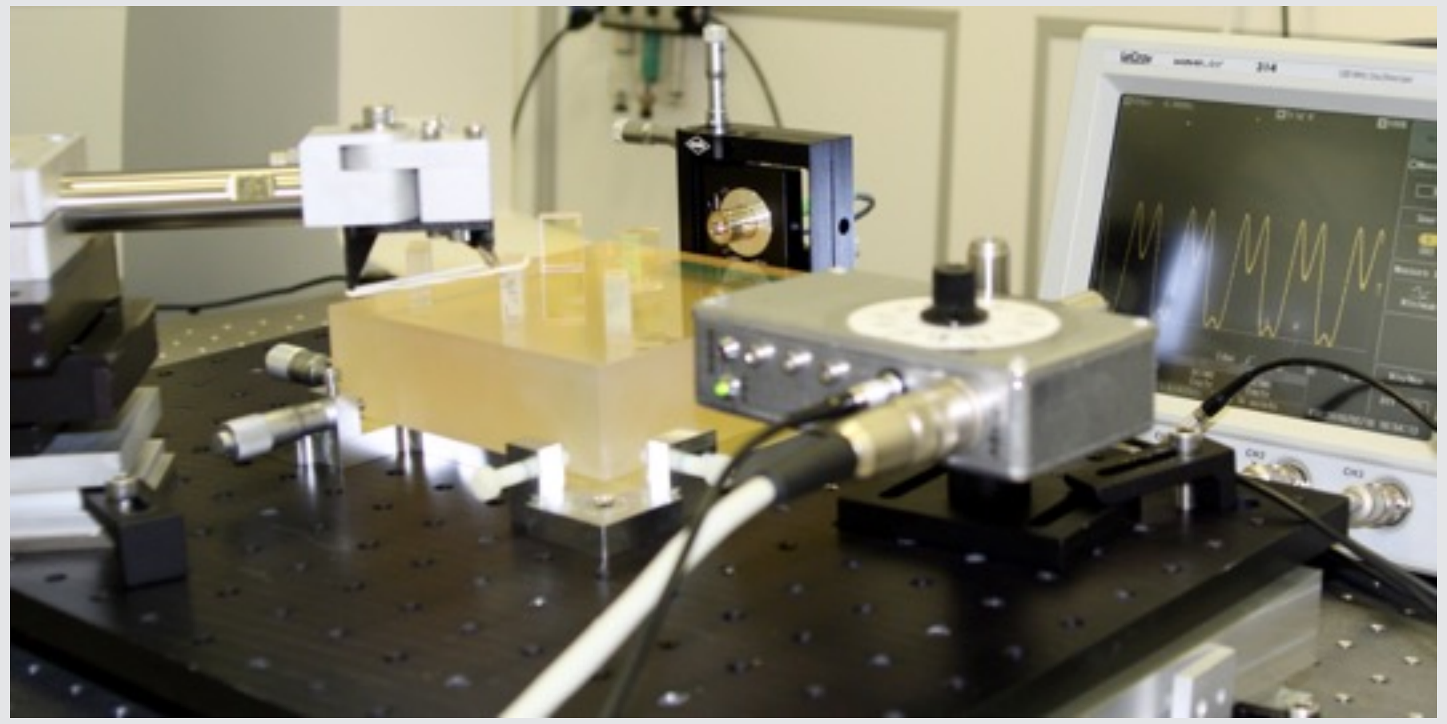












- Extracting positions from IfoCad Simulation
- Production of a template for the components (and mounts, boxes,...)
- Cleaning of mechanics and baseplate (Clearceram Ohara CCZ-HS with 0.1e-7 / K) for the cleanroom
- Glueing the fiber output coupler to the baseplate
- Alignment of the laser beam in respect to the template via CMM
- Glueing the non-critical components (UV glue: EMIUV Optocast 3553- LV-UTF)
- Alignment of the critical recombination beam splitter via CMM and contrast (>90% before and after! glueing)

IfoCAD implementation

implementation of desired interferometer

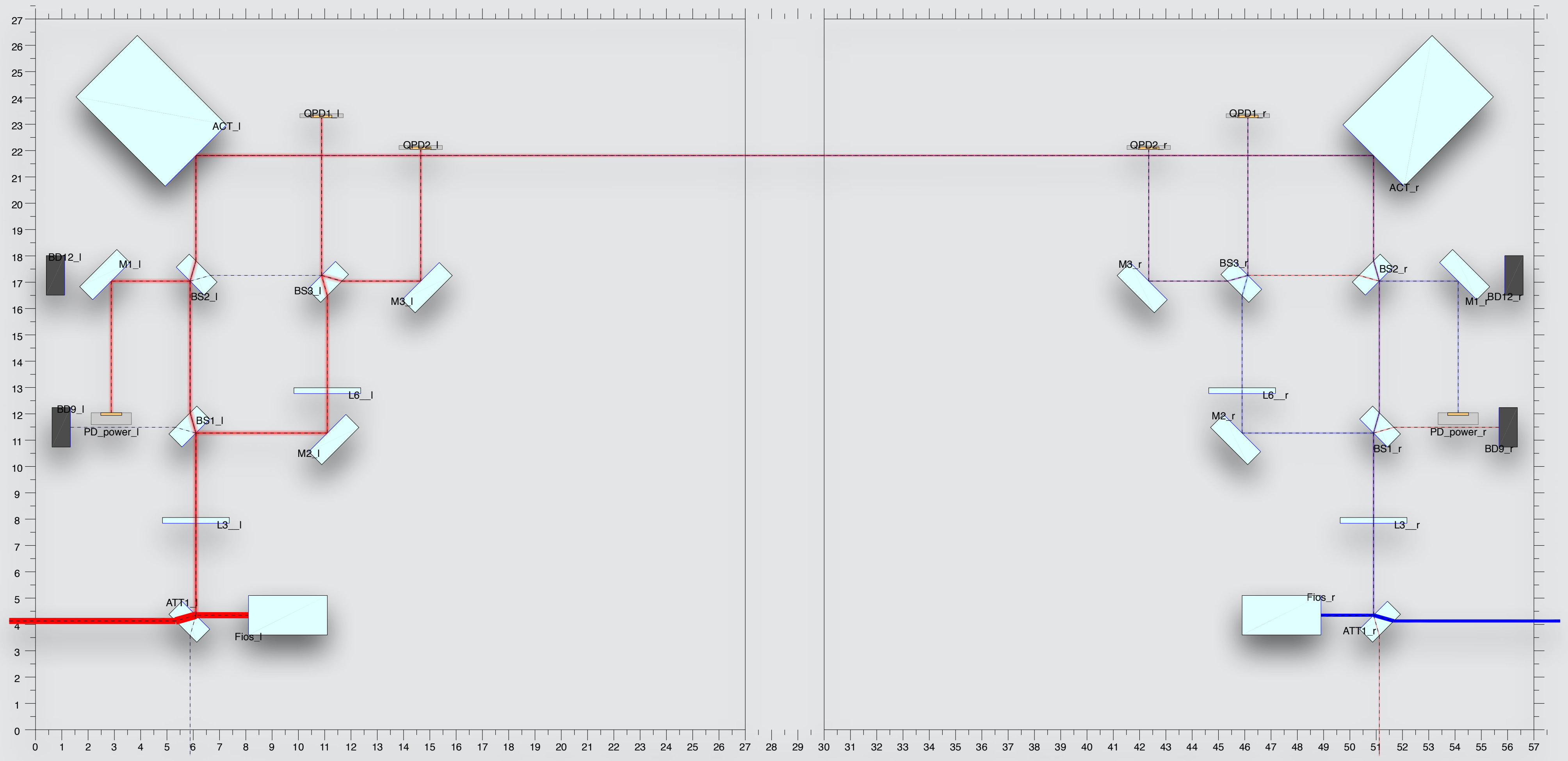
- parametrization (*distances, lens foci,...*)

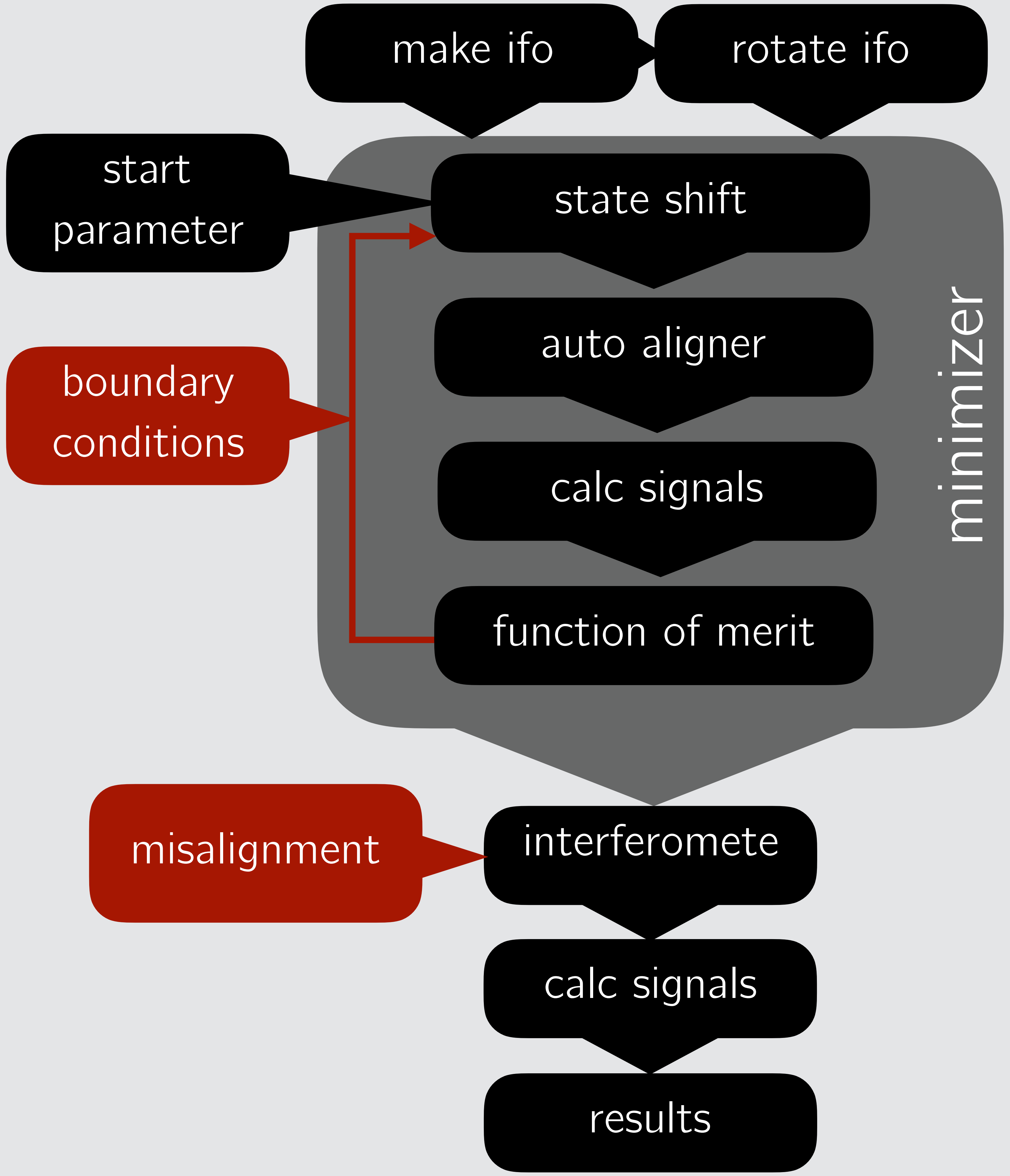
minimizer function:

- parameters allowed to change within boundaries: *beam waist position, lens (focus, position), PD position*
- signals: *heterodyne efficiency, DWS signals*
- function of merit: combination of penalty functions of *heterodyne efficiency, coupling coefficients*

final interferometer:

- alignment requirement for manufacturing (displacement: 100 µm, Angular: 50 µrad)

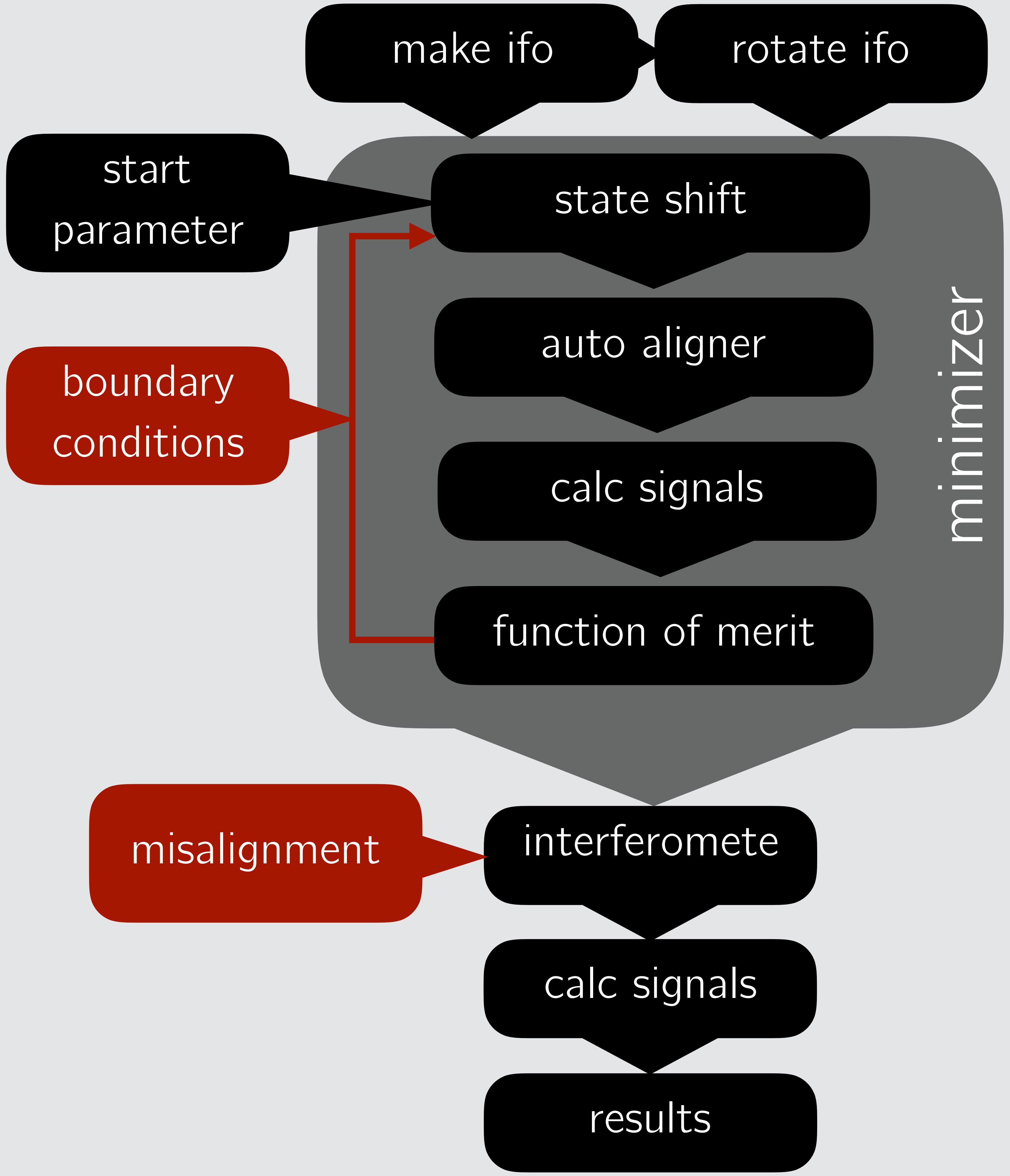




IfoCAD implementation

create an interferometer:

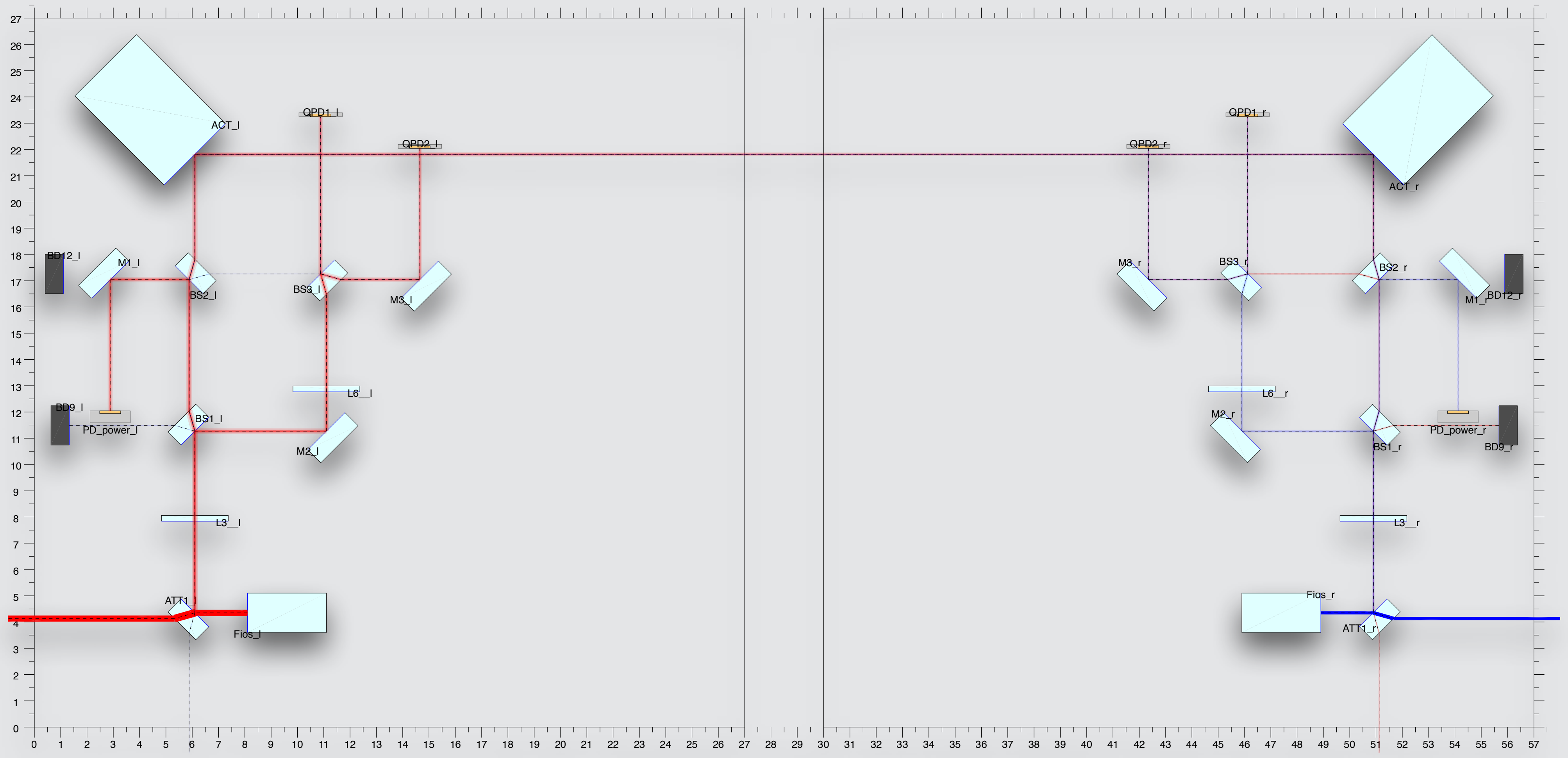
- only free beam
- copy interferometer, rotate it by 3°, align the actuator mirrors

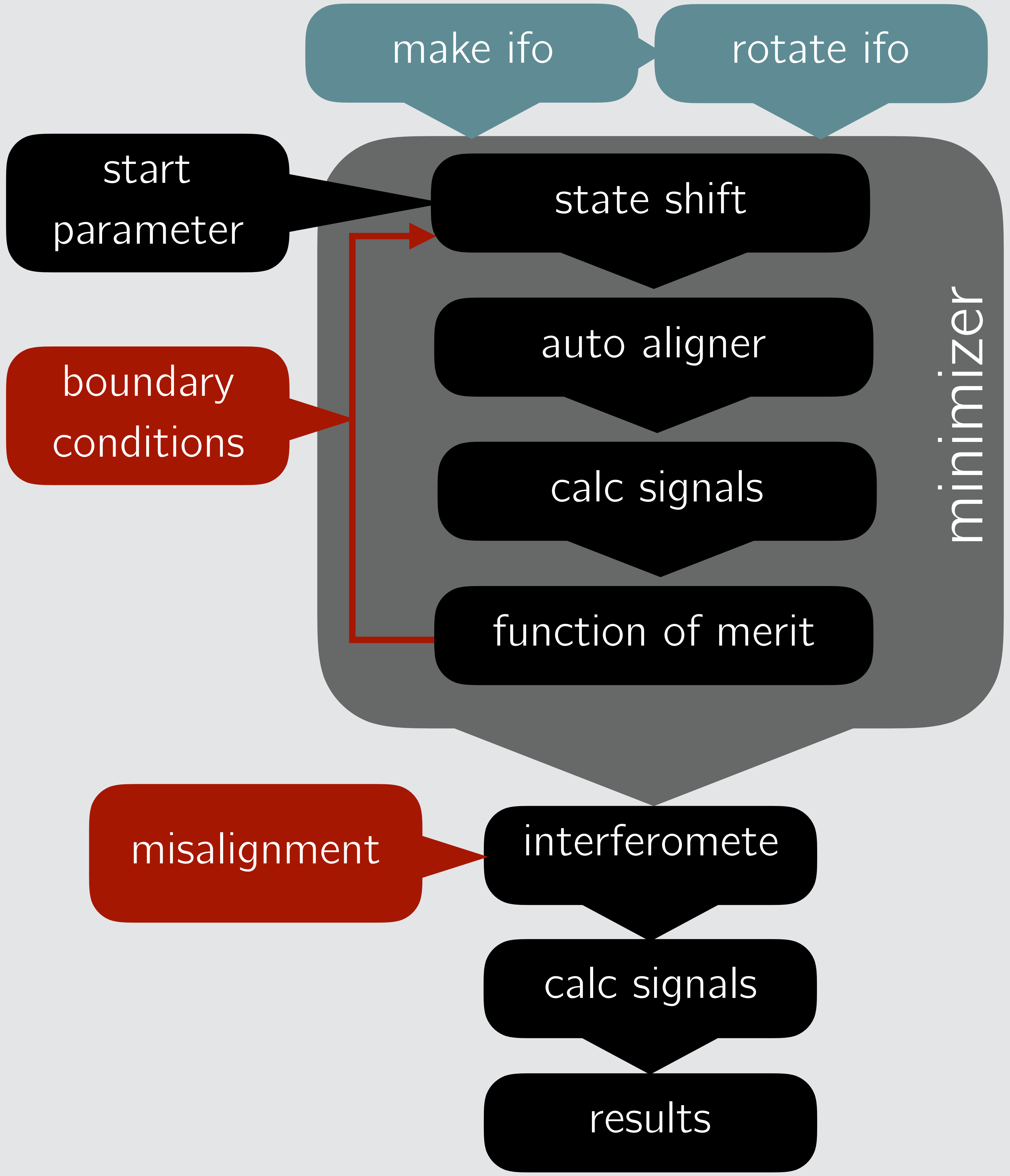


IfoCAD implementation

create an interferometer:

- only free beam
- copy interferometer, rotate it by 3°, align the actuator mirrors

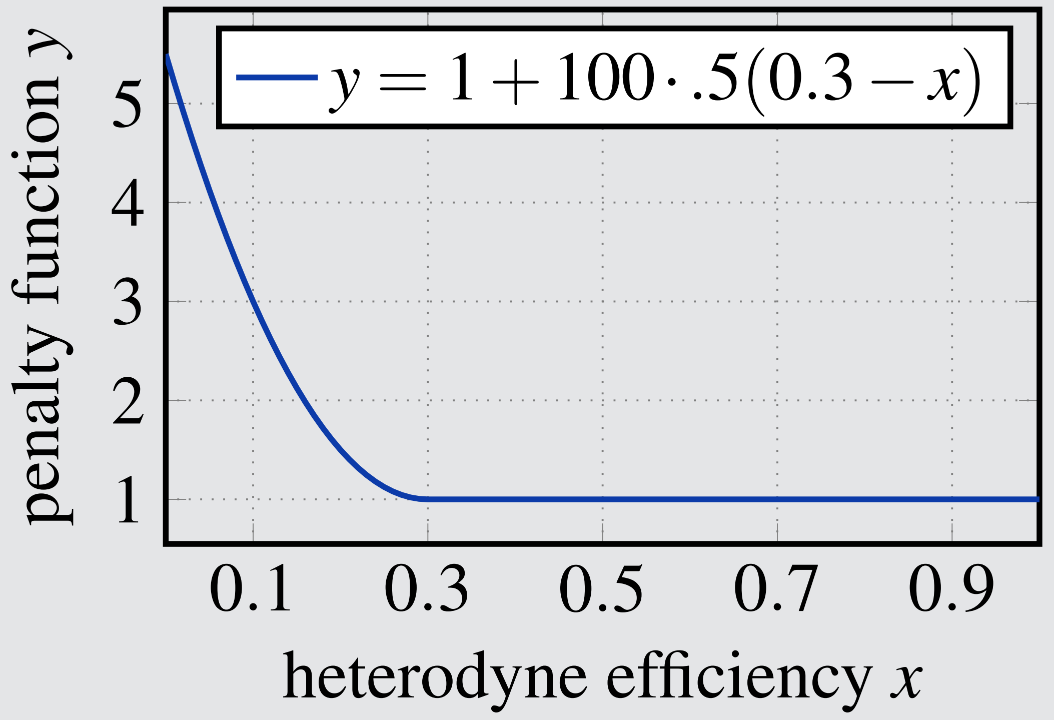


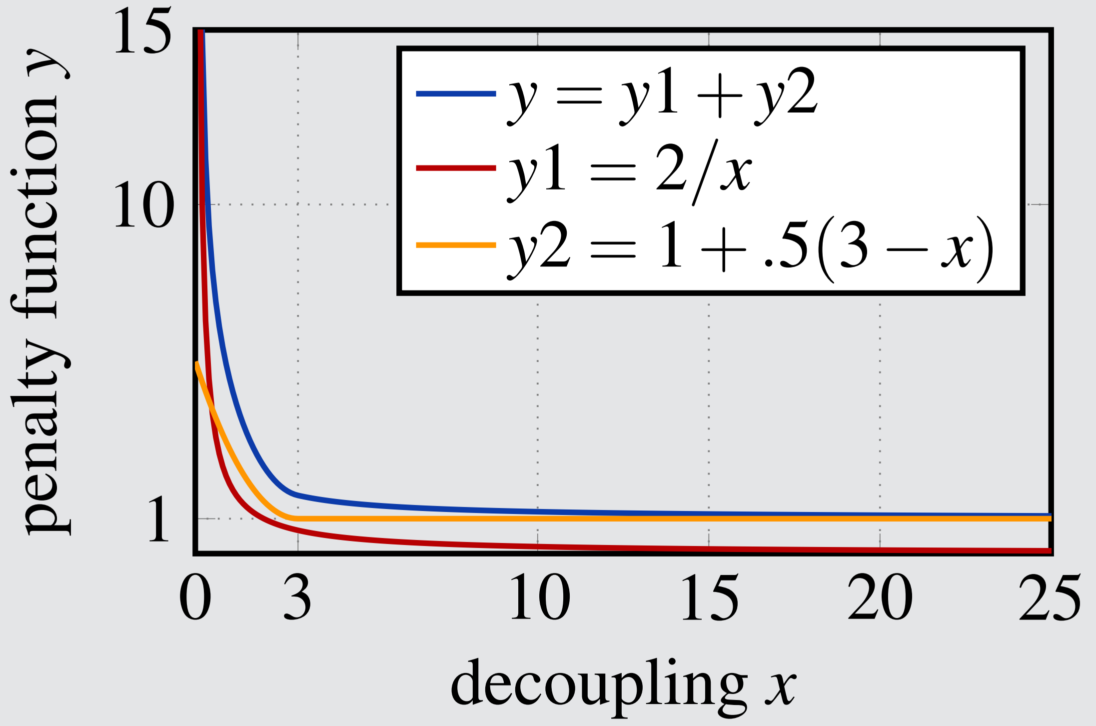


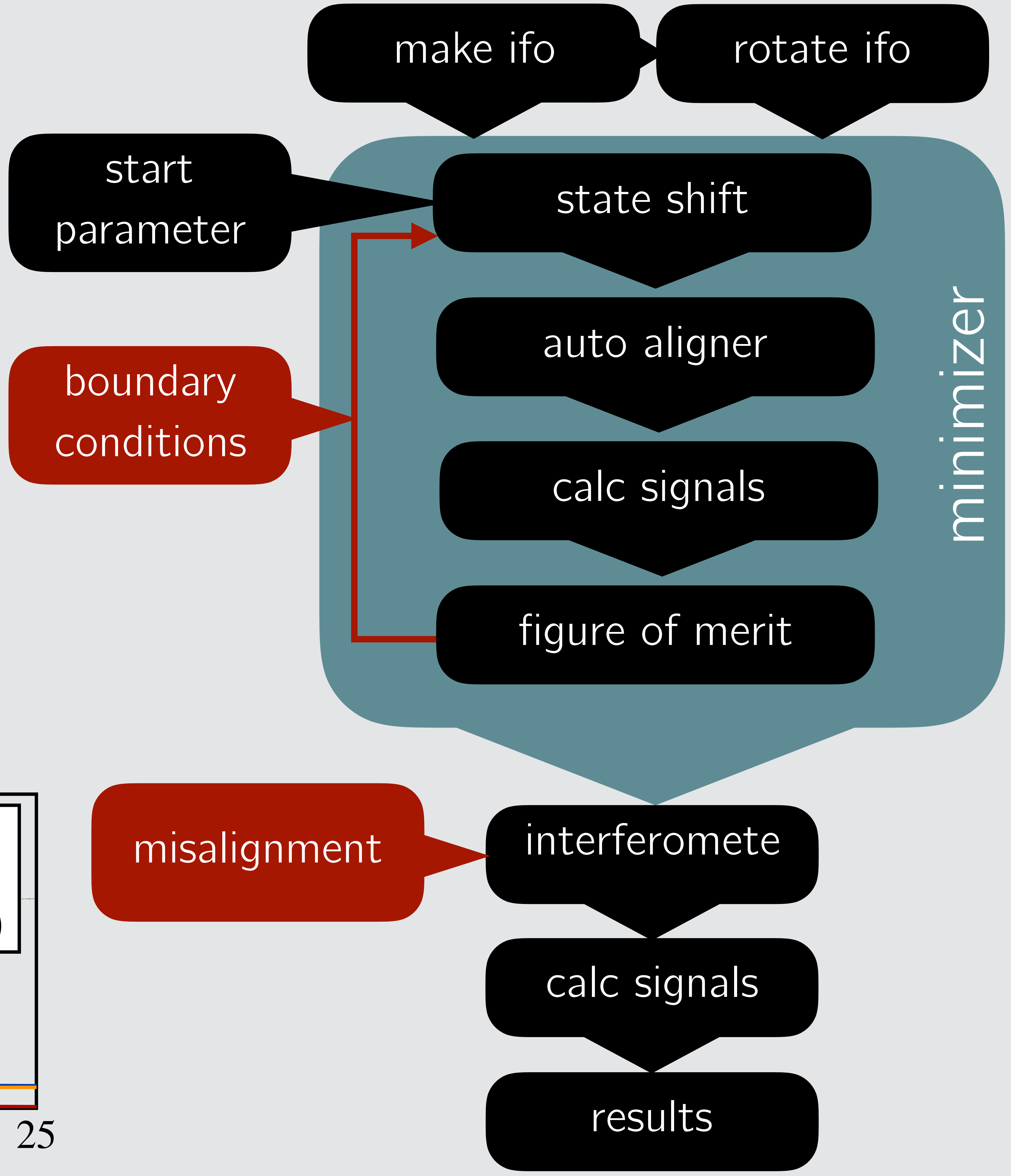
IfoCAD implementation

minimizer:

- parameter to be set with boundaries:
  - waist position
  - PD position
  - imaging system (foci, position)
- parameter to be controlled (signals):
  - coupling coefficients
  - heterodyne efficiency
- figure of merit
  - penalty functions like:



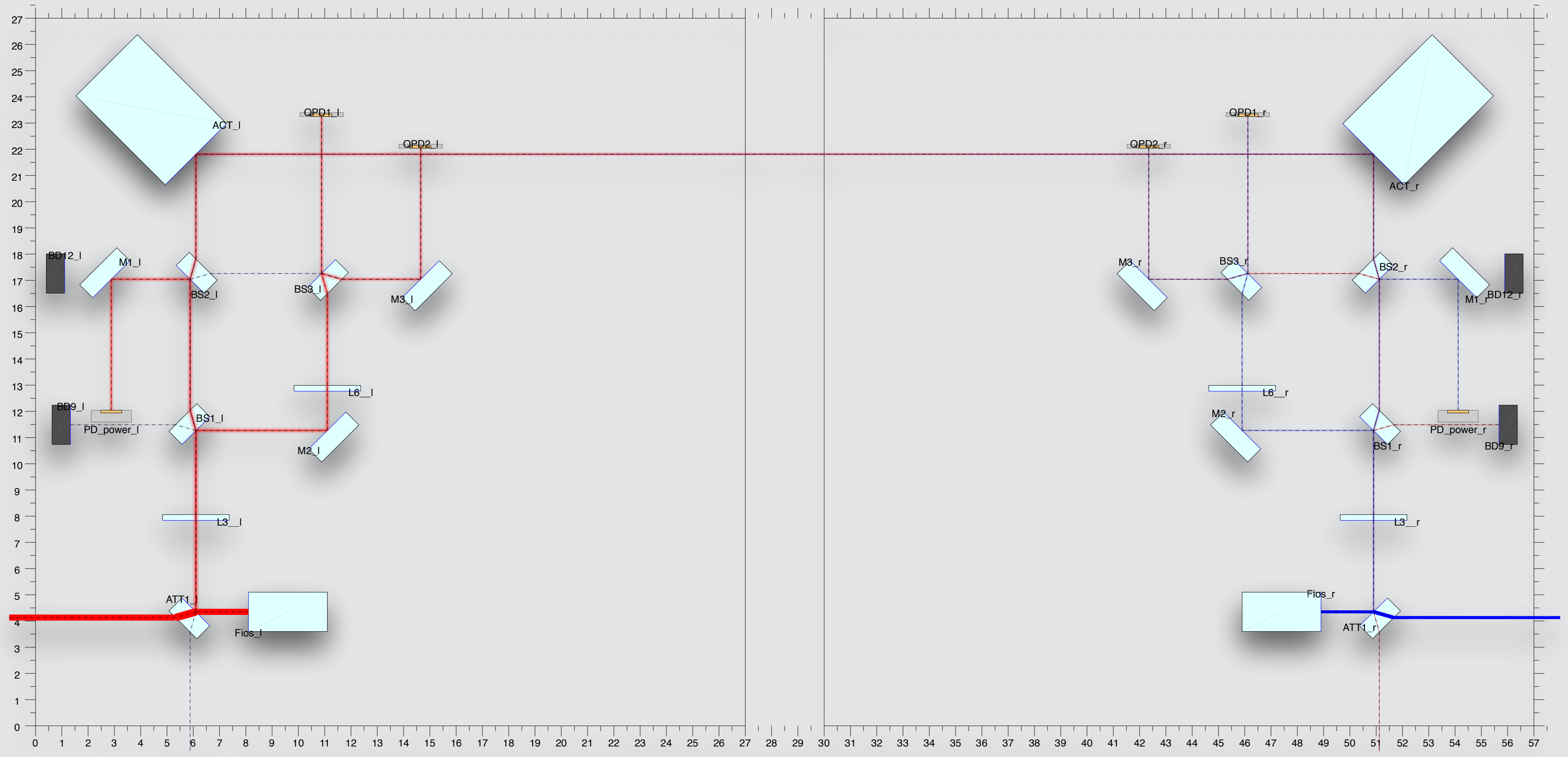


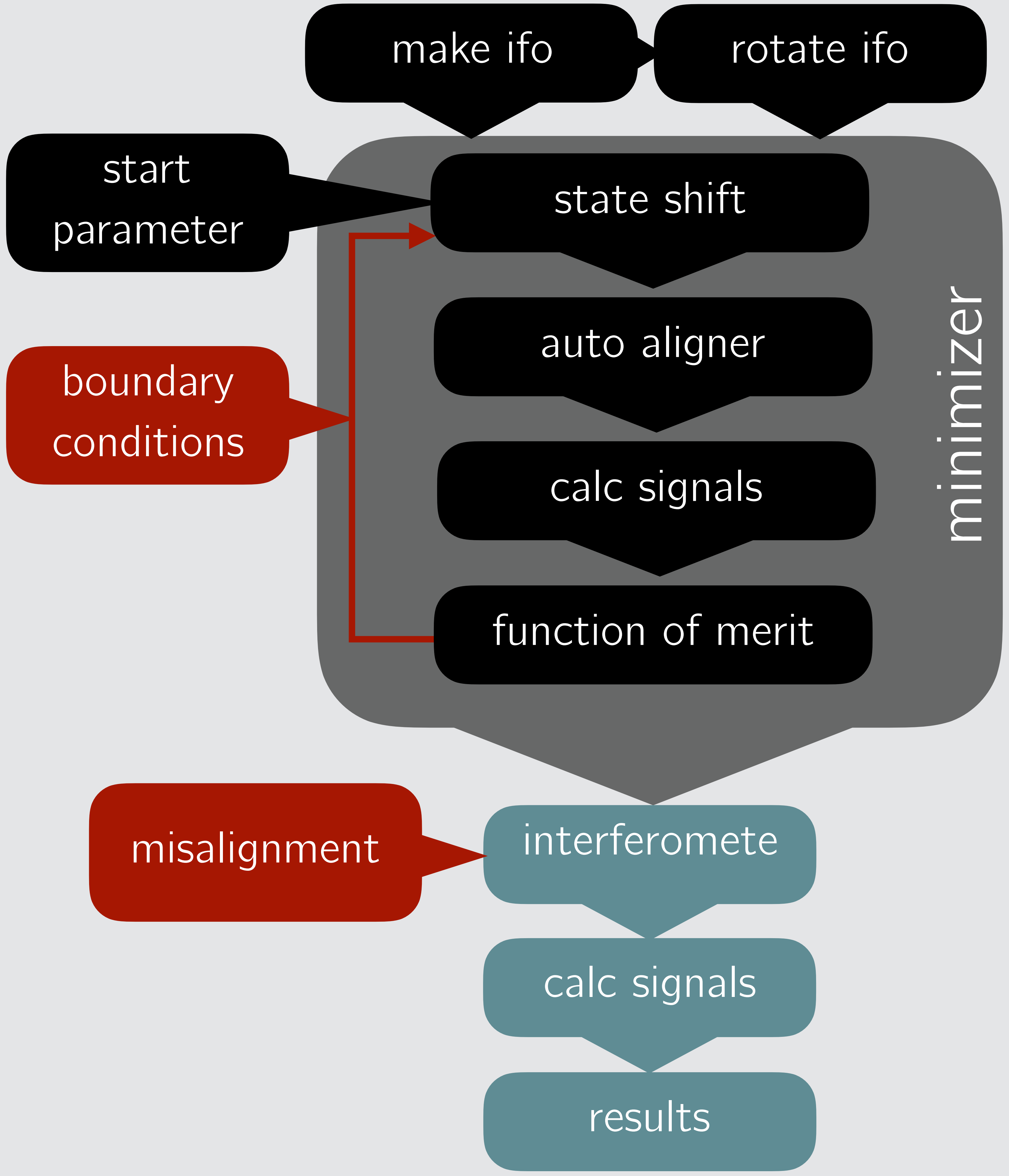


IfoCAD implementation

final interferometer:

- check alignment accuracy:
  - Displacement: 100 µm
  - Angular: 50 µrad
- check signals for the misaligned case
- note minimizer results





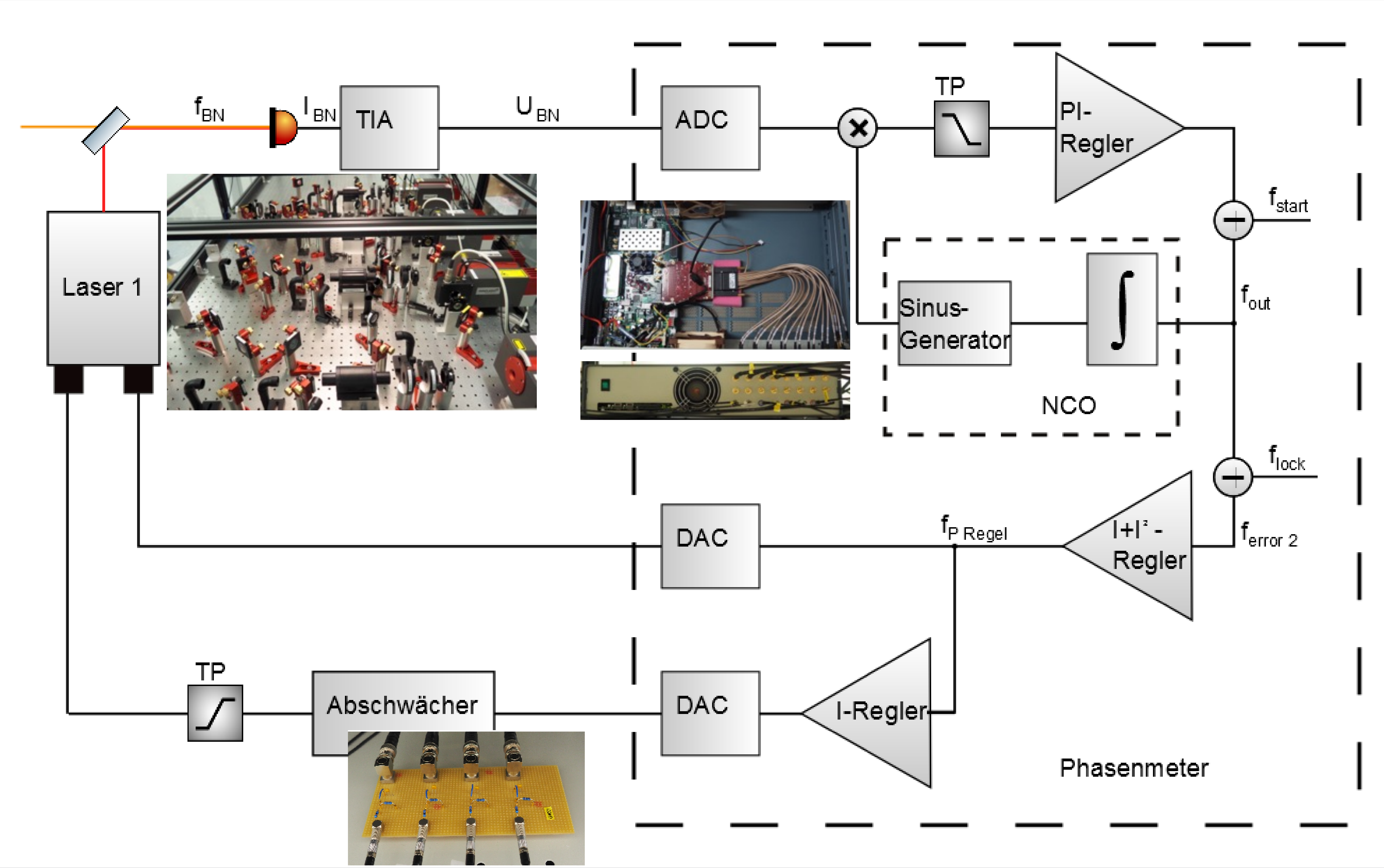
Frequency plan for the laser locks

- phasemeter register: 13bits
- phasemeter sampling rate: 80MHz
- beat note frequencies between NPRO lasers and the iodine stabilized laser

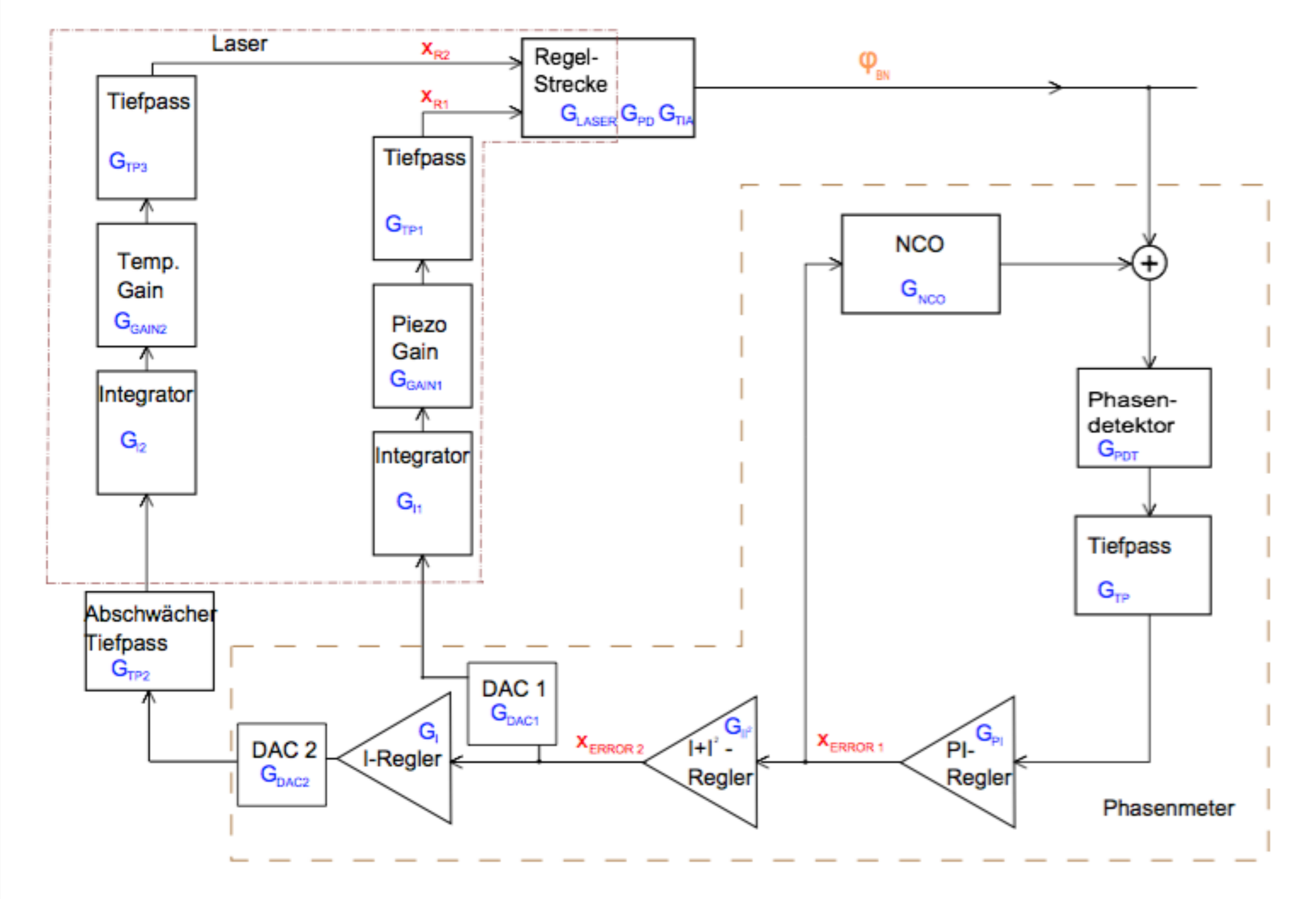
$$\frac{80\,\text{MHz}}{2^4} + \frac{80\,\text{MHz}}{2^5} + 0 \cdot \frac{80\,\text{MHz}}{2^{13}} = 7,5\,\text{MHz}$$
$$\frac{80\,\text{MHz}}{2^4} + \frac{80\,\text{MHz}}{2^5} + 1 \cdot \frac{80\,\text{MHz}}{2^{13}} = 7,5098\,\text{MHz}$$
$$\frac{80\,\text{MHz}}{2^4} + \frac{80\,\text{MHz}}{2^5} + 7 \cdot \frac{80\,\text{MHz}}{2^{13}} = 7,5684\,\text{MHz}$$
$$\frac{80\,\text{MHz}}{2^4} + \frac{80\,\text{MHz}}{2^5} + 11 \cdot \frac{80\,\text{MHz}}{2^{13}} = 7,6074\,\text{MHz}.$$

- beat note frequencies in the 3 Backlink experiment in the kHz band

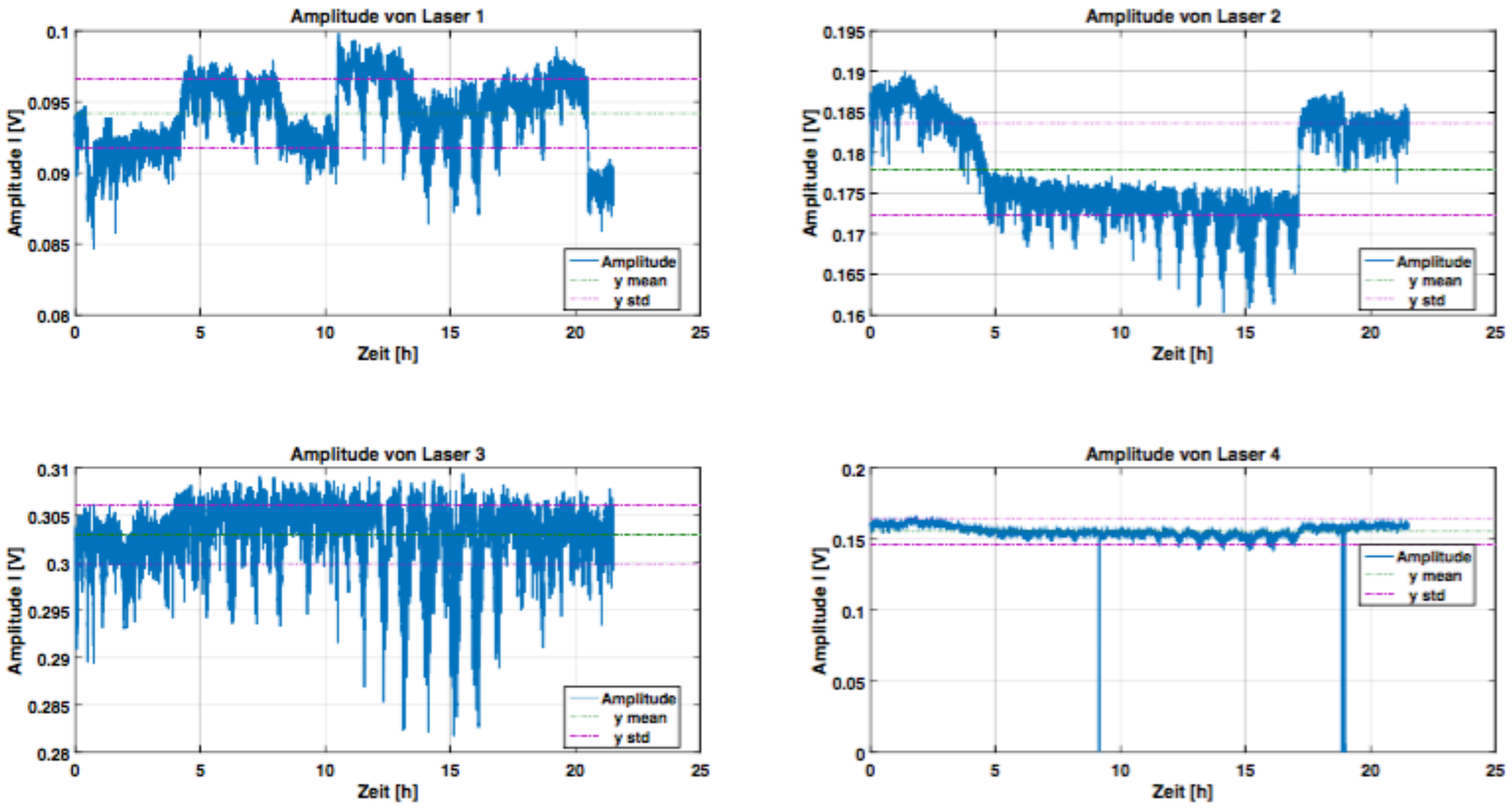
Frequency stabilisation - PM control loop



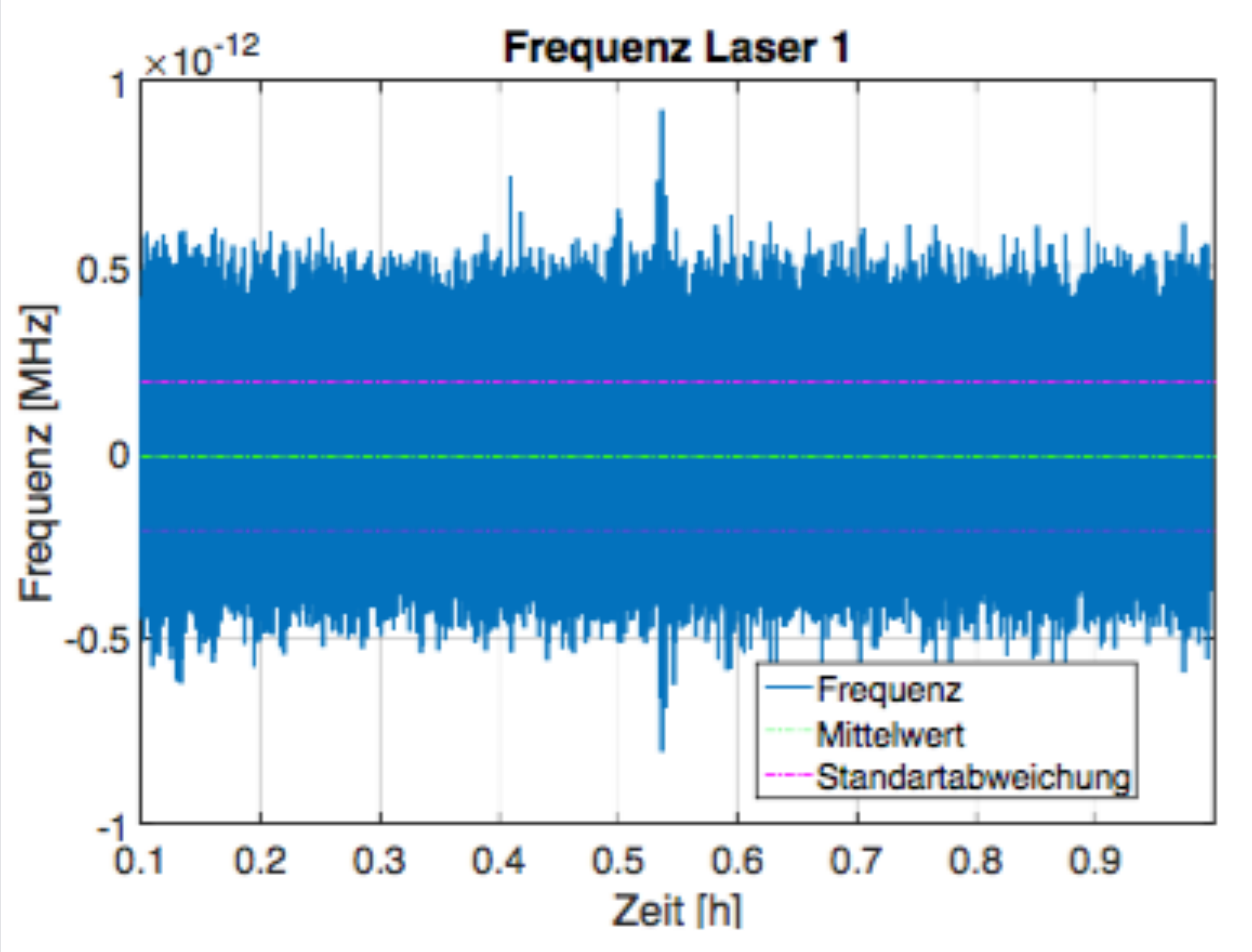
Frequency stabilisation - Block diagram

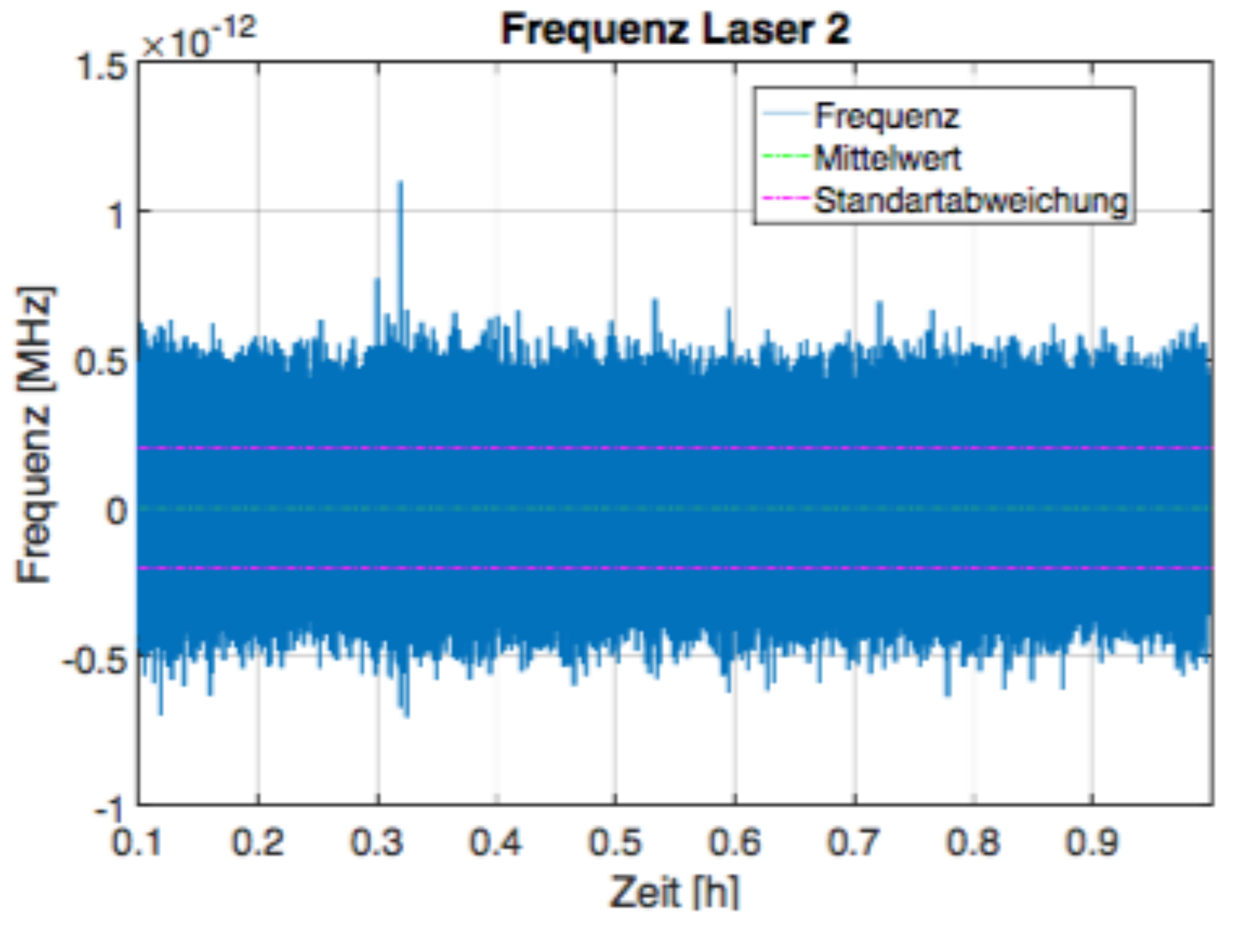


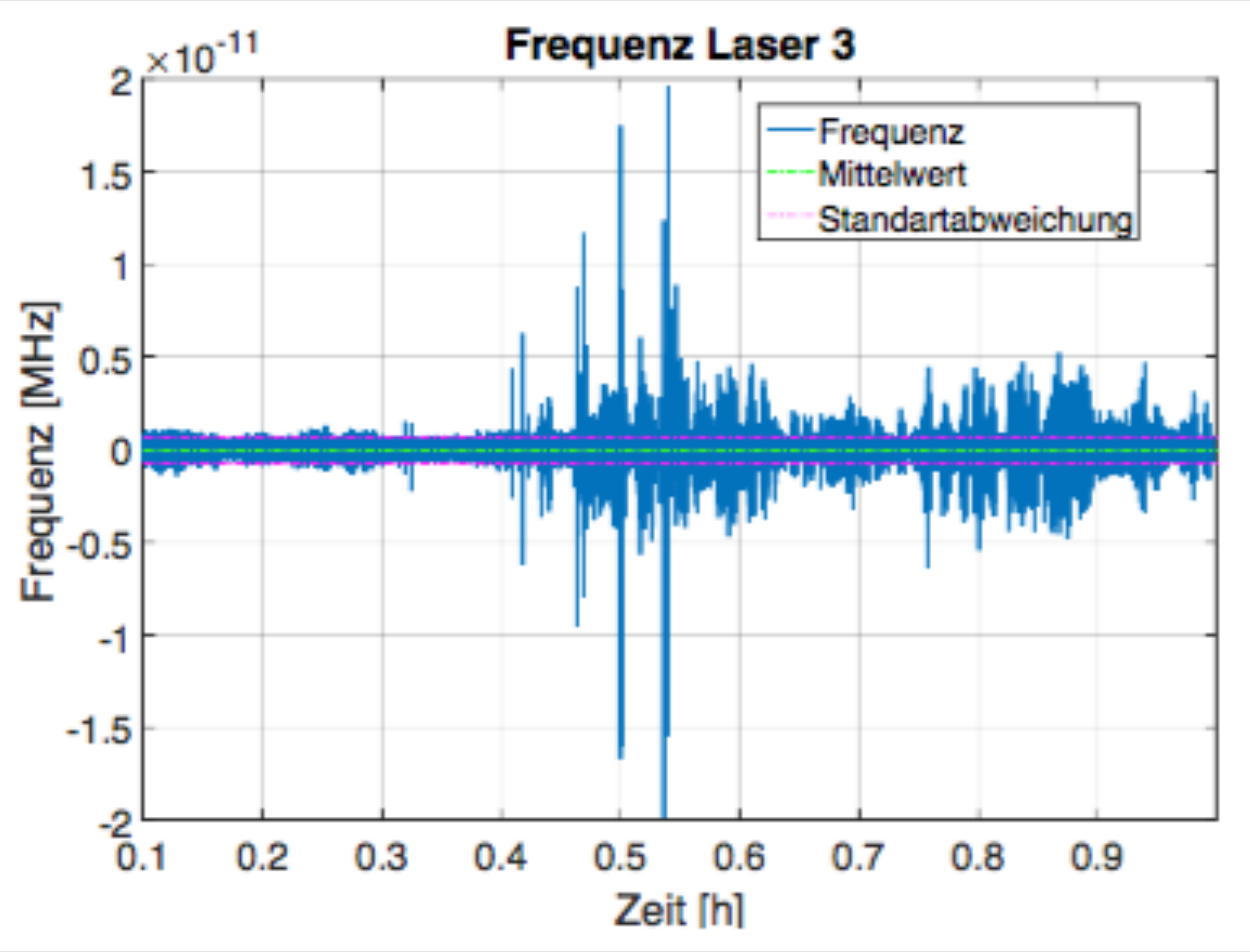
Frequency stabilisation - amplitude timeseries



Frequency stabilisation - frequency timeseries

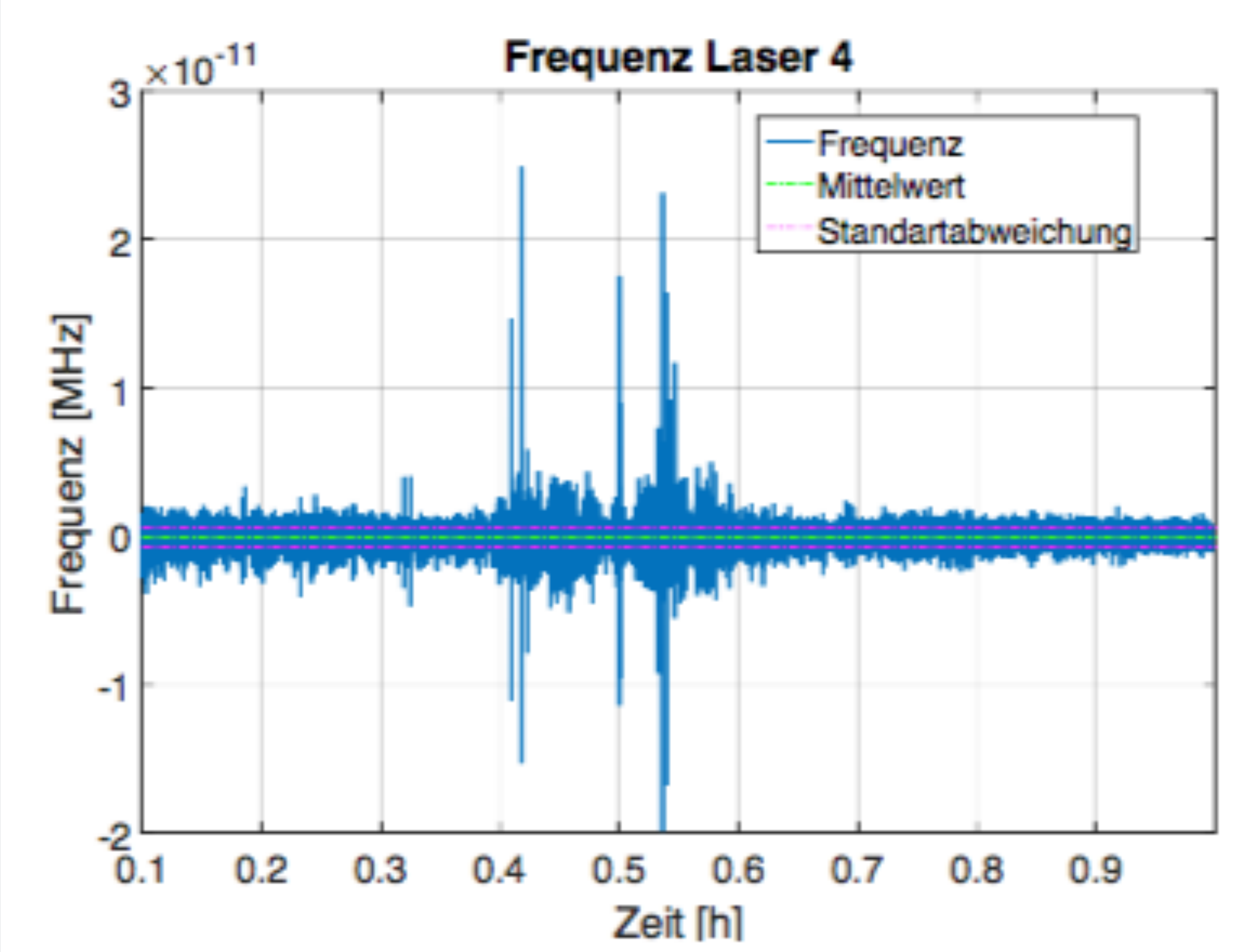






	Mittelwert in MHz	Standardabweichung in Hz	$f_{SOLL} - \bar{f}$ in Hz
Laser 1	7,5098	$2{,}02 \cdot 10^{-7}$	$1 \cdot 10^{-2}$
Laser 2	7,50000000000007	$2{,}05 \cdot 10^{-7}$	$7{,}4 \cdot 10^{-8}$
Laser 3	7,5684	$5{,}9 \cdot 10^{-7}$	$7{,}09 \cdot 10^{-4}$
Laser 4	7,6145	0,5	$7{,}08 \cdot 10^{3}$

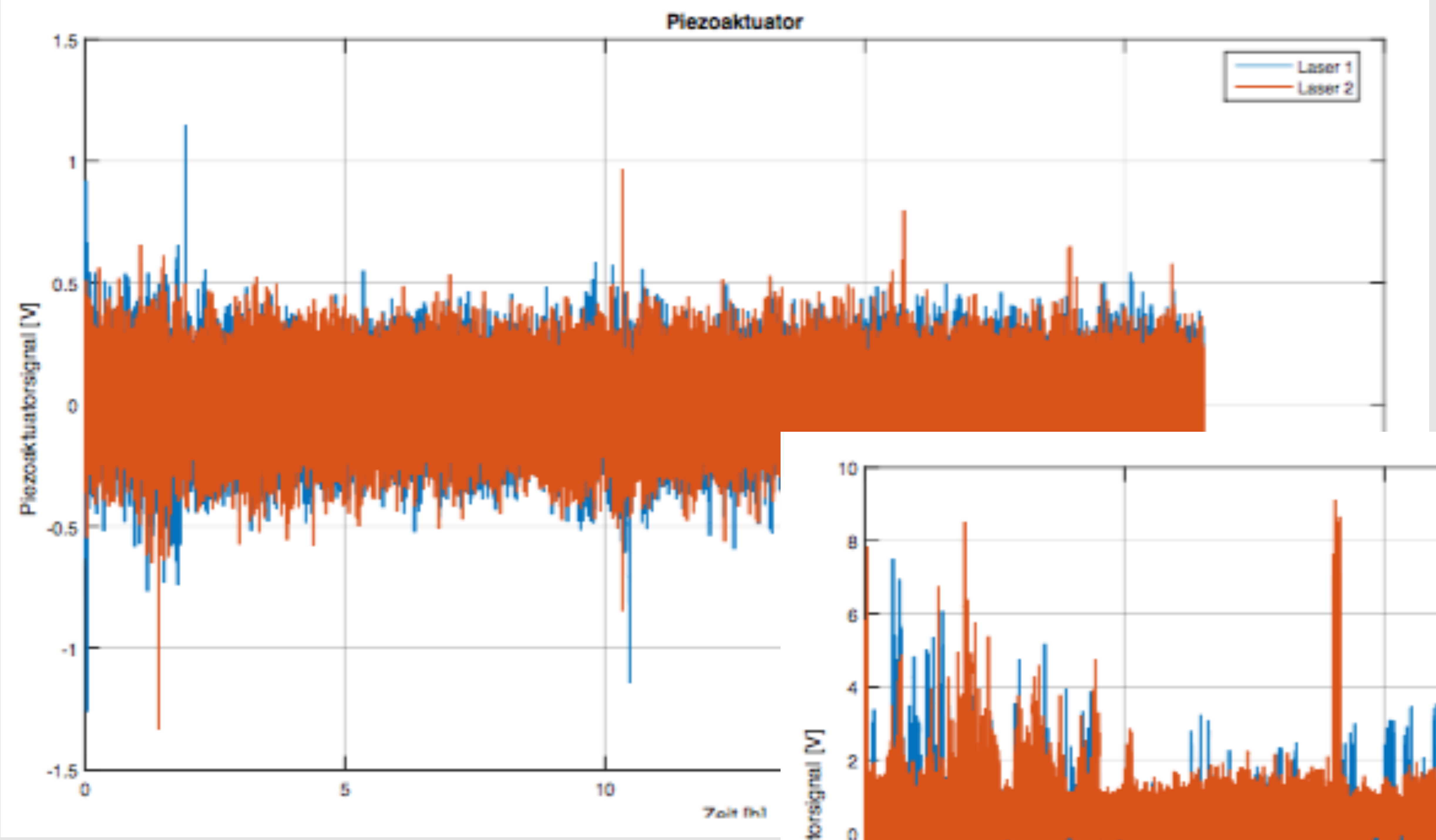
Tabelle 5.4.: Frequenzstatistik über etwa 20 Stunden.

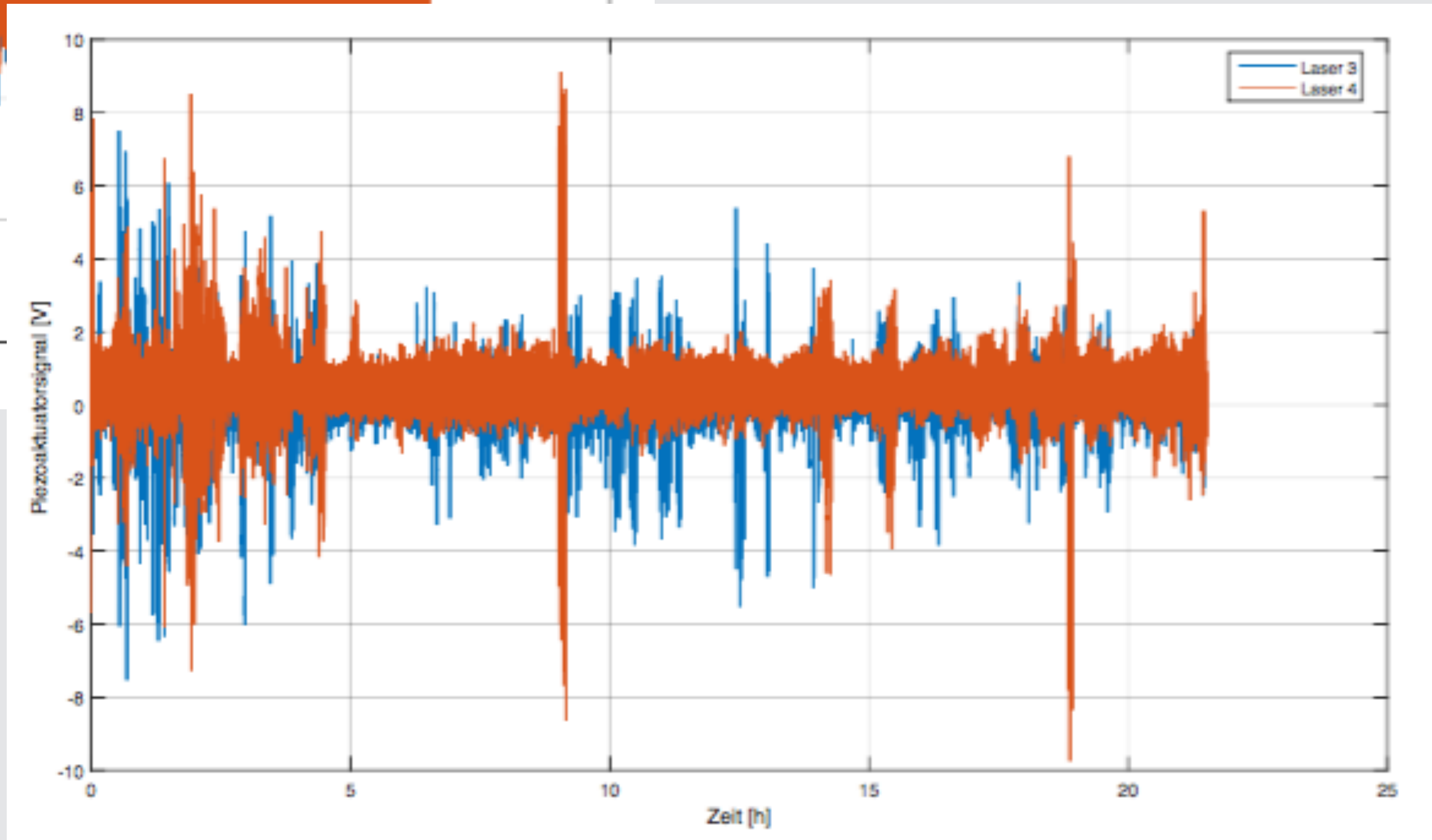


	Mittelwert in MHz	Standardabweichung in Hz	$f_{SOLL} - \bar{f}$ in Hz
Laser 1	7,5098	$2{,}0 \cdot 10^{-7}$	$9{,}2 \cdot 10^{-3}$
Laser 2	7,5000000000008	$2{,}05 \cdot 10^{-7}$	$8{,}38 \cdot 10^{-7}$
Laser 3	7,5684	$6{,}9 \cdot 10^{-7}$	$7{,}0894 \cdot 10^{-4}$
Laser 4	7,6074	$6{,}5 \cdot 10^{-7}$	$1{,}11 \cdot 10^{-2}$

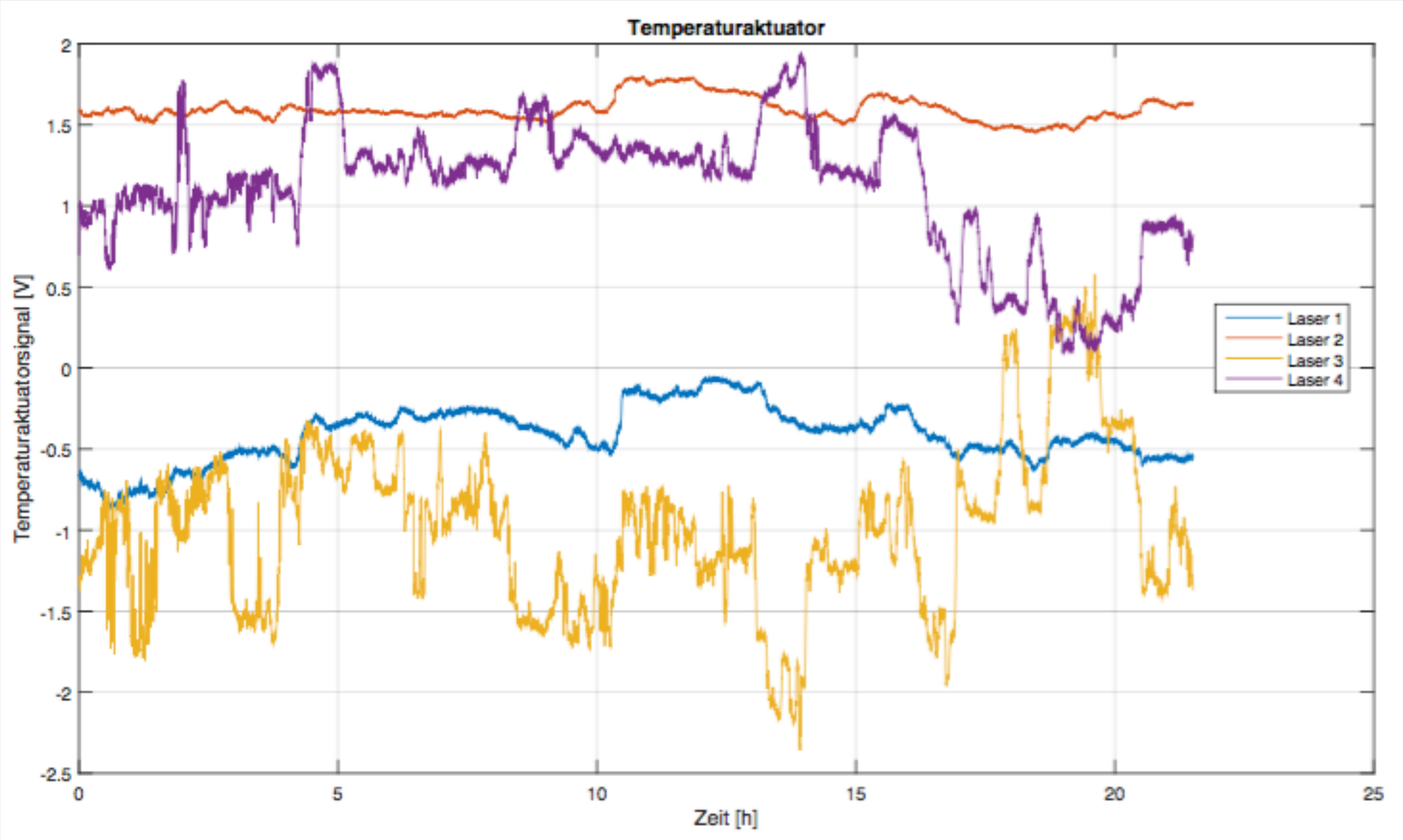
Tabelle 5.5.: Frequenzstatistik über etwa eine Stunde.

Frequency stabilisation - Piezoactuator





Frequency stabilisation - Temperature



Frequency stabilisation - in loop SD

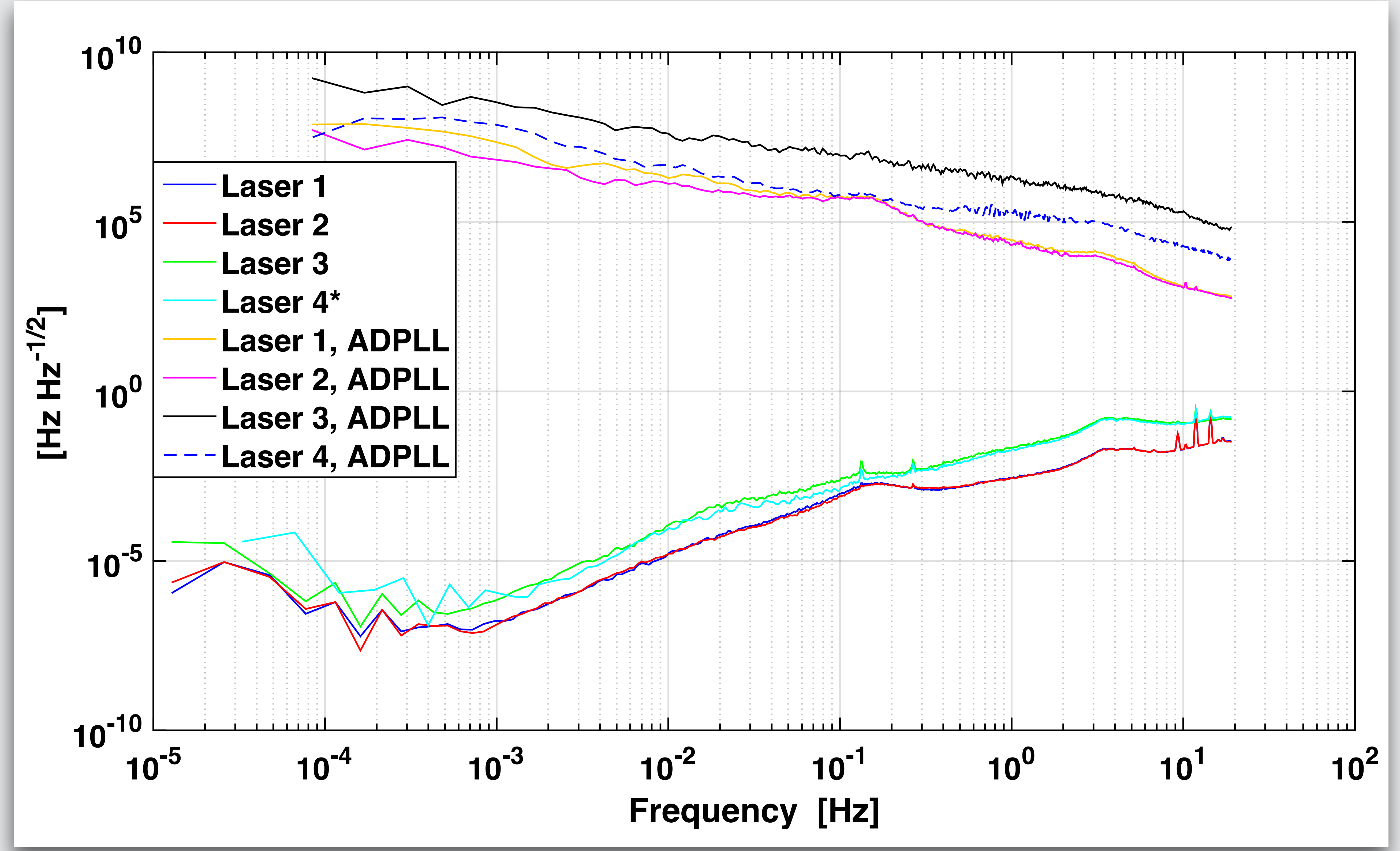
w/o stabilization:

- 10^3-10^5 Hz/√Hz at 10 Hz
- 10^7-10^8 Hz/√Hz at 0.1 mHz

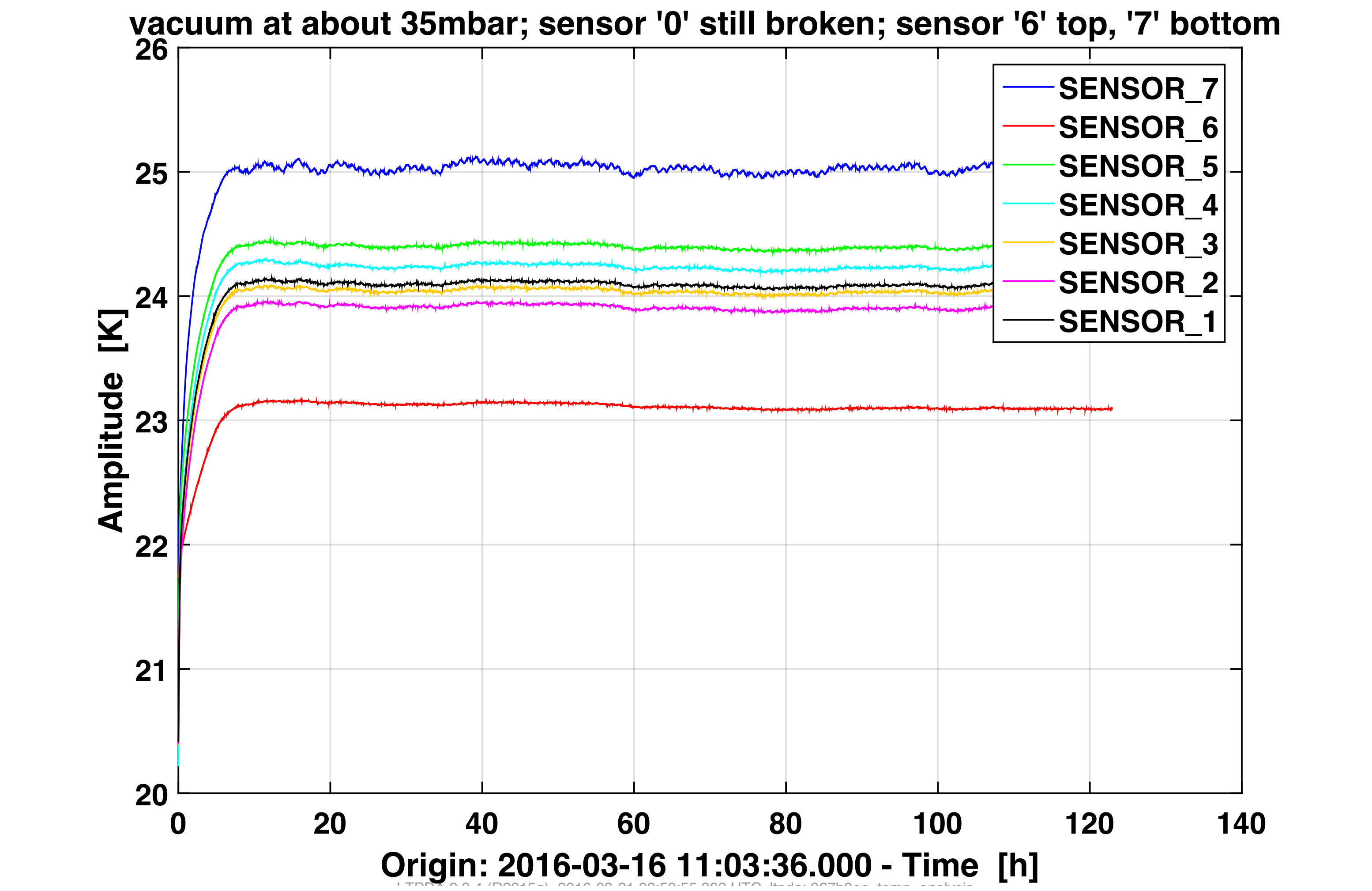
with stabilization:

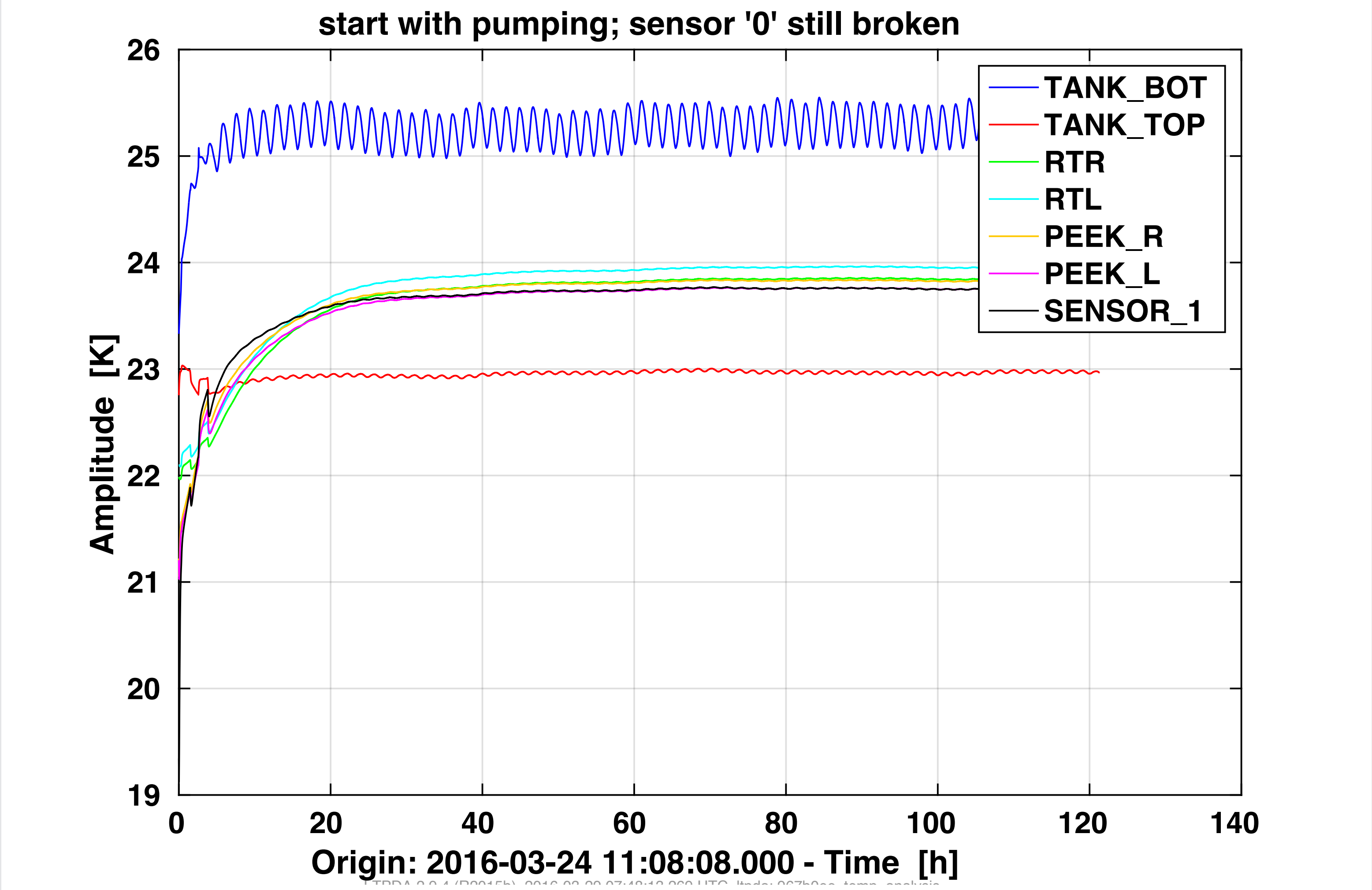
- 10^{-1}-10^{-2} Hz/√Hz at 1 Hz
- 10^{-5}-10^{-7} Hz/√Hz at 0.1 mHz

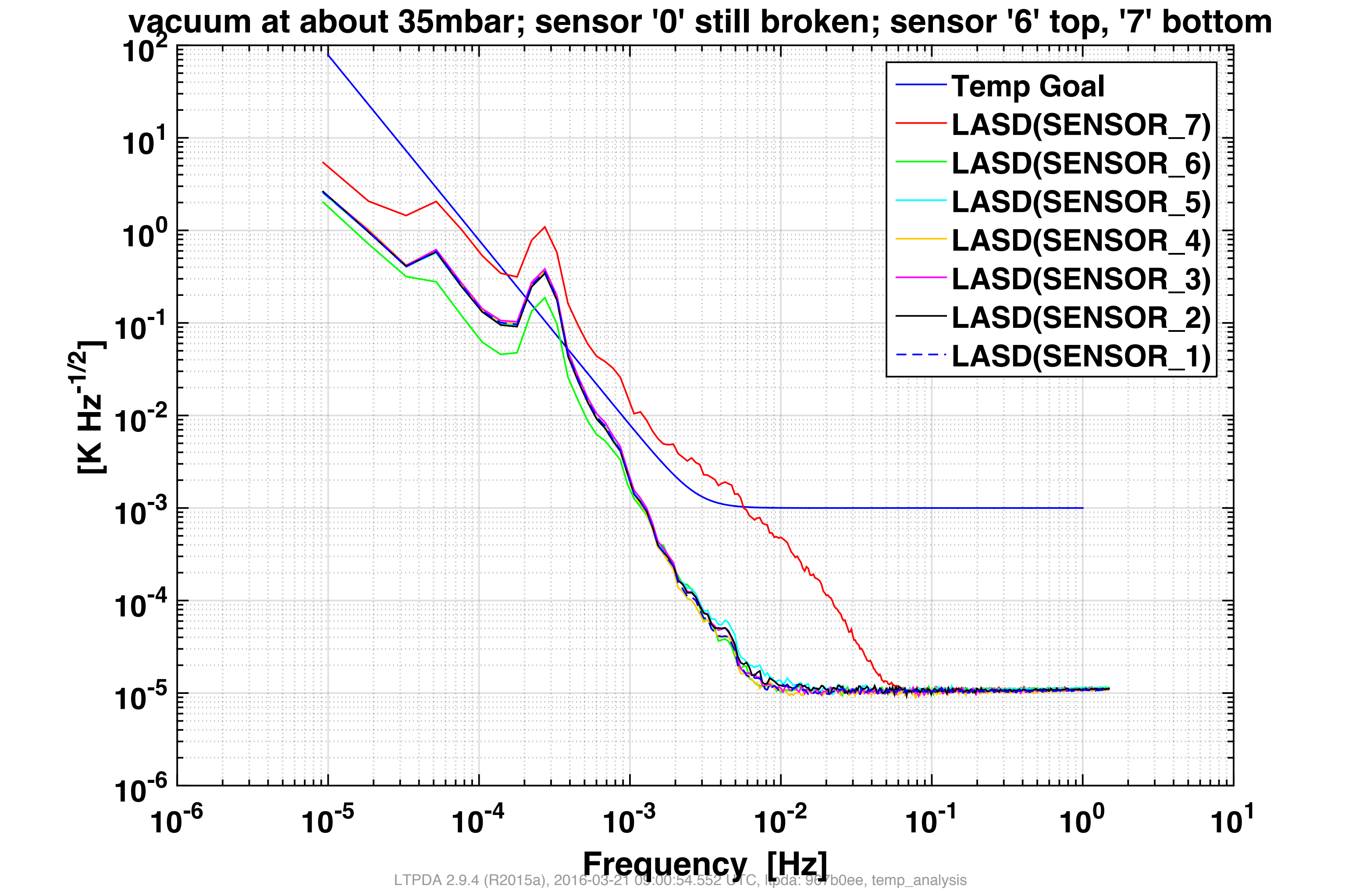
- 10^{15} Hz/√Hz dynamic range

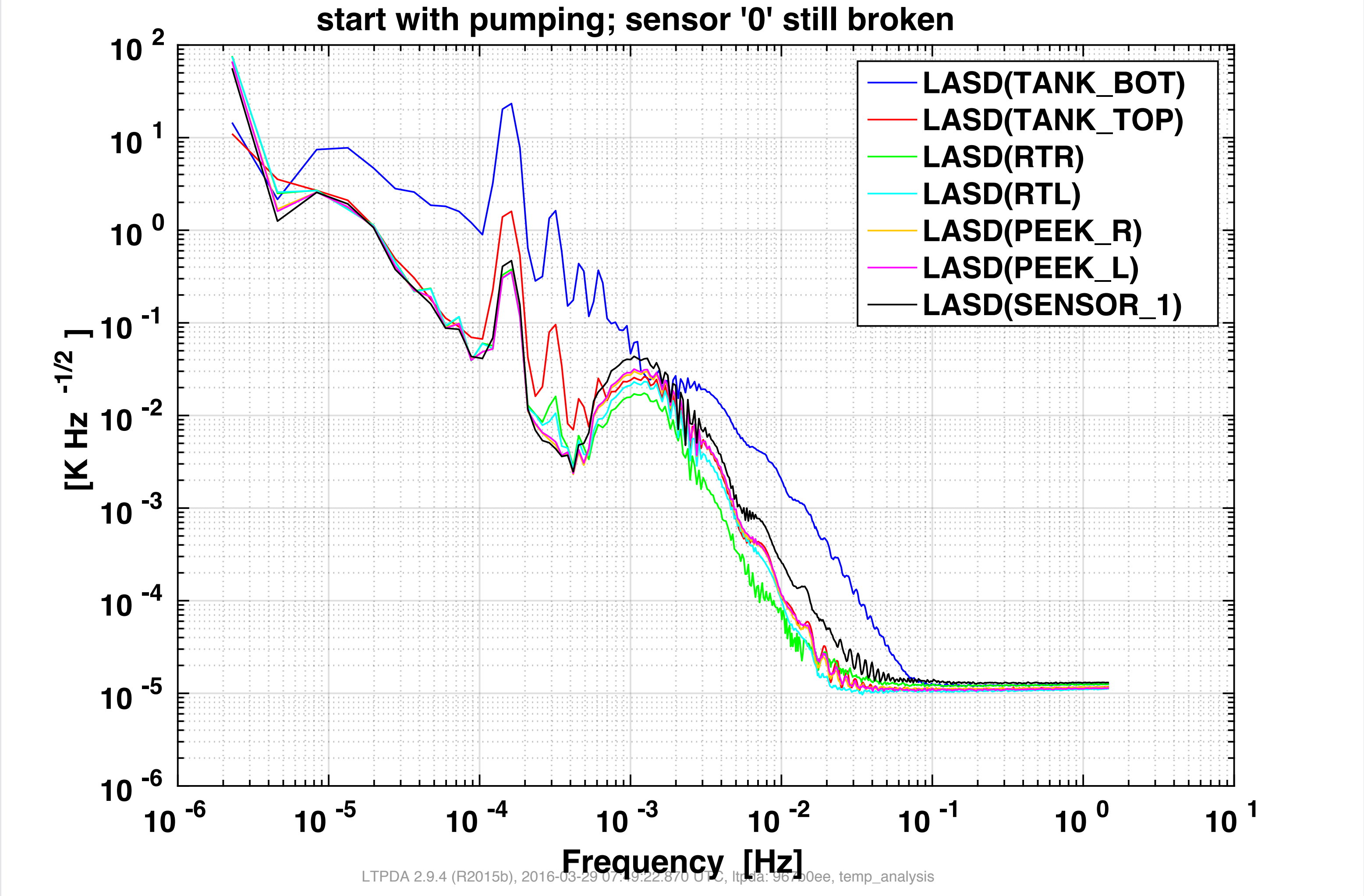


Temperature time series

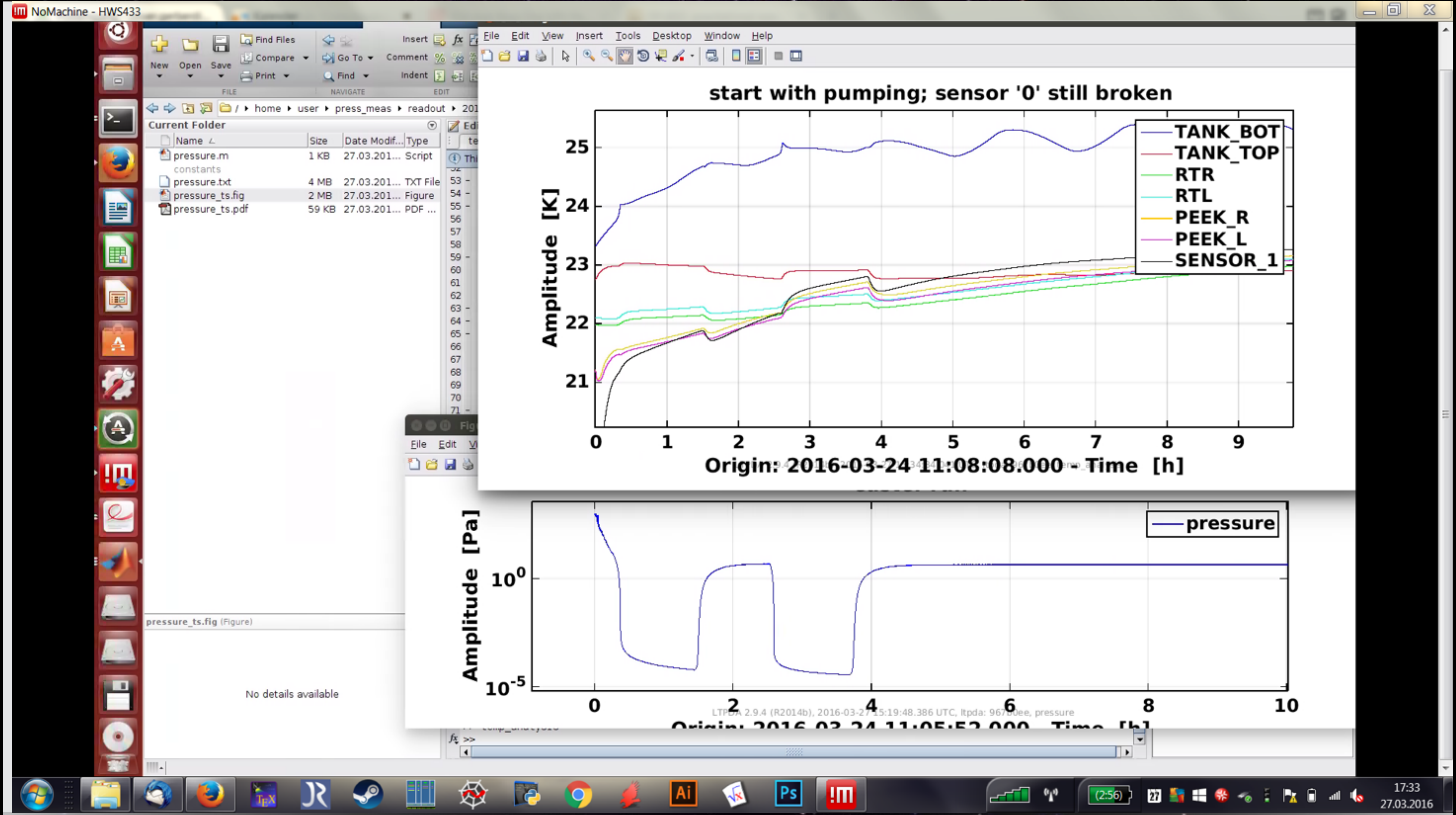




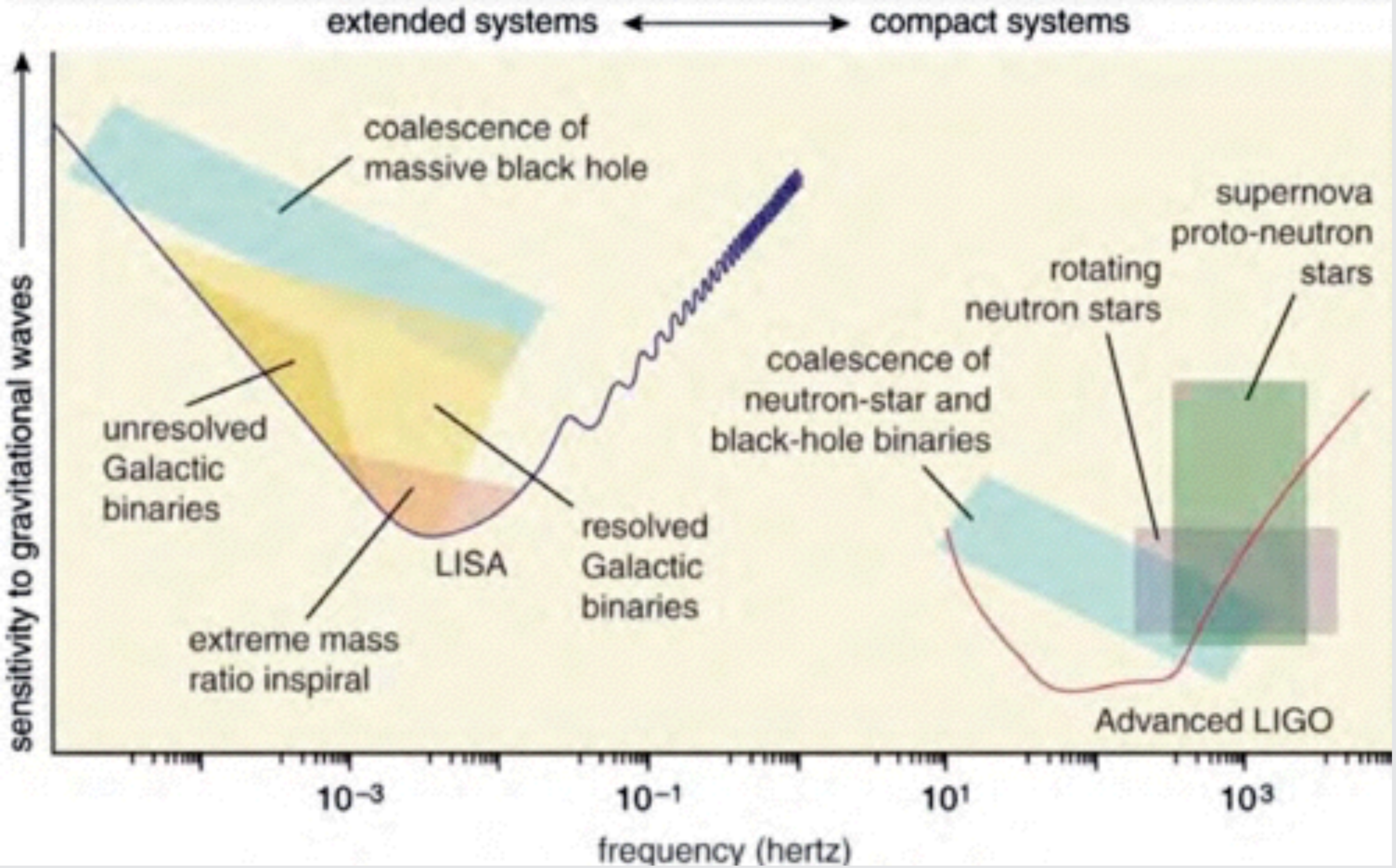




Pumping screenshot



GW Sources


extended systems
compact systems
sensitivity to gravitational waves
coalescence of
massive black hole
unresolved
Galactic
binaries
LISA
resolved
Galactic
binaries
extreme mass
ratio inspiral
supernova
proto-neutron
stars
rotating
neutron stars
coalescence of
neutron-star and
black-hole binaries
Advanced LIGO
10−3
10−1
101
103
frequency (hertz)

Beam alignment - CABAM

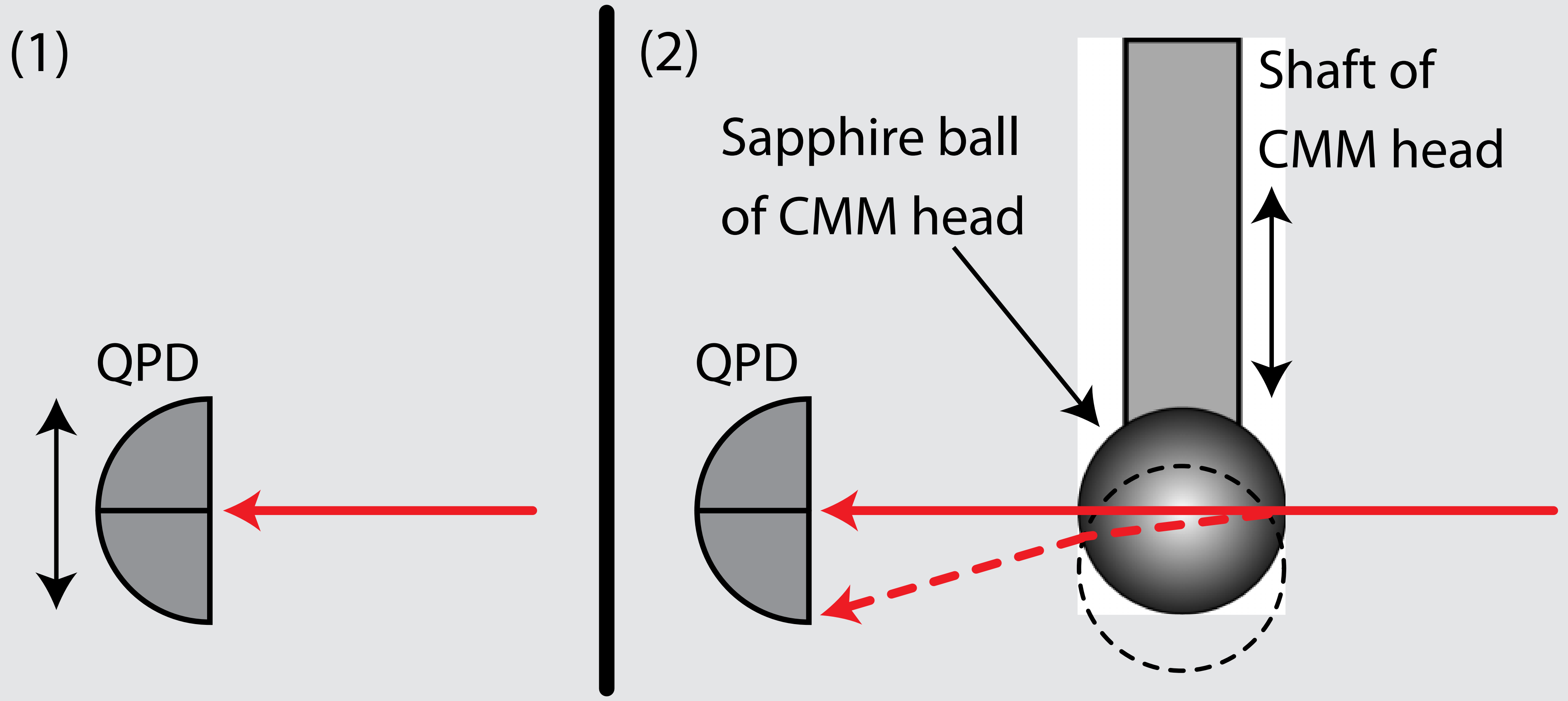
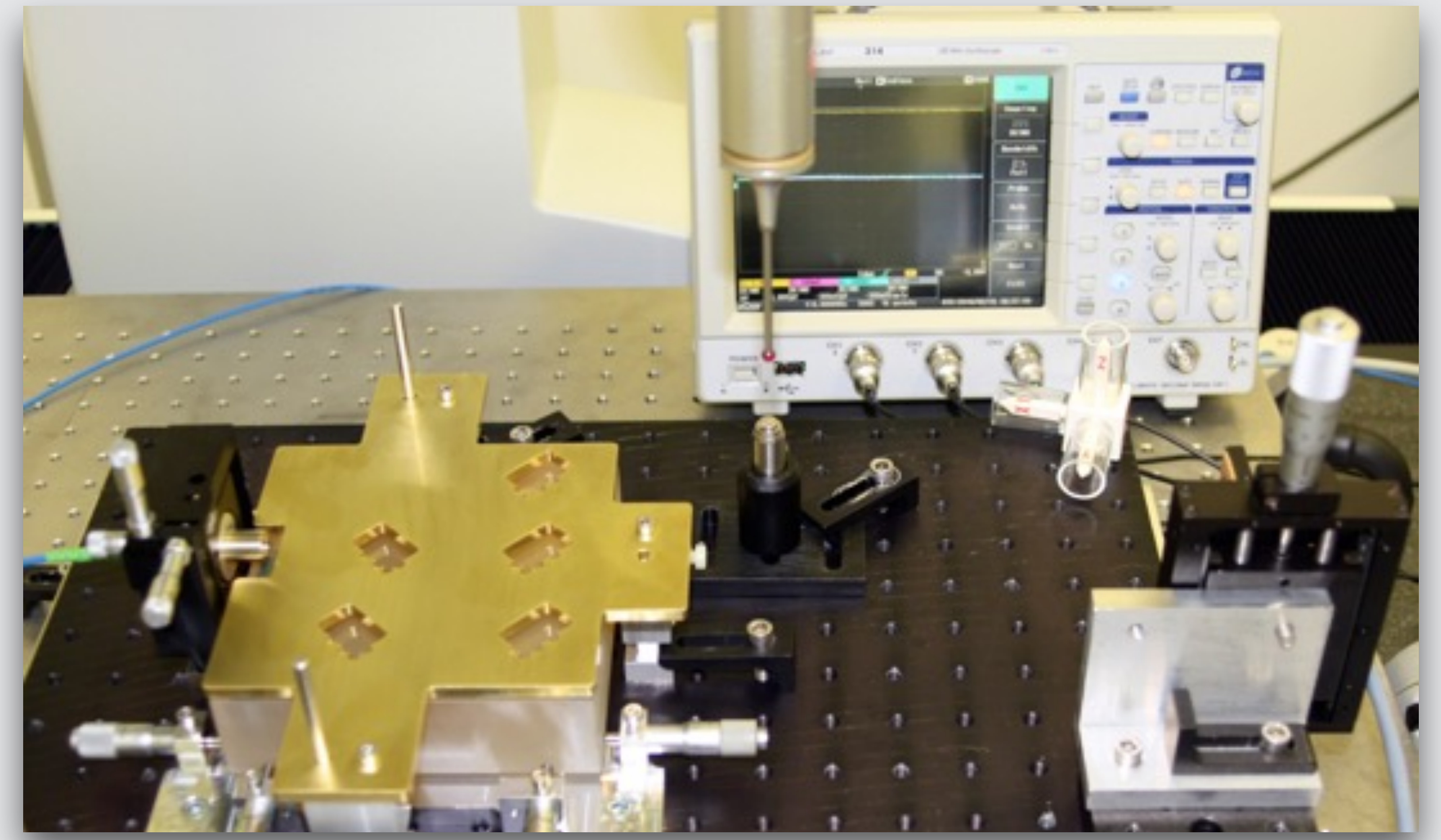


Fig. 1. (1) First, the incoming beam (arrow from right) is centered on a position-sensitive quadrant photodiode (QPD) by moving the QPD on a translation stage in two dimensions transversal to the incident beam. (2) Second, the sapphire ball of the CMM probe head is positioned in the beam such that the beam passing through the sapphire ball remains centered on the QPD. The dashed arrow line indicates the beam path when the CMM sapphire ball is not positioned correctly (dashed ball) in the beam, leading to a nonzero beam-displacement signal from the QPD.



Precision absolute measurement and alignment of laser beam direction and position

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For the construction of high-precision optical assemblies, direction and position measurement and control of the involved laser beams are essential. While optical components such as beamsplitters and mirrors can be positioned and oriented accurately using coordinate measuring machines (CMMs), the position and direction control of laser beams is a much more intriguing task since the beams cannot be physically contacted. We present an easy-to-implement method to both align and measure the direction and position of a laser beam using a CMM in conjunction with a position-sensitive quadrant photodiode. By comparing our results to calibrated angular and positional measurements we can conclude that with the proposed method, a laser beam can be both measured and aligned to the desired direction and position with 10 μrad angular and 3 μm positional accuracy.

OCIS codes: (120.0120) Instrumentation, measurement, and metrology; (120.4640) Optical instruments.
http://dx.doi.org/10.1364/AO.53.006503

UV glue: EMIUV Optocast 3553- LV-UTF

OPTOCAST	Color	Viscosity – cps.	Storage Conditions	Hardness REX D	C.T.E.	Refractive Index [1]	Elongation	Tg - C°	Max. filler size	Cure Method
3400	Gray	175,000	-20°C	90+	18	N/A	2%	>150	100	UV/THermal
3408	Gray	40,000	-20°C	90+	16	N/A	2%	>150	12	UV/Thermal
3410	Gray	95,000	-20°C	90+	14	N/A	2%	>150	24	UV/Thermal
3411	Gray	17,000	-20°C	90	19	N/A	3%	>150	100	UV/Thermal
3415	Gray	100,000	-20°C	90	12	N/A	2%	>150	80	UV/Thermal
3421	Gray	20,000	-20°C	88	19	N/A	8%	115	100	UV/Thermal
3440	Gray	45,000 mixed	-20°C	90+	24	N/A	2%	150	24	UV/Thermal
3505	Clear	350	RT	88	65	1.517	3%	145	N/A	UV
3506	Clear	850	RT	81	65	1.52	12%	120	N/A	UV
3507	Clear	1,000	RT	88	65	152	3%	145	N/A	UV
3514	Clear	8,000	RT	A-80	65	1.495	100%	-10	N/A	UV
3553	Clear	1,000	RT	88	60	1.512	4%	145	N/A	UV
3553-UTF	Clear	800	RT	88	60	1.513	4%	145	N/A	UV
3601	Clear	Mixed 1,800	RT	90	55	1.53	2%	130	N/A	Thermal
3602	Clear	Mixed 1,000	RT	84	65	1.54	15%	65	N/A	Thermal
3653	Amber	Mixed 3,000	RT	85	55	1.563	15%	120	N/A	Thermal
3663	Amber	4,000	0°C	85	55	1.54	15%	100	N/A	Thermal
AC-3723 series	Clear	2,000-250,000	Shelf	75	80	1.48	25%	40	N/A	UV/Thermal
AC-3724 series	Clear	2,000-250,000	Shelf	57	75	1.49	75%	36	N/A	UV/Thermal
AC-3741	White	110,000	-20°C	78	18	N/A	20%	100	24	UV/Thermal
AC-3761	Clear	450	Shelf	85	60	1.52	10%	90	N/A	UV/Thermal
AC-3762	Clear	5,000	Shelf	63	72	1.51	45%	55	N/A	UV/THermal