ETpathfinder sensing and control

Hans Van Haevermaet for the UAntwerpen ETpf team

Workshop: Essential Technologies for the EinsteinTelescope – 27/11/2023

ETpathfinder

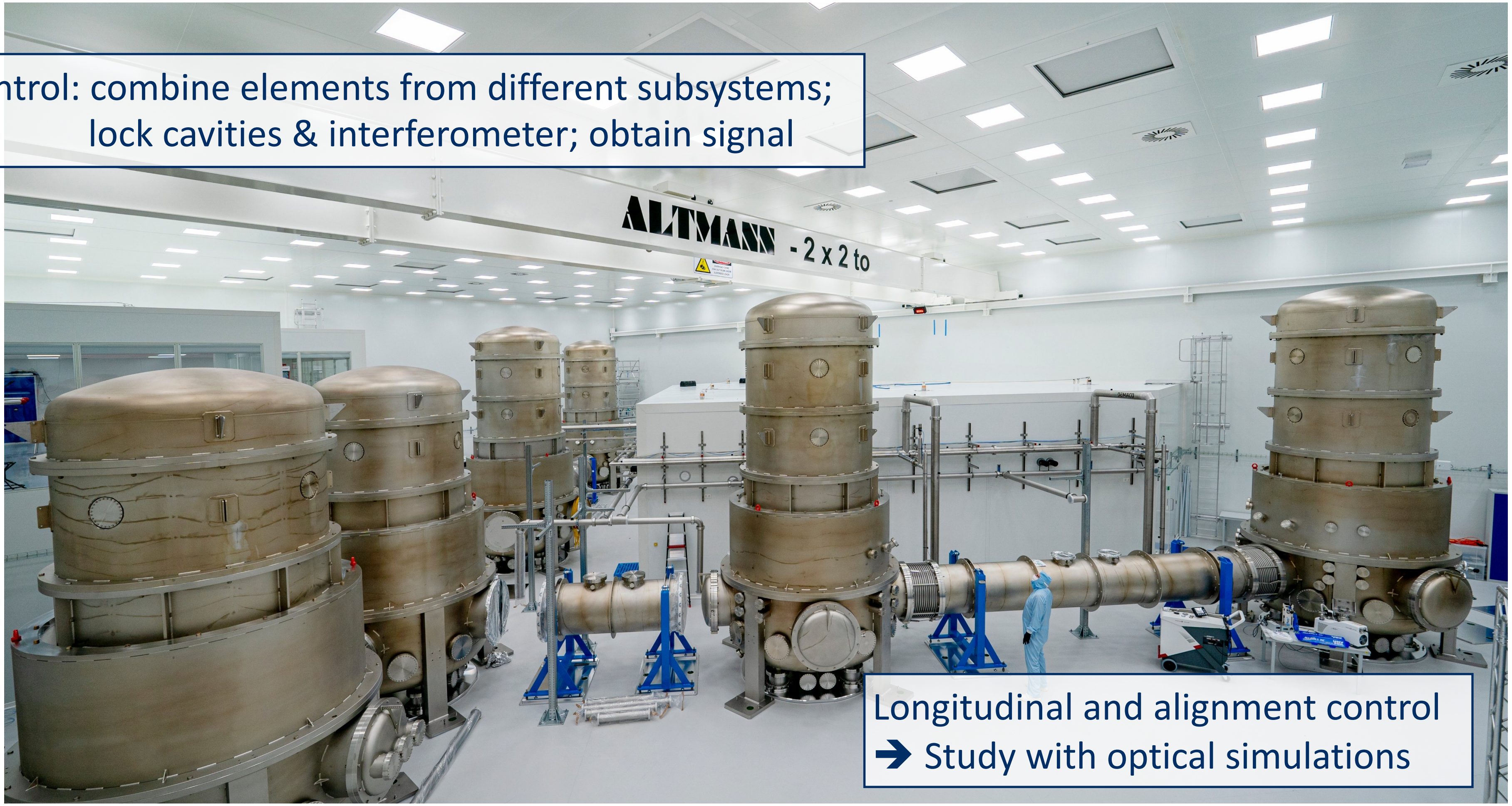
Fully integrated prototype to test key technologies for Einstein Telescope

Under construction in Maastricht

Sensing and control

Crucial to operate GW interferometers and achieve the required sensitivity

Global control: combine elements from different subsystems;
lock cavities & interferometer; obtain signal

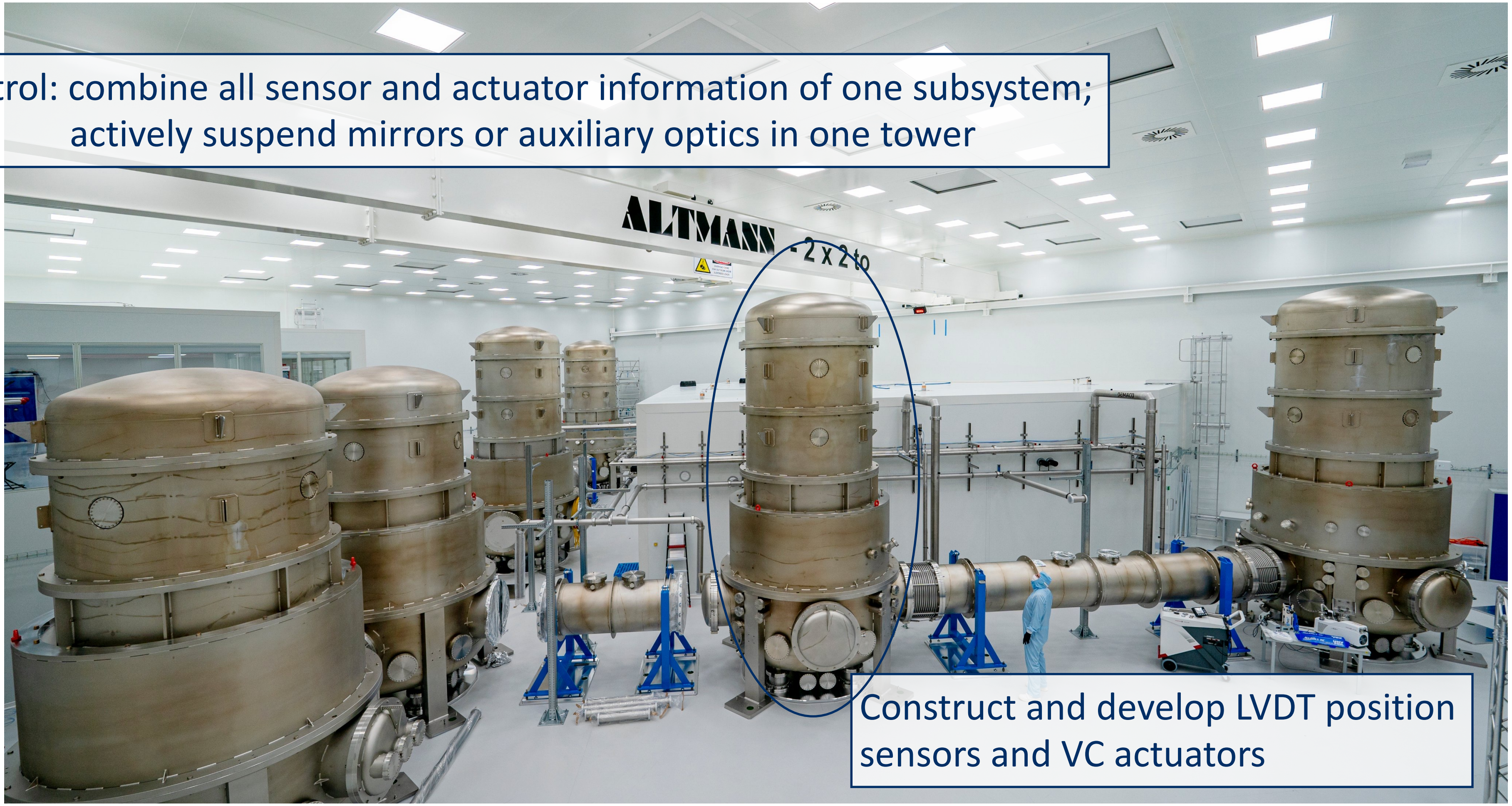


Longitudinal and alignment control
➔ Study with optical simulations

Sensing and control

Crucial to operate GW interferometers and achieve the required sensitivity

Local control: combine all sensor and actuator information of one subsystem; actively suspend mirrors or auxiliary optics in one tower



Construct and develop LVDT position sensors and VC actuators

LVDT sensors and VC actuators

Linear Variable Differential Transformer: highly linear non-contact UHV compatible position sensor

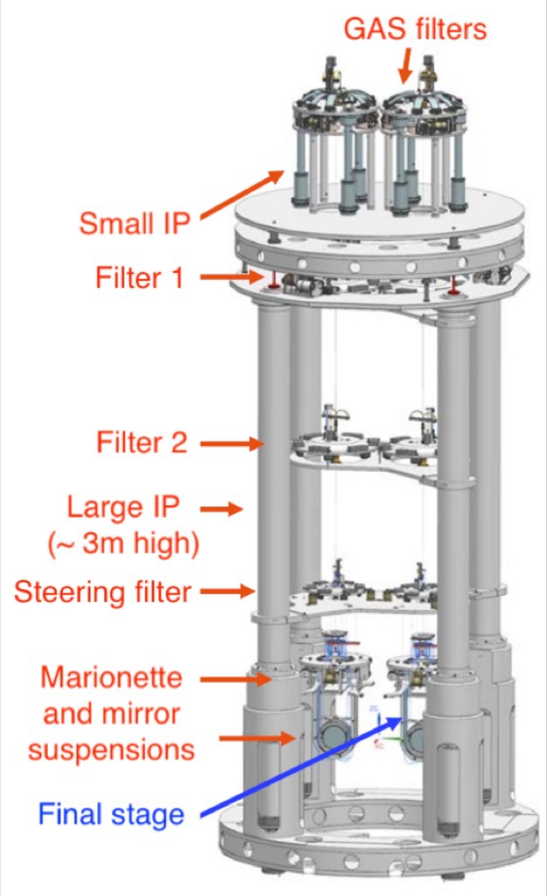
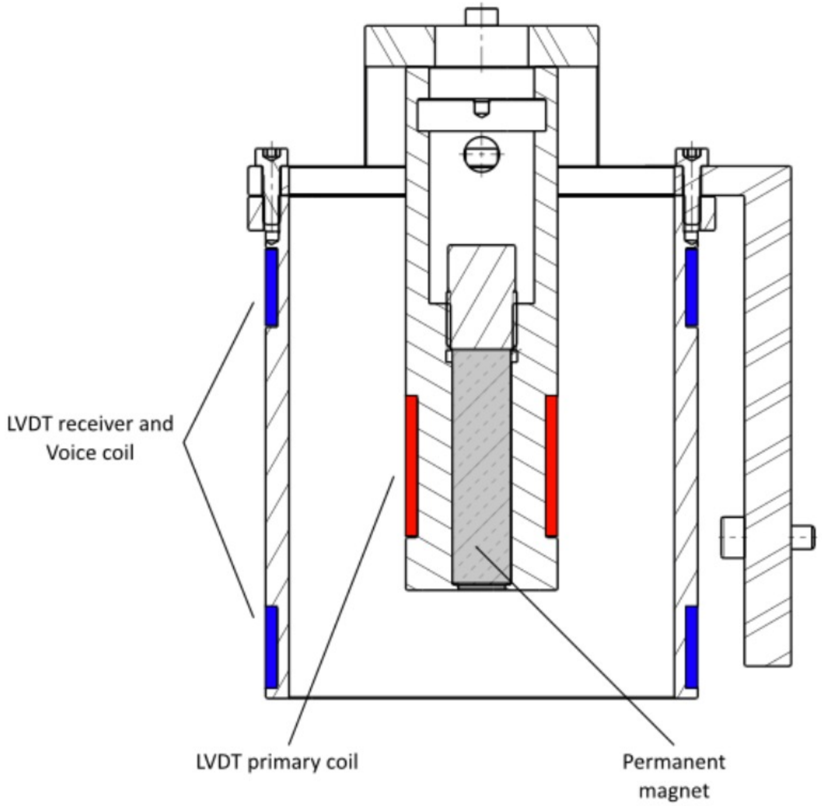


Fig. 2: Seismic attenuation system of ETpathfinder



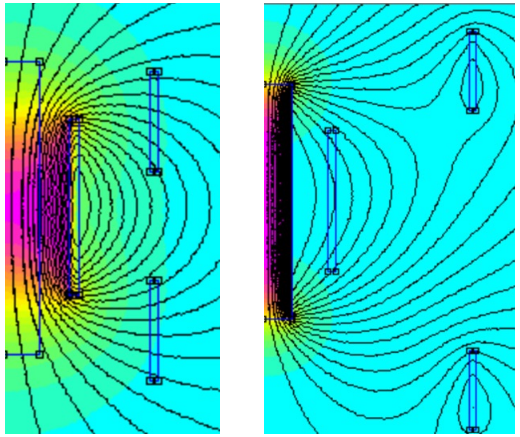
Working principle: mutual induction

Voice Coil actuator:
Placing a magnet inside the primary coil and applying a DC voltage to the secondary coils results in a force on the primary coil.

R&D on LVDT + VC sensors and actuators

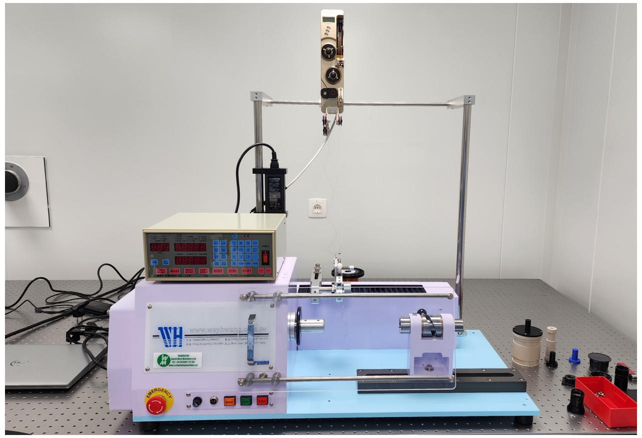
Try to cover all different aspects of such systems

Simulations

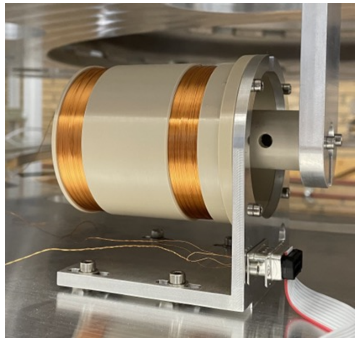


Measurements

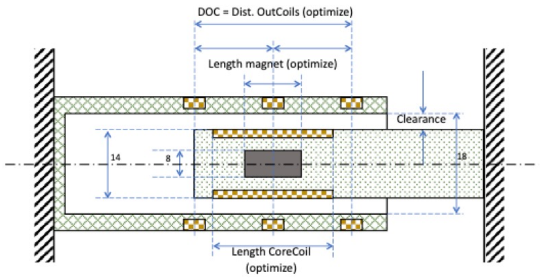
Construction for ETpf



Characterise existing designs



Future: design & test novel concepts



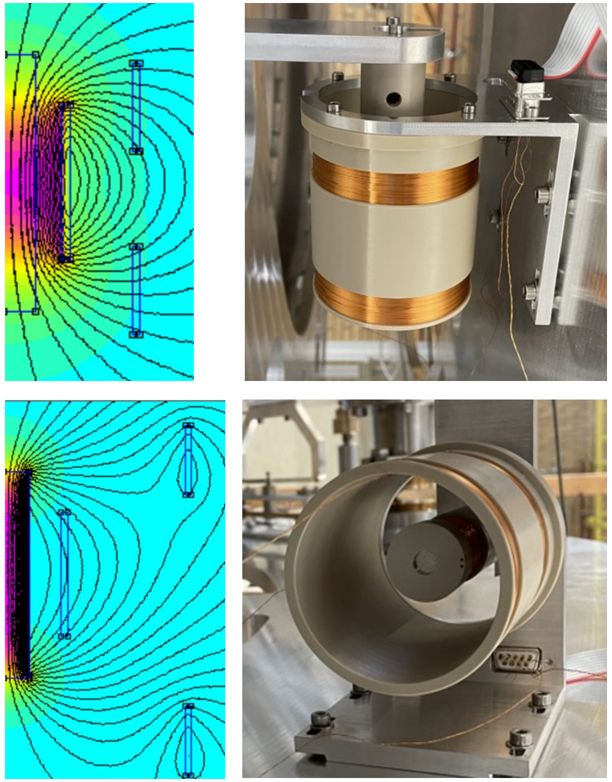
CoreCoil LVDT with cylinder magnet

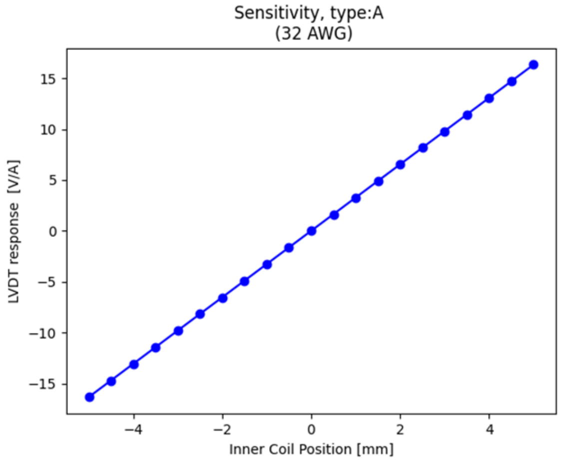
LVDT & VC simulations

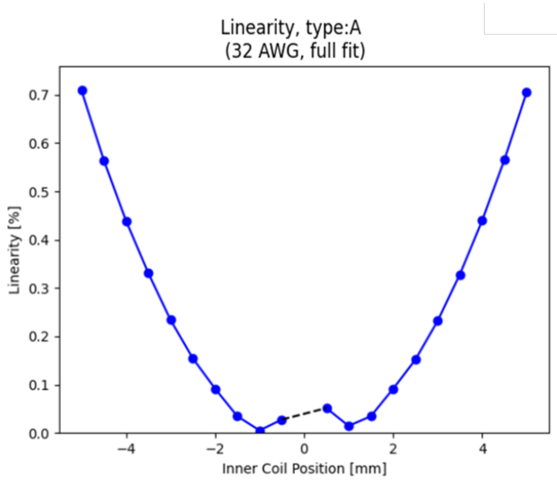
Numerical & semi-analytical simulations based on FEMM, fully implemented using python pipeline

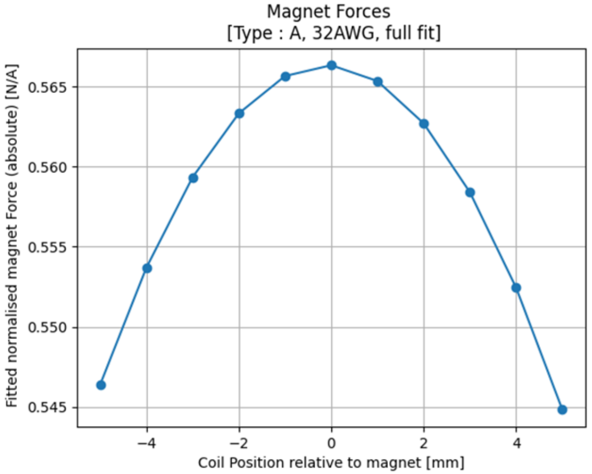
Results on LVDT response and VC force available for all available designs used in ETpf.

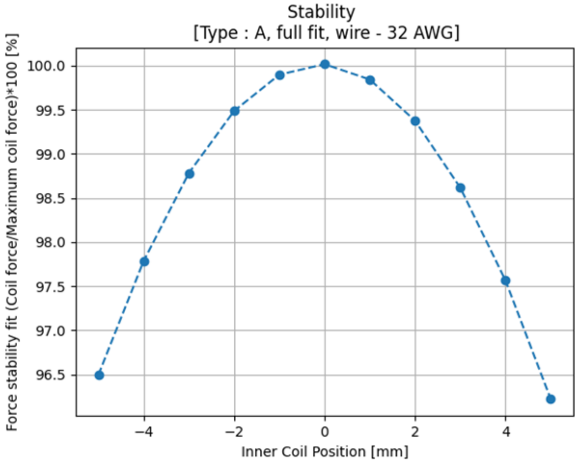
e.g. Type A LVDT+VC combination:







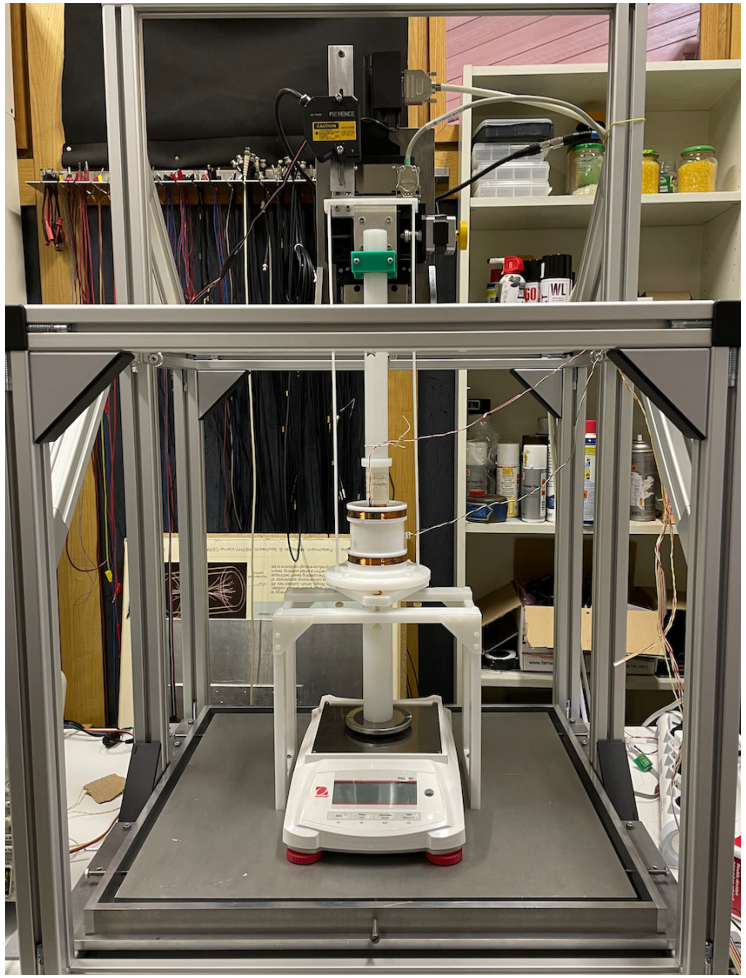




Experimental setup at UAntwerpen

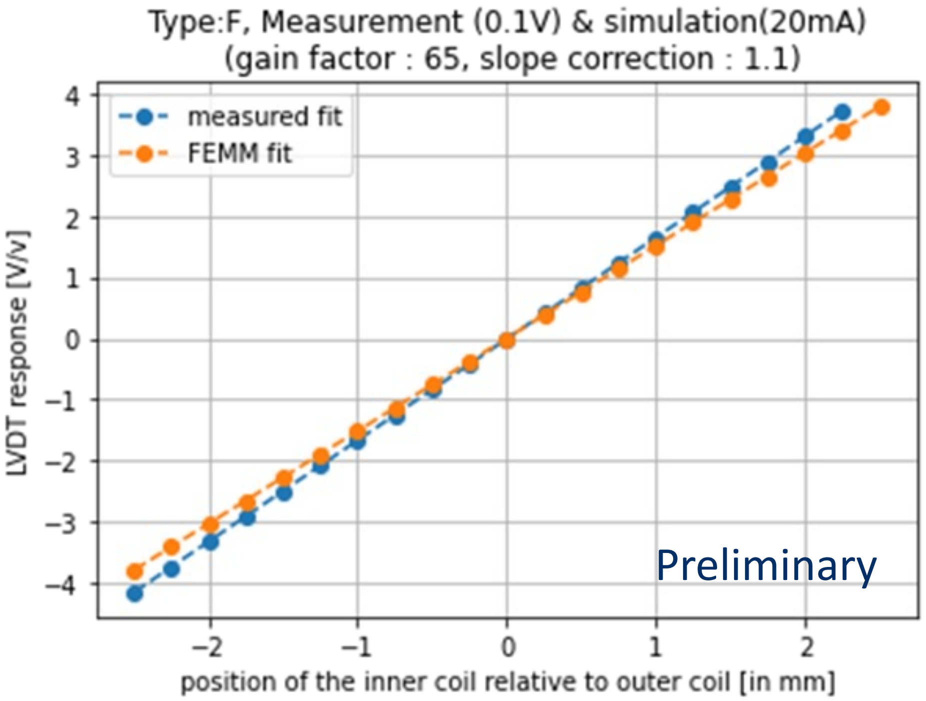
Designed & constructed to measure performance of current & future LVDT+VC designs

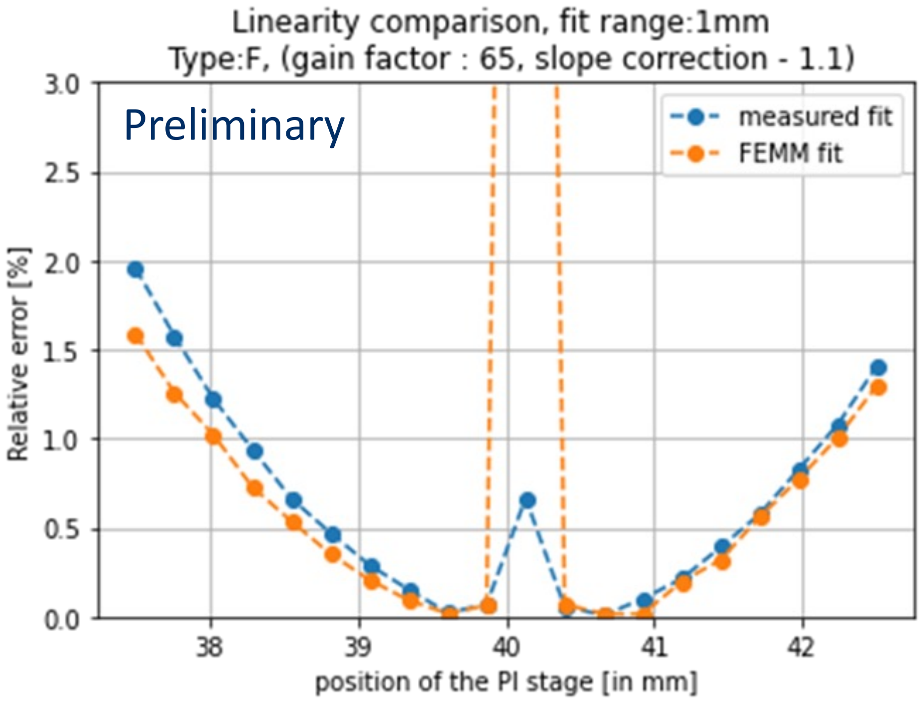
- **Two-Dimensional Position Control**
  - Measurement Range: 50mm
  - Resolution: 0.2µm
- **Position Monitoring:**
  - Utilizing Laser Displacement Sensor
  - Measurement range: 10mm + 50mm(adjustable)
  - Resolution: Up to 25nm
- **Voice Coil Measurement:**
  - Implemented via Weighting Scale
  - Resolution: 0.1mg
- **Data Acquisition:** Virgo DAQBox (LAPP)
- **Software control:** Python-based interface.



First measurements of LVDT response - Axial

Preliminary results for a Type F LVDT.
Simulation output corrected for electronics: amplification gains, non-infinite impedance



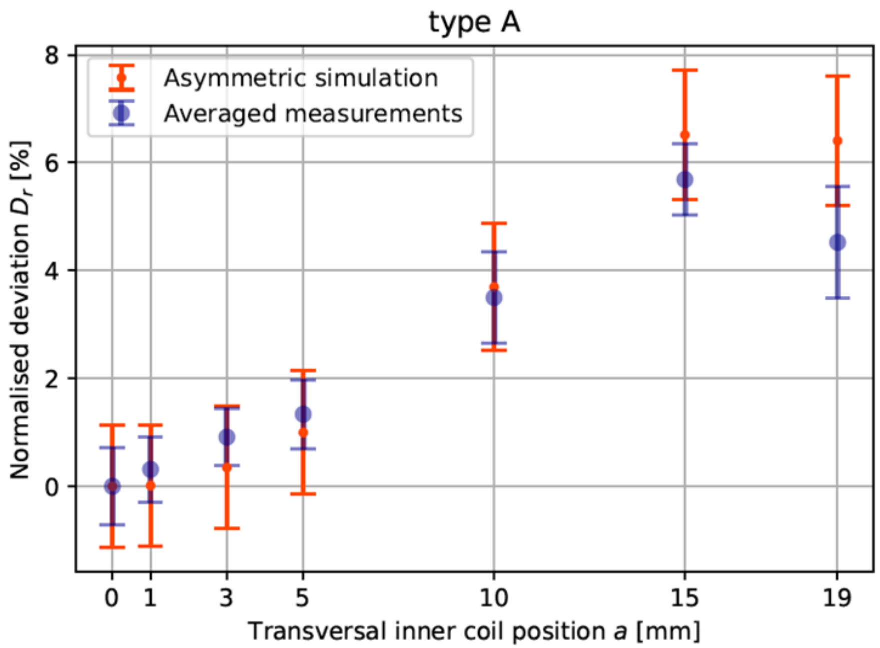


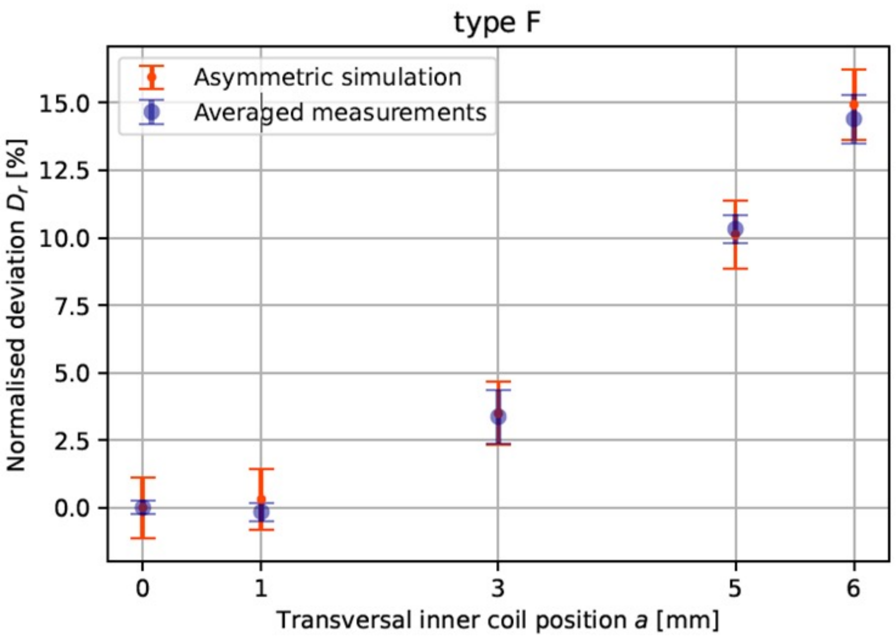
Measured slope [V/mmV]	Simulated slope
1.55	1.49

To do: estimate uncertainties, can we reduce/understand the data vs sim results?

First measurements of LVDT response – Transverse effects

Study how transverse offsets affect the default axial LVDT responses.
Master thesis: developed semi-analytical asymmetric LVDT simulation + performed measurements.





Deviation

$$D_{\mathrm{r}} = (m_{\mathrm{a}} - m_{\mathrm{o}}) / m_{\mathrm{o}}$$

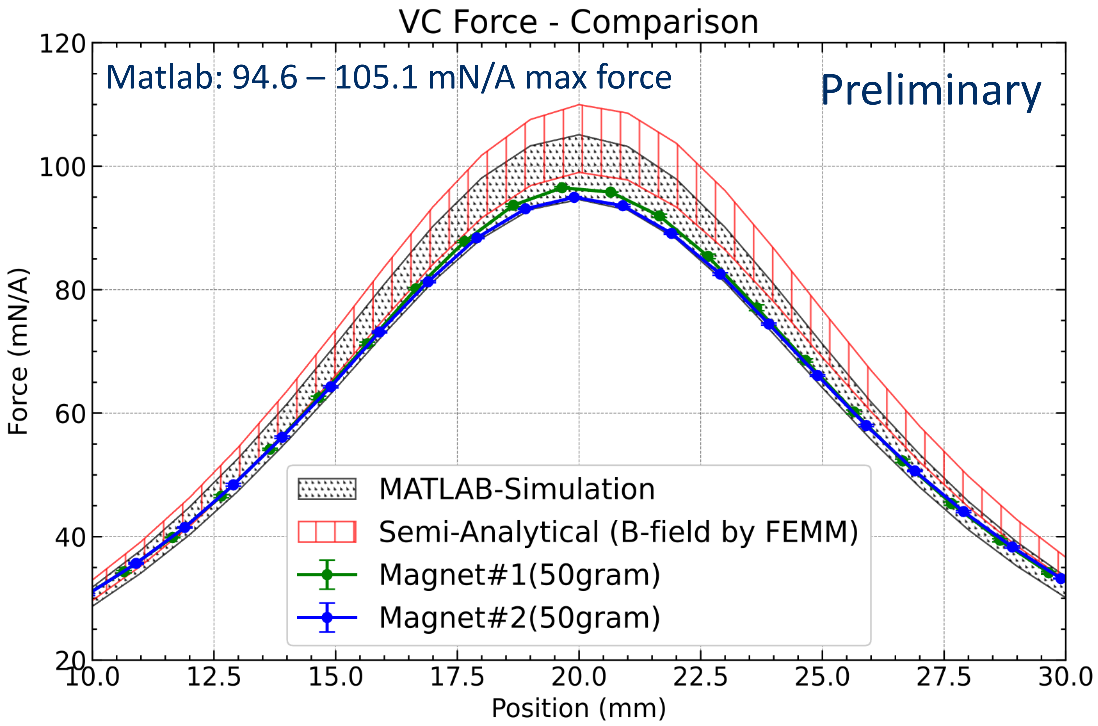
m_{o}: *sensitivity without offset*
m_{a}: *sensitivity with offset* ‘a’mm

Relative response deviation (D_r) increases with transverse offset for both type A & F.

Minimizing this transverse offset during installation is thus important to avoid additional noise

Trial measurement of voice coil forces

Try to validate measurement procedure with custom made voice coil (mirror type)



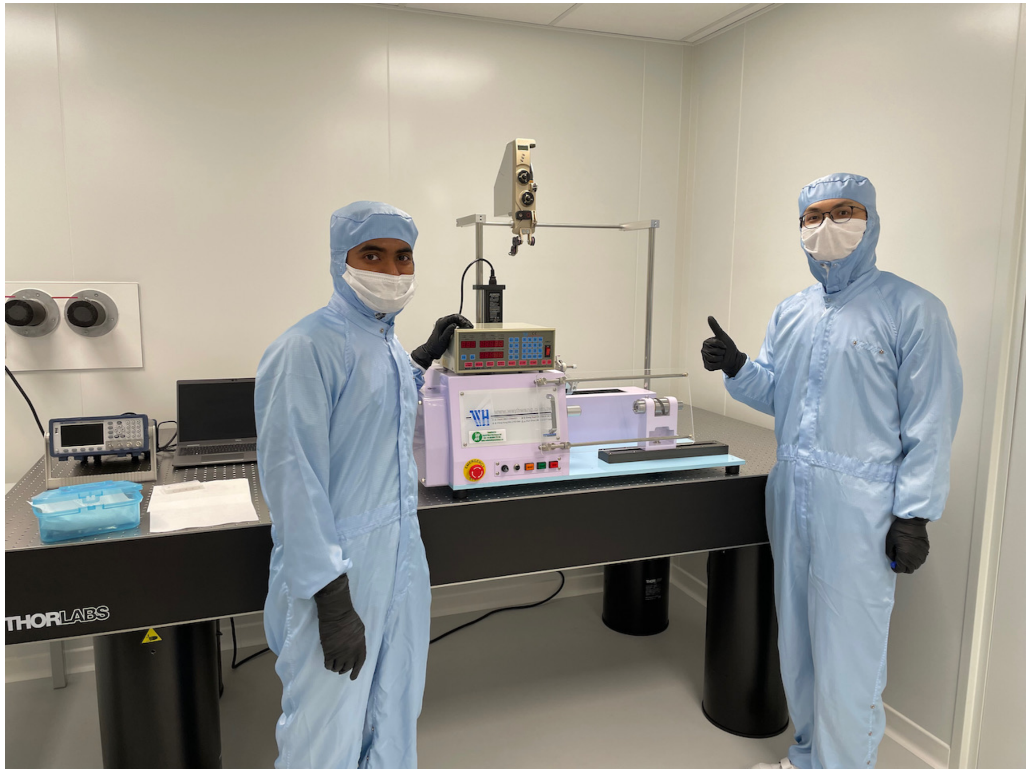
Magnet-N40	Max normalized Force – mN/A
Magnet #1	96.5 +/- 0.5
Magnet #2	95.0 +/- 0.3

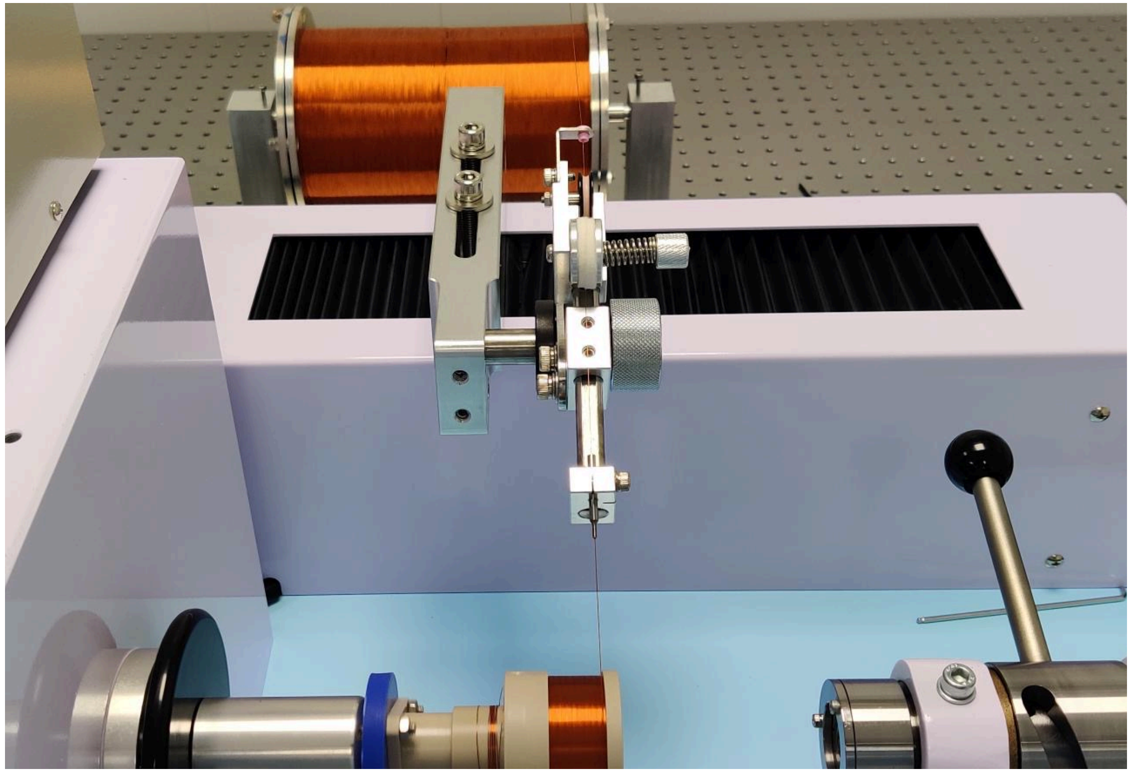
0.1 Hz sine wave signal on coil ➔ force on magnet ➔ weight change on scale ➔ fit curve to obtain force

Springs to balance weight ➔ apply correction factor

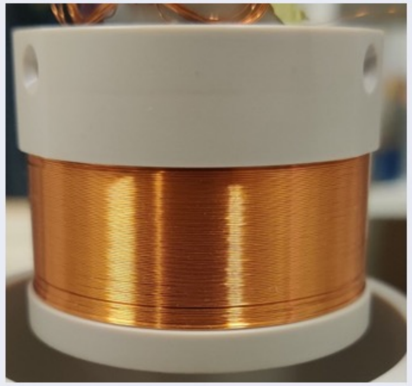
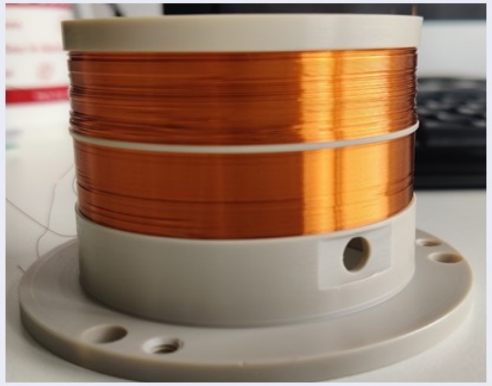
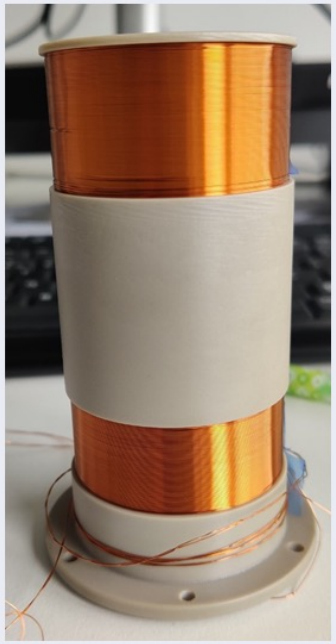
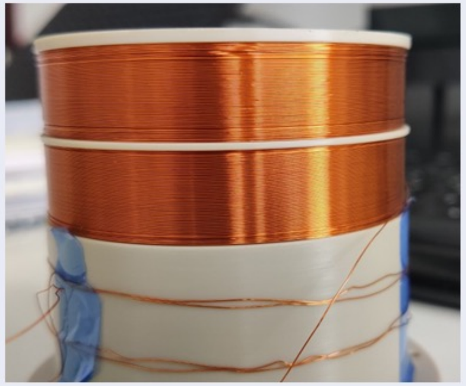
LVDT and VC production for ETpathfinder

Buy/produce all parts, set up winding machine, UHV cleaning, winding & assembly of coils





Finished coils ready for assembly (bench tower)

Type-F		Type-J	
Inner coil	Outer coil	Inner coil	Outer coil
			

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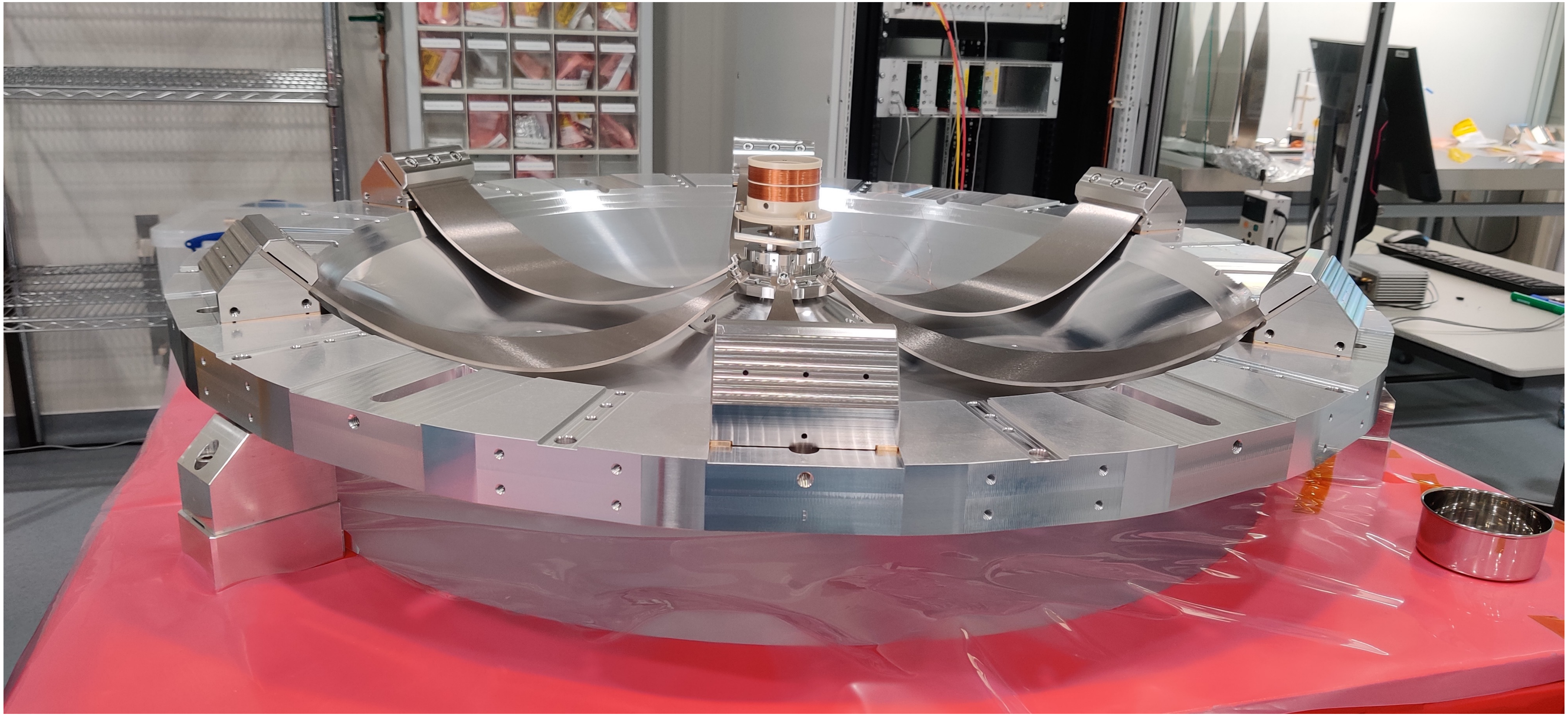
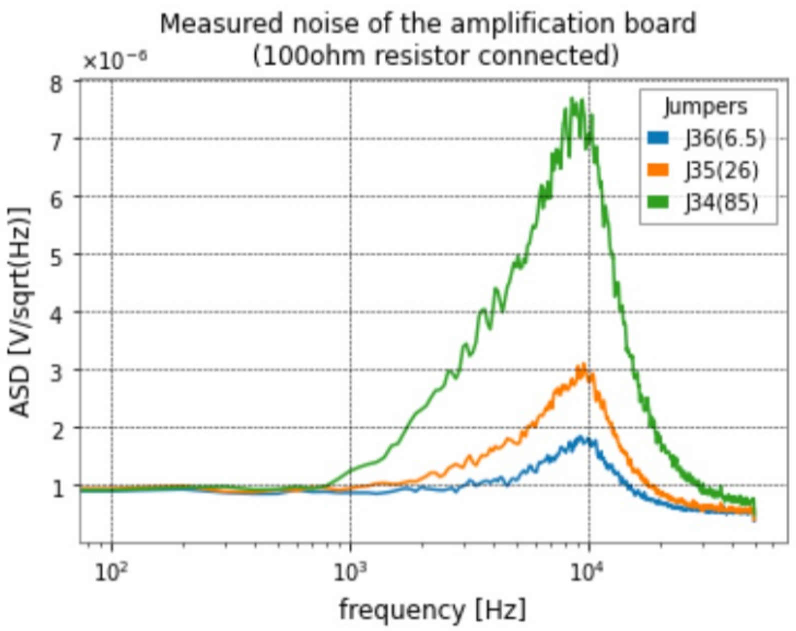


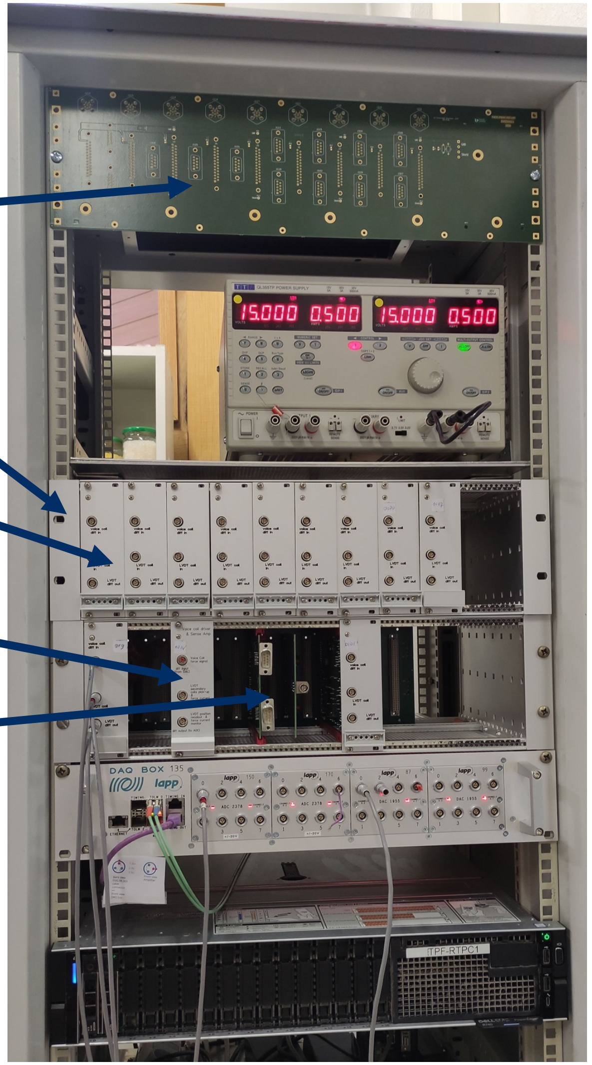
Production & development of LVDT electronics

Building and testing of various components at our lab:

Use LAPP DAQ system for readout

Noise studies of LVDT amplifier boards

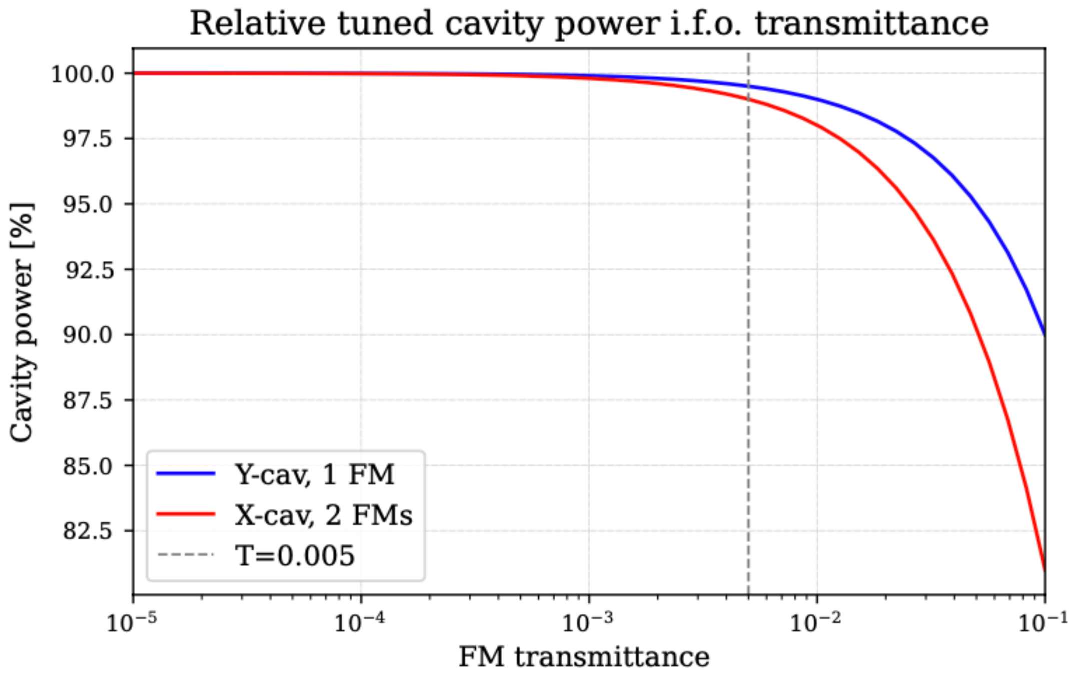


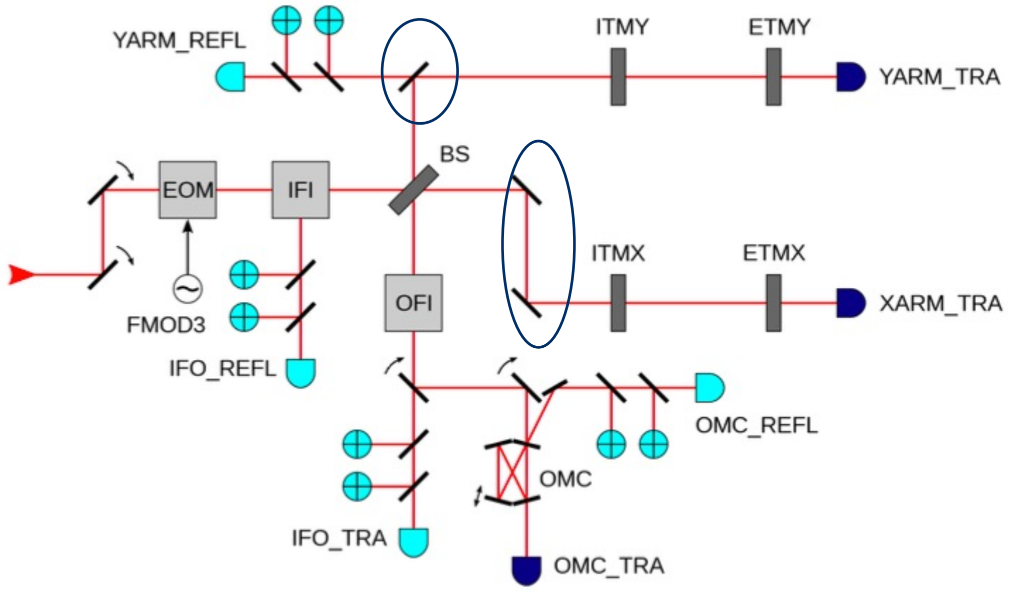


Optical simulations

Contribute to Finesse simulation tasks in ETpathfinder: mostly on longitudinal control

Control of the arm cavities: any effects of the folding mirrors?





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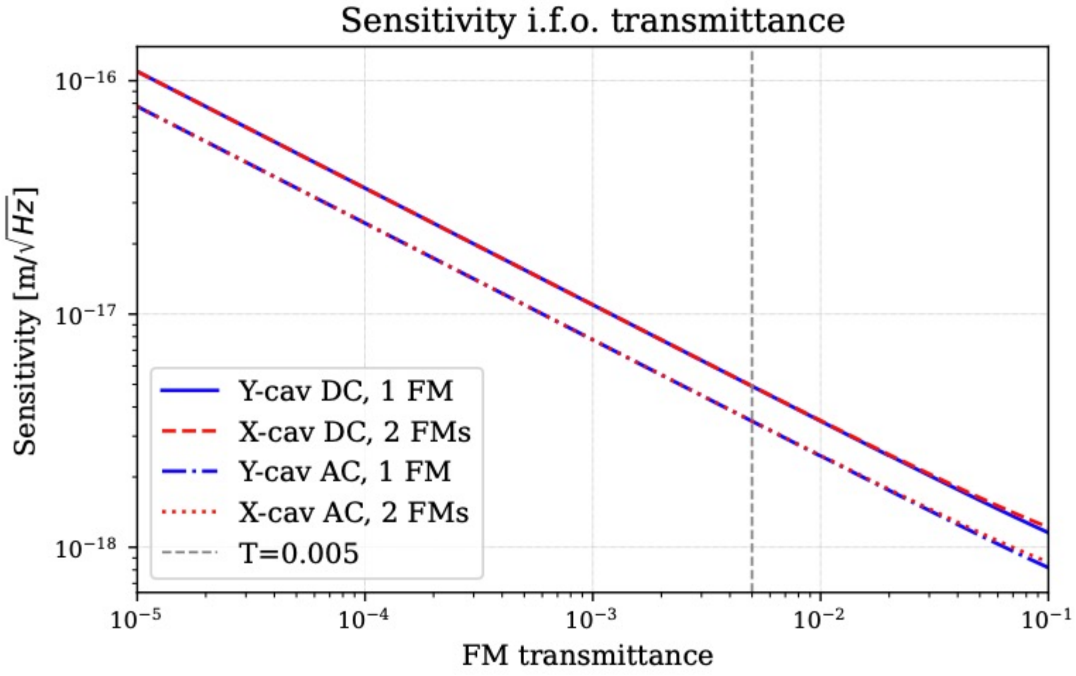

Quantity	Value y-arm	Value x-arm	Percentage change [%]
Optical gain	1.02554×10^{-2} W/°	1.02042×10^{-2} W/°	−0.5%
Cavity power	587.1 W	584.2 W	−0.5%
AC shot-noise	$1.645 \times 10^{-11}\ \frac{\text{W}}{\sqrt{\text{Hz}}}$	$1.640 \times 10^{-11}\ \frac{\text{W}}{\sqrt{\text{Hz}}}$	−0.3%
DC shot-noise	$2.323 \times 10^{-11}\ \frac{\text{W}}{\sqrt{\text{Hz}}}$	$2.317 \times 10^{-11}\ \frac{\text{W}}{\sqrt{\text{Hz}}}$	−0.3%
Sensitivity	$3.452 \times 10^{-18}\ \frac{\text{m}}{\sqrt{\text{Hz}}}$	$3.460 \times 10^{-18}\ \frac{\text{m}}{\sqrt{\text{Hz}}}$	+0.2%

TABLE 3.1: Summary of important values in this section for FM transmittance $T = 0.005$ and modulation index $m = 0.1$.

Asymmetry due to folding mirrors does not affect optical gains significantly

Optical simulations

Control of combined interferometer: study demodulated signals (DARM, CARM, MICH) at different ports

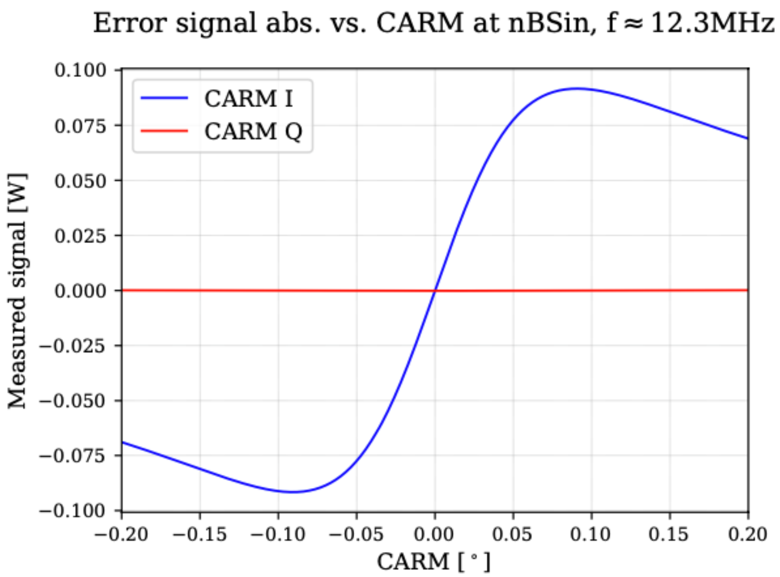

FIGURE 3.18: CARM error signal at REF port.

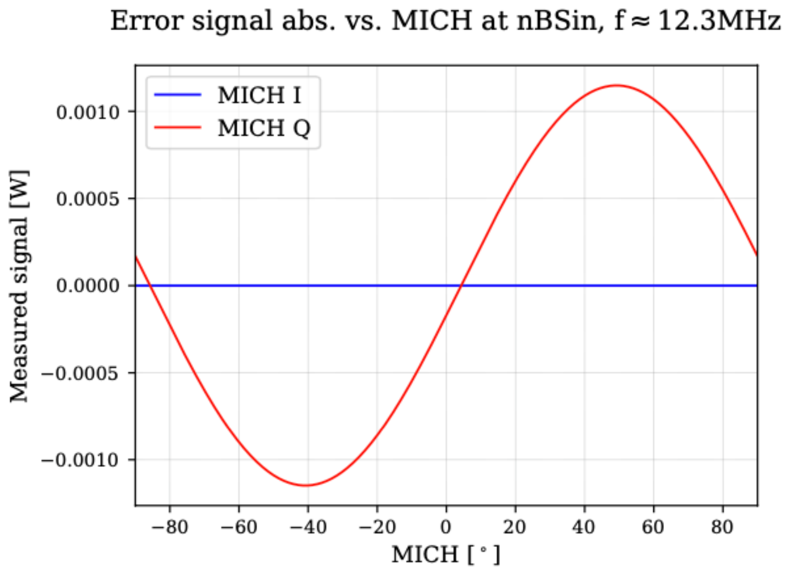

FIGURE 3.20: MICH error signal at REF port.

Determination of optical sensing matrix:

$$\mathbf{M}\vec{\Delta} = \vec{S}_{demod}$$

$$\Longleftrightarrow \begin{bmatrix} M_{CRI} & M_{MRI} & M_{DRI} \\ M_{CRQ} & M_{MRQ} & M_{DRQ} \\ M_{CAI} & M_{MAI} & M_{DAI} \\ M_{CAQ} & M_{MAQ} & M_{DAQ} \end{bmatrix} \cdot \begin{bmatrix} CARM \\ MICH \\ DARM \end{bmatrix} = \begin{bmatrix} REF\ I \\ REF\ Q \\ ASY\ I \\ ASY\ Q \end{bmatrix} \qquad \mathbf{M}'_{simulation} = \begin{bmatrix} 1.00000 & 0.00000 & -0.00252 \\ -0.39615 & 0.17899 & -0.90057 \\ 1.00000 & 0.00035 & -0.00071 \\ 0.02126 & -0.00075 & -0.99977 \end{bmatrix}$$

Optical simulations

Control of combined interferometer: study demodulated signals (DARM, CARM, MICH) at different ports

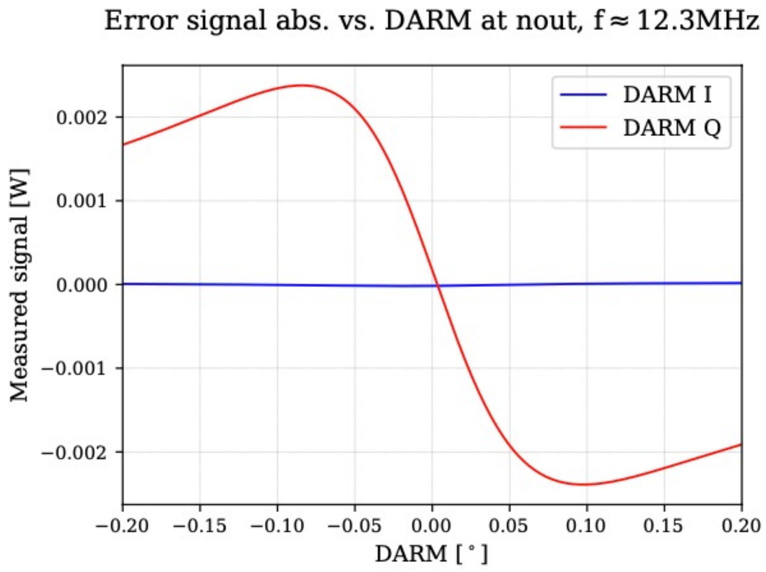

FIGURE 3.17: DARM error signal at ASY port.

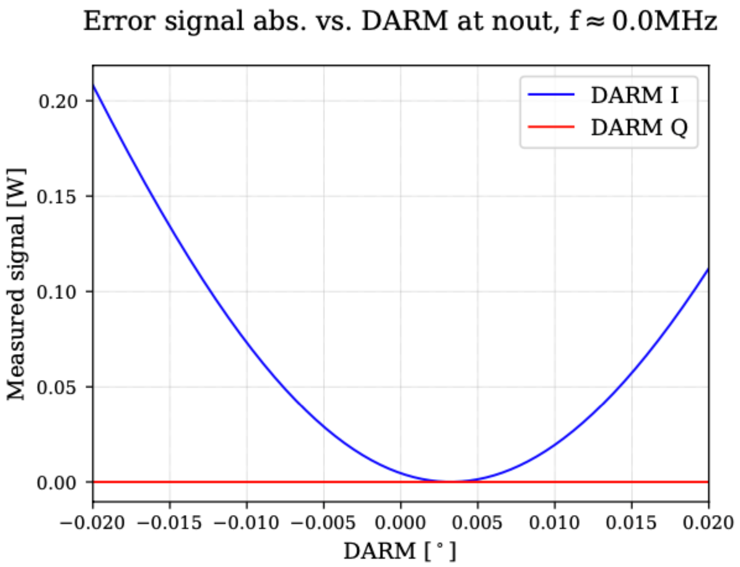

FIGURE 3.23: DARM DC response in the ASY port. The title mentions demodulating at 0 MHz, which gives the same result as not demodulating at all.

	DARM	CARM	MICH
Gain $[W/^\circ]$	-2.775	1.636×10^{-6}	-2.117×10^{-3}
Gain [normalized]	-1	5.89549×10^{-7}	-7.62883×10^{-4}
Sensitivity $\left[\frac{m}{\sqrt{Hz}}\right]$	2.64617×10^{-20}	4.48846×10^{-14}	3.46865×10^{-17}

TABLE 3.3: Summary of DC detection: gain and sensitivity

Next steps:
- look at closed loop systems
- include real noise sources

Results available in Karel Peetermans' master thesis ET-0223A-23: https://apps.et-gw.eu/tds/ql/?c=16723

Summary

- Active contribution to local and global sensing and control systems of ETpathfinder:

  - Construct and develop LVDT position sensors and VC actuators.
  - Contribute to optical simulations to develop longitudinal interferometer control.

- Experimental test setup available at UAntwerpen to fully characterize LVDT+VC sensors: preliminary results indicate proper working principles, ready to finetune & explore novel designs.

- Construction and commissioning for ETpathfinder first bench tower ongoing.

- Finesse simulations of ETpathfinder optical geometry:
  - no significant influence from folding mirrors asymmetry.
  - determined optical sensing matrix; next step to include more realistic scenarios.