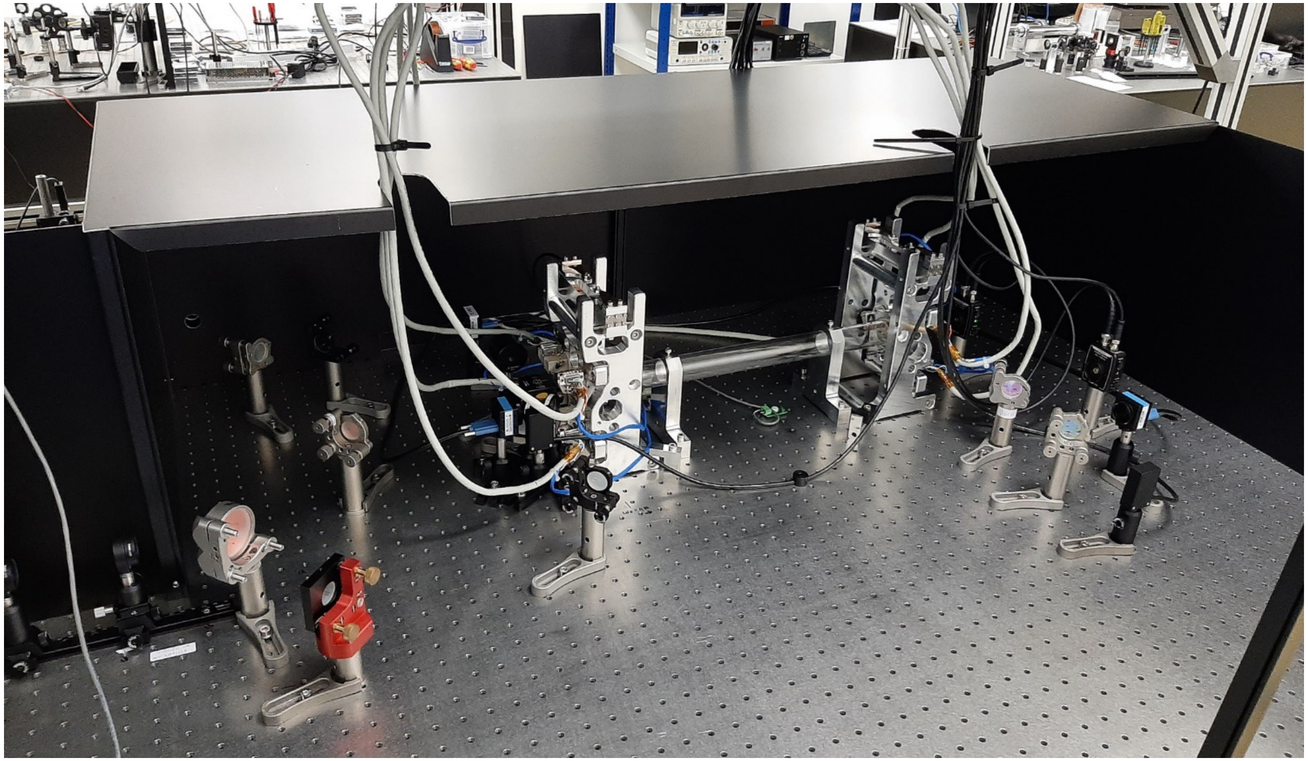
Table top suspended laser interferometry

Overview, status and outlook

Rob Walet

Nikhef Gravitational Waves



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Gravitational Waves Astronomy

Reaching the sensitivity required to measure space time fluctuations originated by binary collisions millions of light years away, makes the detection of gravitational waves, foremost, a technical challenge.

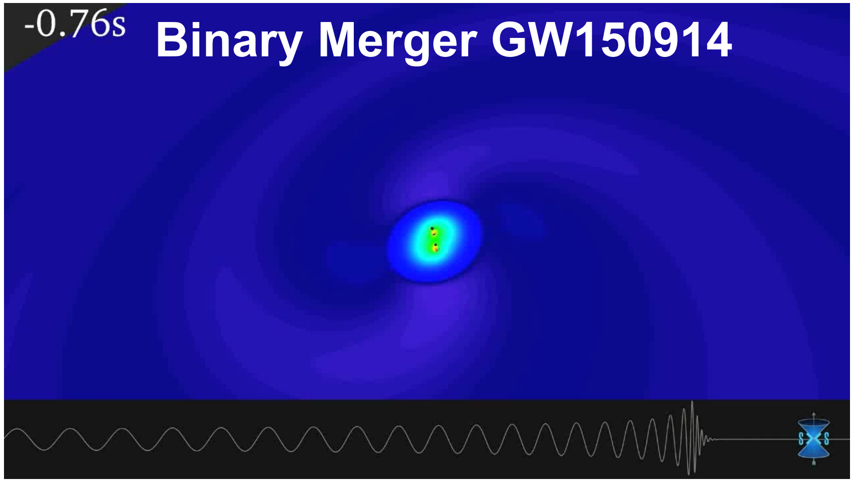
Gravitational waves

generated by accelerating masses (changing quadrupole and multipole moments like binary black holes)

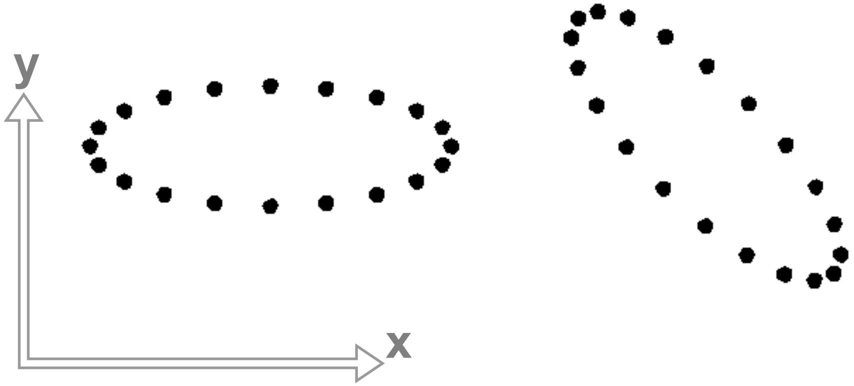
Propagate with the speed of light

Stretches and squeezes space time in transverse directions, in two polarizations

Requiring detectors with extreme strain sensitivity



+ polarization **x polarization**



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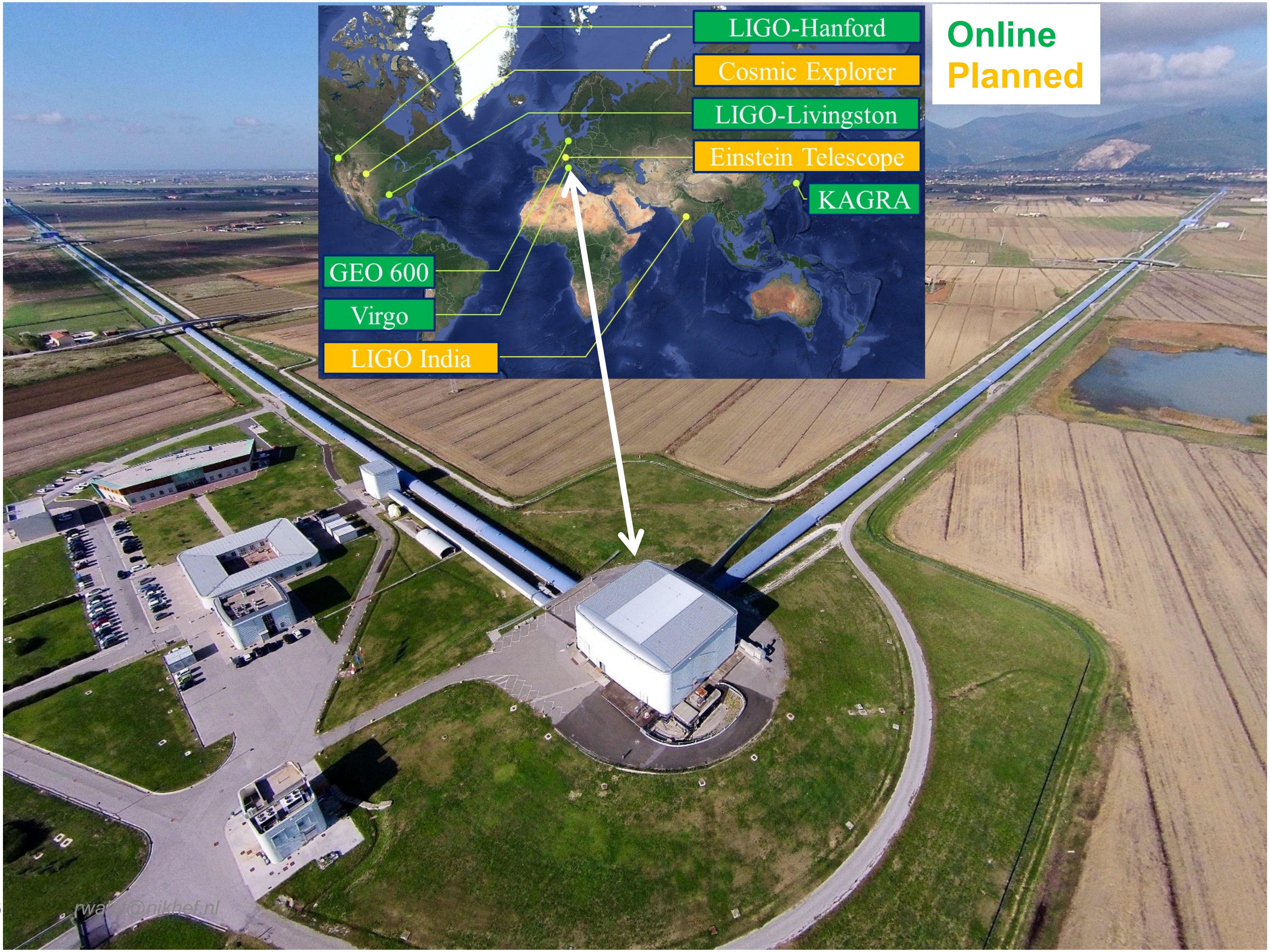
Instrumentation to measure extreme small strains

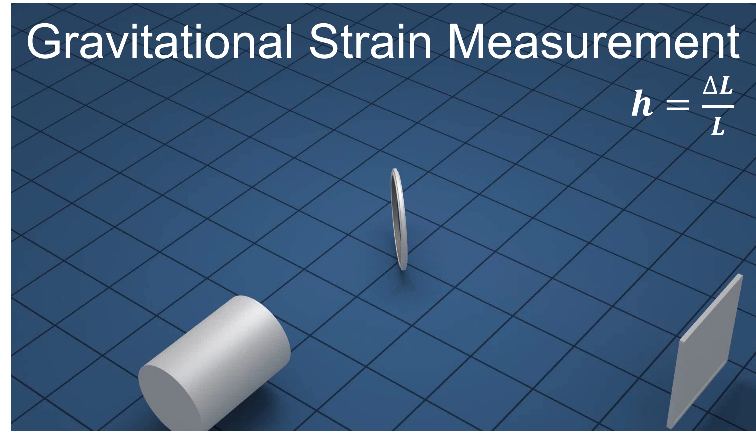


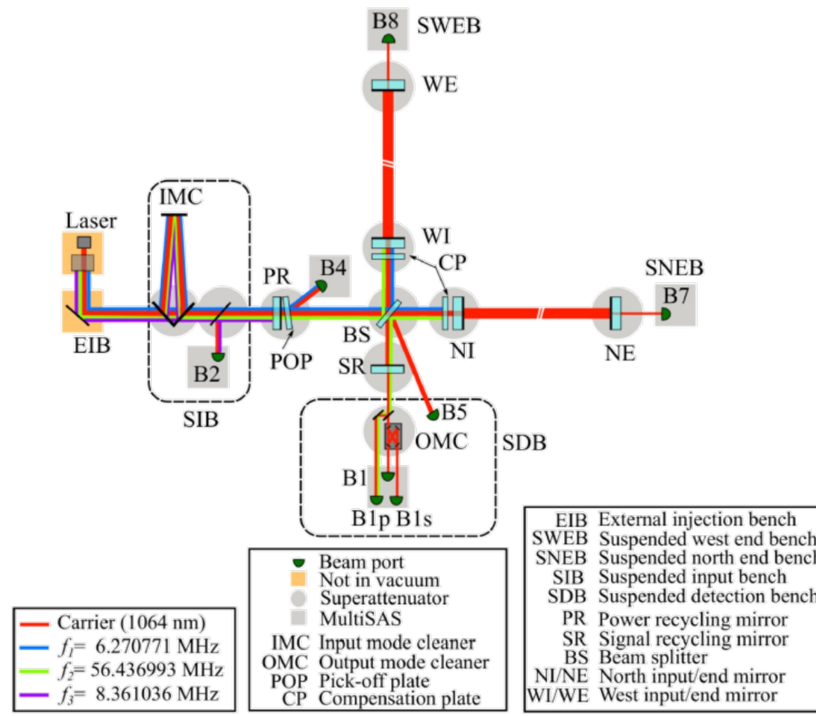
Gravitational Waves Detection

The basic technology behind the LIGO and Virgo detectors is a Michelson laser interferometer, where the effective arm lengths are increased by Fabry-Perot resonance cavities. A wide variety of noise sources must be overcome, eq. quantum noise (shot noise and radiation pressure), seismic noise and thermal noise.

Km-scale laser interferometers

- **Mirrors (known as test-masses)**
  - <u>probing the spacetime perturbations </u>from a passing gravitational wave
  - <u>are brought in free-fall </u>with advanced seismic attenuation systems capable of suppressing ground motion by more than ten orders of magnitude
  - <u>need to be controlled in length and alignment</u> within nanometer / nanoradian precision to from optical resonators
  - <u>Transient disturbances </u>mostly of direct or indirect seismic nature, can occasionally exceed the mirror actuators dynamic range, interrupting the detector operation (such an occurrence is called *unlock*)
    - Quick recovery from unlocks is essential for maximizing the sky observation time and it is usually achieved by means of automatic procedures.
    - However, if the unlock is accompanied by a large misalignment of some optical component, recovery takes longer and human intervention is needed



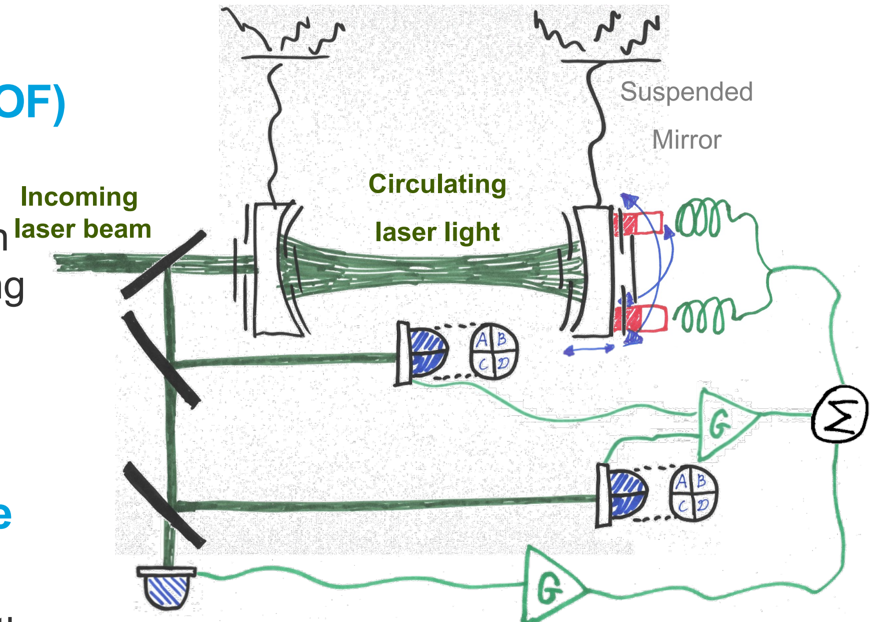


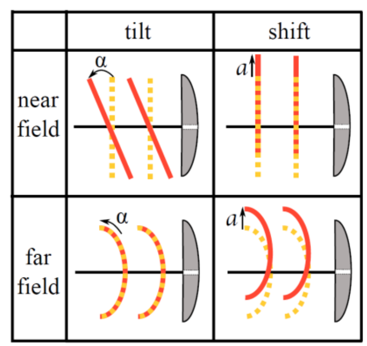
The Fabry-Perot resonator

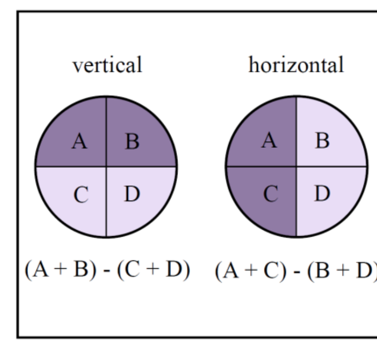
The fundamental building block of an interferometer is a optical resonator where the control strategy is based on a fundamental transverse Gaussian laser beam. Large mirror misalignment's introduce higher order modes spoiling the classical error signals and reduce the resonant laser power of the fundamental mode.

Optical Resonator

- **One longitudinal degrees of freedom (DOF)**
- **Four angular DOF**
  - Misalignments can cause a shift or tilt between the cavity axis and input laser beam introducing HOM
    - decreasing the power of the fundamental mode
    - can change the cavity length
- **Quadrant photodiodes sensing the wave front at two different locations**
  - Carrying the angular alignment information of the mirrors in the optical cavity.
    - Near field sensors measures the tilt
    - Far field measures the shift of the optical axis of the cavity and the incoming laser beam







Now back to my research

Besides the realization of the table-top ITF another two parallel activities are started. Firstly we want to develop an algorithm for the modal decomposition of the phase camera beam images. If successful directly applicable in GW detectors. Secondly we want to measure the noise performance of beam images provided by CCD cameras as error signals. Ultimately useful as low cost and ultra-fast beam diagnostics.

Realize table top ITF; test bench to develop and test alternative control strategies for GW observatories

Long term goals:

- **Phase camera images**
  - Modal decomposition of beam images
- **CCD Beam images**
  - Proof of concept CCD images as error signals
  - NN including memory; 3D convolutional neural network
  - Hybrid control strategy, to operate the interferometer with the modern controls in the linear regime and use ML based image recognition system, including fast data pipeline, to maintain the operation of the interferometer during large mirror displacements

Table top suspended laser interferometry

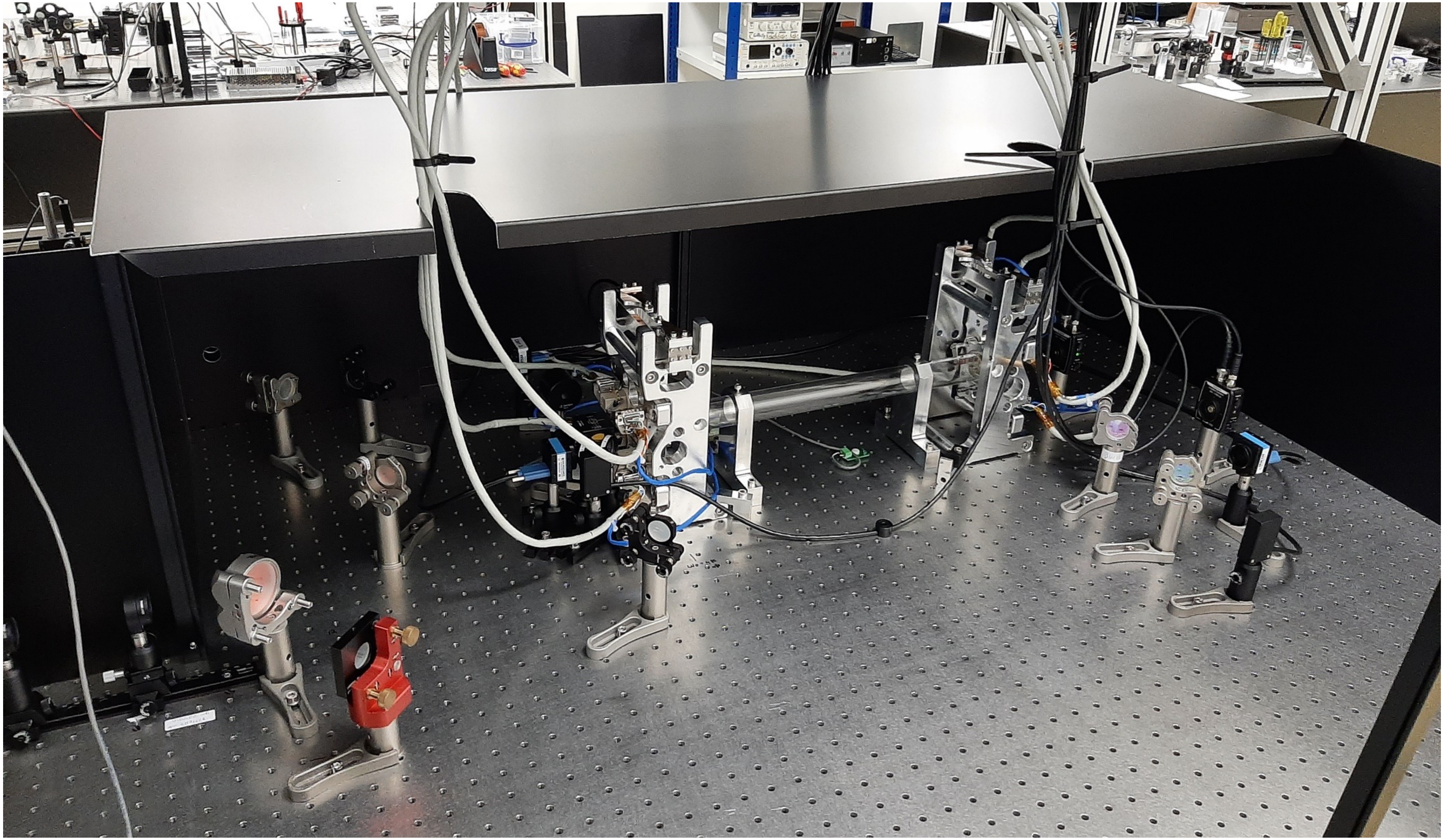


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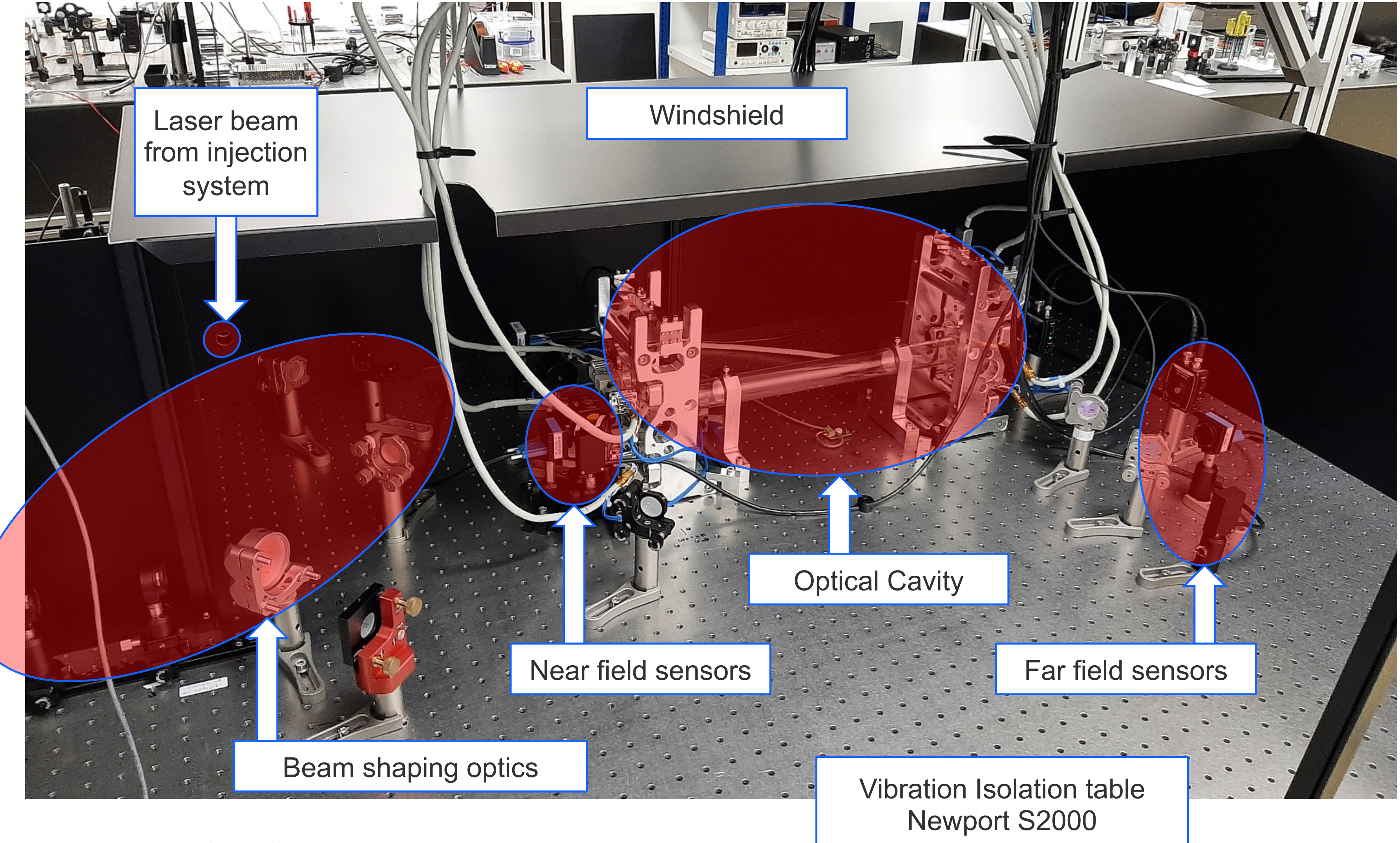
Table top suspended laser interferometry



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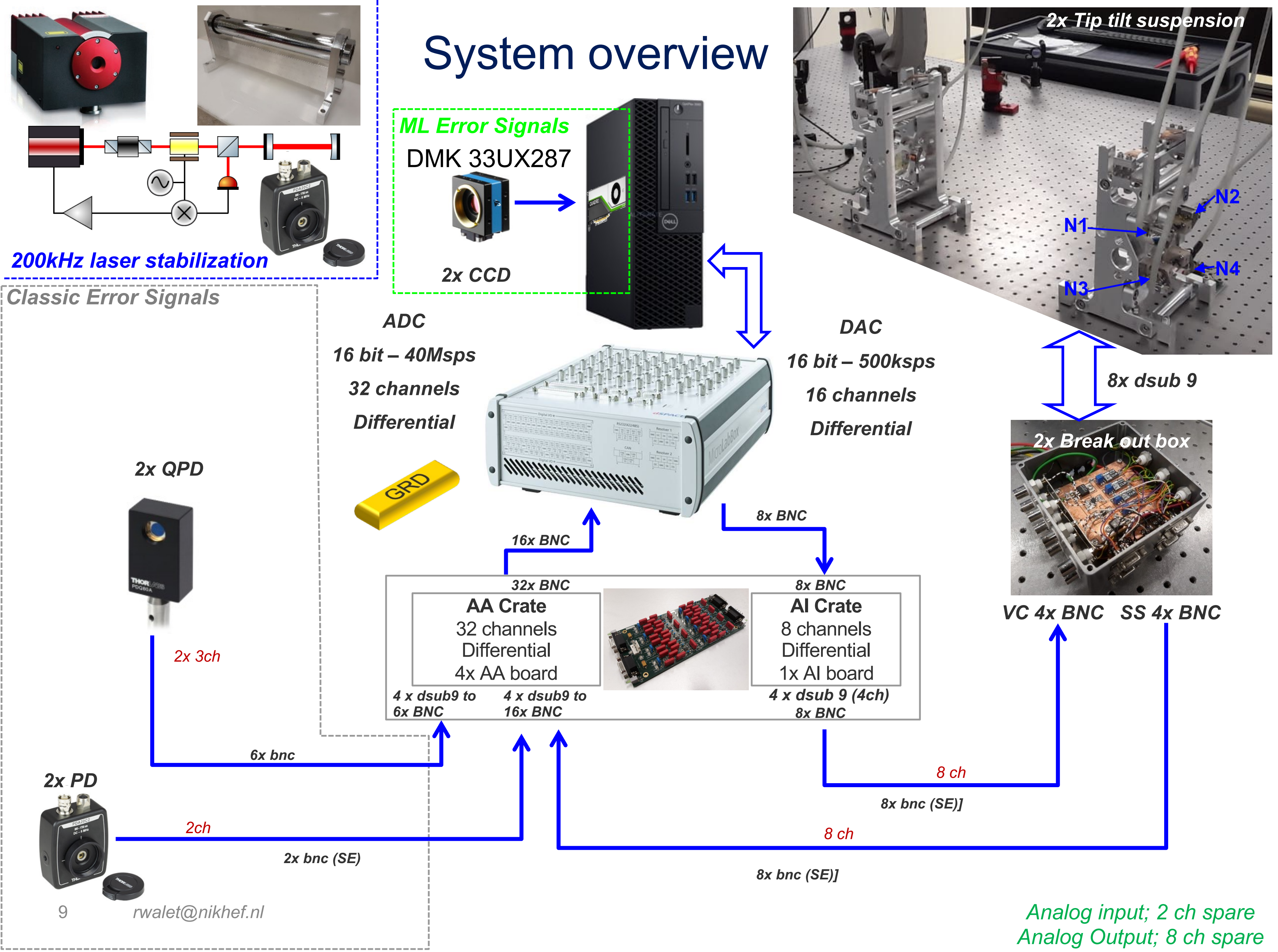
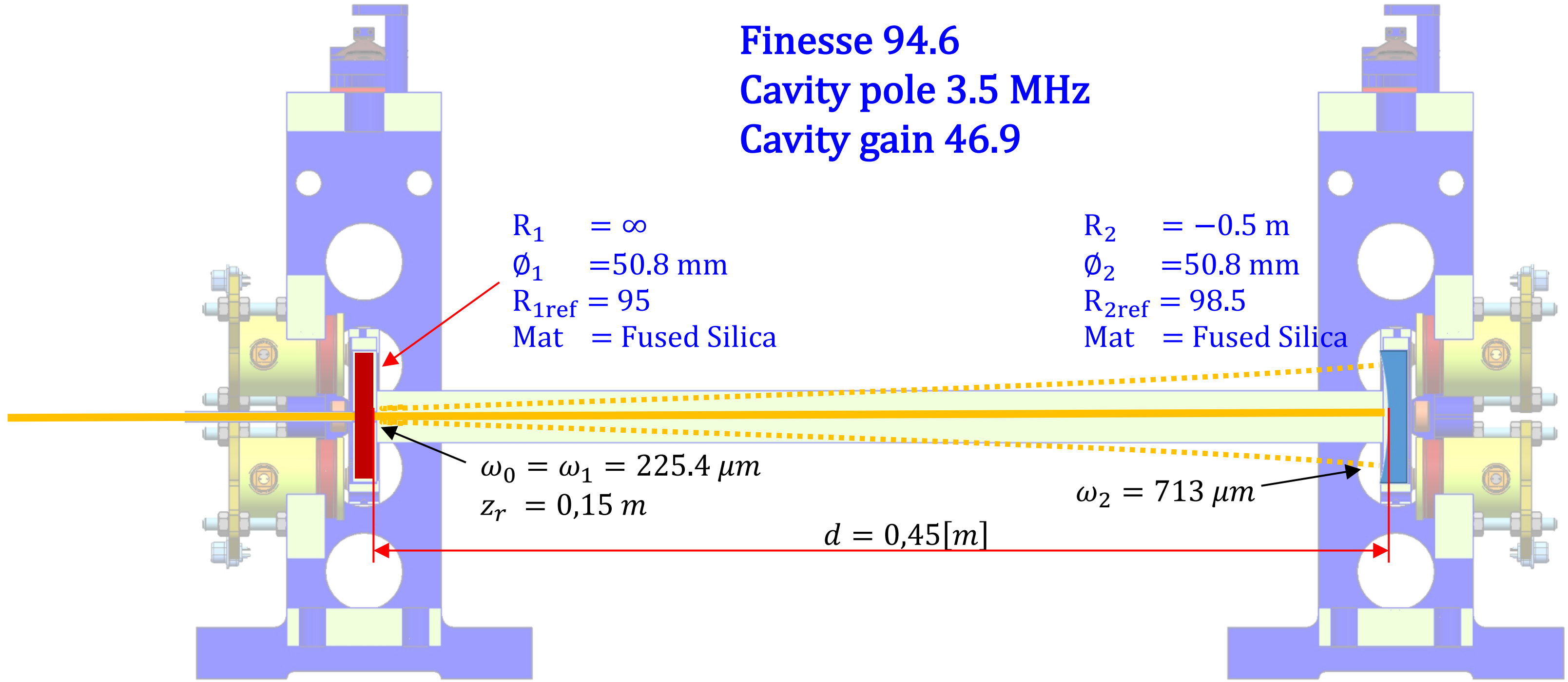
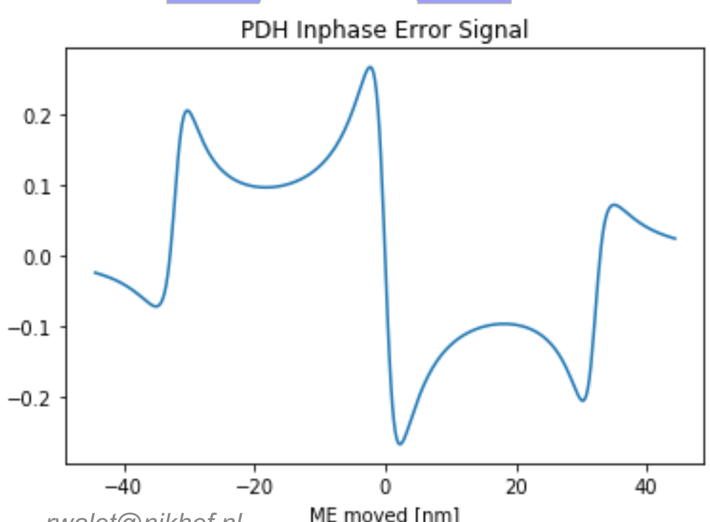
System overview

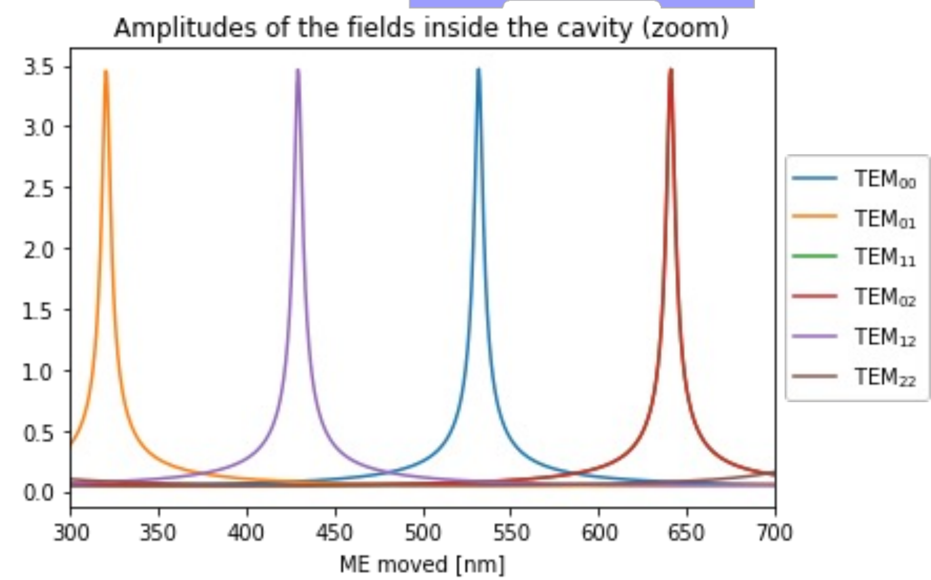


Optics Overview

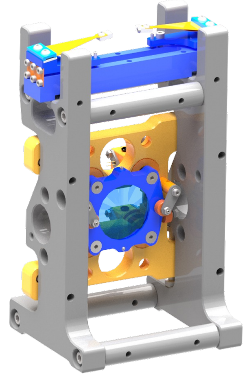
Finesse 94.6
Cavity pole 3.5 MHz
Cavity gain 46.9



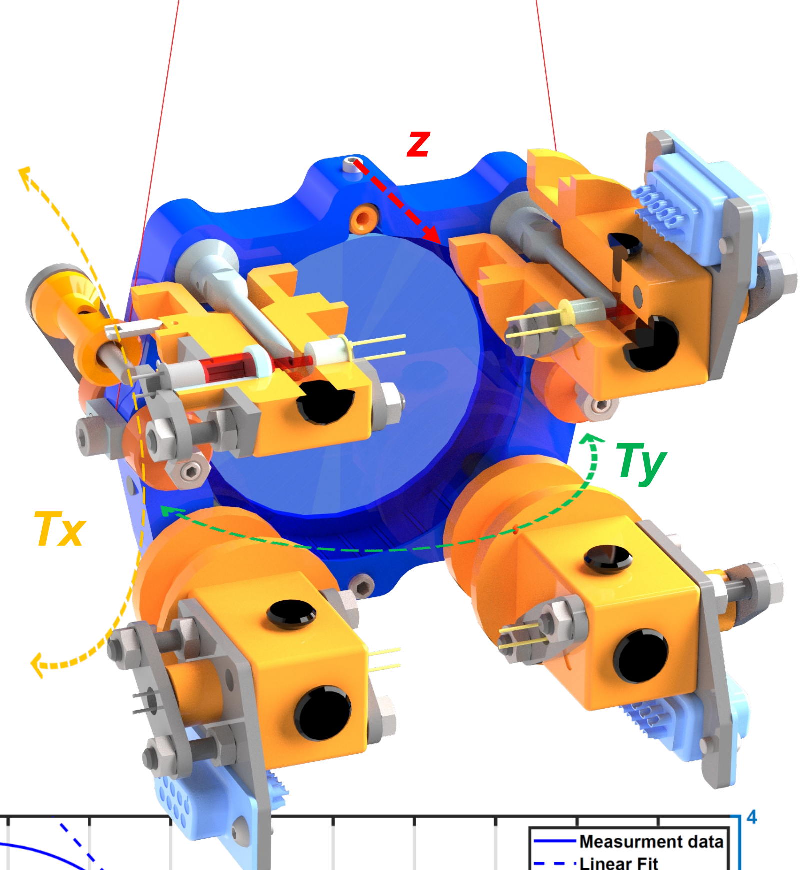




Suspension Systems



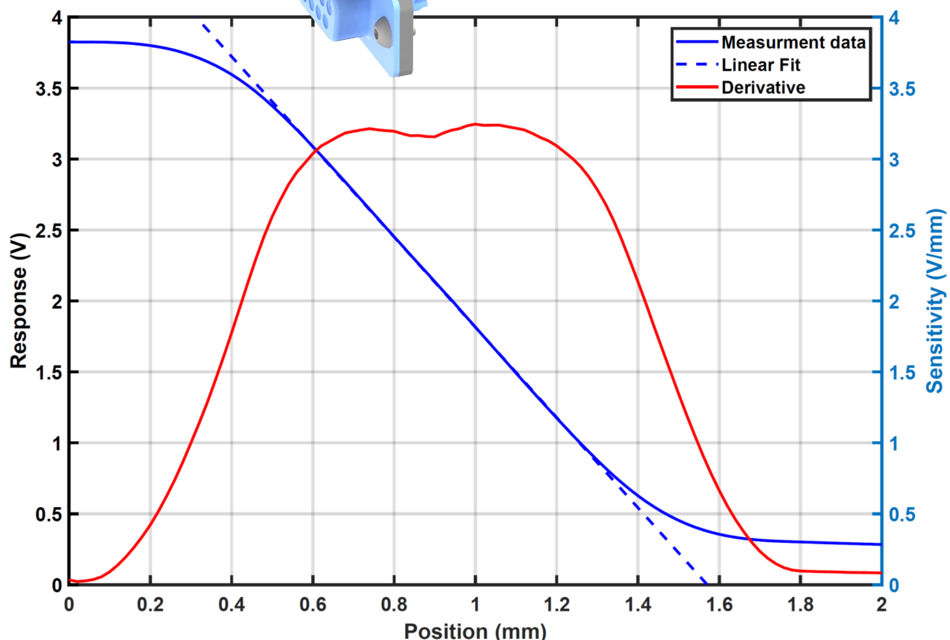
Suitable for
50mm and 2” mirrors
beam splitter and FP cavities



Three DOF actively controlled
Other DOF are passively damped

L x B x H
120 x 140 x 250 mm

Degree-of-Freedom	Modelled	Measured
Longitudinal	1.31 Hz	1.3 Hz
Pitch	1.65 Hz	1.63 Hz
Yaw	1.6 Hz	1.59 Hz
Transverse	1.34 Hz	-
Vertical	6.0 Hz	5.9 Hz
Roll	8.7 Hz	8.6 Hz



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Control [1]

Real-Time controls

- dSPACE MicroLabBox
- C/C++, Matlab (Simulink) & python
  - Simulink used for modeling, control and validation
- FPGA Xilinx® Kintex®-7 XC7K325T
  - CLBs slices 50950, 4Mb
  - DSP slices 840

Analog input;

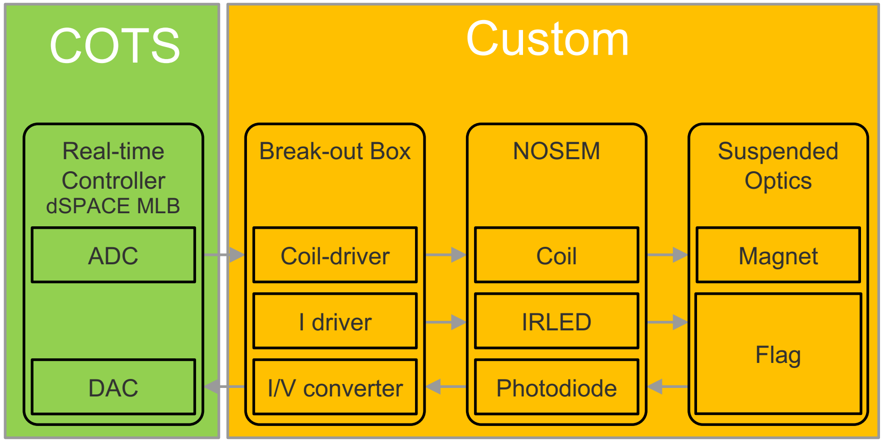
- 8x 14-bit channels, 10 Msps, differential
- 24x 16-bit channels, 1 Msps, differential
- Voltage range ±10 V

Analog output;

- 16x 16-bit channels, 1 Msps
- Voltage range ±10 V

Digital I/O

- 48 bidirectional channels



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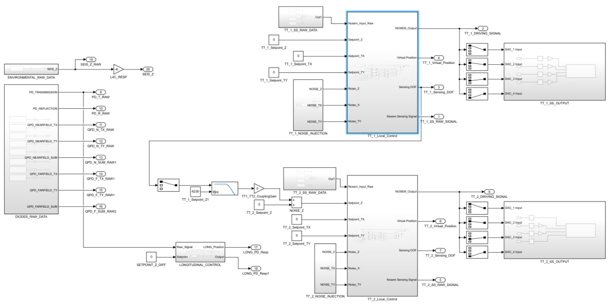
Controls [1]

Development

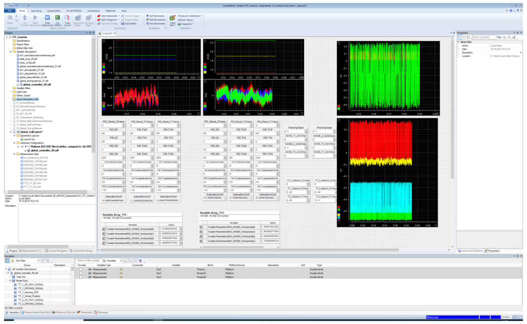
Simulink



dSPACE RTI
building blocks
Model builder
by c compiler

Measurement

ControlDesk



.sdf .map . rta .trc files

Data processing

Matlab

```
%% dSPACE -- ITF Controls -- Openloop TF measurement                  %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
close all
clc

% Load path
addpath ('C:\Users\Local Admin\Documents\10_Matlab_ITF_Controls\98_Matlab_Basic_Scripts')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Parameters_Mat
fs          = 10000;                        % sampling frequency 10 Hz
twin        = 1000;                      %
nfft        = (fs)*twin;               %
win         = hann(nfft);                % fft Window
fres        = 1/twin;                    % frequency resolution (for fft)
BW          = enbw(win, fs);%

%% Read and write Matrices
% Raw_data_01 = 'SENSING_DOF007.mat';
Raw_data_01 = 'TT1_TF_001.mat';
Raw_data_02 = 'exp2_007.mat';
tempdata_x = load(Raw_data_02);
%%
time            = tempdata_x.exp2_007.X(1).Data;
```

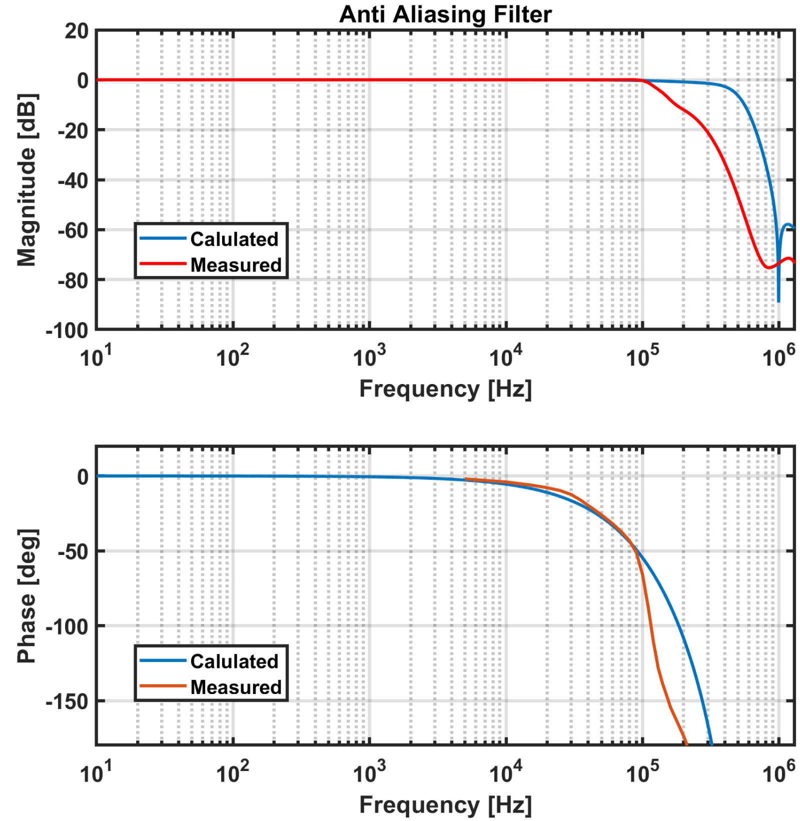
Record data in

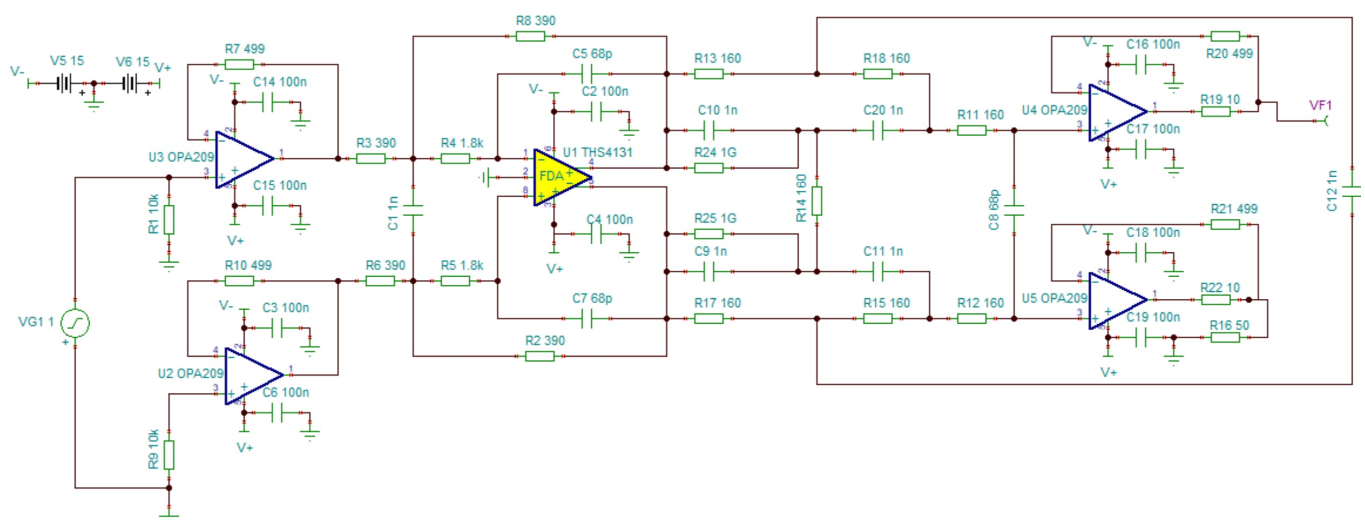
.csv / .mat data file

Signal conditioning

dSPACE MLB → No in/output filters

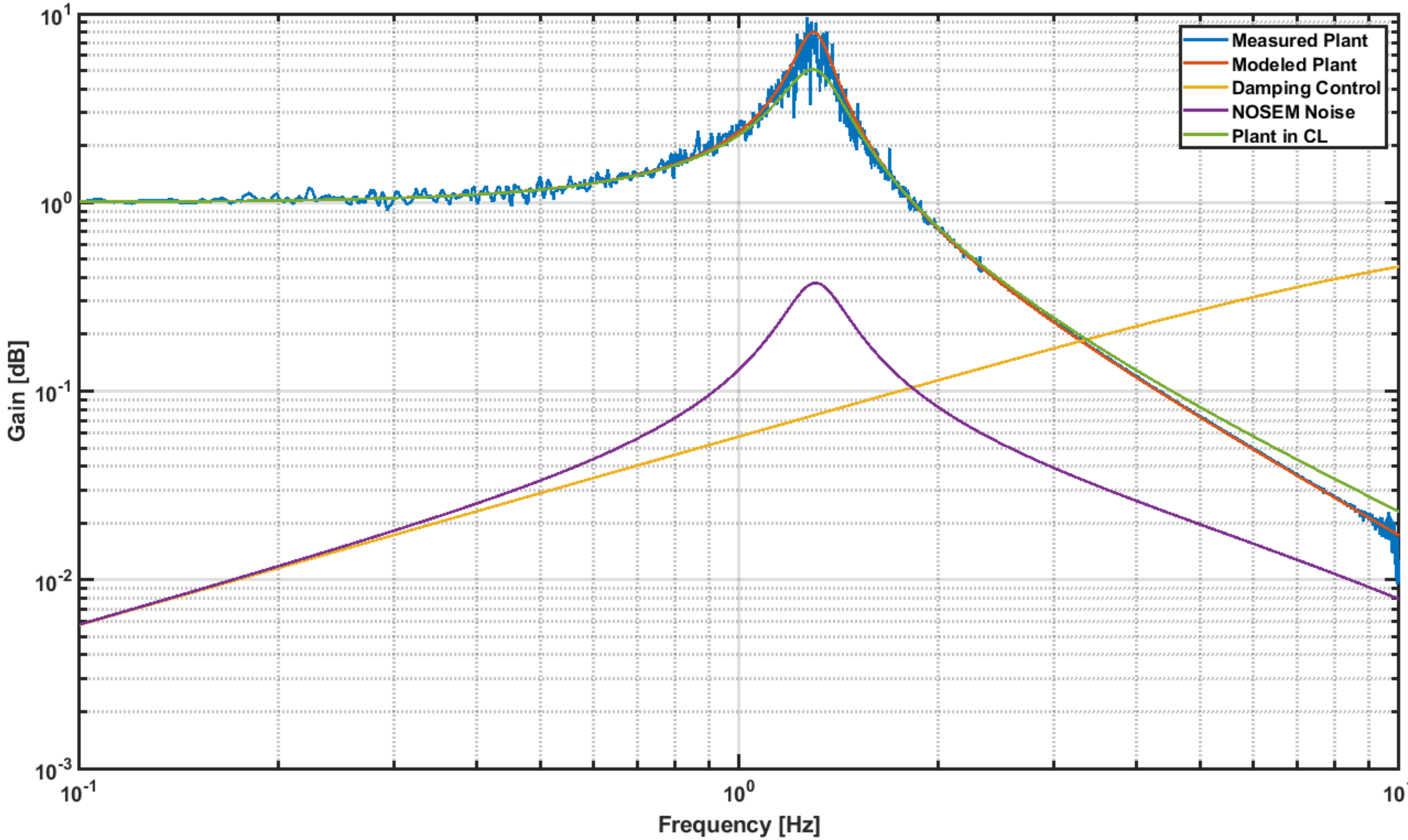
- **Solution: Redesigned LIGO AA/AI filter**
- **Requirements**
  - Cut of frequency → 300 kHz
  - Problems measuring the TF above 100 kHz
  - Notch filter 1Mhz
- **Performance;**
  - 10kHz Magnitude -6dB phase -3.6deg
  - 1MHz Notch >-70dB





Local Control Design

Force transfer function measurement of the longitudinal degree of freedom of the local mirror suspension systems, along with the modeled plant and control filters. To profit from the pendulum attenuation, soft damping control is applied reducing the residual differential mirror motion.



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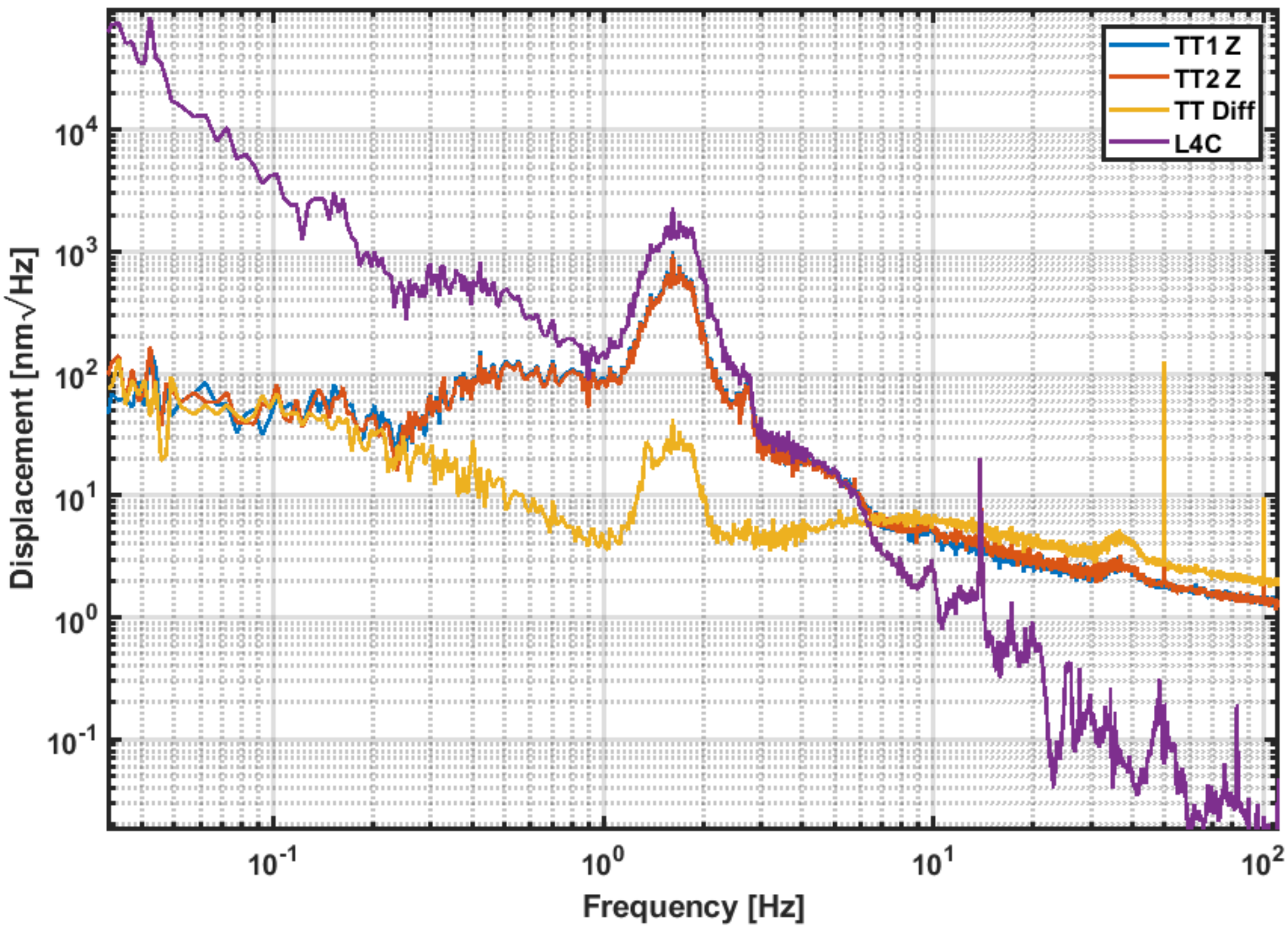
Local Control Design

The Newport S-2000A pneumatic vibration isolators amplify ground motion around one Hz, as shown by the L4C seismometer. The input- and end-mirror are softly damped and move coherently resulting in a residual differential motion as shown by the yellow line. Currently no 50 Hz filtering is applied yet, since we want to find the cause of this noise source.



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Global Control

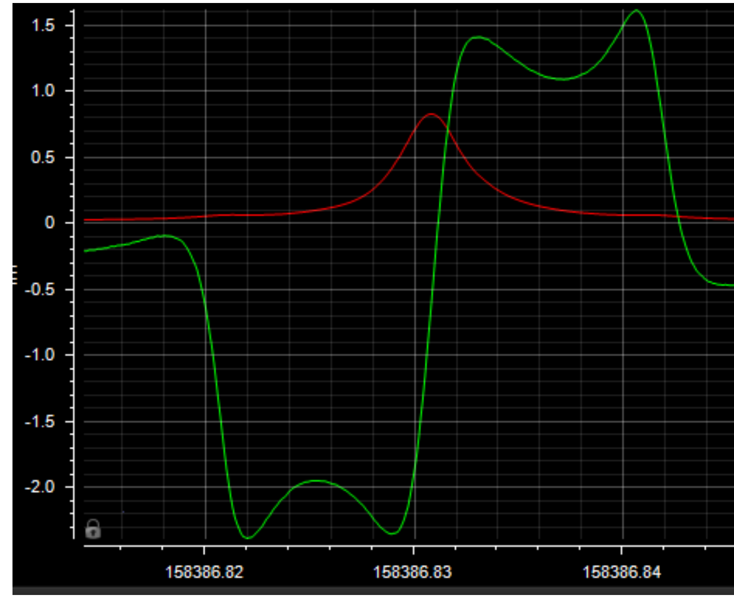
The Table-Top ITF is at its final stage of commissioning and ready to be locked by the global control. The PDH error signals are available

Error signals

- **All optics are well aligned.**
- **PDH error signals required for the longitudinal control available**
- **Beam camera images need to be cleaned up**

Control

- **Reduce RMS mirror motion or implementation guided lock**



Phase camera + ITF control

The table top interferometer is co sharing the optics table with the phase camera, a alternative diagnostic sensor, that can provide an completely independent monitor of the amplitude and phase of the optical beams. The phase cameras are sensitive over a large range of side bend frequencies and able to probe the individual DOF by the modal decomposition of beam images. However, phase cameras images acquired in GW detectors are hard to interpret by all the noise sources. By combining both systems and operation under lab conditions a dedicated NN can be trained and validated before deployment in the real detectors.

Phase camera

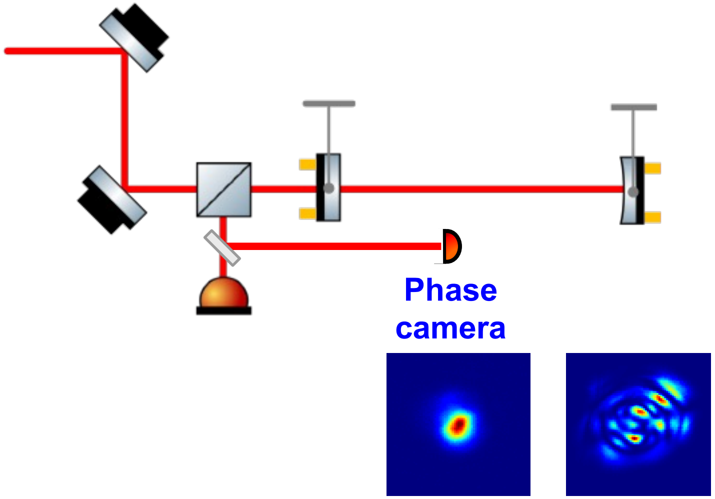
- **sensor which reconstructs amplitude and phase maps by beating the signal beam with a reference beam**
- **separate maps of carrier and sidebands of the signal beam**
- **extremely useful for GW detectors**

Requirements for the phase camera quite stringent

- **R&D always in progress to implement upgrades**

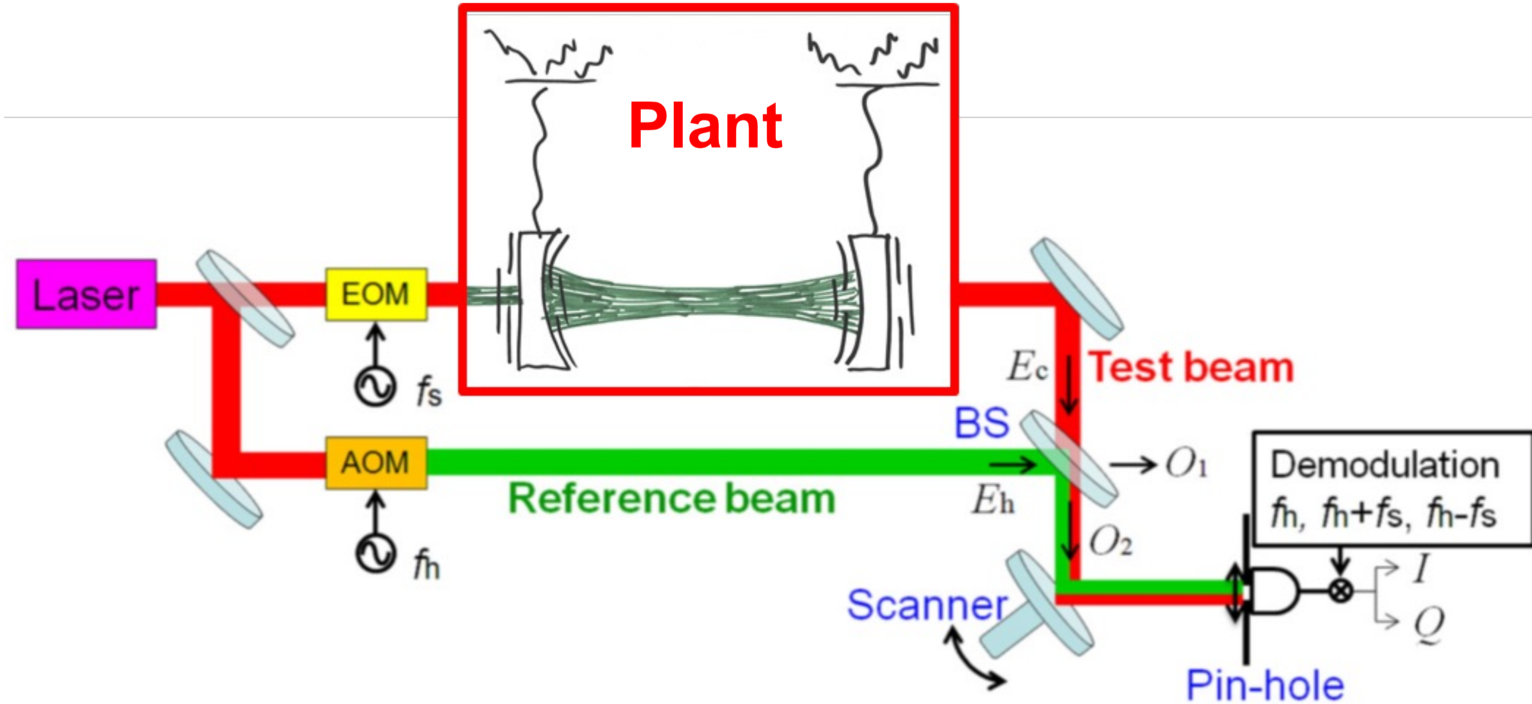
Table-top cavity and interferometer extremely important to study the performances of the phase camera

- **distortion induced on purpose on the beam acquired by the phase camera**

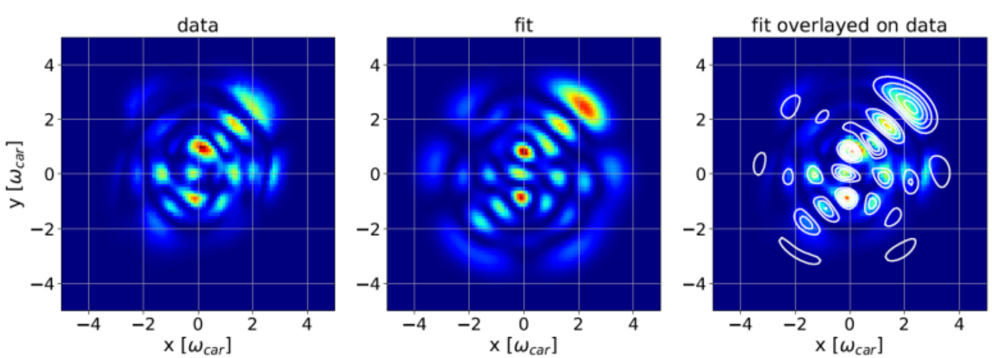


ML: Modal decomposition of beam images (phase camera)

Modal decomposition via CNN are proven to be effective to interpret experimental datasets with high accuracy. The angular DOF of the table-top experiment allows to generate “real” data including noise sources to understand, train and validate the CNN phase camera beam images for modal decomposition.



Example: Fit of the higher order mode content in the carrier on the dark port (Virgo)



Included HOM n+m =0, 1, 7 and 8

https://research.vu.nl/en/publications/the-phase-cameras-of-advanced-virgo

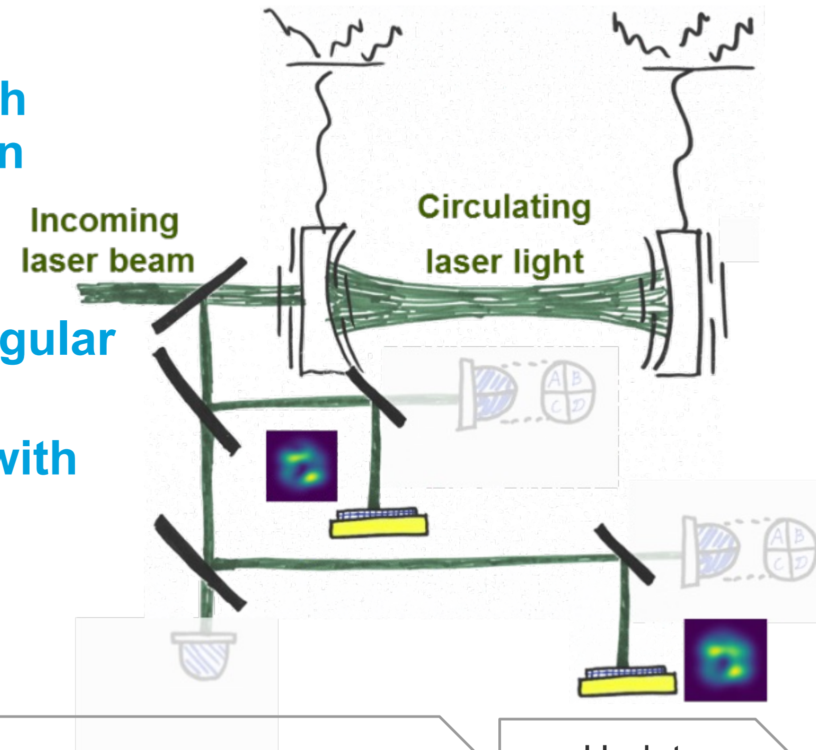
CCD Beam Images

The table-top Fabry-Perrot resonance cavity with classical controls provides a full-state control using the a-priori(physics) knowledge and real-time observations to reconstruct the states of the system. The first step is to validate the noise performance of the CNN for real beam images. The network will be pre-trained by real data

Training data

- **Generated by Finesse and OSCAR. Both codes based on par-axial approximation (modal model and FFT propagation)**
- **Angular misalignments up to 3.5 mrad**
- **First focus; half plane the individual angular degree of freedom (DOF).**
- **Database with 100.000 images argued with gaussian noise.**

Real data mandatory to train network



Method

Preprocessing (Simulation or data) → Alignment Algorithm → Update Mirror Position

Status

Images generated
Images stored in databases
Almost ready to generate real images

Status

Trained CNN for alignment identification
3D CNN under development

Status

Interface to real-time controller

Conclusions and Outlook

The realization of a fully suspended laser interferometer enables the development of alternative control strategies for gravitational waves observatories

Next steps:

Optimize local controls

Close longitudinal/angular controls

Followed by:

Collecting real beam images by CCD cameras and phase camera

Develop next version of the CNN to prove noise performance for beam images as error signals

Integrate phase camera in the ITF setup

Phase camera modal decomposition

powerful diagnostic tool for commissioners

CCD beam images as error signals can

increase the robustness

reduce the downtime

&

Help commissioners to automatize nonlinear tasks

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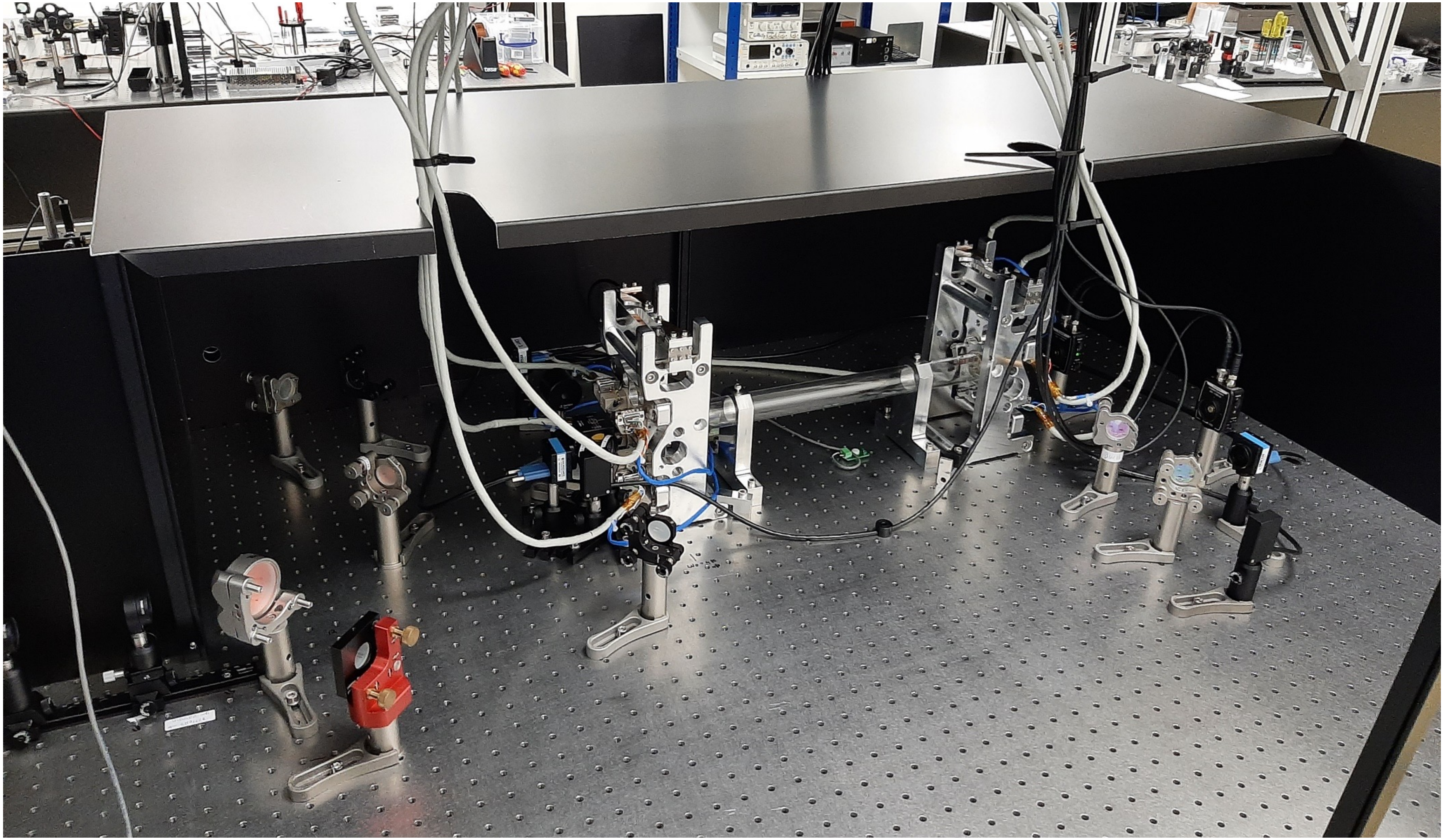
Thanks for your attention!



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