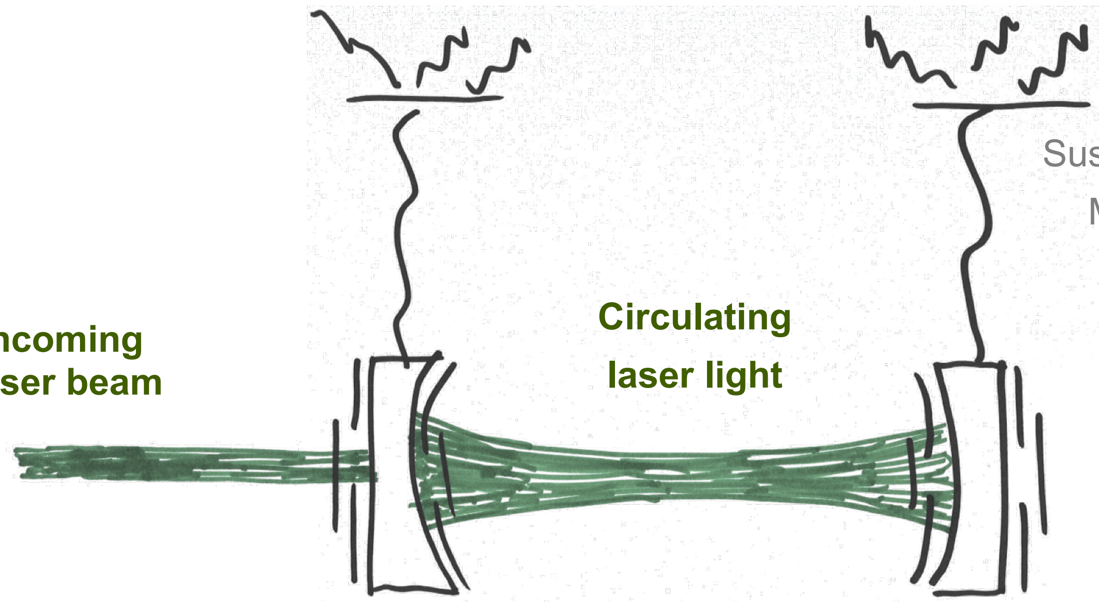
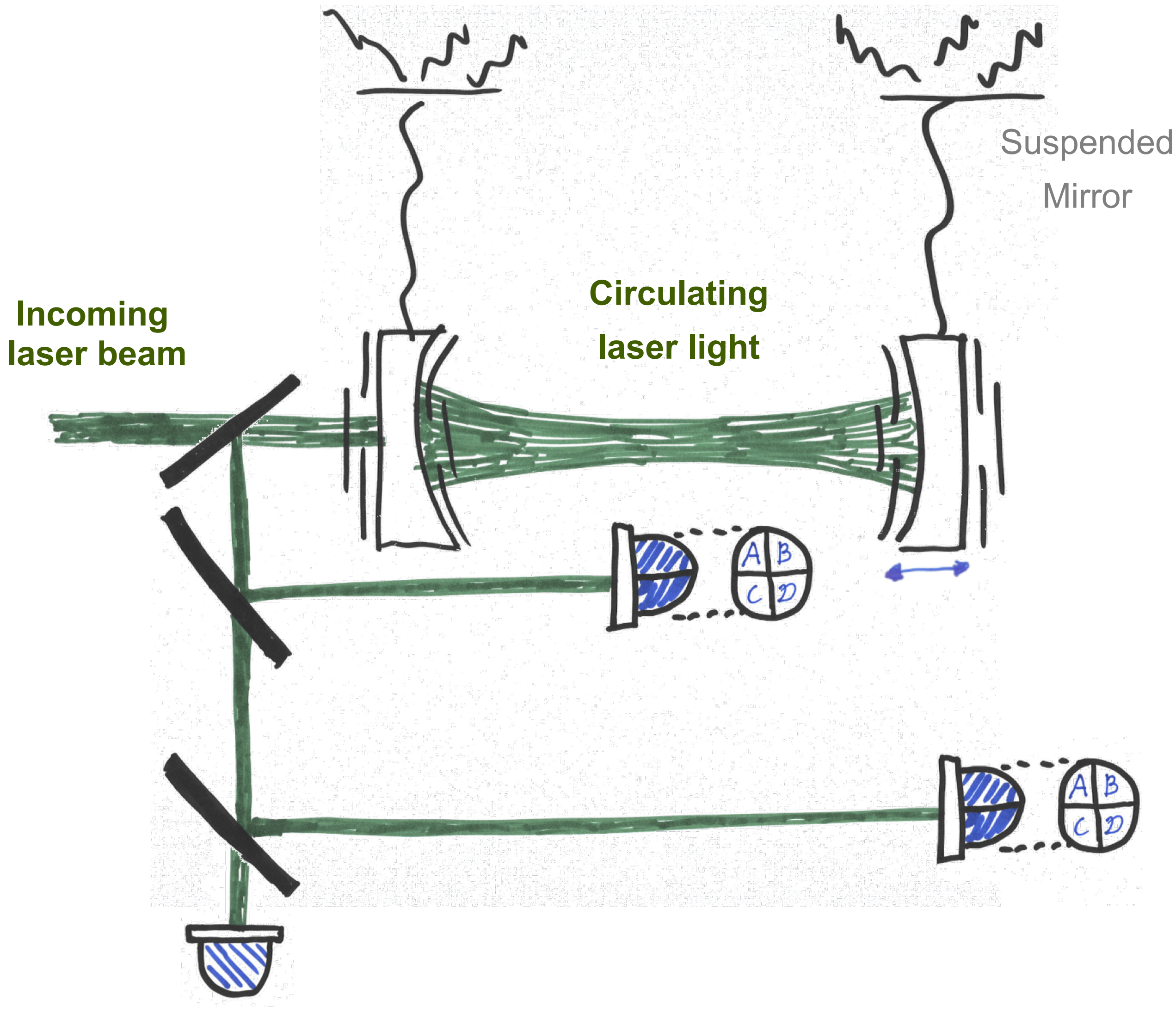
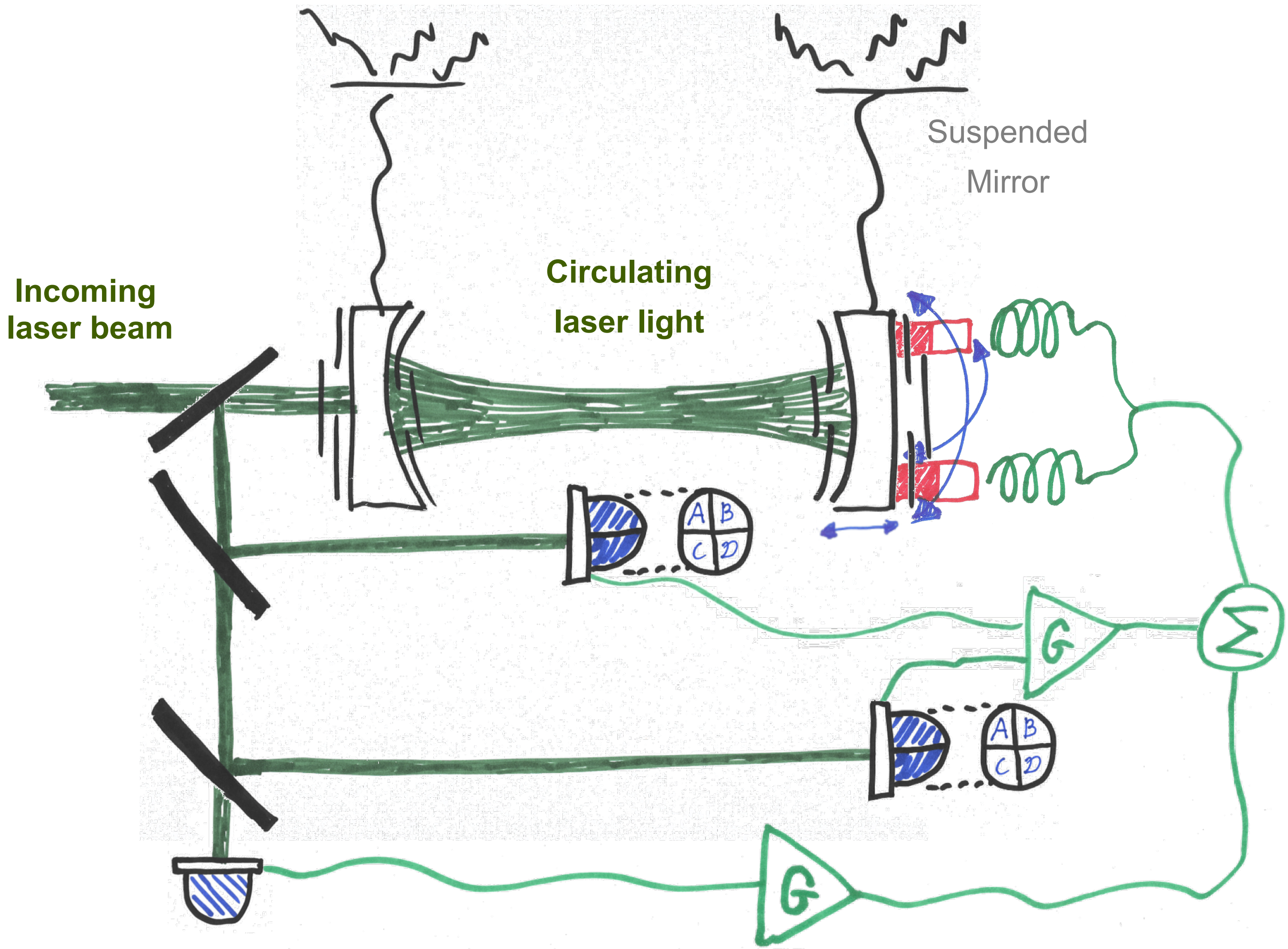
The traditional control of a suspended optical cavity



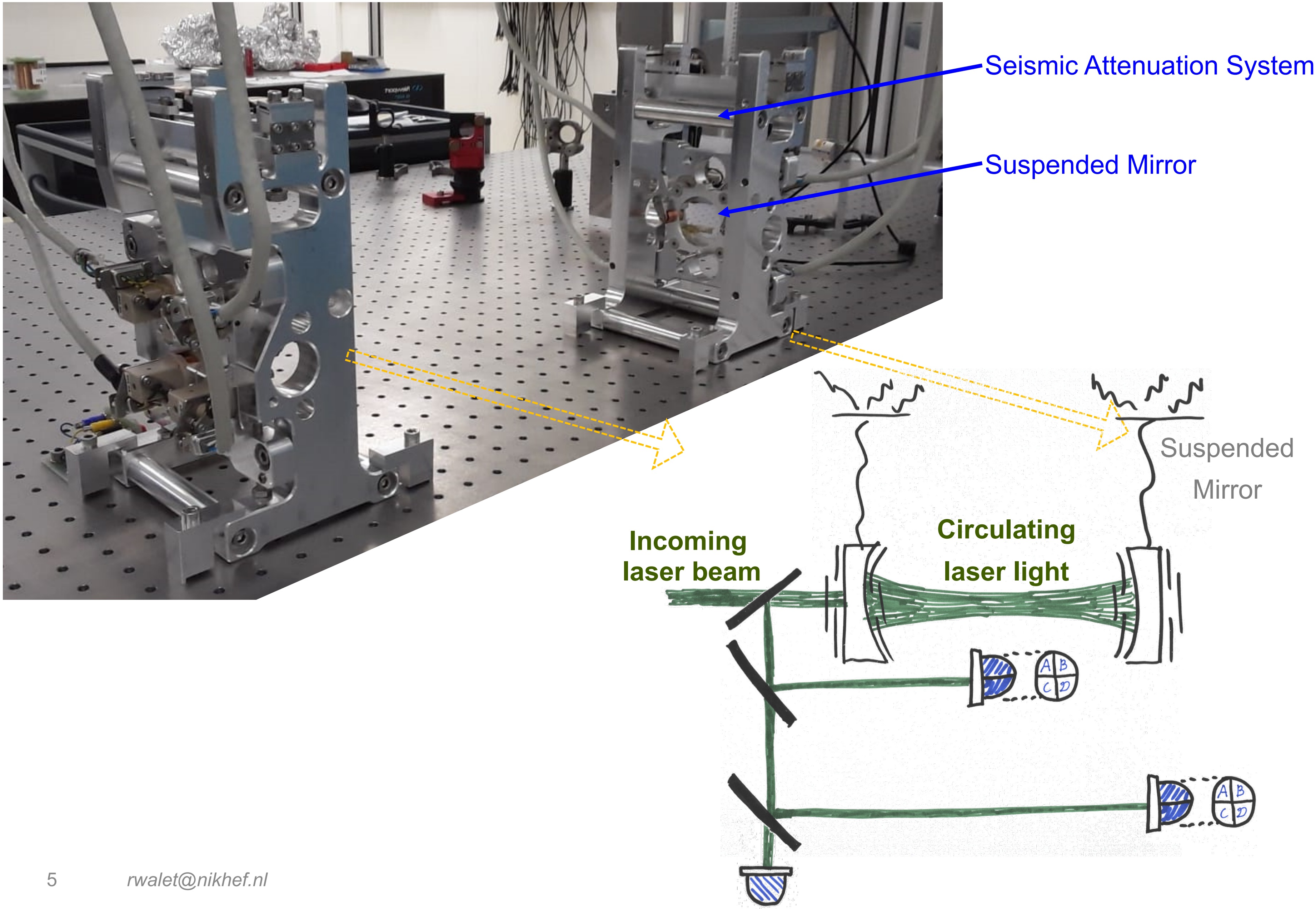
The traditional control of a suspended optical cavity



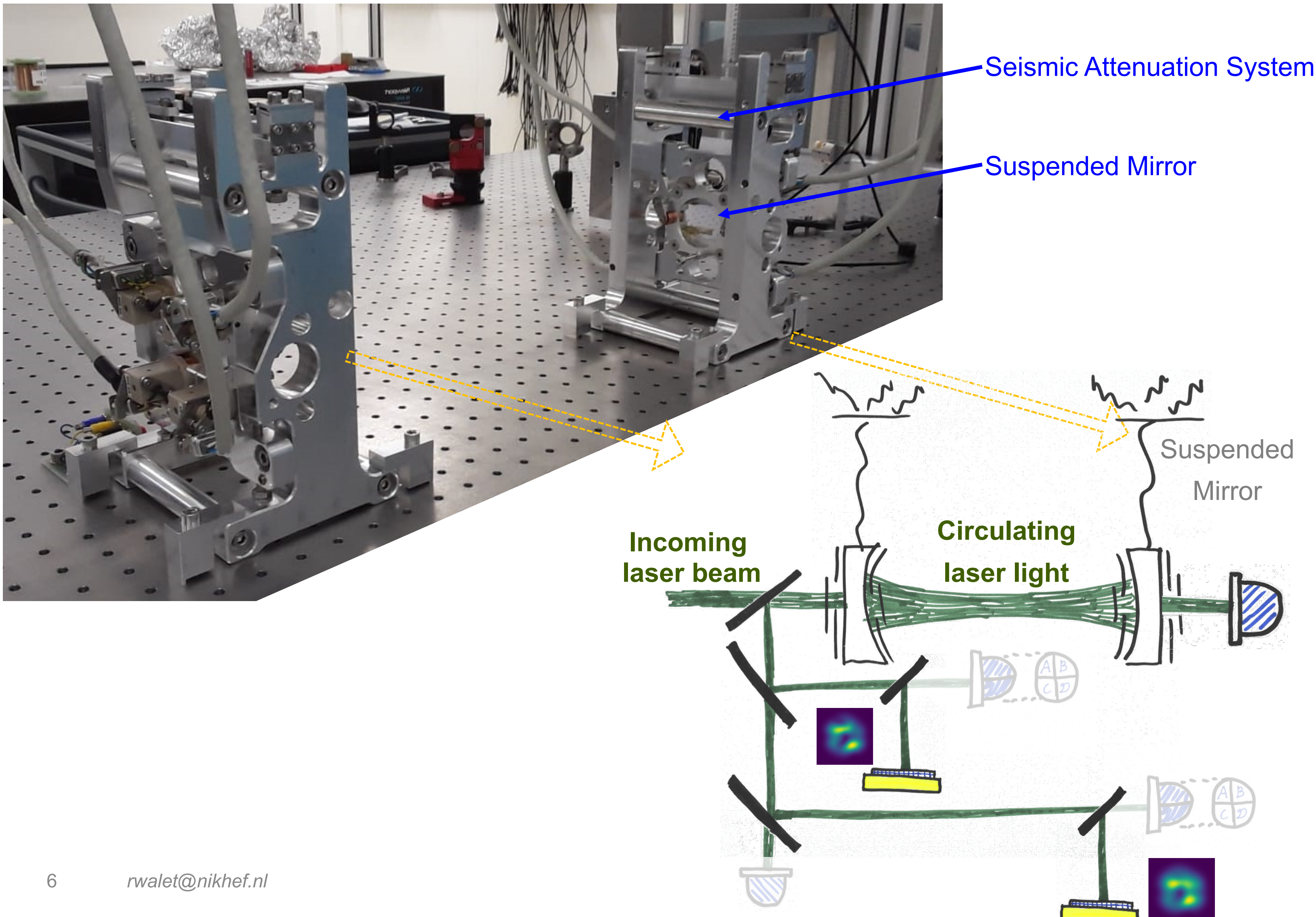
The traditional control of a suspended optical cavity



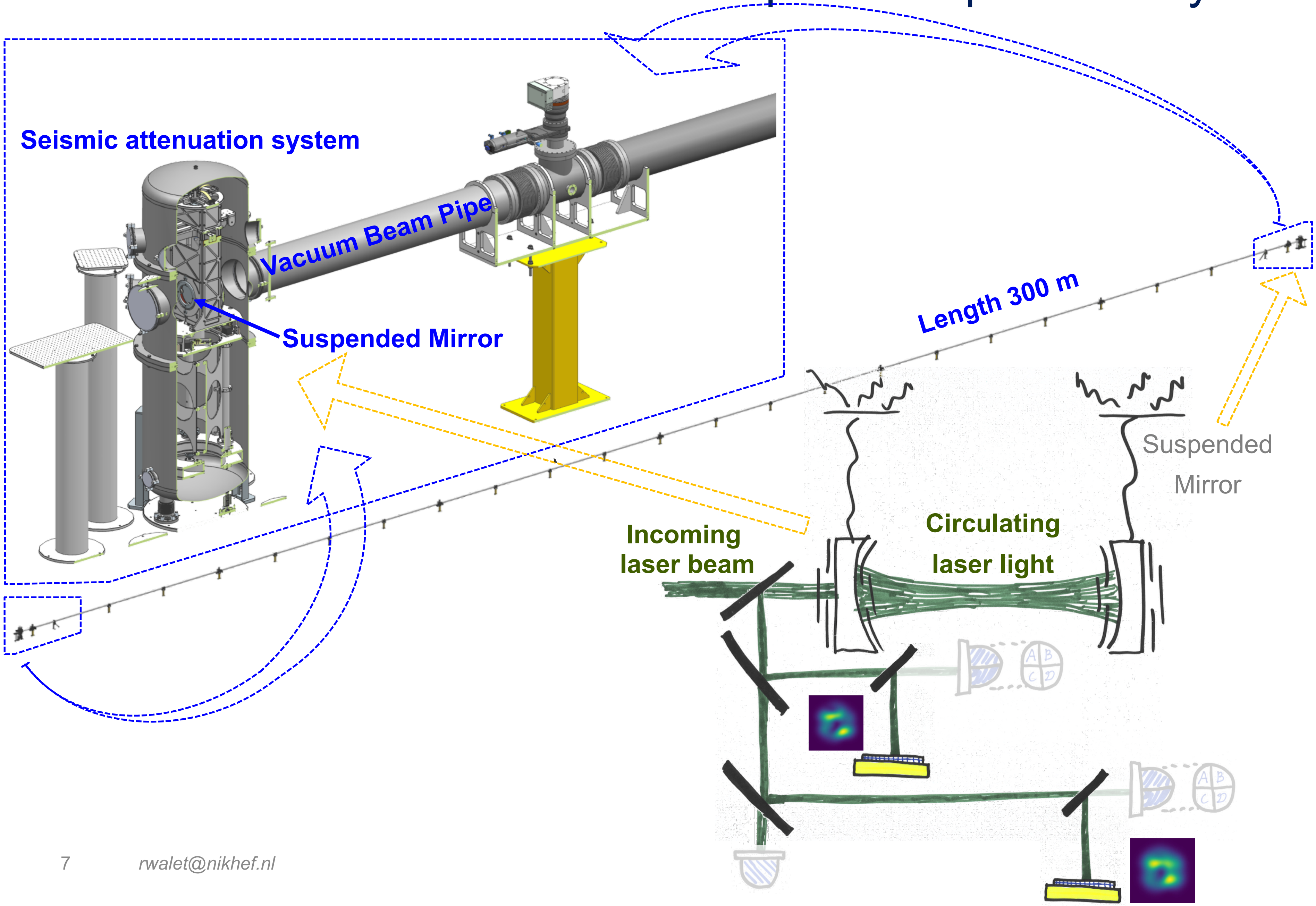
ML bases controls of a suspended optical cavity



ML bases controls of a suspended optical cavity



ML bases controls of a 300m suspended optical cavity



rwalet@nikhef.nl

Questions?

Backup

Single cavity - Longitudinal Control

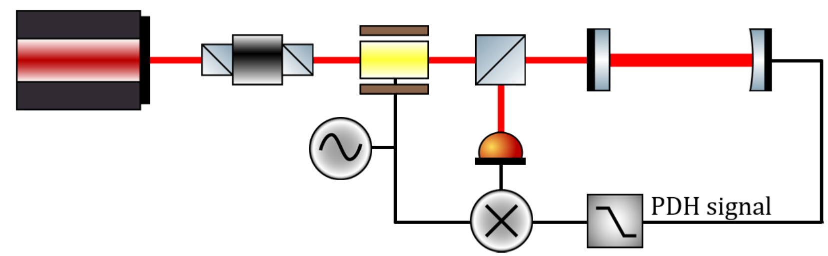
"Let's focus on a single arm cavity. A resonance cavity can not be simply locked by the carrier field. Phase modulation of the carrier is applied to create error signals needed to keep the system at resonance"

Pound-Drever-Hall (PDH) technique

Electro Optical Modulator (EOM)
create sidebands around the carrier

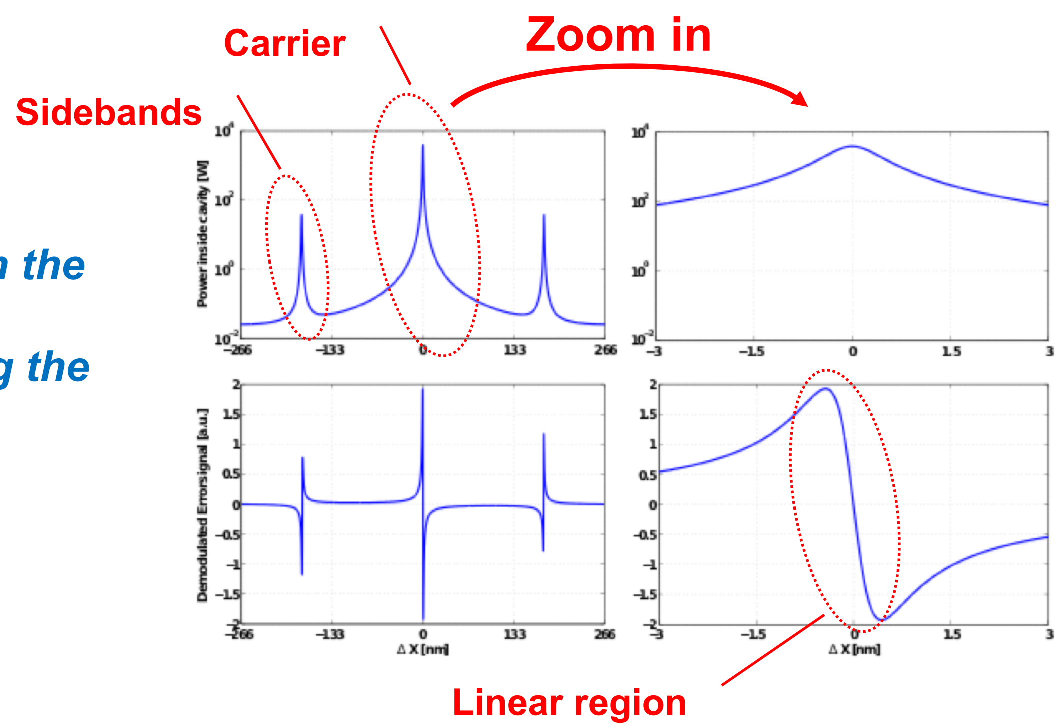
Phase modulation

$$E_{EOM} = E_0 \cdot e^{(i\omega_0 t + m\cos(\Omega t))}$$



The carrier field resonates inside the cavity while the sidebands are anti-resonant, therefor they are reflected

The PDH error signal is given by the be beat note between the carrier and the sidebands (used as phase reference, carrying the cavity length information)



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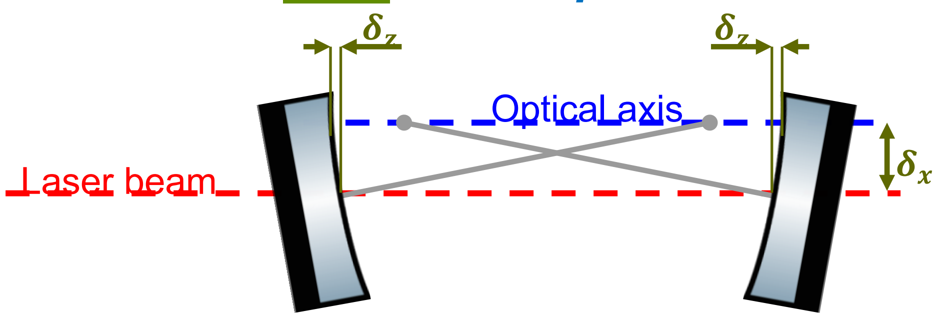
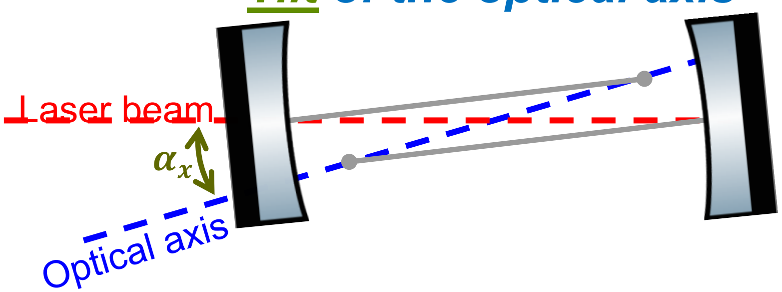
Single Arm Cavity – Angular Alignment

"The input Gaussian beam and the optical axis of a cavity need to be aligned to prevent the occurrence of higher order modes (HOMs)"

Shift of the optical axis



Tilt of the optical axis



Four angular degrees of freedom / cavity

Misalignments introduce HOM

HOMs decrease the power of the fundamental mode

Misalignments change the cavity lengths

Approximation

for $\delta_x \ll \omega_o$

$$E(x+\delta_x) \approx A\left[H_0(x) + \frac{\delta_x}{\omega_o} H_1(x)\right]$$

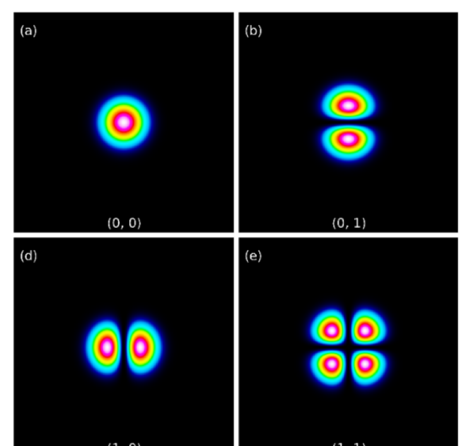
Beam divergence

for $\alpha_x \ll \theta_d$

$$E(x+\delta_x) \approx A\left[H_0(x) + \frac{\alpha_x}{\theta_d} H_1(x)\right]$$

Hermite-Gaussian modes

(with degrees, n and m)



Single Arm Cavity – Angular error signals

Dithering line (mechanical modulation)

Angular oscillation ω_{mij} of the two rotational DOF of the mirror

Misaligned optics create a cavity length change δ_z

Error signal created by demodulating the longitudinal signal by ω_{mij}

Ward technique (Phase modulation)

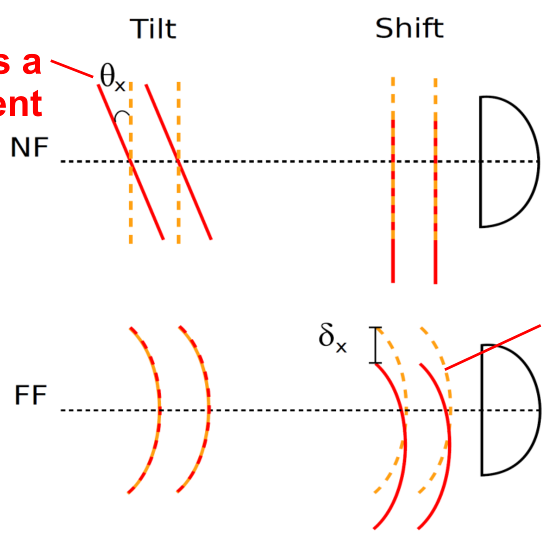
Usage of the longitudinal modulation frequency by EOM

Tip and tilt are both mixed in one error signal

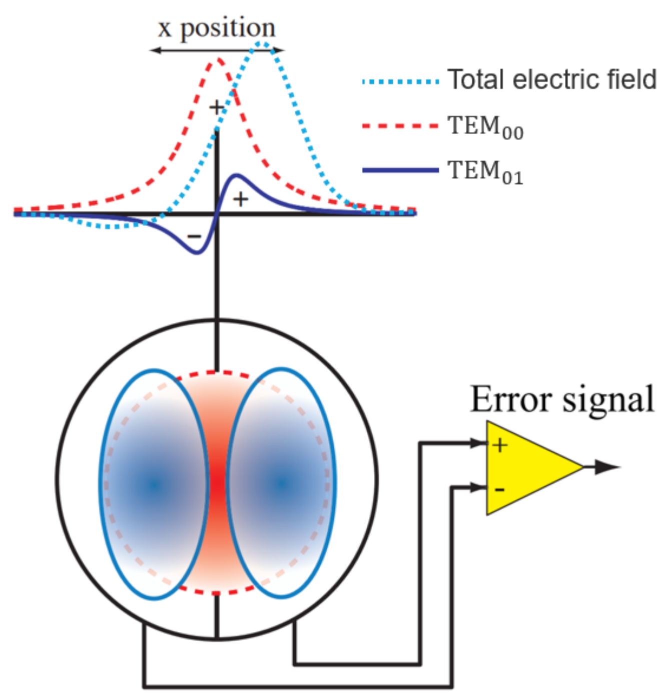
Two* QPDs in reflection of the cavity measures the spatial beam phase distribution

(*near and far field)

Tilt is measured as a phase gradient



Shift generates a phase gradient



VIRGO fact sheet

Test-masses longitudinal degrees of freedom 4 (5)

Test-masses angular degrees of freedom 16 (18)

Longitudinal DOF

$$\mathrm{Carm} = \frac{l_{north}+l_{west}}{2}$$

$$\mathrm{Darm} = \frac{l_{north}-l_{west}}{2}$$

$$\mathrm{Mich} = l_{n\_i} + l_{w\_i}$$

$$\mathrm{PRCL} = l_{pr} + \frac{l_{n\_i}+l_{w\_i}}{2}$$

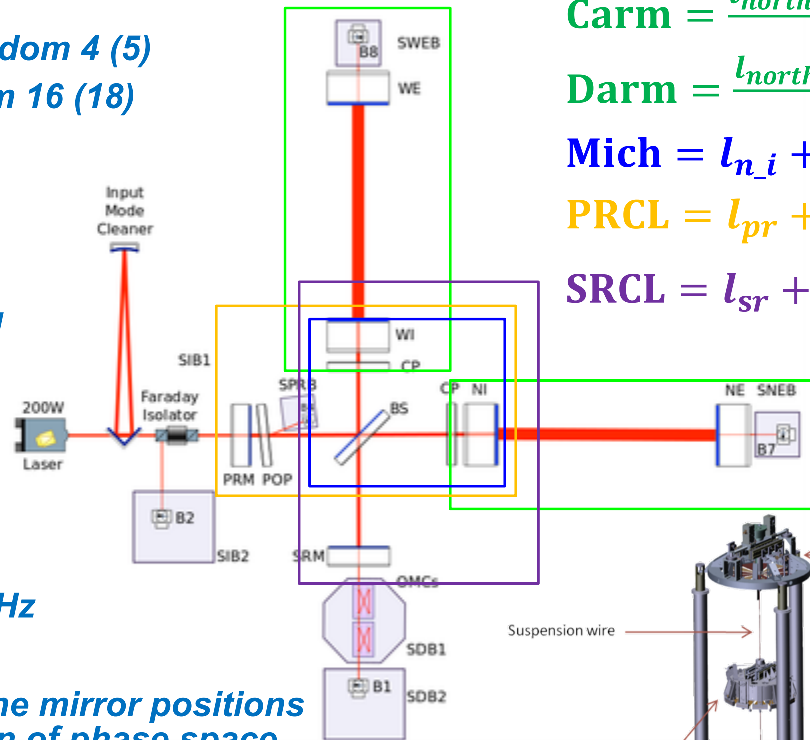
$$\mathrm{SRCL} = l_{sr} + \frac{l_{n\_i}+l_{w\_i}}{2}$$

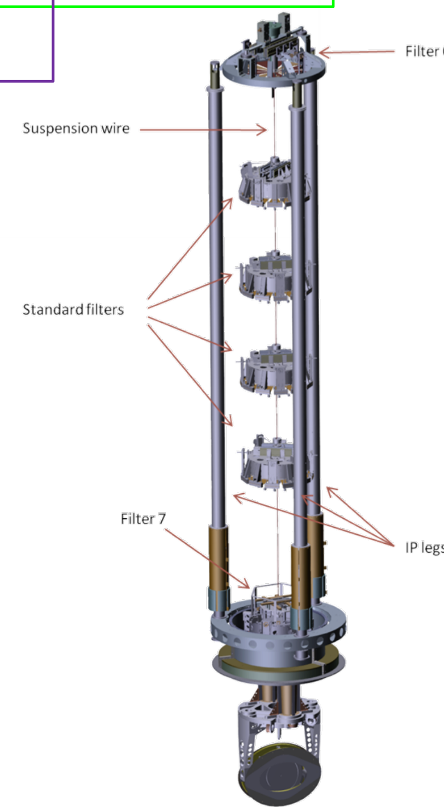
Seismic Attenuation Systems
for all optical components

Mirror Alignment 10^{-9} [rad/min]

Mirror Positioning 10^{-12} [m/min]

But there is more





Real time

~10.000 control loops
ranging from a few Hz up to 200 kHz

Complex

Error signals are strongly nonlinear functions of the mirror positions and can only by linearized in a very small fraction of phase space

Lots of complex tricks and manual actions are involved to enable classical controls

Making the commissioning a continuous challenge relying on well trained, highly experienced people

…M€ systems

GW Observatory → one can not afford downtime

Trade-off between interventions and the risk of downtime

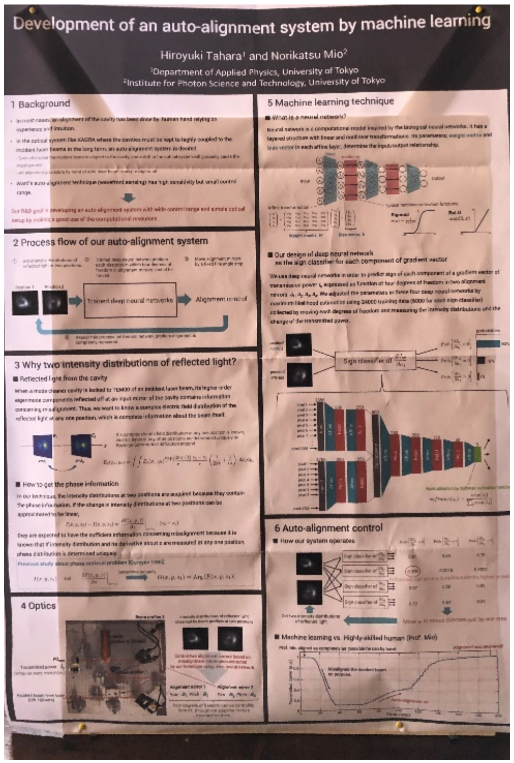
Simulations and test facilities are key to drive break-through innovations

rwalet@nikhef.nl

ML in the GW field

No (public) experimental success stories yet! → not a continuous development

University of Tokyo



Experimental Results!!
But for rigid optic

University of Birmingham

UNIVERSITY OF BIRMINGHAM
SCHOOL OF PHYSICS AND ASTRONOMY

PER ARDUA AD ALTA

Fourth Year Project Report
March 2019

Alignment of LIGO Fabray-Perot Interferometer using Machine Learning

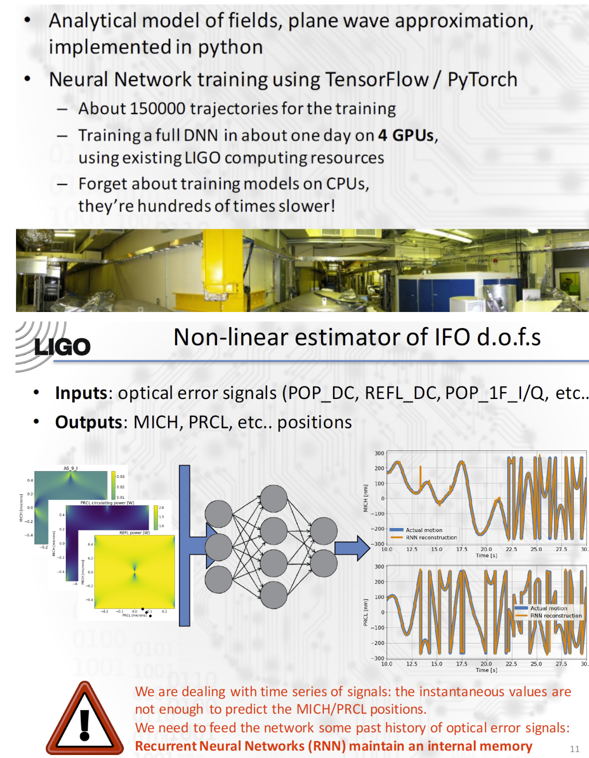
Robert Beesty
Student ID: 1526199
In Collaboration with Emma Morley

Supervisors: Prof. A Freise, Dr. D Martynov
With Thanks to G Smetana

Only theory!!

Just one mirror tilted

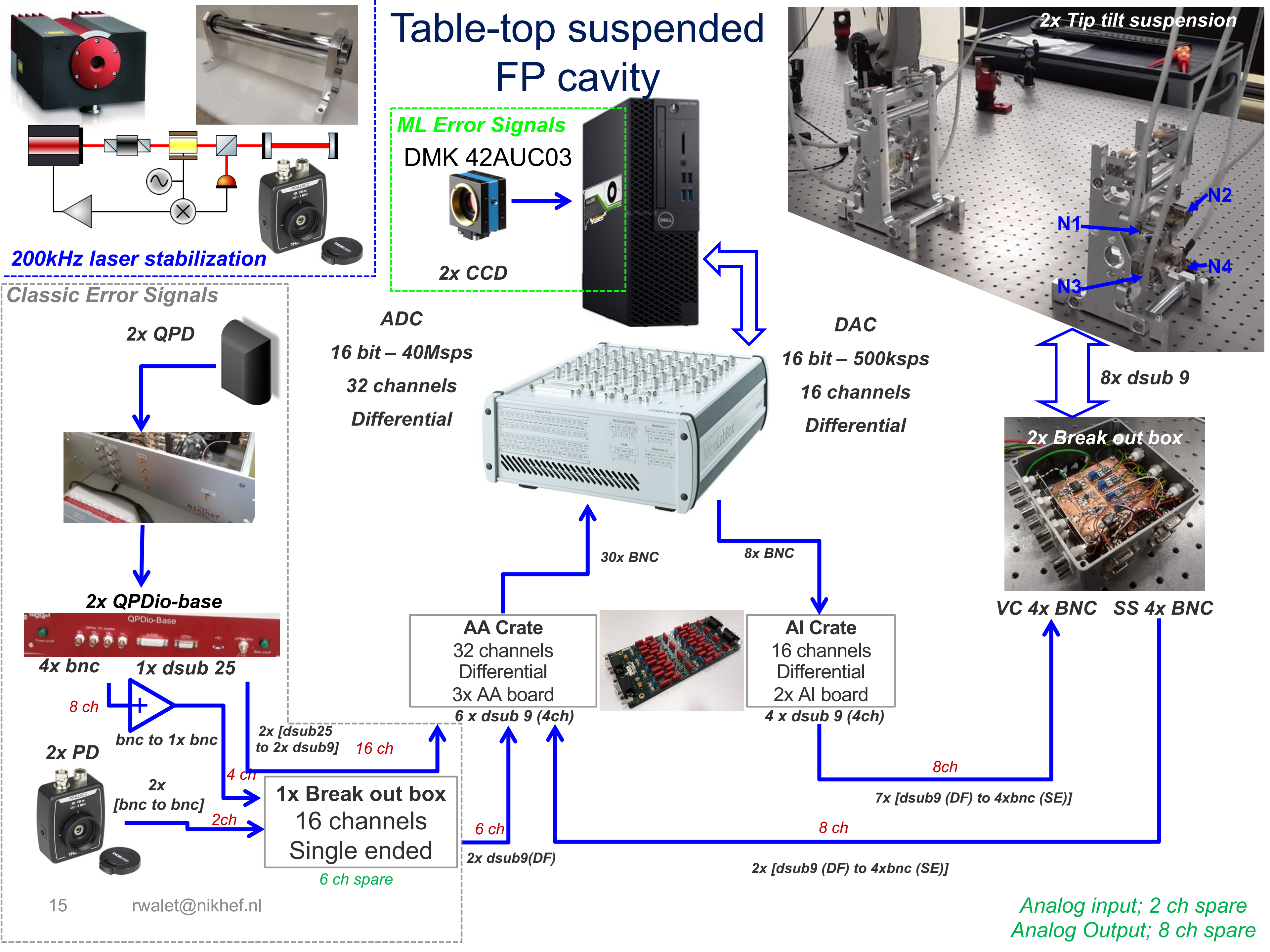
University of Caltech/MIT



Simulations are great!
Network is trained! WORKING

NO experimental results!!

40m Prototype <u>too complex</u> to start with?!



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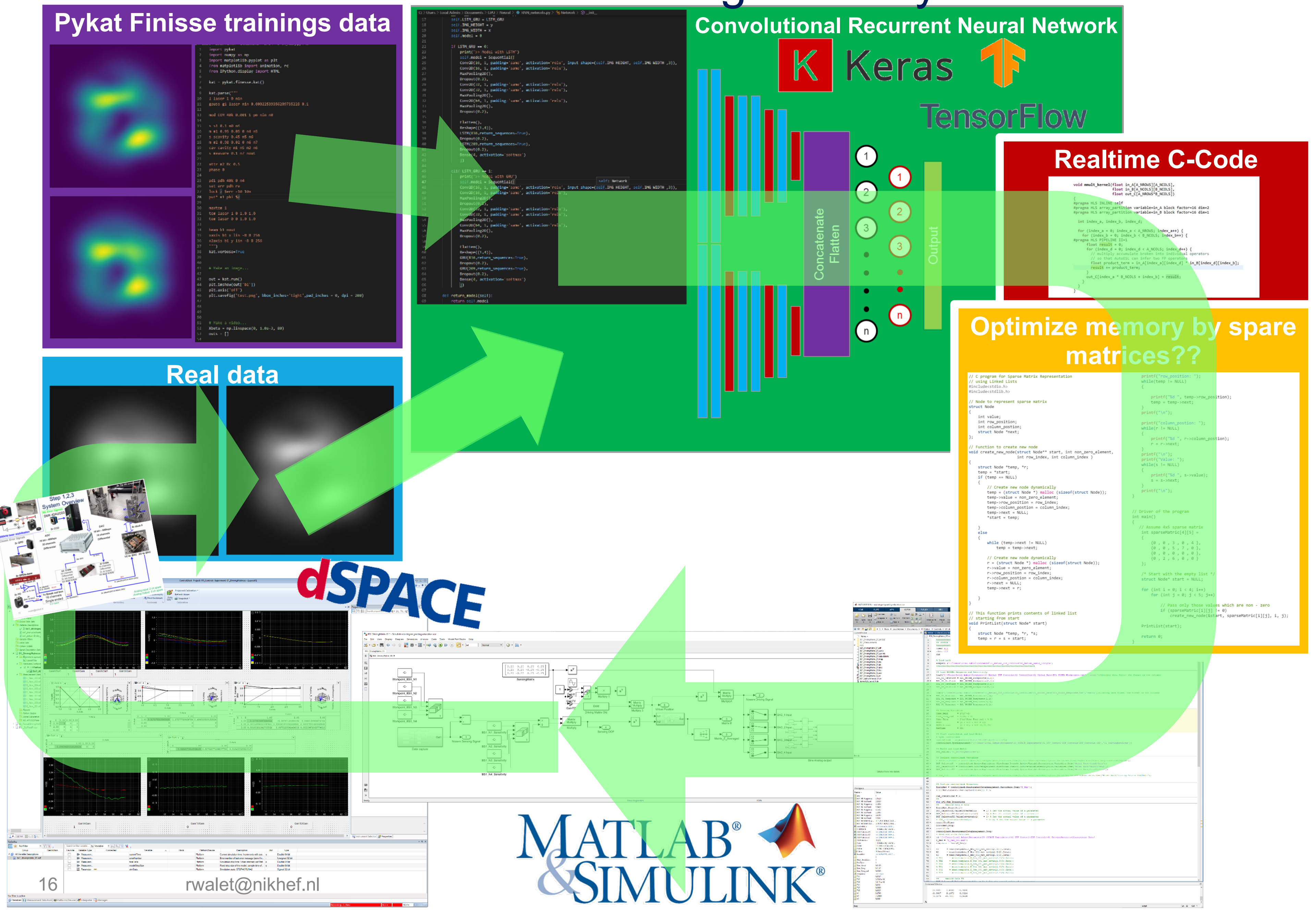
Software Architecture – auto alignment system



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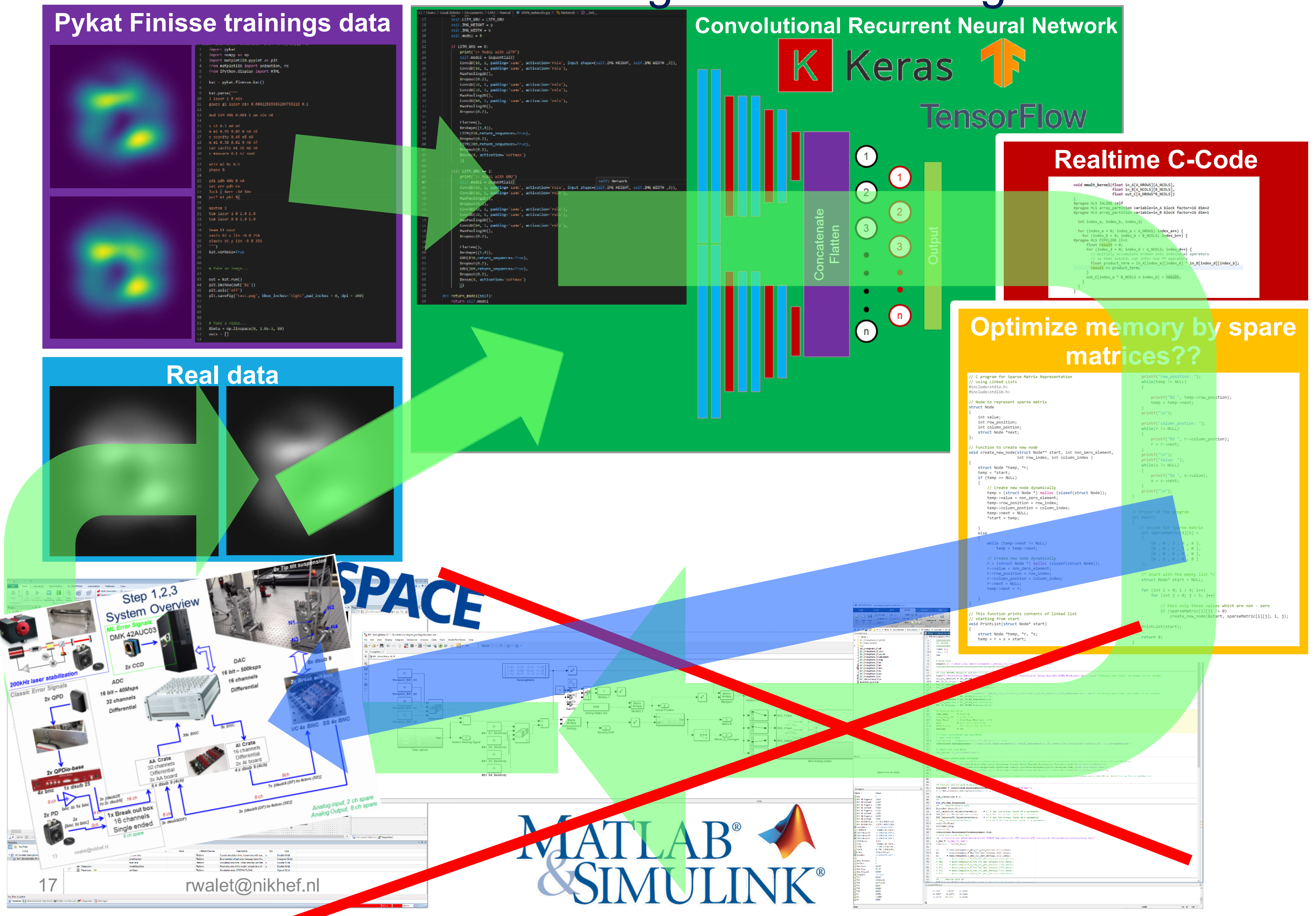
Software Architecture – Longitudinal and angular control



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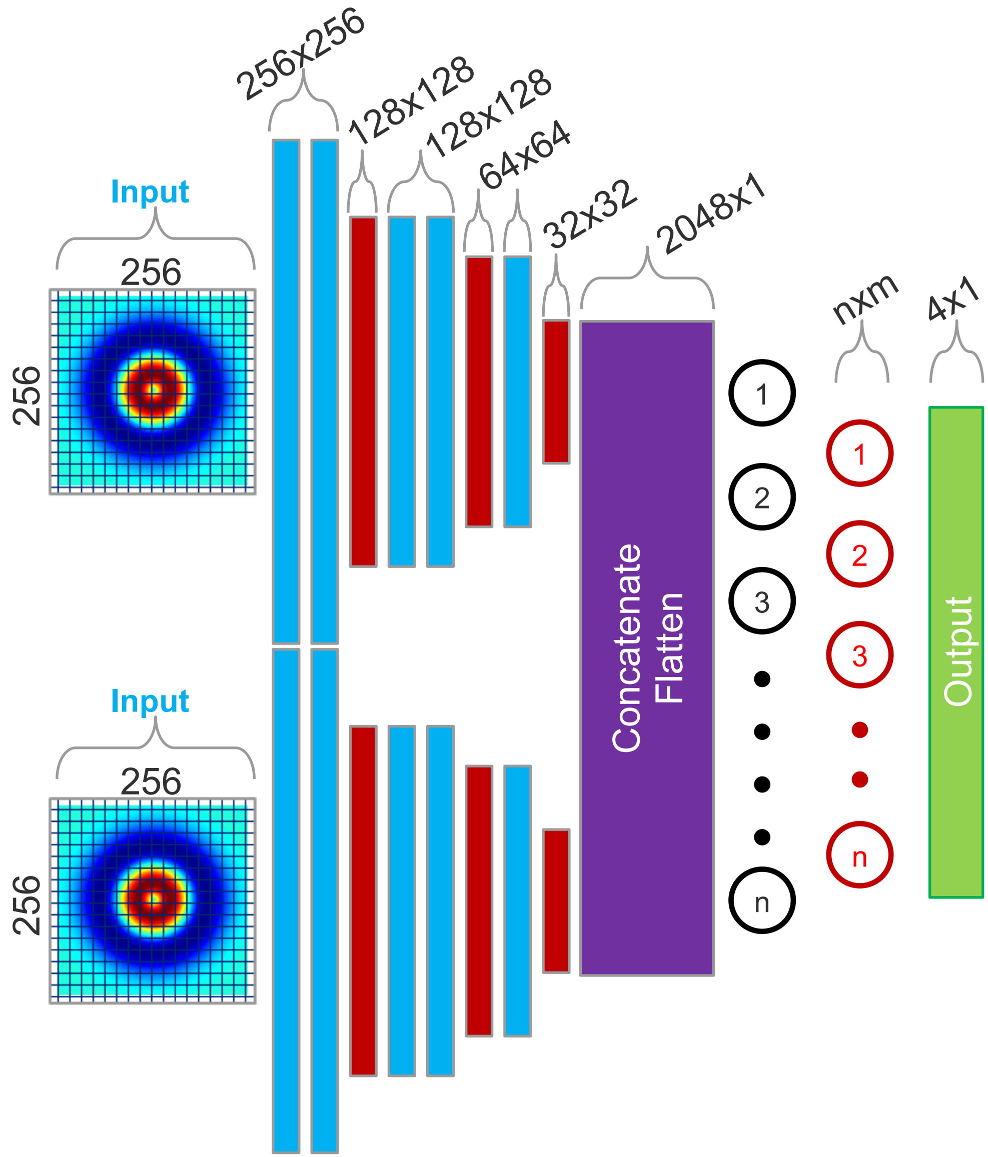
Convolutional Recurrent Neural Network

CCD Image → CRNN → Mirror position



Convolutional Layer

Containing a RELU activation layer

Pooling Layer

Containing a drop-out to reduce overfitting

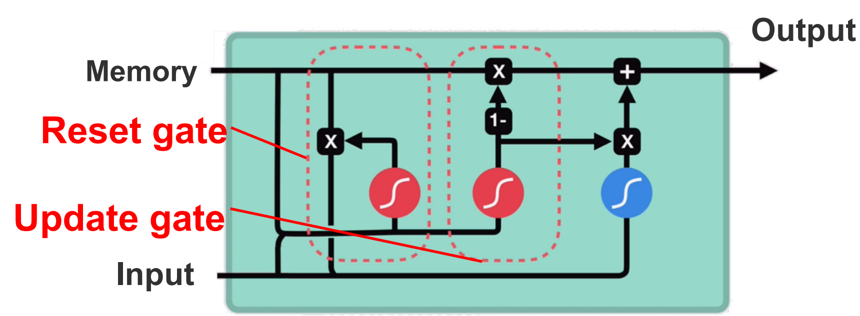
Output

Containing a Sigmoid activation function

The auto-alignment systems needs to deal with discontinued and time varying signals

- *The convolutional recurrent neural network will include Long Short-Term Memory (LSTM) like in speech recognition algorithms*
- *The CRNN enable auto alignment of the Fabry-Perrot resonance cavity*
- *(Atmospheric) disturbances can be compensated to maintain the lock*

Gated Recurrent Unit



Tip-tilt suspension

Suitable for

50mm and 2" mirrors

beam splitter and FP cavities

Three DOF actively controlled

Other DOF are passively damped

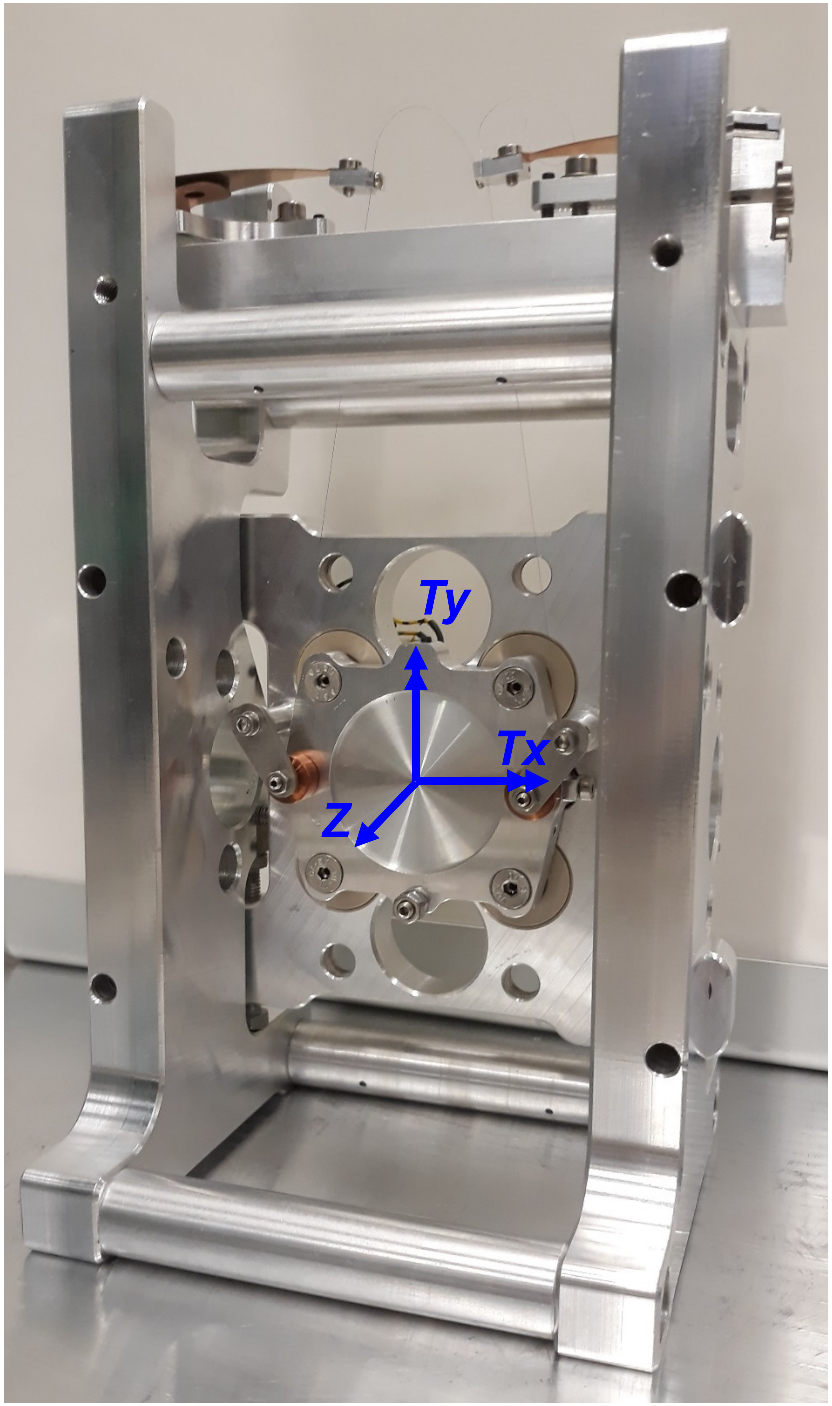
L x B x H

120 x 140 x 250 mm

UGF 200Hz

Seven tip-tilt suspensions

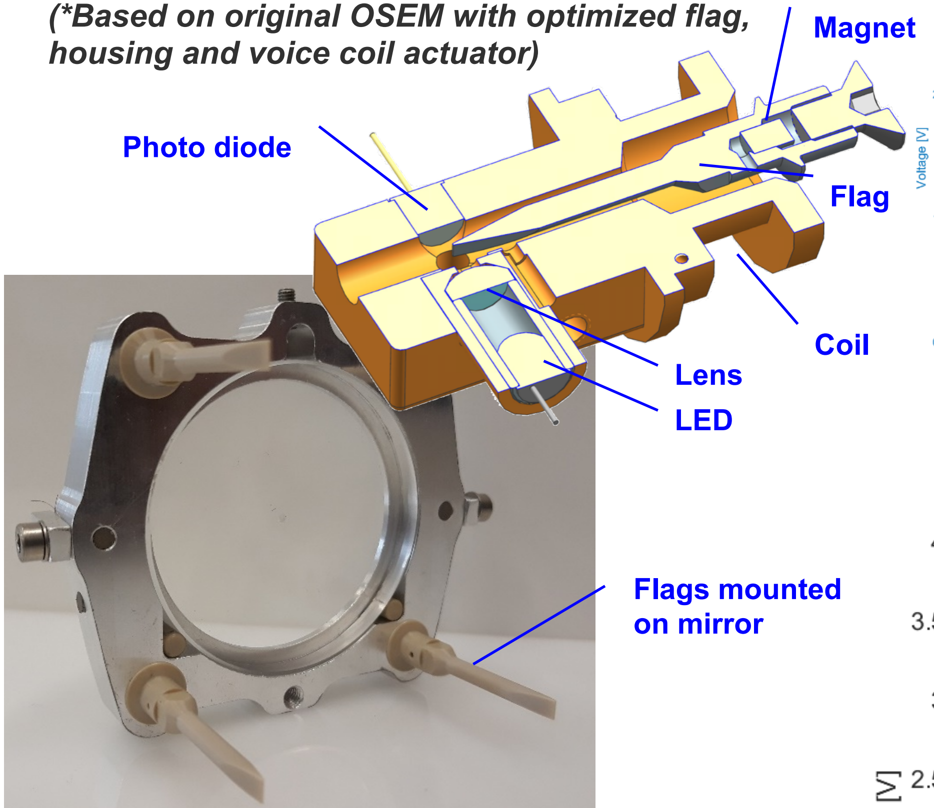
ready for use

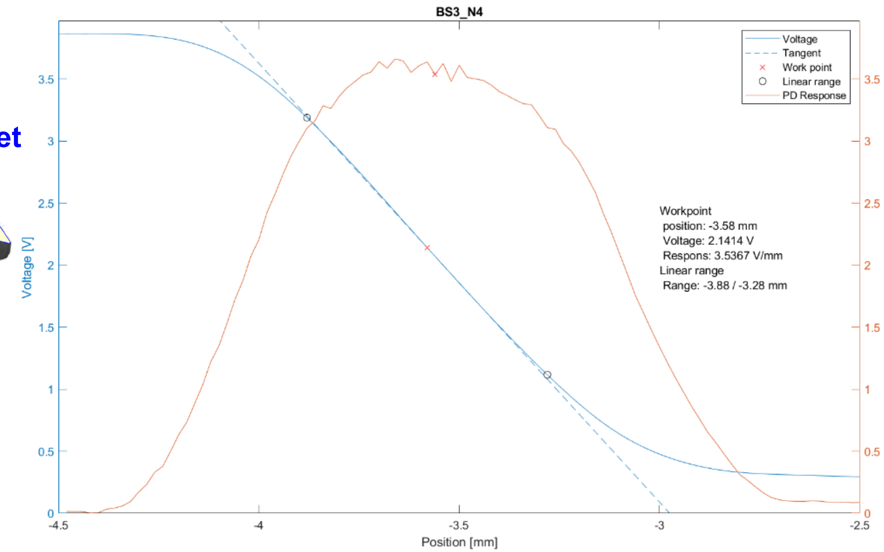


NOSEM*

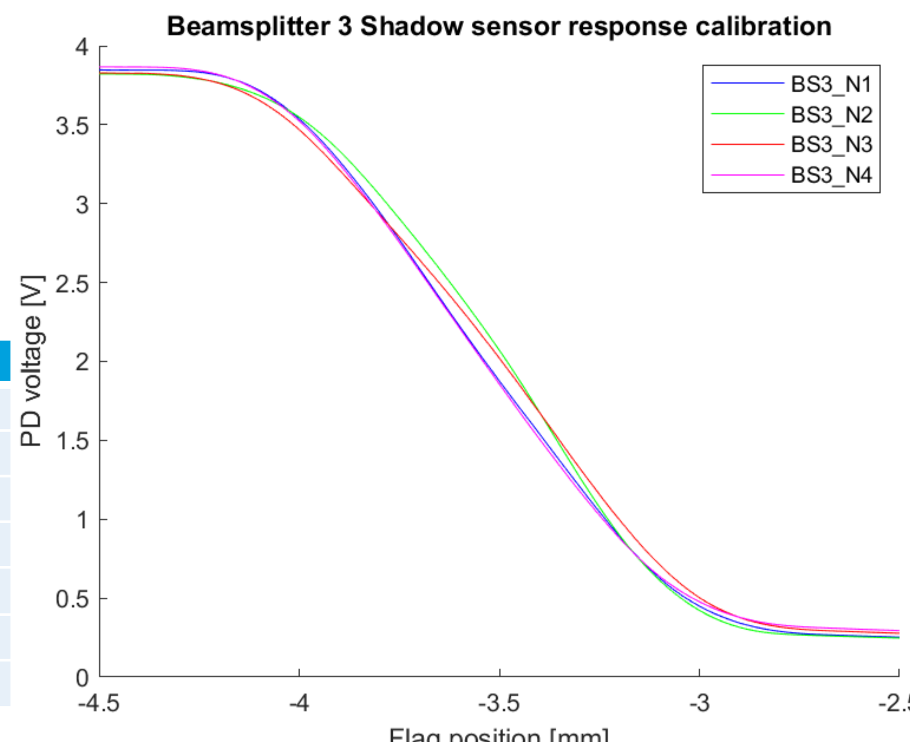
Nikhef* Optical Sensor and Electro-Magnetic actuator

(*Based on original OSEM with optimized flag, housing and voice coil actuator)





Specifications	Value	Unit
Linear range	>0.7	mm
Horizontal coupling	2.3	%
Vertical coupling	0.8	%
Angular coupling	0.5	%
Noise @ 10Hz	2.6E-05	$Vrms/Hz^{1/2}$
Linearized Response	3.6	V/mm
Resolution @ 10 Hz	7.5	Nm$/Hz^{1/2}$



Controls

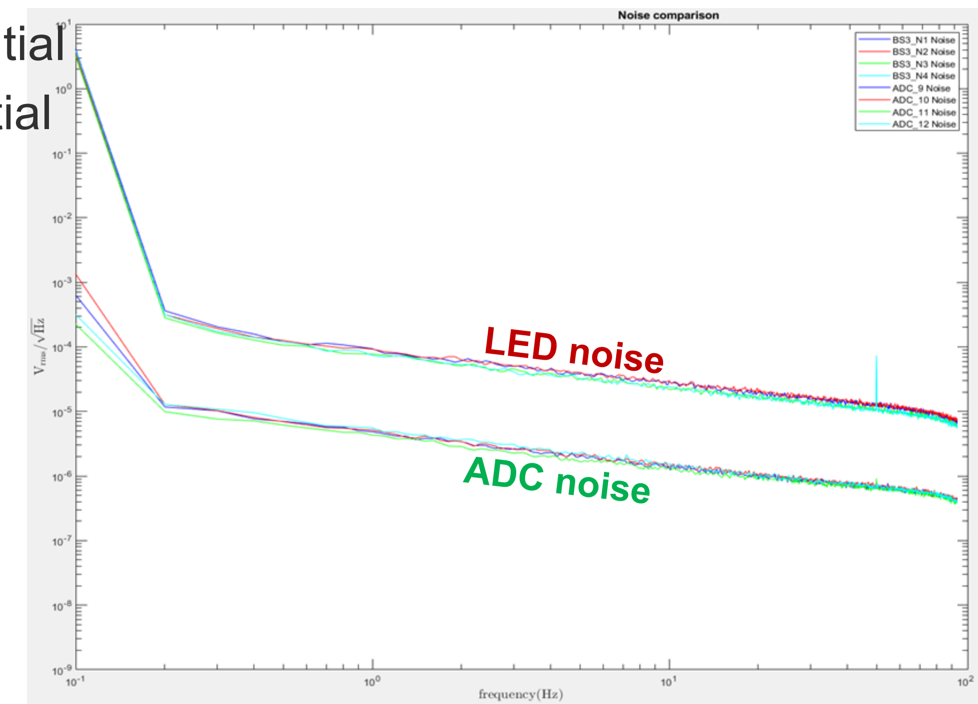
Real-Time controls
- dSPACE MicroLabBox (COTS)
- C/C++, Matlab (Simulink) & python
  - Simulink used for modeling, control and validation
- FPGA Xilinx® Kintex®-7 XC7K325T
  - CLBs slices 50950, 4Mb
  - DSP slices 840

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

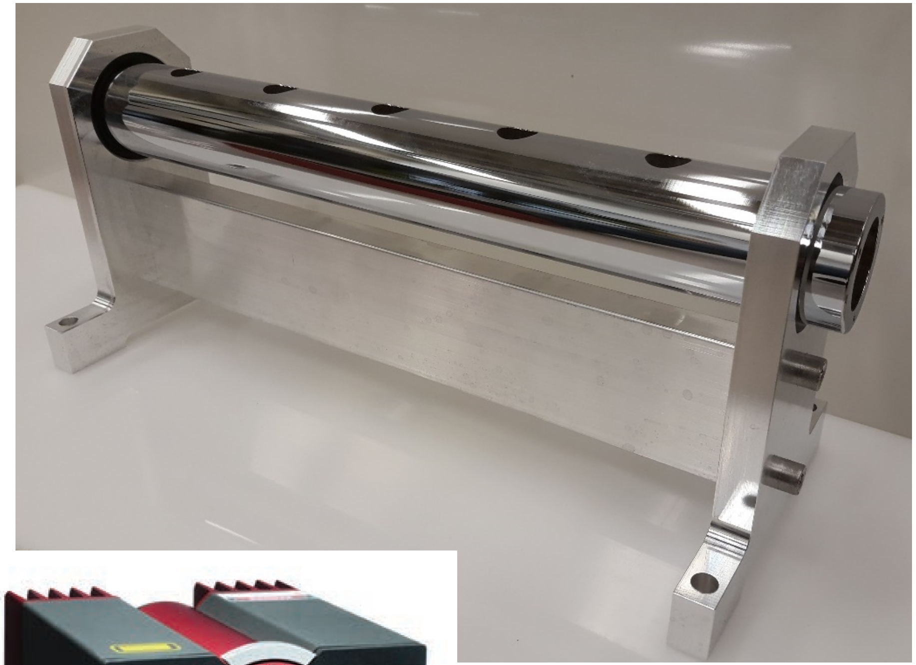
Digital I/O
- 48 bidirectional channels

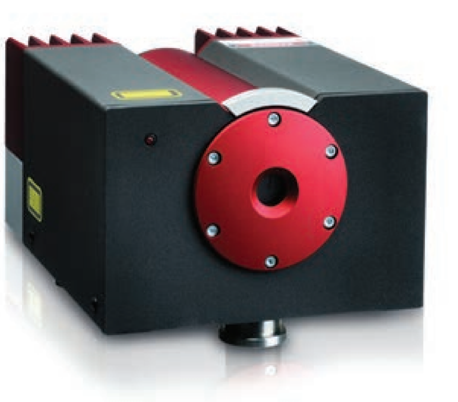
1kHz bandwidth bin 0.01Hz



Laser frequency stabilization

FP cavity (at resonance) used to stabilize the laser frequency by Pound-Drever-Hall locking



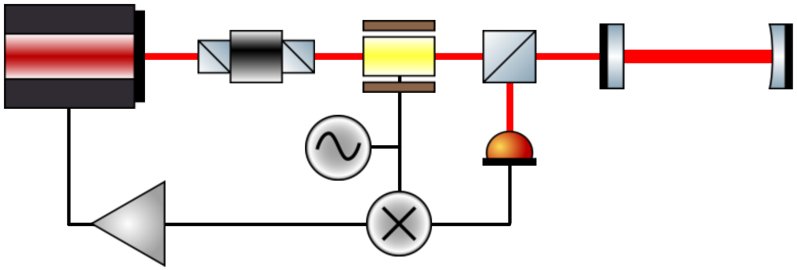


Laser

- **Mephisto 1064 nm**
- **Tunable frequency by thermal tuning of the ND:YAG crystal (slow control) and integrated PZT (fast controls)**

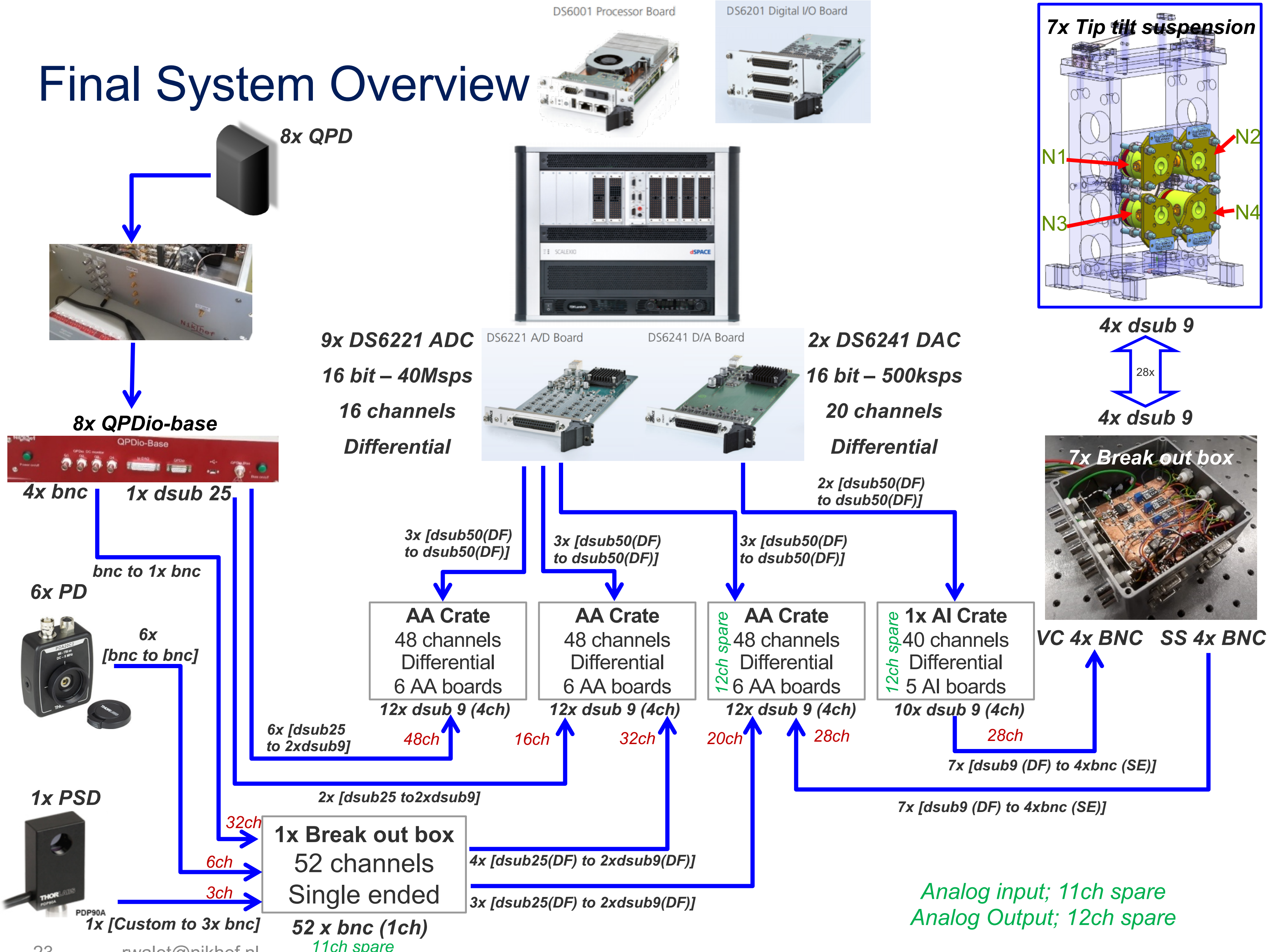
Reference cavity

- **Rigid Fabry-Perot cavity**
- **Plano-concave mirrors**
- **PDH Lock**
- **Invar CTE 1.7e-6 K^-1**
- **UGF 100kHz**
- $\frac{\Delta v}{v} = \frac{\Delta \lambda}{\lambda} = \frac{\Delta L}{L} = \frac{510\ nm/k}{0.3\ m} = 1.7\ ppm/k$



rwalet@nikhef.nl

Final System Overview



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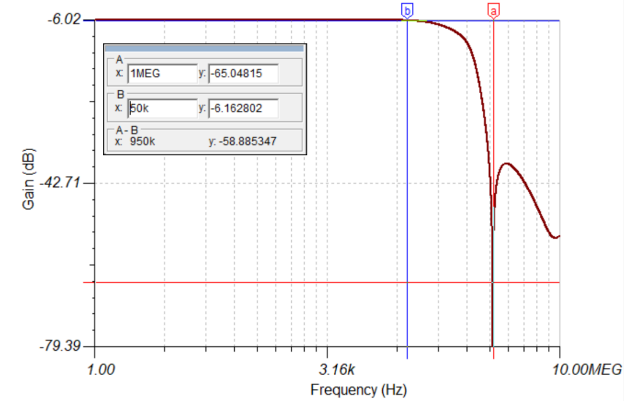
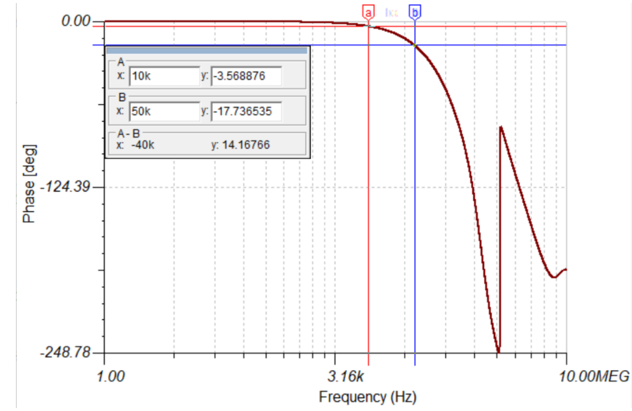
AI Filter_1MHz Notch_v2



Goal; "Optimize LIGO Filter for DAC running at 1Msp/sec and a control loop UGF of 50 kHz"

Requirements;

- *Cut of frequency → 300 kHz -> times 6*
- *Notch filter 1Mhz*



Performance;

- *10kHz Magnitude -6dB phase -3.6deg*
- *20kHz Magnitude -6dB phase -7.1deg*
- *50kHz Magnitude -7dB phase -17.7deg*
- *1MHz Notch -65dB*

Remarks;

- *Resistors replaced by 23.4k ohm (1206)*