An overview of the control layers in LIGO 4km interferometers

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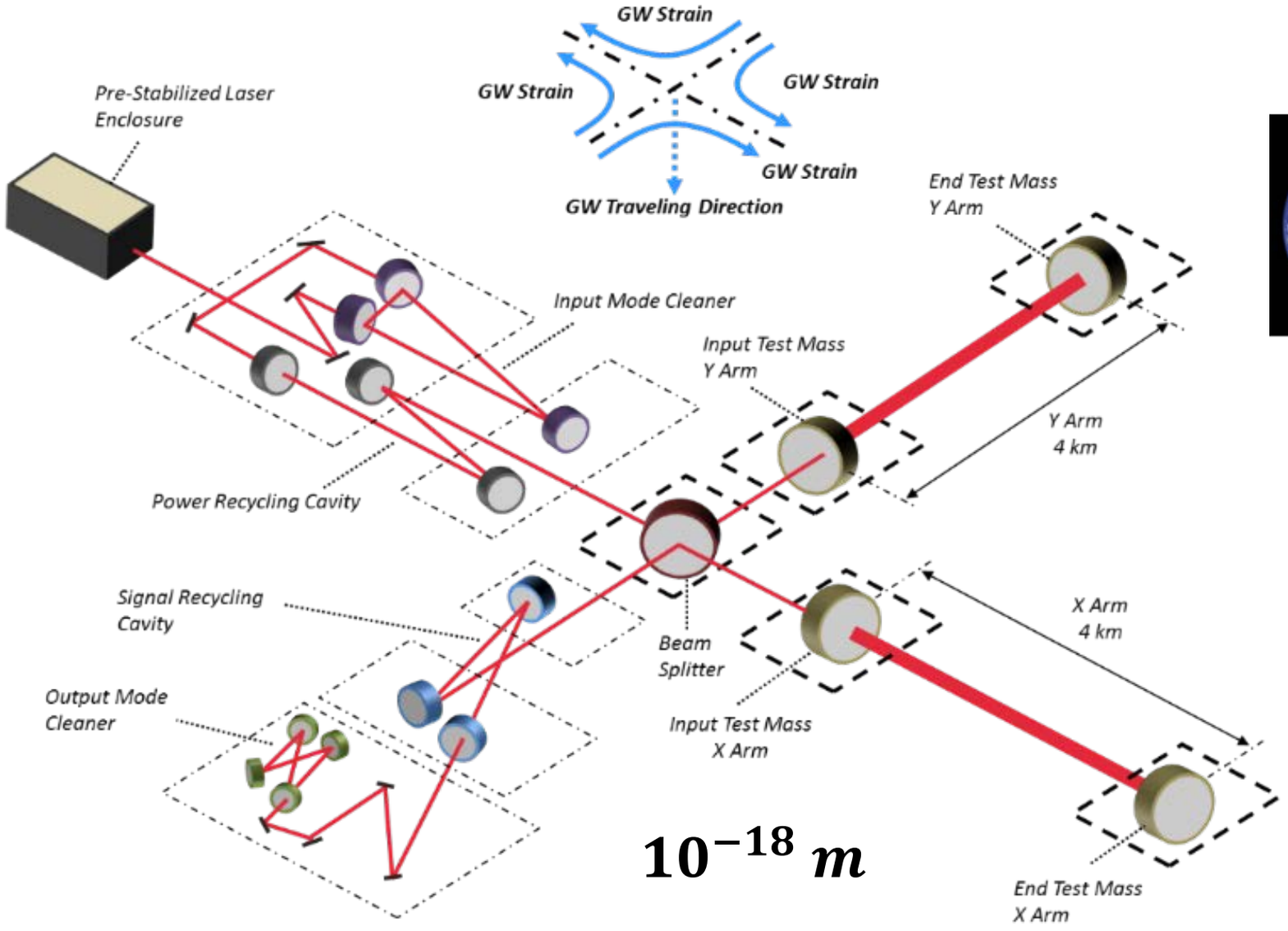
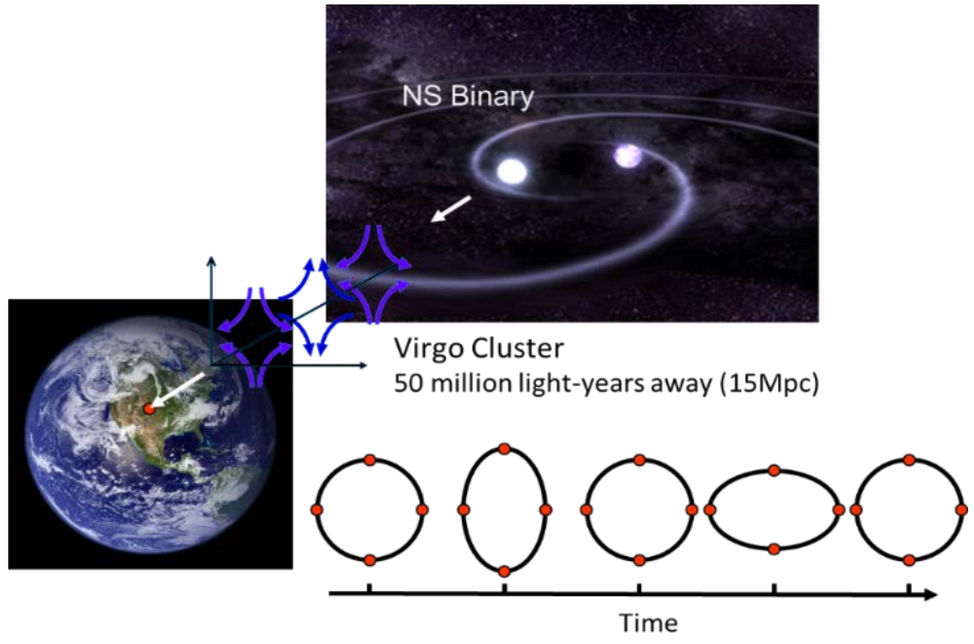
Advanced LIGO detectors

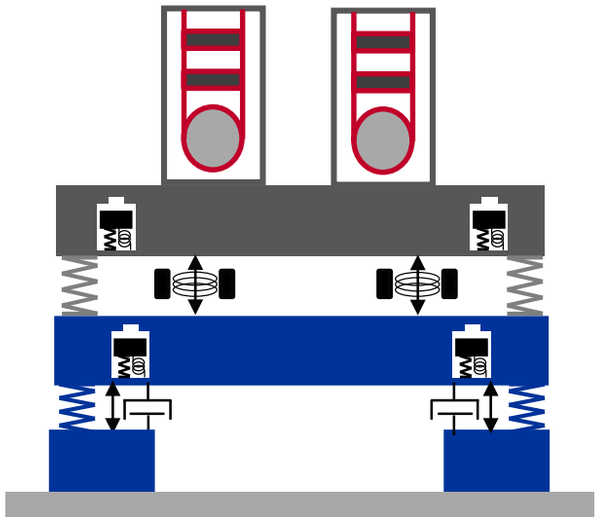




Hundreds of servo systems to isolate the optics and control the interferometer.

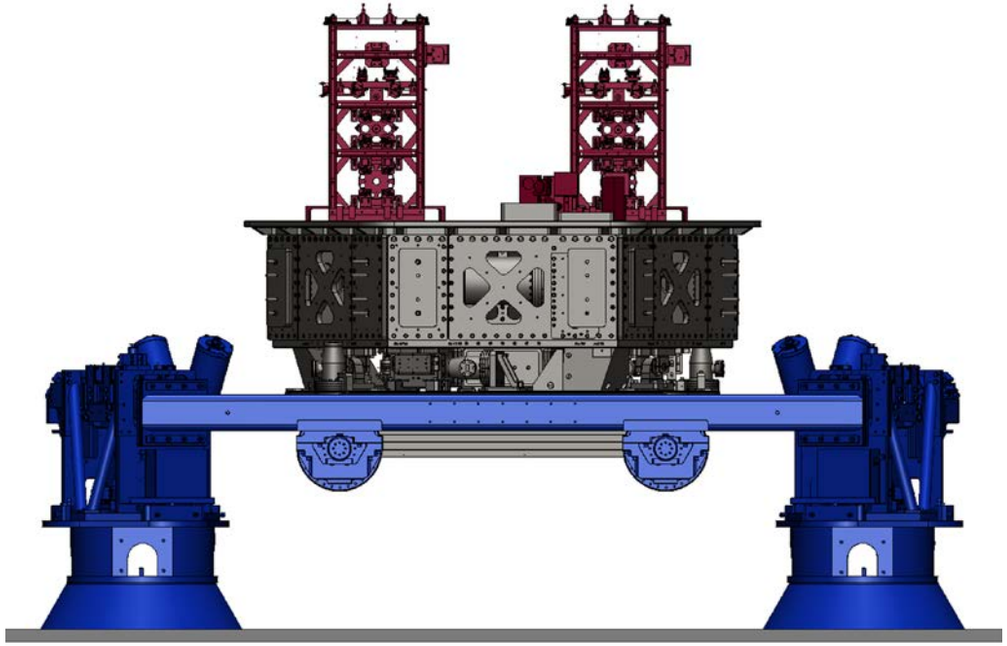
Sub-systems and System controls

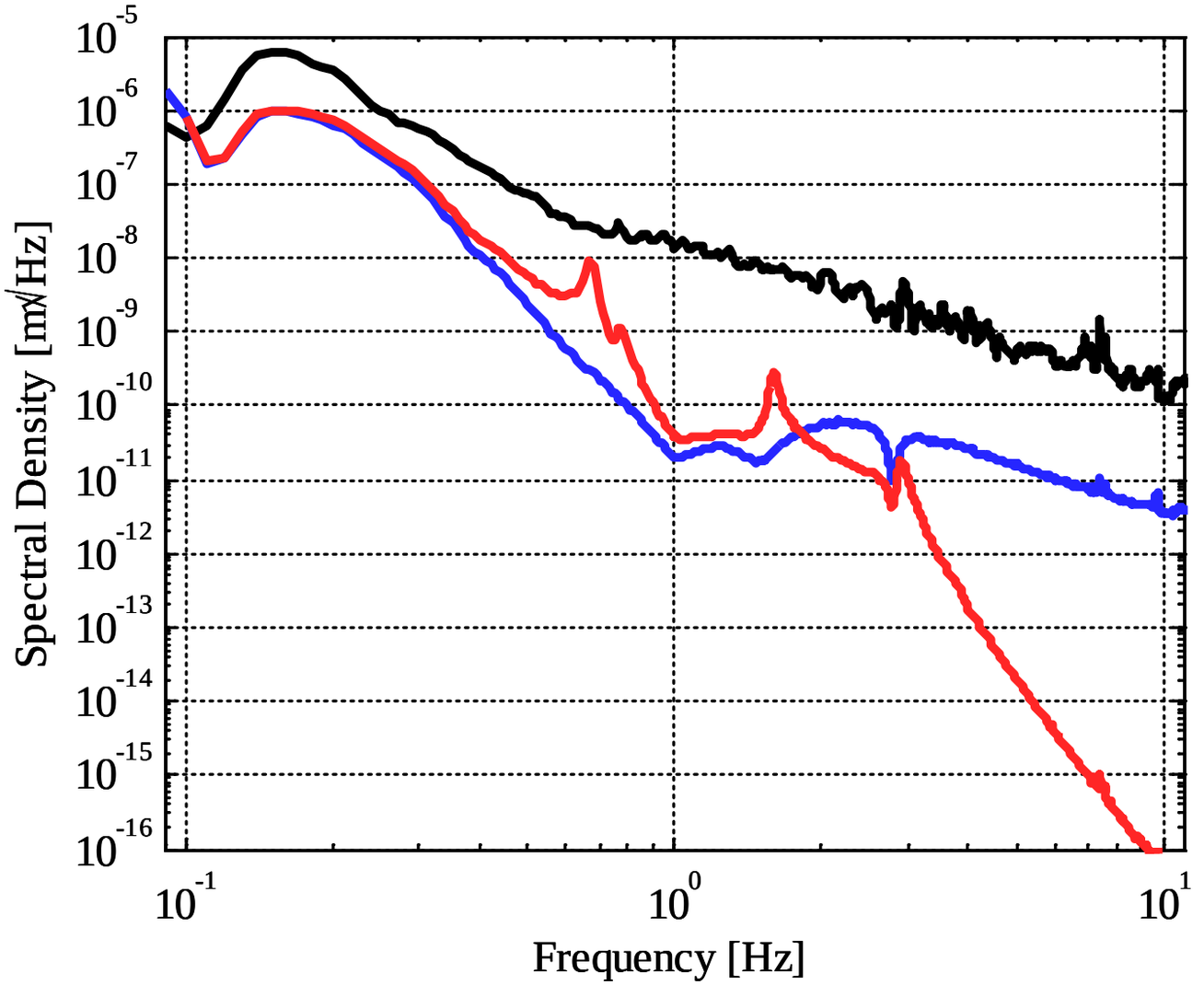
Seismic Isolation



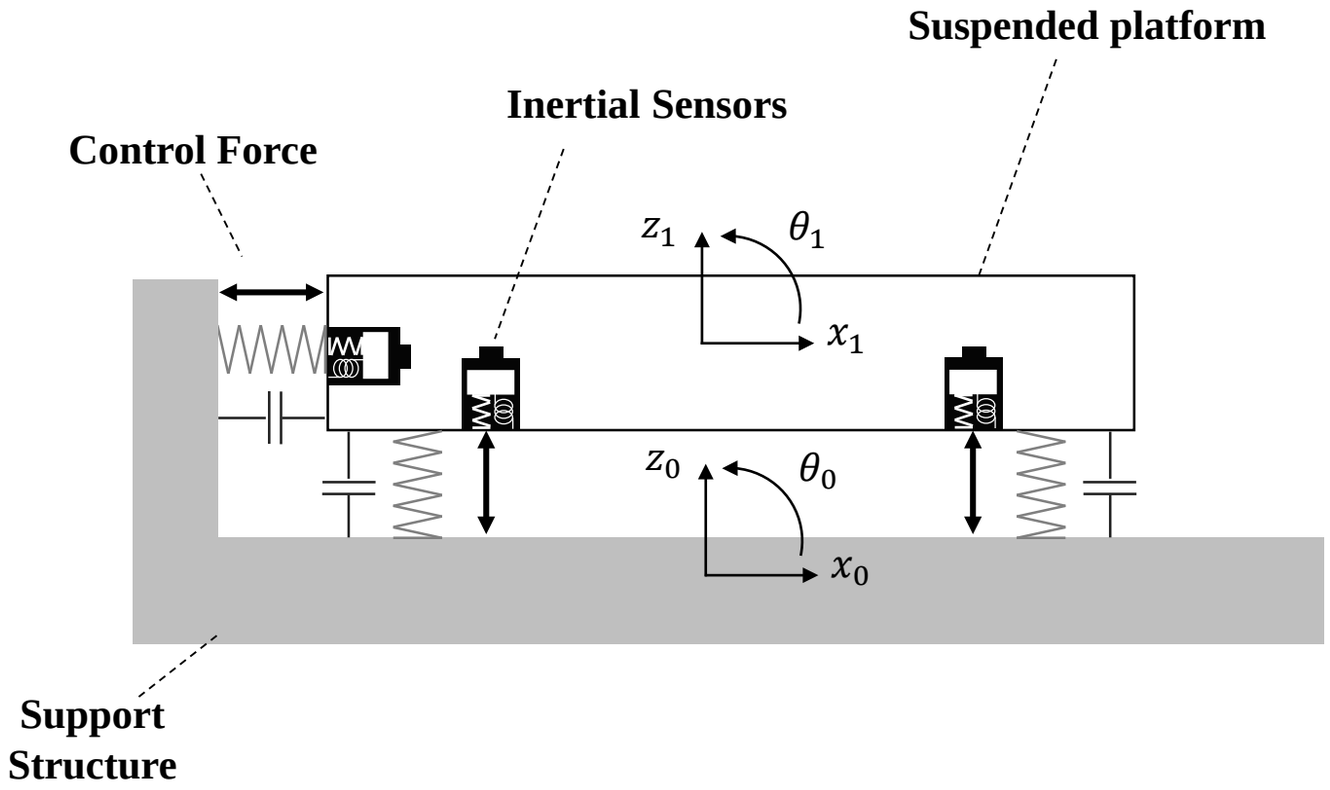
Multi-stage pendulums

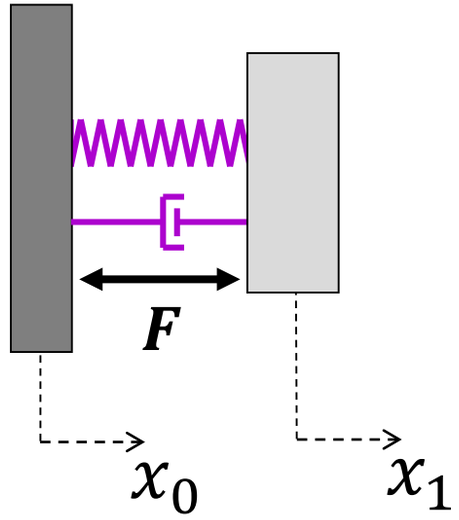
Active inertial isolators





Active inertial control



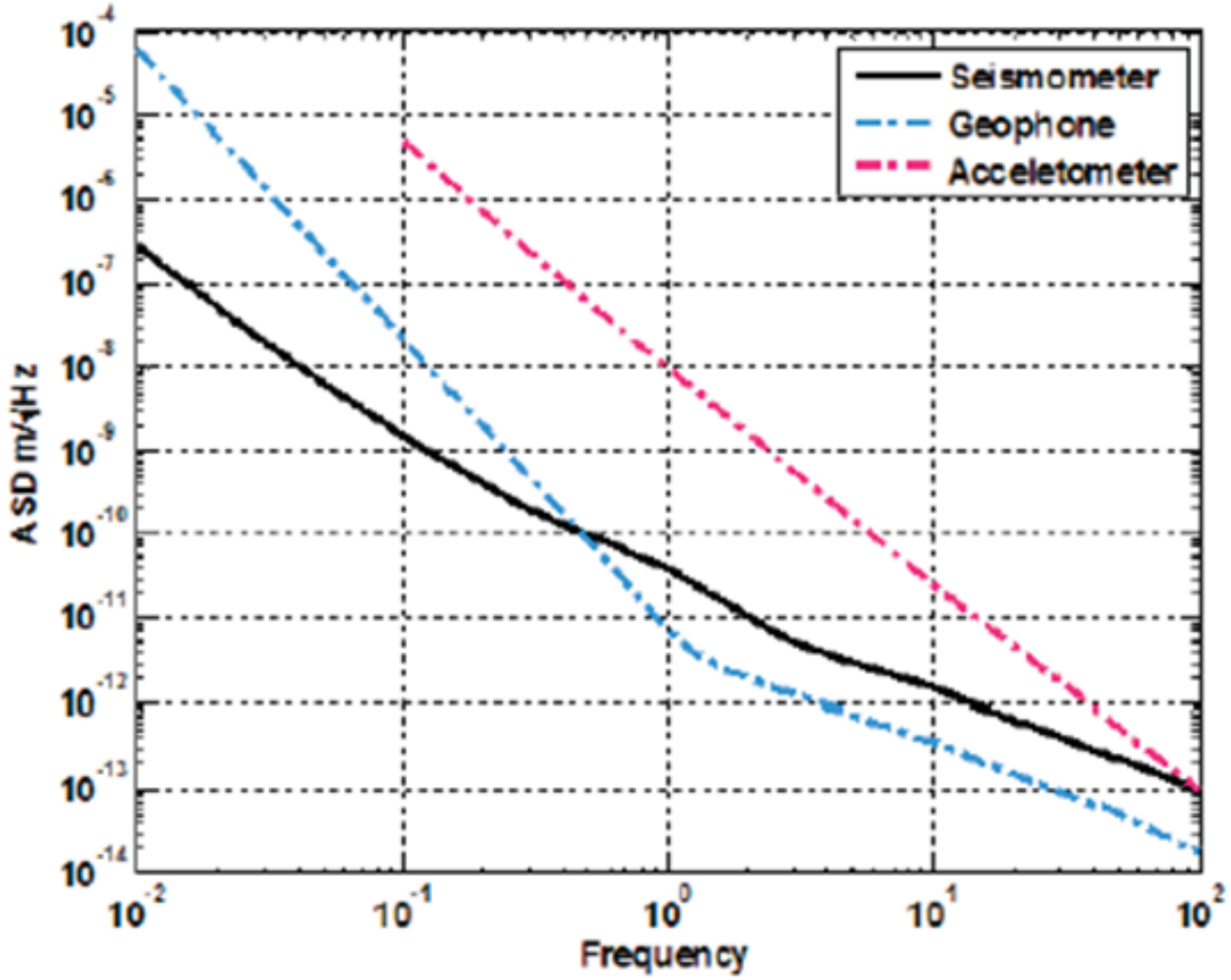


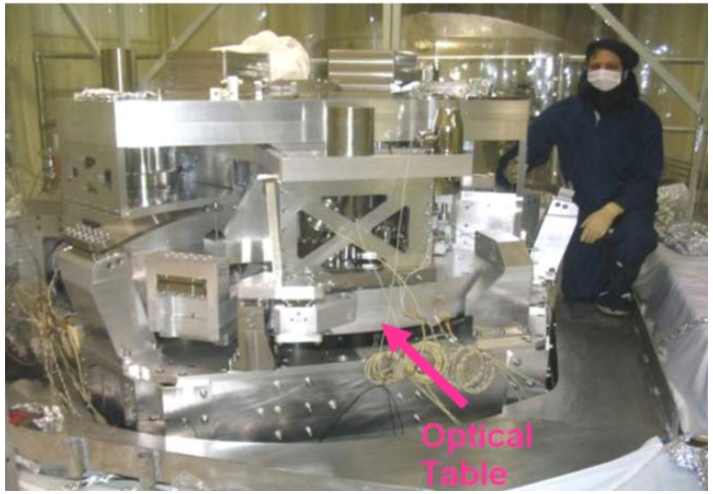
$$F = -H\,(X_1 + N)$$

$$\frac{X_1}{X_0} = \frac{c\,s + k}{ms^2 + cs + k + H}$$

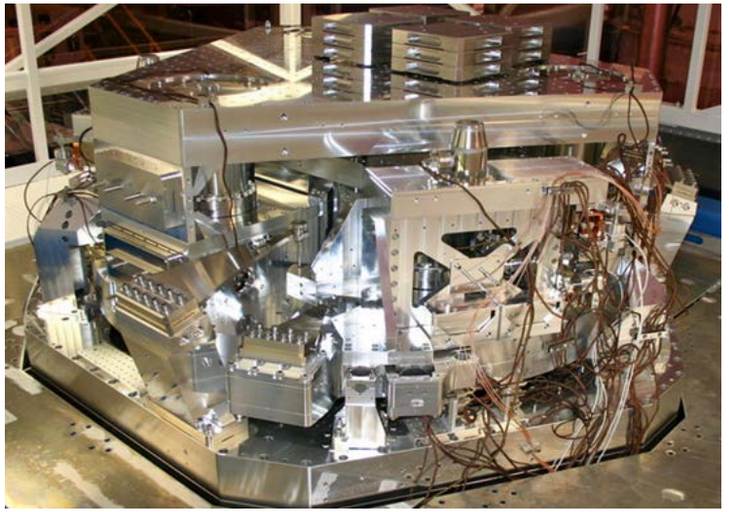
$$\lim_{G \to \infty} X_1 \sim N$$

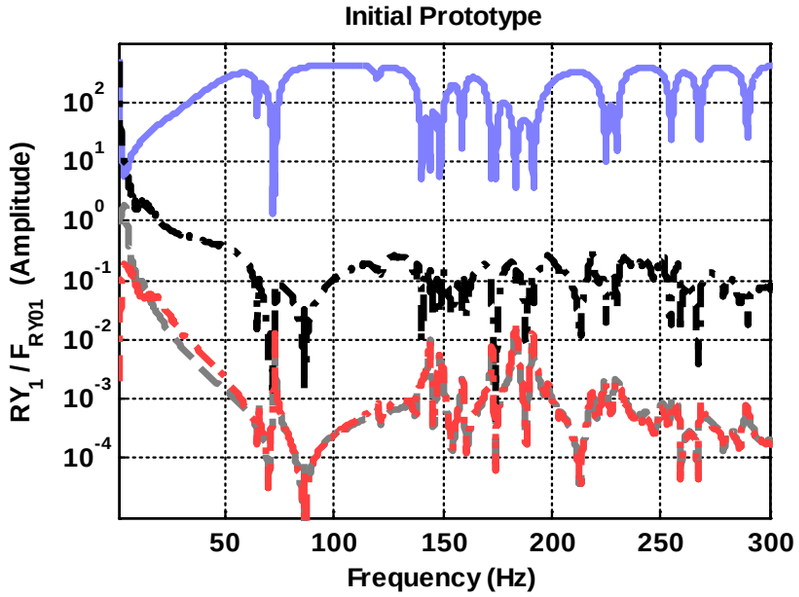
Inertial Sensors Noise



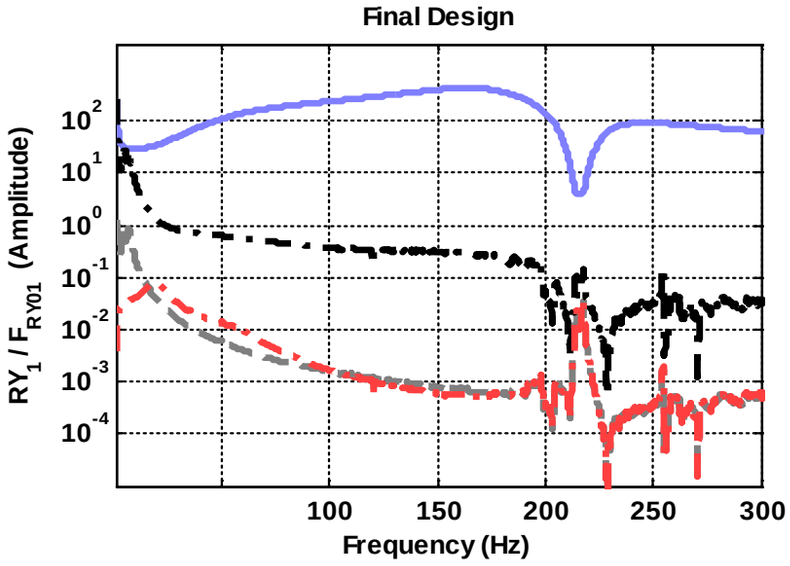


Bandwidth



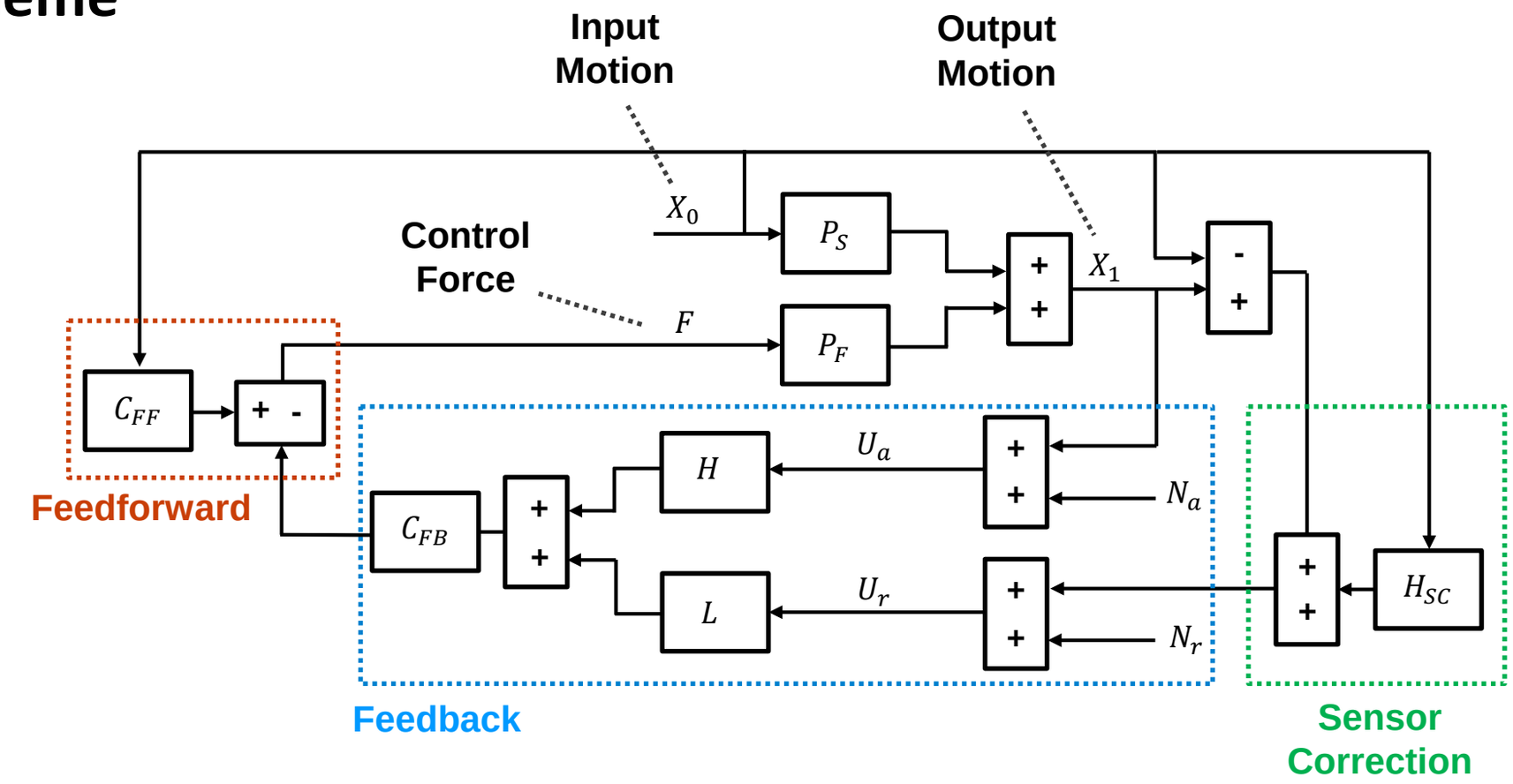


Prototype
Compensator was made of 104 poles and zeros.



Final Design
22 poles and zeros

Control Scheme



$$\langle {X_1}^2 \rangle = \left| \frac{P_s + L\ C\ P_F}{1 + C\ P_F} \right|^2 \langle {X_0}^2 \rangle + \left| \frac{H\ C\ P_F}{1 + C\ P_F} \right|^2 \langle {N_a}^2 \rangle + \left| \frac{L\ C\ P_F}{1 + C\ P_F} \right|^2 \langle {N_r}^2 \rangle$$

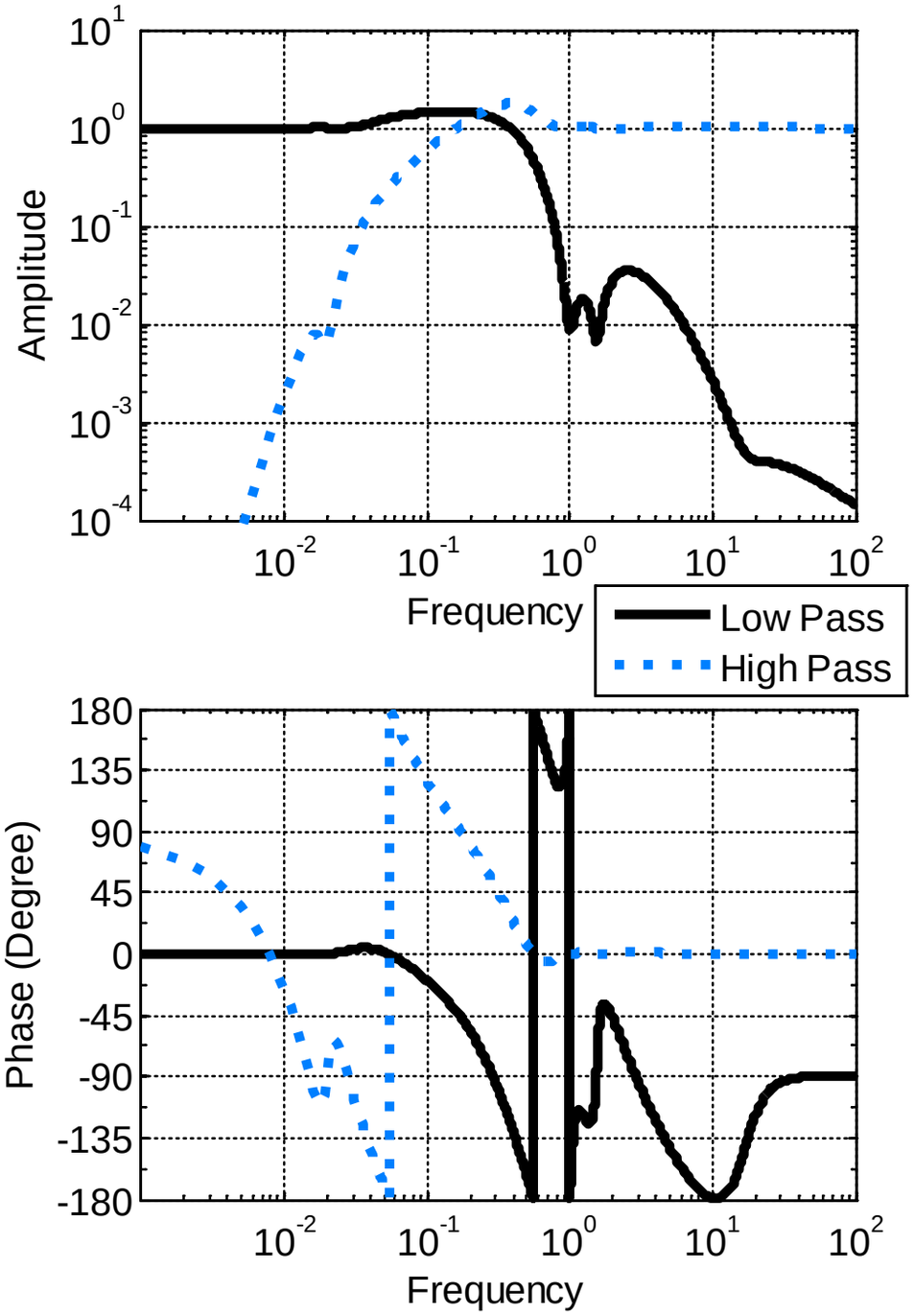
Ouput Motion | **Input Motion** | **Inertial sensor noise** | **Relative sensor noise**

$$\langle {X_1}^2 \rangle = \left| \frac{P_s + L\,C\,P_F}{1 + C\,P_F} \right|^2 \langle {X_0}^2 \rangle + \left| \frac{H\,C\,P_F}{1 + C\,P_F} \right|^2 \langle {N_a}^2 \rangle + \left| \frac{L\,C\,P_F}{1 + C\,P_F} \right|^2 \langle {N_r}^2 \rangle$$

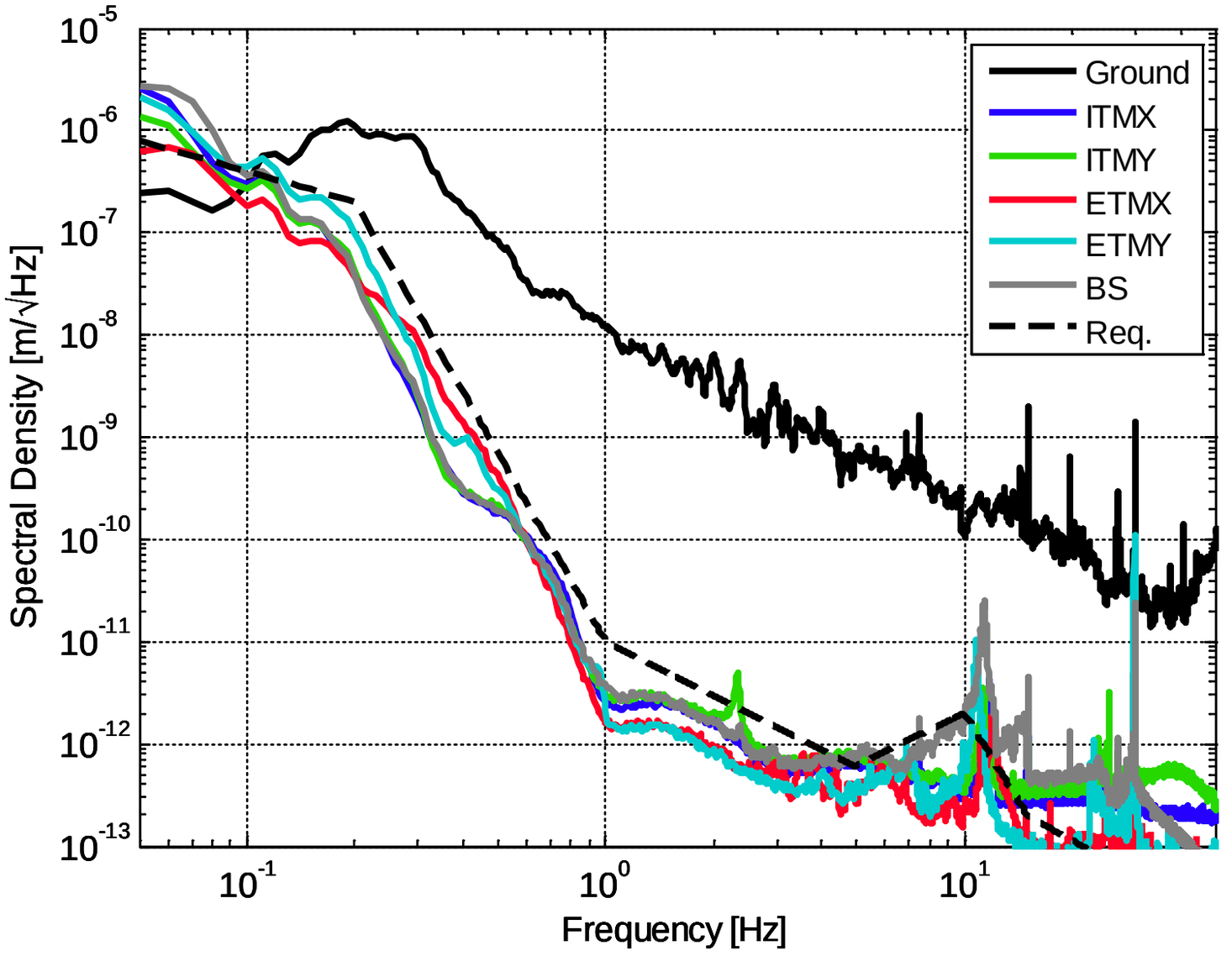
Complementary filters: $L + H = 1$

High loop gain: $C\,P_F \to \infty$

Residual motion: $\langle {X_1}^2 \rangle \sim |L|^2 \langle {X_0}^2 \rangle + |H|^2 \langle {N_a}^2 \rangle + |L|^2 \langle {N_r}^2 \rangle$



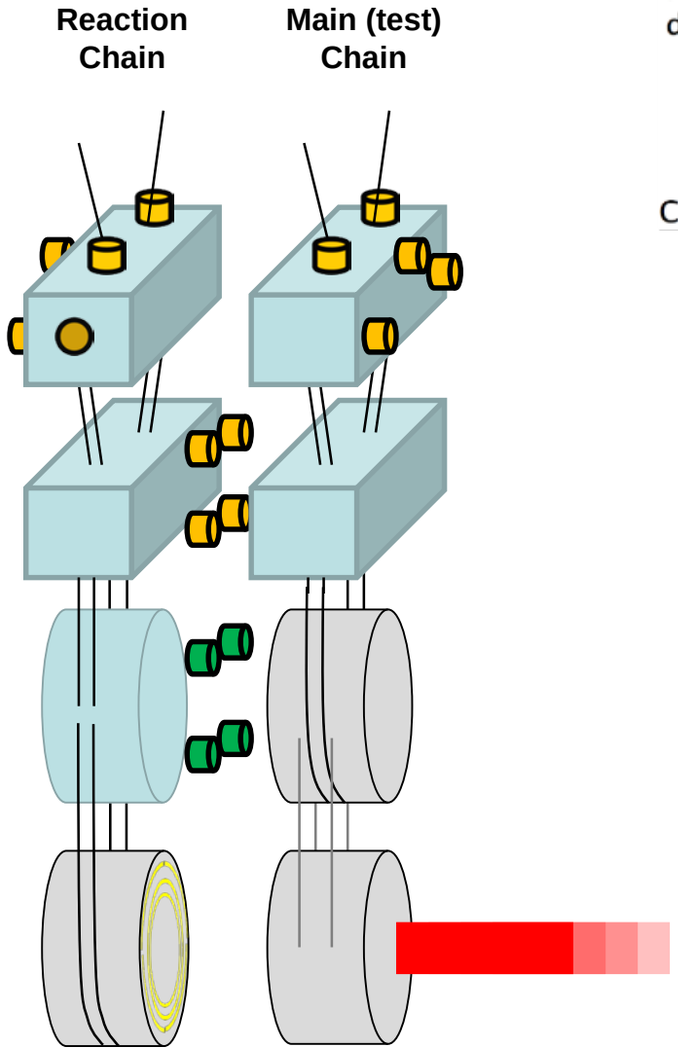
Performance

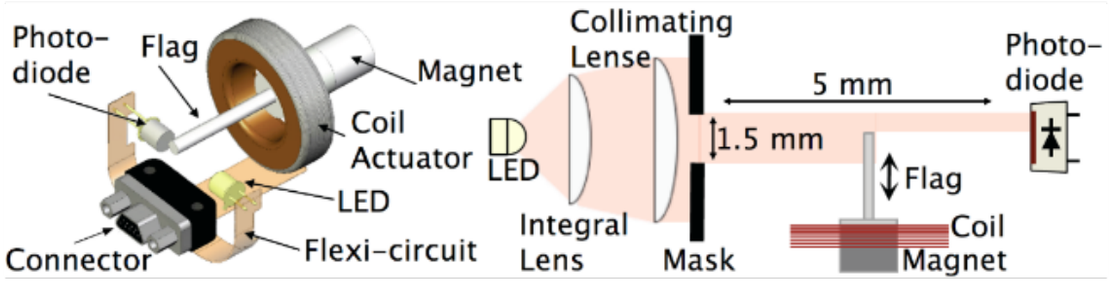


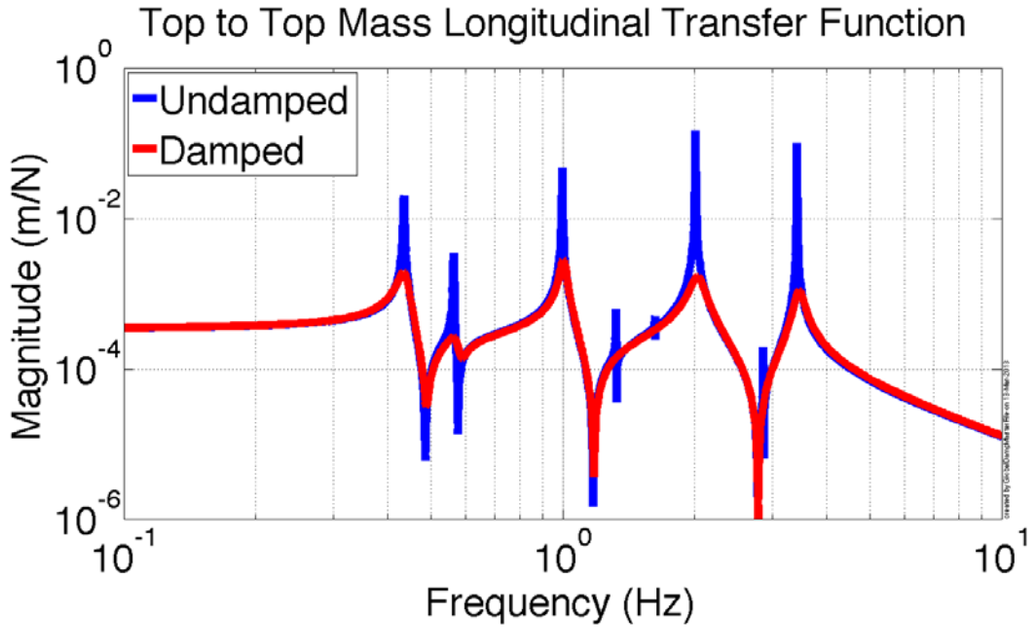
Advanced LIGO two-stage twelve-axis vibration isolation and positioning platform. Part 1: Design and production overview
Precision Engineering 40 (2015): 273-286.

Advanced LIGO two-stage twelve-axis vibration isolation and positioning platform. Part 2: Experimental investigation and tests results.
Precision engineering 40 (2015): 287-297.

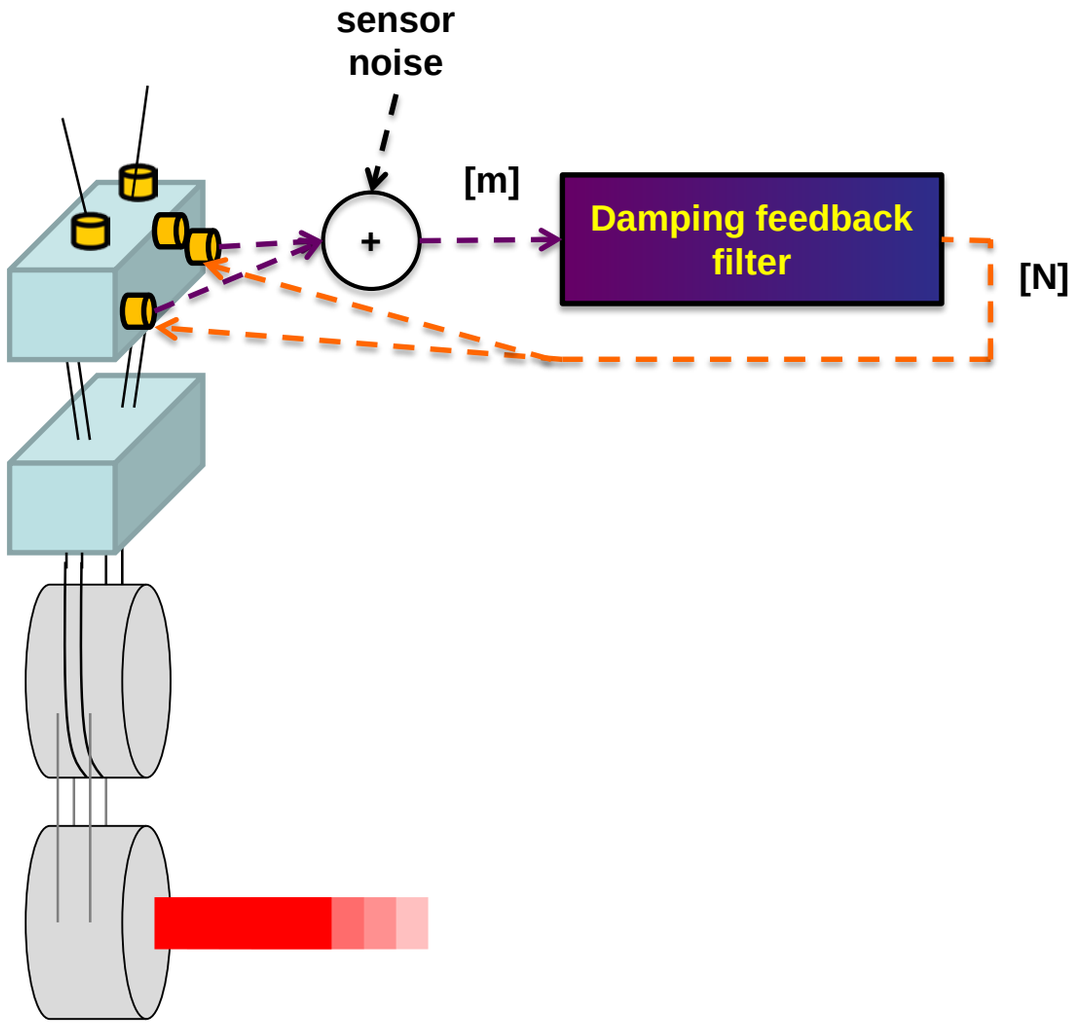
Suspension controls

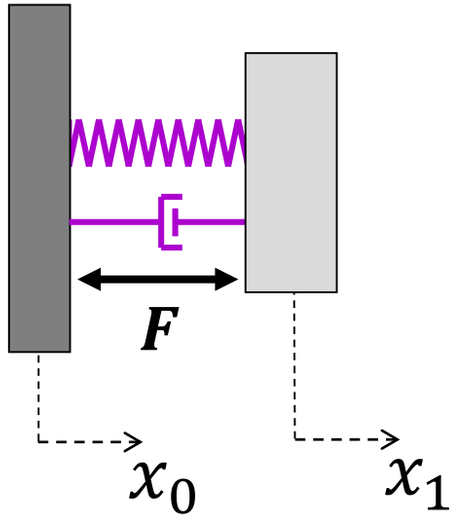






Suspension damping feedback



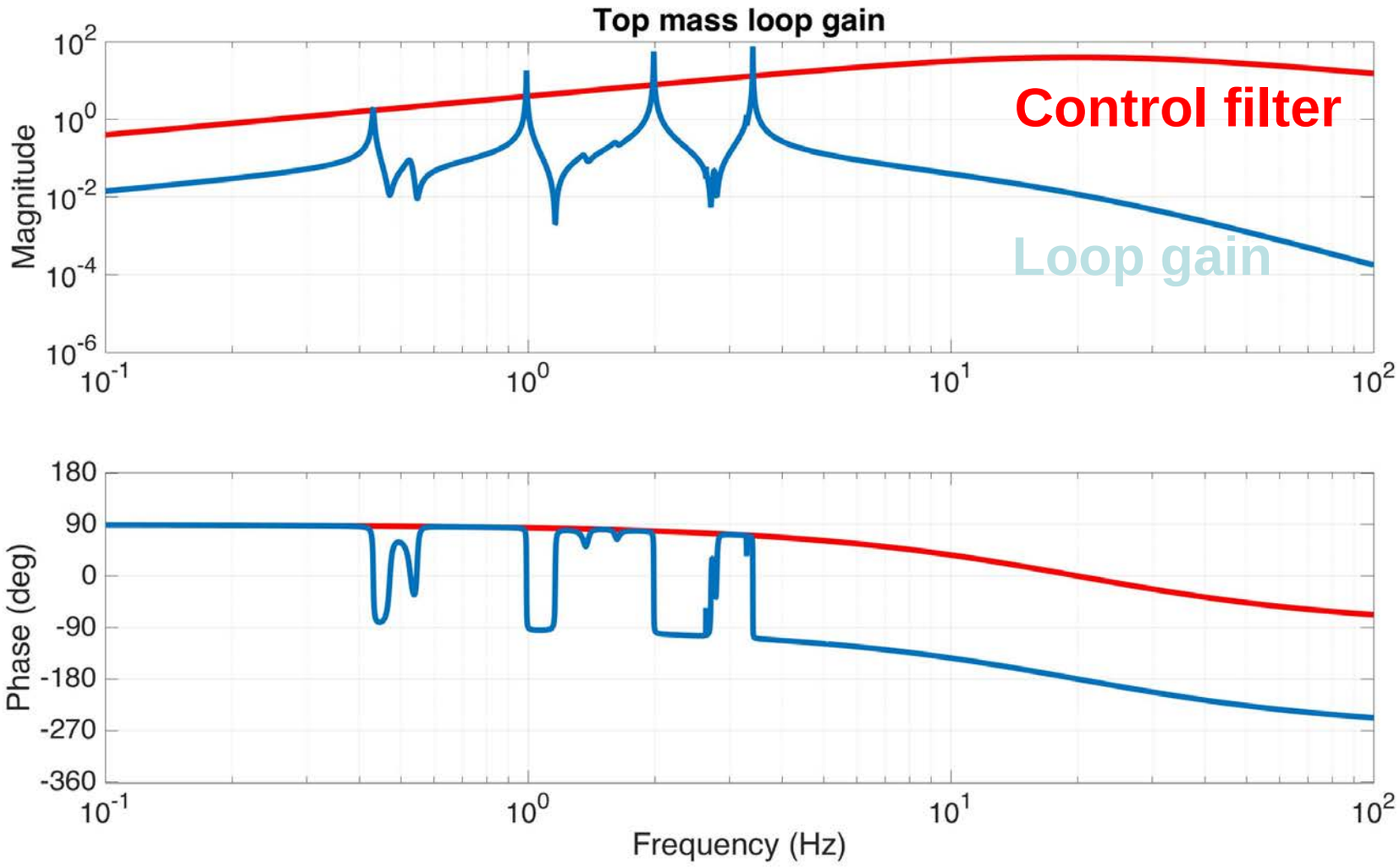


$$F = -H\,(X_1 - X_0 + N)$$

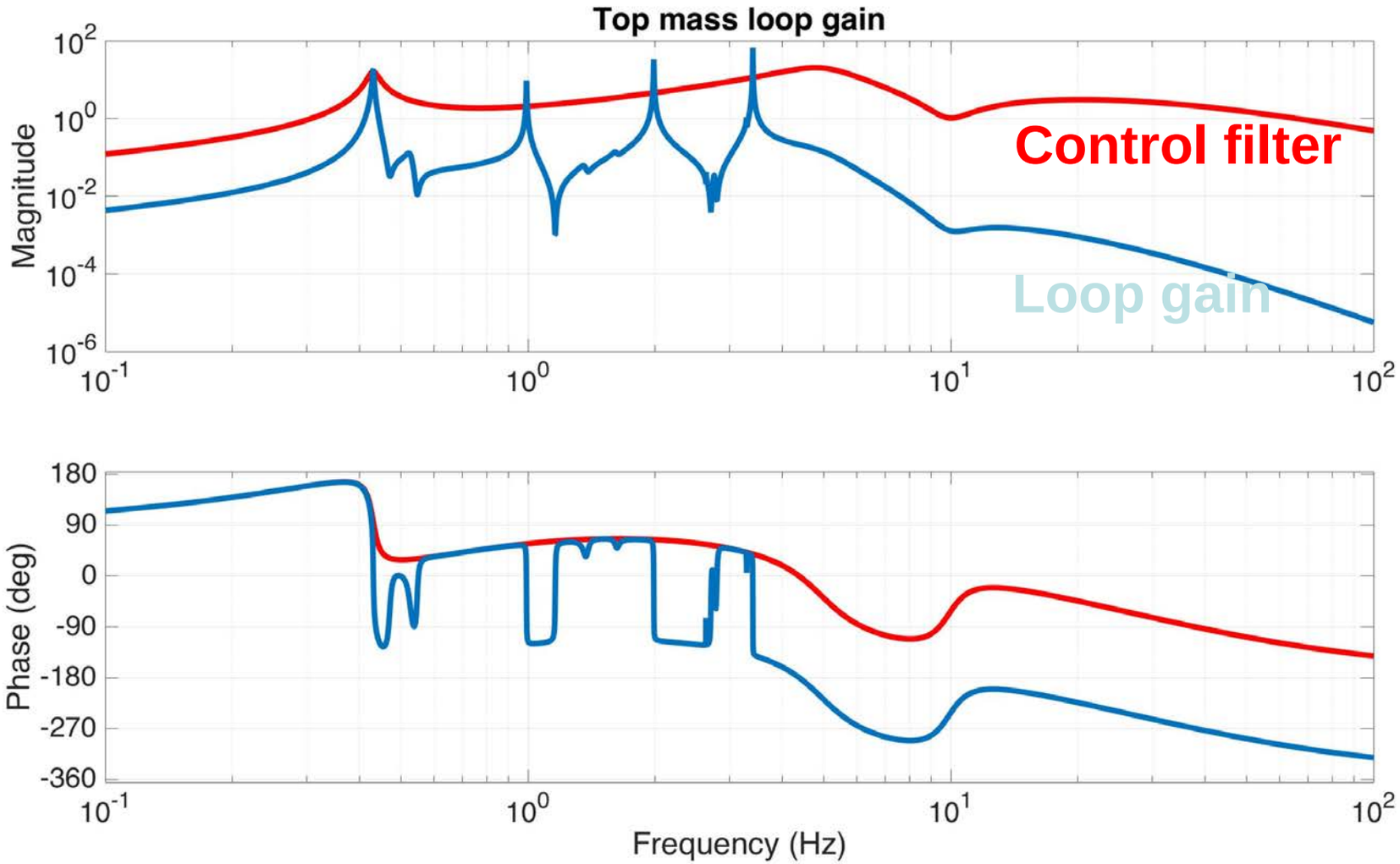
$$\frac{X_1}{X_0} = \frac{c\,s + k + H}{ms^2 + cs + k + H}$$

$$\lim_{H\to\infty} X_1 = X_0 + N$$

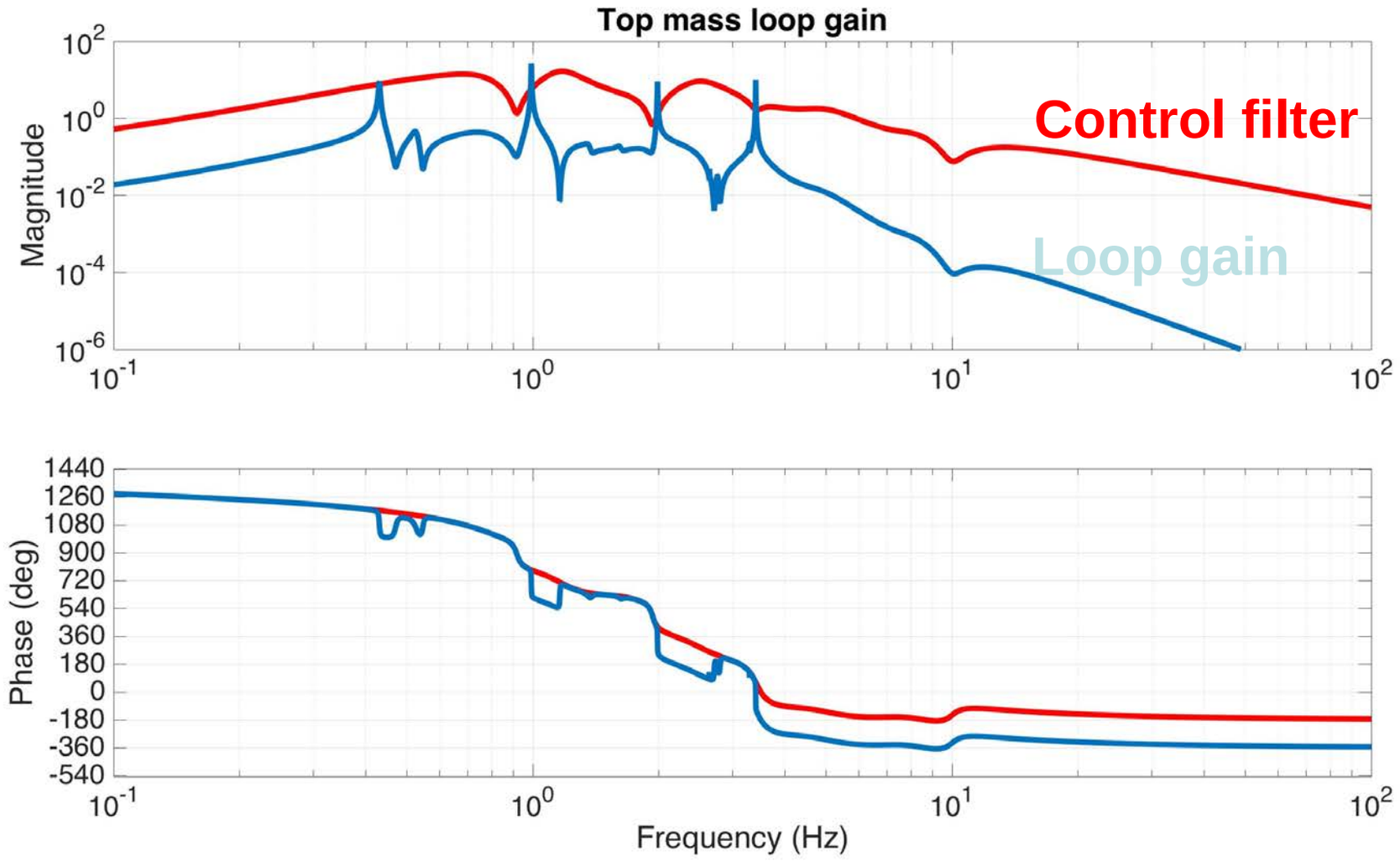
Simple Damping Loop



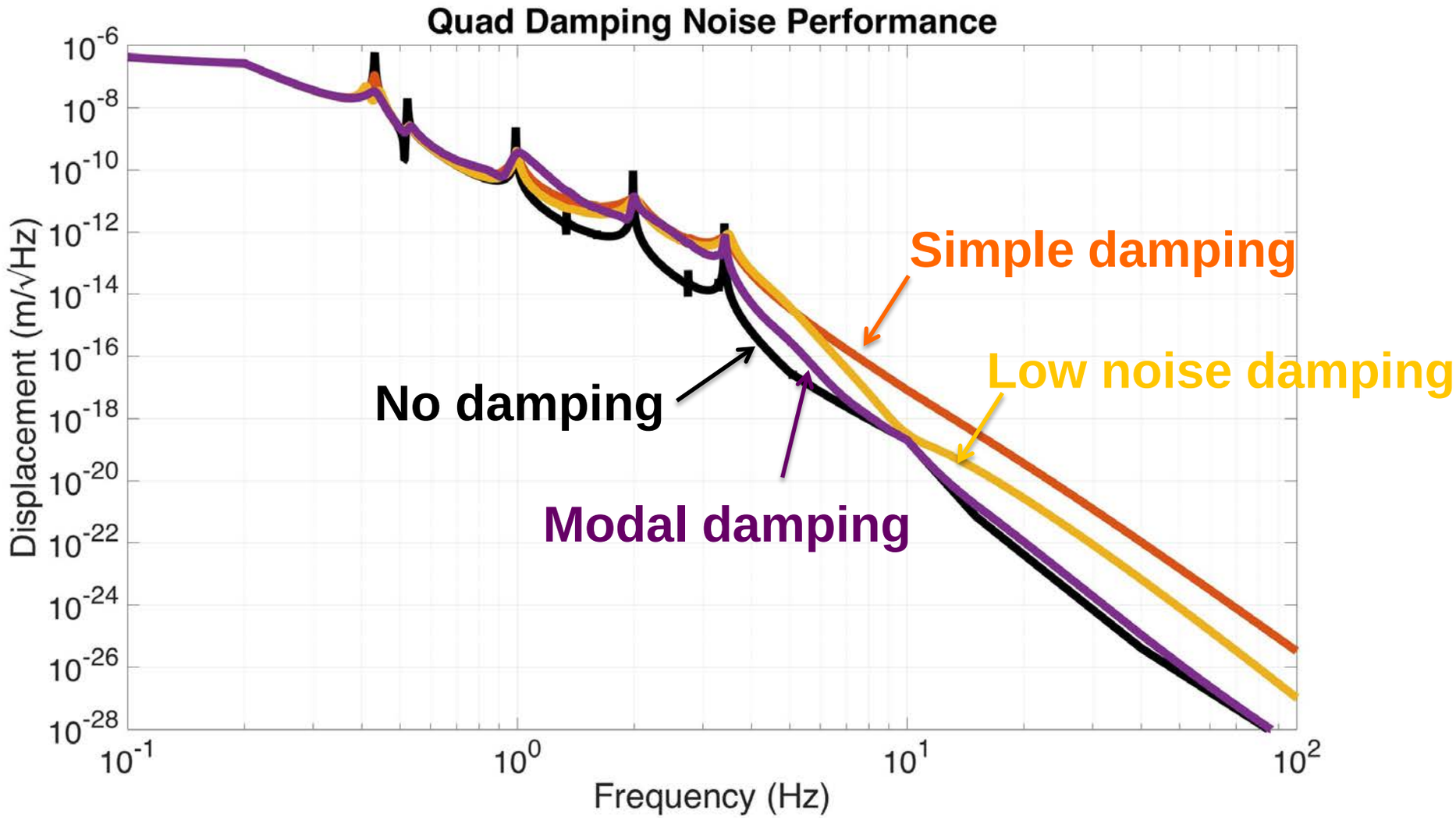
Low Noise Loop



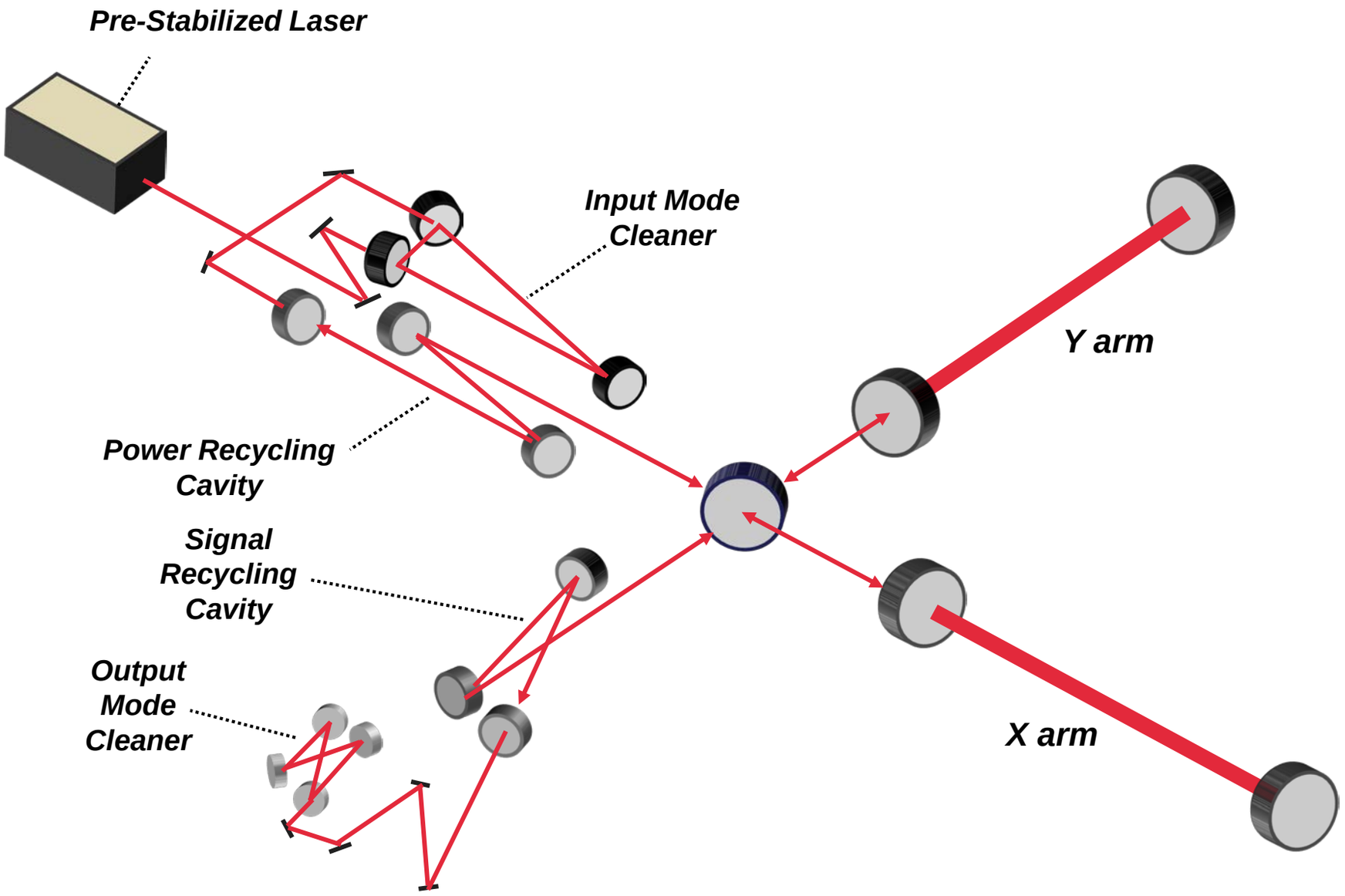
Modal Damping Loop



Damping Noise Performance

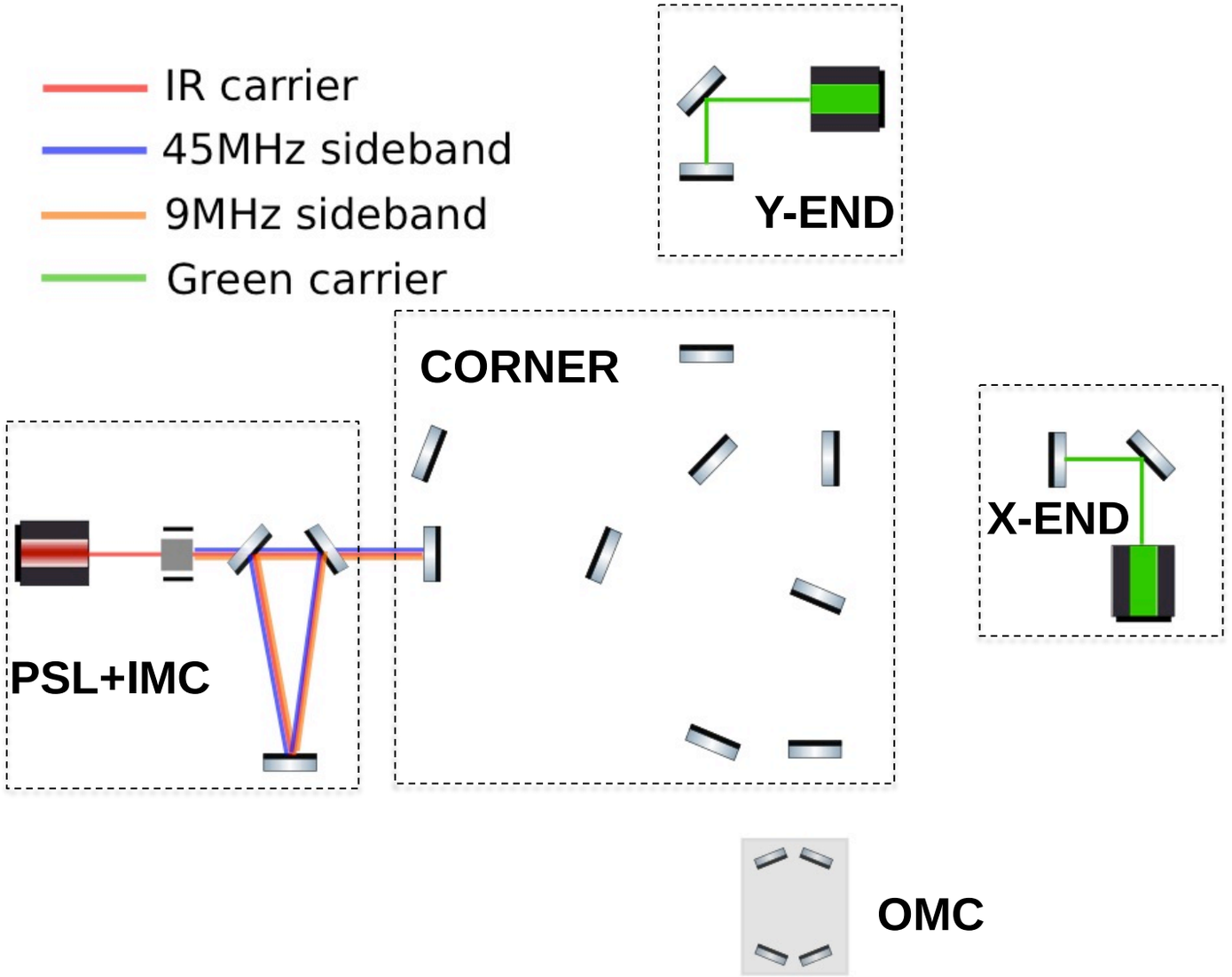


Lock acquisition



From free swinging uncontrolled state to fully locked

Lock acquisition



PSL+IMC

ALS

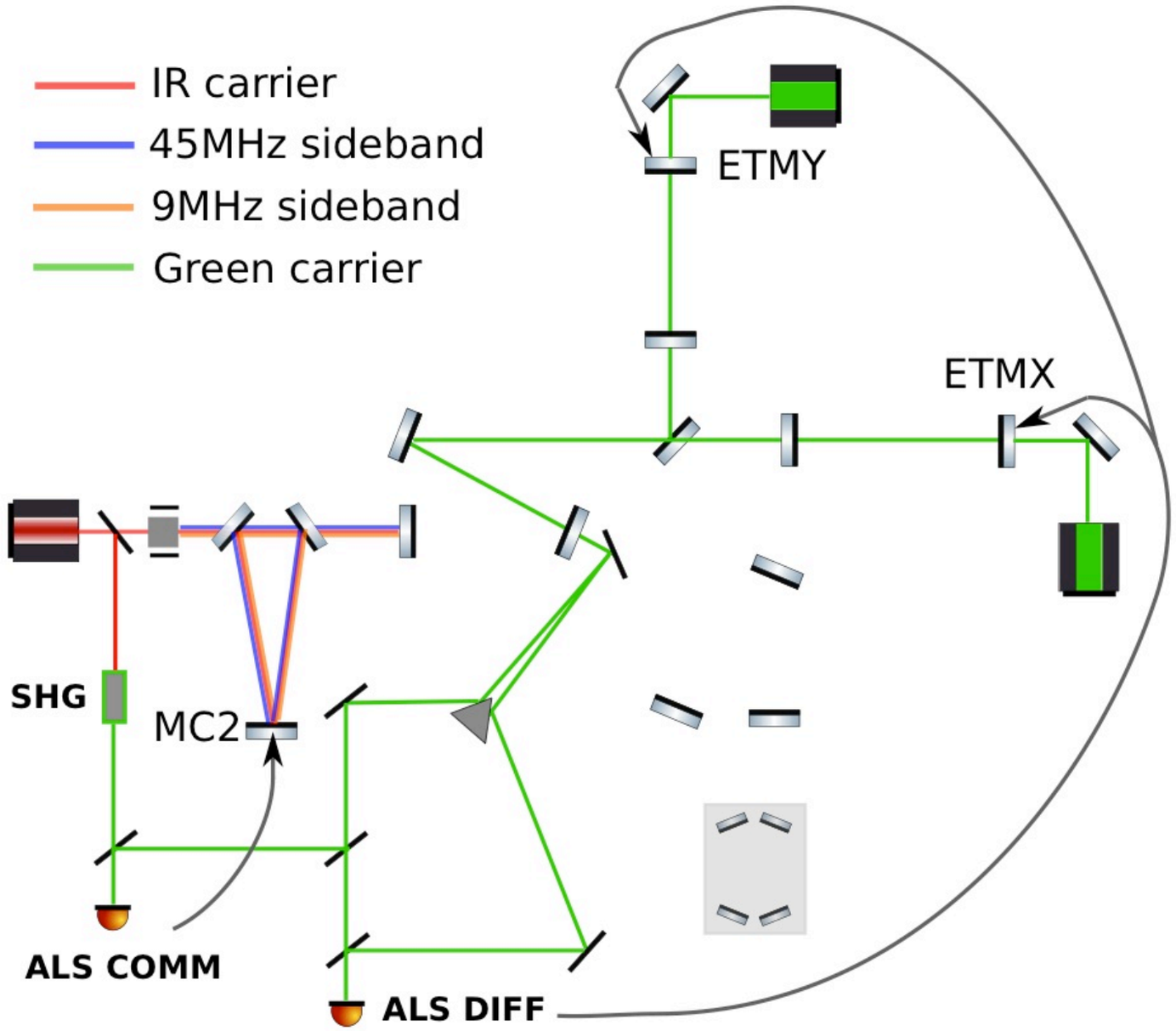
DRMI

CARM offset reduction

Angular controls

DC readout

Lock acquisition



PSL+IMC

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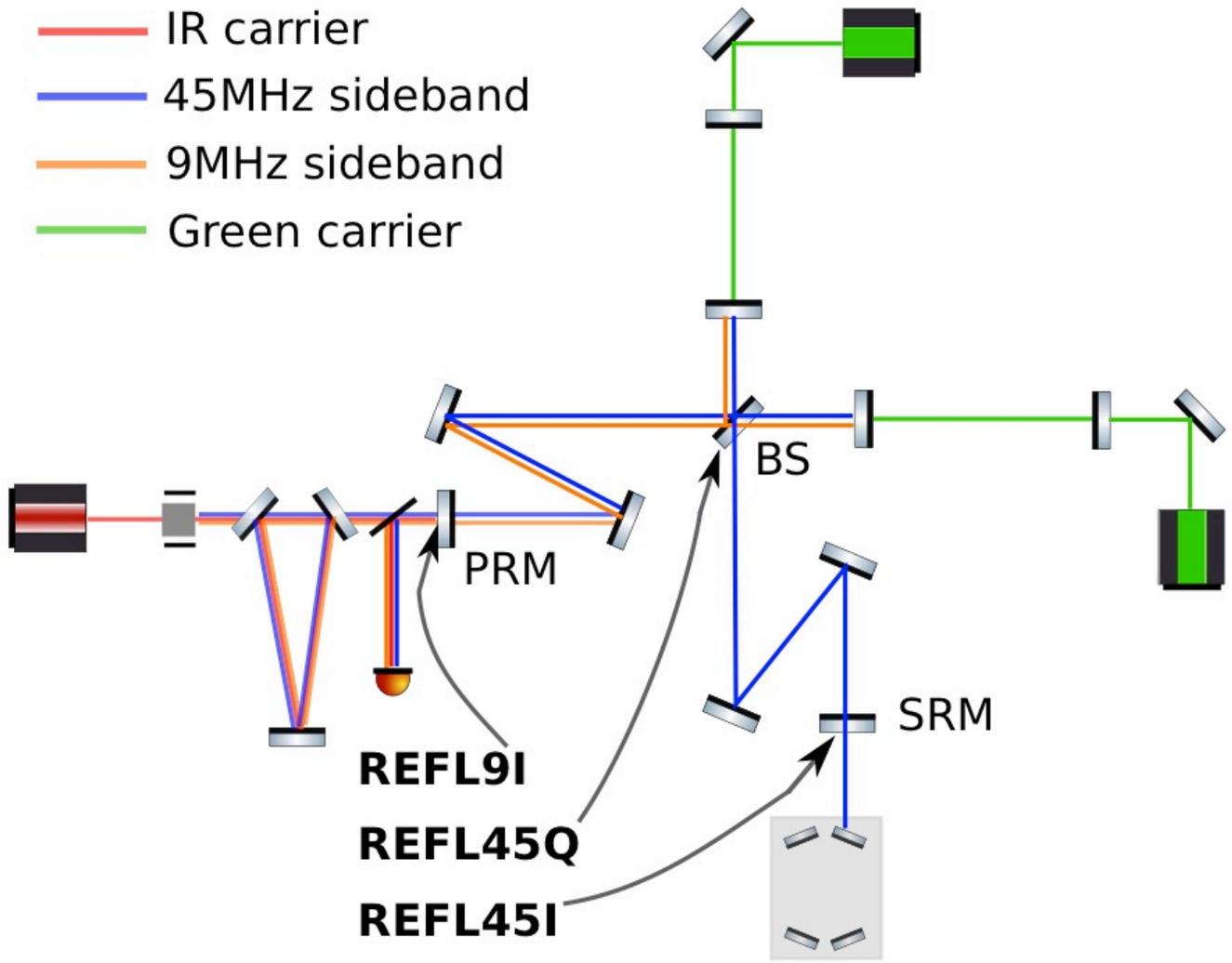
Angular controls

DC readout

Lock acquisition



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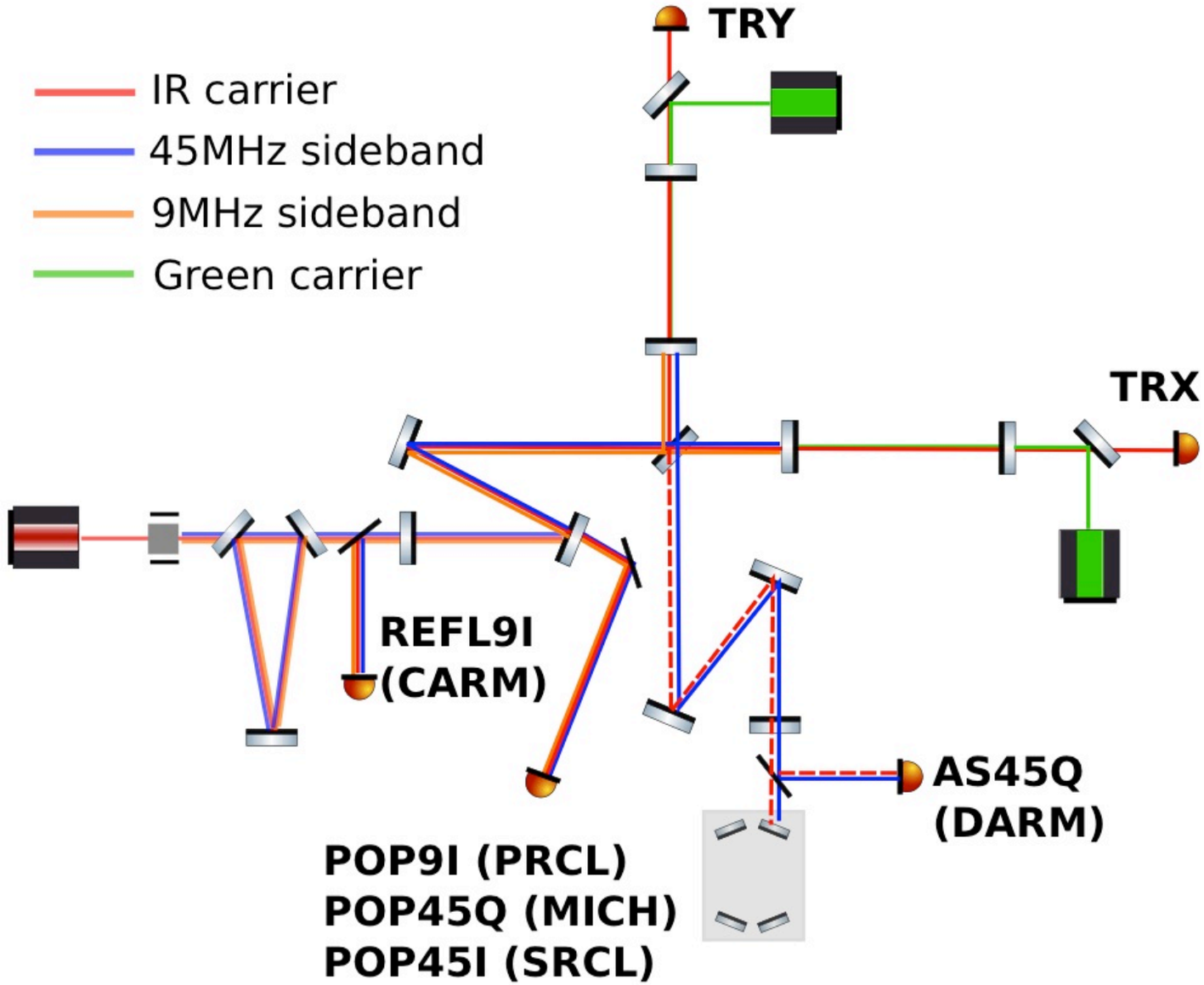

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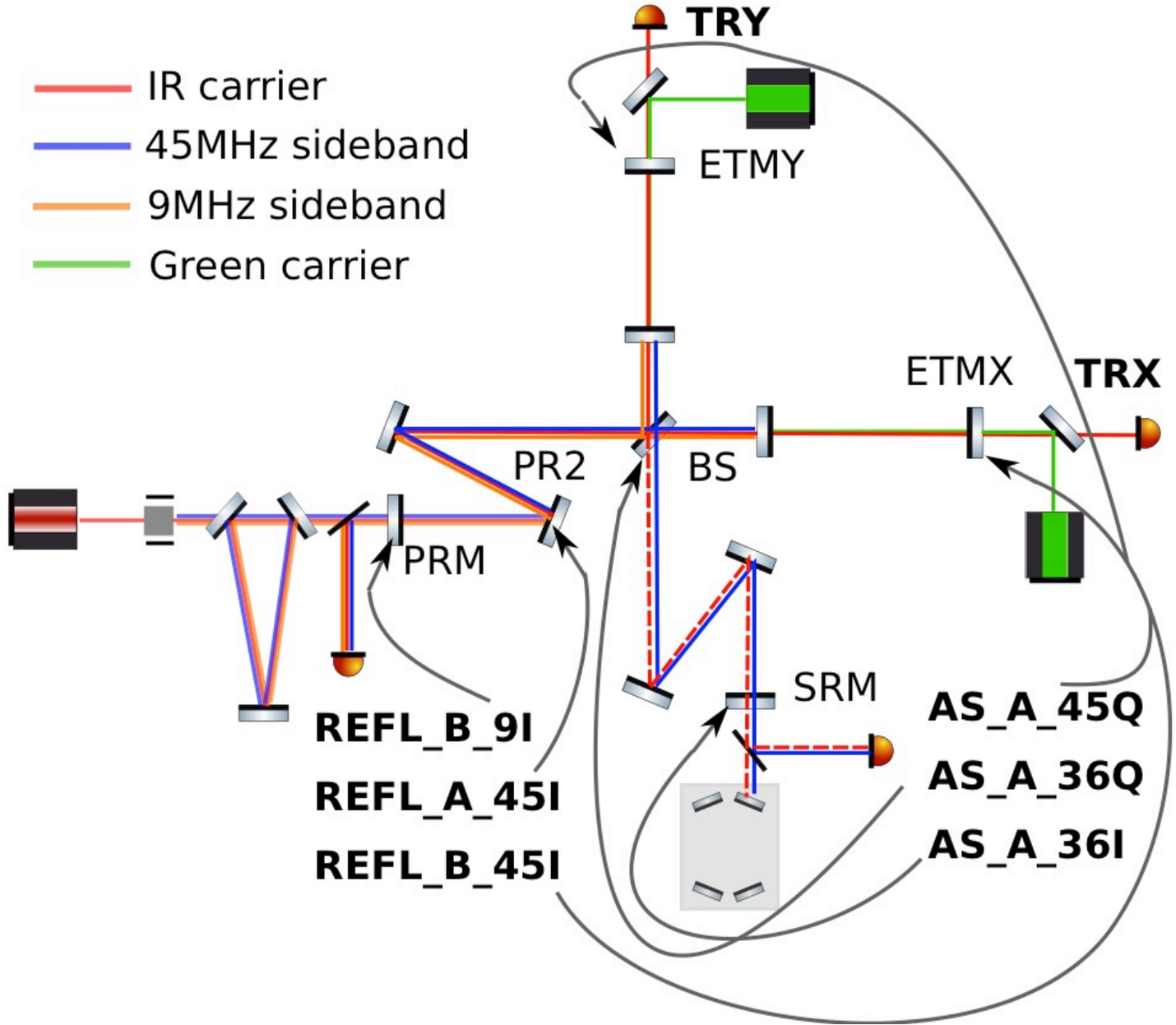

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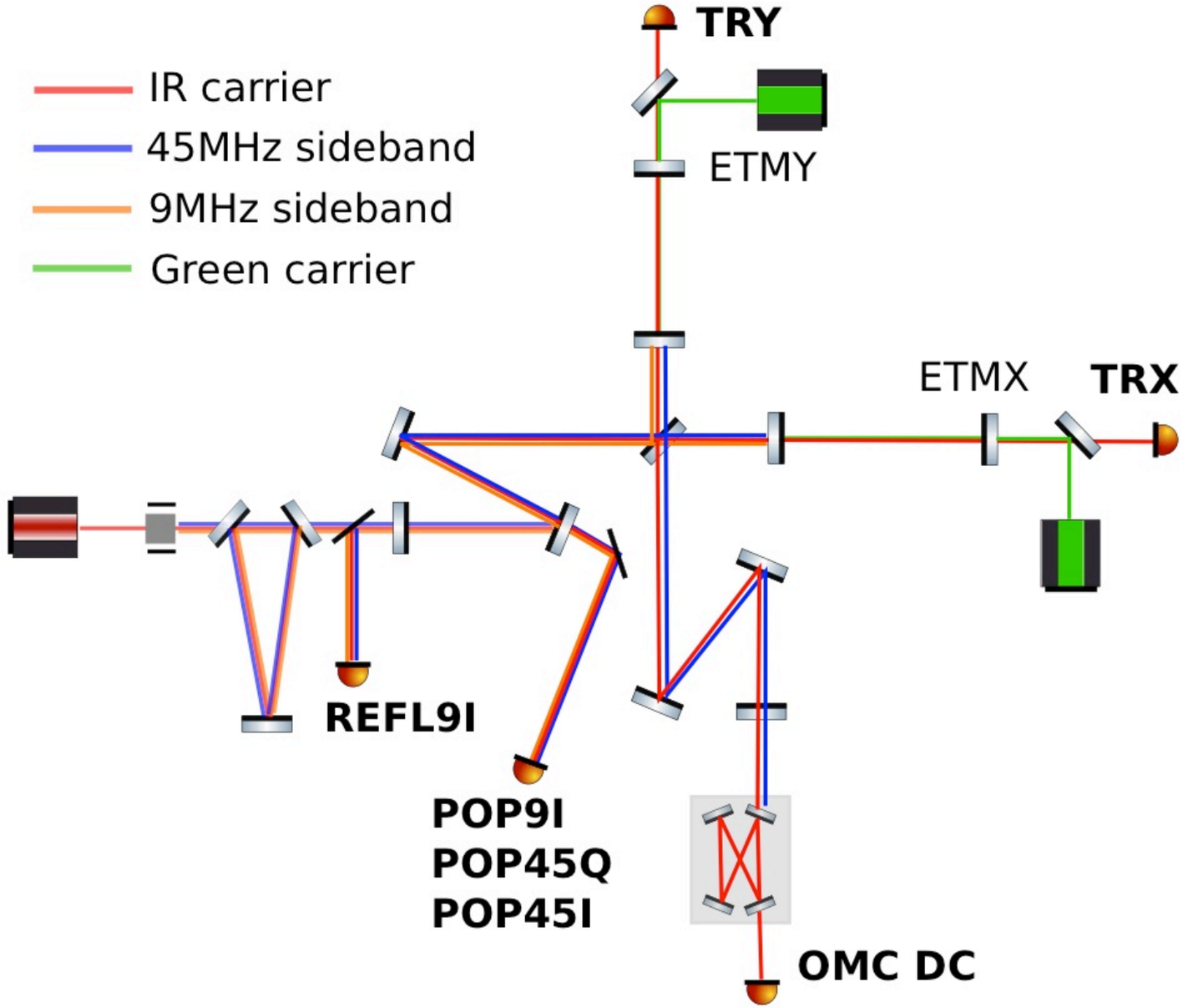


PSL+IMC

ALS

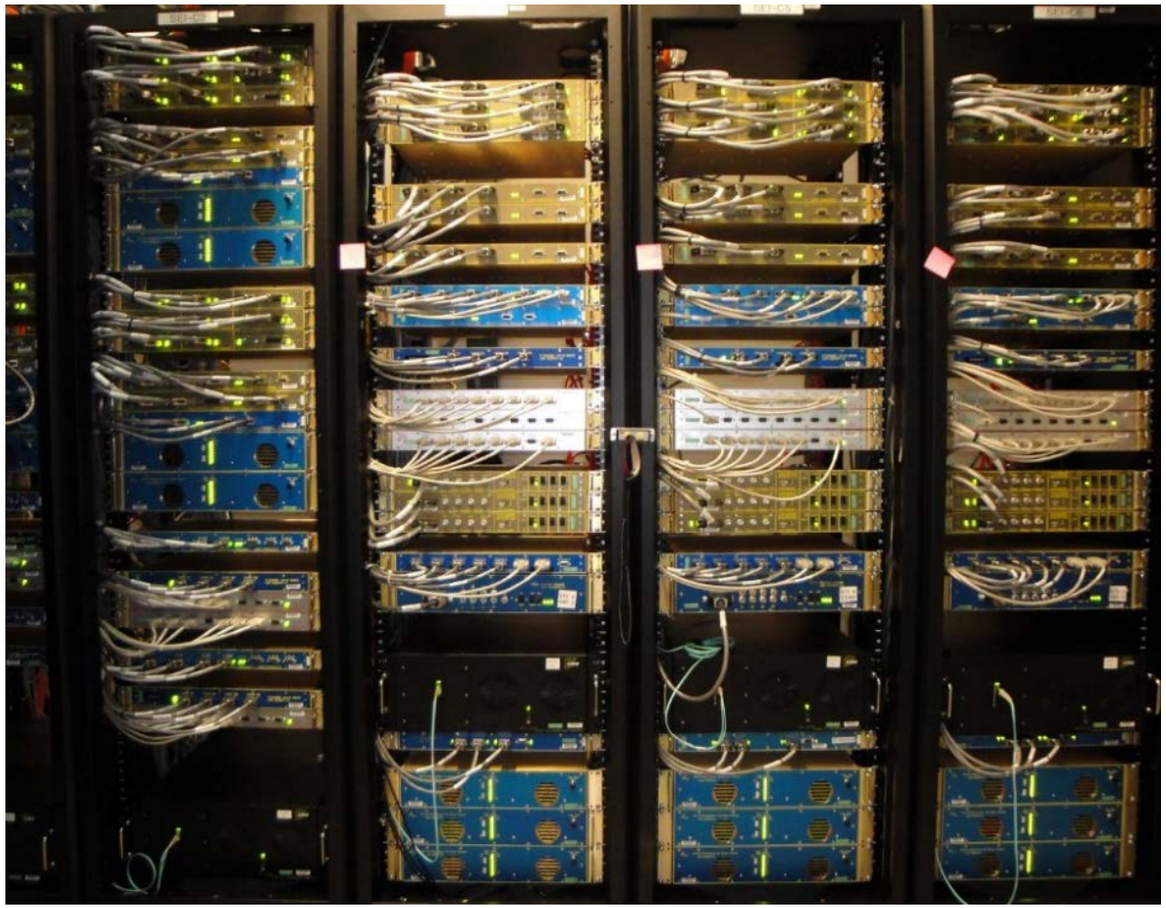
DRMI

CARM offset reduction

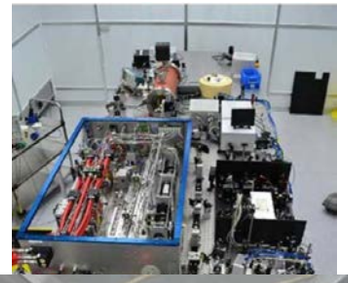
Angular controls

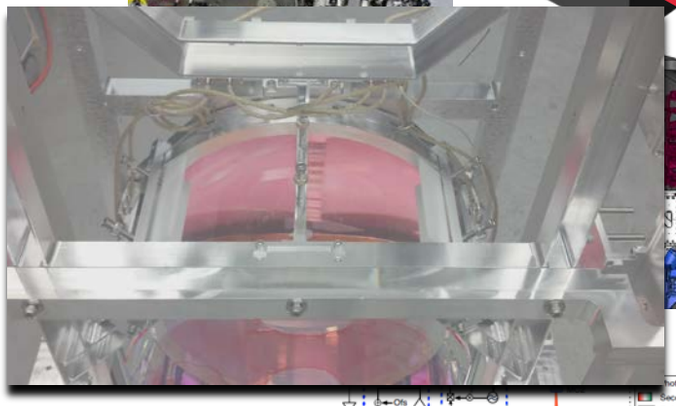
DC readout

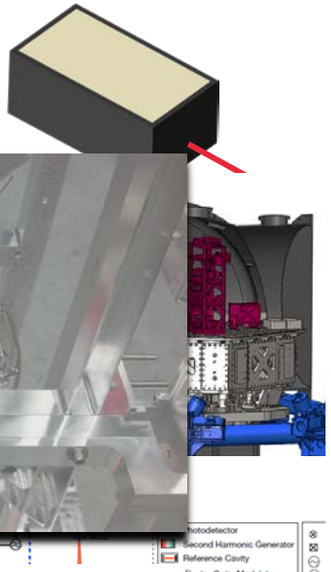
Control and Data Acquisition System

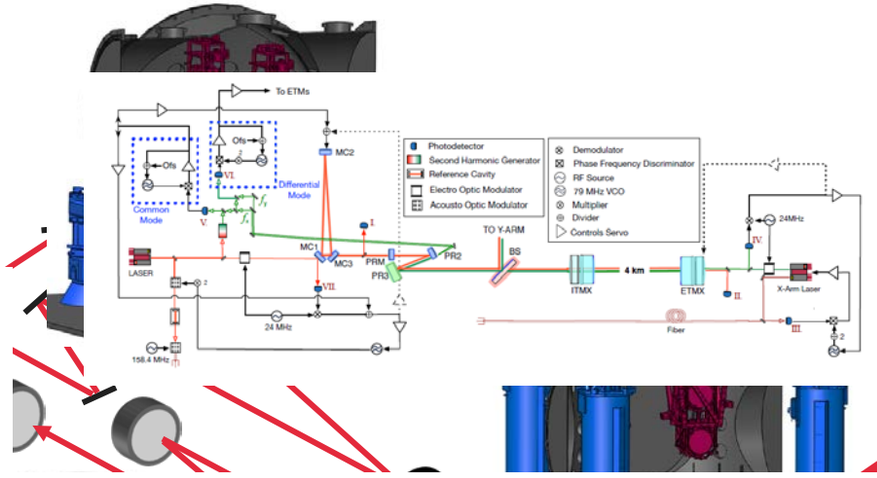


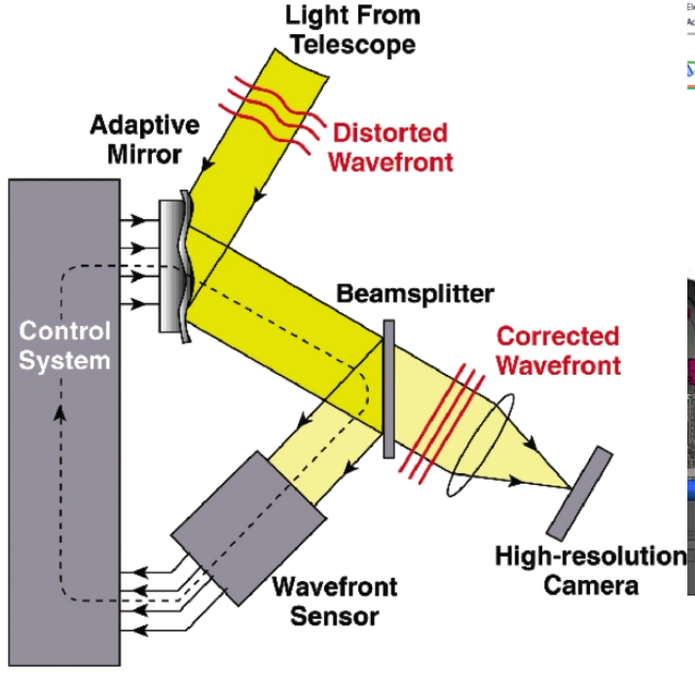
System Supervisory

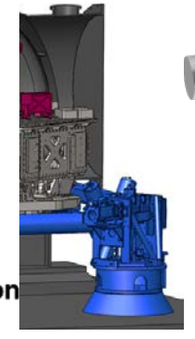


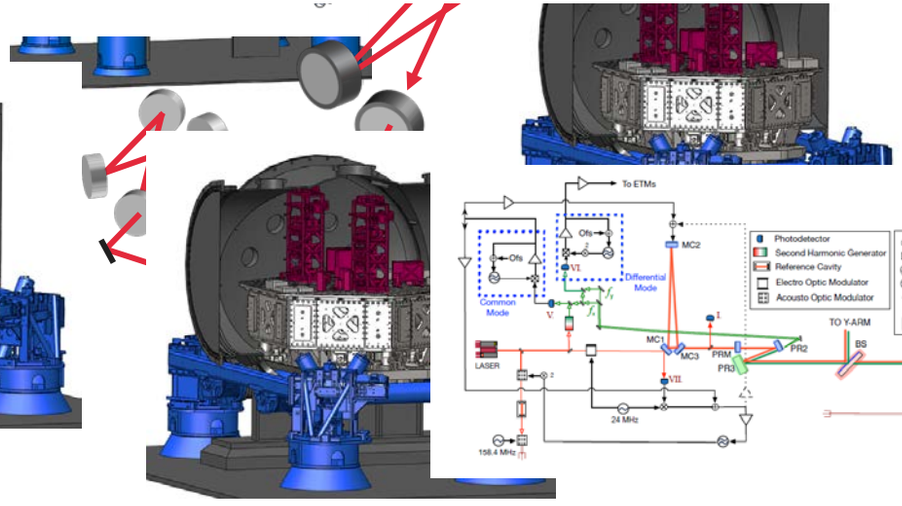


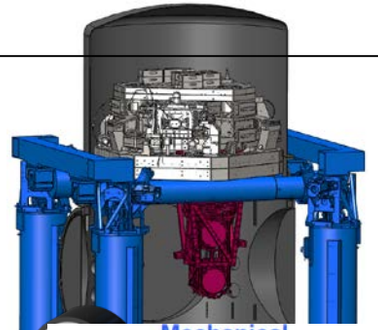


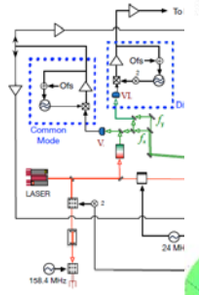


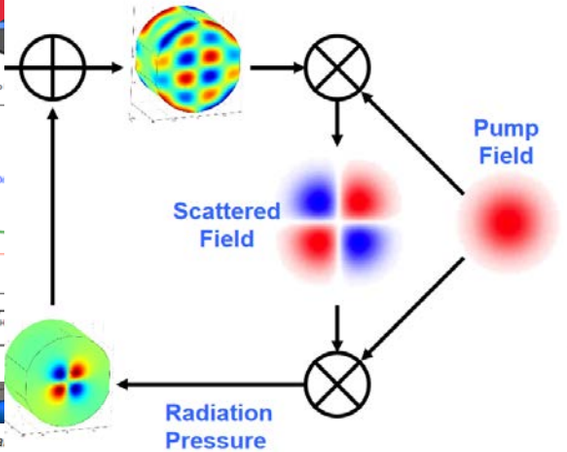


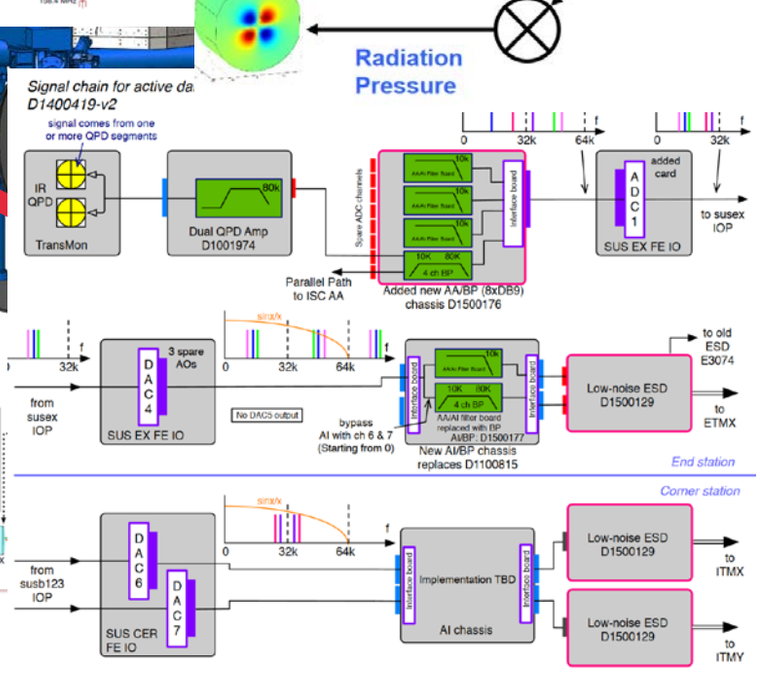




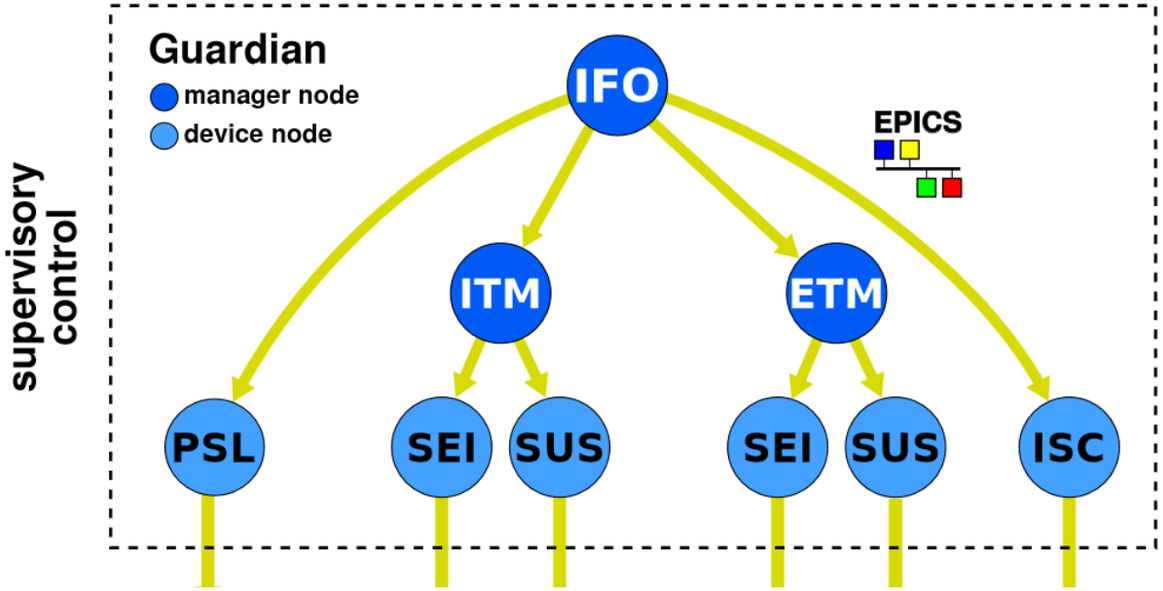


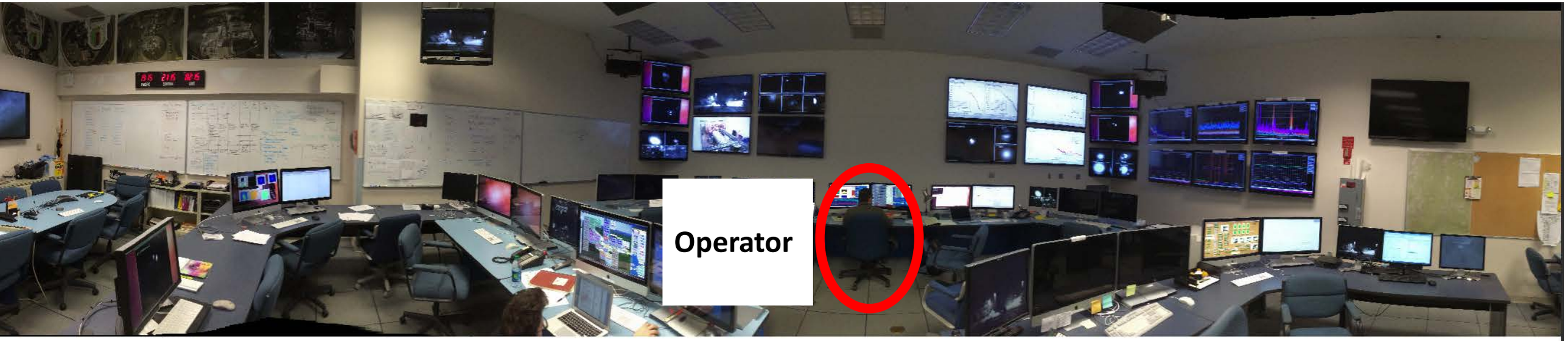




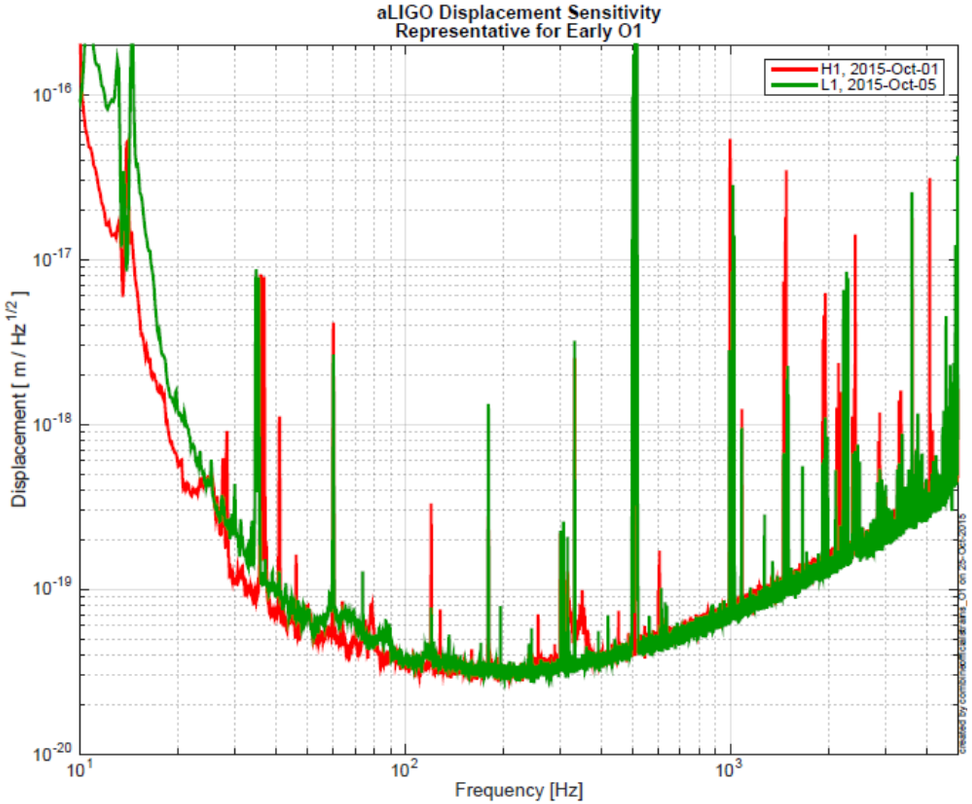


Guardian:

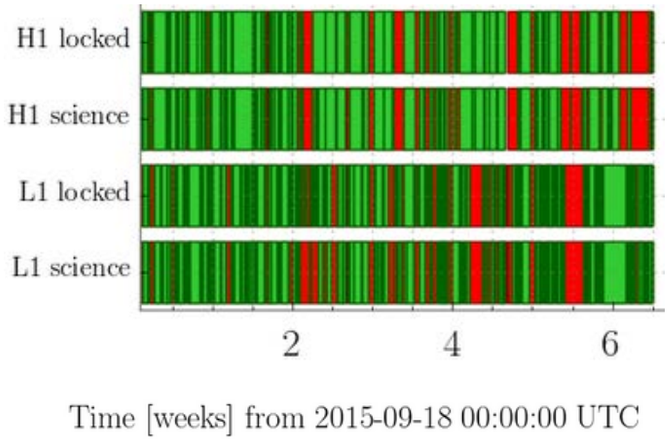

Guardian
manager node
device node
supervisory control
IFO
EPICS
ITM
ETM
PSL
SEI
SUS
SEI
SUS
ISC


Operator

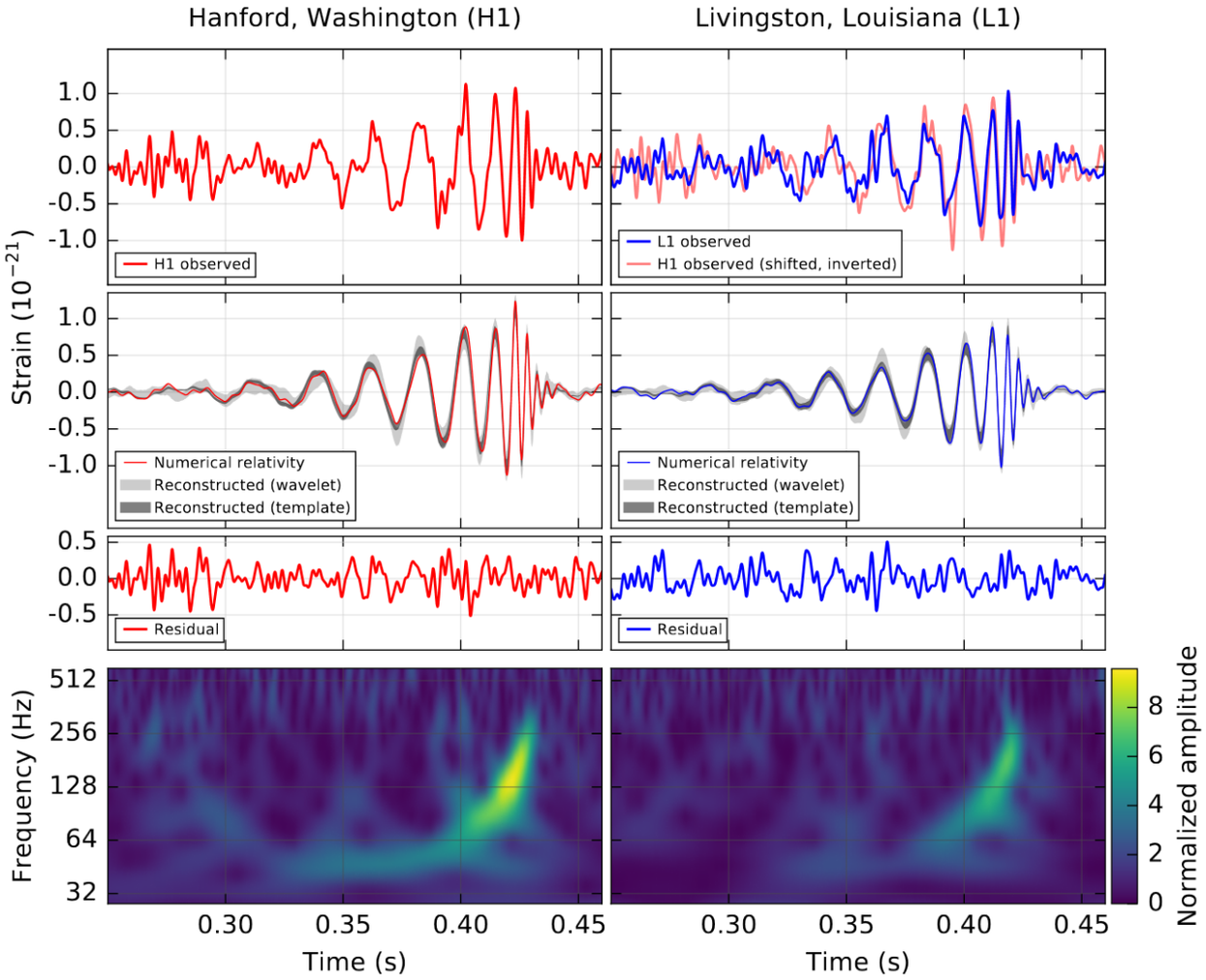
Sensitivity



Duty-Cycle



Detection



Abbott, B. P., et al. "Observation of gravitational waves from a binary black hole merger." Physical review letters 116.6 (2016): 061102.