Advanced LIGO Seismic Isolation and Control

Brett Shapiro

30th Pacific Coast Gravity Meeting

UC San Diego – 29 March 2014

LIGO Doc # G1400398

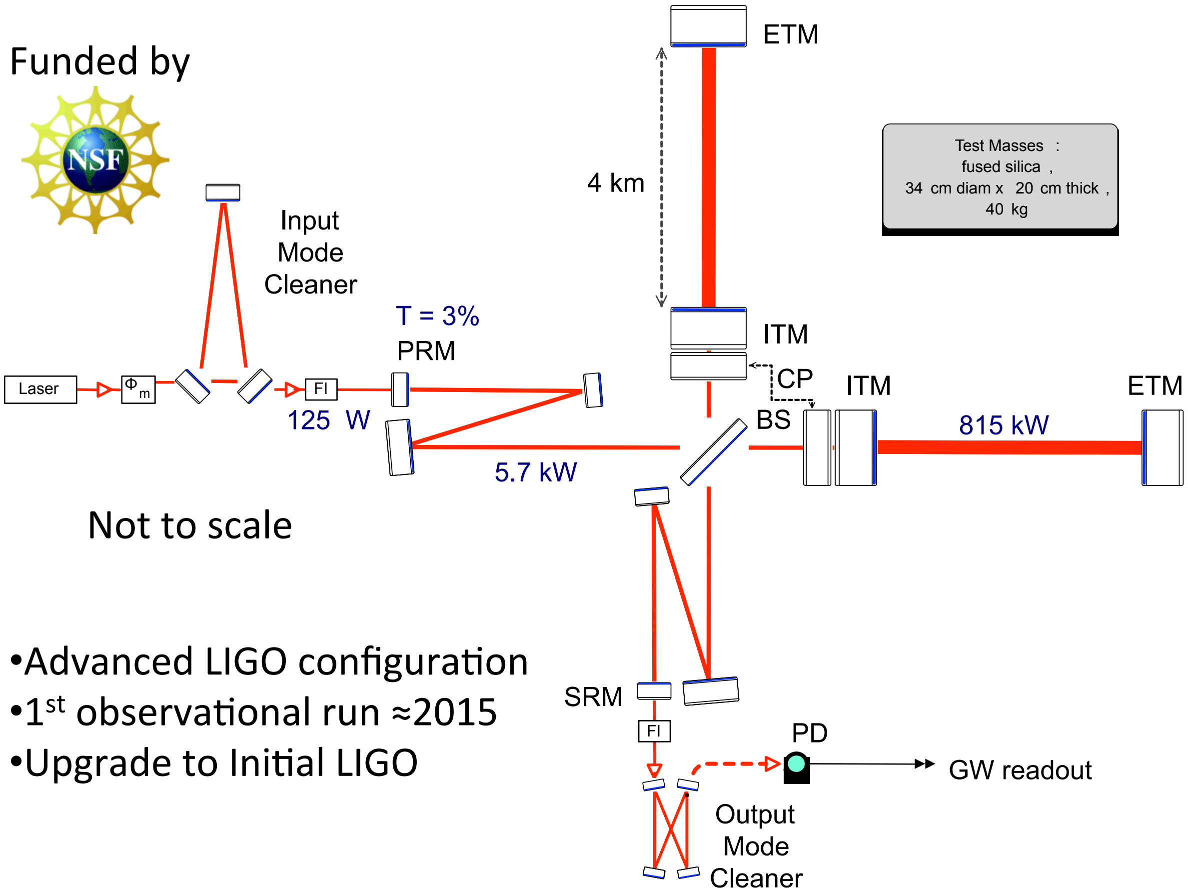
LIGO

Summary

- Advanced LIGO
- Seismic Isolation Systems
- Control design Ex: quadruple pendulum damping
- How control design influences astrophysical sensitivity

The Laser Interferometer Gravitational-wave Observatory (LIGO)

Funded by



Not to scale

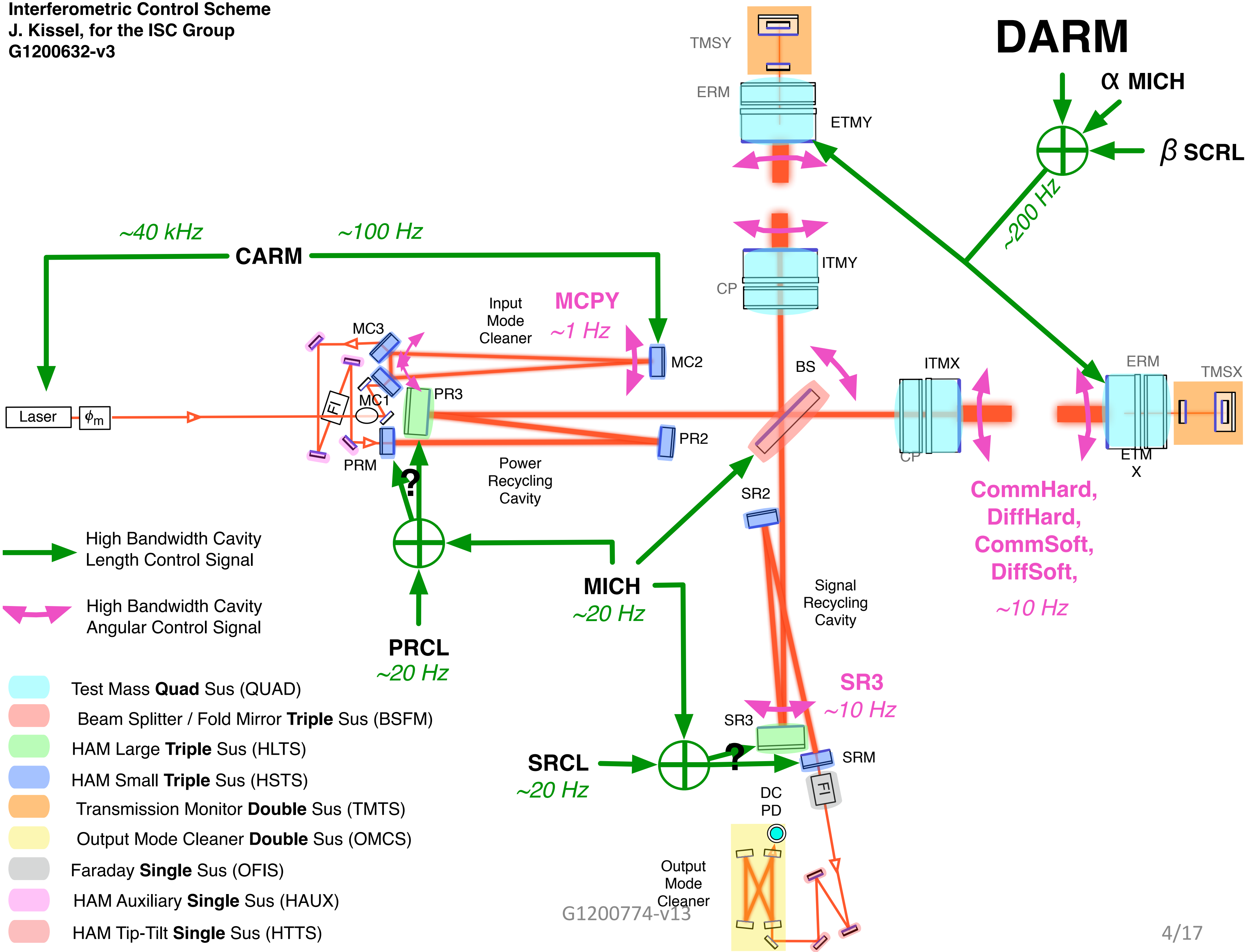
- Advanced LIGO configuration
- 1st observational run ≈2015
- Upgrade to Initial LIGO

Hanford, WA

Livingston, LA

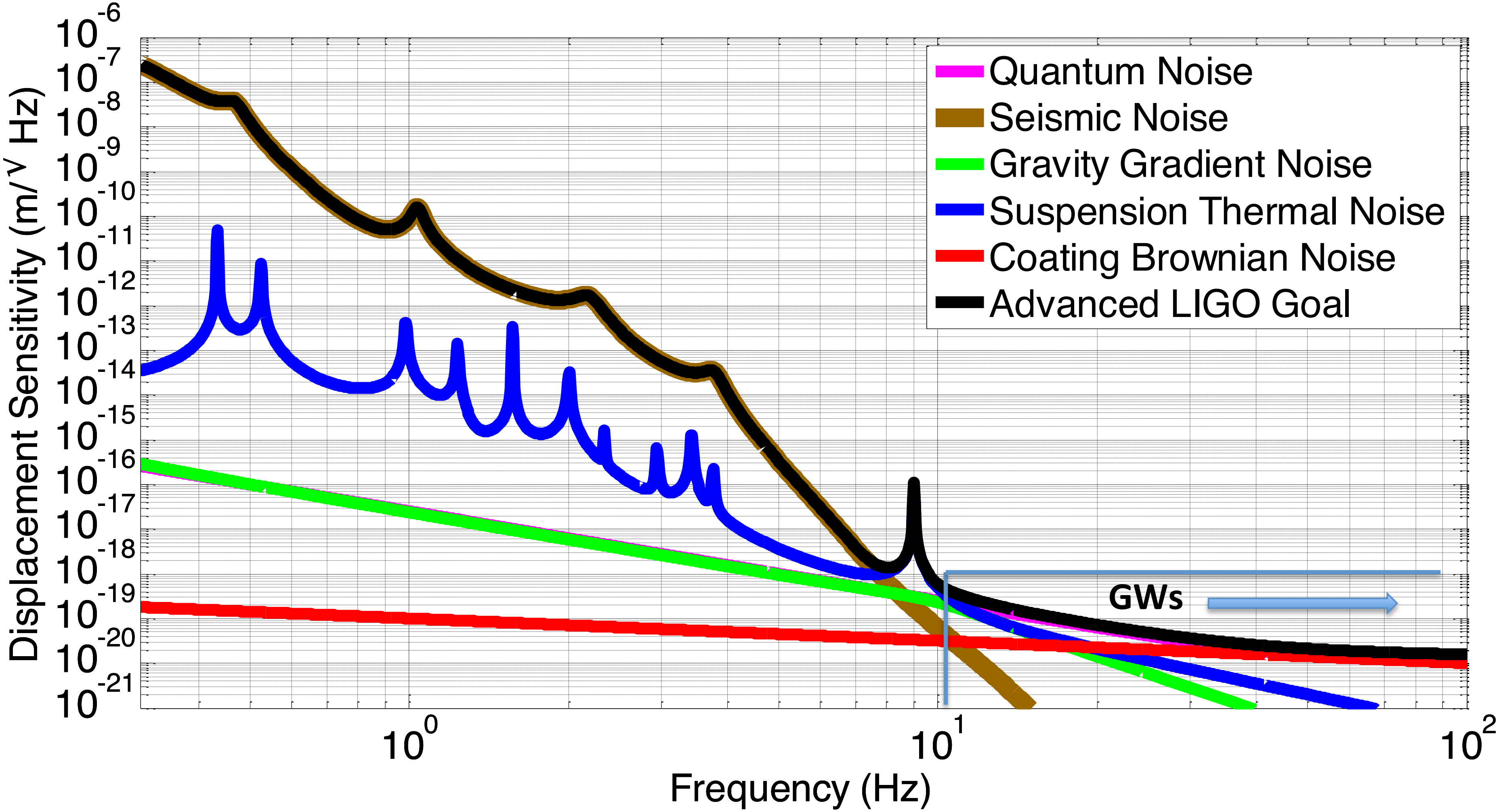
- ***2, 4 km interferometers at 2 sites in the US***
- ***Michelson interferometers with Fabry-Pérot arms***
- ***Optical path enclosed in vacuum***
- ***Sensitive to strains around 10^{-22} -> $10^{-19} m_{rms}$***
- ***LIGO Budget ≈ $60 Million per year from NSF.***
- ***Operated by MIT and Caltech.***

Advanced LIGO
Interferometric Control Scheme
J. Kissel, for the ISC Group
G1200632-v3



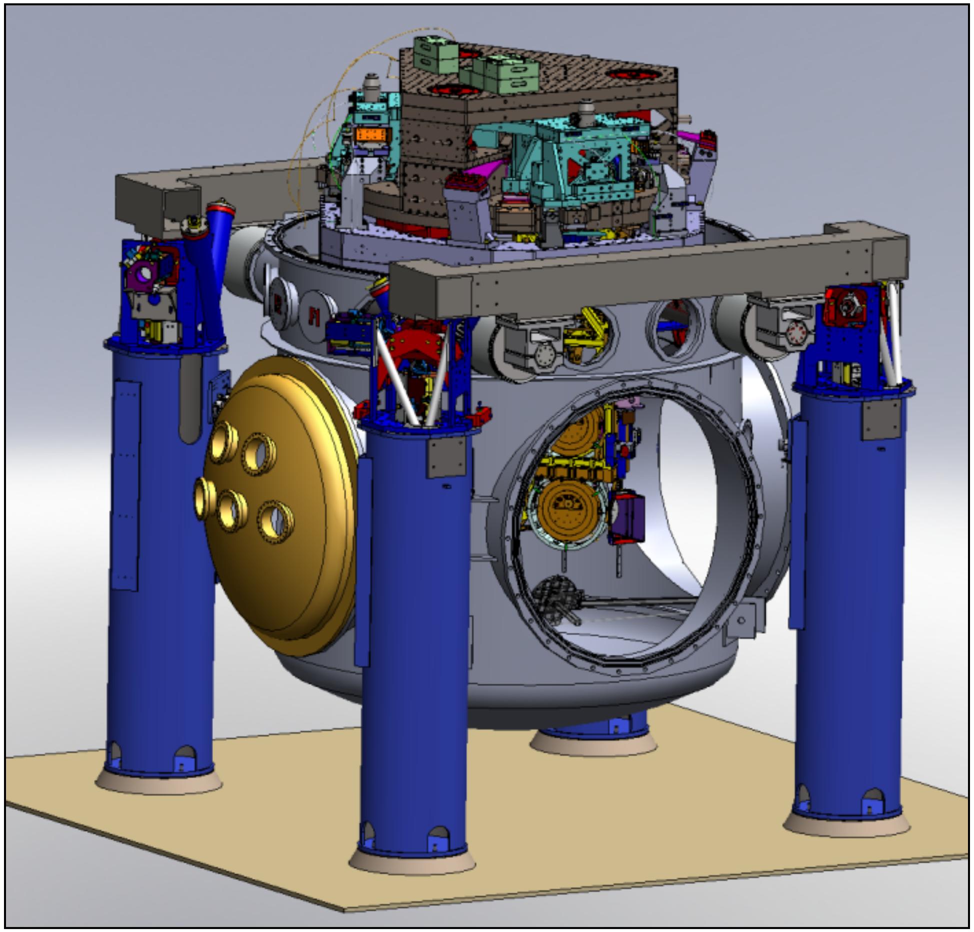
G1200774-v13

Projected Sensitivity for Adv. LIGO



Suspensions and Seismic Isolation

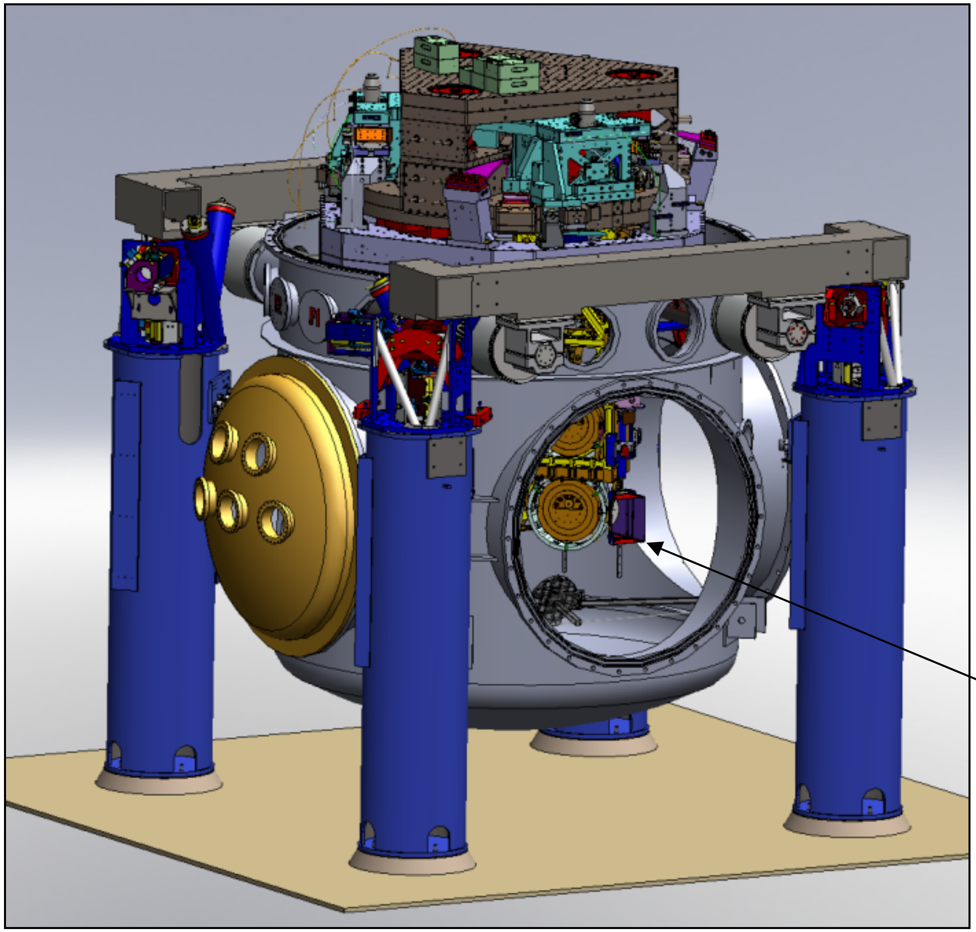
Advanced LIGO test mass isolation



Ref: LIGO-G1000469-v1; Kissel PhD thesis

Suspensions and Seismic Isolation

Advanced LIGO test mass isolation

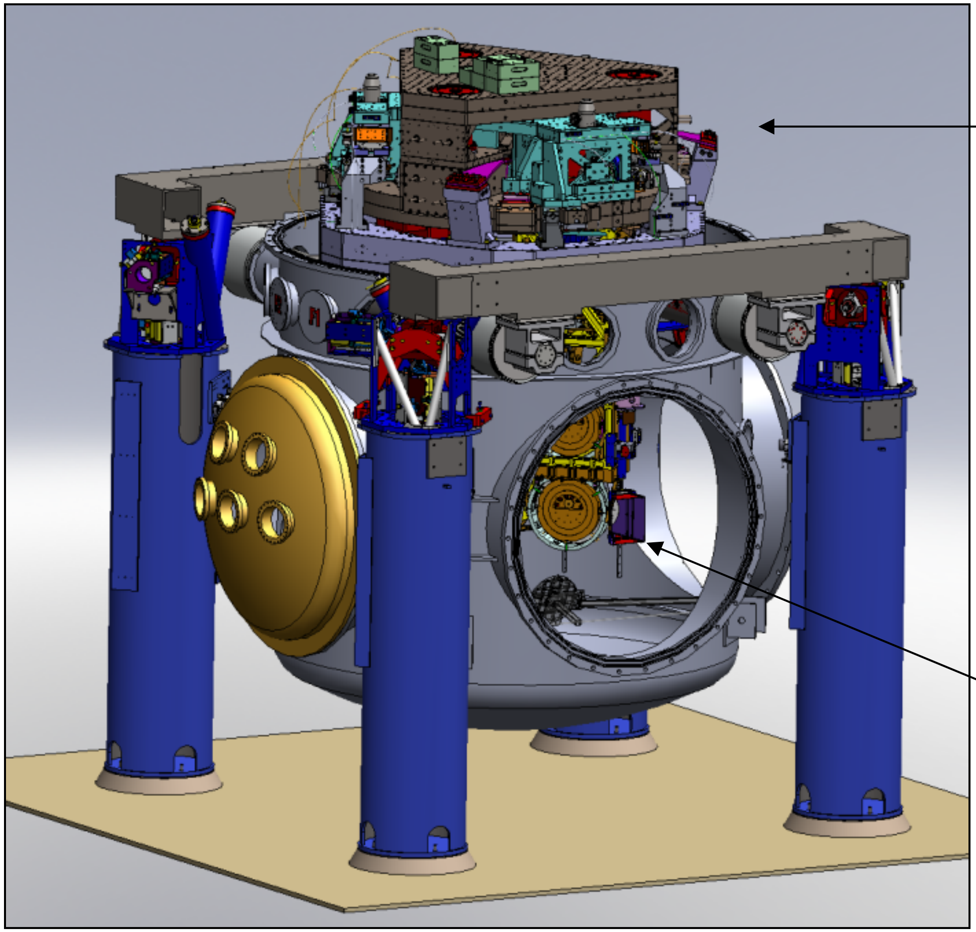


quadruple pendulum (four stages of isolation) with monolithic silica final stage

Ref: LIGO-G1000469-v1; Kissel PhD thesis

Suspensions and Seismic Isolation

Advanced LIGO test mass isolation



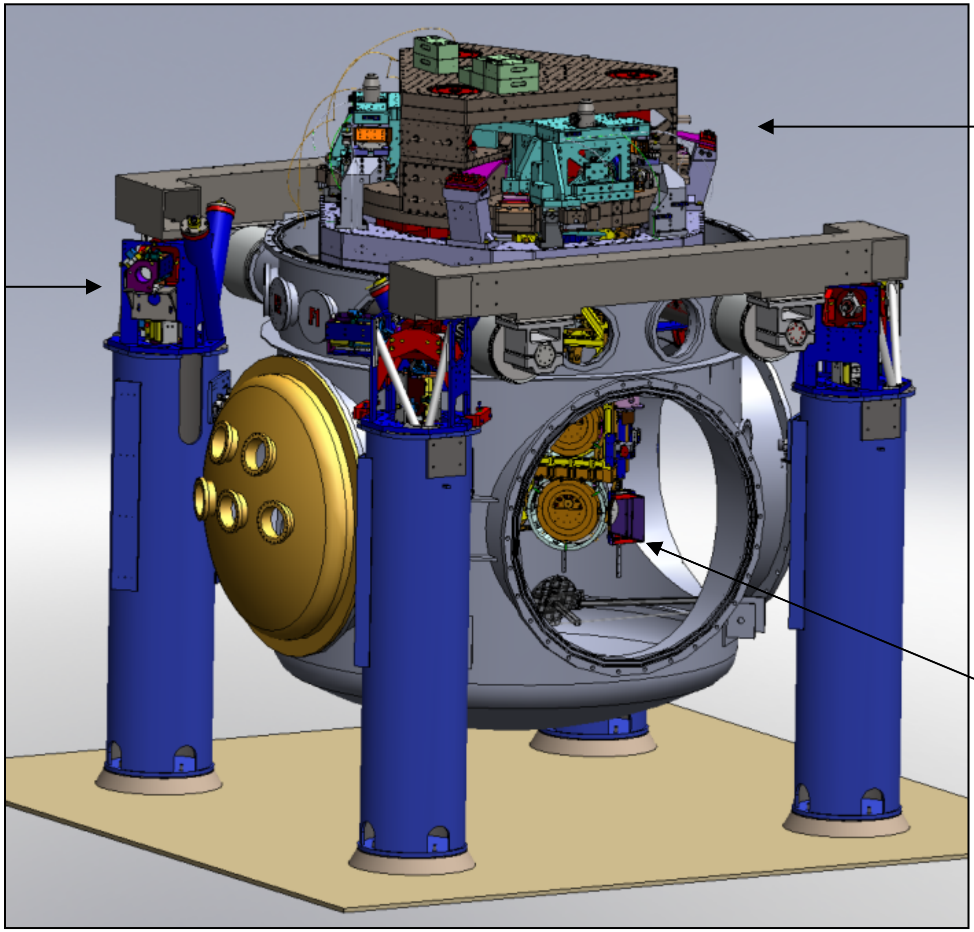
active isolation platform (2 stages of isolation)

quadruple pendulum (four stages of isolation) with monolithic silica final stage

Ref: LIGO-G1000469-v1; Kissel PhD thesis

Suspensions and Seismic Isolation

Advanced LIGO test mass isolation

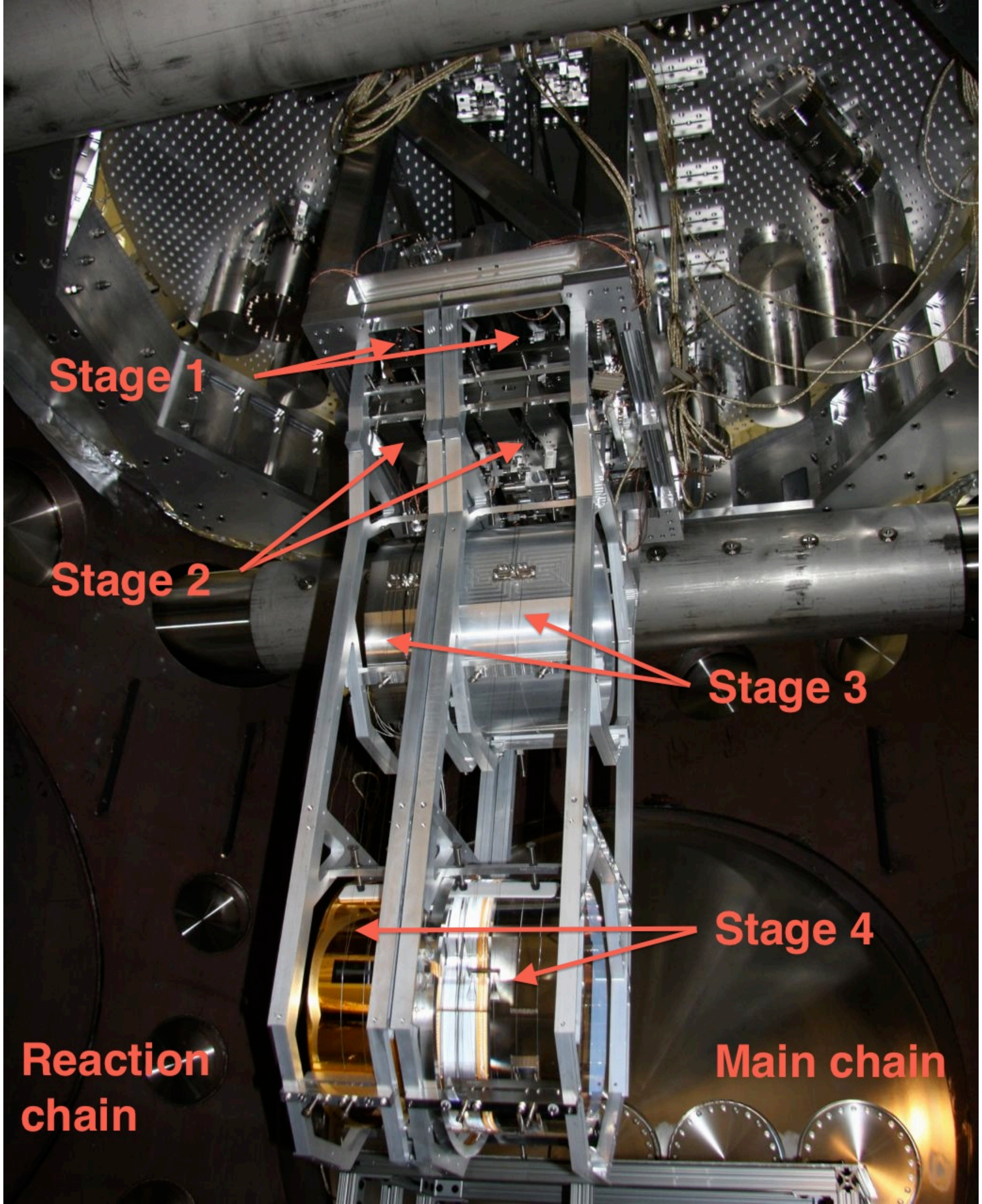


active isolation platform (2 stages of isolation)

hydraulic external pre-isolator (HEPI) (one stage of isolation)

quadruple pendulum (four stages of isolation) with monolithic silica final stage

Ref: LIGO-G1000469-v1; Kissel PhD thesis



prototype quad pendulum installation Jan 2009 at MIT

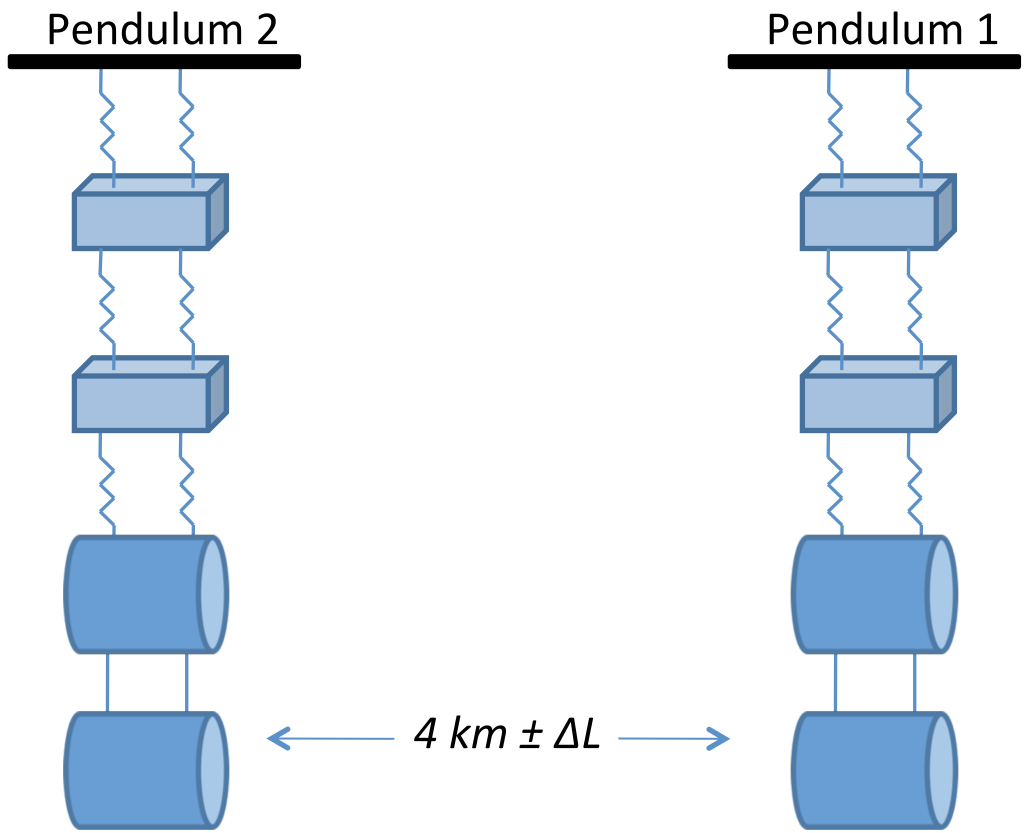
active isolation platform (2 stages of isolation)

quadruple pendulum (four stages of isolation)

prototype quad pendulum installation Jan 2009 at MIT

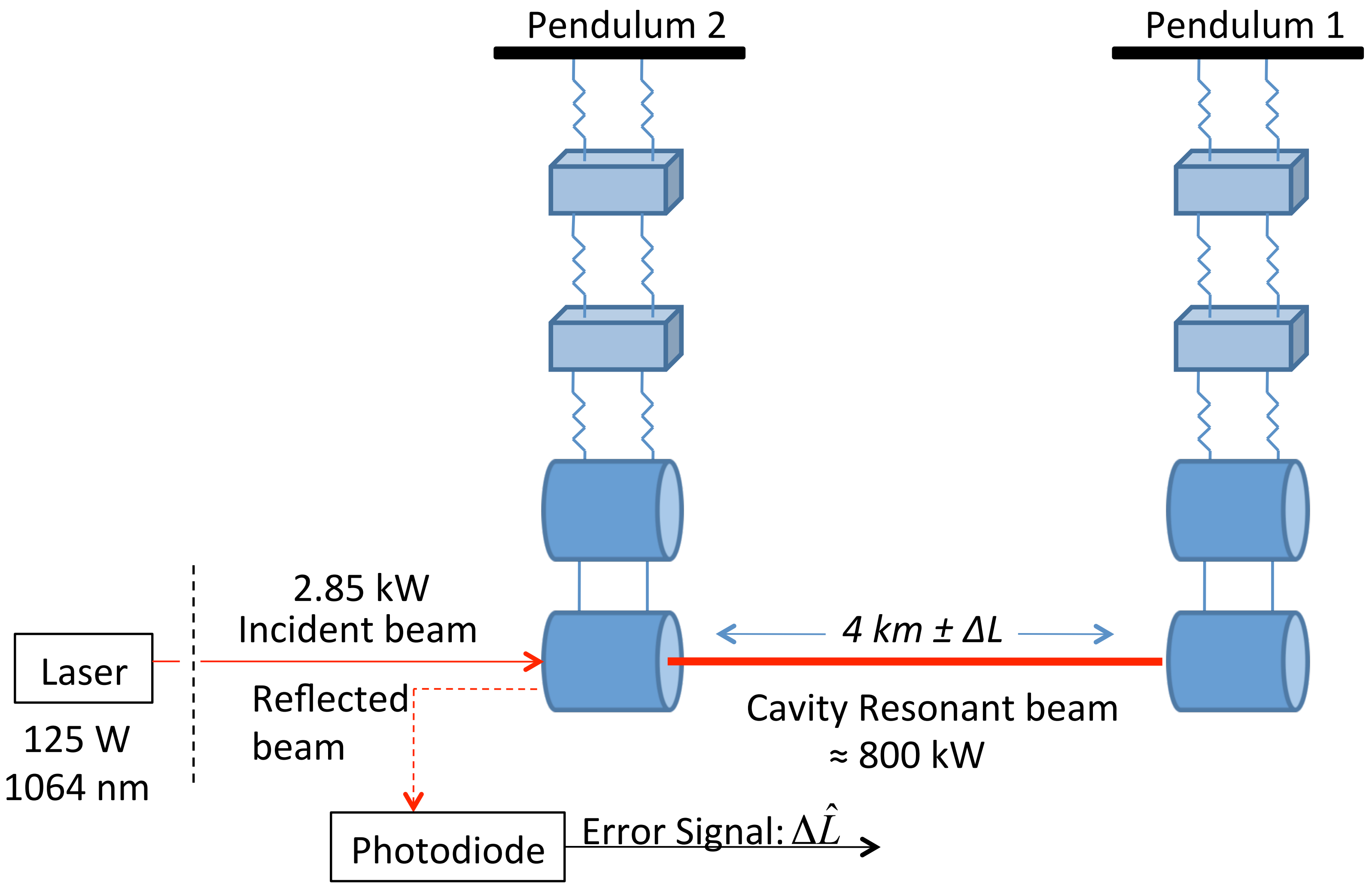
Pendulum Control Layout

Schematic view of one of LIGO's 4 km Fabry-Perot cavity arms



Pendulum Control Layout

Schematic view of one of LIGO's 4 km Fabry-Perot cavity arms



Pendulum Control Layout

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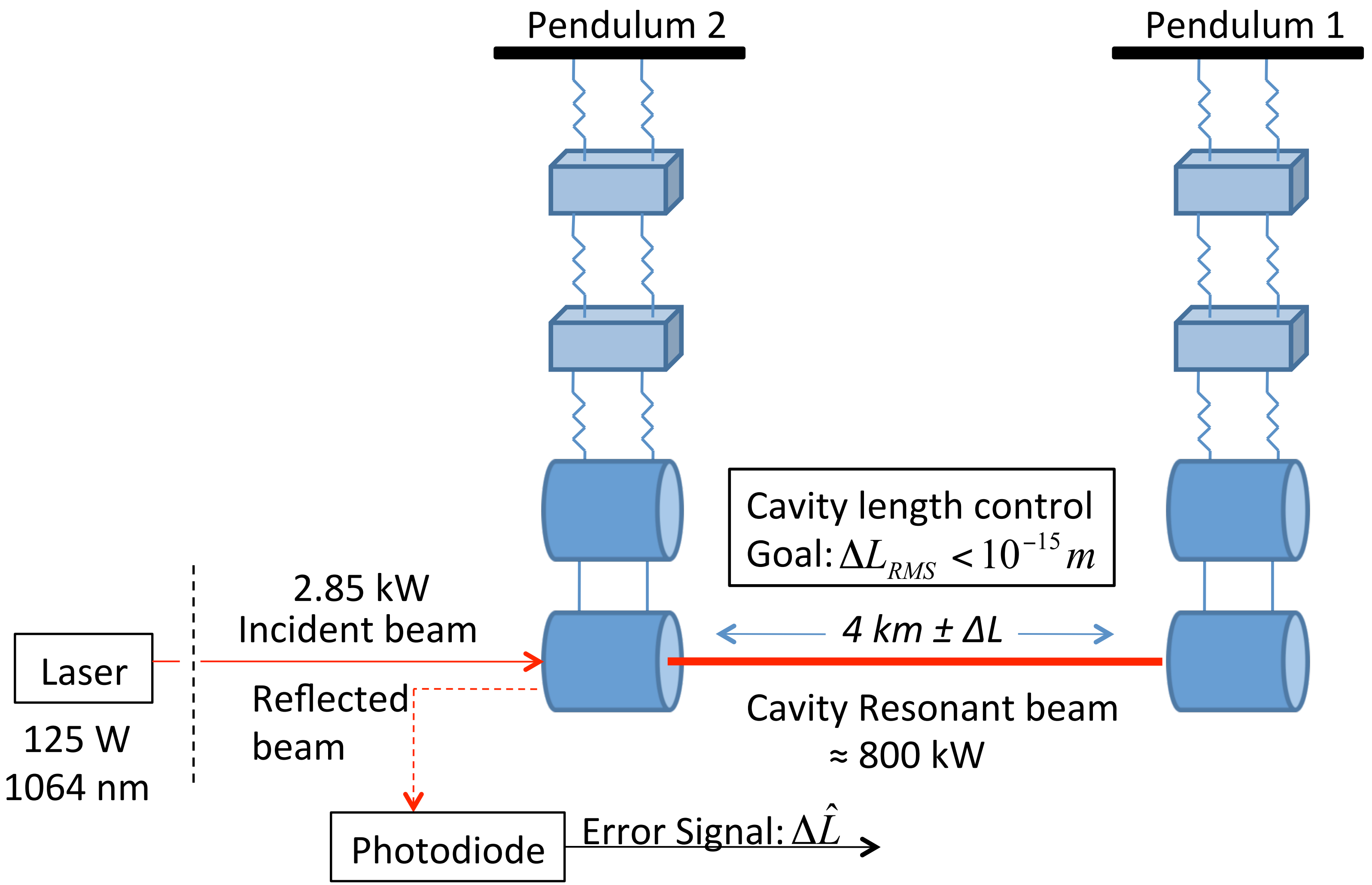

Pendulum Control Layout

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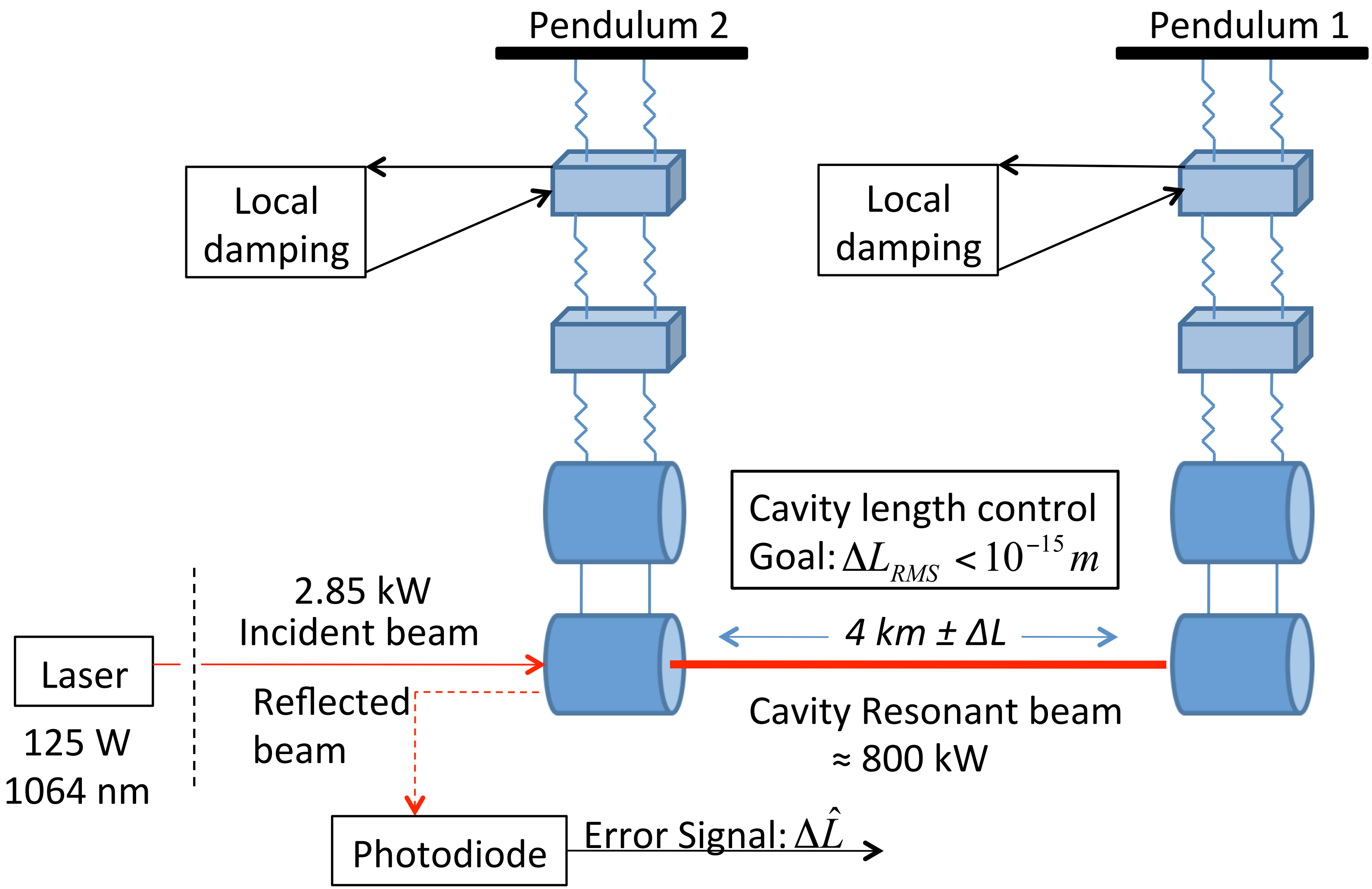

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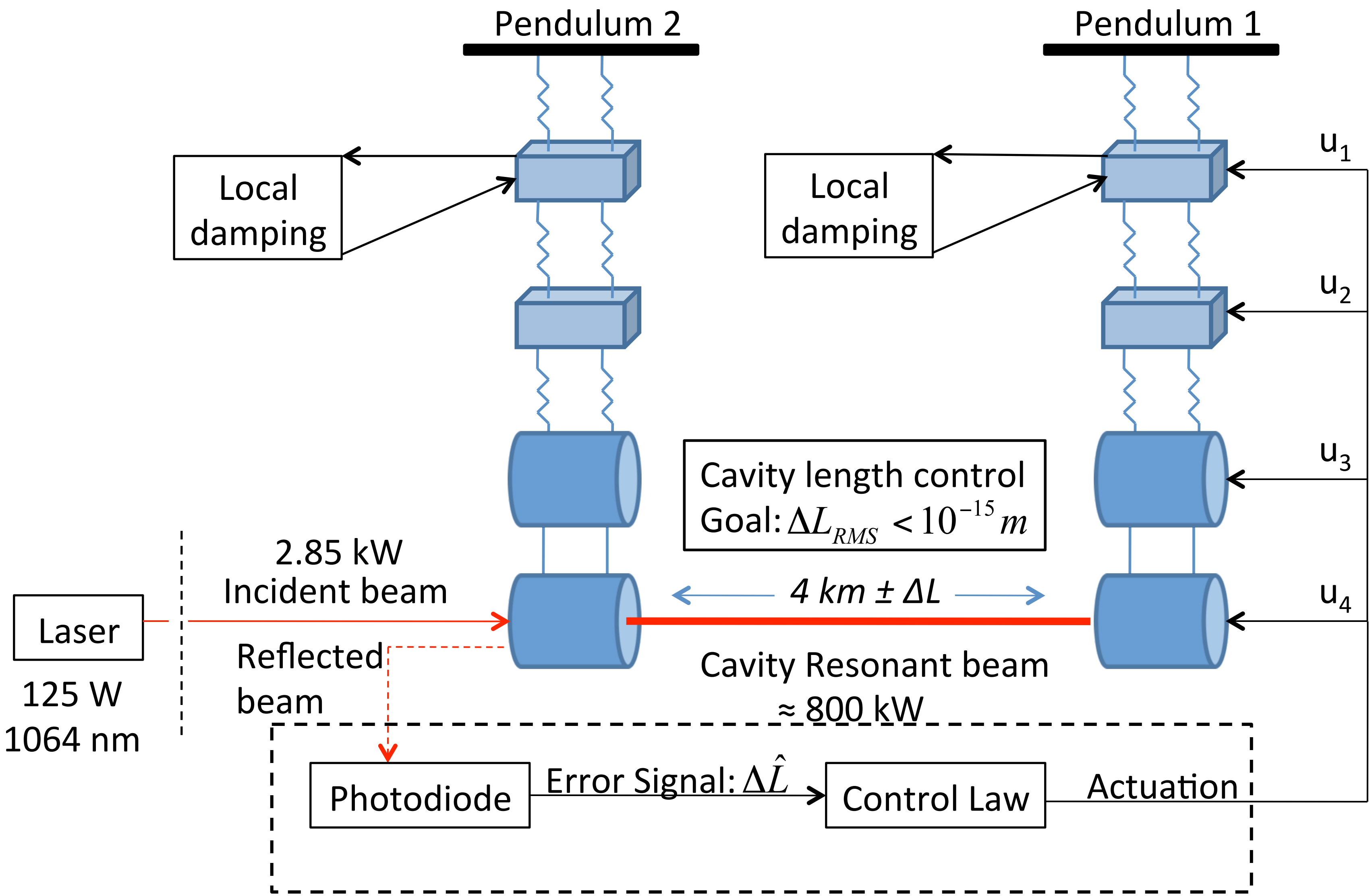

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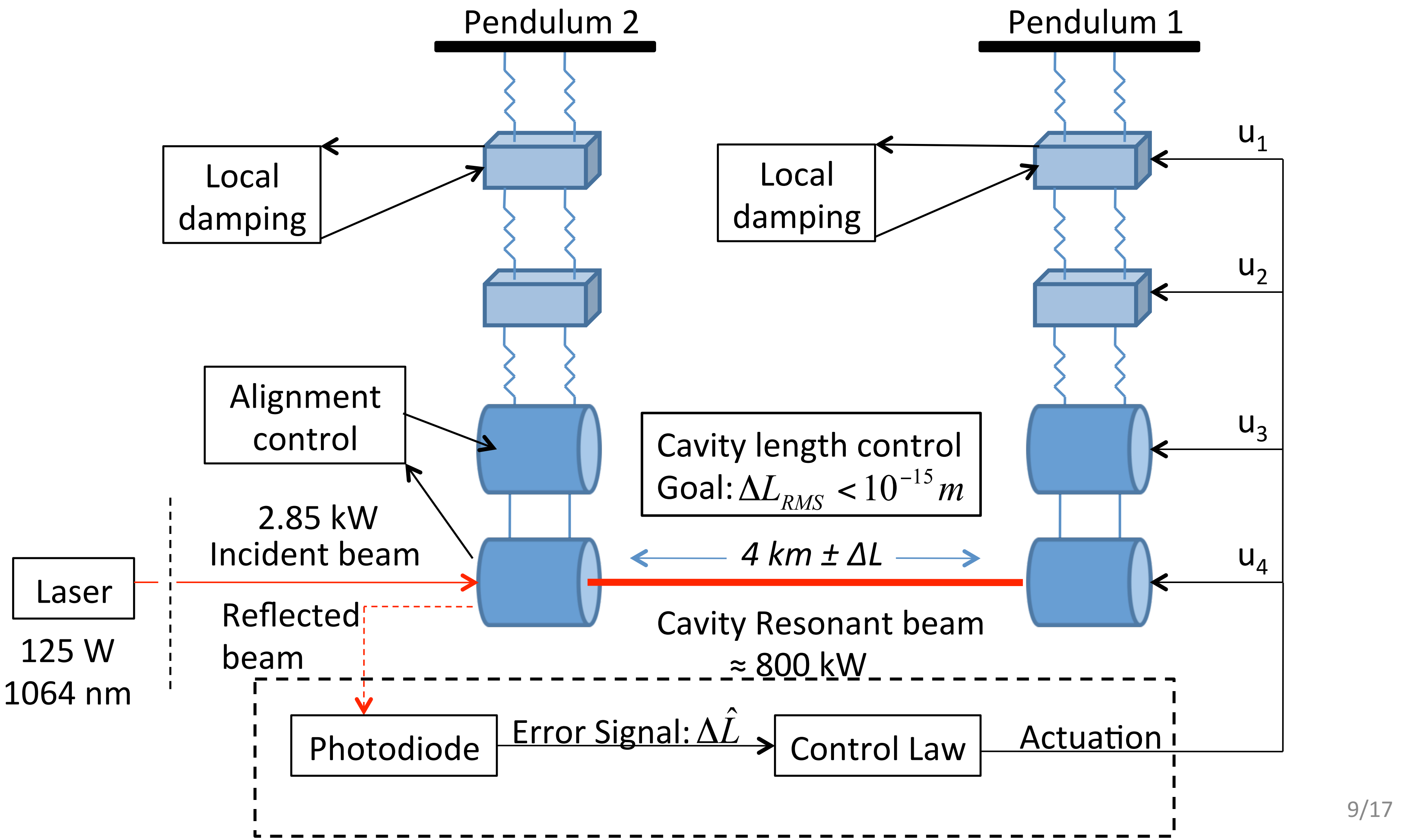

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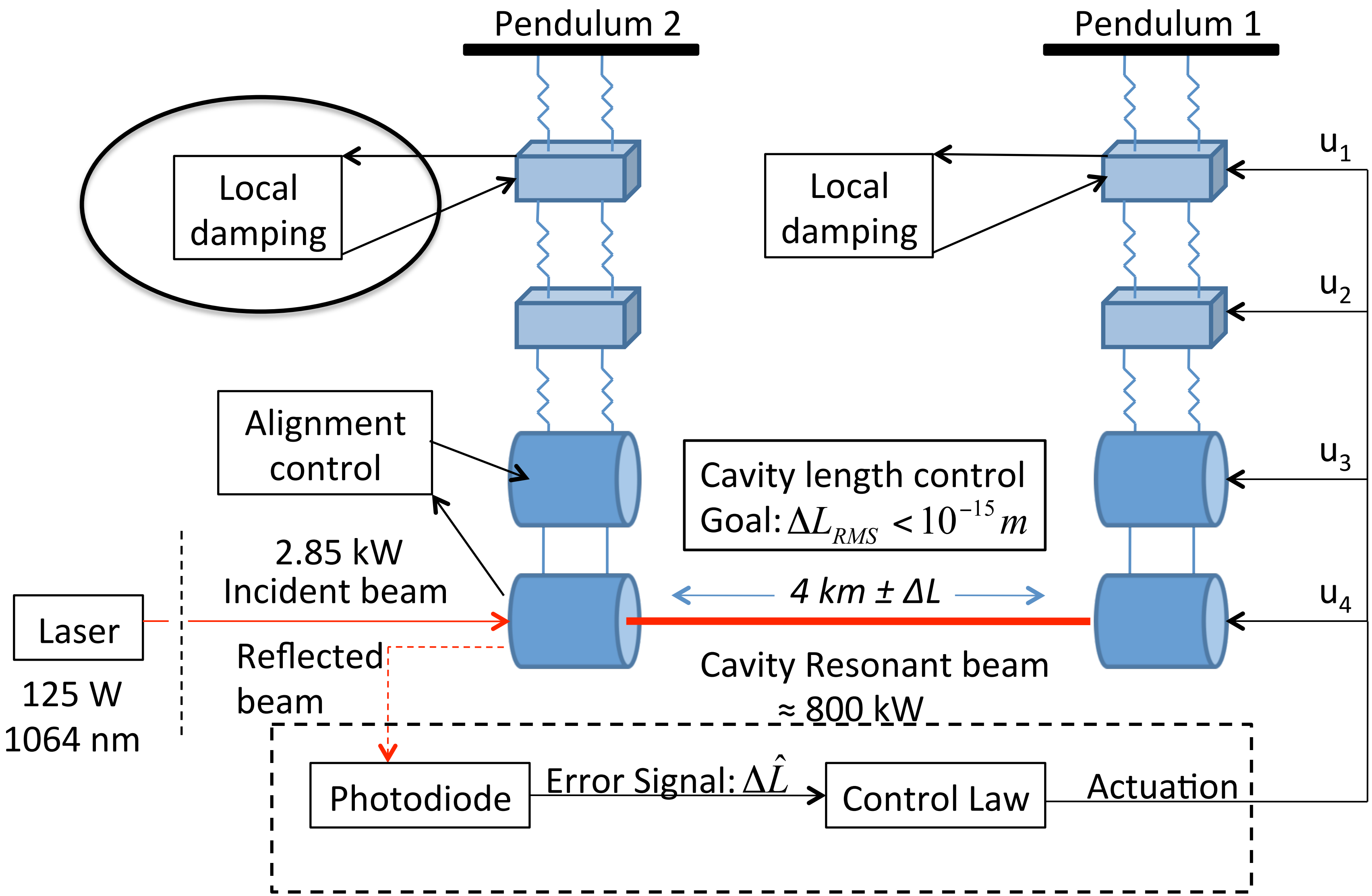
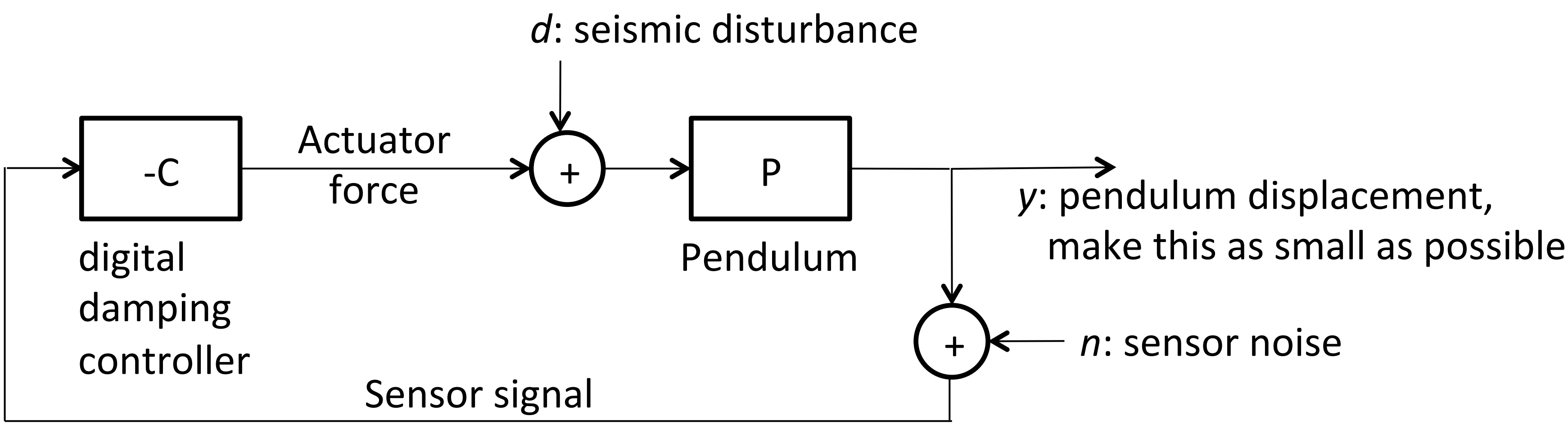


Damping loop block diagram

- Frequency domain signals, i.e. Laplace or Fourier Transform



Damping loop block diagram

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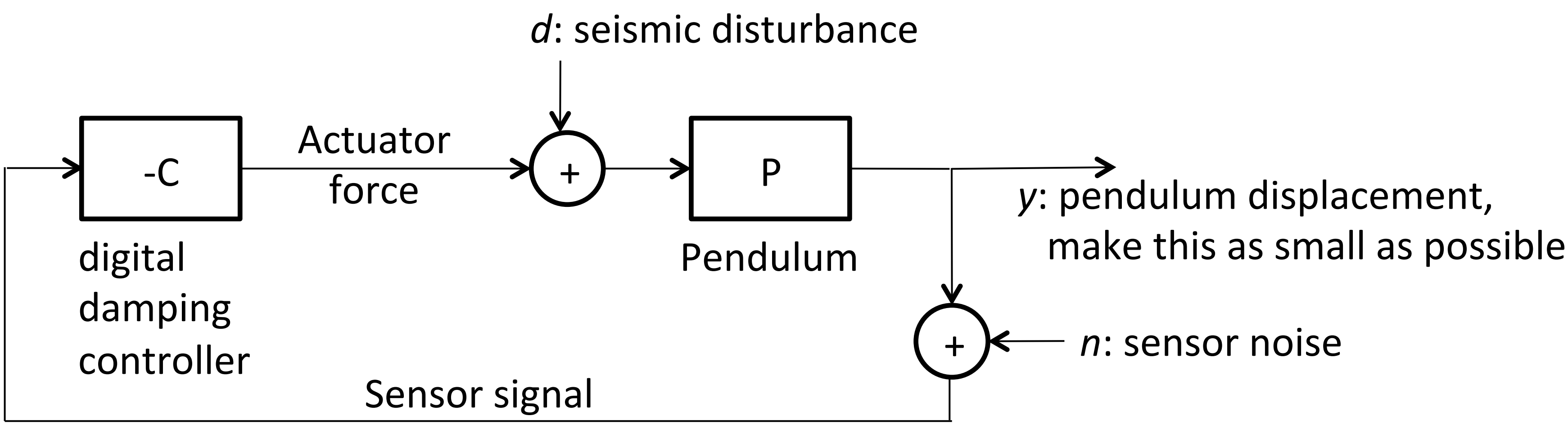


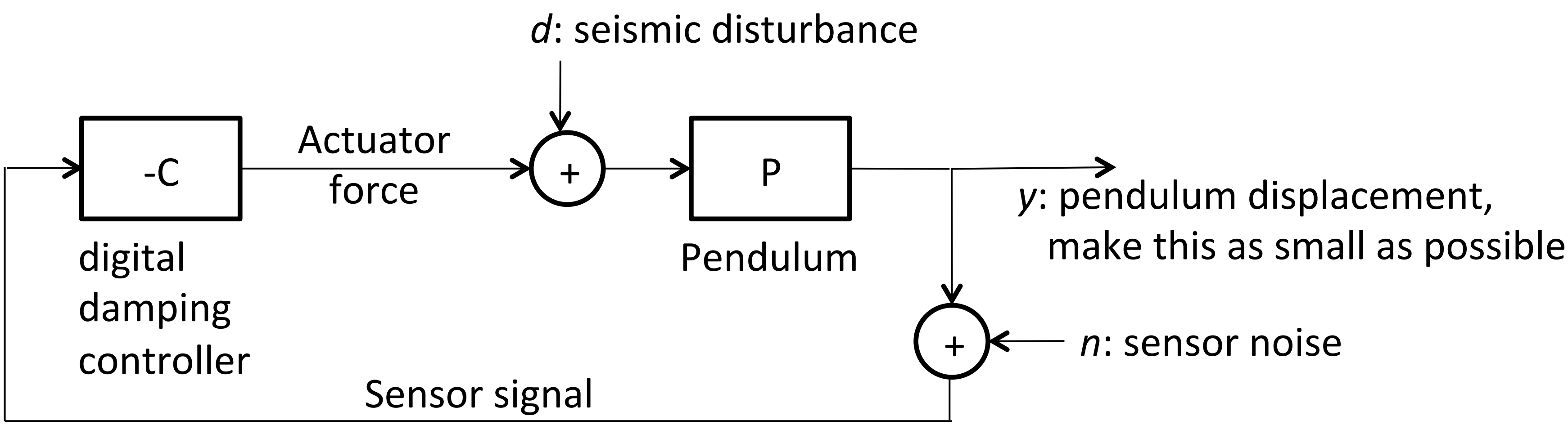
$$y = \frac{P}{1+PC}d + \frac{PC}{1+PC}n$$

Seismic contribution:
Want *PC* big to reduce resonant amplitude

Sensor noise contribution:
Want *PC* small to minimize transmission

Damping loop block diagram

- Frequency domain signals, i.e. Laplace or Fourier Transform



$$y = \frac{P}{1+PC}d + \frac{PC}{1+PC}n$$

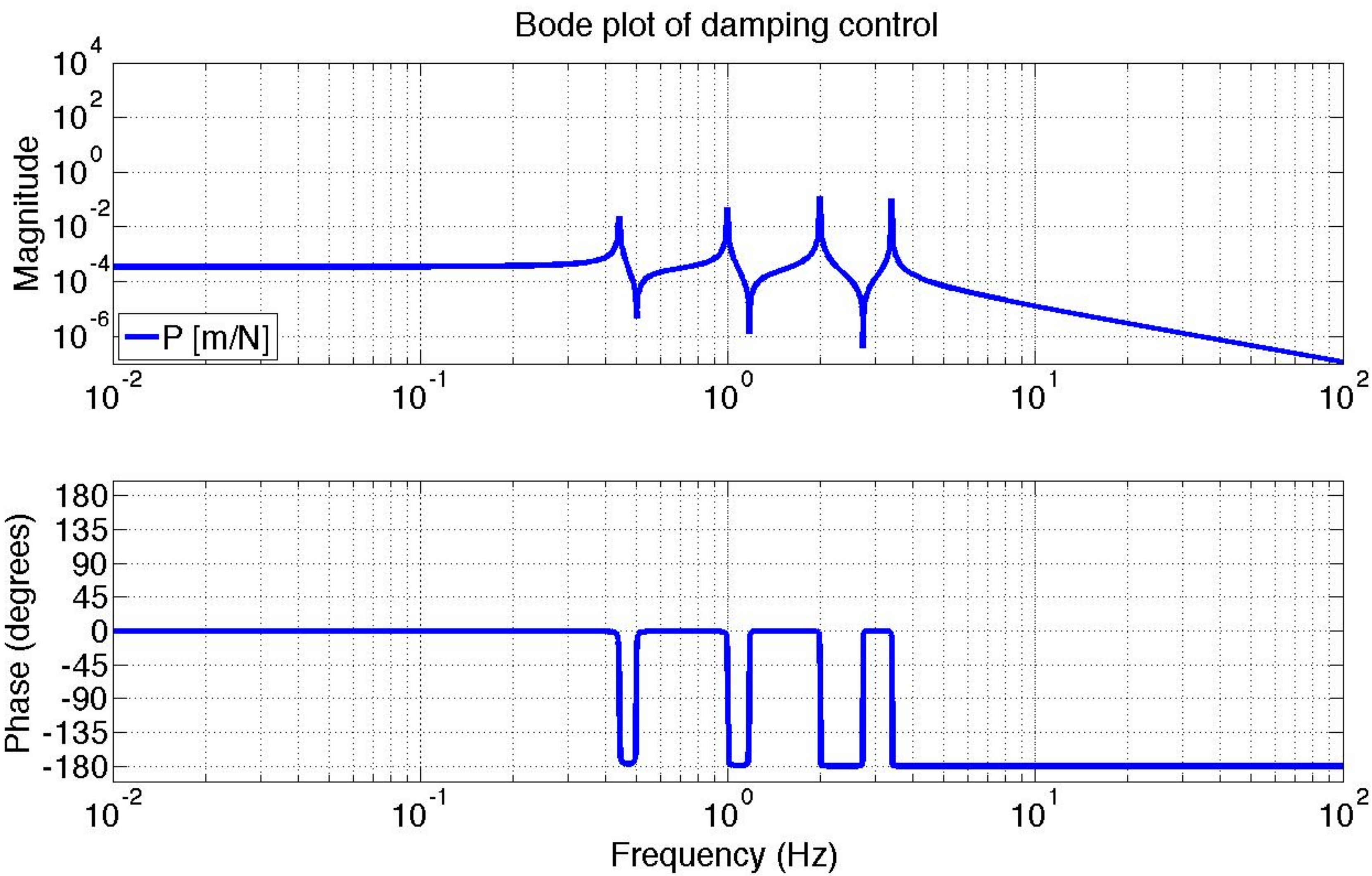
For a stable response

$$1+PC \neq 0 \Rightarrow PC \neq -1$$

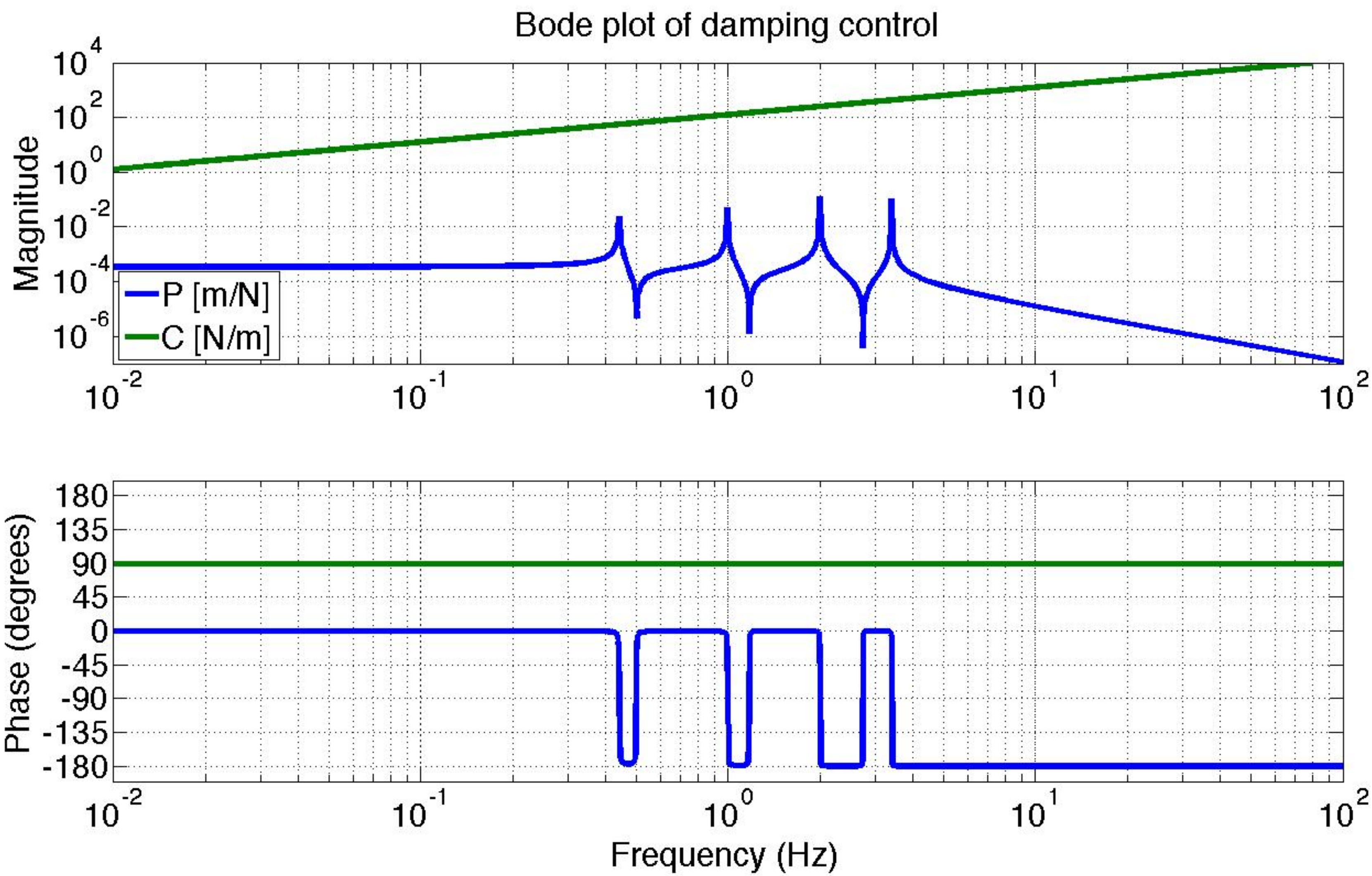
Seismic contribution:
Want *PC* big to reduce resonant amplitude

Sensor noise contribution:
Want *PC* small to minimize transmission

Top Mass Velocity Damping



Top Mass Velocity Damping



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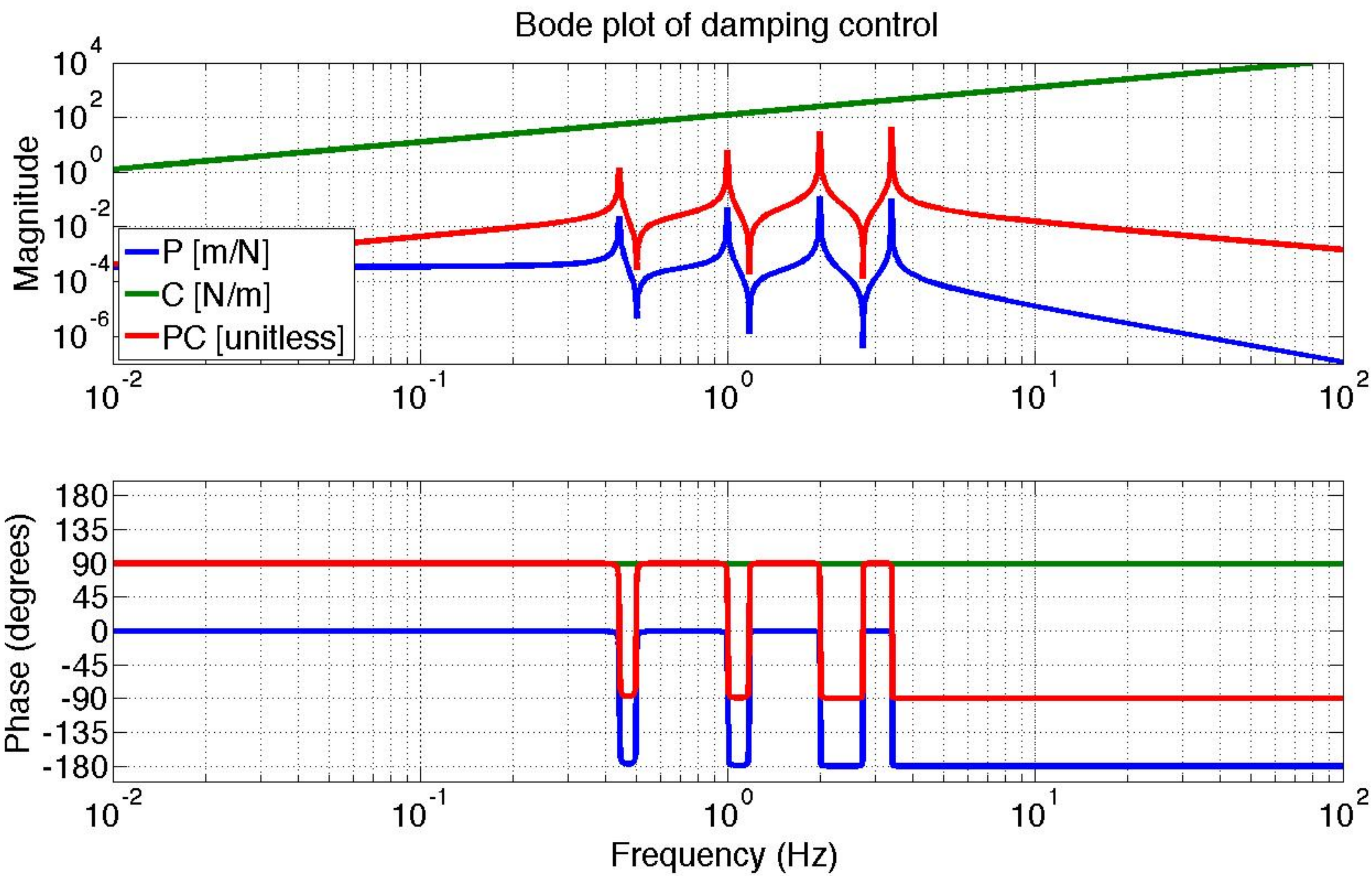

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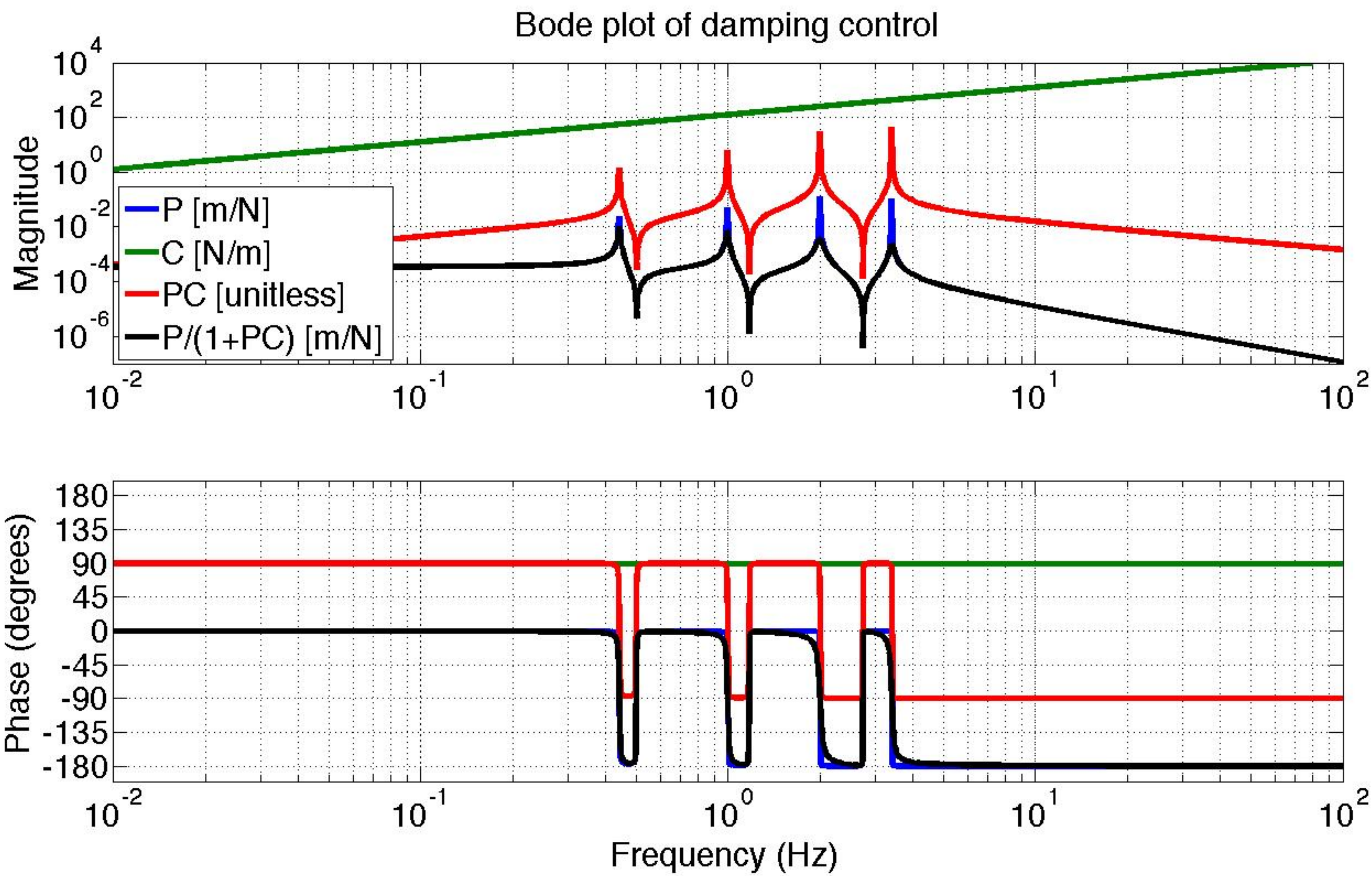
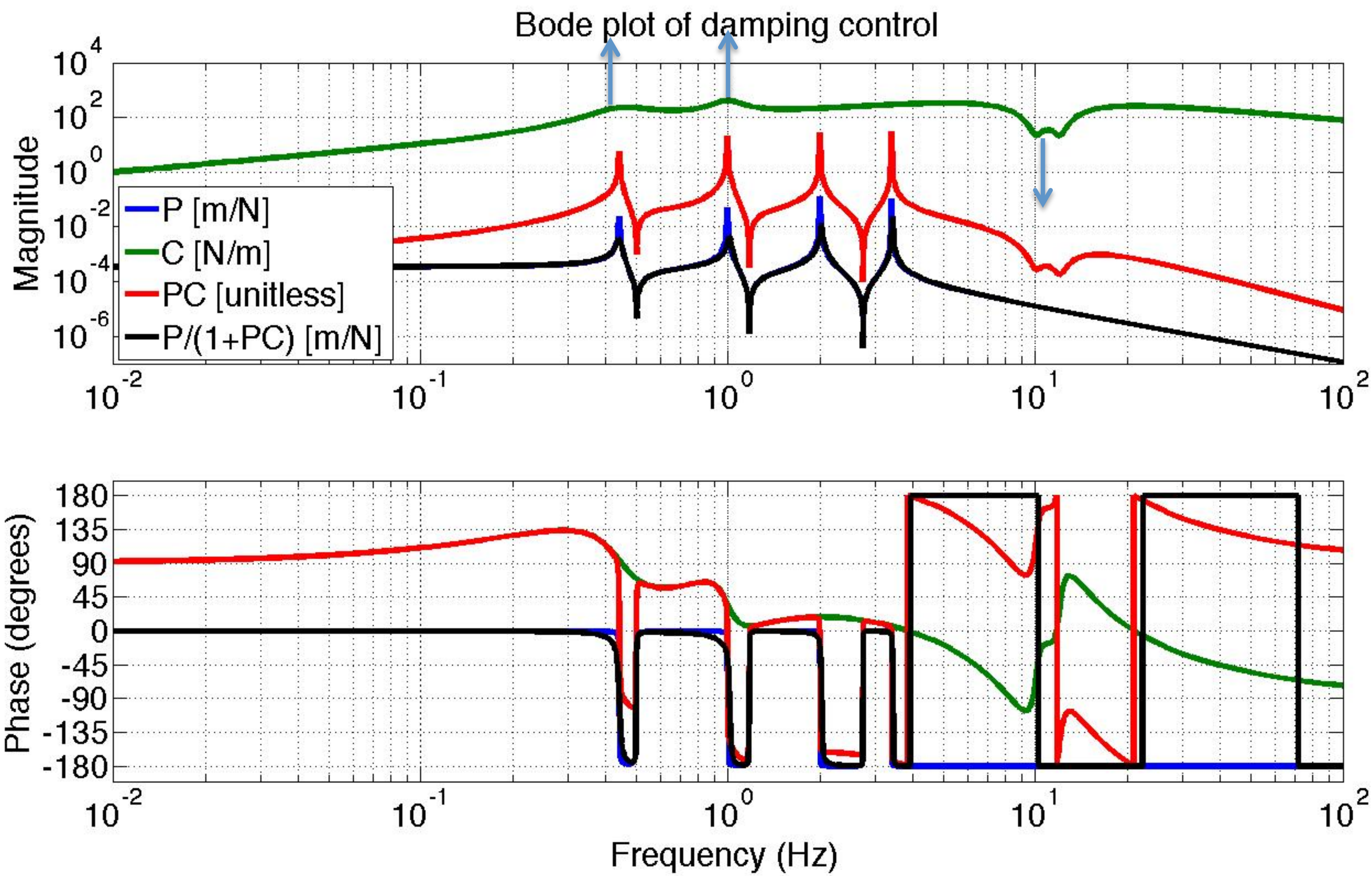
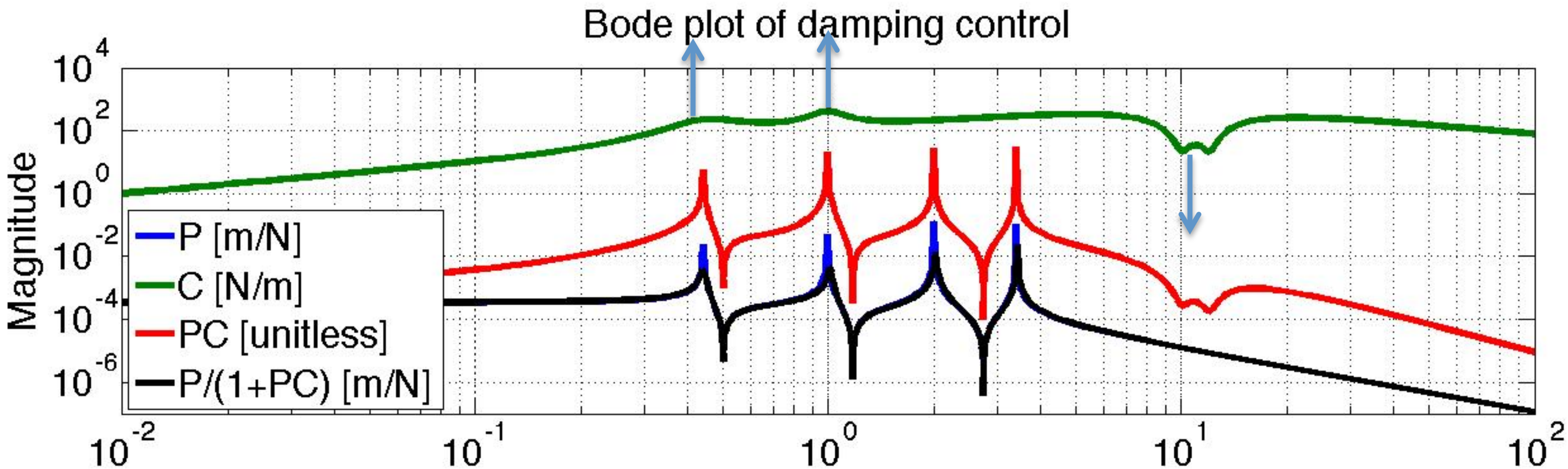


Tuned Top Mass Damping



Tuned Top Mass Damping



Cost parameters:
- Amount of damping
- Sensor noise amp.

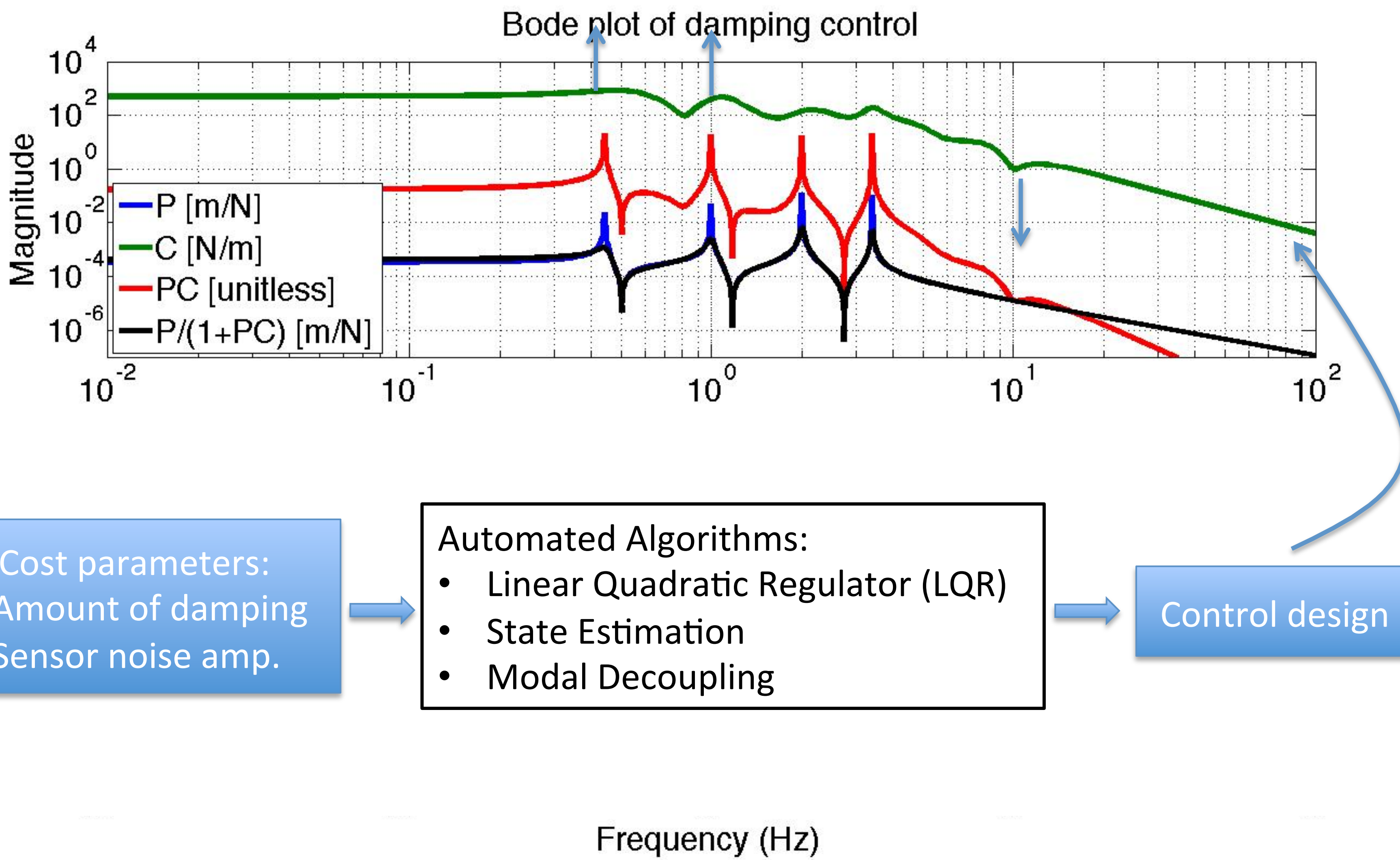
→

Automated Algorithms:
- Linear Quadratic Regulator (LQR)
- State Estimation
- Modal Decoupling

→

Control design

Optimized Top Mass Damping



Cost parameters:

- Amount of damping
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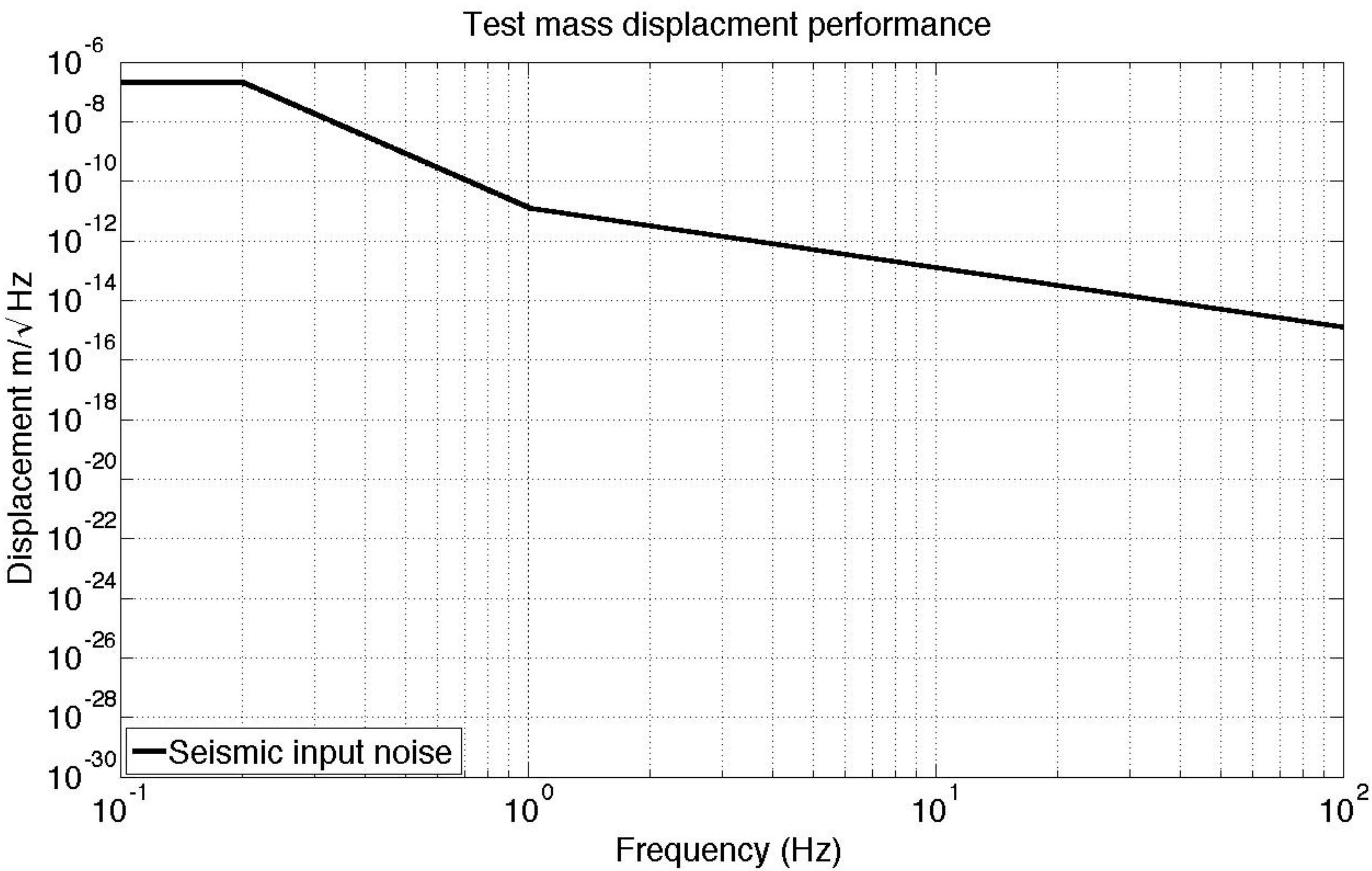
Automated Algorithms:

- Linear Quadratic Regulator (LQR)
- State Estimation
- Modal Decoupling

Control design

Ref: "Adaptive Modal Damping for Advanced LIGO Suspensions." Brett Shapiro, PhD Thesis, MIT Mechanical Engineering, 2012

Test Mass Noise Performance



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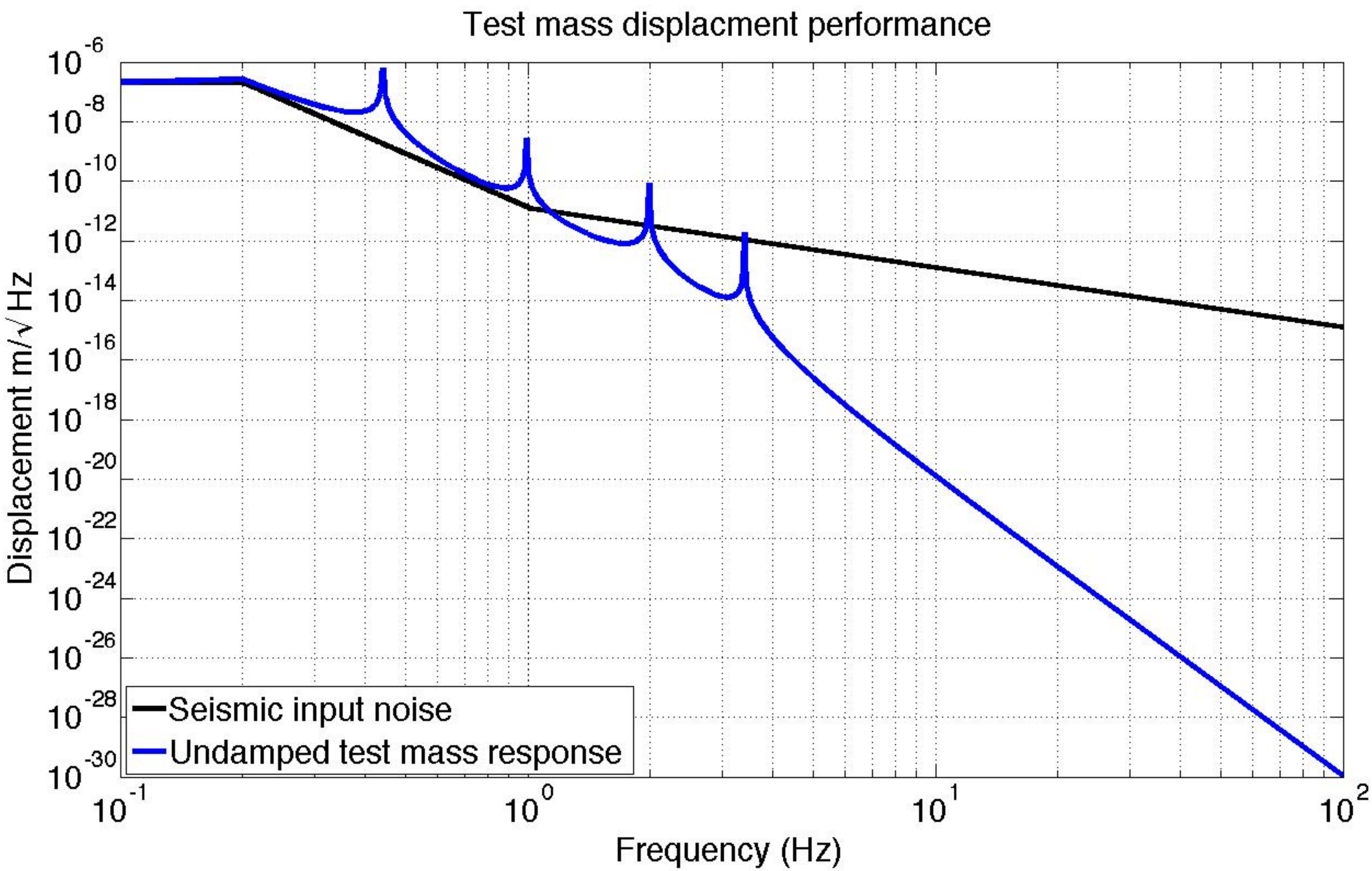

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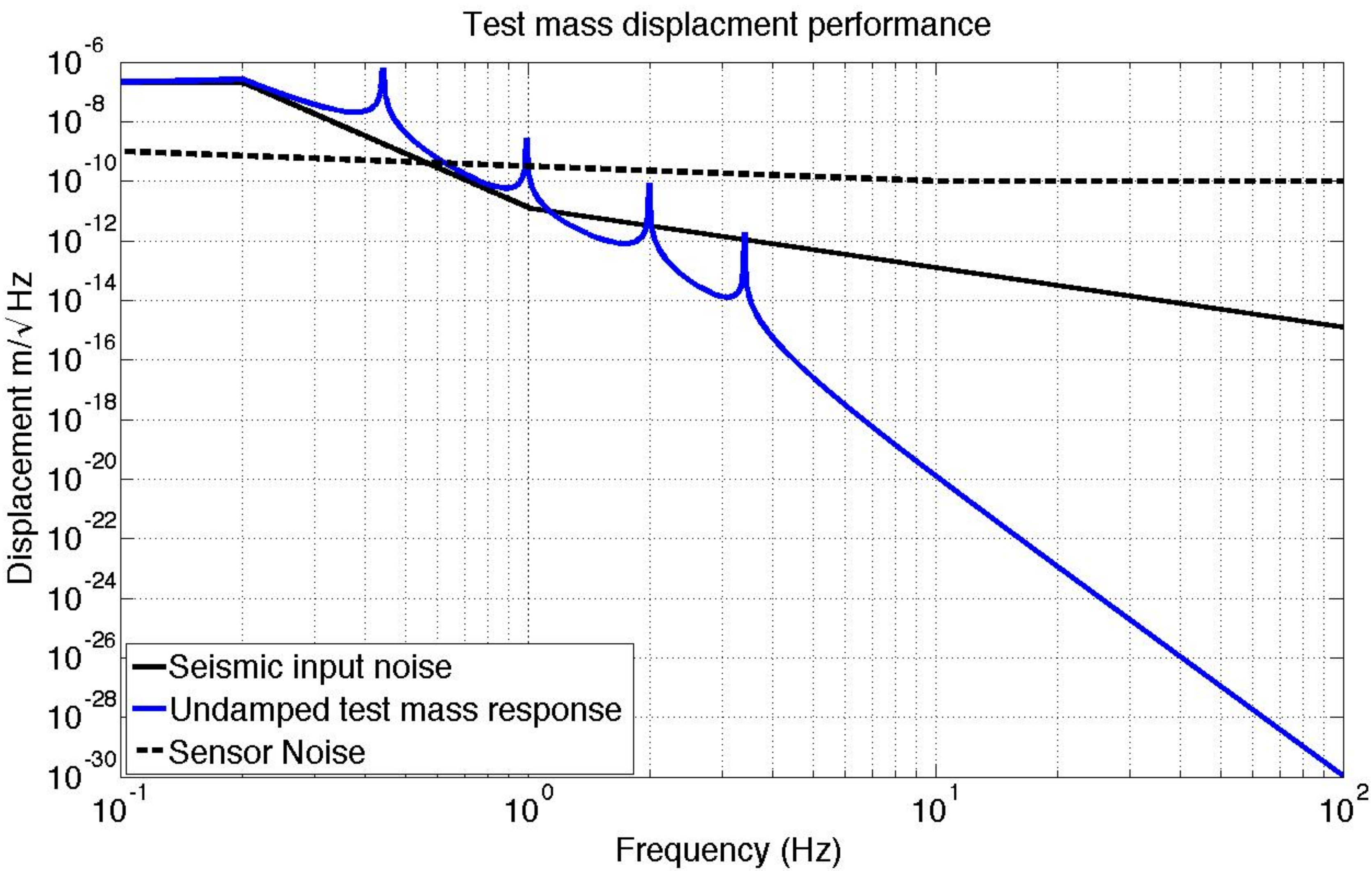

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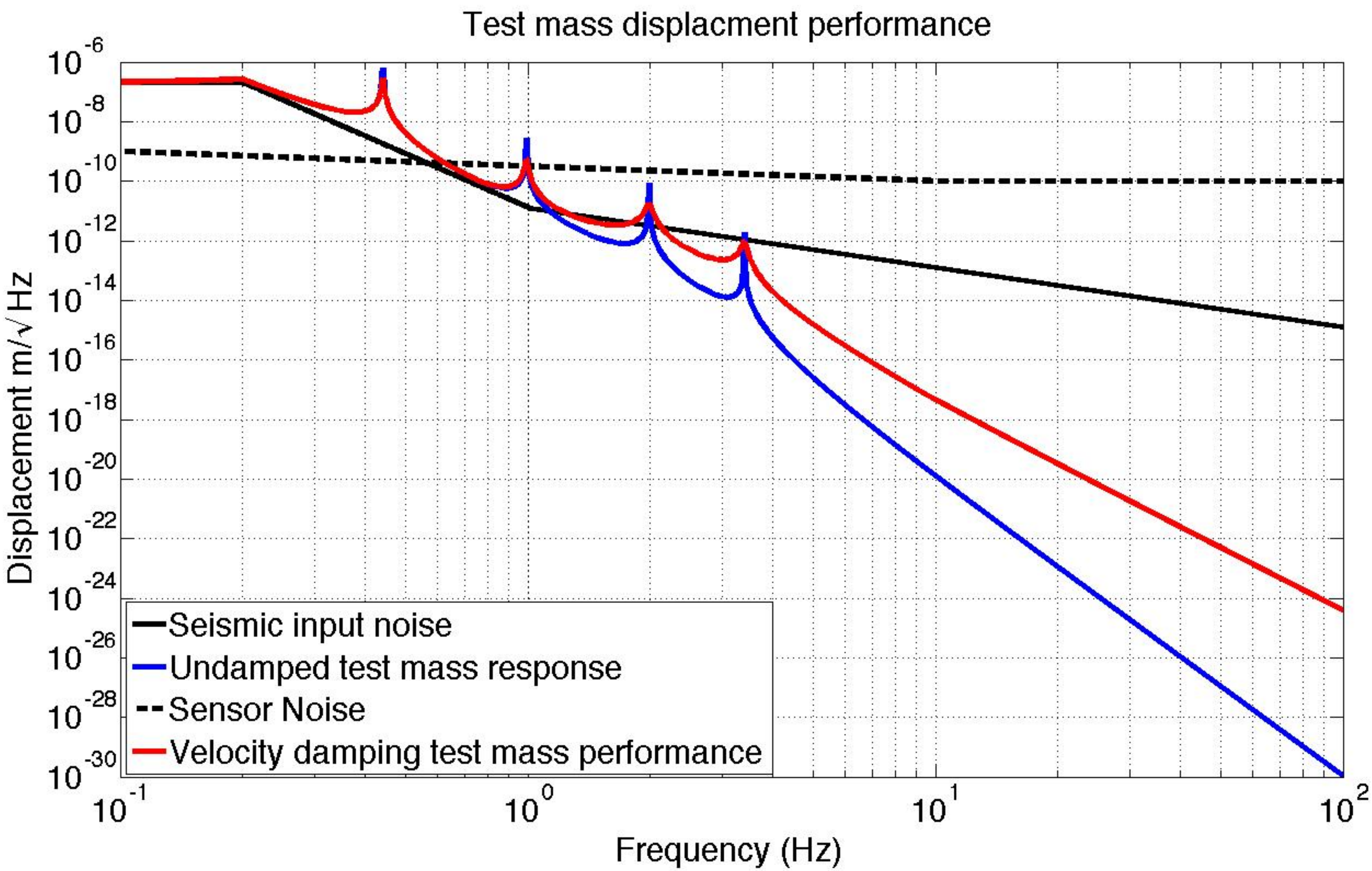

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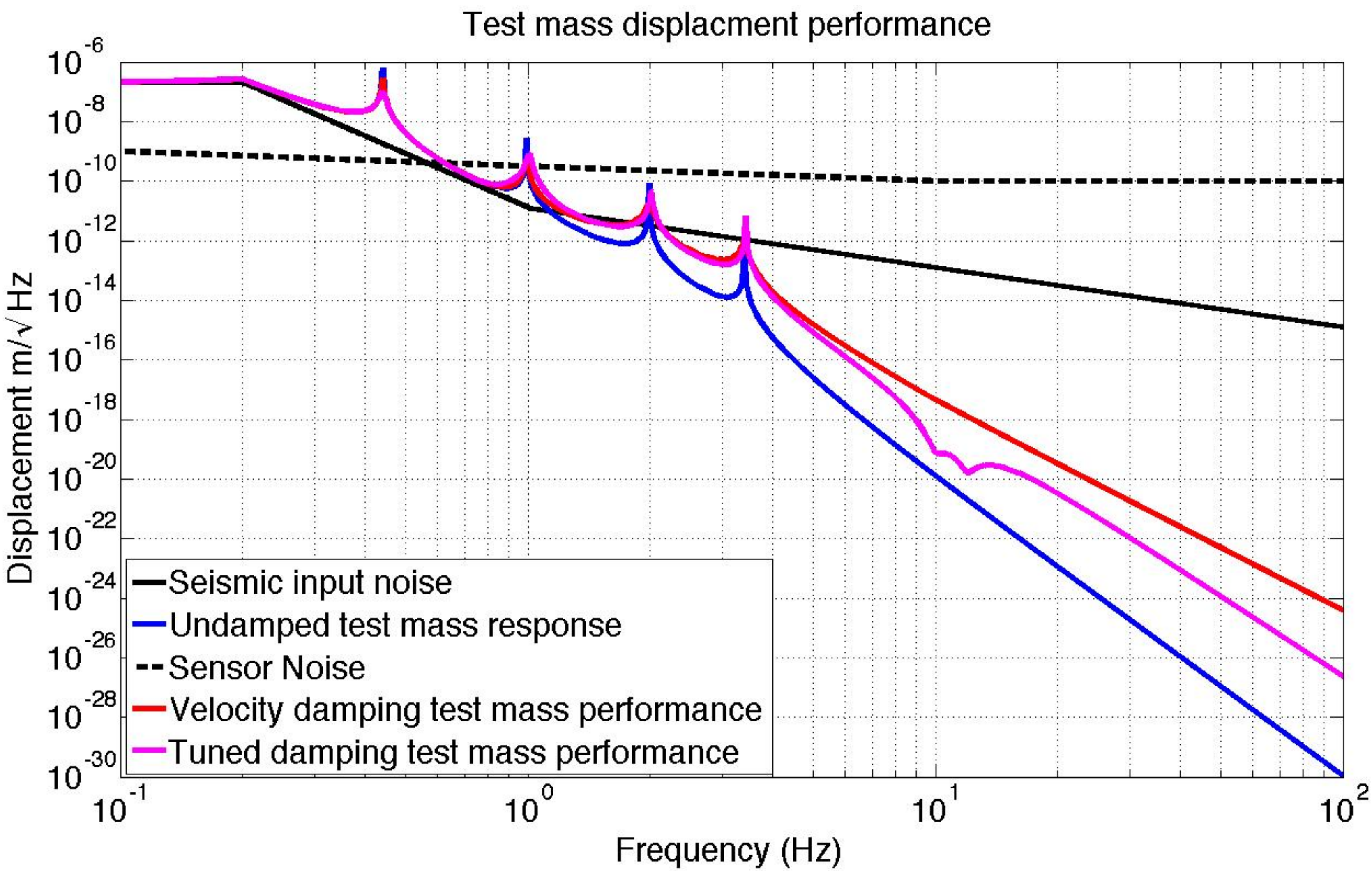

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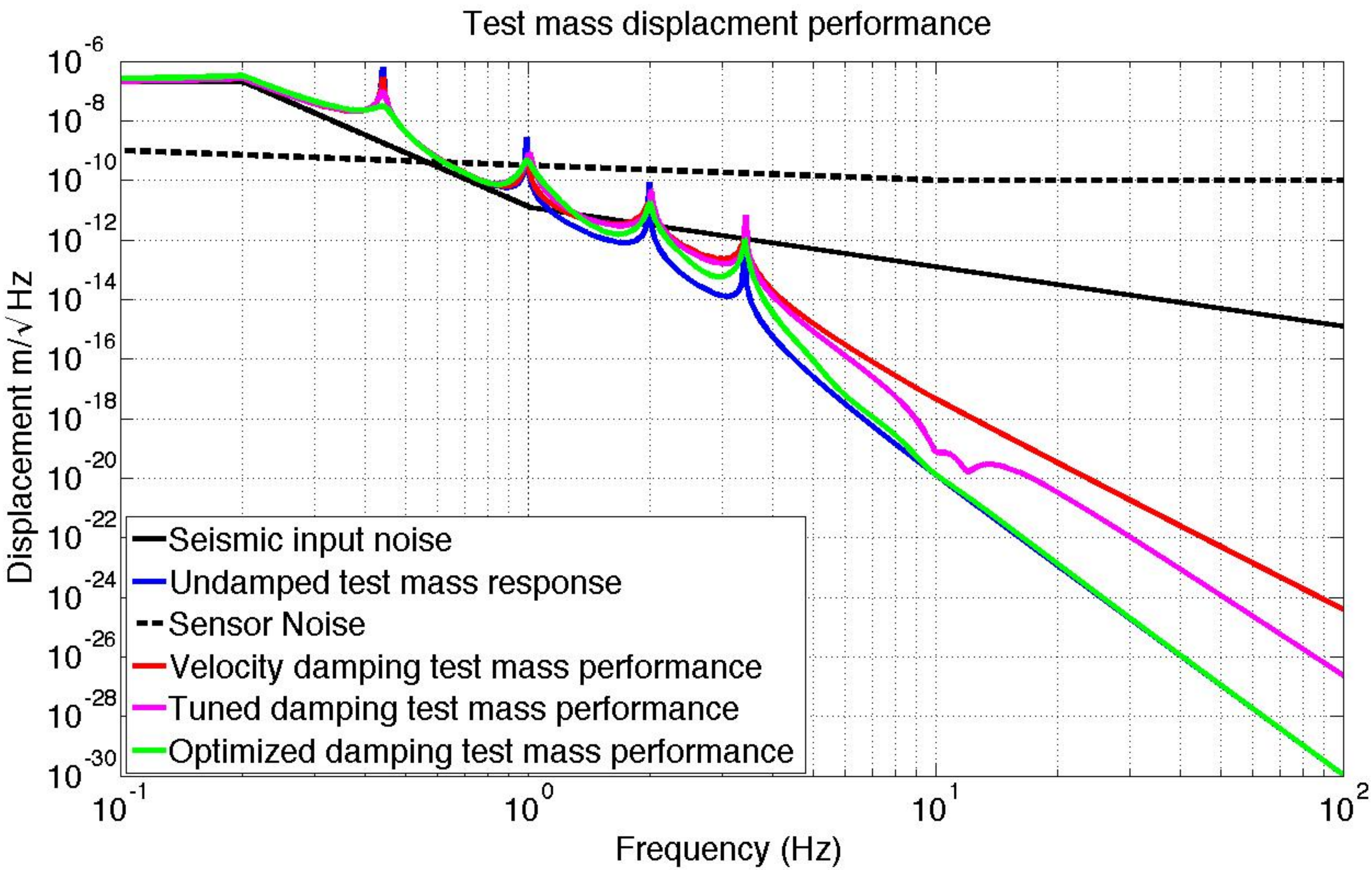
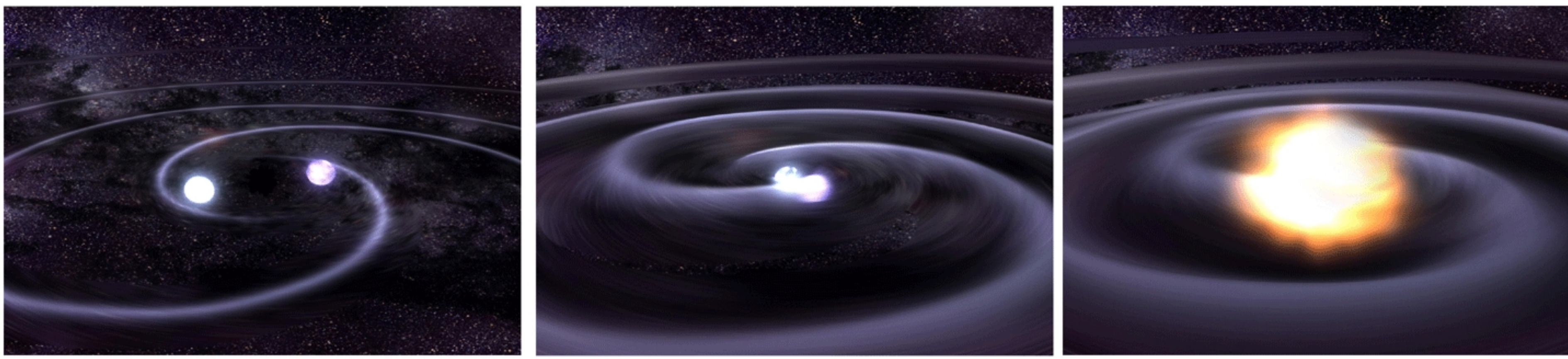


Binary Inspiral Sensitivity

$$r^2 = \frac{5c^{1/3}\mathscr{M}^{5/3}\theta^2}{96\pi^{4/3}\rho^2}\int_0^{f_{ISCO}}\frac{df}{f^{7/3}h^2}$$



Ref: LIGO doc T030276 - https://dcc.ligo.org/LIGO-T030276/public

Binary Inspiral Sensitivity

$$r^2 = \frac{5c^{1/3}\mathscr{M}^{5/3}\theta^2}{96\pi^{4/3}\rho^2}\int_0^{f_{ISCO}} \frac{df}{f^{7/3}h^2}$$

$$\mathscr{M} = \frac{G}{c^2}\frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$

$$f_{ISCO} = \frac{c^3}{6^{1.5}\pi G(M_1 + M_2)}$$

$c =$ the speed of light

$\mathscr{M} =$ intermediate variable called the chirp mass

$\theta =$ 1.77, accounts for the averaging over the binary positions and orientations

$p = 8$, the desired signal to noise ratio

$f =$ frequency in Hz

$h =$ the strain sensitivity of the inteferometer ←

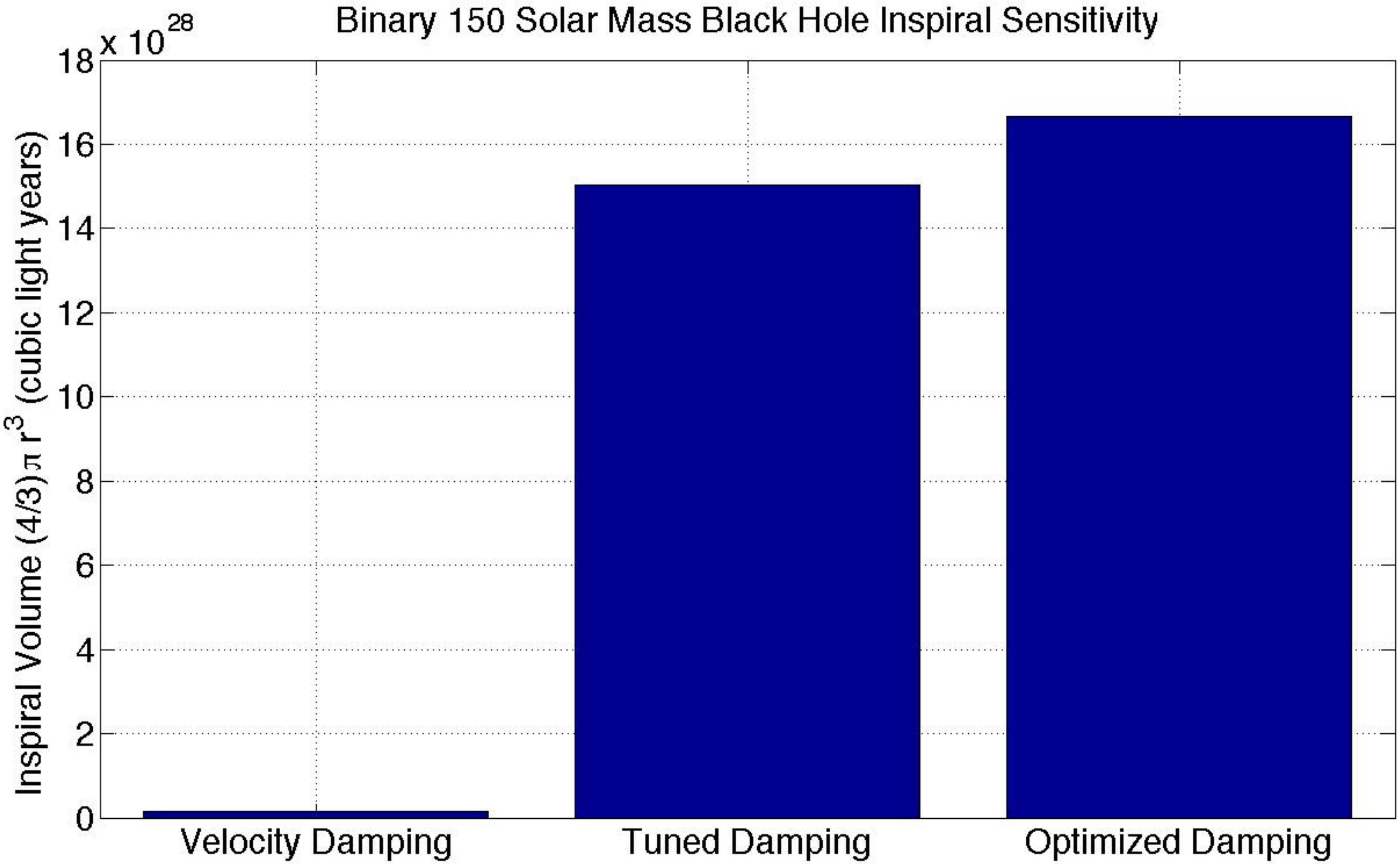
$G =$ gravitational constant

M_1 and M_2 are the masses of the inspiraling objects

$f_{ISCO} =$ frequency of the Inner-most Stable Circular Orbit

Ref: LIGO doc T030276 - https://dcc.ligo.org/LIGO-T030276/public

Observable Range to Binary Inspirals



Conclusions

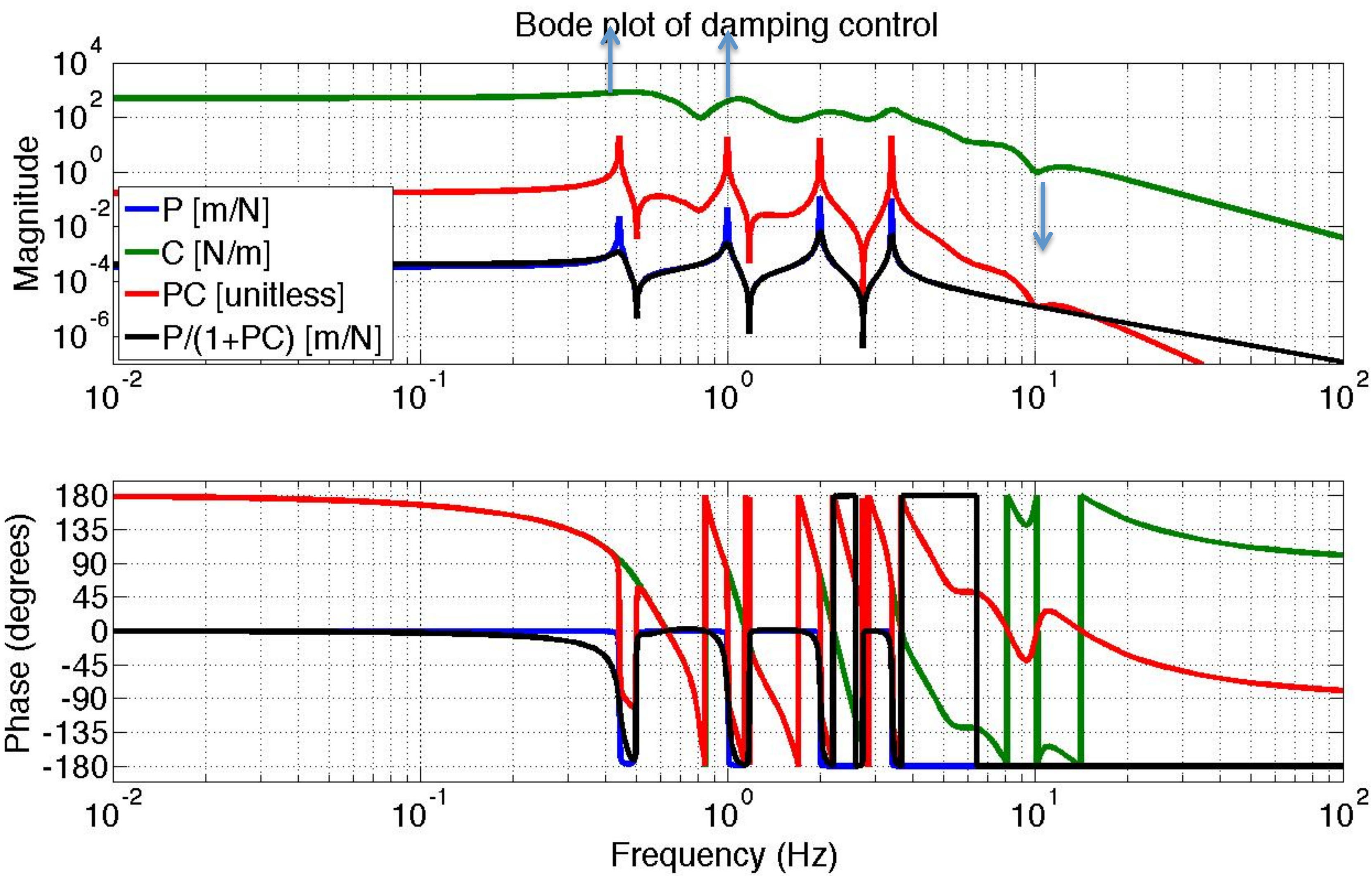
- Many control systems are needed to operate the interferometer

- Good controls are needed for good science

Questions?

Backups

Optimized Top Mass Damping



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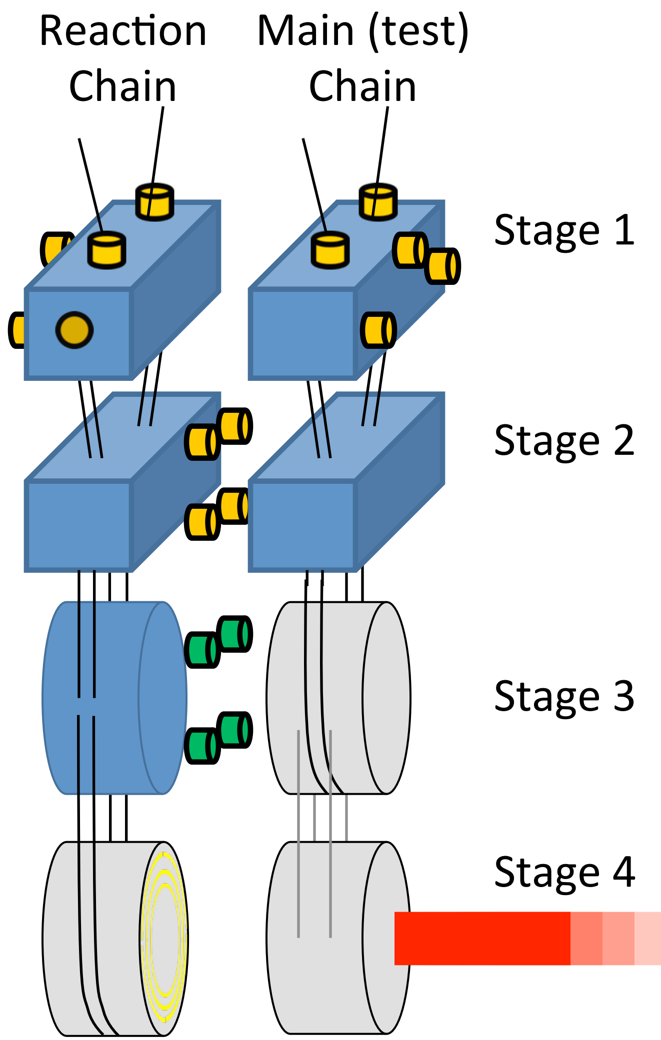
Quadruple Pendulum



Purpose

- Test mass (stage 4) isolation.

the test mass consists of a 40 kg high reflective mirror

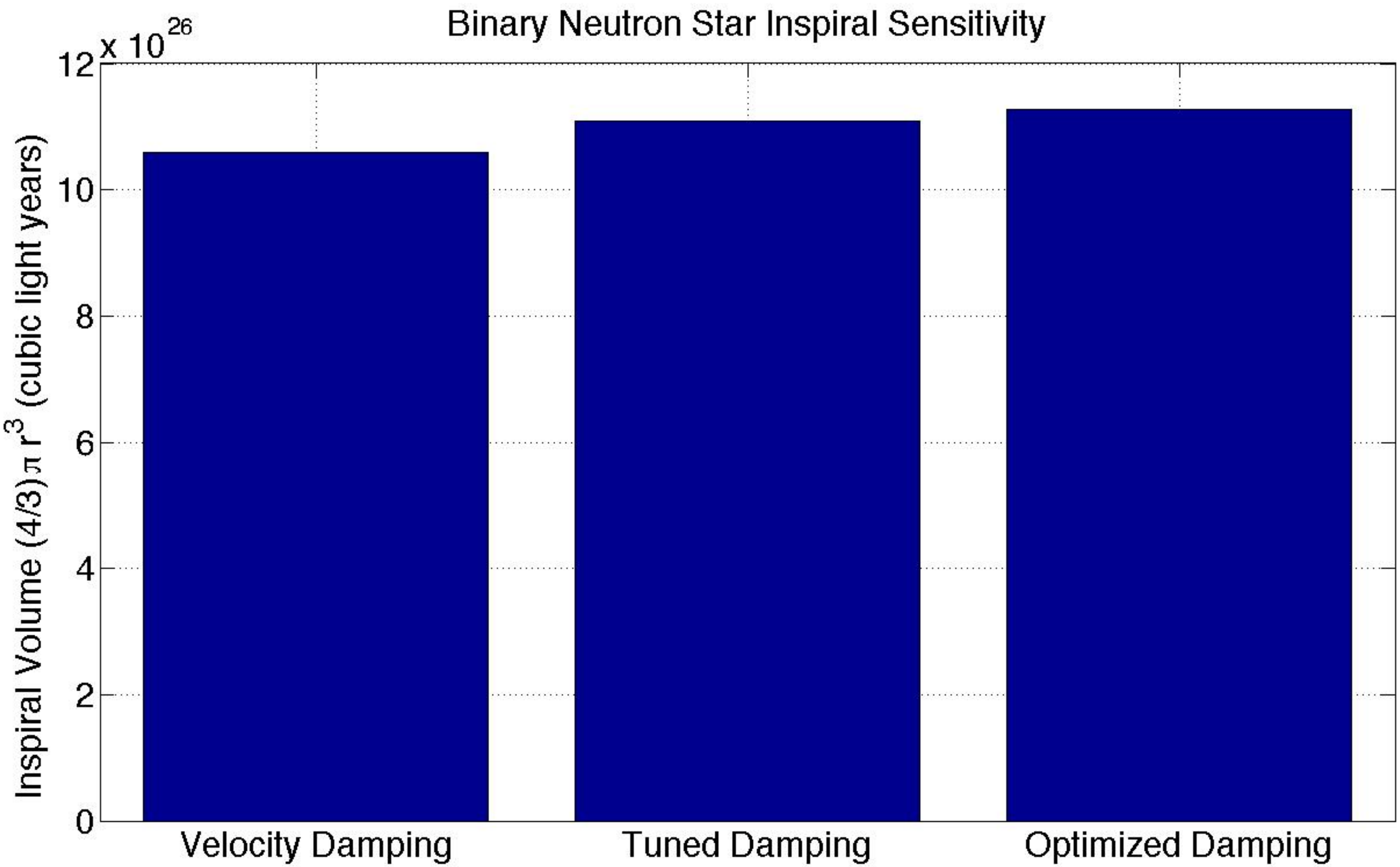
Control

- Damping - stage 1
- Cavity length - all stages

Sensors/Actuators

- BOSEMs at stage 1 & 2
- AOSEMs at stage 3
- Opt. levs. and interf. sigs. at stage 2
- Electrostatic drive (ESD) at stage 4

Observable Range to Binary Inspirals



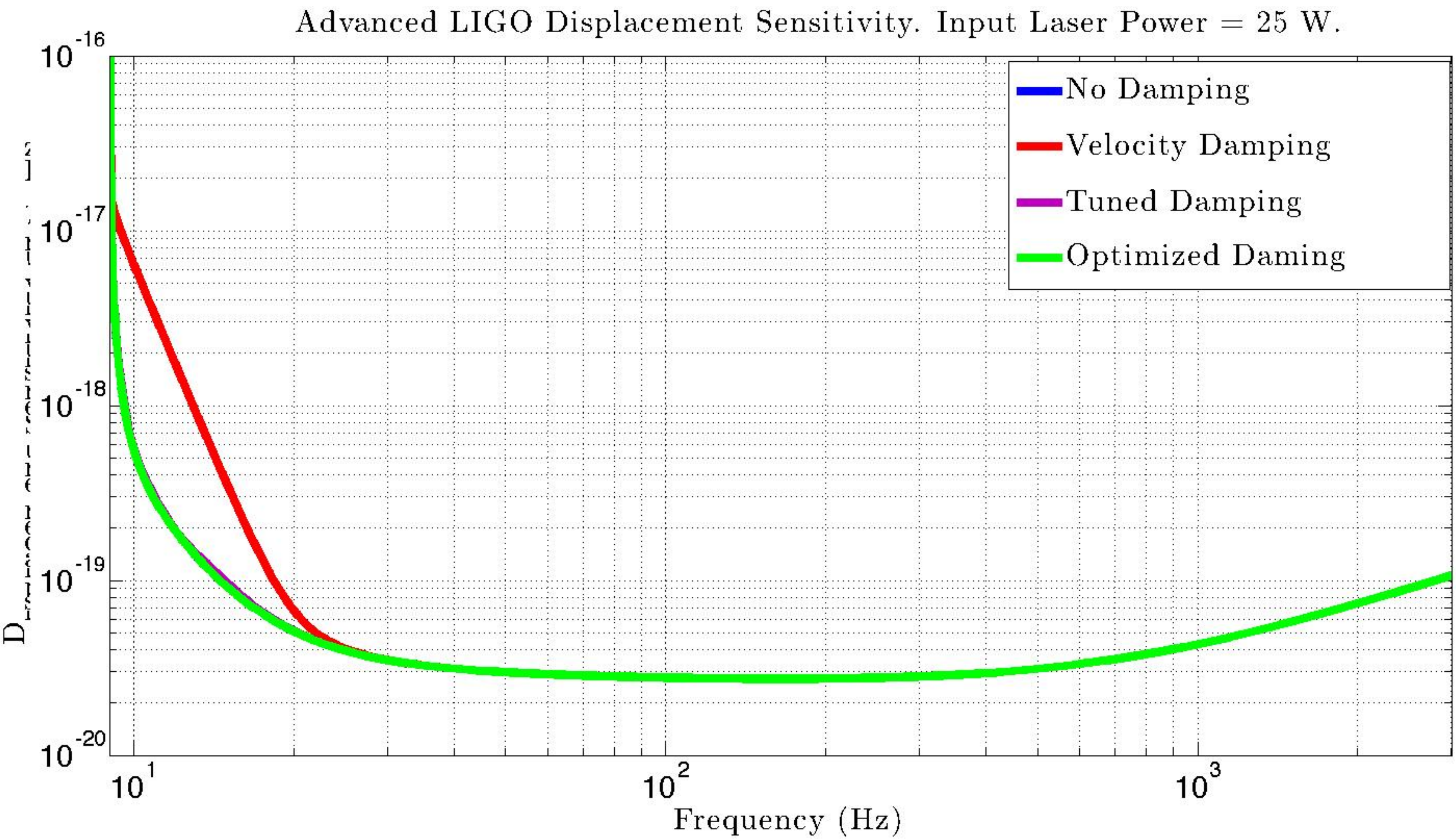
Advanced LIGO Timeline

Livingston, LA

Hanford, WA

- Last core optics — March 2014
- Full lock testing — Aug-Sept 2014
- 1st science run — Sept-Dec 2015
- GW astronomy — Soon after
- Build LIGO III — Far after

GW sensitivity with various damping



Observable Range to Binary Inspirals

25 W input laser power

Damping type	Binary neutron star range (Mpc)	Binary 150 solar mass black hole range (Mpc)
Velocity damping	143	229
Tuned damping	153	1331
Optimized damping	154	1396

125 W input laser power

Damping type	Binary neutron star range (Mpc)	Binary 150 solar mass black hole range (Mpc)
Velocity damping	194	225
Tuned damping	197	1012
Optimized damping	198	1047

LIGO Scientific Collaboration

LIGO

LSC

University of Maryland 1856

Michigan

University of Strathclyde

ACIGA

Loyola University New Orleans

Leland Stanford Junior University 1891

Montana State University

University of Washington

ANU
THE AUSTRALIAN NATIONAL UNIVERSITY

Syracuse University
Suos cultores scientia coronat
Founded AD 1870

Montclair State University

清華大學
Tsinghua University

Trinity University

San José State University

University of Wisconsin
UWMilwaukee

부산대학교
PUSAN NATIONAL UNIVERSITY

The University of Western Australia

1754

University of Glasgow

NASA
GODDARD SPACE FLIGHT CENTER

Università degli Studi del Sannio

LSU

UTB TSC

R·I·T

The University of Melbourne

KiSTi

Andrews University

Massachusetts Institute of Technology

Southeastern Louisiana University

Moscow State University

California Institute of Technology 1891

Northwestern University

Hanyang University 한양 1939

University of Cambridge

The University of Adelaide Australia

PAN

The University of Texas at Austin

GEO 600

Embry-Riddle Aeronautical University

University of Massachusetts Amherst 1863

Lund University

ISI

University of New Hampshire

PennState 1855

Coll. Carleton Northfield, Minn. A.D. 1866

Cardiff University

California State University Fullerton

Washington State University

국가수리과학연구소
National Institute for Mathematical Sciences

The University of Mississippi 1848

Charles Sturt University

Universitat de les Illes Balears

UF University of Florida

PI Perimeter Institute

CITA-ICAT

Seoul National University

University of Rochester

NAOJ

University of Southampton

Hobart College

William Smith College

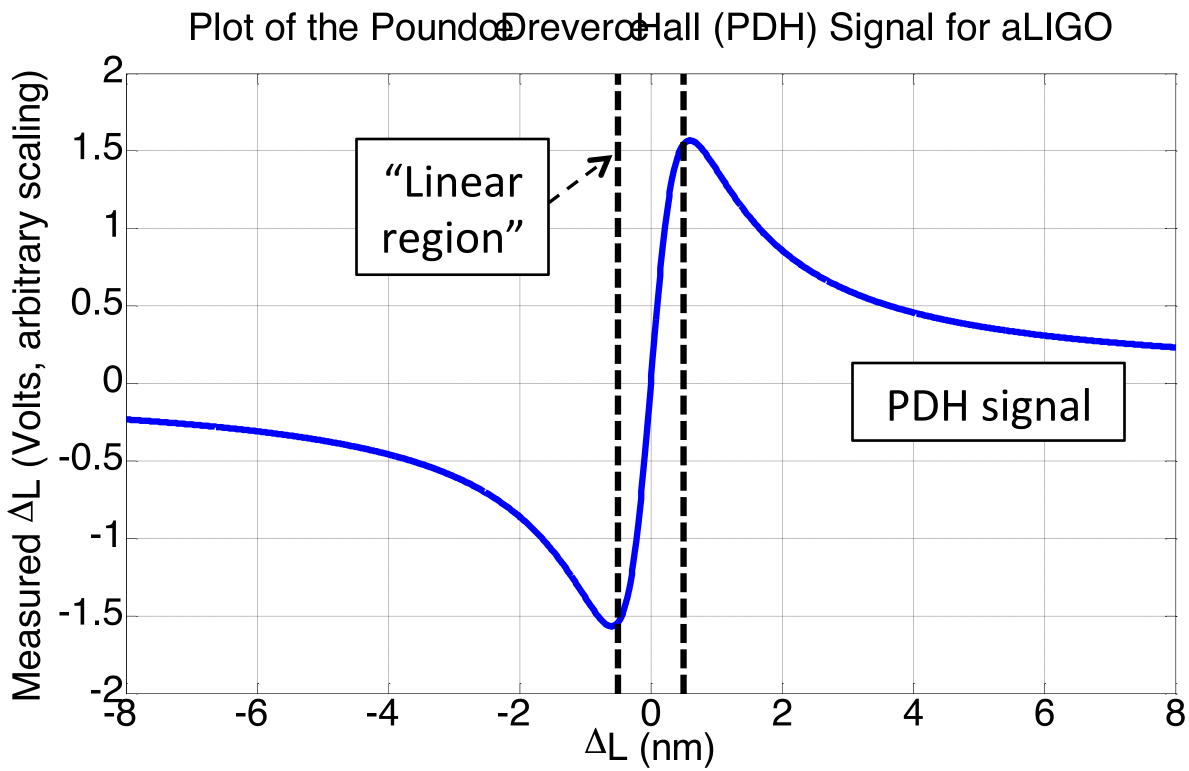
University of Minnesota

Universität Hannover

Southern University Agricultural & Mechanical College

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Problem 3: Cavity Signal



The PDH signal for a 4 km aLIGO Fabry-Perot cavity with mirror power transmissions of 1.4% and 7.5 ppm. The cavity finesse is 445. The linear region between the dashed lines is 1 nm wide.

$$PDH = C\frac{\sin\left(4\pi\frac{\Delta L}{\lambda}\right)}{1+\left[\frac{2F}{\pi}\sin\left(2\pi\frac{\Delta L}{\lambda}\right)\right]^2}$$

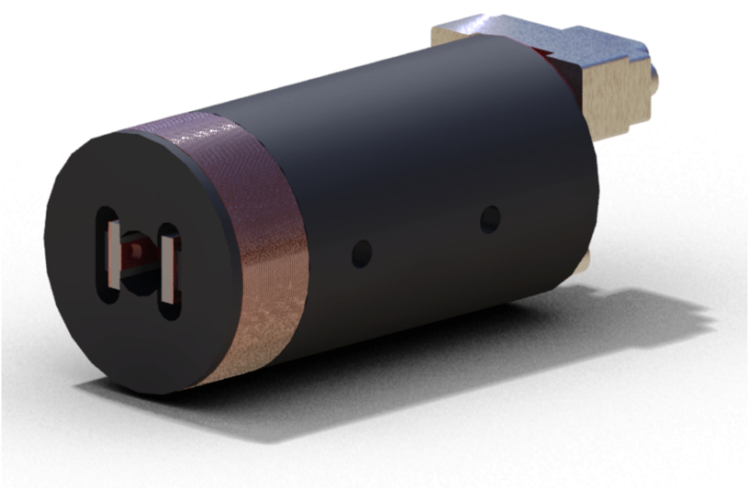
F = cavity finesse = 445

λ = laser wavelength = 1064 nm

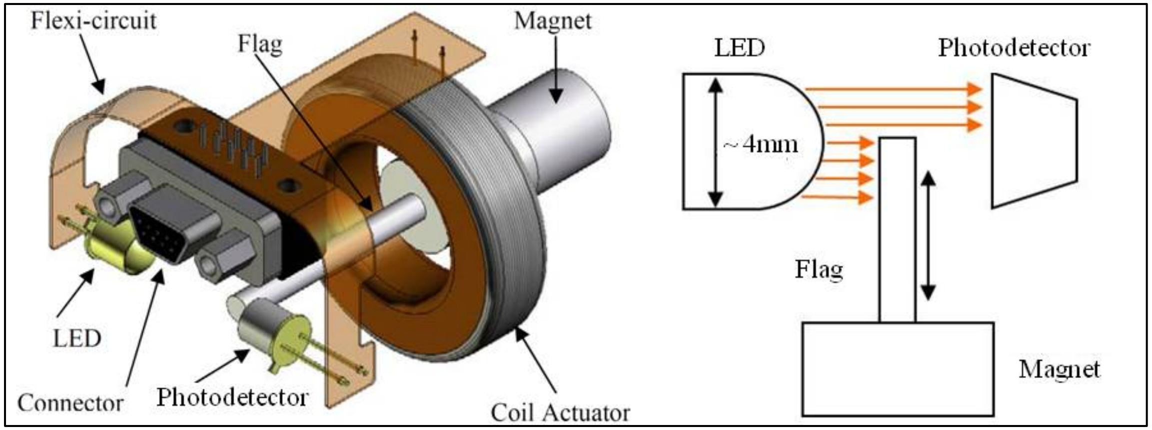
C = arbitrary electronic scaling

Backups: Optical Sensor ElectroMagnet (OSEM)

Birmingham OSEM (BOSEM)



Advanced LIGO OSEM (AOSEM)
- modified iLIGO OSEM

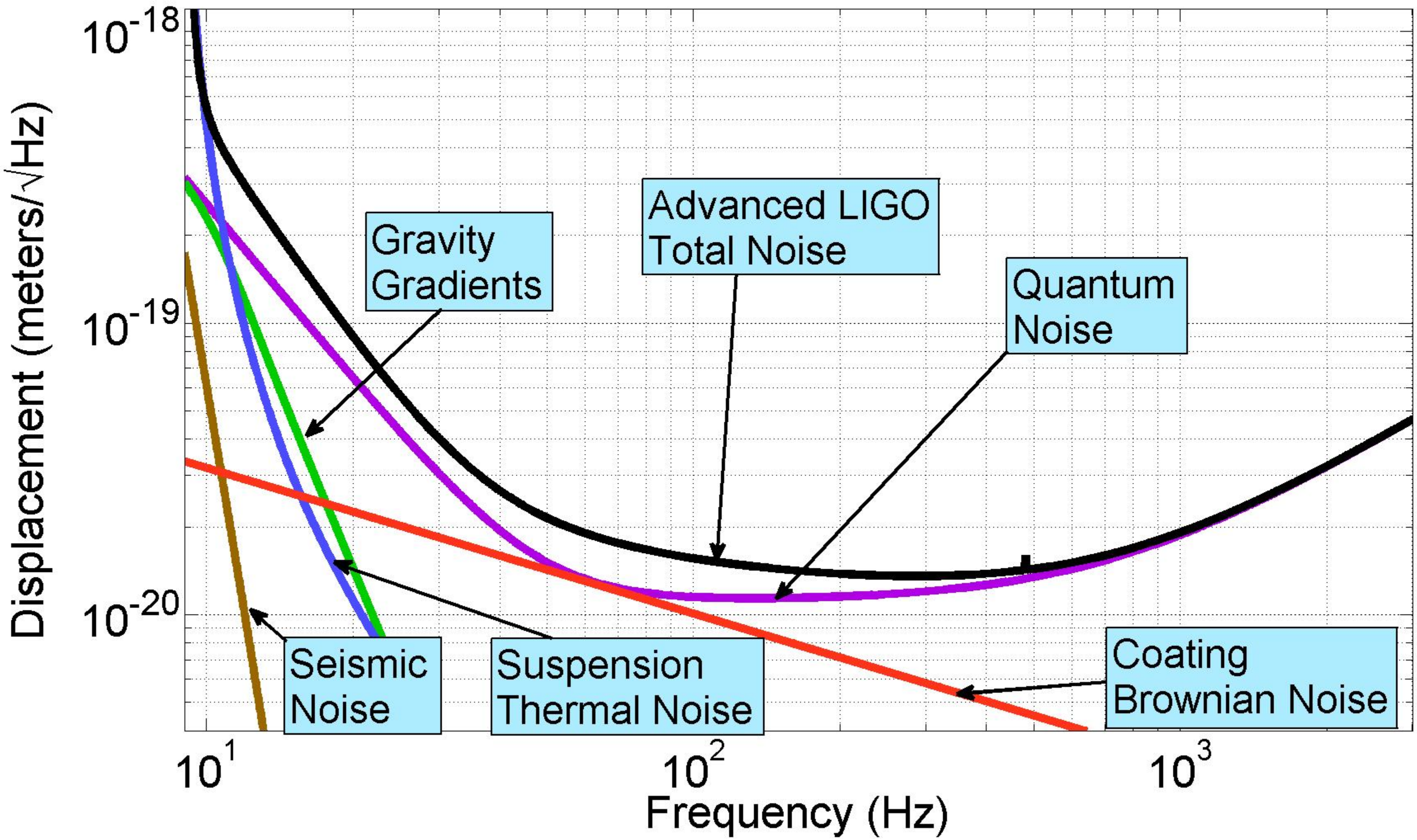


BOSEM Schematic

Magnet Types (M0900034)

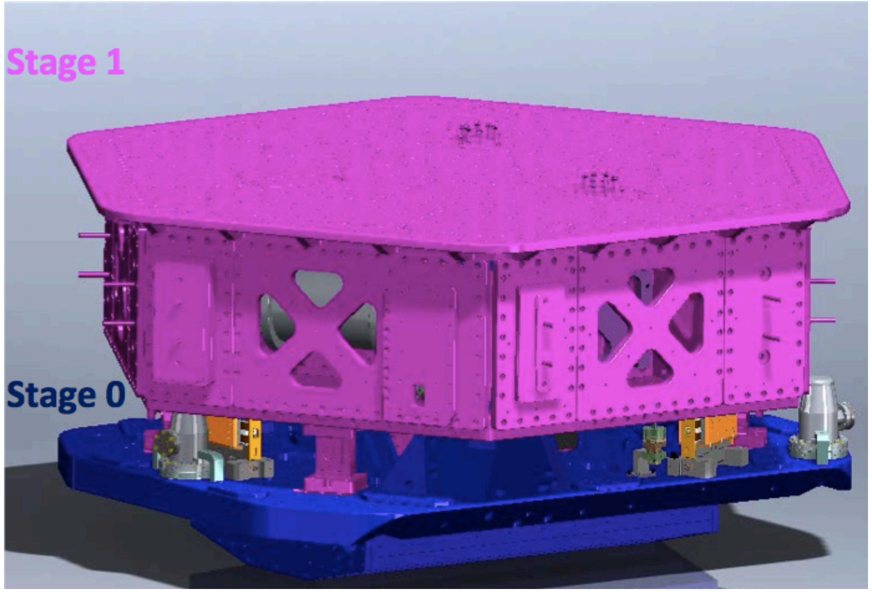
- BOSEM – 10 X 10 mm, NdFeB , SmCo
  10 X 5 mm, NdFeB, SmCo
- AOSEM – 2 X 3 mm, SmCo
  2 X 6 mm, SmCo
  2 X 0.5 mm, SmCo

Predicted Advanced LIGO Sensitivity

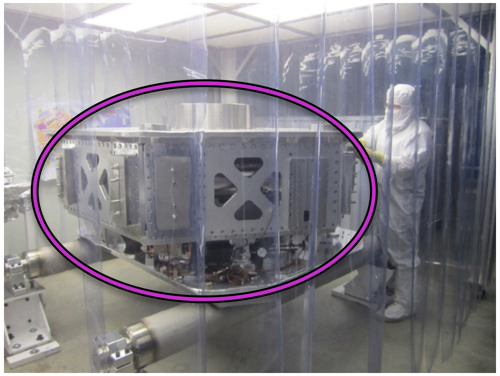


Assembly, Installation & Performance

- HAM-ISI:
  - Single Stage
  - Passive Isolation above Natural frequency: 1.8 Hz
  - Active Isolation ~ .1 Hz - 35 Hz



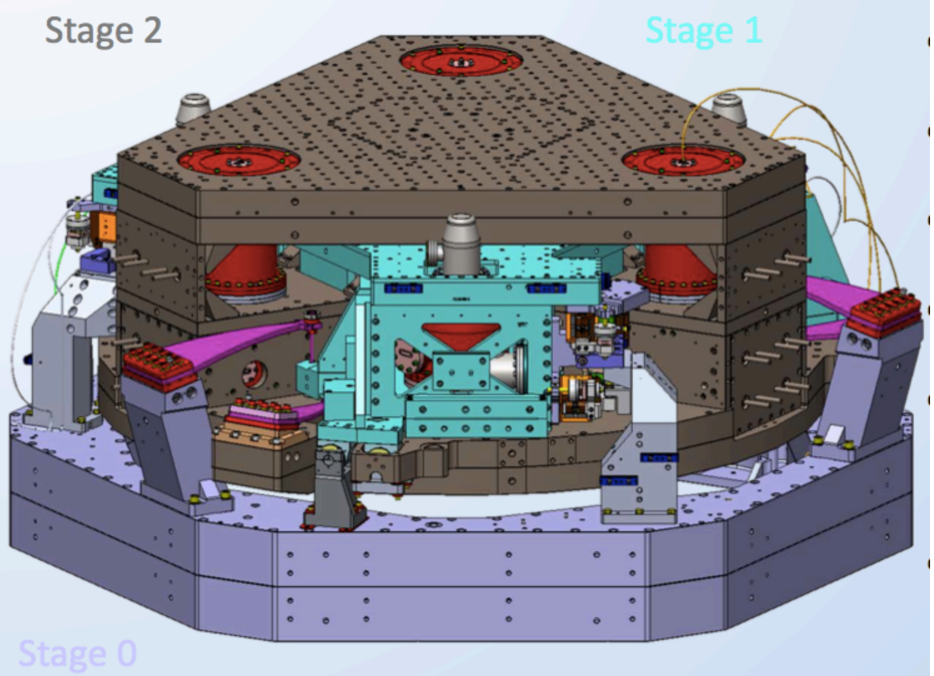
- Installed:
  - LHO: 5/5
  - LLO: 5/5



Courtesy of C. Ramet

Assembly, Installation & Performance

- BSC-ISI:
  - Two Stages
  - Passive isolation above Natural Frequencies: 1 Hz - 7 Hz
  - Active Isolation ~.1 Hz – 40 Hz



- Installed:
  - LHO: 5/5
  - LLO: 5/5

Courtesy of C. Ramet

Assembly, Installation & Performance

- HEPI:
  - Single Stage
  - Hydraulic actuation
  - Isolation bandwidth 0.1 Hz - 10 Hz

- Installed:
  - LHO: 11/11*
  - LLO: 11/11

*: A few HEPI still need to be wired up

Courtesy of
C. Ramet