Stabilization Techniques at LIGO

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Gravitational wave detection

Gravitational waves

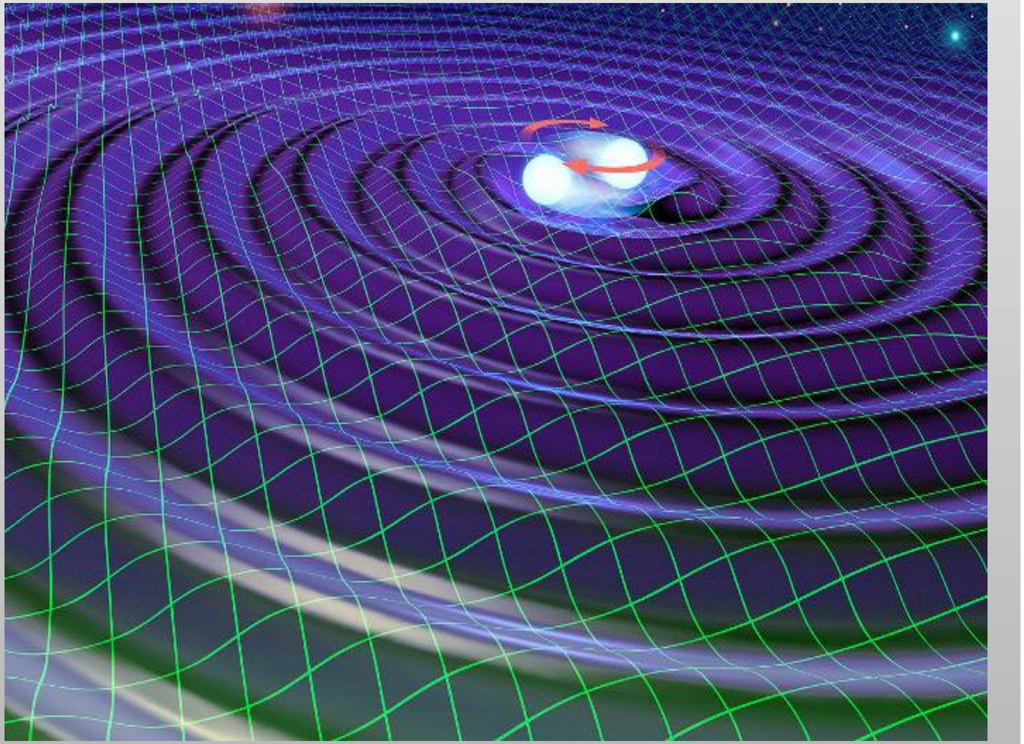
- Wave of **space-time** curvature

- Radiated from astrophysical sources

- Existence confirmed by the radio observation of binary pulsars
  (1993 Nobel Prize)

- Direct detection:
  Not yet achieved by mankind

- Direct detection:
  Test of GR, Astrophysics of
  Neutron star, Black Hole,
  Early universe, etc.



Gravitational wave detection

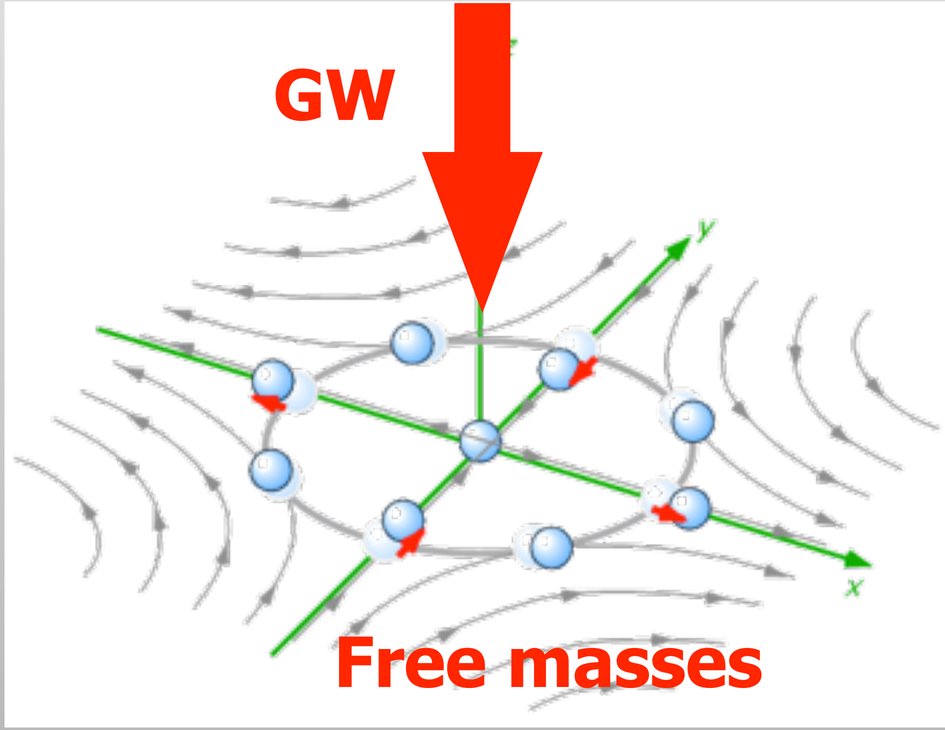
= Precision length measurement with a laser interferometer

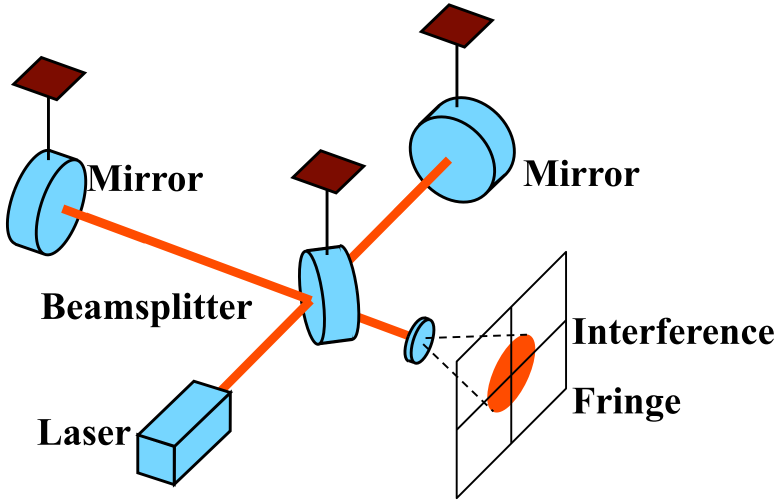
- Interaction of GWs and free masses

Proper distances between the free masses change (quadrupole mode)

- Michelson interferometer with suspended mirrors

Sensitive to the differential change of the arm path lengths





Gravitational wave detection

LIGO observatories

- LIGO (Laser Interferometer Gravitational-wave Observatory)
- Advanced LIGO Project: 4-km interferometers at two sites
  The longer, the better

- Target displacement to be detected: $\sim 10^{-20}$ m/Hz$^{-1/2}$

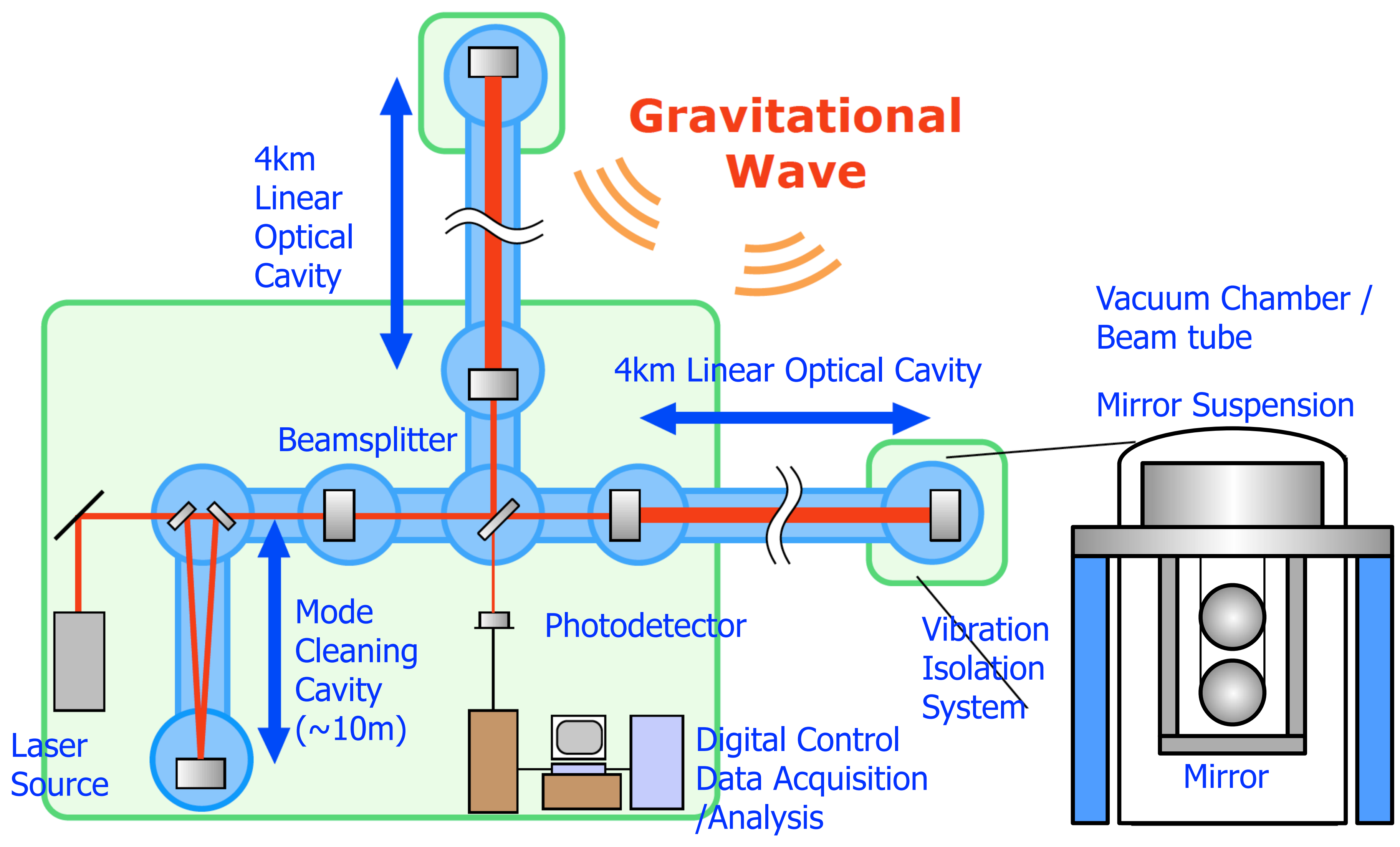
Any disturbance of the mirror can't be separated from GW signals

Hanford, Washington

Livingston, Louisiana

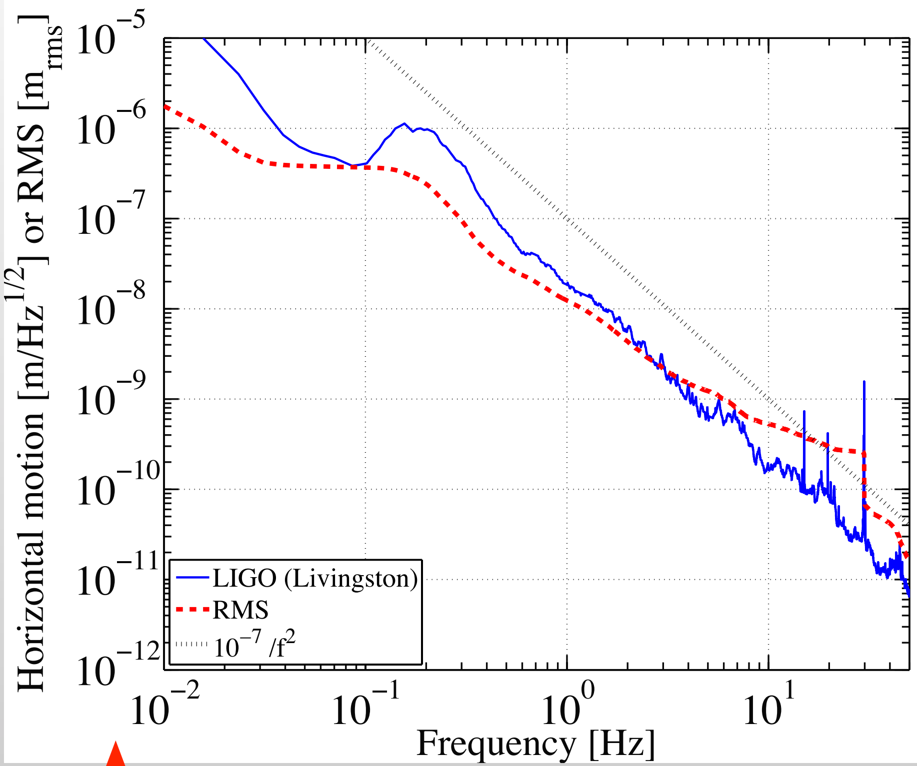
Elements of the GW detector

Detailed (yet simplified) overview of the detector



Evaluation of the stability

Power Spectral Density (PSD) & Root Mean Square (RMS)



Seismic motion spectrum (LIGO Livingston)

$$x_{RMS}(f) = \int_f^\infty x_{PSD}^2(f')df'$$

PSD:

- Distribution of fluctuation power

RMS:

- Integrated fluctuation amplitude over a specified frequency band

The fluctuation power is concentrated at the low freq band (f<1Hz)

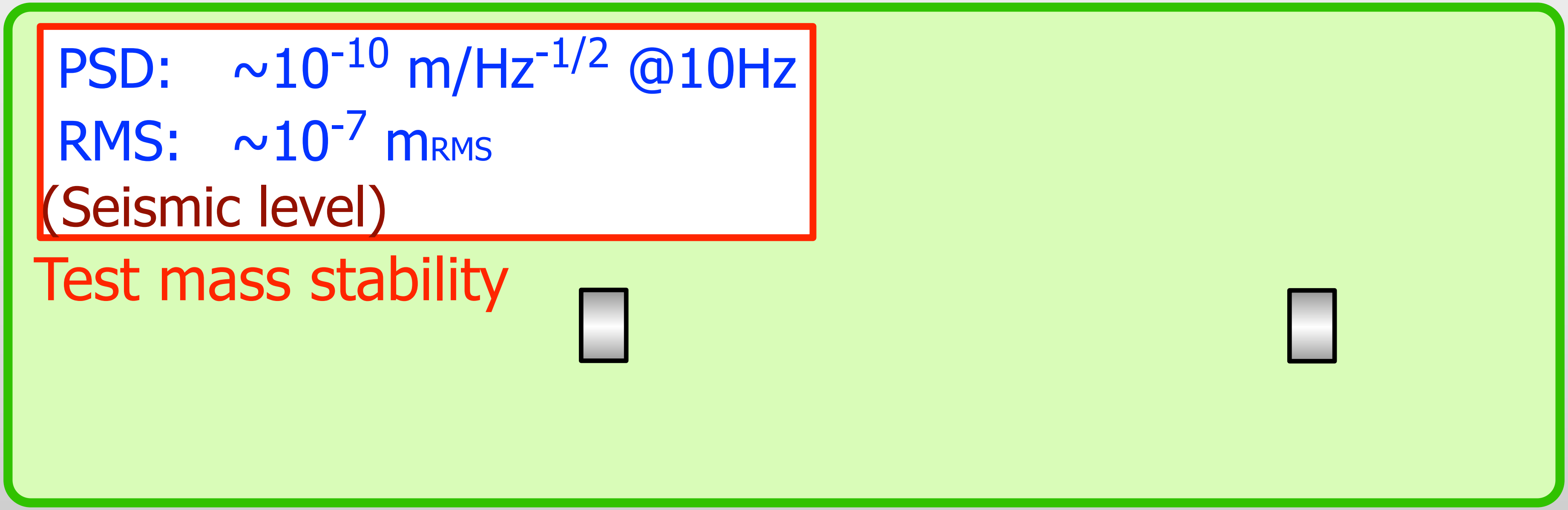
The high freq component is not negligible (RMS 10^{-8}~10^{-7} m_{RMS}) and susceptible to the environmental excitation

… more problematic for active stabilization.

Stabilization strategy

Target stability

- $x_{PSD} < \sim 10^{-19}$ m/Hz$^{-1/2}$ @10Hz (~10^9 attenuation from the seismic level)
- $x_{RMS} < \sim 10^{-13}$ m_{RMS} (~10^7 suppression)



PSD: ~10^{-10} m/Hz$^{-1/2}$ @10Hz

RMS: ~10^{-7} m_{RMS}

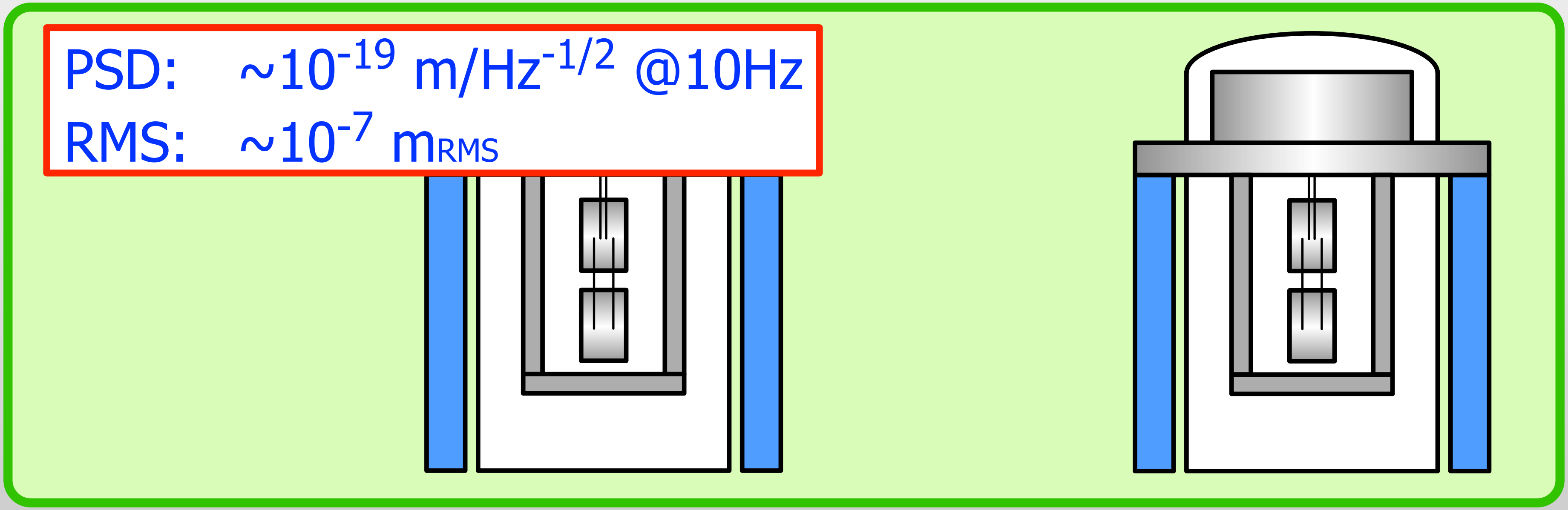
(Seismic level)

Test mass stability

Stabilization strategy

Target stability

- $x_{PSD} < \sim 10^{-19}$ m/Hz$^{-1/2}$ @10Hz (~10^{9} attenuation from the seismic level)
- $x_{RMS} < \sim 10^{-13}$ m_{RMS} (~10^{7} suppression)



PSD: ~10^{-19} m/Hz$^{-1/2}$ @10Hz

RMS: ~10^{-7} m_{RMS}

1. Employing cascaded vibration isolation systems to obtain:

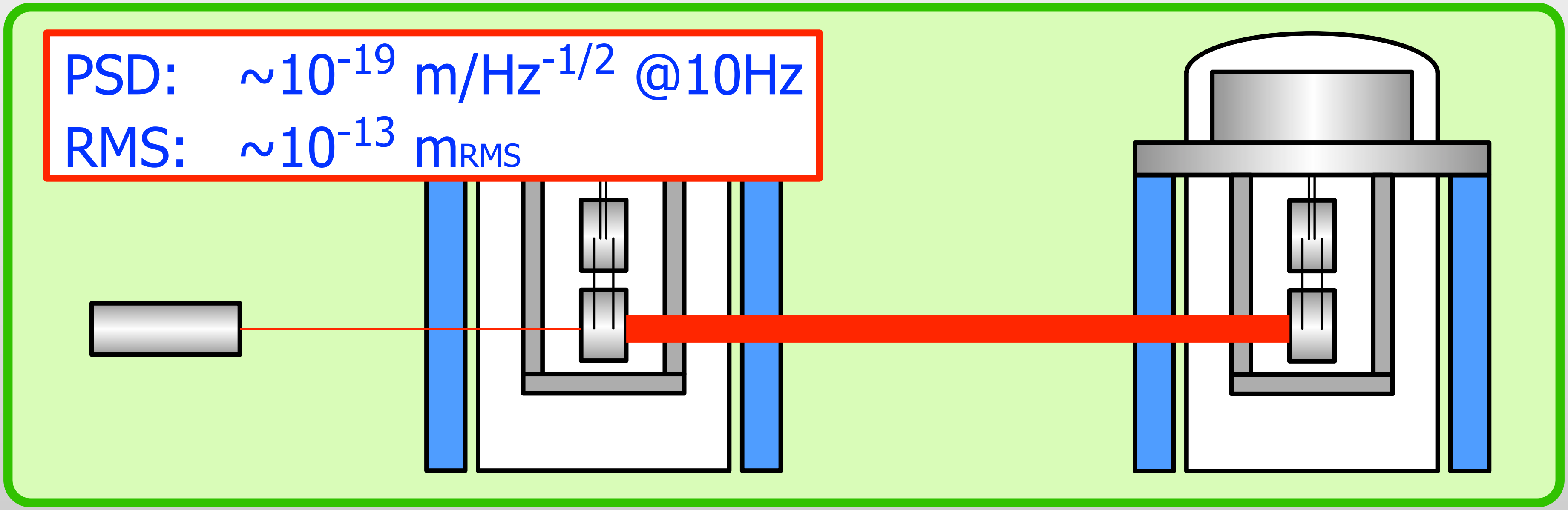
   $x_{PSD} < \sim 10^{-19}$ m/Hz$^{-1/2}$ @10Hz, $x_{RMS} < \sim 10^{-7}$ m_{RMS}

Local stabilization

Stabilization strategy

Target stability

- $x_{PSD} < \sim 10^{-19}\ \mathrm{m/Hz^{-1/2}}$ @10Hz (~10^{9} attenuation from the seismic level)
- $x_{RMS} < \sim 10^{-13}\ \mathrm{m_{RMS}}$ (~10^{7} suppression)



PSD: ~$10^{-19}\ \mathrm{m/Hz^{-1/2}}$ @10Hz

RMS: ~$10^{-13}\ \mathrm{m_{RMS}}$

1. Employing cascaded vibration isolation systems to obtain:

   $x_{PSD} < \sim 10^{-19}\ \mathrm{m/Hz^{-1/2}}$ @10Hz, $x_{RMS} < \sim 10^{-7}\ \mathrm{m_{RMS}}$

2. Using optical sensing and feedback control to suppress

   $x_{PSD} < \sim 10^{-20}\ \mathrm{m/Hz^{-1/2}}$, $x_{RMS} < \sim 10^{-13}\ \mathrm{m_{RMS}}$

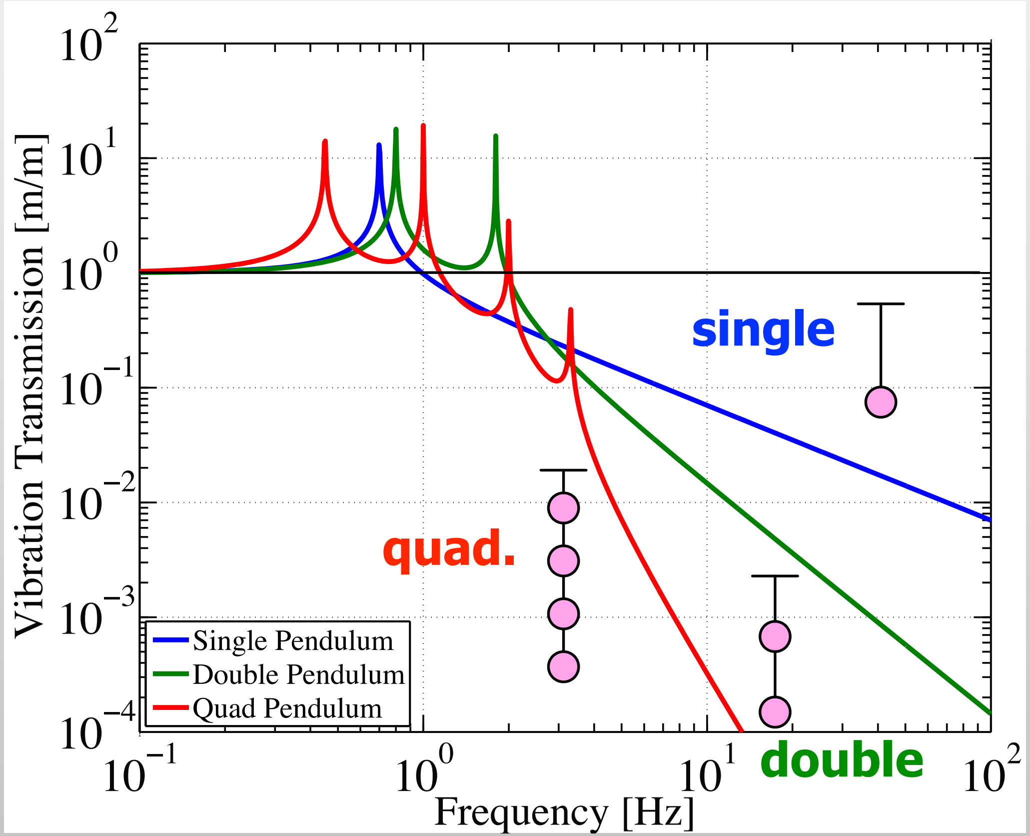
   (sensing limit from shot noise)

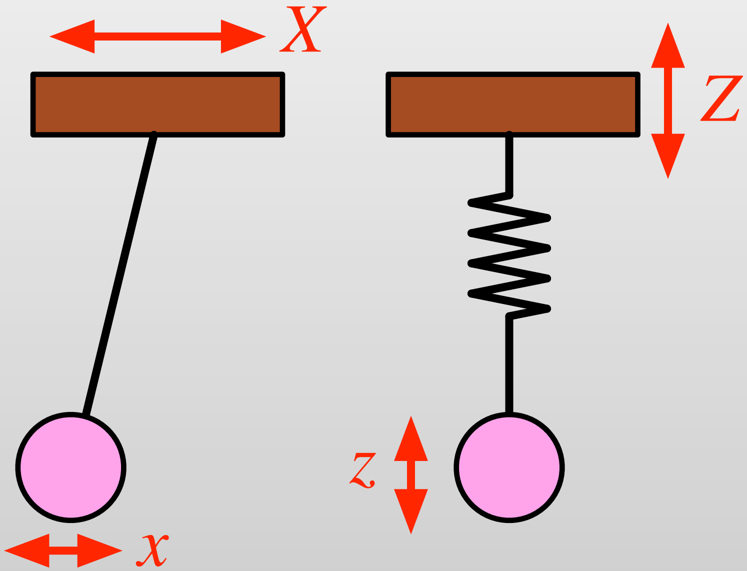
Global control

Vibration Isolation ~ Passive

Utilizing mechanical oscillators: pendulum or spring

- Attenuation of the vibration above the resonant frequency



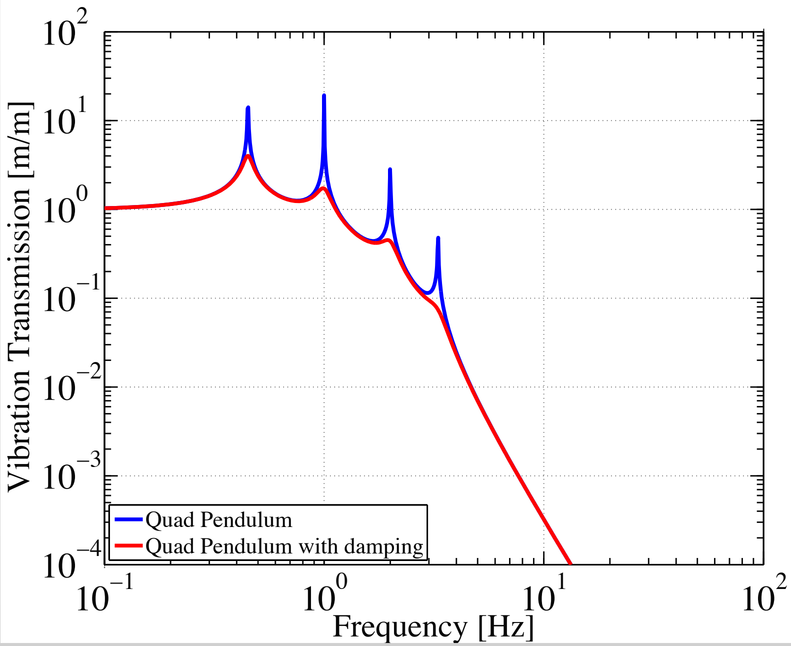


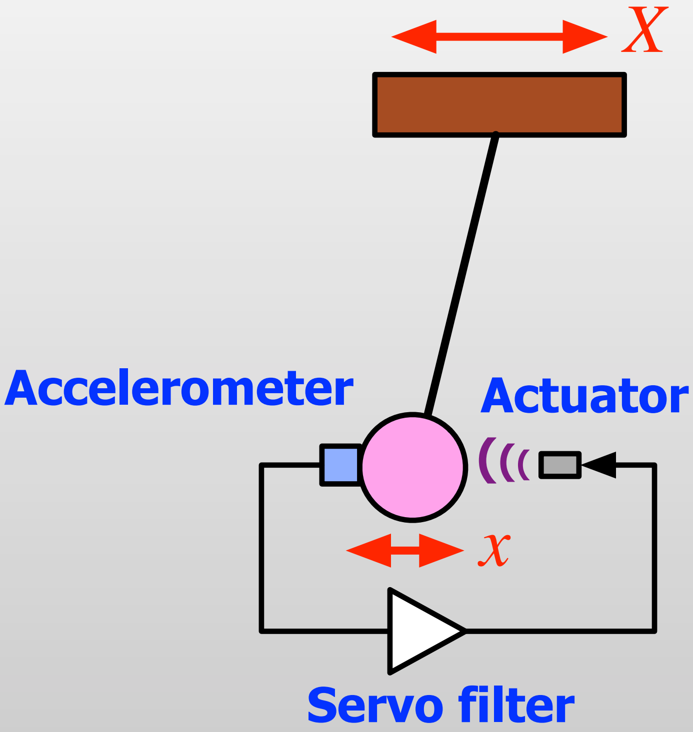
- More cascading
  => more attanuation
  => more resonance & more low freq motion

Vibration Isolation ~ Active control

Damping of the resonant motion

- by local inertial damping servo

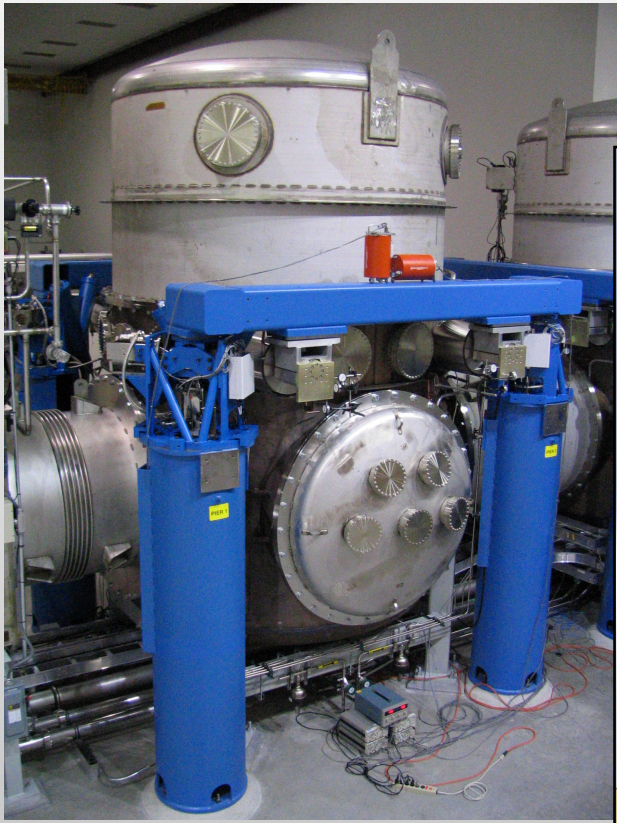




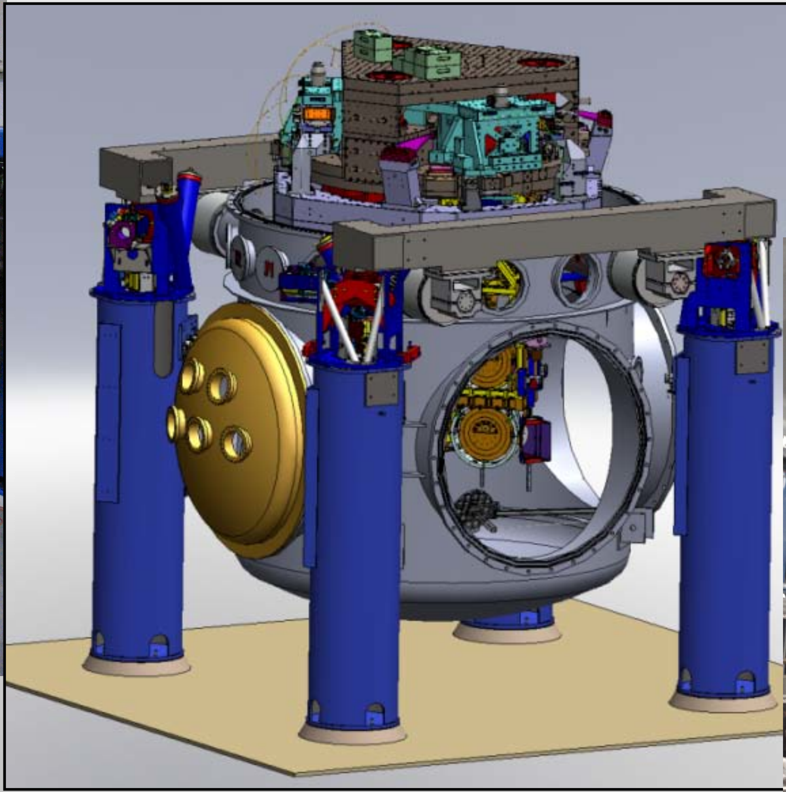
- Inertial damping
  - => can avoid seismic re-injection through the servo
  - => tends to inject sensor noise at low frequency (f<0.1Hz)

Vibration Isolation

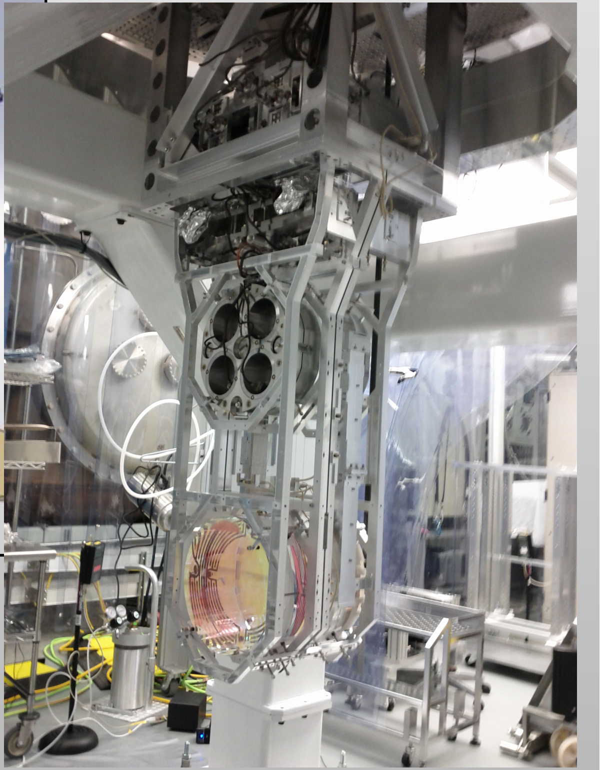
HEPI (Hydraulic External Pre-Isolator)



ISI (Internal Seismic Isolator)



Quadruple Pendulum



1/10@10Hz → **1/1000** → **$1/10^6$**

Attenuation of $10^9 \sim 10^{10}$

Optical readout & feedback control

Mirrors are still moving at the low frequency band

- Mirror motion needs to be stabilized down to 10^{-13} m_{RMS} level
- Variant of Pound-Drever-Hall technique is used.

High sensitivity

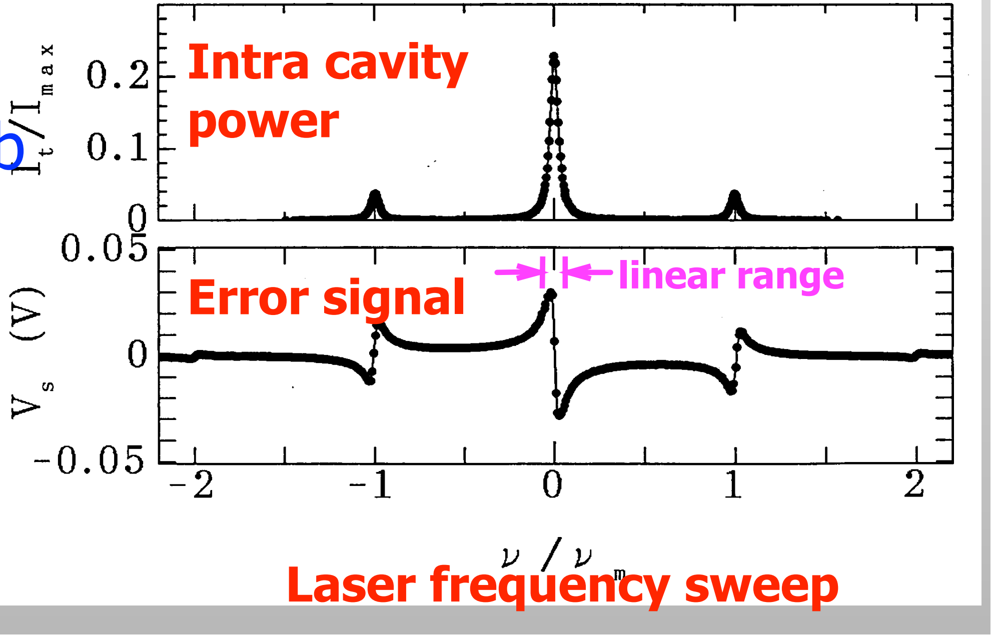
- sufficiently low noise not to disturb the intrinsic stability of the mirrors

= Narrow range

- very narrow linear range (~1nm)

Relative stabilization

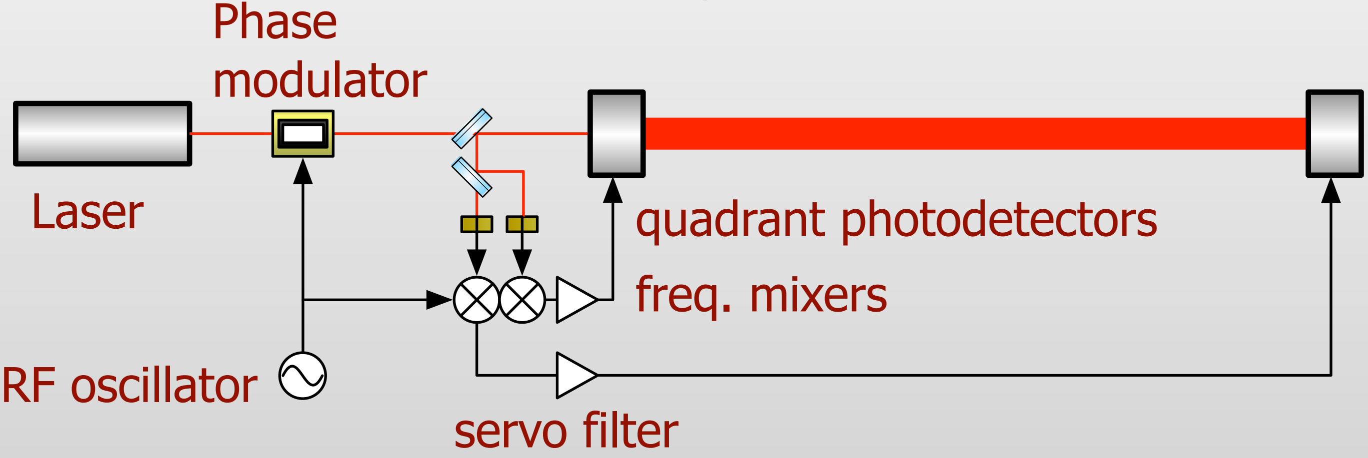
- with regard to the laser frequency



Angular control control

Differential wave front sensing

- Heterodyne signals obtained from segmented photodetectors
  => sensitive to cavity misalignment



Phase modulator

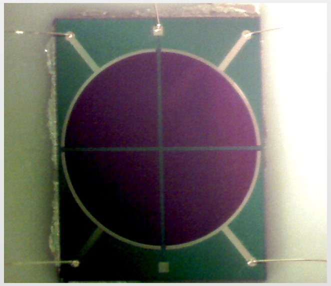
Laser

quadrant photodetectors

freq. mixers

RF oscillator

servo filter



High sensitivity

- $\theta_{PSD} < 10^{-12} \sim 10^{-14}$ rad/Hz$^{-1/2}$

Relative measurement

- between the incident beam and the cavity resonant mode

Relevance to XFELO

	LIGO	**XFELO**
Cavity:	4km infrared resonator	~100m X-ray resonator
Object:	Suspended mass (40kg)	Diamond mirrors lens element (grazing mirror)
Prestabilized displacement in PSD:	$\sim 10^{-19}$ m/Hz$^{-1/2}$ @10Hz	Not applicable

LIGO requires the intrinsic stability of the mirror while XFELO only concerns with the stabilized level.

Stabilized cavity round-trip length in RMS:	$\sim 10^{-13}\ \mathrm{m_{RMS}}$	$\sim 10^{-6}\ \mathrm{m_{RMS}}$ or $\sim 10^{-12}\ \mathrm{m_{RMS}}$ (ultimate)
Stabilized angular stability:	$\sim 10^{-9}\ \mathrm{rad_{RMS}}$	$\sim 10^{-8}\ \mathrm{rad_{RMS}}$

XFELO specific issues

Stability reference

LIGO needs to resonate the infrared laser
=> Use the laser itself for sensing (cf. PDH, WFS)
=> Use the cavities itself as a frequency reference (cf. two arms)

XFELO resonates the X-ray beam in the oscillator
=> Use the X-ray itself for the sensors? Ultimately, yes
(Bernard's talk: 57Fe resonance)
Some vibration isolation will help to reduce
the control bandwidth significantly

Or, connect optical interferometers to the X-ray cavity?
=> Possible, (e.g. Optical truss, Platform interferometer)
but requires a freq stabilized laser

iodine stabilized laser? (better long term stability)
rigid-cavity stabilized laser? (better short term stability)

XFELO specific issues

Lock acquisition

For the 56Fe stabilization case:

1um motion @0.1~1Hz -> 10^3~10^4 fringes per second

=> Can't capture the resonance while the cavity is passing through a resonance.

Solution:

Mild mechanical stabilization

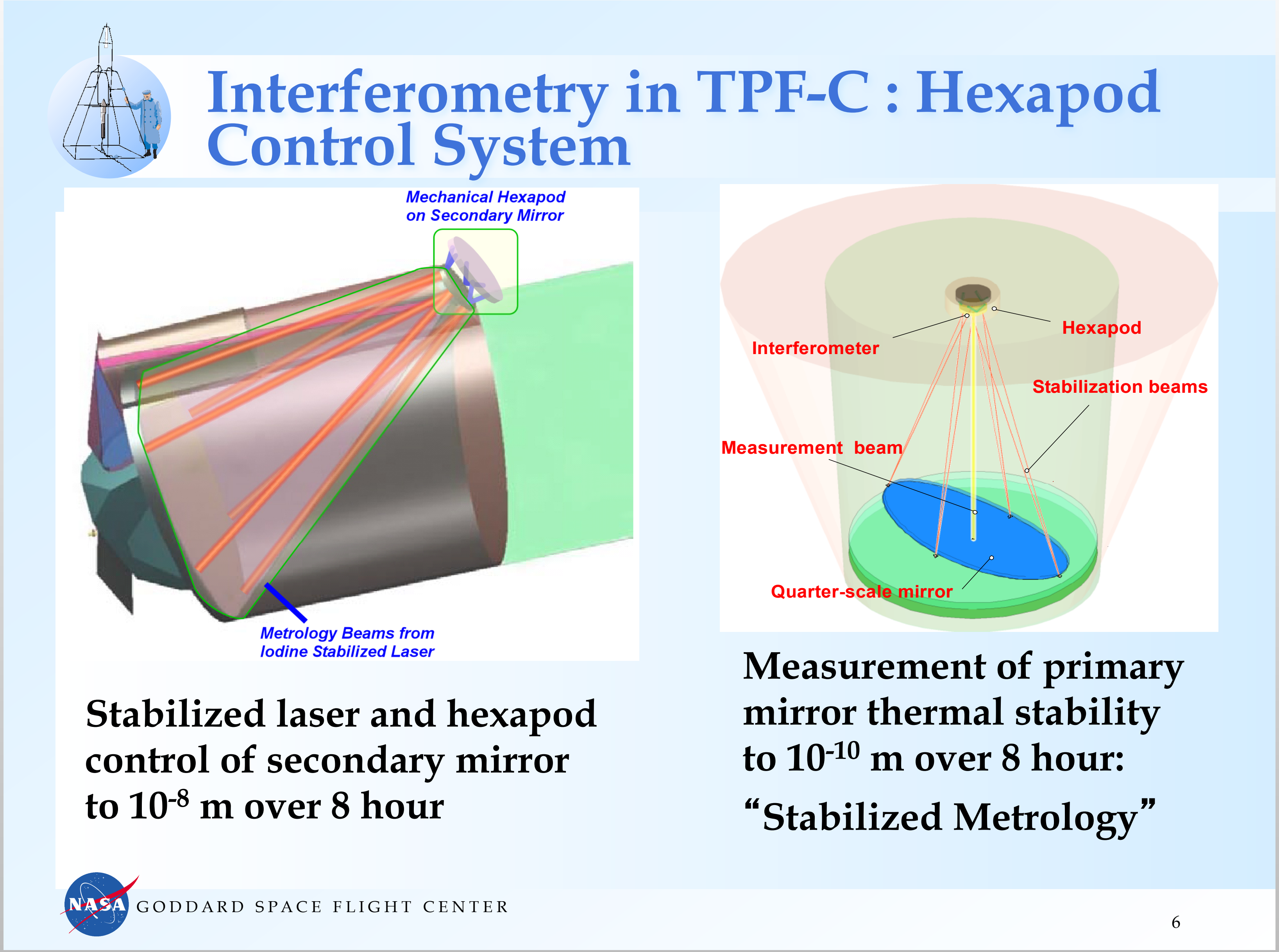
(single stage vibration isolation)

\+ Stabilization with optical interferometry

(continuous optical metrology)

\+ Ultimate stabilization with the 56Fe resonance

Optical Truss (TPF-C)



Interferometry in TPF-C : Hexapod Control System

Stabilized laser and hexapod control of secondary mirror to 10^{-8} m over 8 hour

Measurement of primary mirror thermal stability to 10^{-10} m over 8 hour:

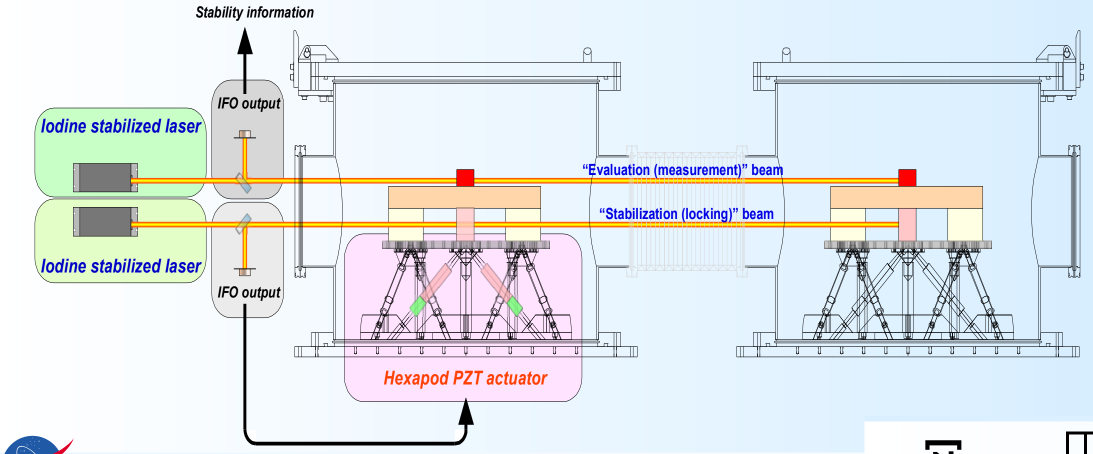
“Stabilized Metrology”

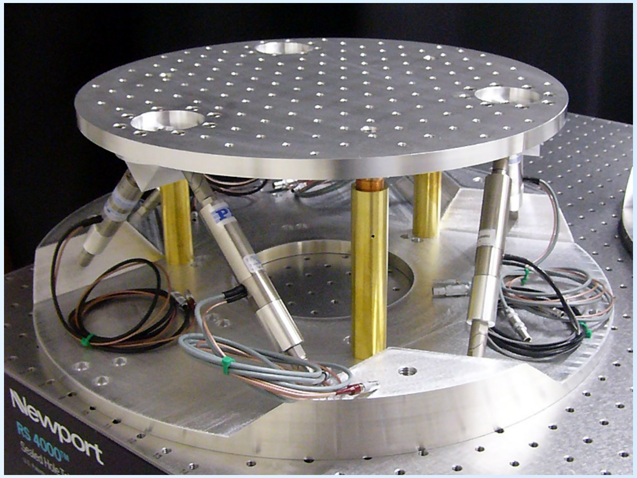
Jordan Camp, NASA Goddard

Platform Interferometer

Suspension Point Interferometer testing platform

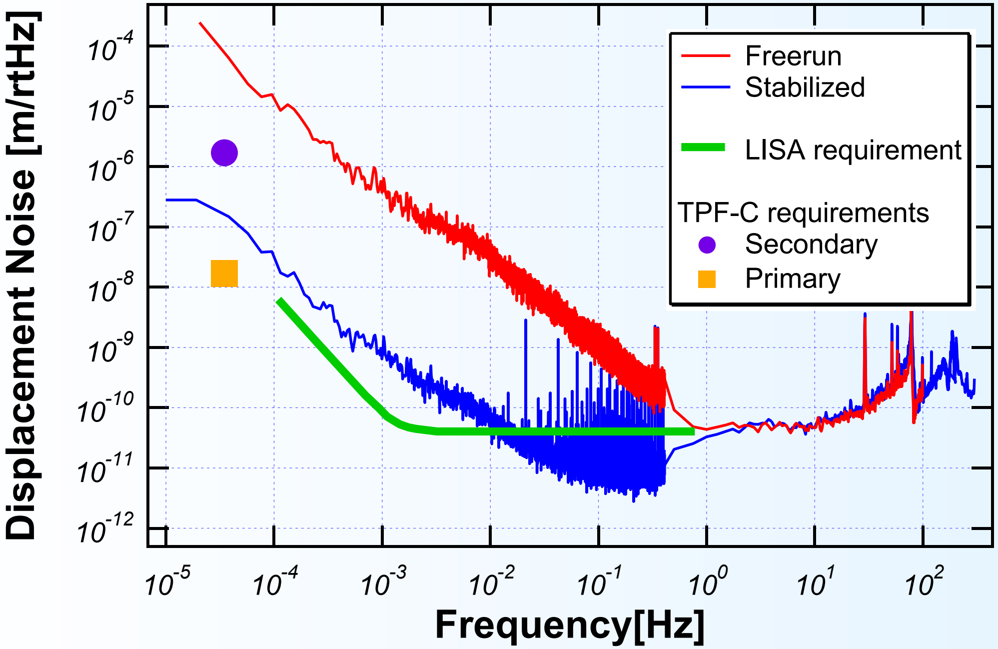
- goal: lock platforms at picometer, nanoradian level
- use to test interferometry of LISA, TPF-C, etc.





Hexapod: 6 PZT' s for 6 DOF control

$\nu_{res} \sim 230$ Hz, Q ~ 6

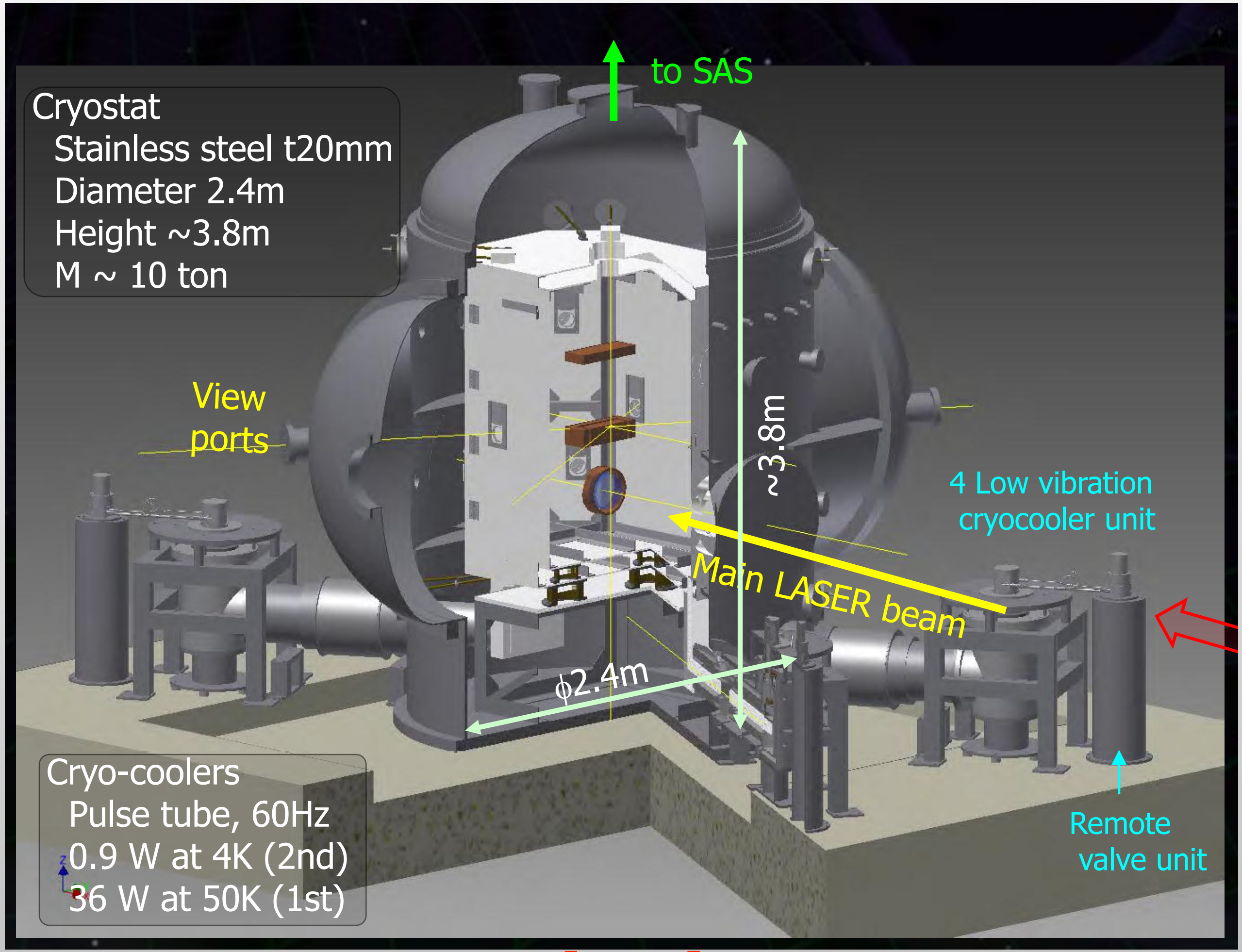


Jordan Camp, Kenji Numata
NASA Goddard

Applied Optics **47**,
6832-6841 (2008)

Quiet cryogenic system

Cooling down of the diamond crystals



Cryostat
  Stainless steel t20mm
  Diameter 2.4m
  Height ~3.8m
  M ~ 10 ton

Cryo-coolers
  Pulse tube, 60Hz
  0.9 W at 4K (2nd)
  36 W at 50K (1st)

KAGRA (Japanese GW Project)

Sapphire mirror @20K / Compliant heat link
Low vibration PT cryocoolers (KEK)

T. Tomaru et al,
Cryocoolers 13,
695-702 (2005)

Summary

LIGO ~ gravitational wave detection

- Requires extremely high stability of the optics

Mechanical stabilization

- Passive & active vibration isolation
- Feedback control with optical sensing

Stabilization of XFELO

- Looks feasible by possible combination of
  mechanical stabilization
  \+ optical interferometry
  \+ x-ray atomic resonance