Title: Parametric Instability in Future Gravitational Wave Detectors

Date: Jun 12, 2018 02:00 PM

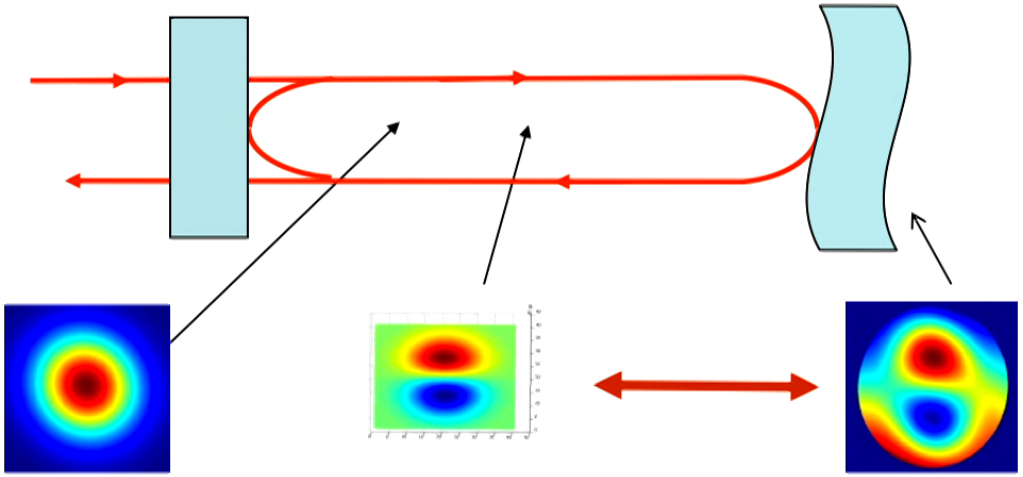
URL: http://pirsa.org/18060053

Abstract:

Contents

- Parametric instability (PI) and observation results
- Current PI control at aLIGO
  - Thermal tuning, Electrostatic feedback, Acoustic mode damper (AMD)
- AMD potential thermal noise implications
- PI simulation results of Voyager
- PI simulation results of CE
- Mechanical resonators for optomechnical filter

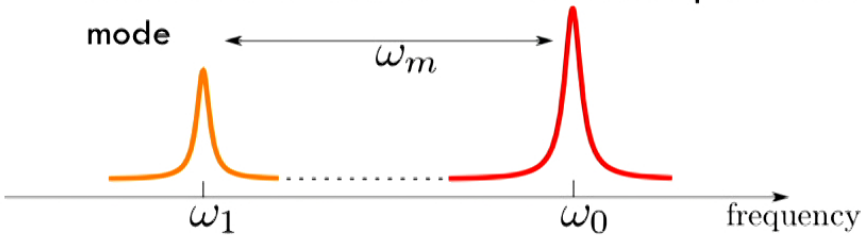
Parametric Instability



High power fundamental mode ω_o

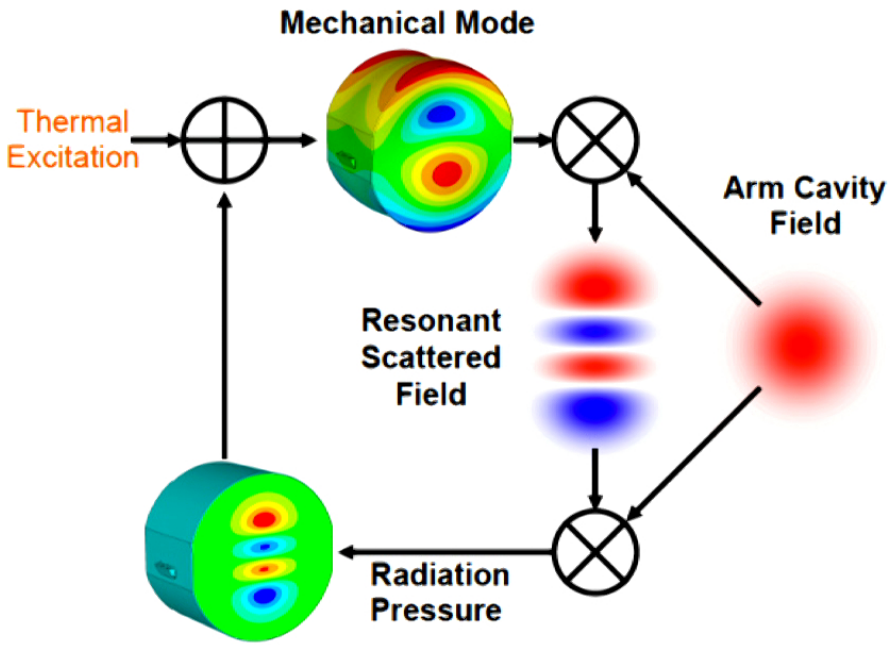
Cavity high order transverse mode ω_1 scattered from acoustic mode

Thermally excited acoustic mode ω_m amplified by radiation pressure feedback



Parametric Instability

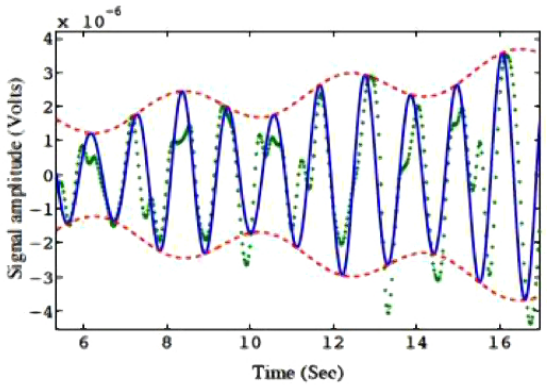
The parametric instability can be described as a classical feedback phenomenon.



M. Evans, L. Barsotti, P. Fritschel, Physics Letters A 374 (2010) 665–671

Path to kHz GW detectors

Parametric Instability at Gingin 80m

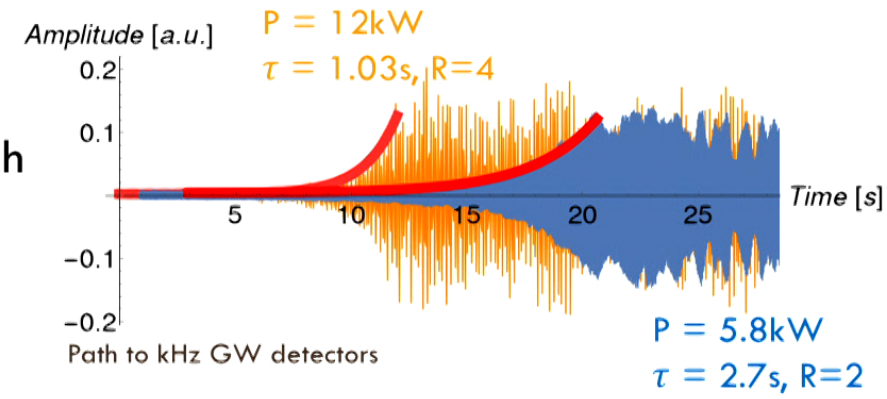


Observation of parametric instability and modulation effect

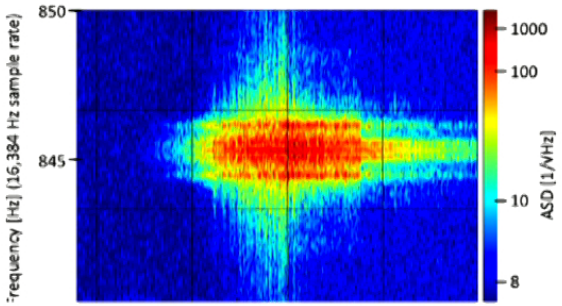
C. Zhao *et al. Phys. Rev. D, 2015*

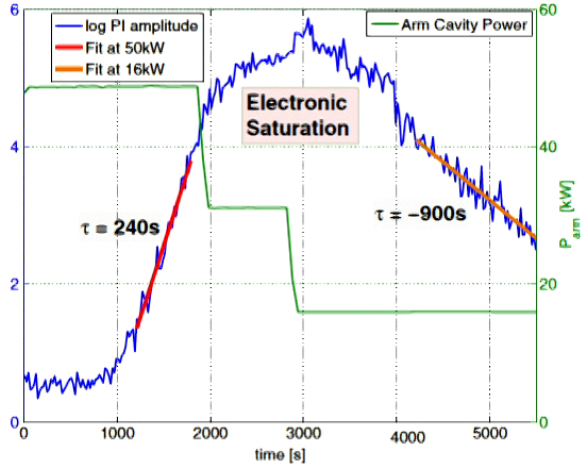
R = 1.45

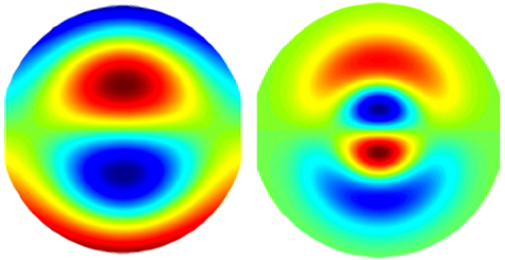
Observation of strong parametric instability at high circulating power



Parametric Instability at aLIGO







Mirror surface displacement

The 3rd order optical mode

- PI exists
- Current power level PI is controlled

M. Evans, et al. Phys. Rev. Lett. 114, 161102

Factors Affecting Parametric Gain

- Parametric gain

$$R = \pm \frac{8P_{in}Q_0Q_1Q_m}{L^2\omega_0\omega_m} \frac{\gamma B}{1+(\Delta\omega/\delta_1)^2}$$

$$\Delta\omega = \omega_m - (\omega_0 - \omega_{mn})$$

$$\omega_0 - \omega_a = \frac{c}{L}(m+n)\arccos\left(\pm\sqrt{\left(1-\frac{L}{R_1}\right)\left(1-\frac{L}{R_2}\right)}\right)$$

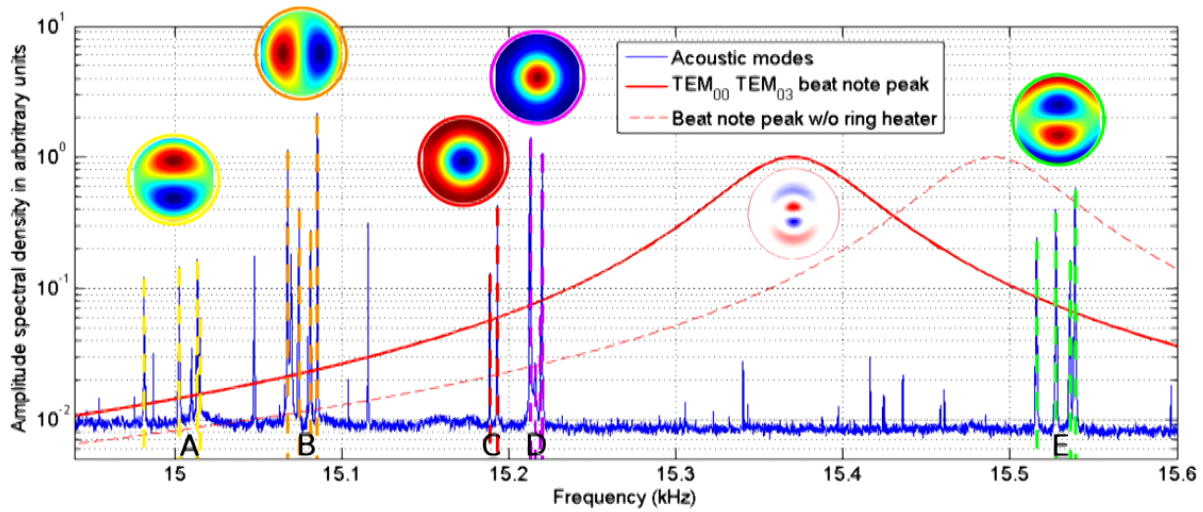
- Acoustic mode amplitude

$$x \sim Ae^{-(1-R)t/\tau}$$

- Control Strategies
  - Thermal tuning
  - Electrostatic feedback
  - Acoustic Mode Damper

Thermal tuning

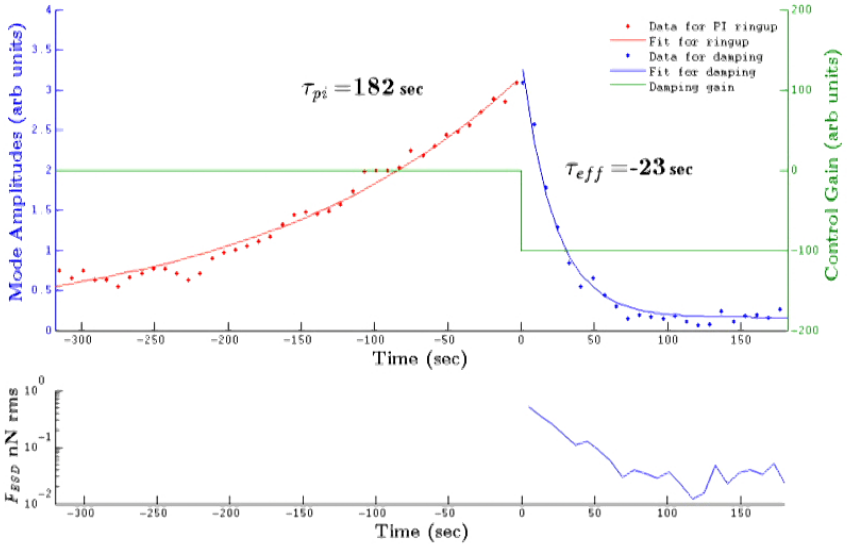
LLO: ring heaters tuned to no PI sweet spot

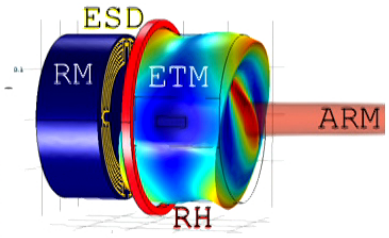


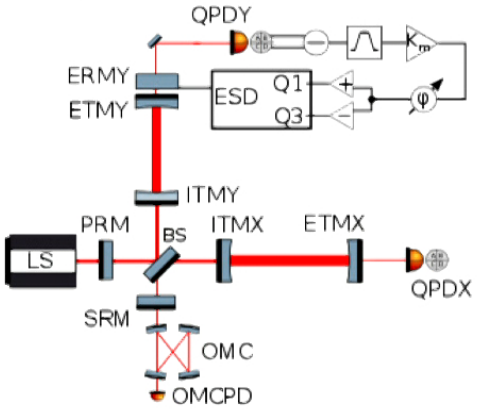
C. Blair: PRL 118, 151102 (2017)

Electrostatic feedback

LHO: Electrostatic Drives used to damp at 50W





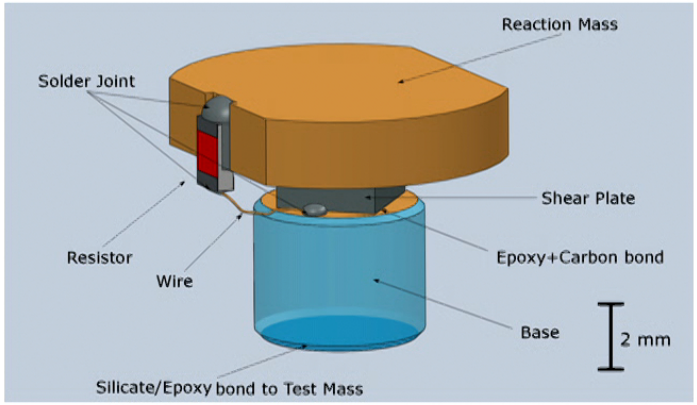


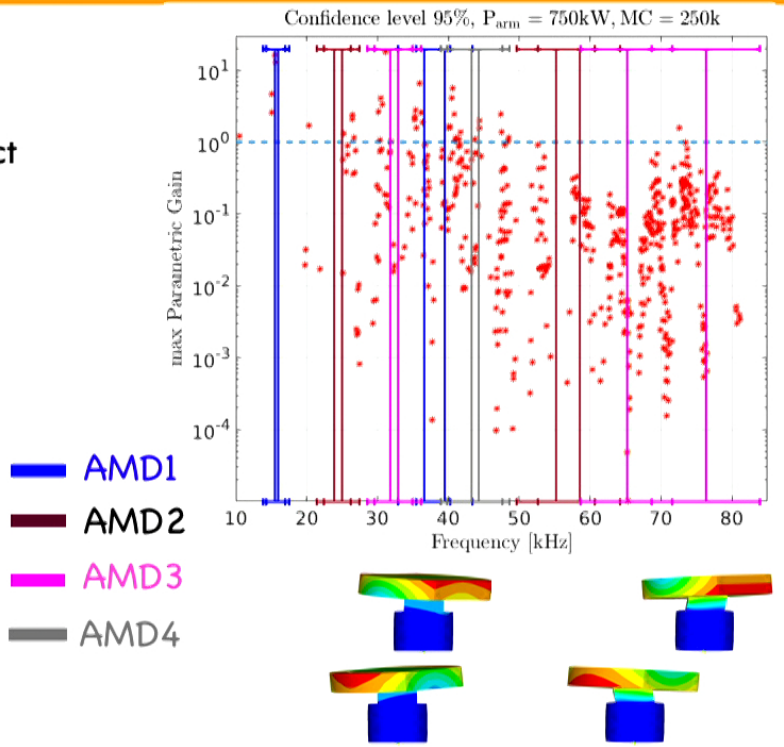
C. Blair et al: PRL 118, 151102 (2017)

Path to kHz GW detectors

Acoustic Mode Dampers

- 4 AMD per test mass
- 4 damping modes per AMD
- 1.5% predicted thermal noise impact





LIGO Document G1800454-v1 and, G1800975

Path to kHz GW detectors

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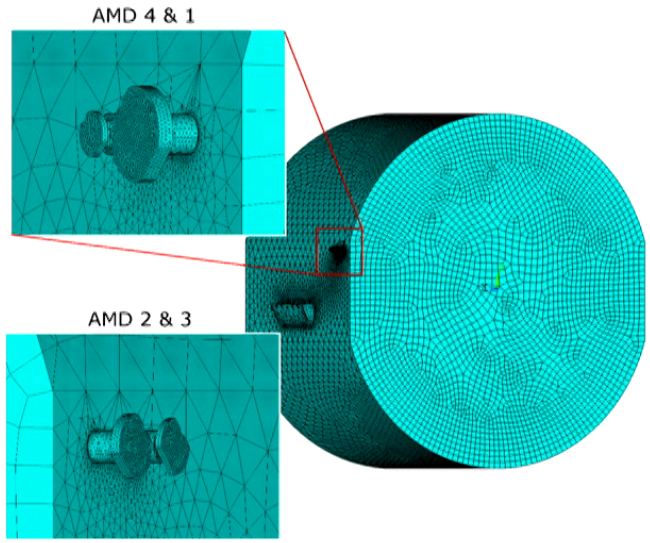
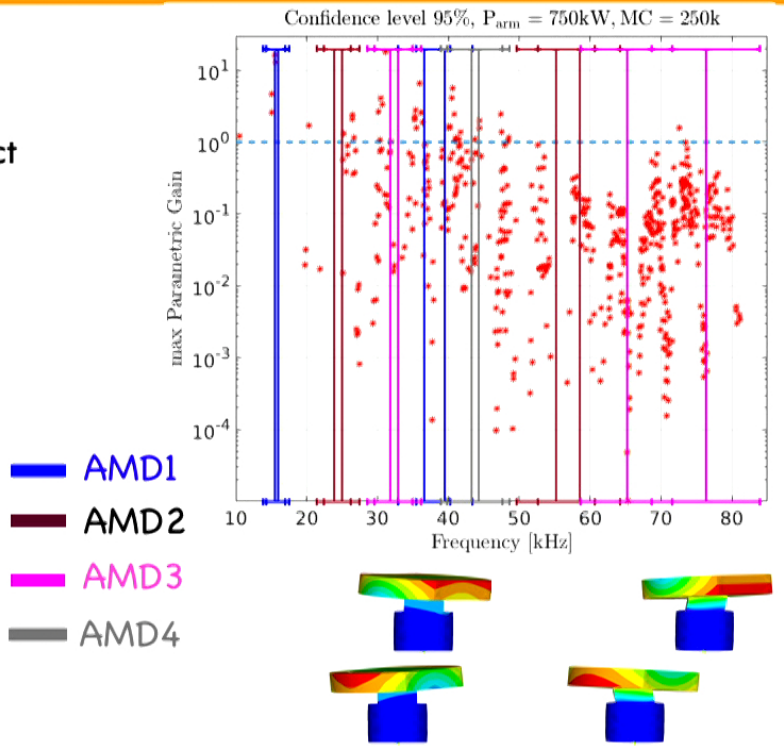


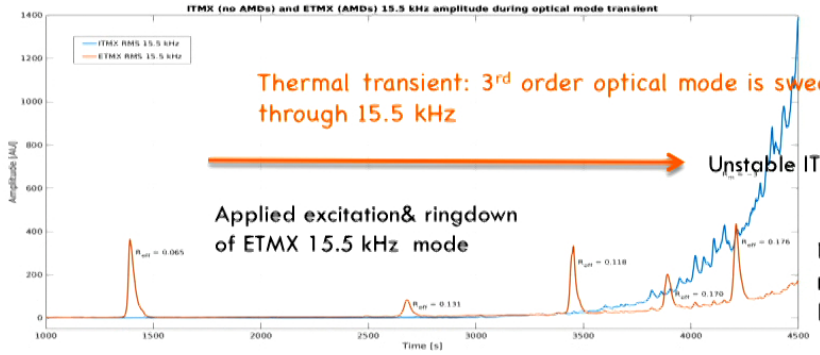


LIGO Document G1800454-v1 and, G1800975

Path to kHz GW detectors

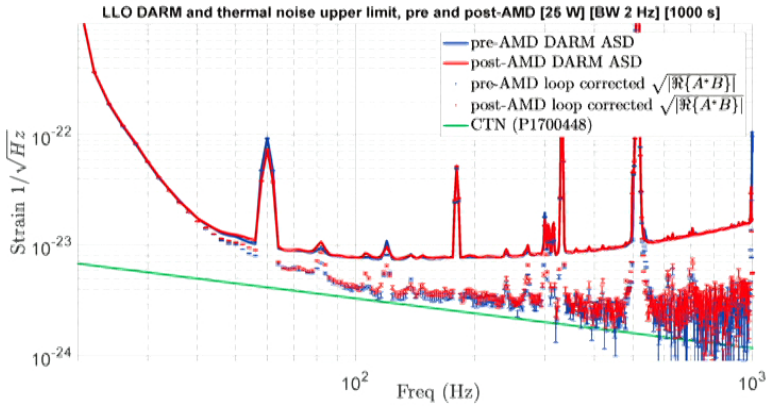
Acoustic Mode Dampers

Stability of 15.5 kHz mode: ITMX vs ETMX



@ 100 kW arm power

Thermal noise

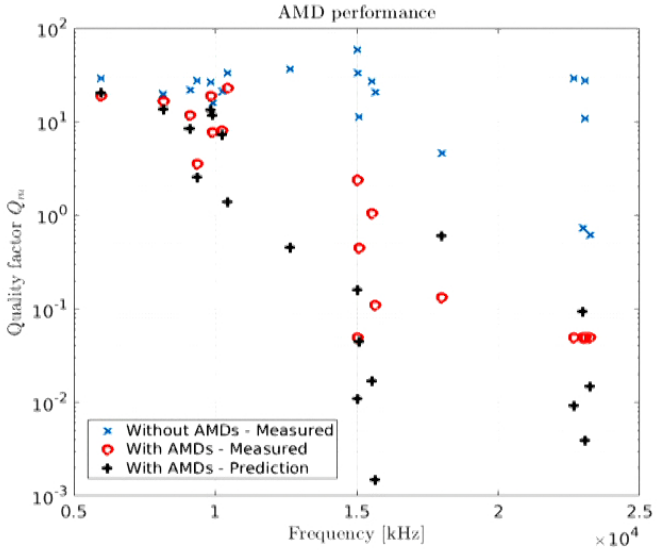


LIGO Document G1800454-v1

Acoustic Mode Dampers

Before AMDs (measured) & After (measured & predicted)

freq (Hz)	mode #	Pre-AMD Q (x10^6)	Post-AMD Q (x10^6)	Predicted Post-AMD Q (x10^6)
5948	1	29.3	19.1	20.3
6050			18.7	
8158	3	20.2	16.7	13.8
9101	6	21.8	11.8	8.5
9338	7	27.6	3.55	2.6
9827	9	26.9	18.9	13.5
9878	10	15.7	7.73	11.8
10216	11	21.2	8.03	7.3
10424	12	33.3	22.8	1.4
12627	15	36.7		0.46
15006	30	59.3	2.39	0.011
15017	31	33.2	NA (ETMY)	0.16
15071	32	11.4	0.45	0.045
15538	36	27.1	1.05	0.017
15630	37	20.6	0.11	0.0015
18001	50	4.65	0.134	0.61
18051			<0.04	
22662	84	29.1	NA (<0.1)	0.0093
22969	87	0.73	NA (<0.1)	0.095
23049	88	10.9	NA (<0.1)	0.004
23060		28	NA (ETMY)	0.004
23222	89	0.62	NA (<0.1)	0.015
38106		9.5	0.019	
47468		2.3	0.03	
47485		5.3	0.041	



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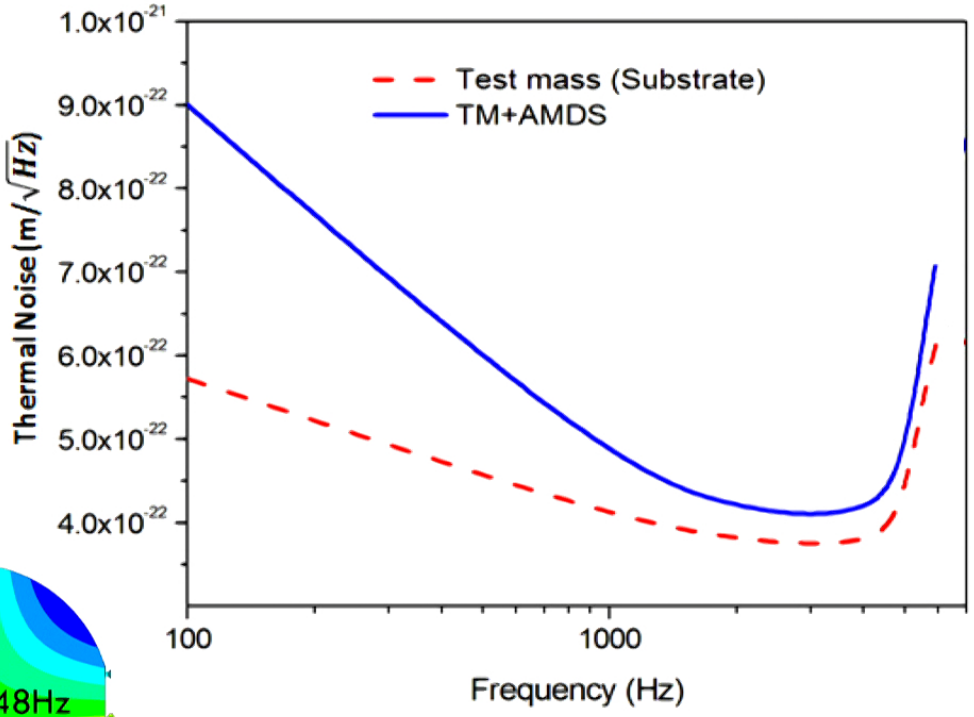
Path to kHz GW detectors

Preliminary FEM simulation of AMD thermal noise contribution

- FEM simulation shows the first TM internal mode dominates the thermal noise contribution at around 5.9 kHz (no coating thermal noise included)

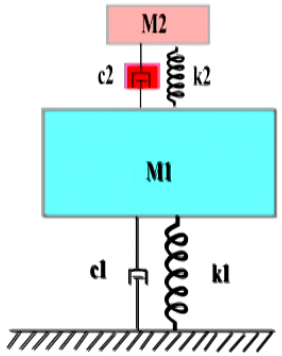


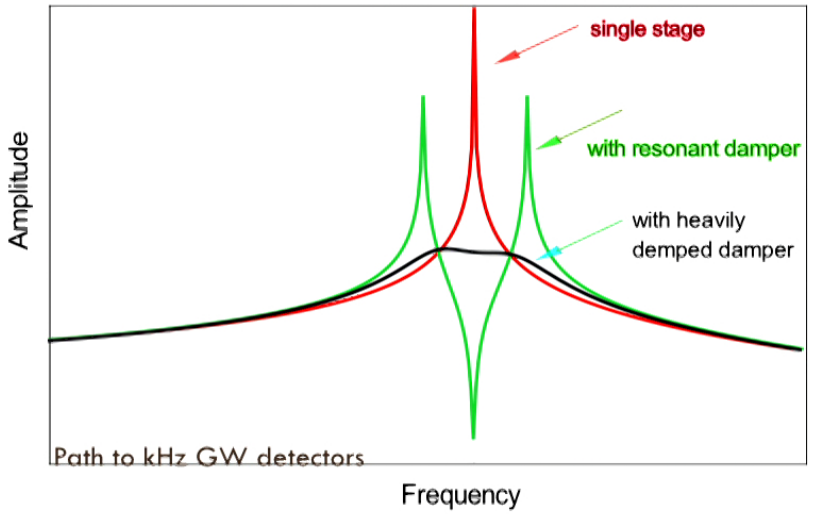
Test mass first mode @ 5948Hz

Path to kHz GW detectors

Resonant Damper-one dimensional model

- One dimensional model—single stage
  - M1: test mass
  - M2: Damper
  - Heavily damped damper
  - Lossy damper in direct contact with the test mass
  - Thermal noise?





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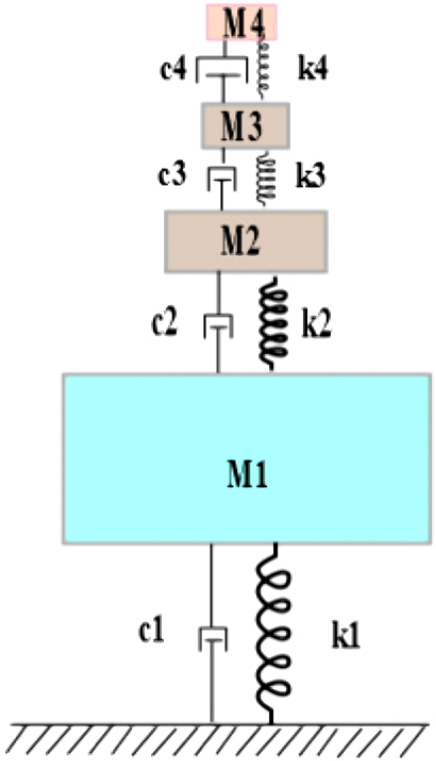
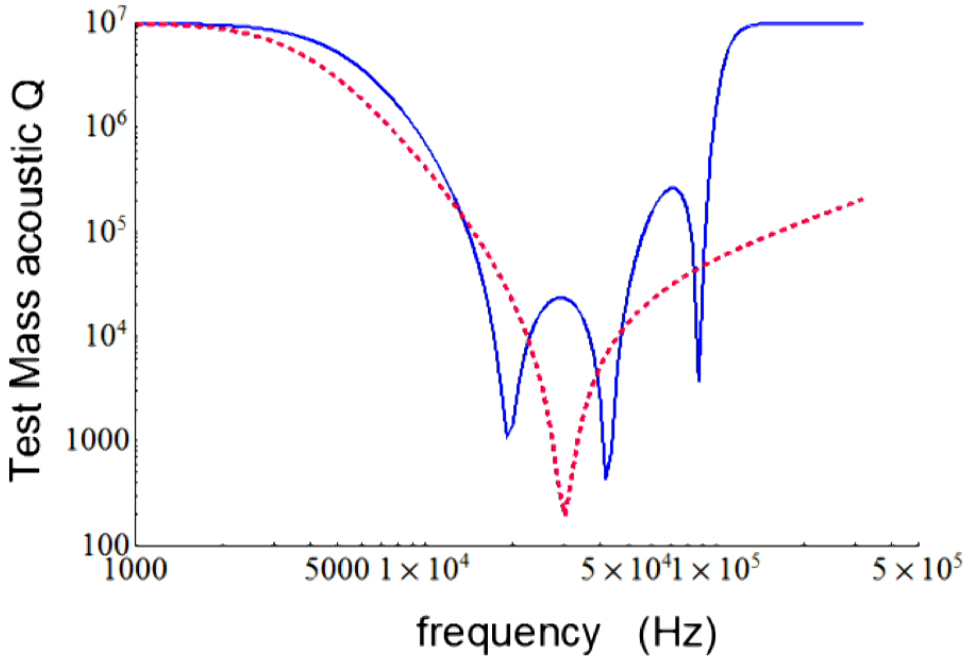
Is it possible to improve?

- Multi-Stage Damper
- Only the last stage is lossy
- Very small lossy stage to achieve effective damping



3-stage damper

One dimensional acoustic modes
Q estimation



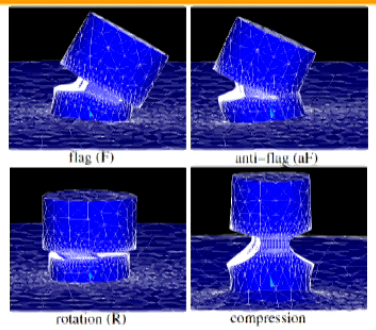
$Q_0=10^7$

Single damper:
m=10g,f=3 0kHz, Q=10

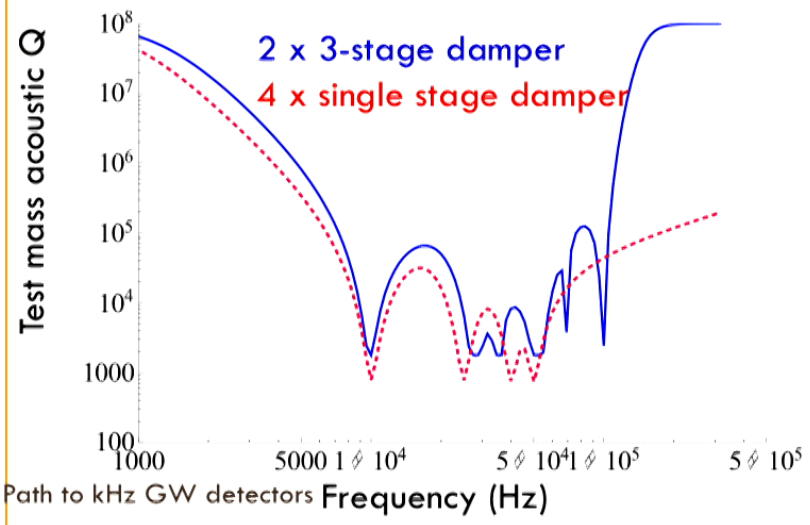
3-Stage damper:
m_2=6g, f_2=60kHz, $Q_2=10^7$
m_3=3g, f_3=60kHz, $Q_3=10^7$
m_4=1g, f_2=20kHz, Q_2=10

Multiple multi-stage

- 3D single stage = effective a couple of dampers
- For high Q damper, could use multiple multi-stage dampers



*S. Gras, et. al. PRD, **92**, 082001 (2015)*



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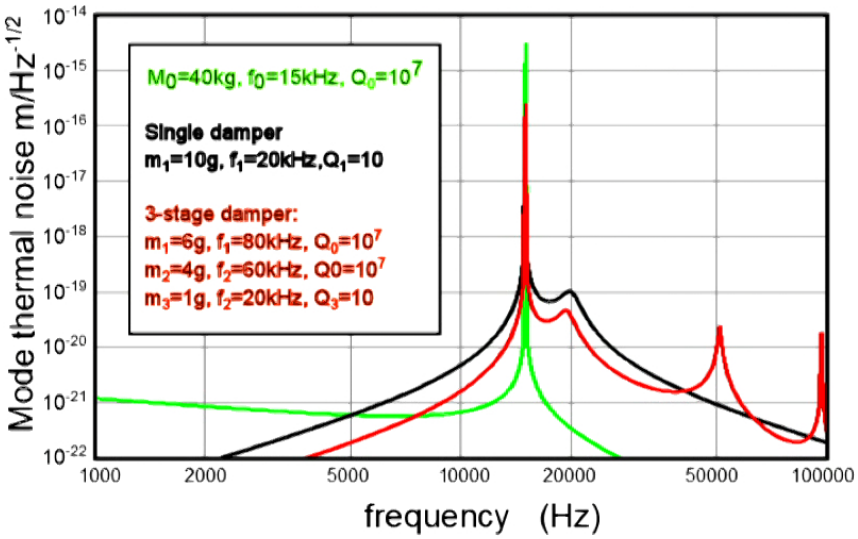
Path to kHz GW detectors

Thermal noise rough estimation

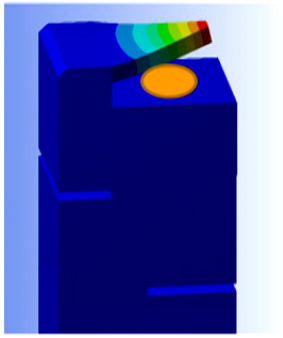
- Example for a single acoustic mode
- Multi-stage damper has lower thermal noise contribution
- Over simplified model here
- Need more detailed thermal noise analysis for multi-stage damper

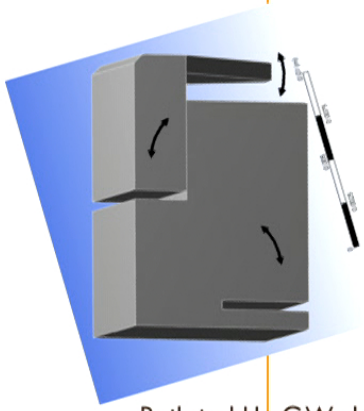
Thermal noise contribution from EACH element



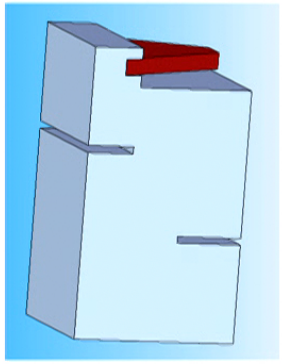
Practical design

- Monolithic high Q metal
- Electrical discharge Machining
- Using magnet eddy-current damping





- Monolithic high Q material
- Last stage with different lossy material (Viton) tight fit



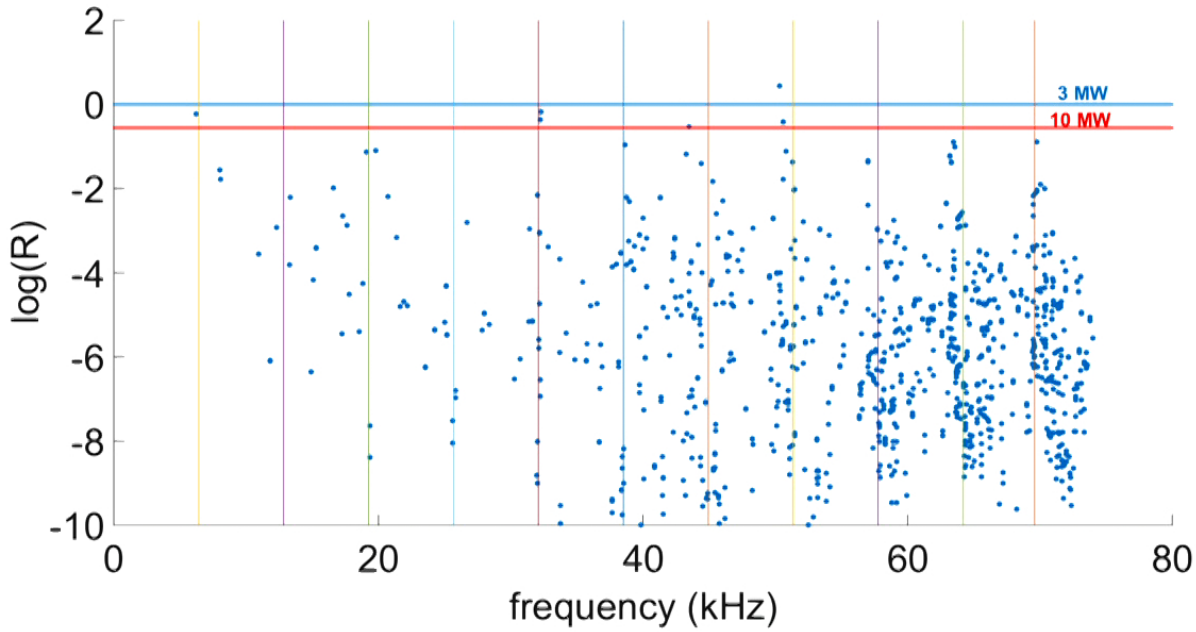
PI simulation for Voyager: simple cavity

Parameters:

- laser wavelength : 2 μm
- Large Silicon mirror: 204 kg
- Cryogenic : at 123 K
- Assume Q ~10^7 after all coatings
- High power laser: Arm cavity powers will reach ~3/10 MW
- Mirror radius: 0.225m
- Mirror thickness: 0.55m
- Beam radius on ITM/ETM: 0.059m/0.084m

Path to kHz GW detectors

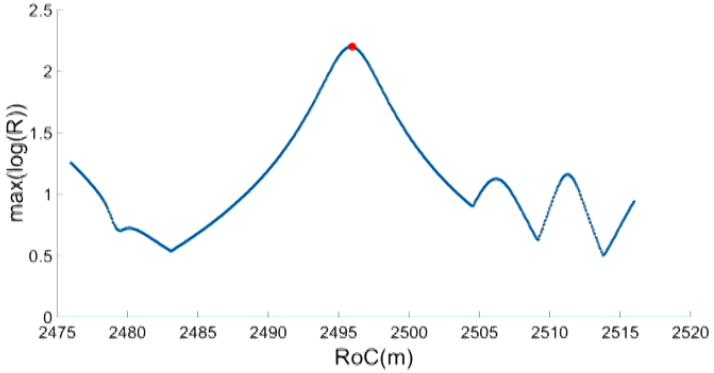
PI simulation for Voyager: simple cavity

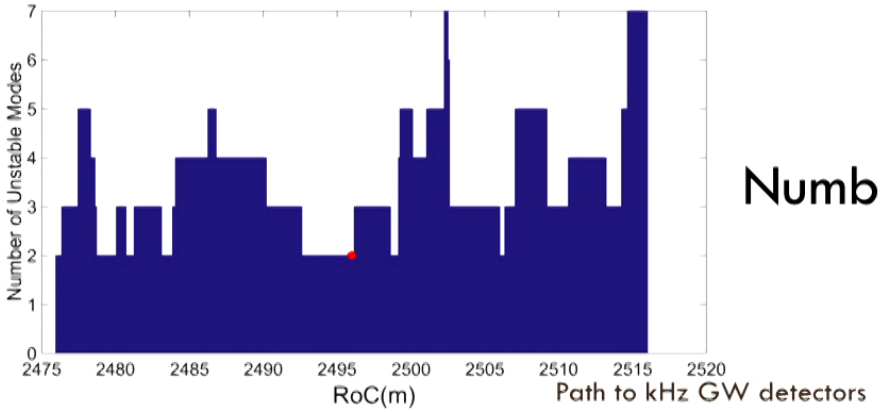


Path to kHz GW detectors

PI simulation for Voyager: simple cavity (3 MW circulating power)

Max R

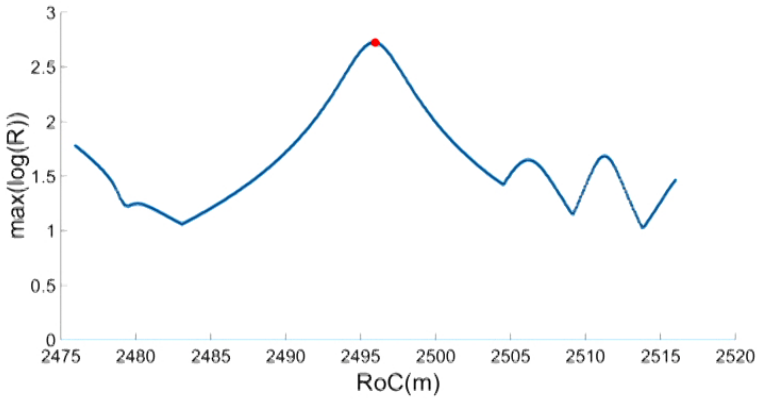


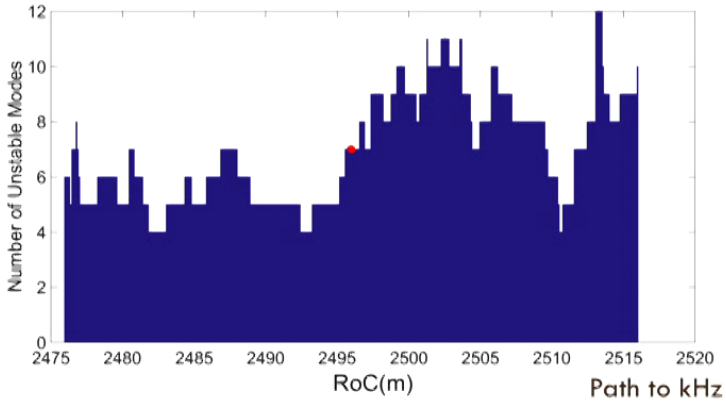


Number of unstable modes

PI simulation for Voyager: simple cavity (10 MW circulating power)

Max R



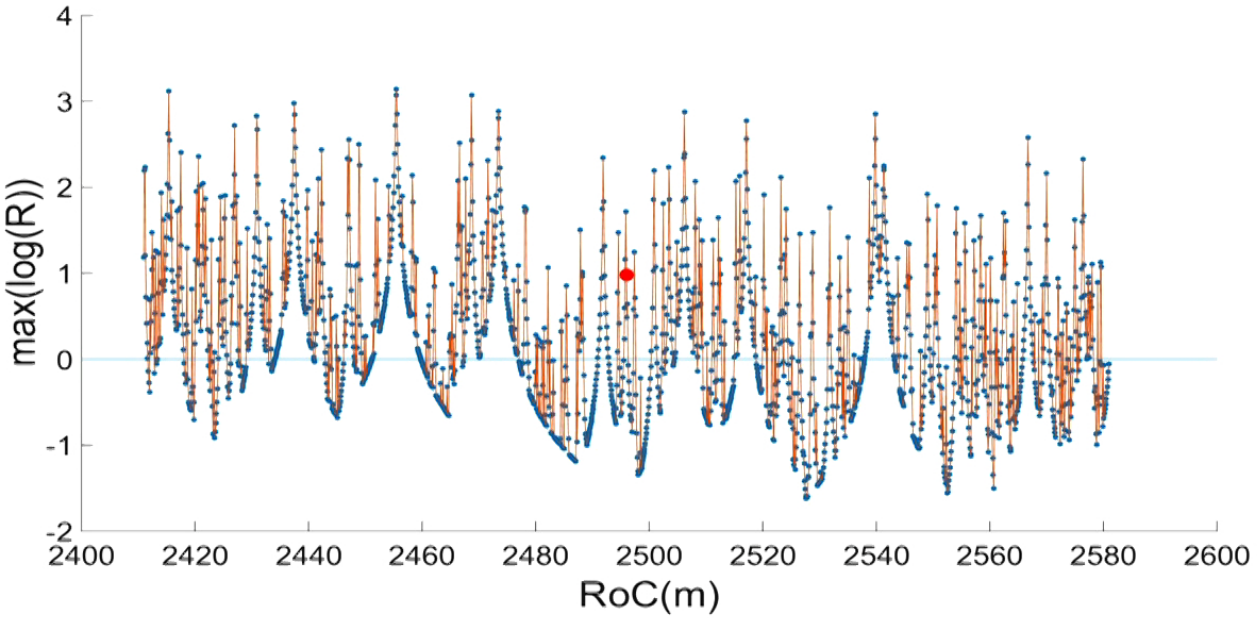


Number of unstable modes

Path to kHz GW detectors

PI simulation for Voyager: Dual-recycling

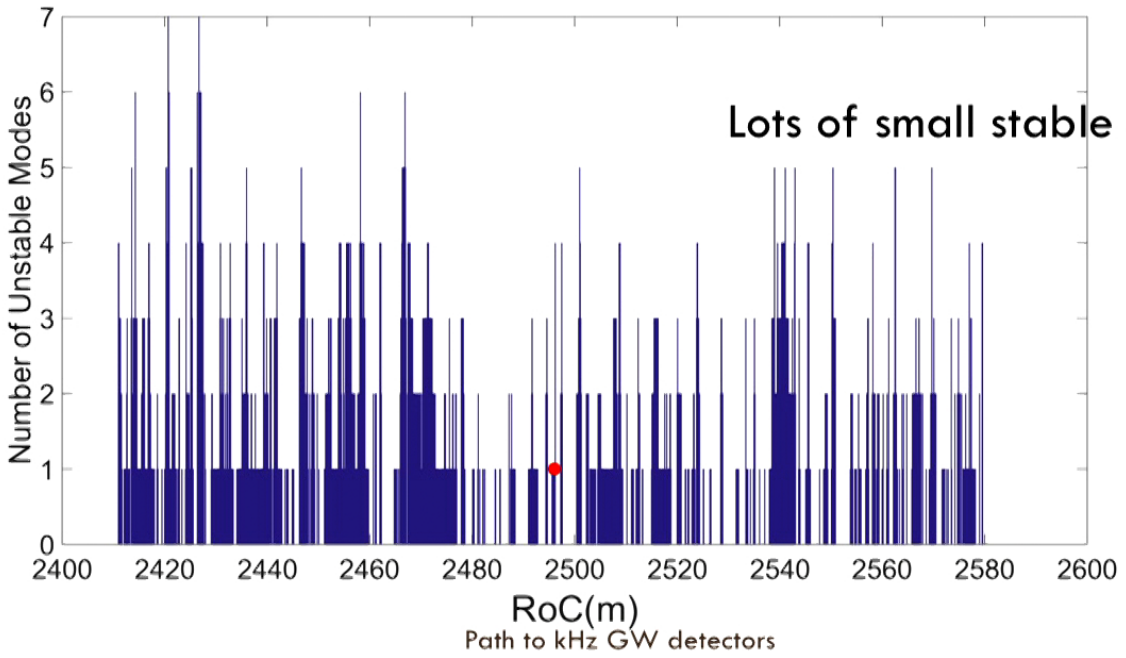
Assuming all high order modes are ***resonant*** in both PRC and SRC



Path to kHz GW detectors

PI simulation for Voyager: Dual-recycling

Assuming all high order modes are ***resonant*** in both PRC and SRC



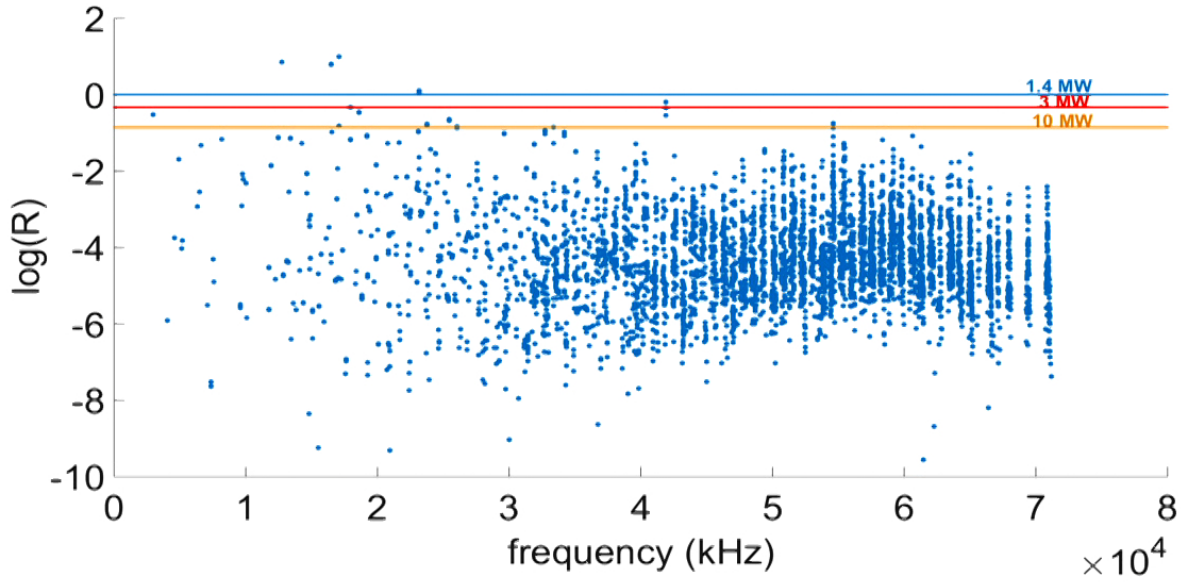
PI simulation for 40km interferometer

Test mass parameters	
Radius of test mass	0.34 m
Thickness of test mass	0.4 m
Mass of test mass	322 kg
Cavity Length	40 km
Beam sizes on ITM/ETM	12 /12 cm

Path to kHz GW detectors

PI simulation for 40km: simple cavity

Parametric Gain

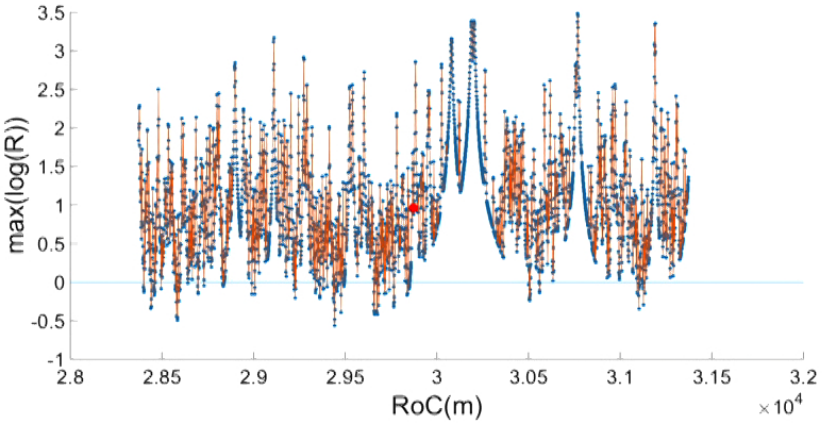


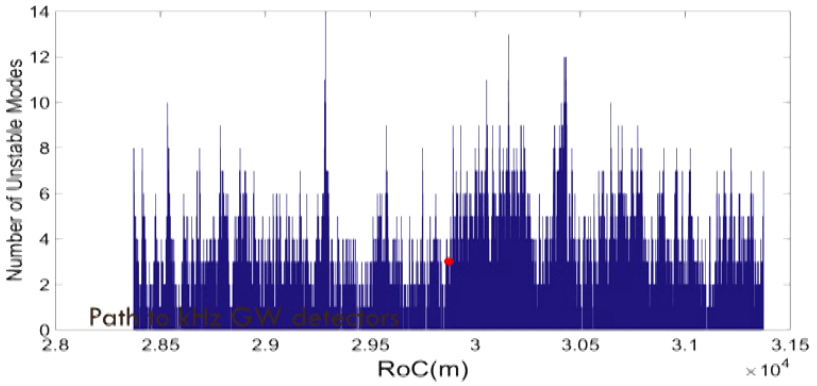
Path to kHz GW detectors

PI simulation for 40km: Dual-recycling

Assuming all high order modes are ***resonant*** in both PRC and SRC, @circulating power 3 MW

Windows of PI-free exit.





PI: Summary

- AMDs are promising to damp almost all unstable acoustic mode for current aLIGO;
- To damp low frequency unstable mode, the AMD may have potential to introduce extra thermal noise in the kHz band;
- Detailed FEM simulation is required to optimize the AMD design and to confirm the thermal noise contribution;
- For future detector design, may consider to choose PI free configuration through simulation, with optimized AMDs included.

Mechanical resonators for optomechanical filters

Requirements: Low mechanical and optical losses

SiN membrane: PRL **116**,147202 (2016)

140 kHz mode Q~100 million,

optical reflectivity>99% with photonic crystal

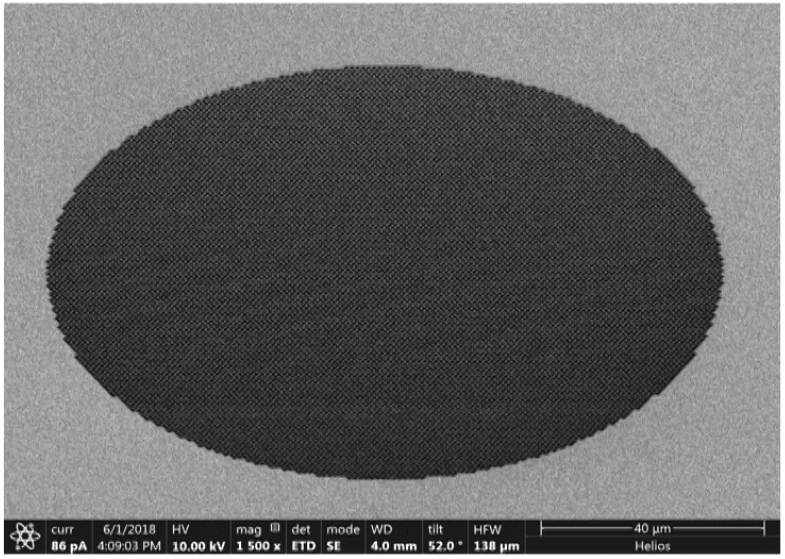
GaAs/AlGaAs:

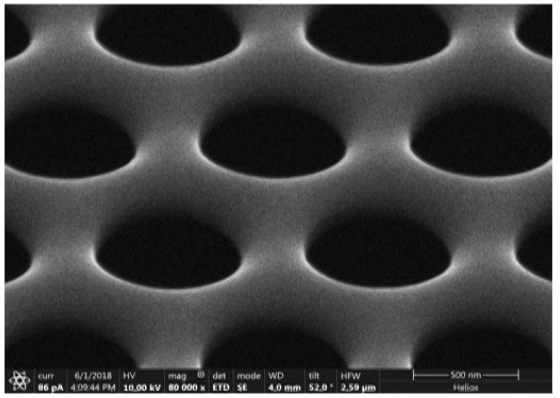
a few hundred Hz mode, Q~10^4; optical loss ~ppm

Next talk by Thomas

Mechanical resonators: SiN

0.1 mm diameter pattern on 200nm think SiN membrane
Machined by Focused Ion Beam (FIB)



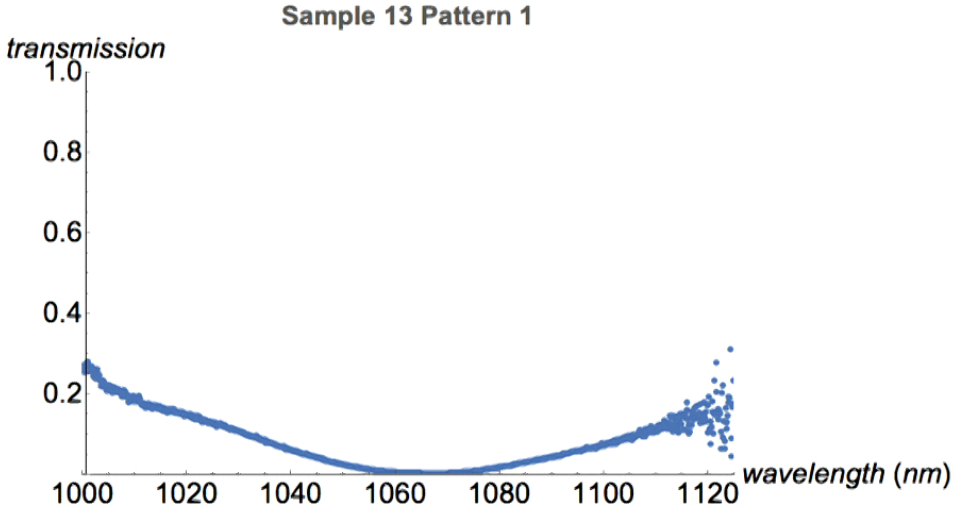


Zoom in of the structure:
~700nm diameter holes;
~1000nm gap.

Path to kHz GW detectors

Mechanical resonators: SiN

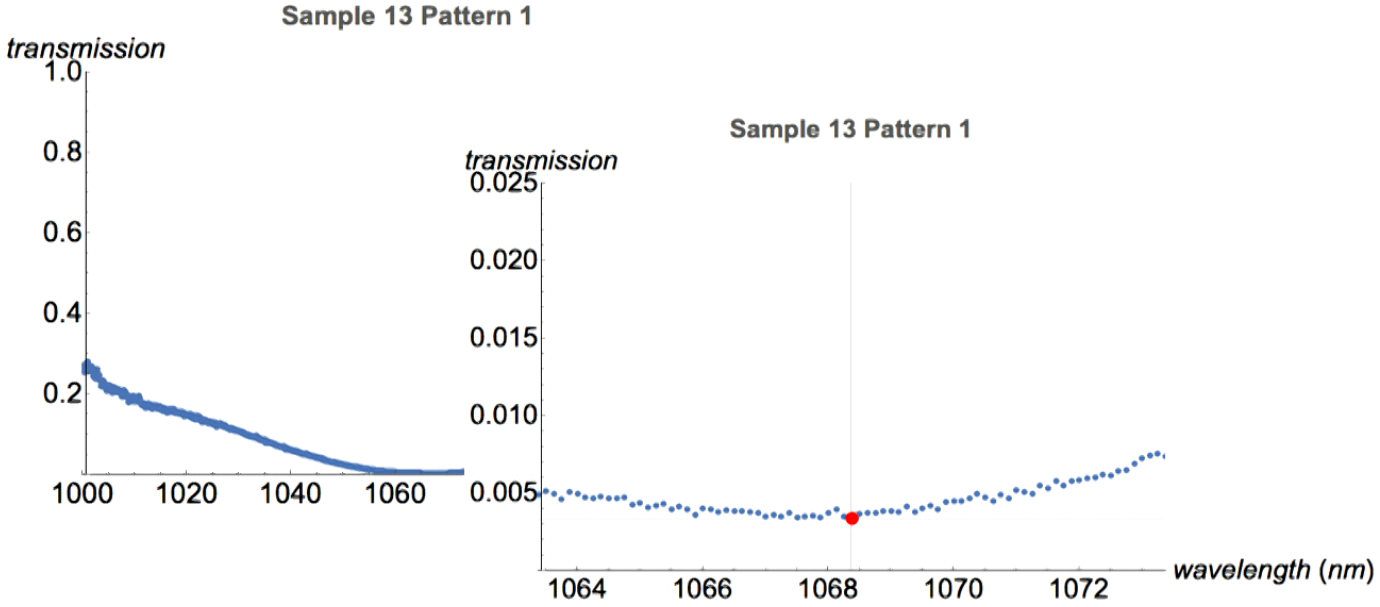
Optical reflectivity



Path to kHz GW detectors

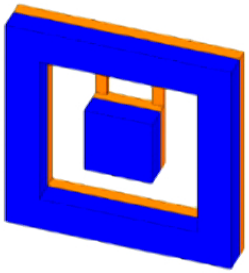
Mechanical resonators: SiN

Optical reflectivity



Path to kHz GW detectors

Mechanical resonators: AlGaAs/GaAs



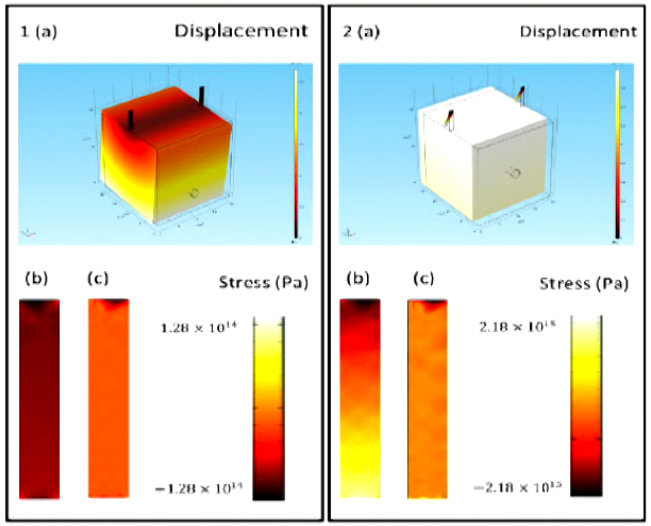
Small mirror suspended by ribbons;
Optical dilution to high effective Q-factors

$$Q_{tot} = \frac{E_{int}+E_{sus}+E_{opt}}{\Delta E_{int}+\Delta E_{sus}}$$

Path to kHz GW detectors

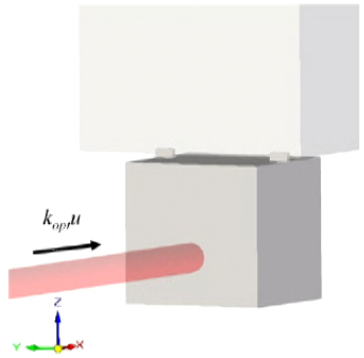
Mechanical resonators

1) Central percussion issue:



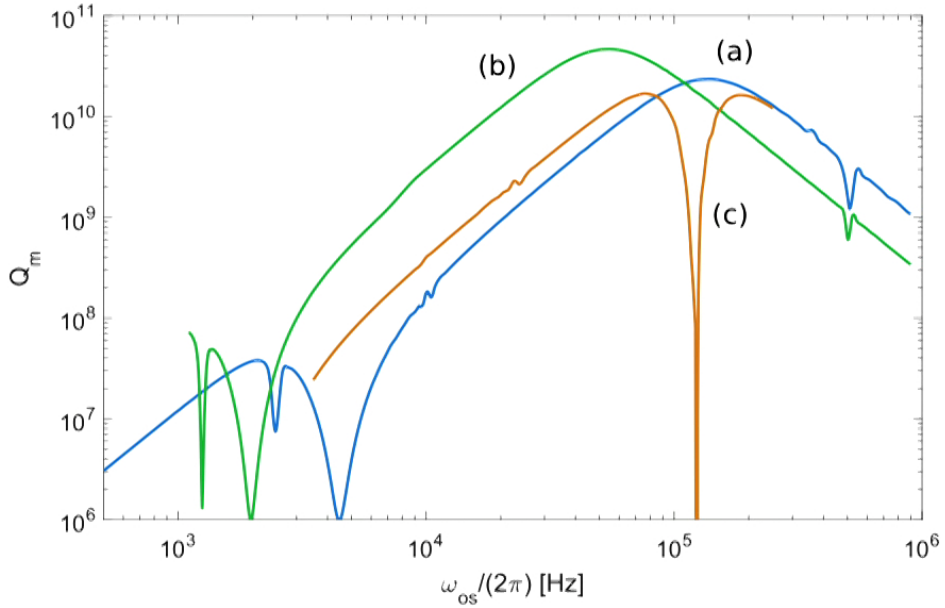
Below central percussion At the central percussion

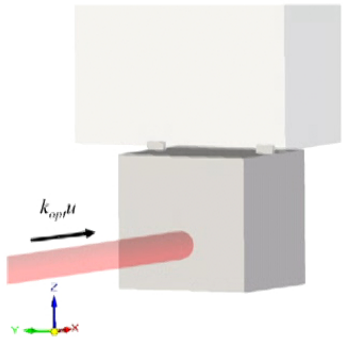
2) Acceleration loss: the optical spring force exciting the internal mode and the energy lost because of mechanical loss of the material.



Path to kHz GW detectors

Mechanical resonators: acc. loss





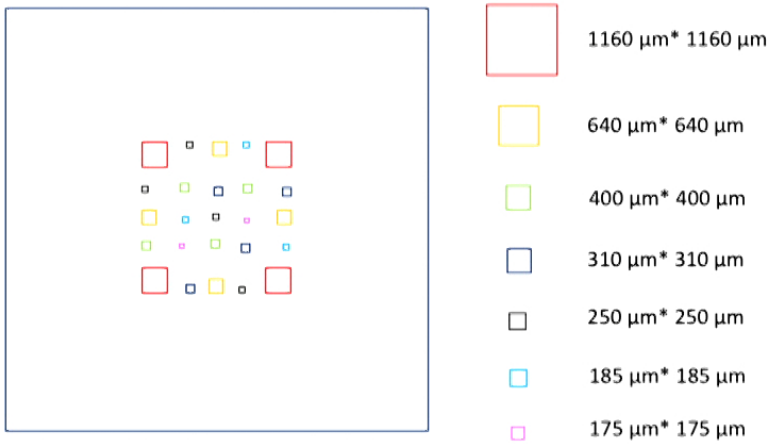
(a): 30 μm square by 10 μm thick. 15 μm x 6 μm x 25 nm ribbon suspension.

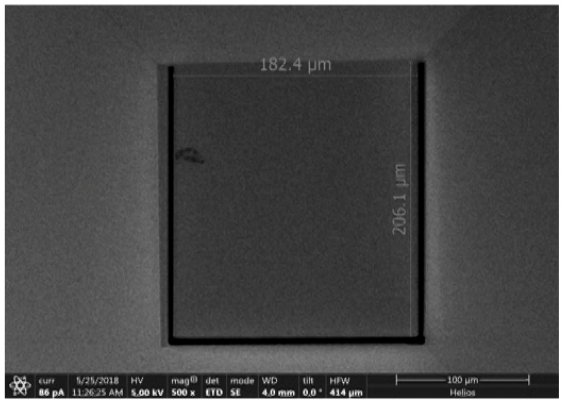
(b): increase to 50 μm square, but other parameters same;

(c): same size mirror as in(a) but the suspension is increased to 30 μm, which causes a problematic transverse suspension mode near $\omega_{opt}/(2\pi) = 170$ kHz.

Path to kHz GW detectors

Mechanical resonators: Fabrication





Multiple 6 µm thick AlGaAs/GaAs windows on a 0.5mm think silicon frame

The first cantilever using FIB cutting; The top of the cantilever will be thinned to suspension ribbons.

Path to kHz GW detectors

Mechanical resonators: summary

- High Q-factor mechanical resonator to meet the requirements of optomechanical filters is difficult to achieve, but, it is possible in principle
- We are still at the starting point.