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LIGO Surf Project Q

Of the Thermal Noise Interferometer

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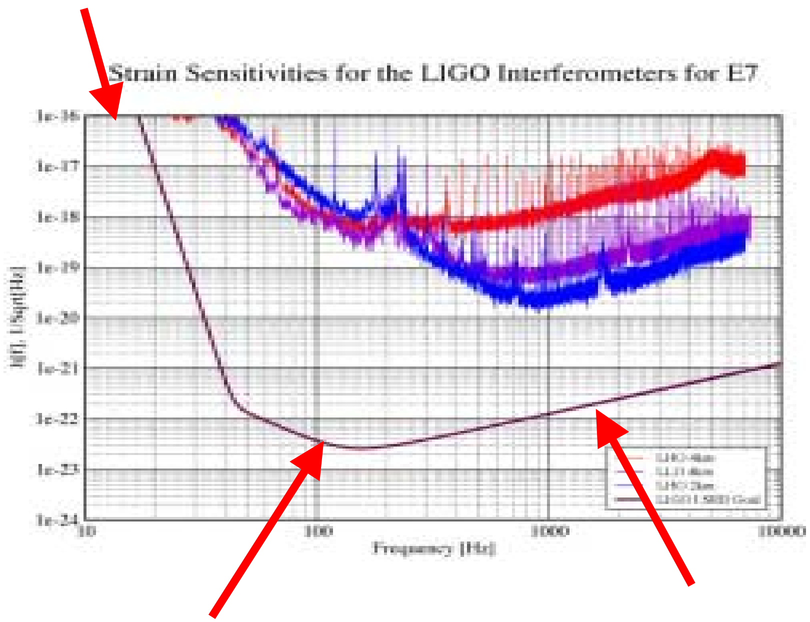
LIGO-G030232-00-D

Why build a Thermal Noise Interferometer?

Seismic Noise (Expected)

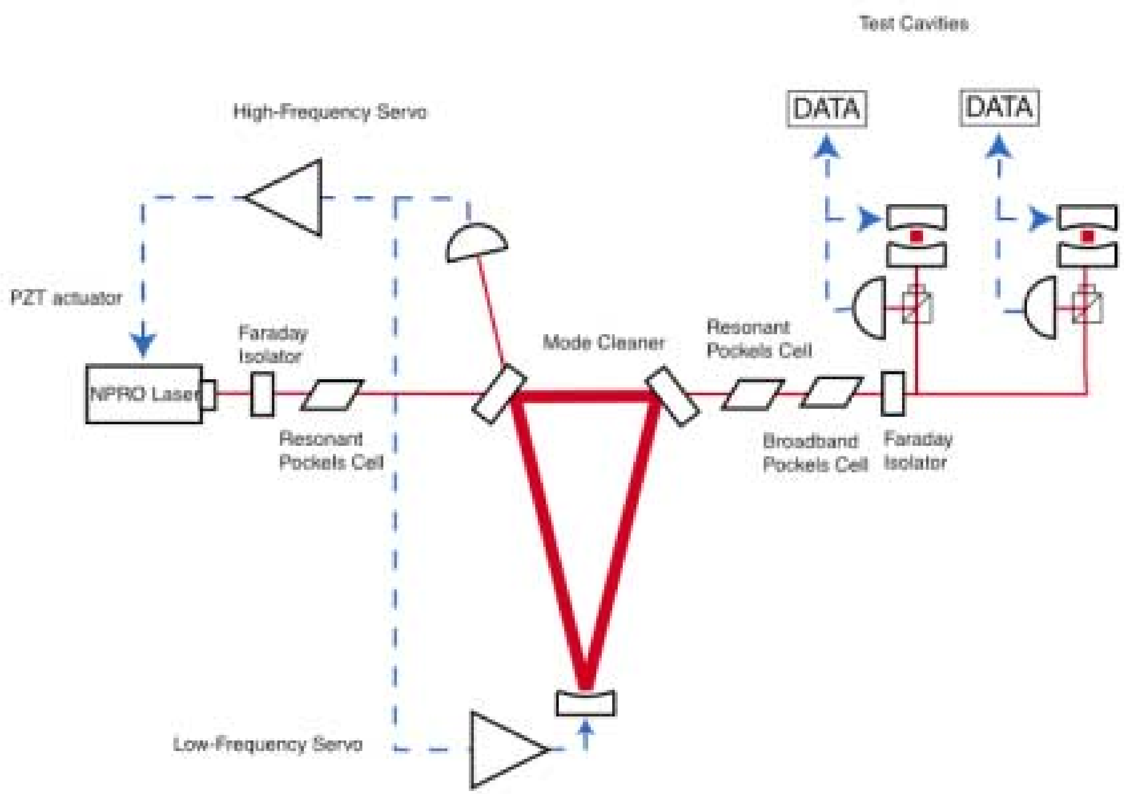


Thermal Noise (Expected)

Shot Noise (Expected)

- Thermal noise is expected to limit the sensitivity of LIGO, and other gravitational-wave detectors, over a crucial range of frequencies (~50-200Hz).
- Broadband thermal noise has not been studied in the high-Q mirrors and suspensions that gravitational-wave detectors use.
- In a small interferometer, we can isolate and study just thermal noise.

TNI Layout


Test Cavities
DATA
DATA
High-Frequency Servo
PZT actuator
Faraday
Isolator
NPRO Laser
Resonant
Pockels Cell
Mode Cleaner
Resonant
Pockels Cell
Broadband
Pockels Cell
Faraday
Isolator
Low-Frequency Servo

Project Goals

1.) To gain an understanding of the Mode vibrations in the fused silica and sapphire mirrors of the TNI.

2.) To measure the Q factor in the fused silica and sapphire mirrors, so that we may be able to make testable predictions for the thermal noise level in the TNI.

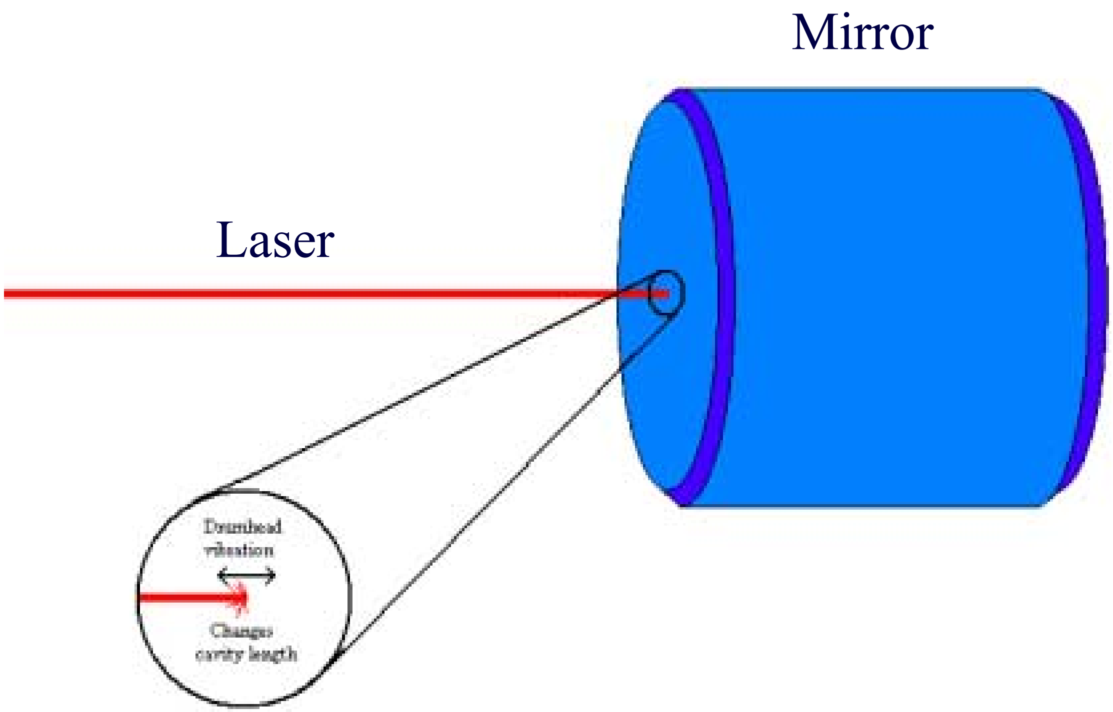
Mode Vibrations in the Mirrors – Part 1

- Mode vibrations = resonant frequencies
- Understanding these vibrations is crucial, because they are included in the current model of thermal noise, which is used to predict the level of thermal noise expected.

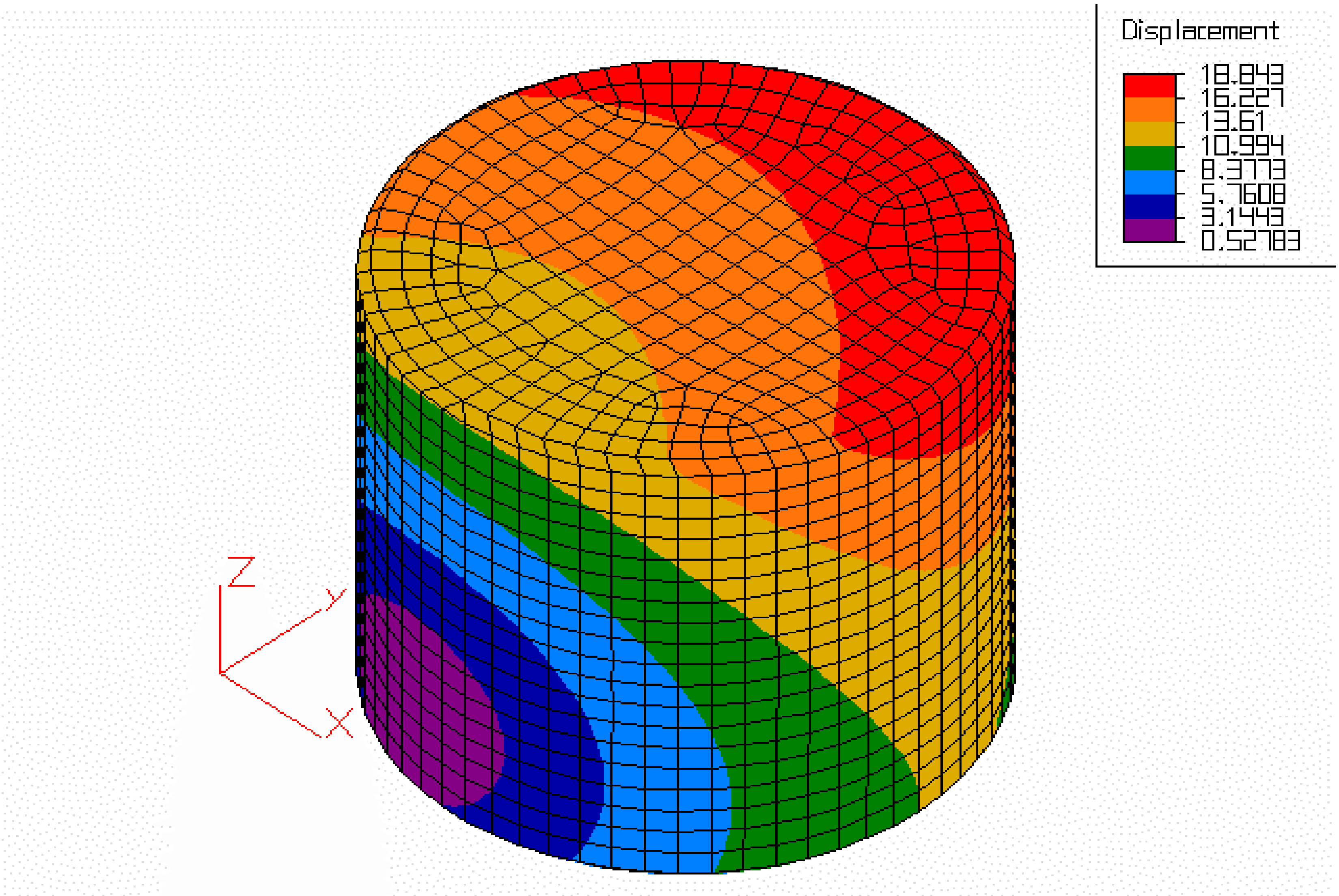
Algor FEA

- Algor software uses Finite Element Analysis to predict the mode vibrations in a material with a given shape and mechanical properties.
- Television mode
- Observed modes

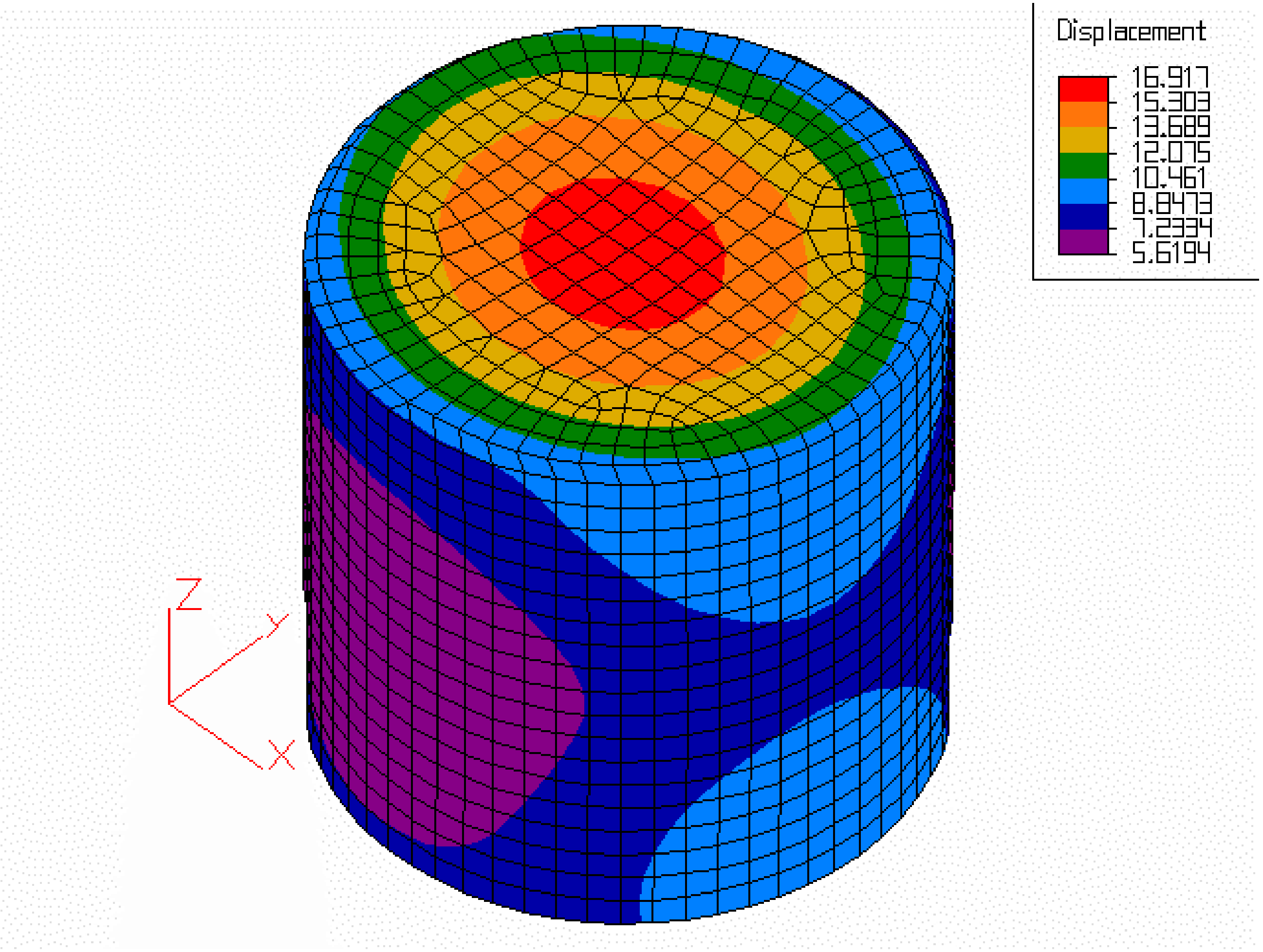
Drumhead vibration



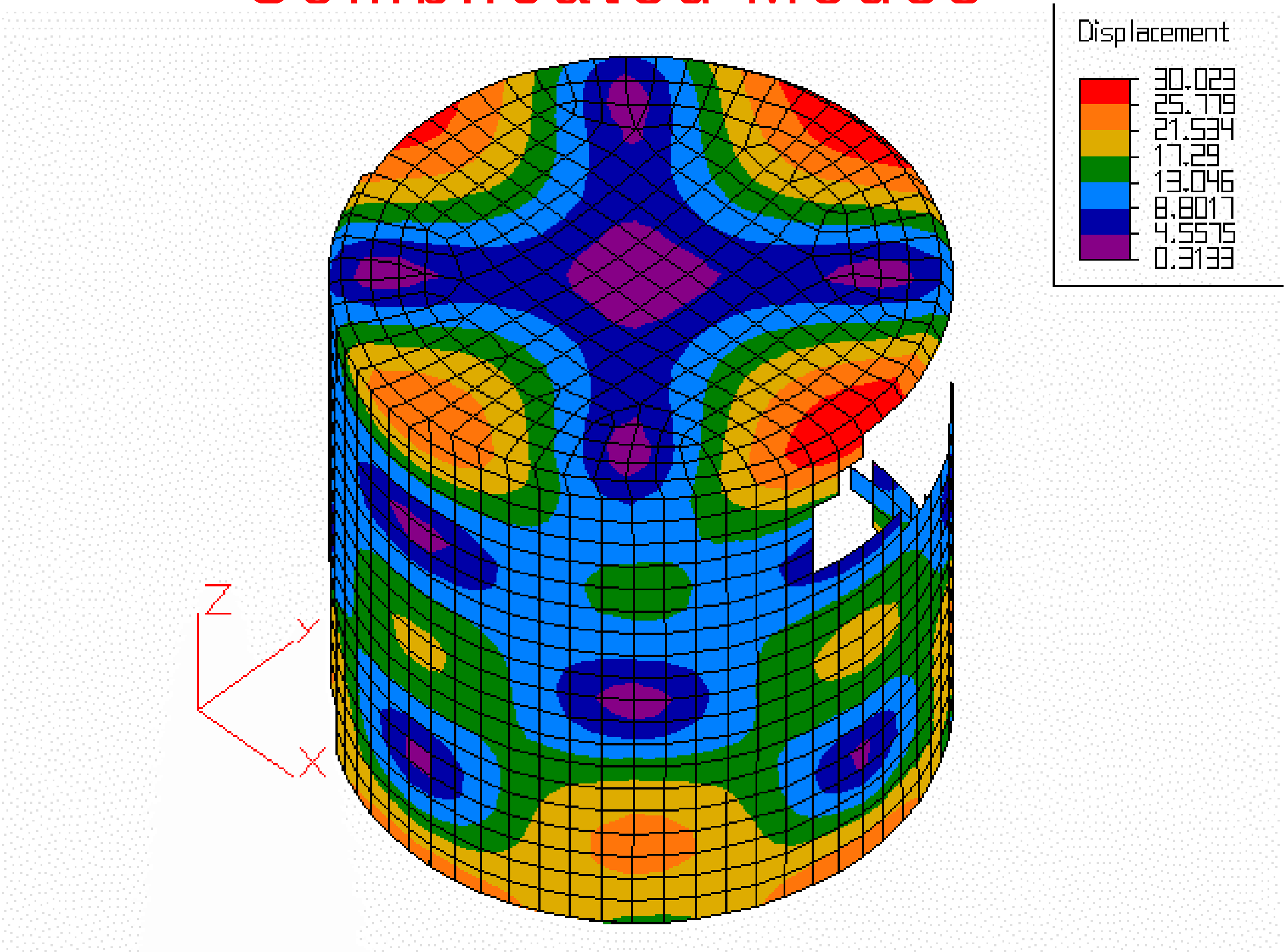
Algor Mode Vibration Simulation: Low Order Modes



Algor Mode Vibration Simulation: 1st, 2nd, 3rd, and 4th Drumhead Modes



Algor Mode Vibration Simulation: Higher Order, Complicated Modes



Uncertainty

- Uncertainty was calculated for the physical constants numerically, using the partial derivatives of the variables and quadrature.
- Uncertainty in the dimensions was calculated analytically.

$$\Delta f = \sqrt{(\Delta E)^2\left(\frac{\partial f}{\partial E}\right)^2 + (\Delta G)^2\left(\frac{\partial f}{\partial G}\right)^2 + (\Delta \sigma)^2\left(\frac{\partial f}{\partial \sigma}\right)^2 + (\Delta L)^2\left(\frac{\partial f}{\partial L}\right)^2}$$

E = Young's Modulus

G = Shear Modulus

σ = Poisson's Ratio

L = Length of mirror

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An Unstable System

- The frequencies of these modes can ring up due to feedback though the servos, and this process can throw the Fabry-Perot cavities out of lock.

Notch Filters

- Lowers the Gain of the control system at the mode frequencies, so that there will be no feedback through the system.
- Frequencies for the sapphire mirrors must be predicted, then notch filters can be ordered.

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Results for Mode Vibration Analysis

Predicted Fused Silica Mode Vibrations				
Mode #	Description	Frequency (kHz)		Actual Frequency
7	Torsional	18.8	☺ 300 Hz	
8	1st Caterpillar	22.9	☺ 300 Hz	
9	1st Caterpillar, 2nd Degeneration	22.9	☺ 300 Hz	
10	1st Butterfly	23.2	☺ 300 Hz	
11	1st Butterfly, 2nd Degeneration	23.2	☺ 300 Hz	
12	1st Shearing	25.4	☺ 300 Hz	
13	1st Shearing, 2nd Degeneration	25.4	☺ 300 Hz	
14	1st Drumhead Mode	27.5	☺ 300 Hz	27.5
15	1st Quadrapole	27.6	☺ 300 Hz	
16	1st Quadrapole, 2nd Degeneration	27.6	☺ 300 Hz	
17	2nd Butterfly	28.6	☺ 300 Hz	
18	2nd Butterfly, 2nd Degeneration	28.7	☺ 300 Hz	
19	2nd Drumhead Mode	30.7	☺ 300 Hz	30.7
20	1st Shrugging	31.2	☺ 300 Hz	
21	1st Shrugging, 2nd Degeneration	31.2	☺ 300 Hz	
22	3rd Drumhead Mode	32.3	☺ 300 Hz	32.6
23	2nd Shrugging	35.4	☺ 300 Hz	
24	2nd Shrugging, 2nd Degeneration	35.4	☺ 300 Hz	
25	3rd Butterfly	37.2	☺ 300 Hz	
26	3rd Butterfly, 2nd Degeneration	37.2	☺ 300 Hz	
27	1st Hexagonal Butterfly	37.3	☺ 300 Hz	
28	1st Hexagonal Butterfly, 2nd Deg.	37.3	☺ 300 Hz	
29	2nd Torsional	37.4	☺ 300 Hz	
30	1st Breathing Mode	37.6	☺ 300 Hz	
31	2nd Hexagonal Butterfly	38.8	☺ 300 Hz	
32	2nd Hexagonal Butterfly, 2nd Deg.	38.8	☺ 300 Hz	
33	2nd Shearing	39.0	☺ 300 Hz	
34	2nd Shearing, 2nd Degeneration	39.0	☺ 300 Hz	
35	4th Drumhead Mode	40.5	☺ 300 Hz	40.7
36	1st Hexpole Mode	42.4	☺ 300 Hz	
...	...	...		

Predicted Sapphire Mode Vibrations				
Mode #	Description	Frequency (kHz)		Actual Frequency
7	Torsional	30.3	+ 4 kHz	Unknown for
8	1st Butterfly	36.1	+ 4 kHz	All Sapphire Modes
9	1st Caterpillar	36.9	+ 4 kHz	
10	1st Caterpillar, 2nd Degeneration	36.9	+ 4 kHz	
11	1st Butterfly, 2nd Degeneration	37.6	+ 4 kHz	
12	1st Shearing	41.3	+ 4 kHz	
13	1st Shearing, 2nd Degeneration	41.3	+ 4 kHz	
14	1st Quadrapole	42.4	+ 4 kHz	
15	1st Drumhead Mode	42.6	+ 4 kHz	
16	1st Quadrapole, 2nd Degeneration	44.5	+ 4 kHz	
17	2nd Butterfly	45.0	+ 4 kHz	
18	2nd Butterfly, 2nd Degeneration	46.3	+ 4 kHz	
19	1st Shrugging	51.7	+ 4 kHz	
20	1st Shrugging, 2nd Degeneration	51.7	+ 4 kHz	
21	2nd Drumhead Mode	52.2	+ 4 kHz	
22	3rd Drumhead Mode	55.0	+ 4 kHz	
23	2nd Shrugging	56.9	+ 4 kHz	
24	2nd Shrugging, 2nd Degeneration	56.9	+ 4 kHz	
25	1st Hexagonal Butterfly	59.4	+ 4 kHz	
26	1st Hexagonal Butterfly, 2nd Deg.	59.5	+ 4 kHz	
27	3rd Butterfly	59.8	+ 4 kHz	
28	2nd Torsional	60.4	+ 4 kHz	
29	3rd Butterfly, 2nd Degeneration	60.8	+ 4 kHz	
30	2nd Hexagonal Butterfly	61.4	+ 4 kHz	
31	2nd Hexagonal Butterfly, 2nd Deg.	61.4	+ 4 kHz	
32	2nd Shearing	63.4	+ 4 kHz	
33	2nd Shearing, 2nd Degeneration	63.4	+ 4 kHz	
34	4th Drumhead Mode	65.1	+ 4 kHz	
35	1st Hexpole Mode	67.5	+ 4 kHz	
36	1st Hexpole Mode, 2nd Degeneration	67.6	+ 4 kHz	
37	1st Breathing Mode	71.9	+ 4 kHz	
...	...	...		

- All information found on this analysis will be available in a paper submitted to the Document Control Center (DCC).

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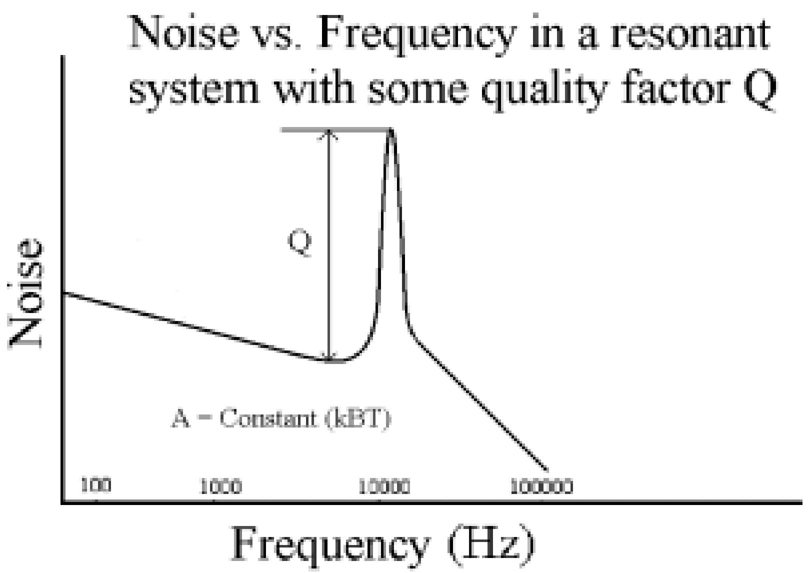
The "Q" in Project Q – Part 2

- The Q, or Quality factor is the measure of how much an object damps vibrations in it.
- A high Q means vibrations continue for a long time.

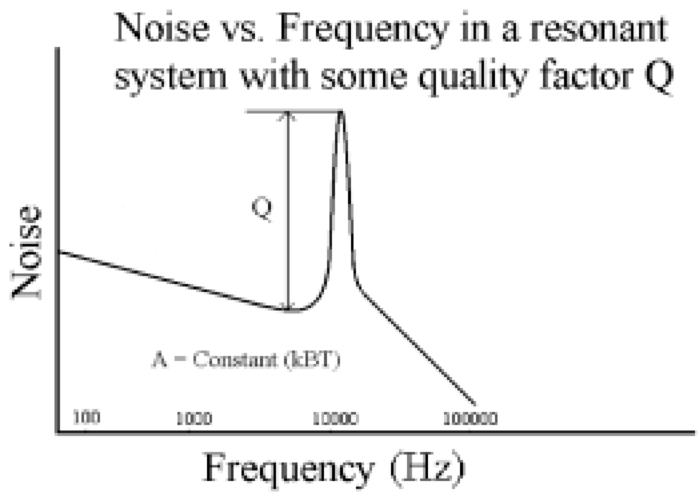
Q and thermal noise.

- Q is also the measure of the difference between the on and off resonance noise level in a system.
- High Q materials were chosen so that the noise level off resonance is low.



The Fluctuation-Dissipation Theorem

- This is a prediction of the fluctuation-dissipation theorem, which relates thermal energy in a material to noise levels. (Assumption of a constant loss angle $\Phi(\omega)$.)
- With this relation, the Q factor can be used to make testable predictions for the thermal noise floor level in the TNI.



Fluctuation-dissipation equation

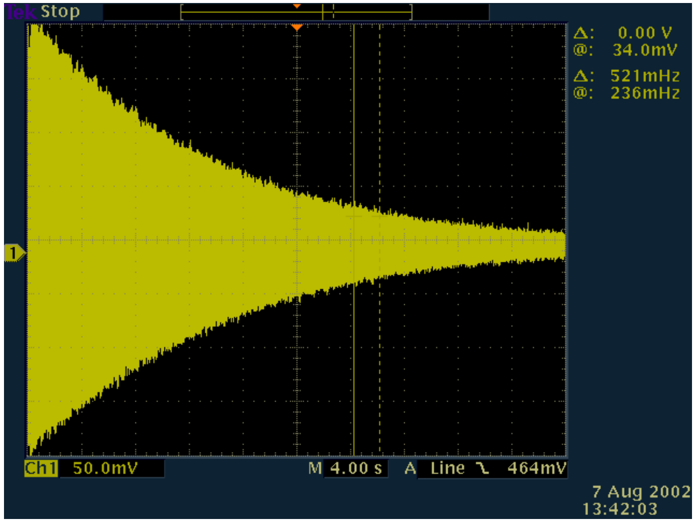
$$x^2 = \frac{4k_B T k \phi(\omega)}{\omega\left[\left(k - m\omega^2\right)^2 + k^2\phi^2\right]}$$

$$Q = \frac{1}{\phi(\omega_0)}$$

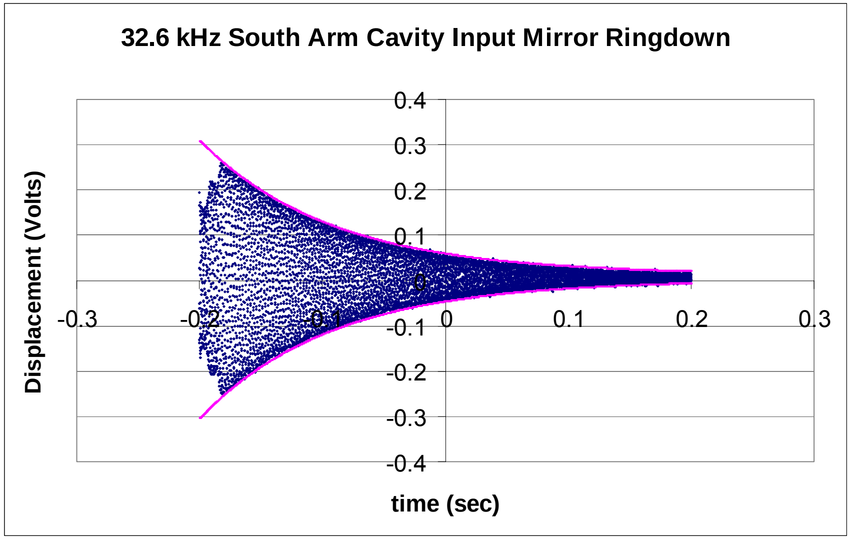
(Saulson)

Measuring the Q

- The Q factor is measured by ringing up the mirrors, and then watching the decay of their vibrations at the resonant frequencies.
- This can be done by introducing white noise at the resonant frequency electronically.



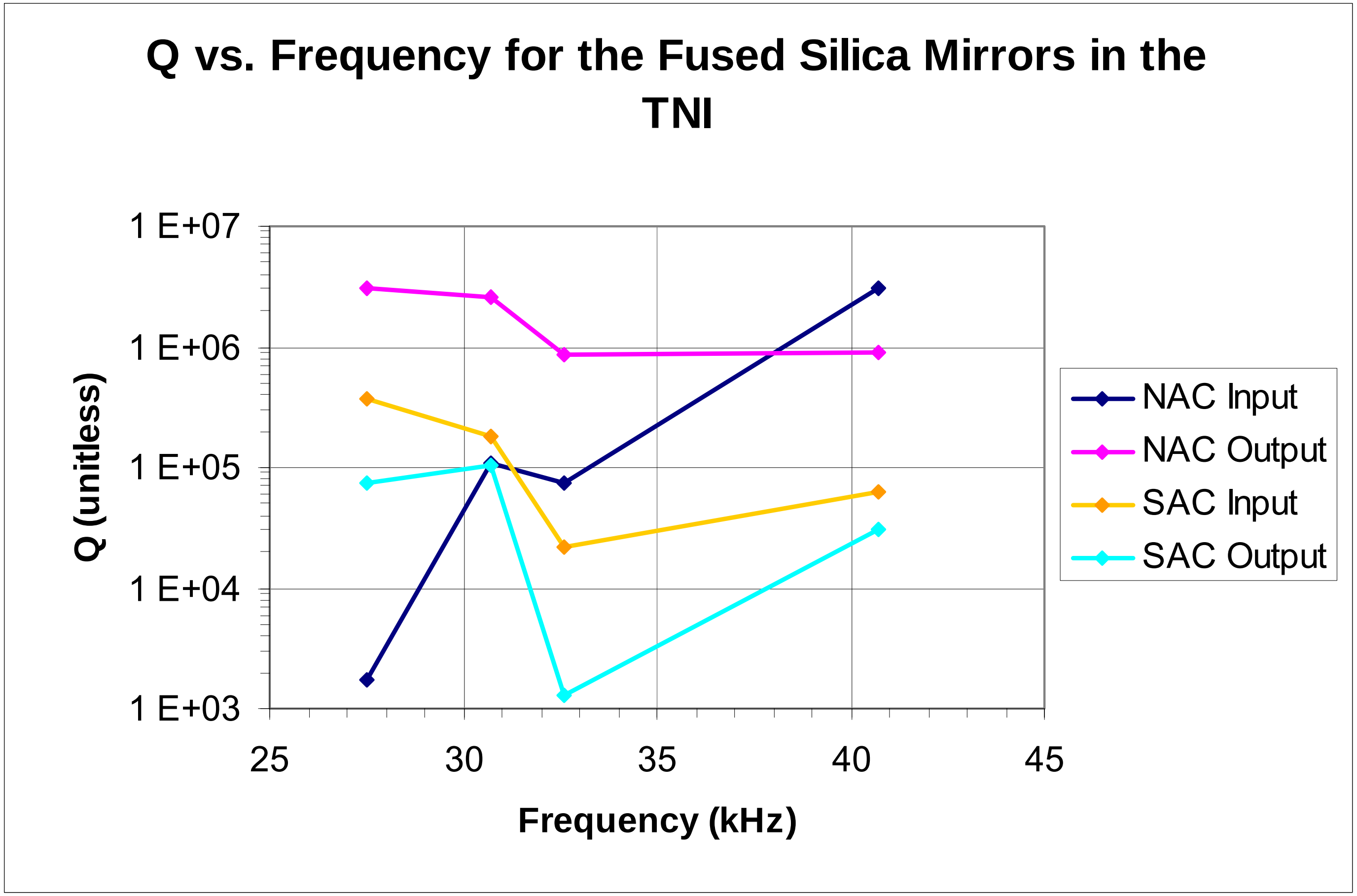
Osciliscope Screenshot of a Ringdown



Measuring the Ringdown in Excel using a curve fit

Results

- Q measurements were found to vary from 1700 to over 3 million.



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Conclusions I

- We have accurately modeled the vibration modes of the TNI's test masses. Observed resonant frequencies agree well with predictions.
- Observed mirror Q's varied by more than three orders of magnitude. This variation was seen both between mirrors for the same mode and between modes in the same mirror.
- Our naïve assumptions that both Q=1/♐☎◆) and that ♐☎◆✆ is constant do not appear to be valid in this system.

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Conclusions II

- Several possibilities for explanation.
  - -Violin mode of suspension wire.
  - -Resonant mode in servo magnets.
  - -Mirror Coating losses.
- Unknown explanation for apparent correlations.

Future Work

- Determining the cause of the large Q variation.
- Determining new model to relate Q to the level of thermal noise.
- Taking more Q measurements at different frequencies and on different modes.

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