Mechanical Loss of TRA-DUCT 2902 Epoxy

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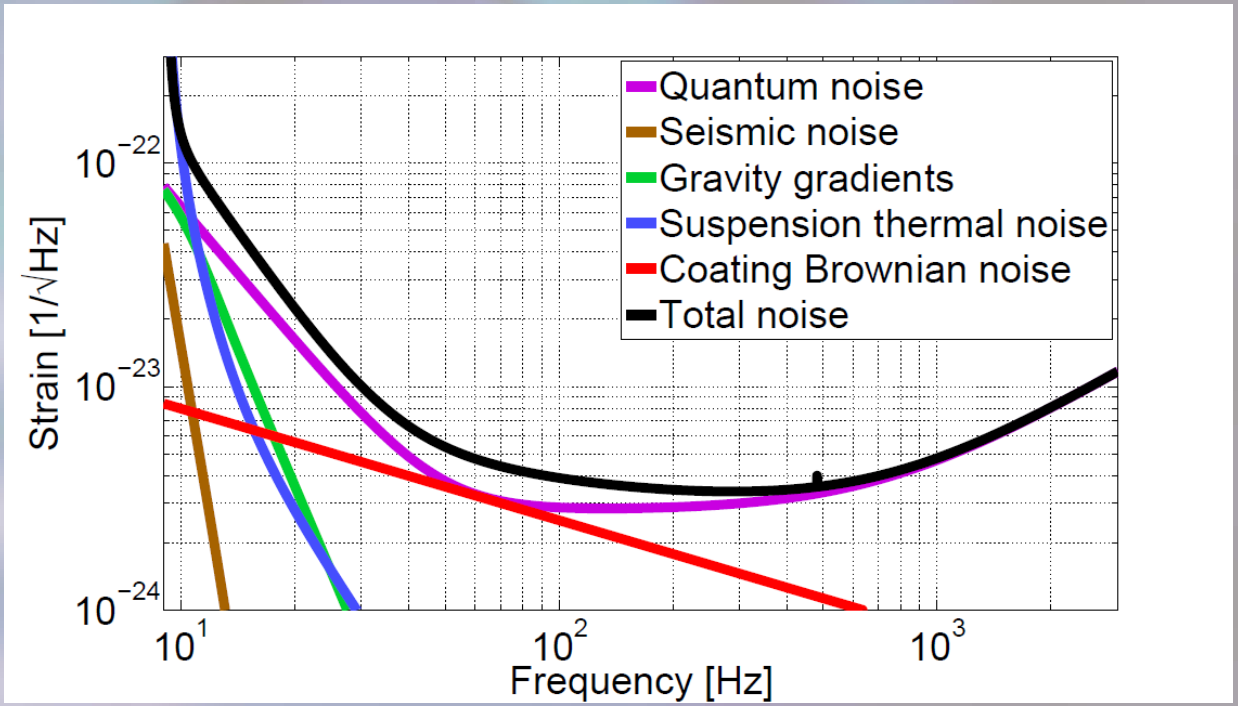
LVC Meeting
Bethesda Maryland
March 18, 2013

LIGO-G1300207

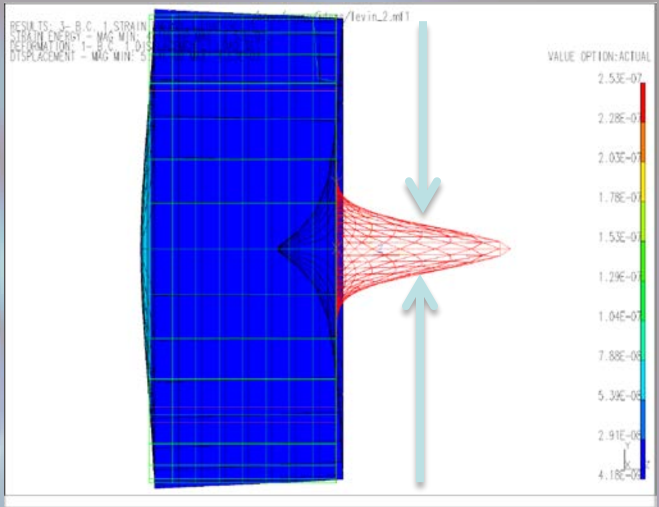
Advanced LIGO Core Optics

- Advanced LIGO test mass properties are expected to be major contributors to sensitivity across most frequency bands
- High optical power is necessary for low quantum noise at mid and high frequencies
- Thermal noise from mechanical loss in the test masses important at mid frequencies
- Any changes to the test masses must be made carefully

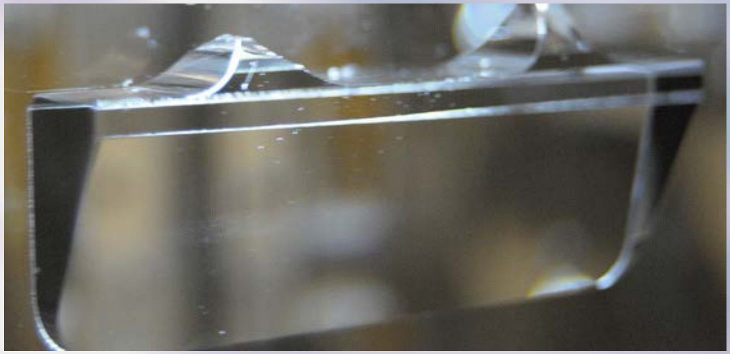


Test Mass Thermal Noise

- Primary contributor to test mass thermal noise is mechanical loss in optical coatings
- Large beam spot sizes reduce this thermal noise
  - Employed in Advanced LIGO
  - ETM 6.2 cm, ITM 5.5 cm
  - Test mass radius 17 cm

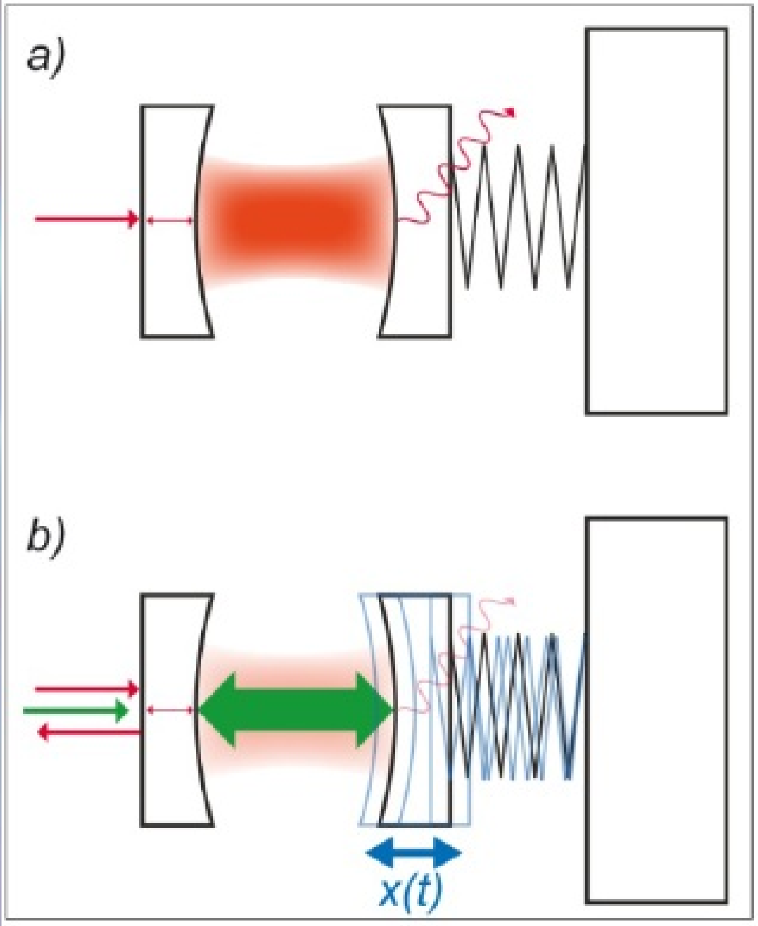


- Suspension must be connected to test masses
- Silicate bonding used to reduce thermal noise
  - Silicate bond still has high mechanical loss
  - Keep area of bond small
  - Bonding region far from readout beam location



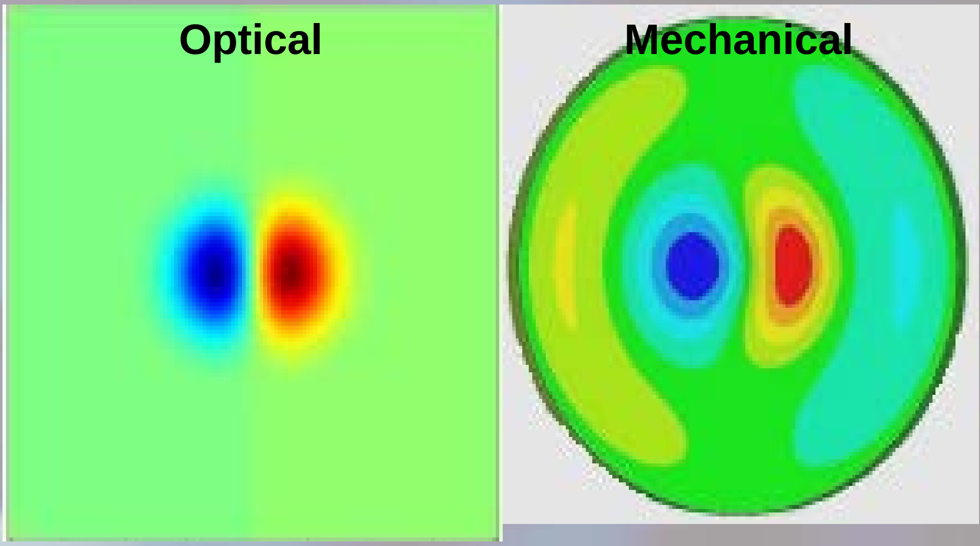
Parametric Instability

- Exchange of energy between optical cavity modes and acoustic test mass modes
- Radiation pressure from stored light can ring up acoustic modes to high amplitudes
- High modal amplitudes can cause lock loss
- Mitigation not part of Advanced LIGO project but considered for post-project upgrade
  - See T1300176



Instability Criteria

$$R \propto \frac{PQ\Lambda}{1 + \Delta\omega^2/\delta^2}$$

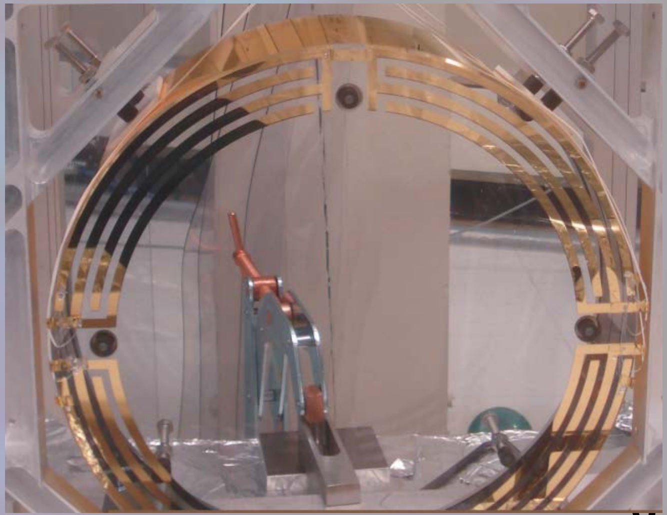


- R characterizes stability
- $R > 1$ means parametric instability occurs

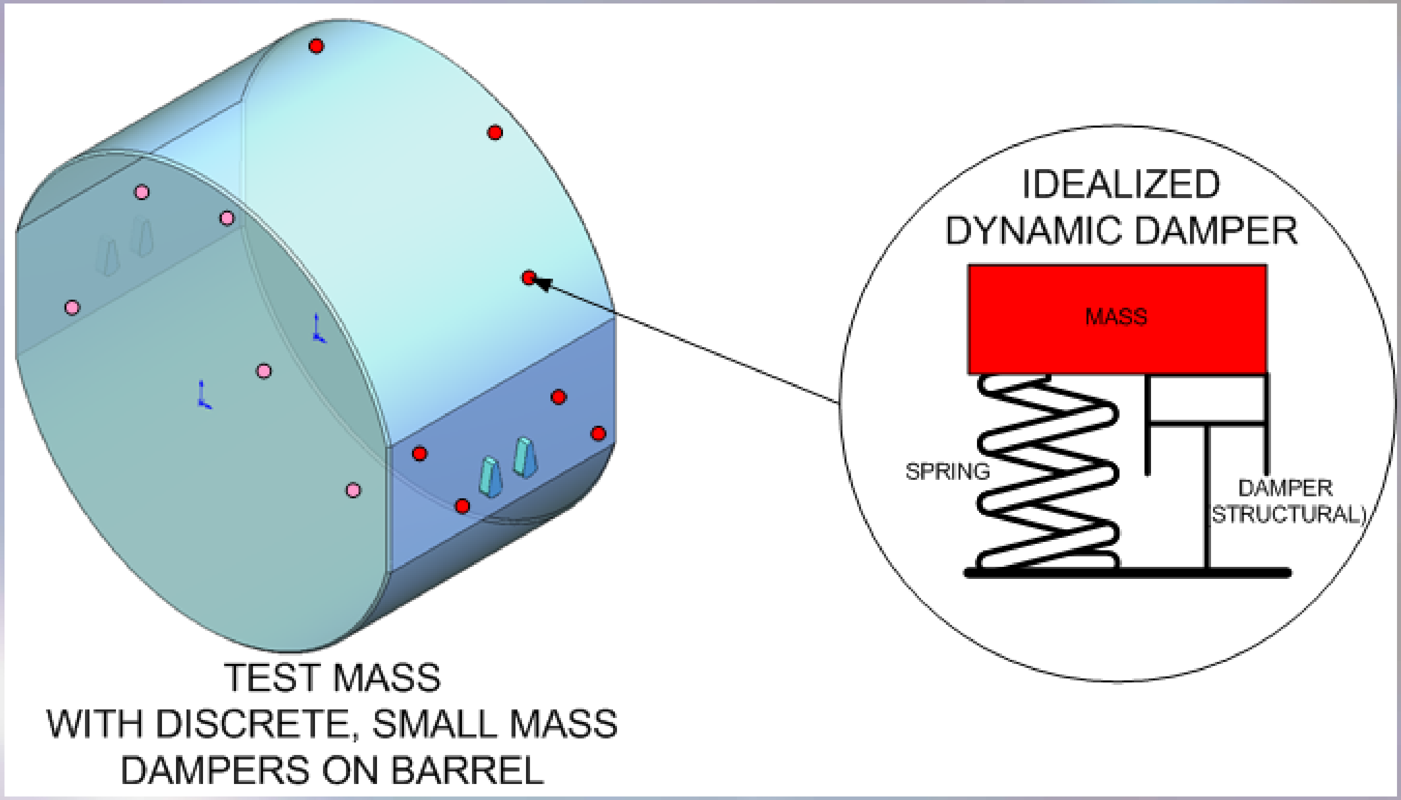
- Low thermal noise requires low mechanical loss
  - High Q , the modal quality factors
- Low thermal noise requires large spot sizes
  - High overlap, Λ, between optical and mechanical modes
- High power, P, needed to reduce quantum noise
- Modes must be close in frequency, $\Delta\omega^2/\delta^2$, as well as shape

Mitigation of Parametric Instability

- Mirror radius of curvature can be tuned using ring heaters
  - Changes frequency of optical modes
  - Ring heaters already in place
- Electrostatic drive can be used to actuate on mechanical modes
  - Damp out modes as they excite
  - Electrostatic drive already in place
- Attach mechanical mode dampers to test masses
  - Reduce mechanical Q's
  - Dampers would need to be installed
- T1300176 prioritizes these for post project upgrades as
  - 1- ring heater, 2- electrostatic drive, 3- dampers



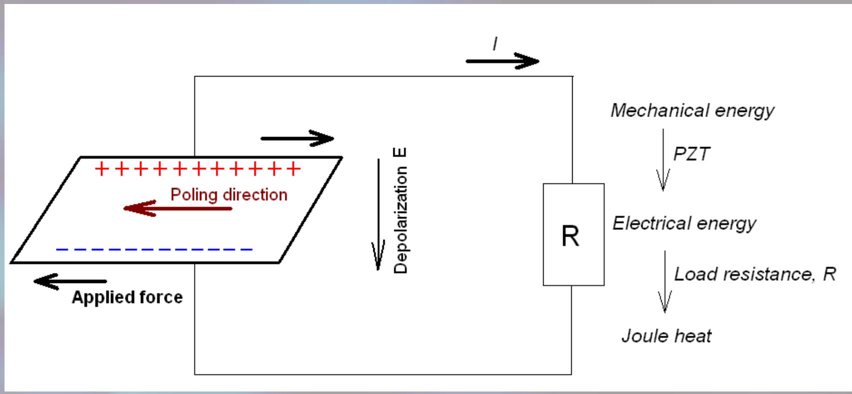
Mechanical Mode Damping

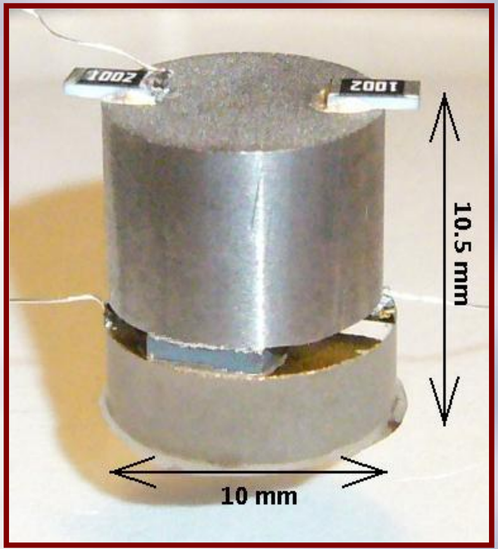


- Dampers at specific frequencies attached at small number of places on test mass
- Small number of dampers can lower Q on most problematic modes

Mechanical Mode Damper Design

- Reaction mass attached to piezoelectric crystals (PZTs)
  - Resonant frequency tuned to test mass mode frequency
- PZTs connected to silica base
- PZTs stressed in shear during resonant motion





- PZTs generate voltage when stressed
- Resistor shunted across PZT to dissipate energy into heat
- Epoxy used to connect PZT to base and reaction mass as well as base to test mass
  - Silicate bonding not practical in a retrofit

LASTI Results

- Tests done at LASTI in 2010 by S. Gras and LASTI team
- Two dampers connected to LASTI test mass
  - Used EP30 epoxy

- Even without shunting PZTs, dampers reduce most mode Q's
- Epoxy mechanical loss largest contributor to damper loss
- Thermal noise from dampers (100 Hz)

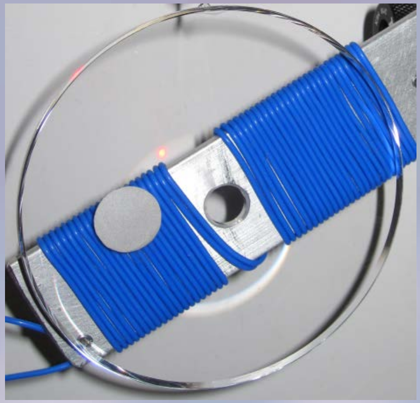
$$1.3 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$$

- Advanced LIGO thermal noise limit (100 Hz)

$$5.2 \times 10^{-21} \mathrm{m}/\sqrt{\mathrm{Hz}}$$

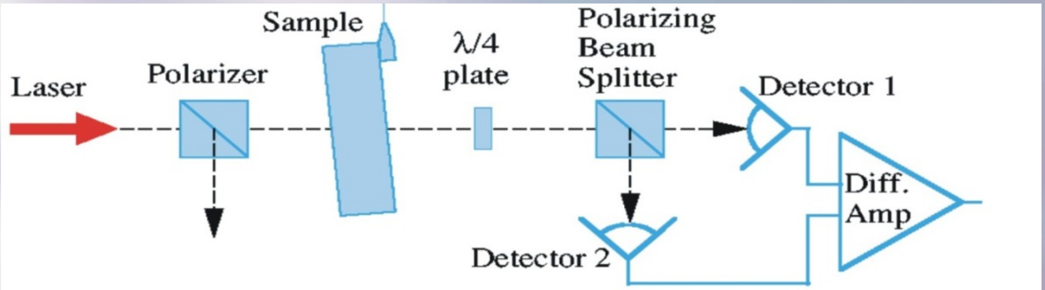
- Unacceptable thermal noise increase
- Need lower mechanical loss epoxy
- All results from G1001023

Epoxy Q Measurements

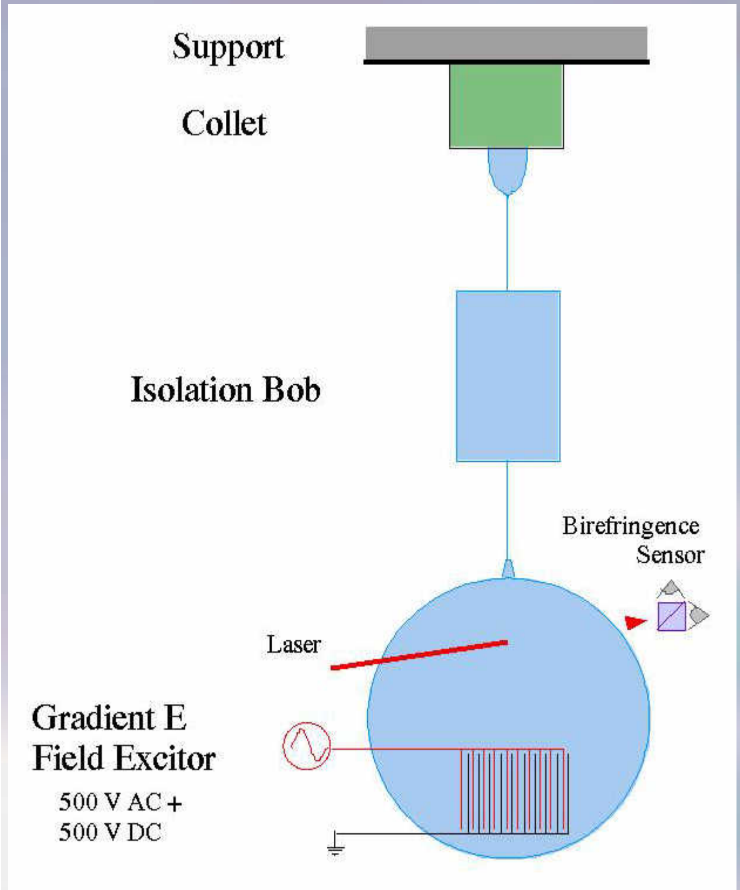


- American University Q measuring apparatus
  - Study epoxy mechanical loss
- Silica sample with epoxy spot
- Vacuum chamber to reduce air interaction
- Capacitive comb excites modes of silica samples with epoxy

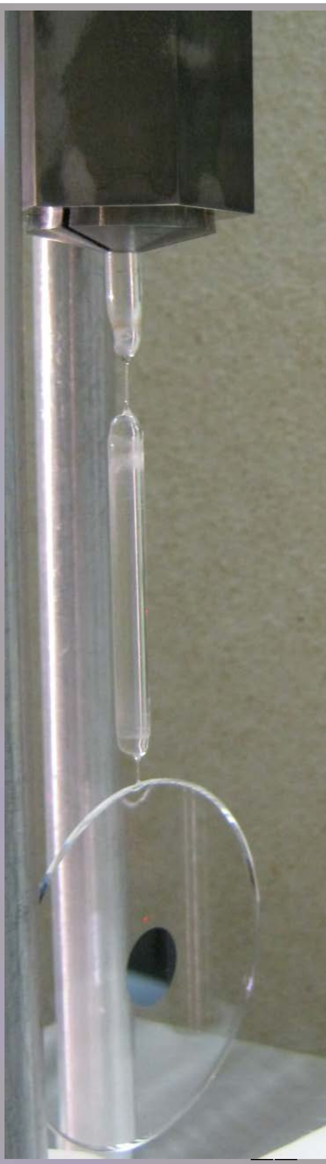
- Birefringence readout sensitive to stress in samples
- Measurements summer of 2012 limited by environmental coupling
  - New, larger bell jar and support table installed fall 2012



Sample Suspension



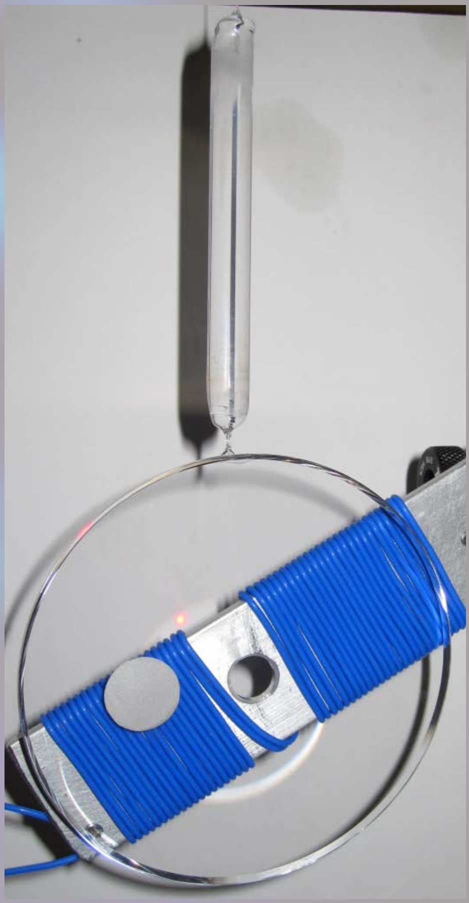
- Monolithic silica suspension used to reduce mechanical loss
- Intermediate bob between collet and sample reduce coupling to environment
- Silica fibers between clamped bob and intermediate bob and sample



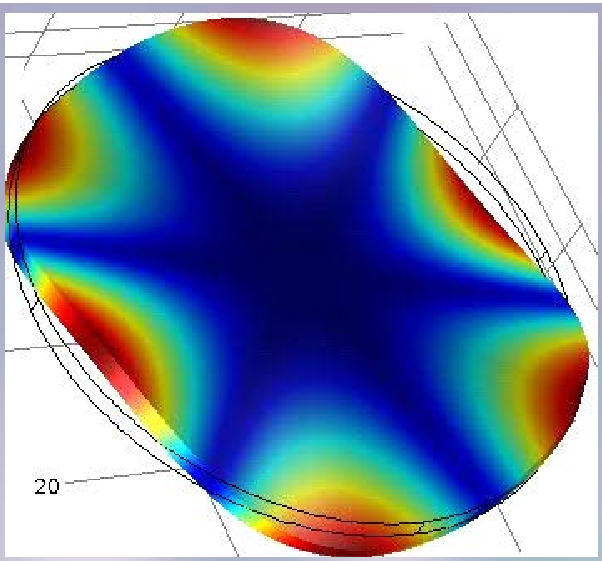
- Fiber welded to silica sample mechanical loss
- Hydrogen torch used to draw fibers and weld sample

Epoxy Sample

- TRA-DUCT 2902 conducting epoxy
  - Suggestion from S. Gras
- Positioned off center of silica disk
  - Silica disk 3 inch diameter, 0.1 inch thick
  - Epoxy position chosen to couple elastic energy to epoxy while keeping Q's in measurable range
- Thin silica top piece keeps epoxy boundary conditions as in damper
  - 100 μm thick, 0.5 inch diameter
- Epoxy applied as single drop then pressed by hand with top piece
- Epoxy thickness 0.140 mm
- Epoxy hardened at room temperature for > 5 days



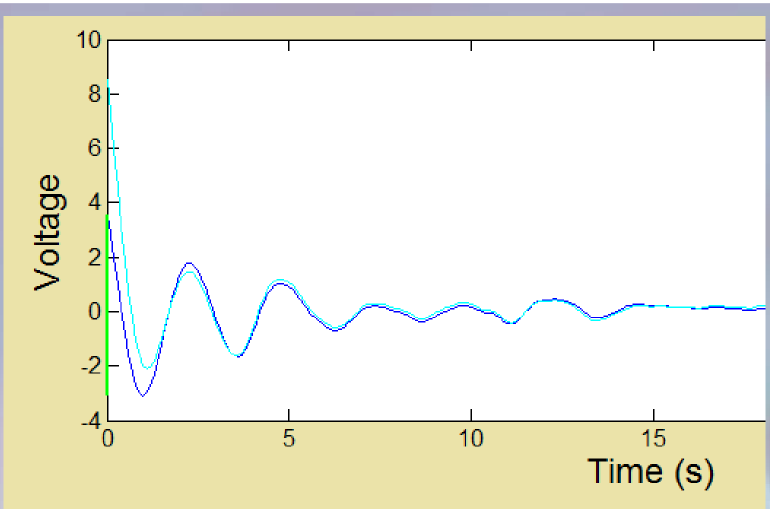
Finite Element Model



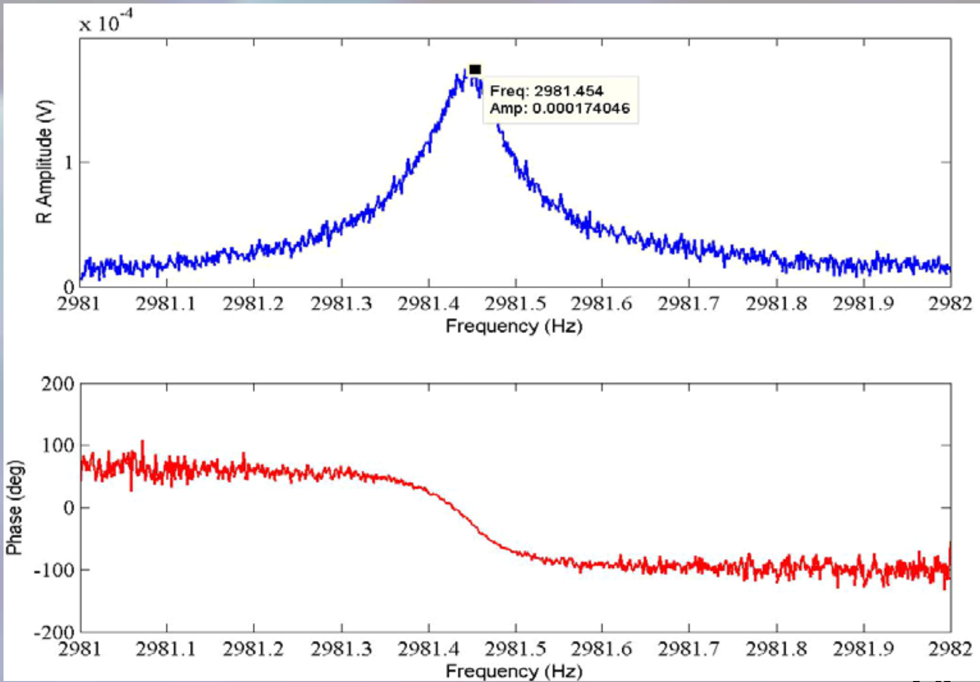
- Finite element models of oscillations calculated to determine energy in epoxy
- First 94 modes calculated
- Epoxy properties from manufacturers data sheet
  - Young's modulus 260 MPa
  - Density 3193 kg/m^3
  - Poisson ratio 0.4
- Shear and bulk elastic energy in epoxy calculated for each mode
  - >80% of energy in shear for all modes
  - >98% in shear for all measured modes
- Frequency predictions compared to experimental results
  - Degenerate mode splitting not predicted
  - Poor agreement not understood

Mode	FEA (Hz)	Exp. (Hz)
n=0, ℓ=1	2682	2707.5
	2683	2981.5
n=1, ℓ=0	4065	4137.5
n=0, ℓ=3	6131	6157.6
	6133	6312.8
n=1, ℓ=1	9384	9457.8
Shear	36794	37071.2
	36818	37155.1

Q Measurements



- Typical ringdown times ~ 2 second
  - Too short for good fits
- Frequency domain data collected from driving near modal frequencies



- FWHM fit by hand

$$Q = \frac{f_0}{\text{FWHM}}$$

- Working on complete fit of peaks with Matlab
- Measured mostly low frequency (< 10 kHz)
  - Shear modes at 37 kHz measured

Q Results

Mode	Frequency (Hz)	Q $(\times 10^4)$	% of Energy in Epoxy
n=0, ℓ=1	2707.5	1.76	0.11
	2981.5	2.07	0.09
n=1, ℓ=0	4137.5	1.63	0.11
n=0, ℓ=3	6157.6	4.11	0.09
	6312.8	5.49	0.08
n=1, ℓ=1	9457.8	2.15	0.07
Shear	37071.2	9.51	0.04
	37155.1	8.64	0.04

- Q of bare silica measured > 10 million
- Not used in fitting for epoxy mechanical loss

Loss Angle Calculation

$$\varphi_{\mathbf{epoxy}} = \frac{\mathbf{1}}{a\,Q}$$

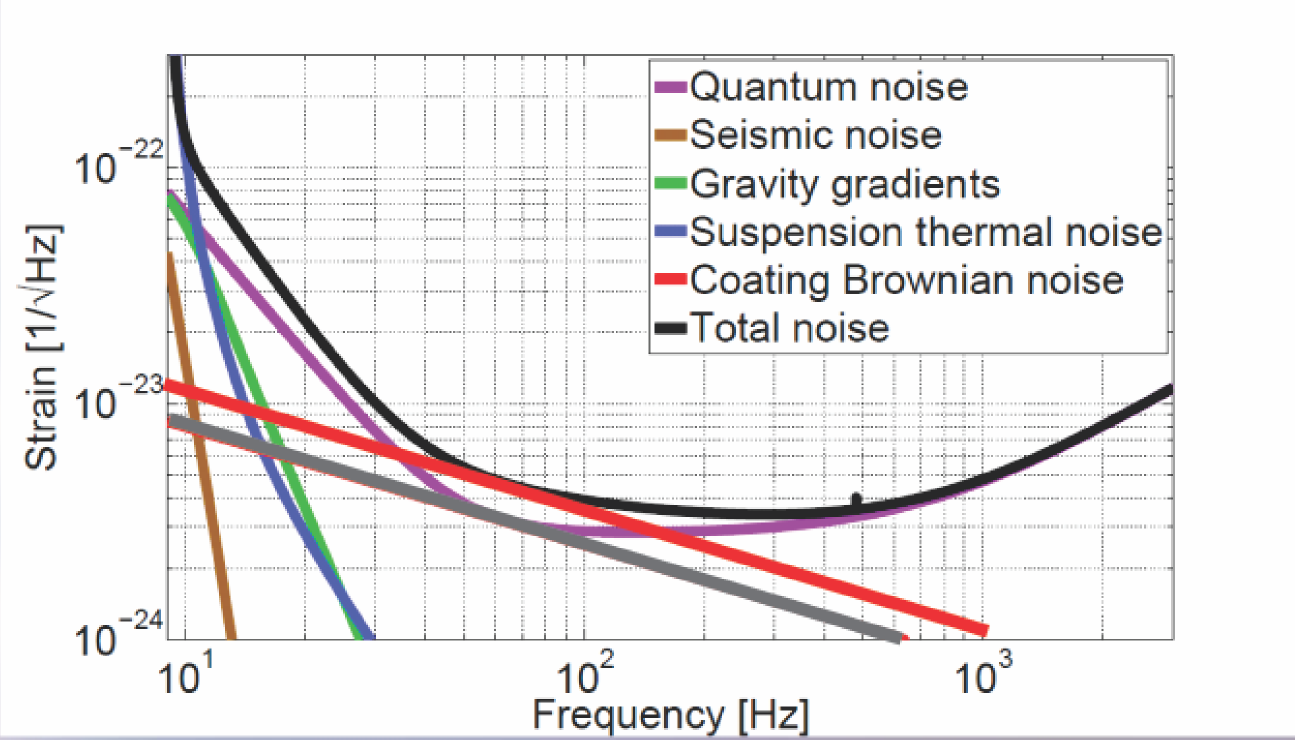
- Energy *a* in epoxy from FEA model
- Q from FWHM
- Scale $\varphi \approx 10^{-2}$
- Two typical values

  ~2.5, ~5.5
- Unknown why separation

Mode	Frequency (Hz)	Loss angle $(\times 10^{-2})$
n=0, ℓ=1	2707.5	5.2
	2981.5	5.4
n=1, ℓ=0	4137.5	5.6
n=0, ℓ=3	6157.6	2.7
	6312.8	2.3
n=1, ℓ=1	9457.8	6.6
	37071.2	2.6
Shear	37155.1	2.9
Average		4 ± 1

Thermal Noise Prediction

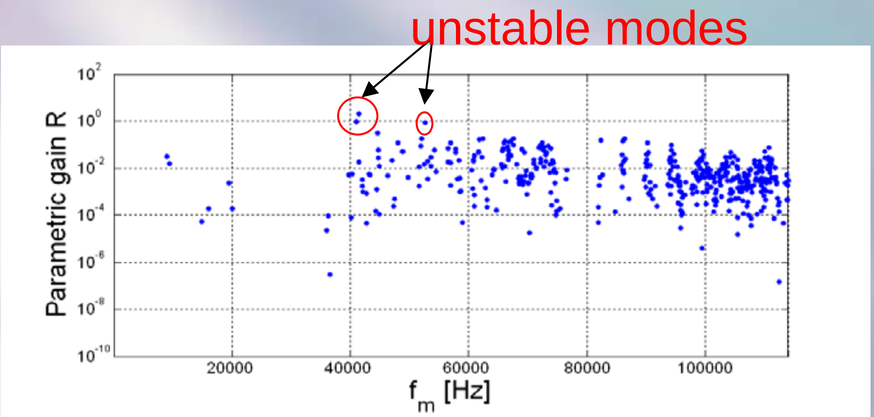
- Measured mechanical loss about a factor of 2 better than φ used in G1001023
- Thermal noise $\sim 9 \times 10^{-21} \mathrm{m}/\sqrt{\mathrm{Hz}}$
- Predicted thermal noise still about a factor of 2 worse than Advanced LIGO requirement



Future Plans

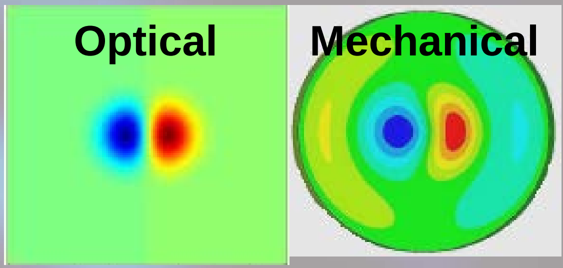
Epoxies

- HYSOL TRA-BOND
  - Used in LISA pathfinder
- EPOTEK 353ND
  - Glass transition, may be harder
- MasterBond EP30-2
- Natural Yacca gum from Australia
  - Shown to have low mechanical loss
  - Concerns about vacuum performance

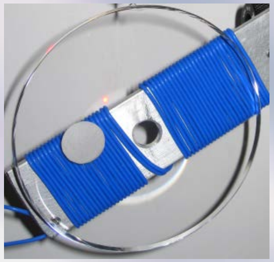


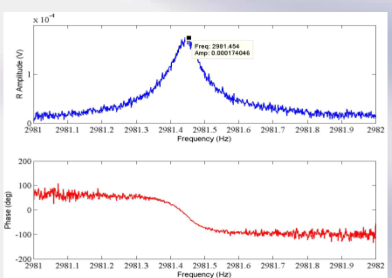
- Matlab fitting of complete peaks for Q's
- Higher frequency modes
- Determine frequency dependence of loss
- Bulk loss in addition to shear

Conclusions



- Parametric instability potentially problematic for Advanced LIGO
- Mechanical mode dampers attached to test masses one possible solution
- Epoxy to construct and attach dampers can increase thermal noise and reduce sensitivity





- Tested TRA-DUCT 2902 epoxy for mechanical loss to determine thermal noise properties
- Better than modeled, but still not good enough

$$\varphi \approx (4 \pm 1) \times 10^{-2}$$

$$S_x(100\text{ Hz}) = 9 \times 10^{-21}\text{m}/\sqrt{\text{Hz}}$$

- Other epoxies to be measured in near future
- Hopefully one will work out