MECHANICAL LOSS IN SILICA SUBSTRATES

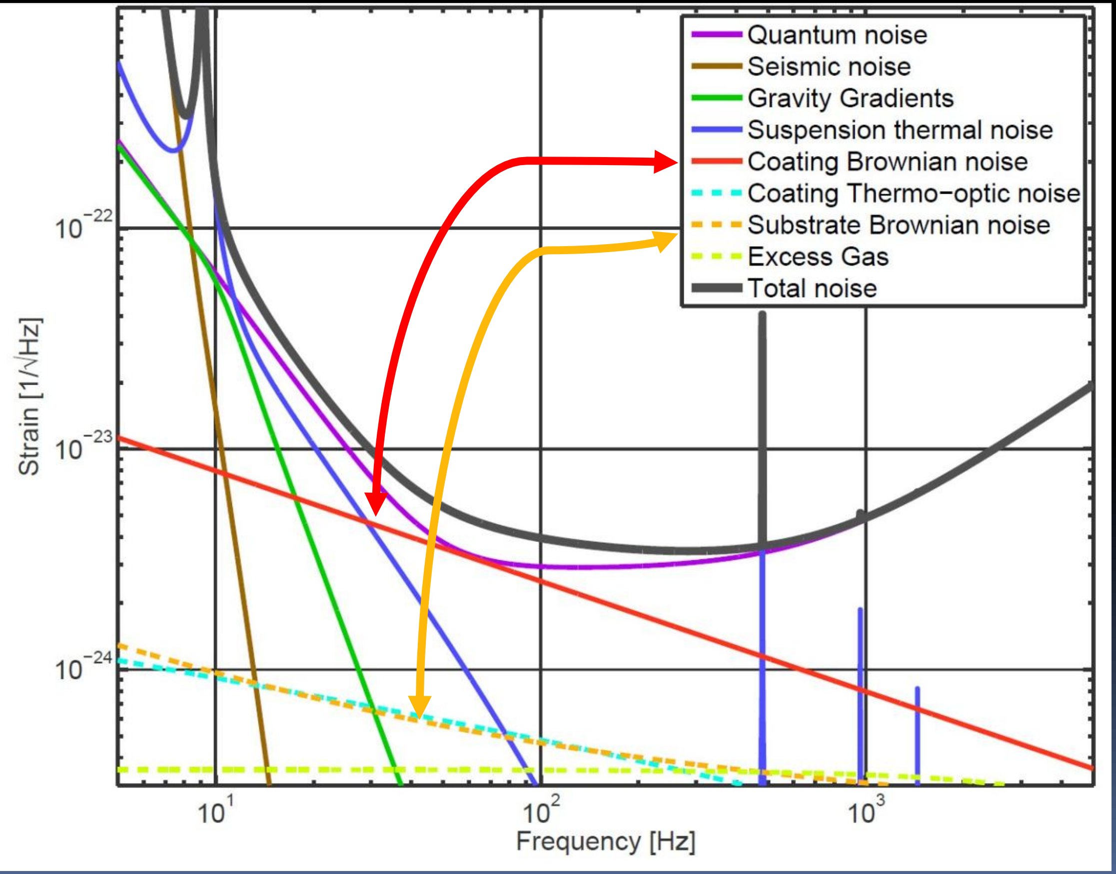
Jonathan Newport
American University
Gregg Harry, Raymond Robie, David Belyea, Matt Abernathy

LIGO-G1300309

LVC Meeting
Bethesda, MD
March 18th 2013

Introduction

- Thermal noise from internal degrees of freedom of interferometer test masses is a limiting noise source in the sensitive mid-frequency bands.
- Must quantify mechanical loss in both Silica Substrate and Coating Layers.



History: Old Formalism for Loss

"Thermal noise in interferometric gravitational wave detectors due to dielectric optical coatings"

[Harry, et al., Classical & Quantum Gravity, 19 (2002) 897-917]

- Derives thermal noise power spectrum in terms of $\phi_{substrate}$ and coating losses $\phi_{\parallel}$ and $\phi_{\perp}$.
- Assuming $\sigma = \sigma' = 0$,

$$S_x(f) = \frac{1}{wY}\frac{2k_BT}{f\pi^{3/2}}\left\{\phi_{substrate} + \frac{1}{\sqrt{\pi}}\frac{d}{w}\left(\frac{Y'}{Y}\phi_{\parallel} + \frac{Y}{Y'}\phi_{\perp}\right)\right\}$$

- Finding $\phi_{\parallel}$,

Measured

$$\frac{1}{Q} = \phi = \frac{U_{Substrate}}{U_{Total}}\phi_{substrate} + \frac{U_{\parallel}}{U_{Total}}\phi_{\parallel}$$

Calculated

- Finding $\phi_{\perp}$ ...???
- Assumes $\phi_{\parallel} = \phi_{\perp}$

Impetus: New Formalism for Loss

"Brownian Thermal Noise in Multilayer Coated Mirrors"
[Hong, et al, LIGO-G1200614-v1, Submitted to Phys. Rev. D]

- $\phi_{\parallel}$ and $\phi_{\perp}$ formalism of Harry, et al. can lead to erroneous values – require new formalism.
- When applying a force with known pressure profile:

$$U_{coating} = U_B + U_S = \iiint_{coating} \left(\frac{K}{2} \Theta^2 + \mu \Sigma_{ij} \Sigma_{ij} \right) dV$$

- New formalism for mechanical loss in coating starting from elastic energy contained in *bulk energy* U_B and *shear energy* U_S.

loss in coating

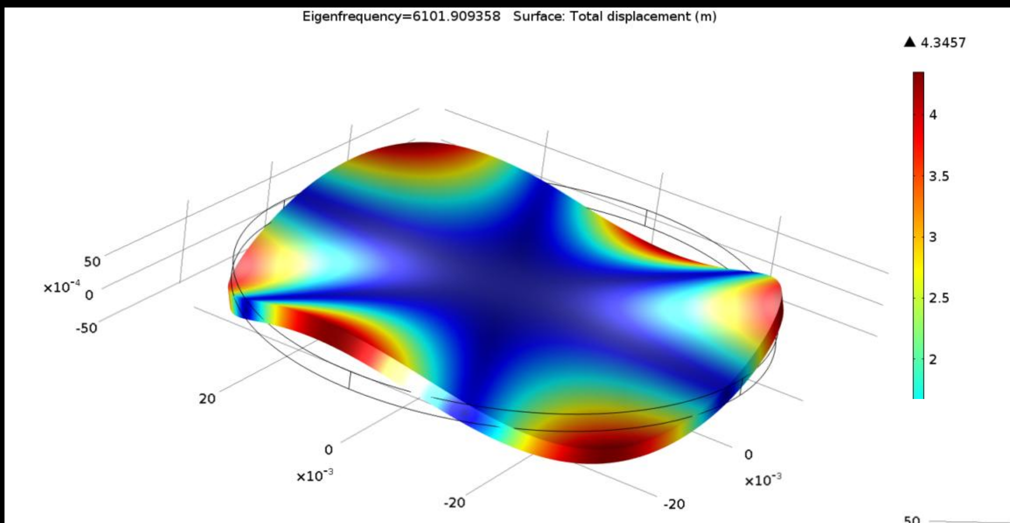
$$\phi_{coated} = \frac{U_{substrate}}{U_{Total}} \phi_{substrate} + \frac{U_B}{U_{Total}} \phi_B + \frac{U_S}{U_{Total}} \phi_S$$

$$\phi_{substrate} = \frac{U_{B,Sub}}{U_{Total}} \phi_{B,Sub} + \frac{U_{S,Sub}}{U_{Total}} \phi_{S,Sub}$$

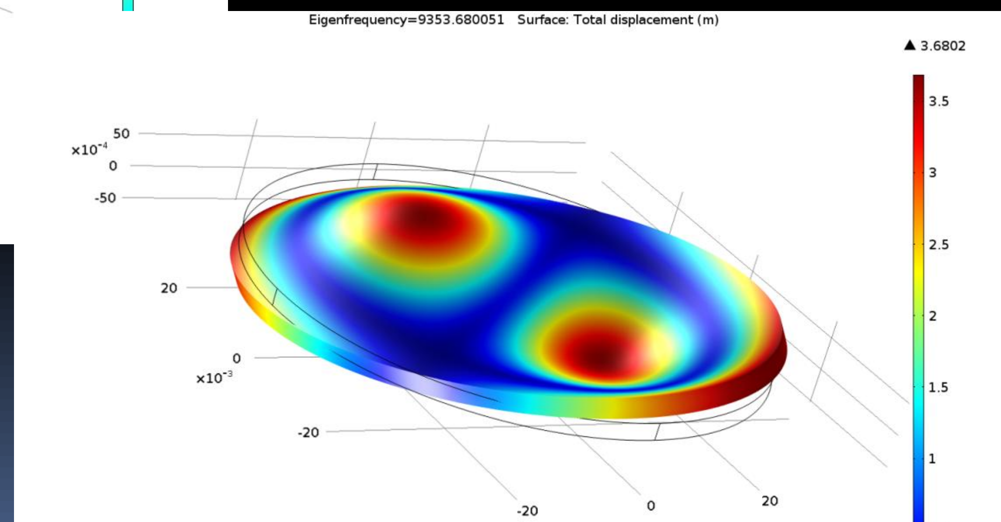
- Without a coating, should be able to extend this analysis to bulk and shear loss in substrate

Measurement Techniques: FEA

- A finite element analysis of an uncoated silica sample is used to find its approximate resonance frequencies.

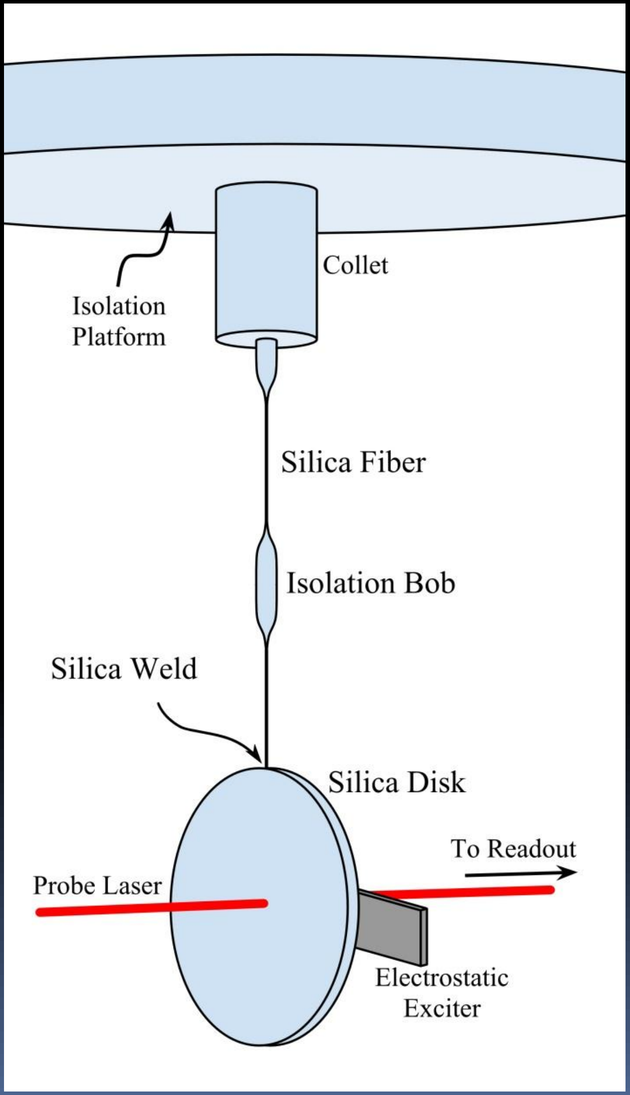


$f \approx 6102\text{Hz}$

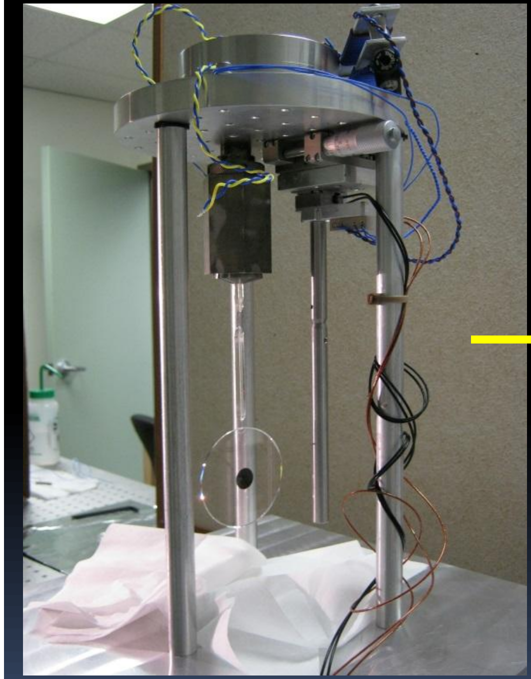


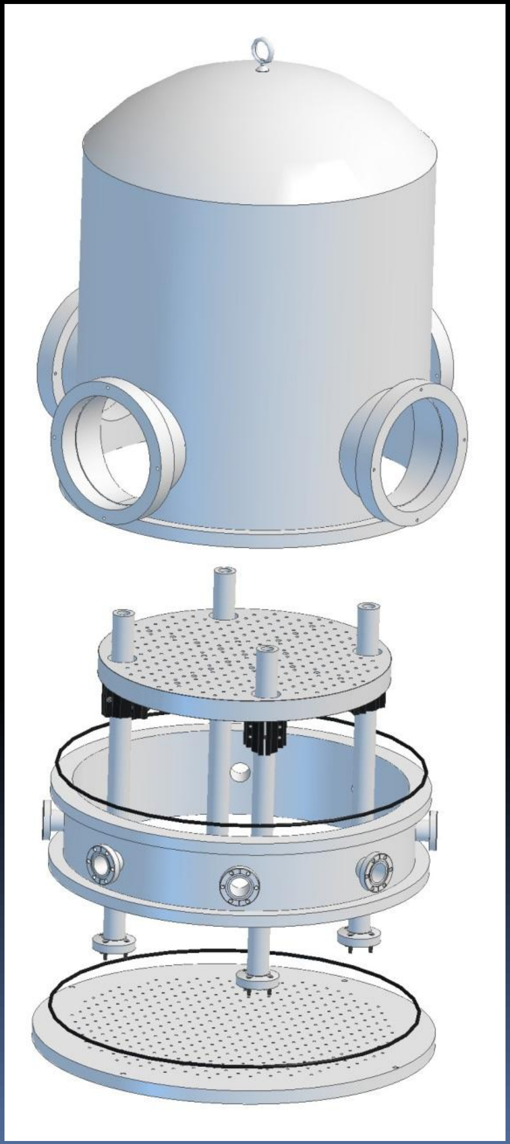
$f \approx 9354\text{Hz}$

Measurement Techniques: Hanging Sample

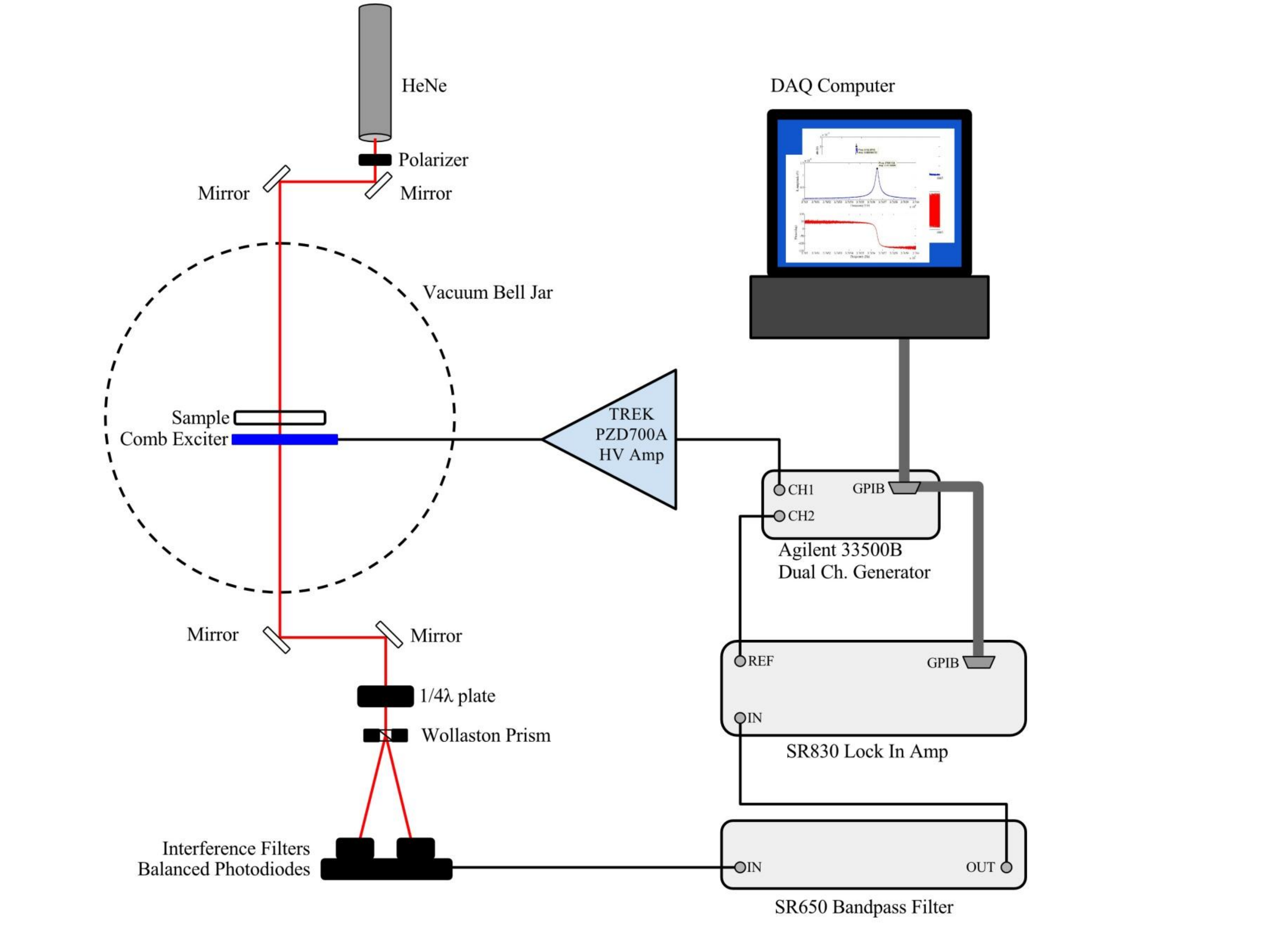


Measurement Techniques: Bell Jar Upgrade



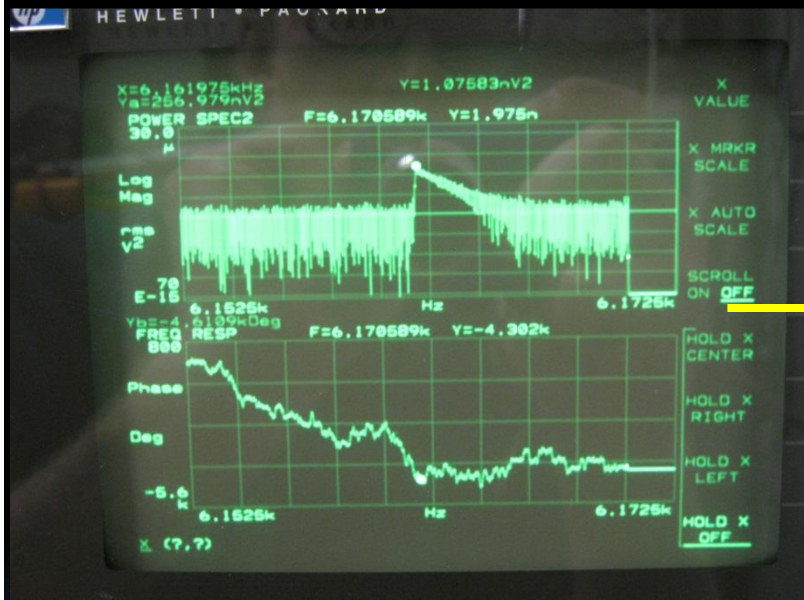


Measurement Techniques: Birefringence Sensor

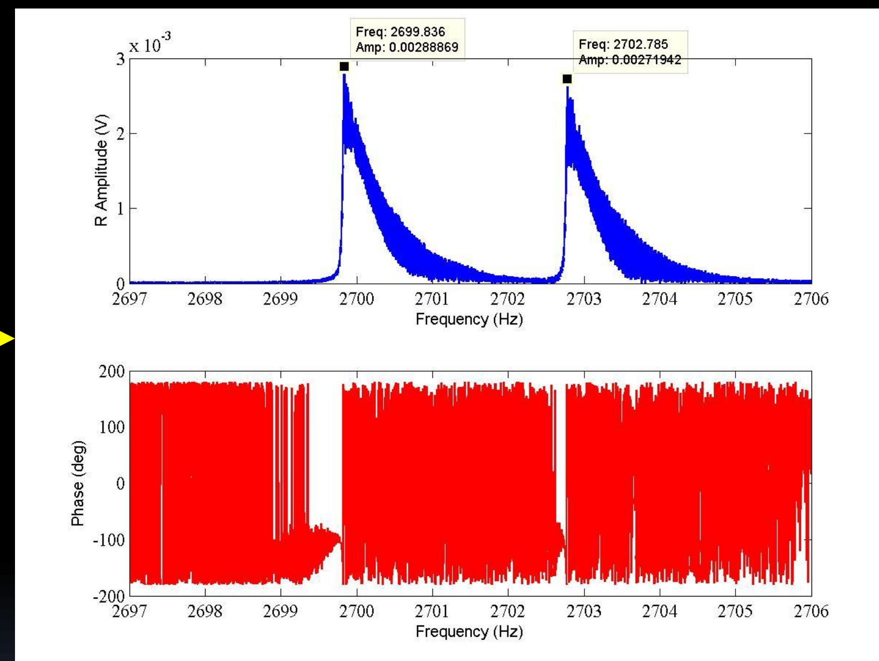


Measurement Techniques: Mode Hunting

Network/Signal Analyzer

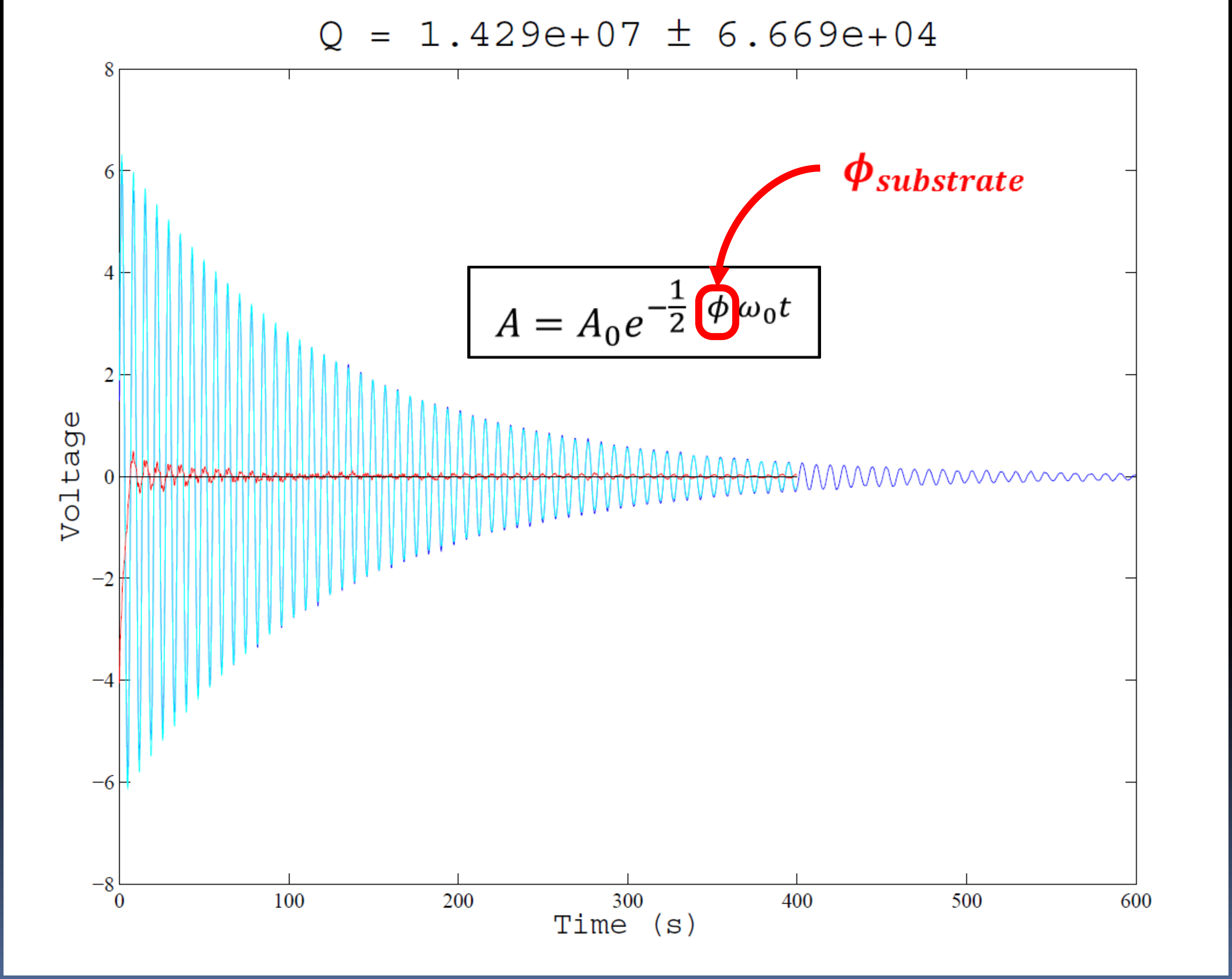


Matlab Instrument Control



Matlab + Waveform Generator + Lockin Amplifer allows for complete control of all sweep parameters: input filter bandwidth, step time and step size down to 1μHz.

Measurement Techniques: Ringdowns



Measurement Techniques: Q Results

Sample	Mode Freq [Hz]	Q
Sample 24	2706.5	2.009×10^7
	6162.4	1.47×10^7
	9445.8	5.49×10^6
Sample 25	2699.2	1.9×10^7
	6149.6	1.89×10^7
	9438.3	1.326×10^7
	10,612.5	7.66×10^6
Sample 26	2758.1	1.911×10^7
	4163.2	8.88×10^6
	37,039.1	1.488×10^7

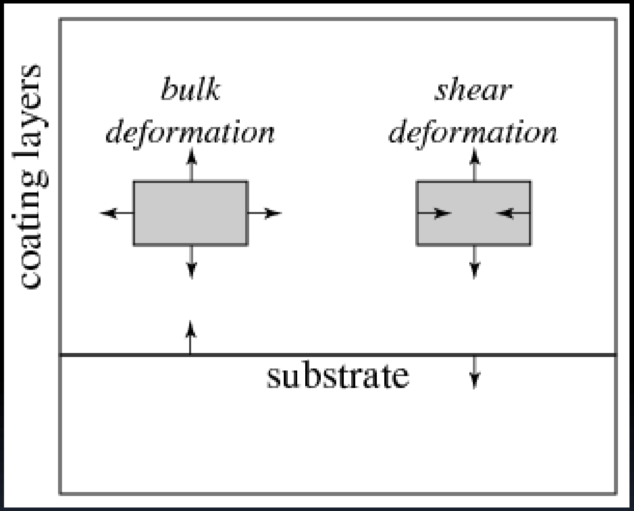
Analysis: Return to FEA with New Formalism

- Elastic energy can be divided into *bulk energy* U_B and *shear energy* U_S when applying a force with a known pressure profile,

$$U_{Total} = U_{B,Sub} + U_{S,Sub} = \iiint_{Sub} \left(\frac{K}{2} \Theta^2 + G\, \Sigma_{ij} \Sigma_{ij} \right) dV$$

Bulk:

$$\Theta = S_{11} + S_{22} + S_{33}$$



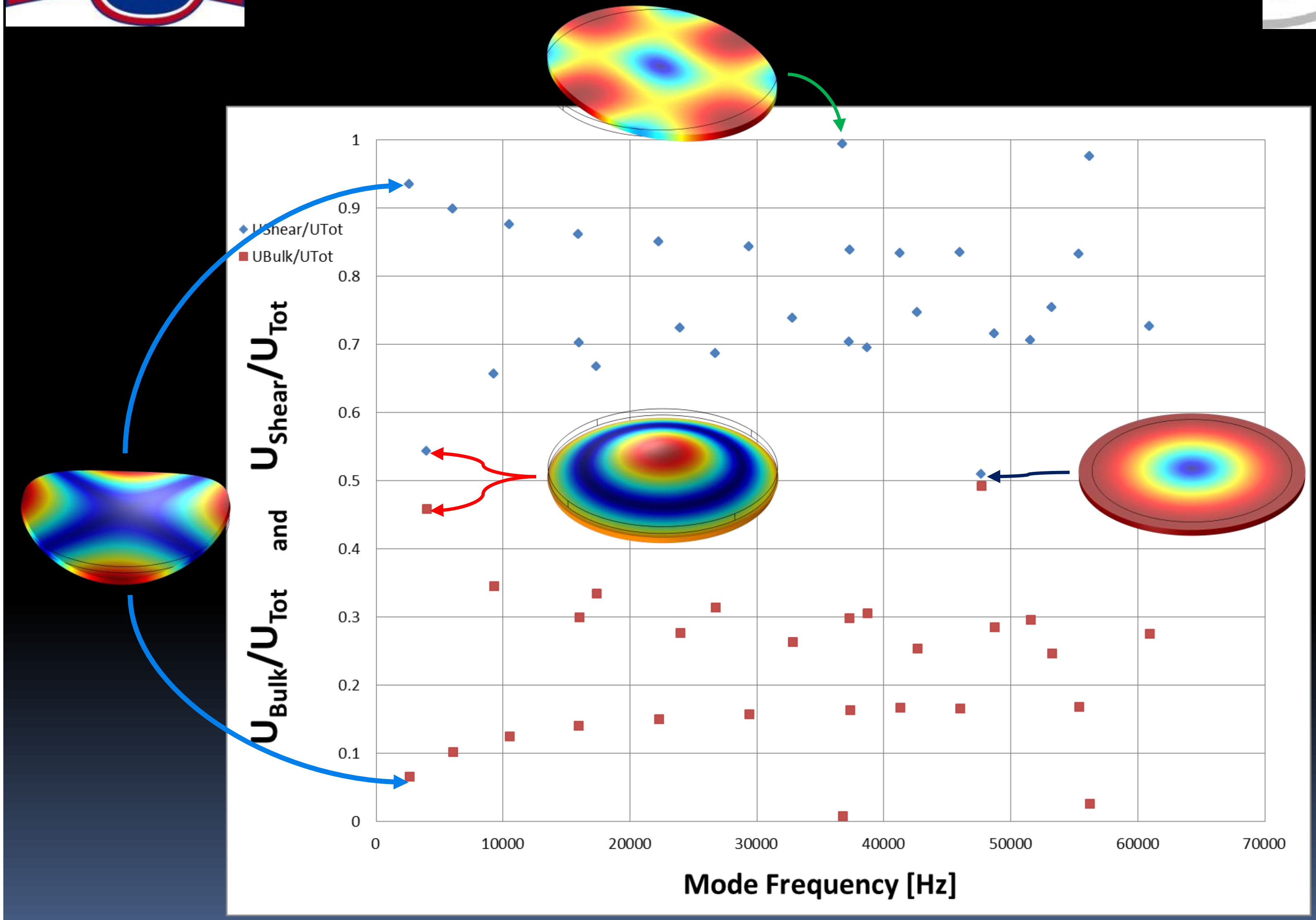
Shear:

$$\Sigma_{ij} = \frac{1}{2}\left[S_{ij} + S_{ji}\right] - \frac{1}{3}\delta_{ij}\Theta$$

FEA

$$\phi_{substrate} = \frac{U_{B,Sub}}{U_{Total}} \phi_{B,Sub} + \frac{U_{S,Sub}}{U_{Total}} \phi_{S,Sub}$$

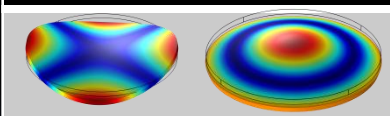
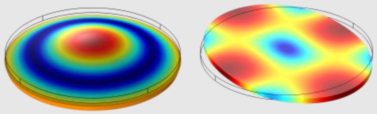
Analysis: FEA Energy Ratios



Preleminary Results

- Bulk and Shear loss can be then be calculated:

$$\begin{bmatrix}\phi_a \\ \phi_b\end{bmatrix} = \begin{bmatrix}\frac{U_{a,Bulk}}{U_{a,Tot}} & \frac{U_{a,Shear}}{U_{a,Tot}} \\ \frac{U_{b,Bulk}}{U_{b,Tot}} & \frac{U_{b,Shear}}{U_{b,Tot}}\end{bmatrix} \begin{bmatrix}\phi_{Bulk} \\ \phi_{Shear}\end{bmatrix}$$

Sample 26	ϕ_{Bulk}	ϕ_{Shear}
	1.96×10^{-7}	4.24×10^{-8}
	1.67×10^{-7}	6.66×10^{-8}

- Note that we lose frequency information! (or it’s buried, at least)

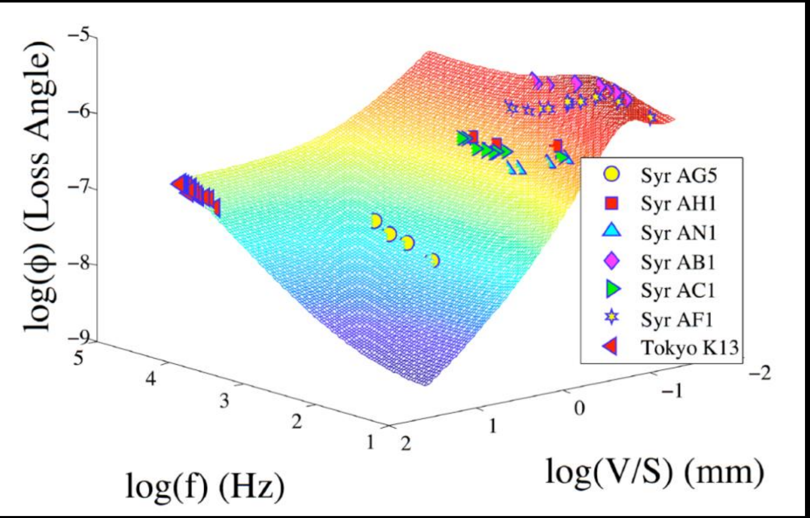
"Frequency and surface dependence of mechanical loss in fused silica"

[Penn, et al., Physics Letters A, 352 (2006) 3-6]

- Shows that mechanical loss of silica substrate $\phi_{substrate}$ depends on frequency and surface-to-volume ratio.

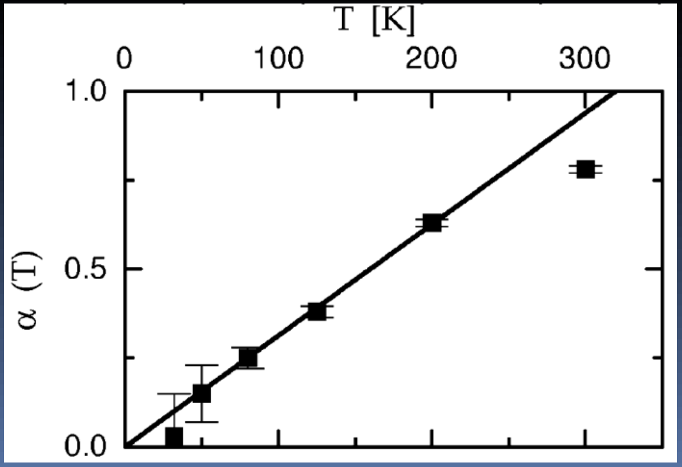
$$\phi\left(f,\frac{V}{S}\right) = \phi_{surf} + \phi_{vol} + \phi_{th}$$
$$= C_1\left(\frac{V}{S}\right)^{-1} + C_2\left(\frac{f}{(1\mathrm{Hz})}\right)^{C_3} + C_4\phi_{th}$$

Type	C1 (pm)	C2 ($\times 10^{-11}$)	C3	C4
Suprasil 2	12.1	1.18	0.77	0.61



- Frequency dependence of loss agrees well with results of modeling asymmetric double-well potential in Si-O-Si bond angle. [Weidersich, et al., Phys. Rev. Lett. 84 (2000) 2718]

Type	C3
Suprasil 300	≈0.75



Still Lots to Do!

- Frequency Dependence $\phi(f)$:
  - More Data Pairs – easier to probe higher order modes with wideband HV Amplifier and computer control
  - Design second sample with different energy ratios, but similar mode frequencies
- Include dependence of loss on Surface to Volume ratio in analysis $\phi\left(\frac{V}{S}\right)$
- Include Shear/Bulk loss in Surface analysis
- Compare to other theoretical models (Hai Ping Cheng, etc.)
- Annealing
- More modes, reanalyzing old data

$$\phi\left(f,\frac{V}{S}\right) = \phi_{surf} + \phi_{vol} \rightarrow \phi\left(f,\frac{V}{S}\right) = \phi_{surf,B} + \phi_{surf,S} + \phi_{vol,B} + \phi_{vol,S}$$