Mechanical Quality Factor of Cryogenic Silicon

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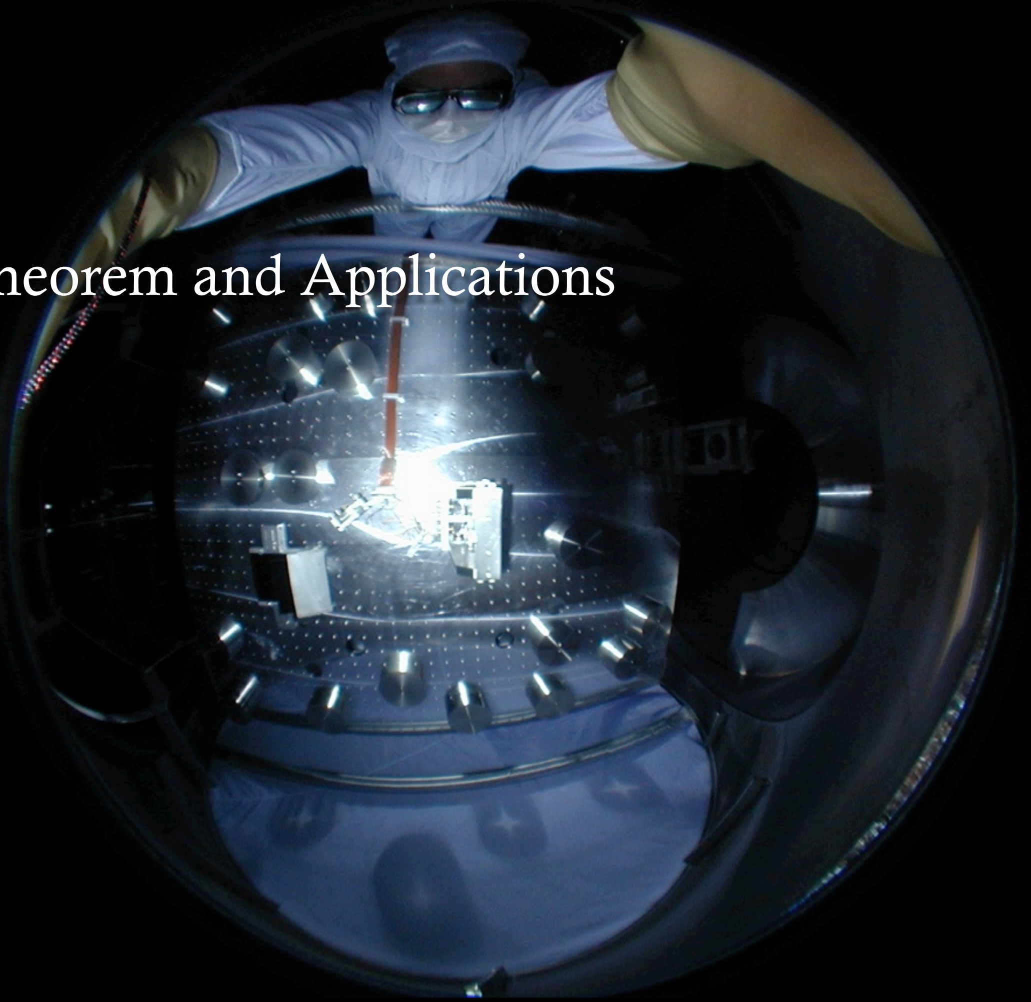
Overview

- Background
- Fluctuation-Dissipation Theorem and Applications
- Making Measurements
- Experimental Design
- Theoretical Predictions
- Results
- Future plans



Background

- Future LIGO detectors
- Cryogenic silicon replace silica for test masses
- Minimizes thermal elastic noise. Coefficient of the thermal expansion goes to 0 at 120K
- Need to understand behavior of noise spectrum produced by silicon.
- Difficult to detect tiny thermal fluctuations
- Saved by the Fluctuation Dissipation Theorem!

Fluctuation-Dissipation Theorem

Relates noise spectrum + system's linear responses to applied perturbations:

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

Power spectrum of noise

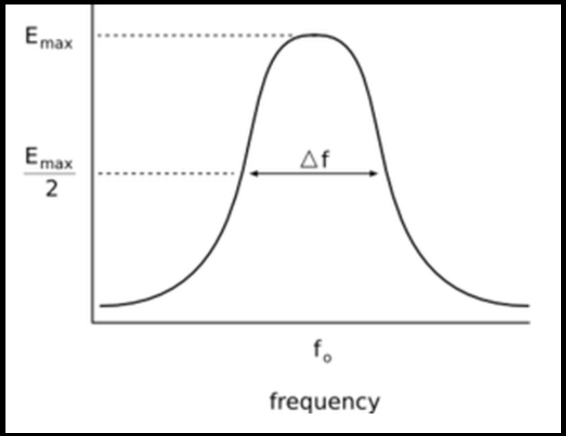
Applications

- Note that our equation depends on one unknown, ϕ, the loss angle:

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

- We will show that ϕ is related to the quality factor Q.
- Q = dimensionless, a description of how under-damped an oscillator is.

Q and ϕ



- By definition, $$Q \equiv \frac{\omega_0}{\Delta\omega}$$

If we derive from the equation of motion,

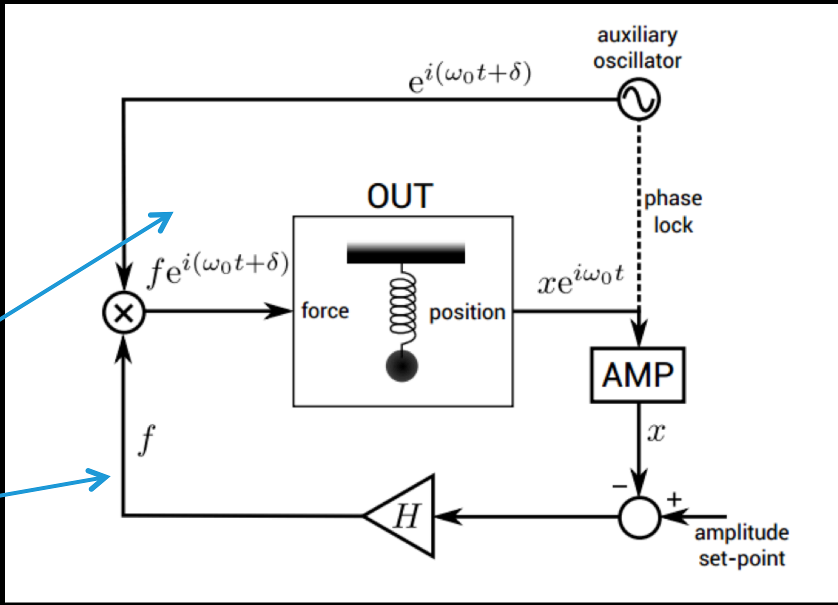
$$\ddot{x} = -\omega_0^2(1 + i\phi)x + F$$

we find that

$$Q = \frac{\omega_0 \tau}{2}$$ and $$Q = \frac{1}{\phi}$$

Measuring Q

- Thus we have a relationship between Q and ϕ.
- By measuring Q, we can find the power spectrum.
- How?
  - Method 1: Ring down
  - Method 2: Transfer function
  - Method 3: Control loops (Future)



Phase locked loop

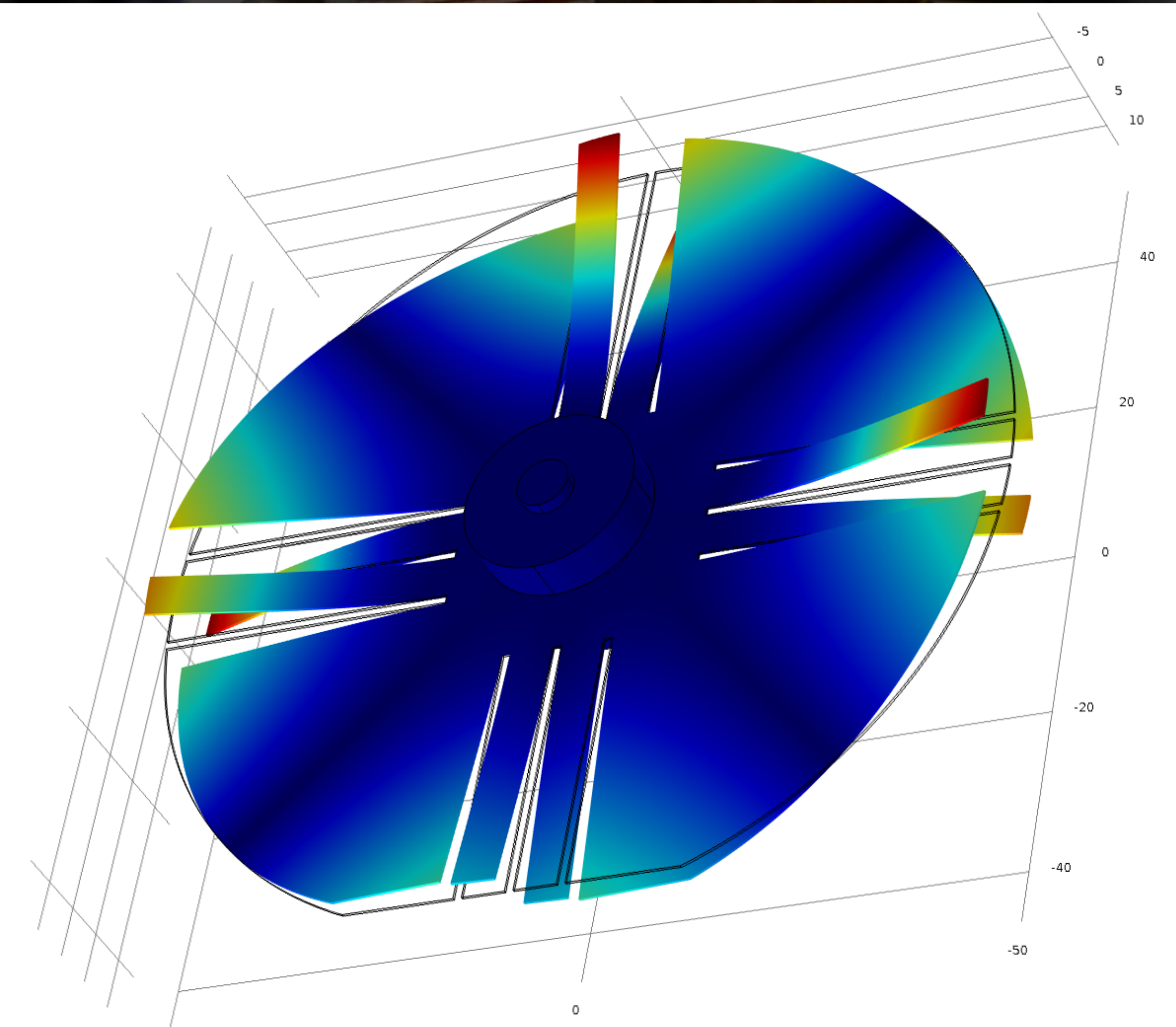
Amplitude locked loop

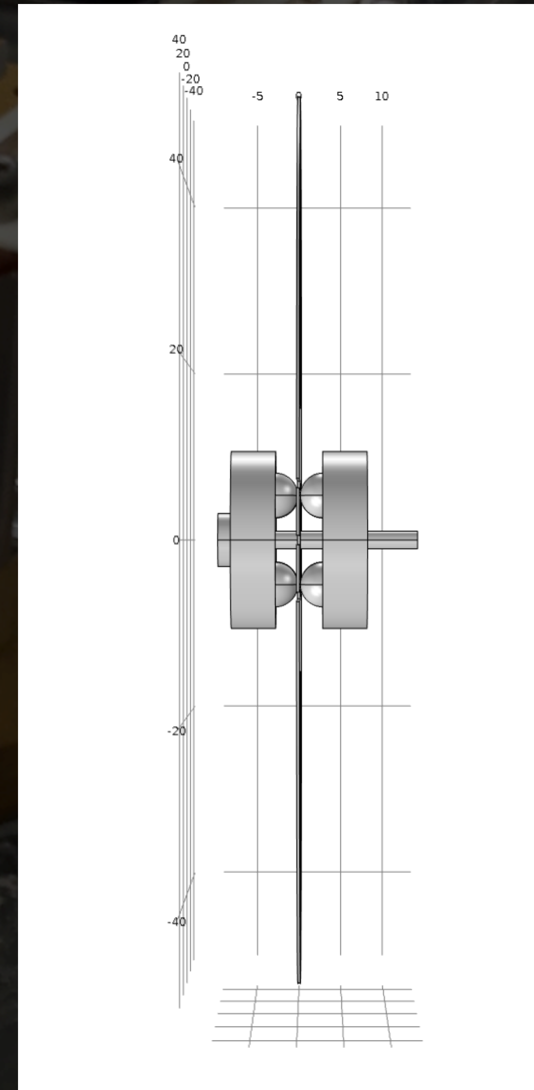
Reducing clamp loss

- Important to reduce clamp loss in order to measure true loss of silicon

$$\phi \approx \phi_{Si} + R\phi_{Steel}$$

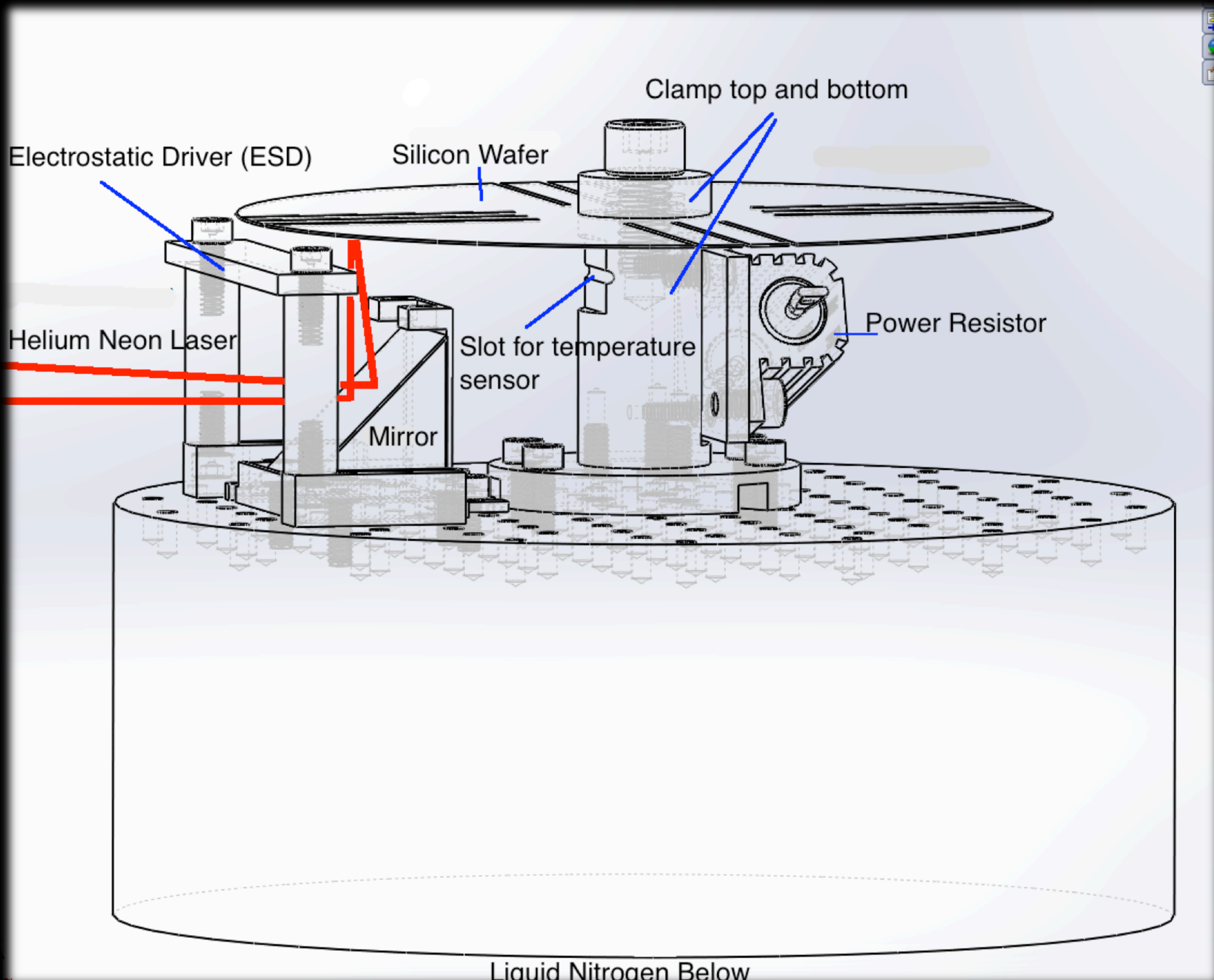
where R = strain energy ratio = $E_{steel}/(E_{steel}+E_{Si})$

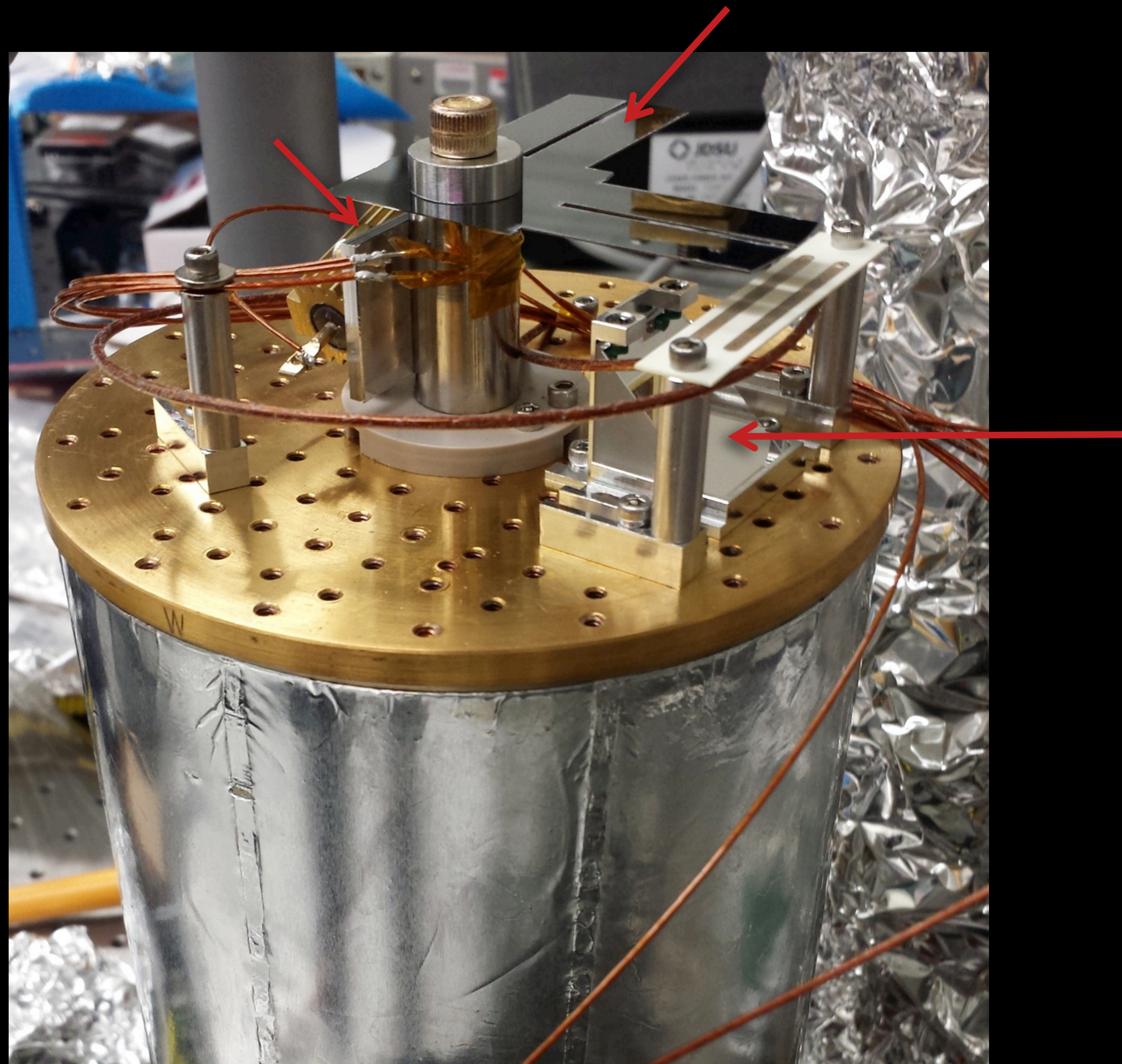




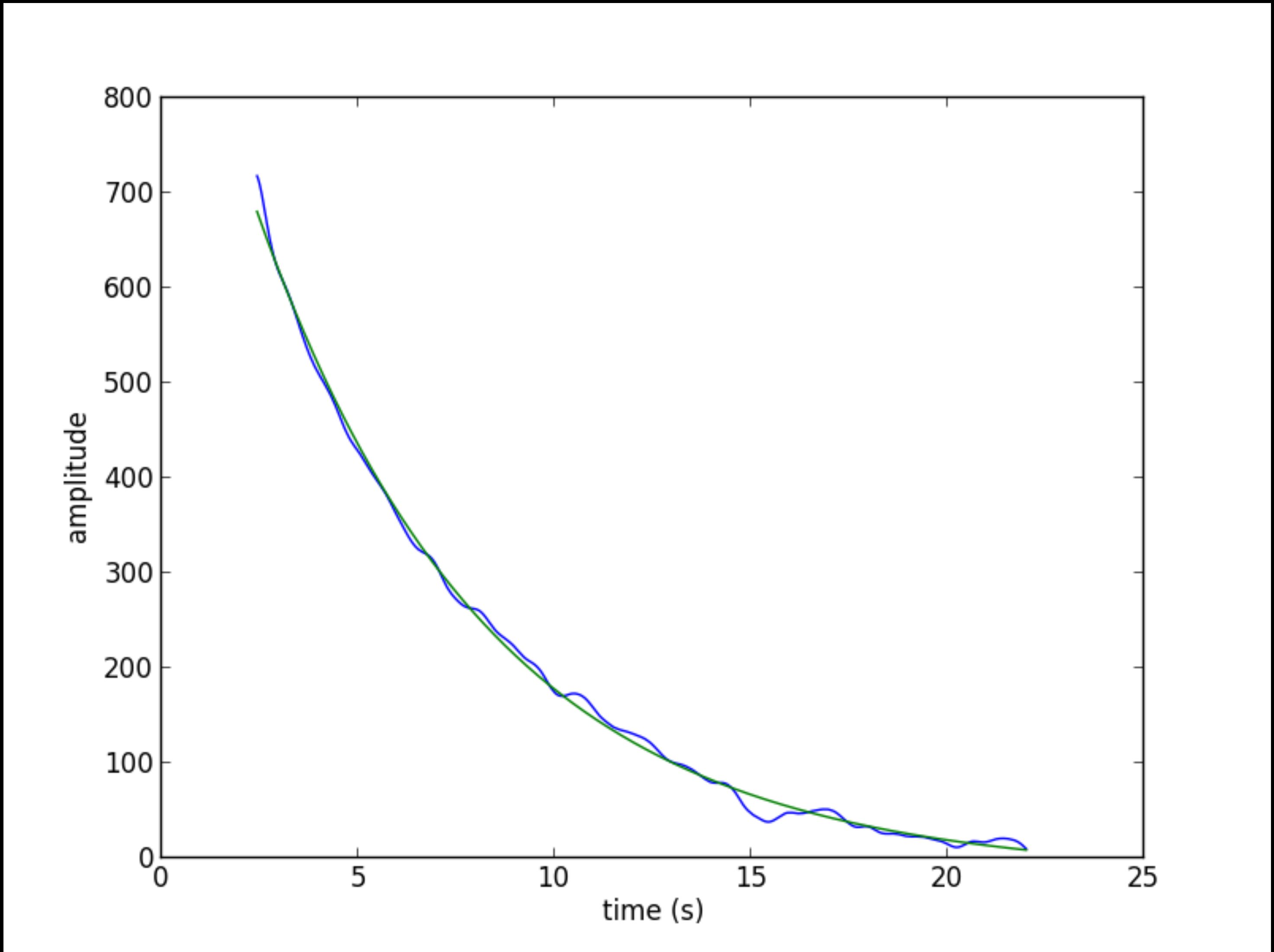
Clamp and Wafer Design

CRYOSTAT DESIGN

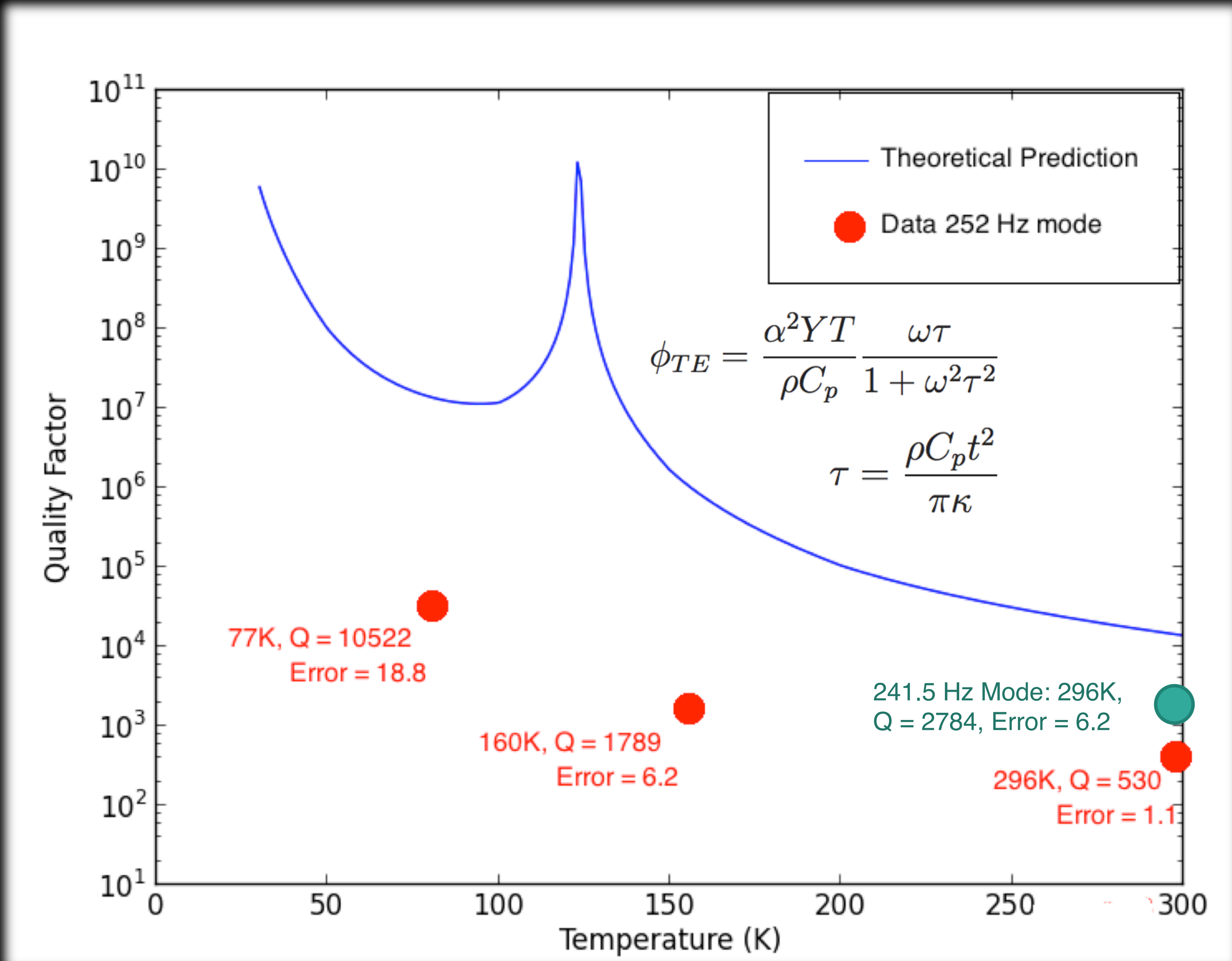




Obtaining ϕ



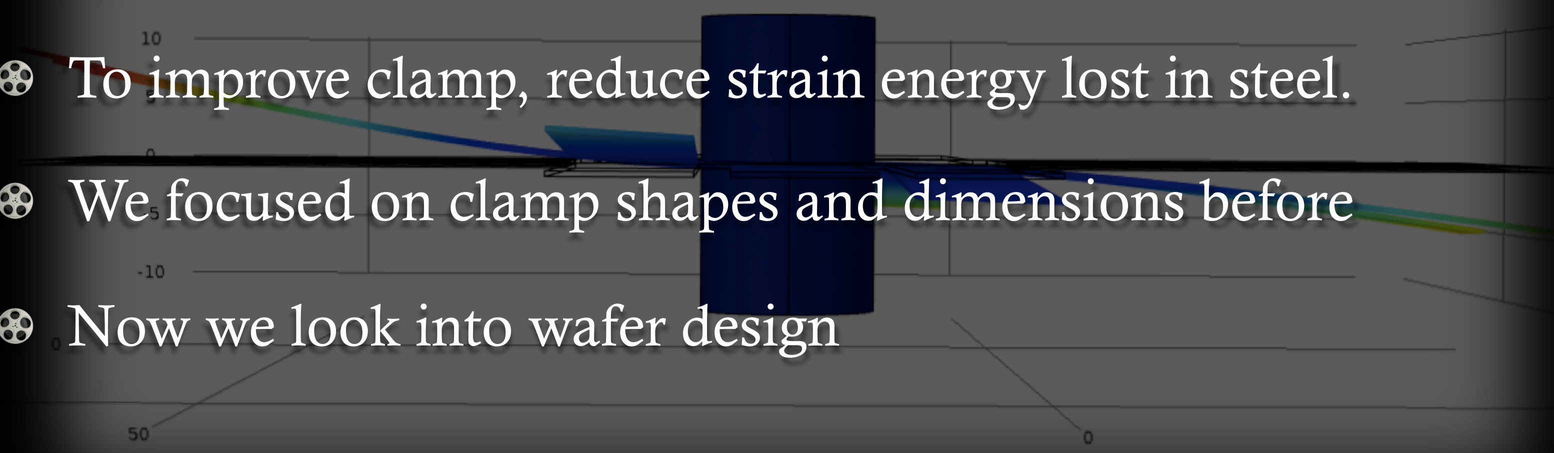
Results

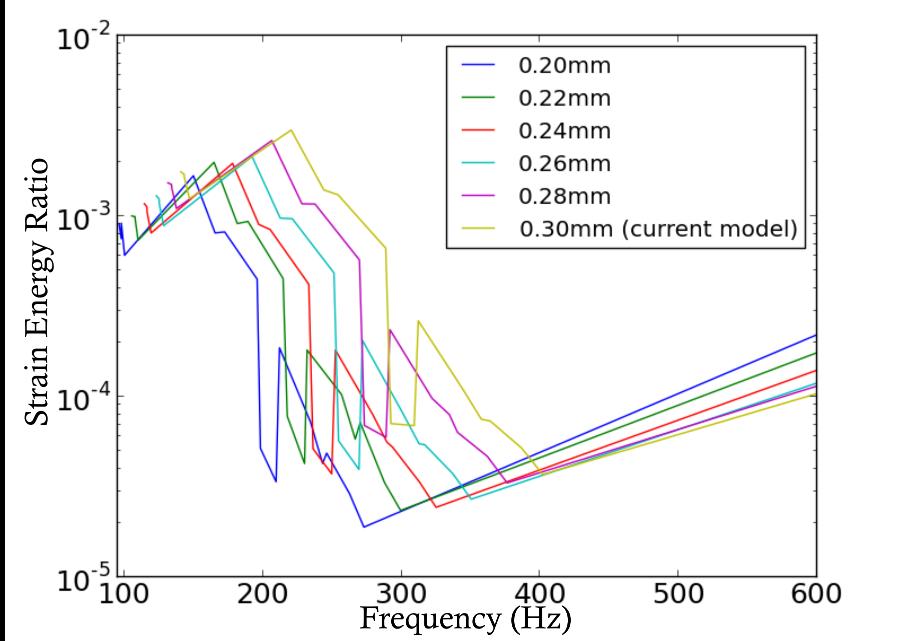


Theoretical Prediction
Data 252 Hz mode
$\phi_{TE} = \frac{\alpha^2 Y T}{\rho C_p} \frac{\omega\tau}{1+\omega^2\tau^2}$
$\tau = \frac{\rho C_p t^2}{\pi\kappa}$
77K, Q = 10522
Error = 18.8
160K, Q = 1789
Error = 6.2
241.5 Hz Mode: 296K,
Q = 2784, Error = 6.2
296K, Q = 530
Error = 1.1
Quality Factor
Temperature (K)

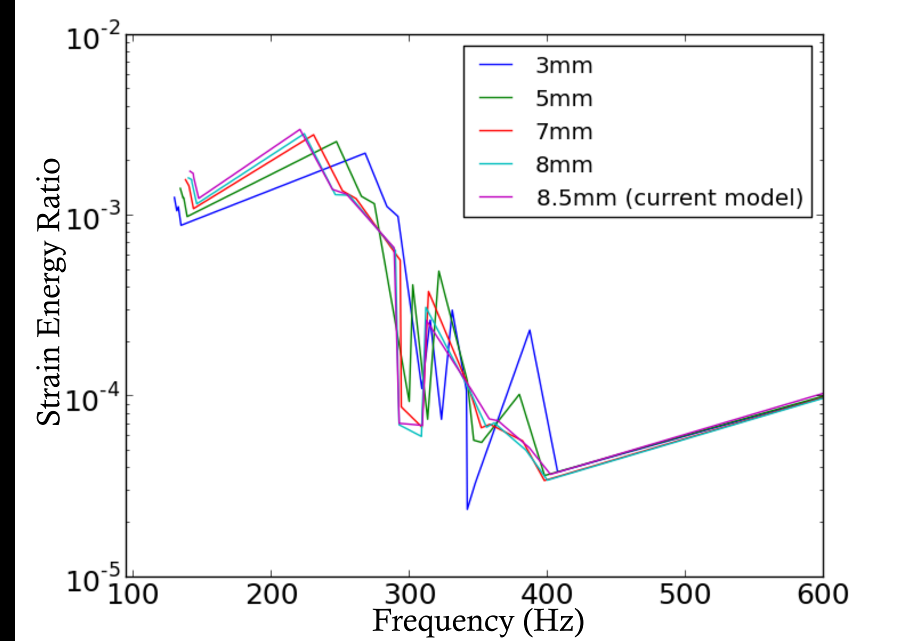
Analysis

- Results indicate that clamp loss is still dominant
- To improve clamp, reduce strain energy lost in steel.
- We focused on clamp shapes and dimensions before
- Now we look into wafer design

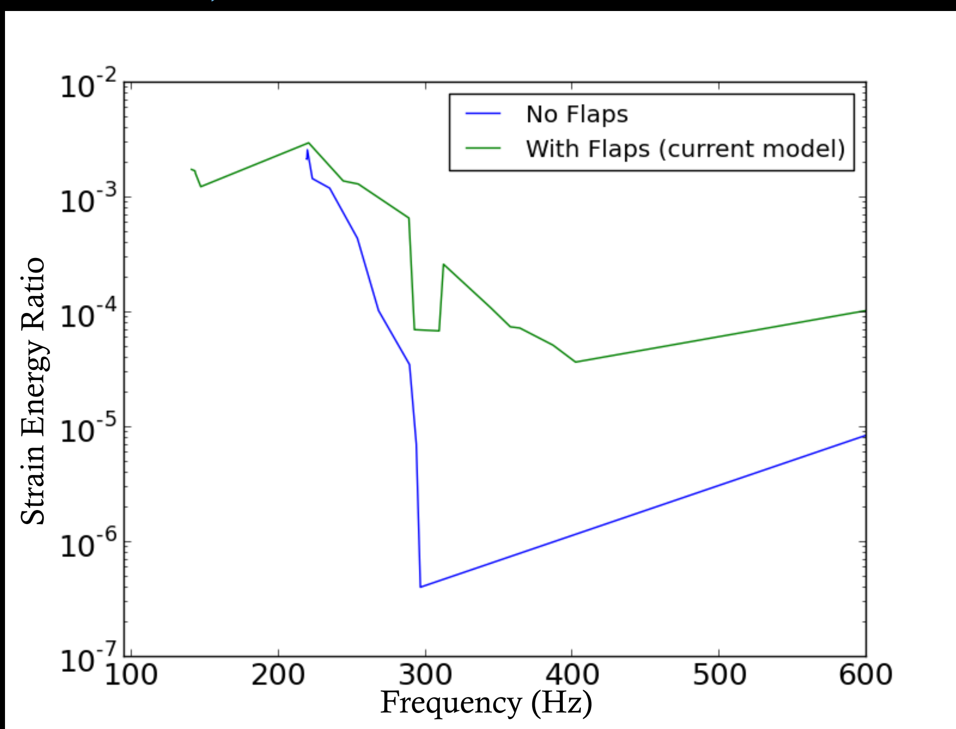




1) Reduce wafer thickness.



2) Decrease cantilever width



3) Simplify the geometry.

Geometry might be why the 241.5 Hz mode had less loss than the 242 Hz mode. Use higher order modes too?

4) Study oscillation of the flaps rather than cantilevers

Future Work

- Improve our current experimental design until we can measure a maximum $Q \approx 10^8$ or better.
- Implement the control loops to continuously measure Q
- Understand changes in Q with temperature and frequency
- Then study the changes in Q of the silicon due to thin film deposition.
  - Films will be for controlling reflectivity of masses.
  - There could be deformations due to thin film deposition
  - Additional sources of loss between
  - How the curvature will affect laser reflectivity.

Acknowledgements

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Questions?