Explorations in Cryogenic High-Q Mechanical Resonators

Shubhabroto Mukherjee

Mentors : Aaron Markowitz, Duo Tao, Rana Adhikari

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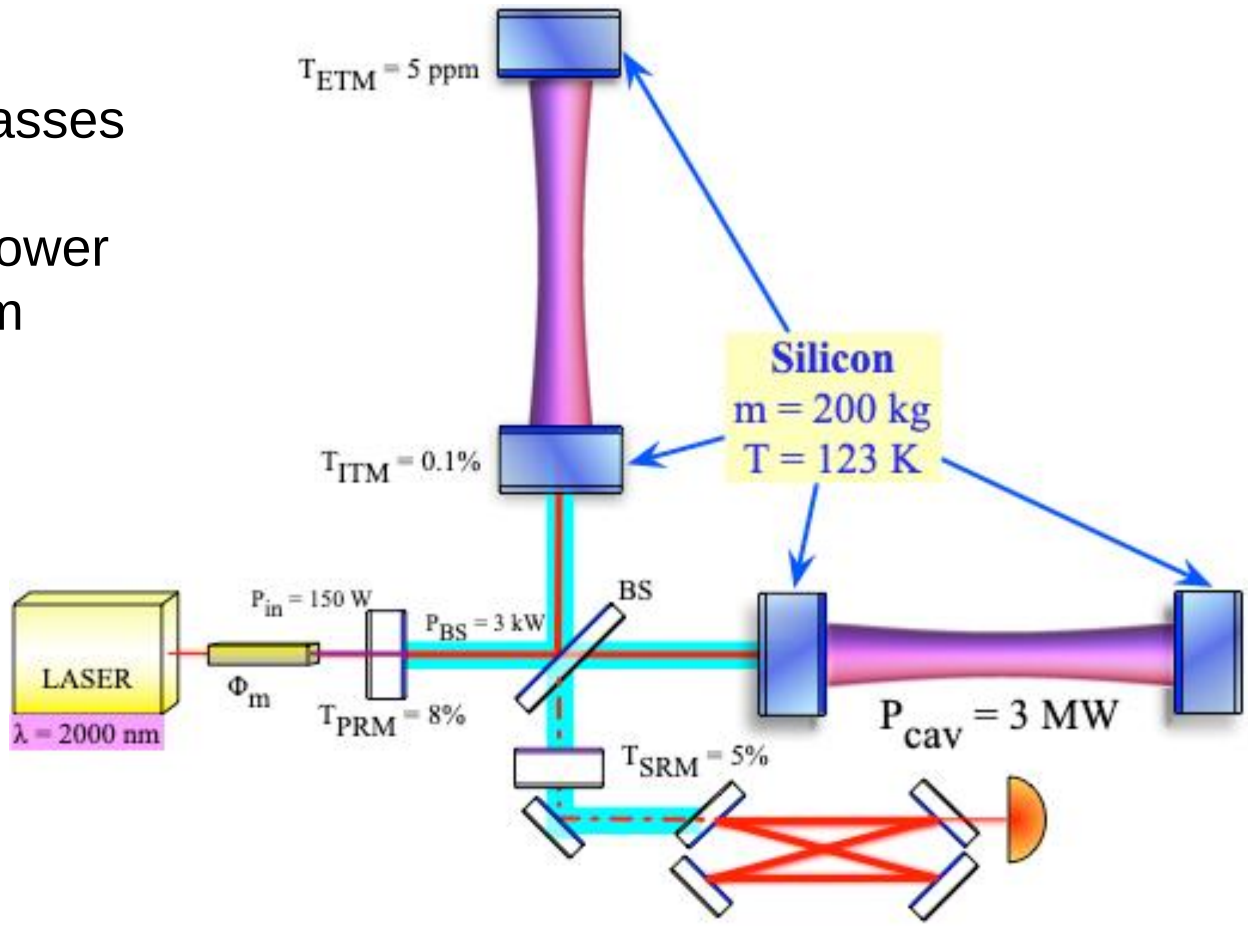
Outline

- LIGO Voyager Design and Noise Budget
- Properties of Silicon
- Cryo-Q Experiment
- Non – contact temperature probe
- Modified Setup
- FEA Model
- Circuit Analysis
- Future Work
- Acknowledgement

LIGO Voyager

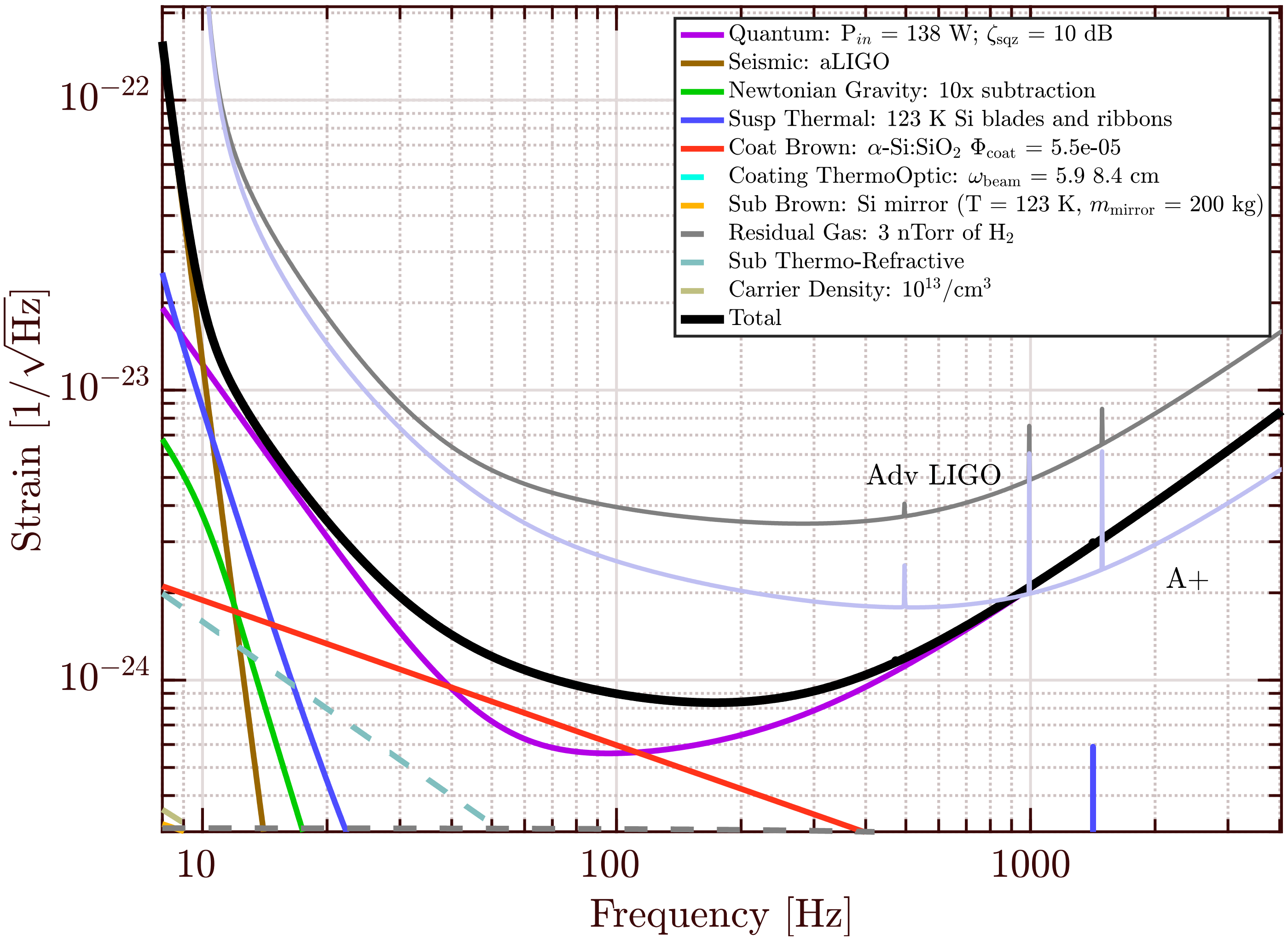
Key Updates :

- 200 kg Silicon test masses at 123 K
- 3 MW of arm cavity power
- ~25% increased beam spot size



LIGO Voyager Update presentation by Christopher Wipf (DCC G1900594-v1)

Noise Budget of LIGO Voyager



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Coating Brownian Noise

- According to the fluctuation-dissipation theorem, Brownian motion is directly linked to the mechanical damping in the constituent materials of the coating.
- High reflectivity and low mechanical dissipation
- Optical precise measurement → Sense changes in phase of a probe laser beam →Ultra-stable optical interferometers

Silicon Properties

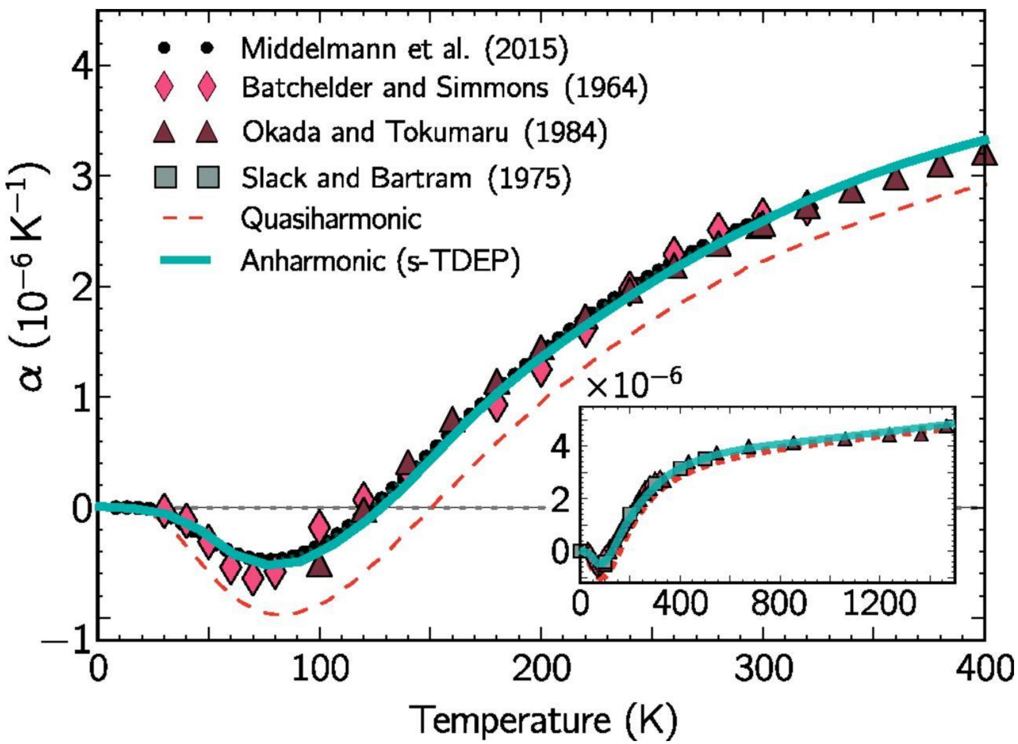
- Coefficient of thermal expansion, $\alpha \rightarrow 0$ at T~123 K

  → Thermo-elastic Noise 🚫

- High thermal Conductivity

  ↓

  Higher Laser Power



Graph reproduced from '*Nuclear quantum effect with pure anharmonicity and the anomalous thermal expansion of silicon*', B. Fultz et al.

Loss Budget for Silicon

- According to fluctuation-dissipation relationship,

$$Thermal\ fluctuations \propto \frac{1}{Q\ factor}$$

- $Q = 2\pi \left(\frac{Total\ energy\ of\ the\ system}{Energy\ loss\ per\ cycle\ of\ operation}\right)$
- $\frac{1}{Q_{Total}} = \sum \frac{1}{Q_{factors}} = \frac{1}{Q_{TED}} + \frac{1}{Q_{Akheizer}} + \frac{1}{Q_{Surface}} + \frac{1}{Q_{Gas}} + \frac{1}{Q_{Others}}$

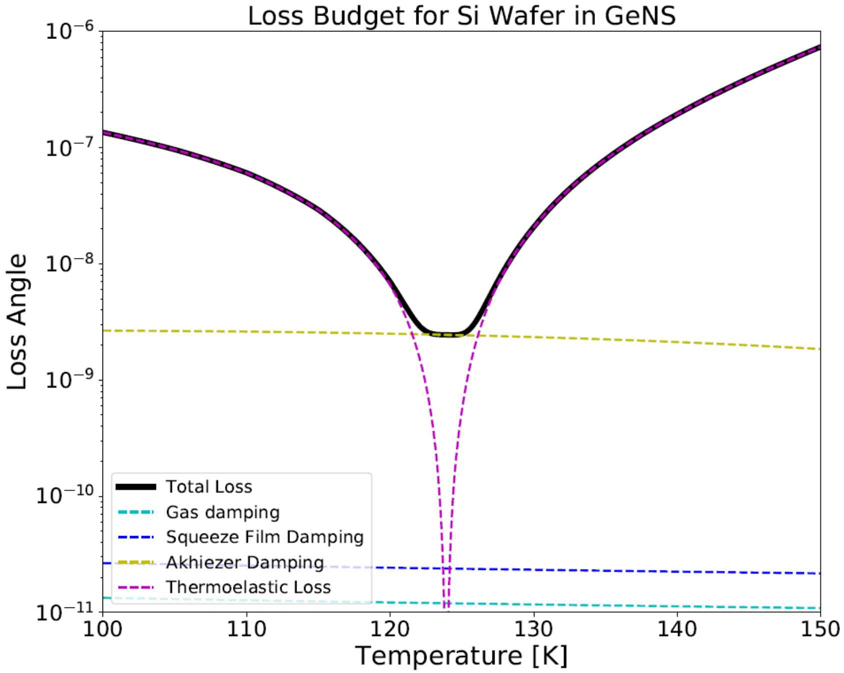
❑ $Q_{TED} = \left(\frac{\rho C_p}{E\alpha^2 T_0}\right) \frac{1+(w\tau)^2}{w\tau}$

- Akhiezer damping :

❑ Phonon-phonon dissipation

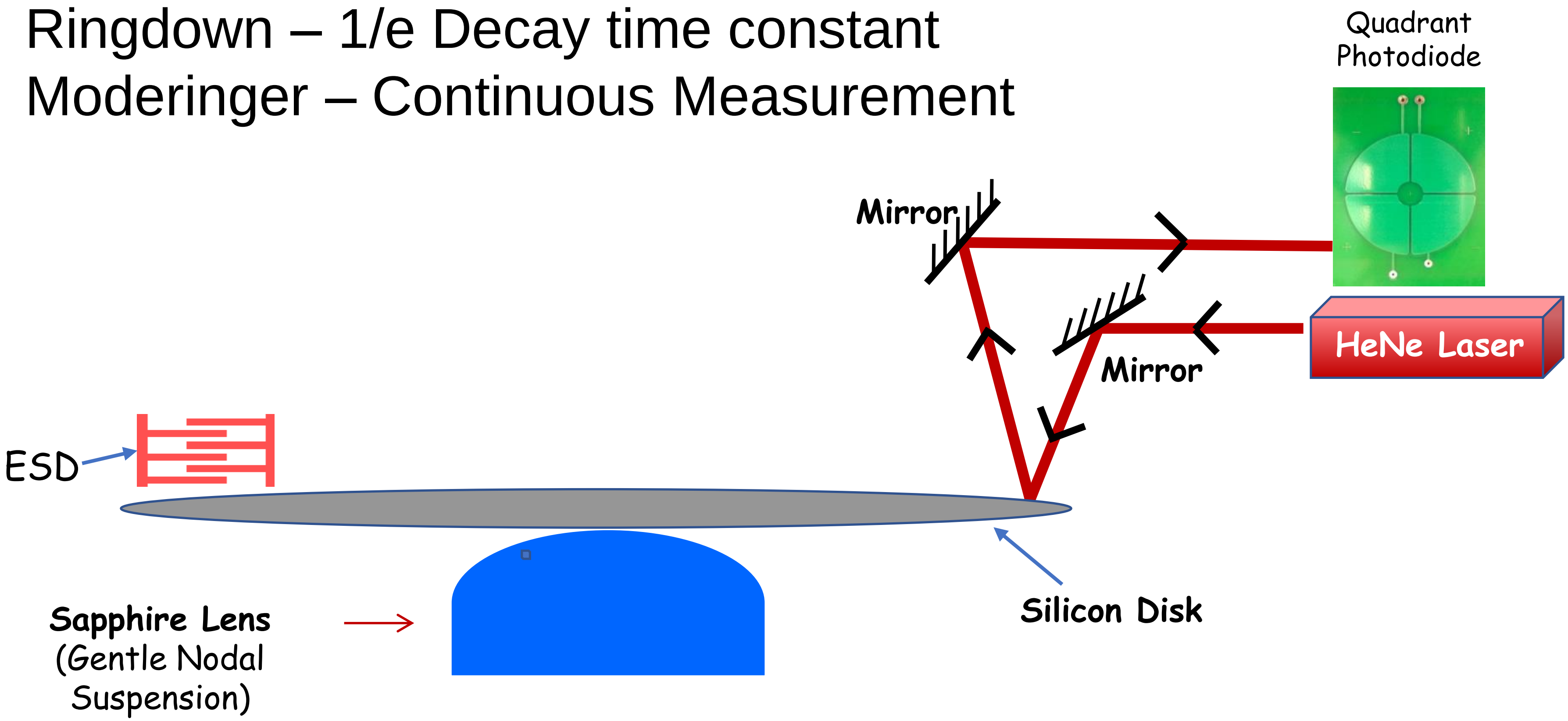
❑ Independent of geometry

❑ Determines upper limit of Q_{Total}

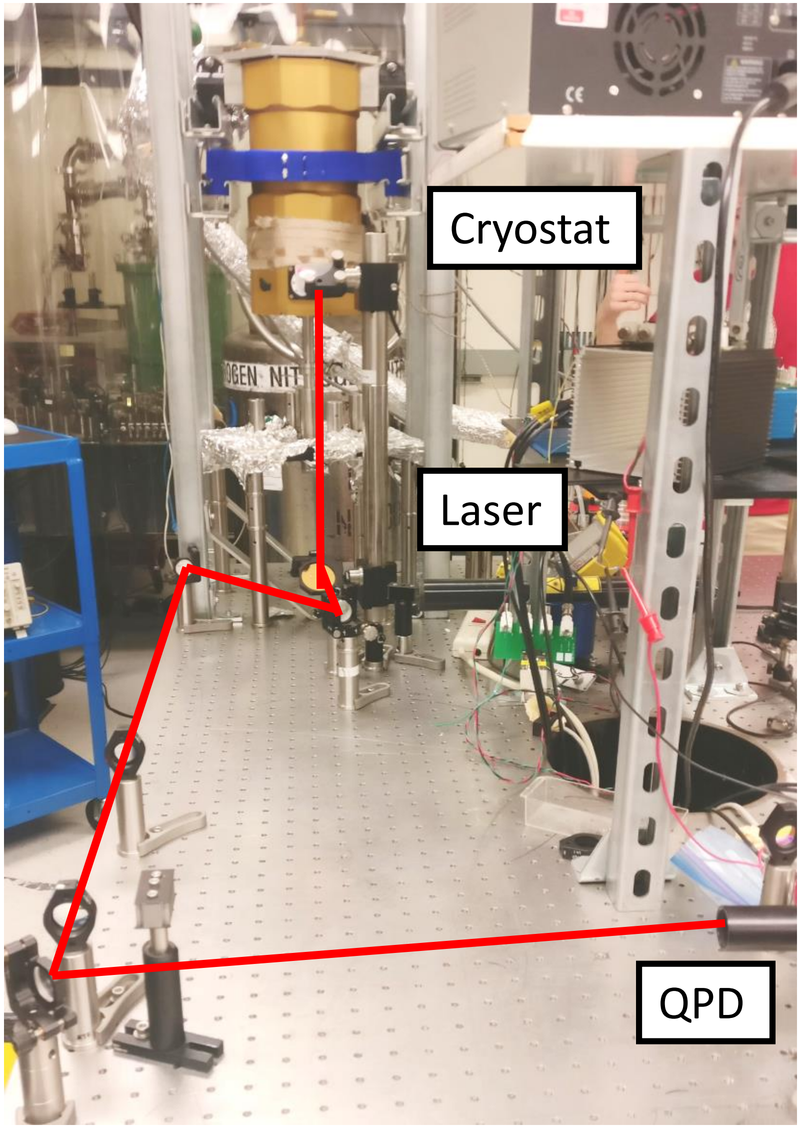


Cryo-Q Setup

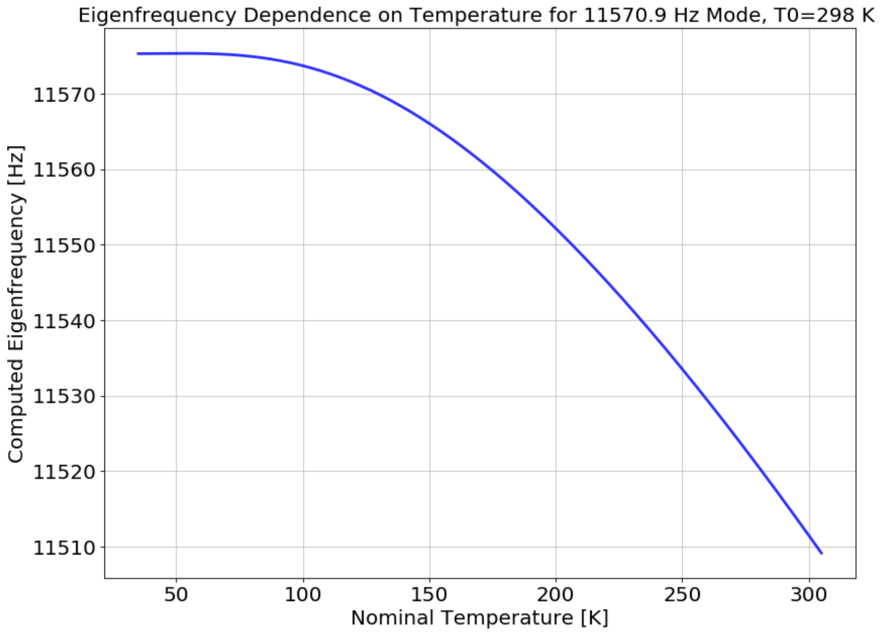
- Gentle Nodal Suspension
- Ringdown – 1/e Decay time constant
- Moderinger – Continuous Measurement

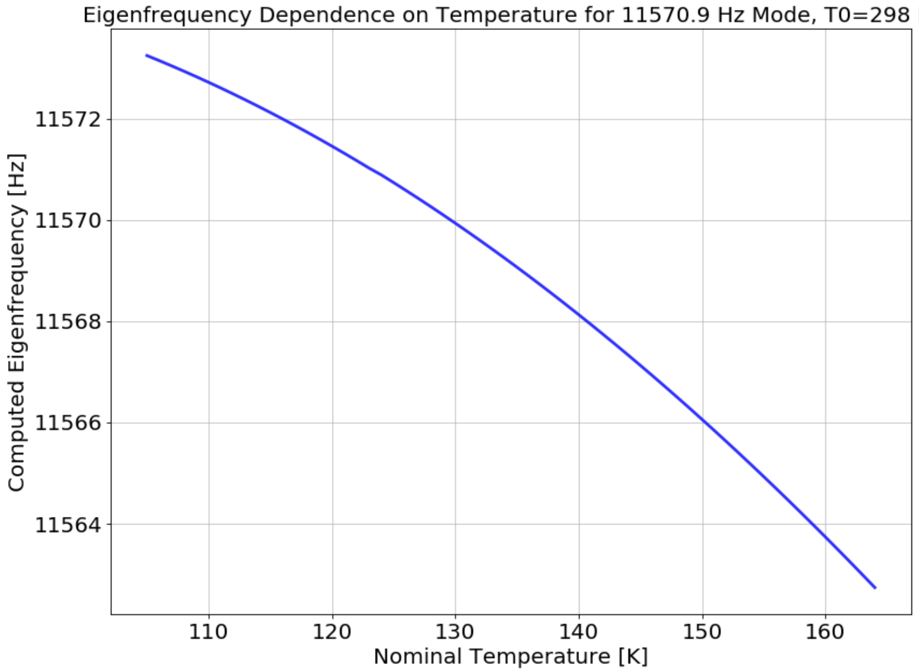


…Actual Setup

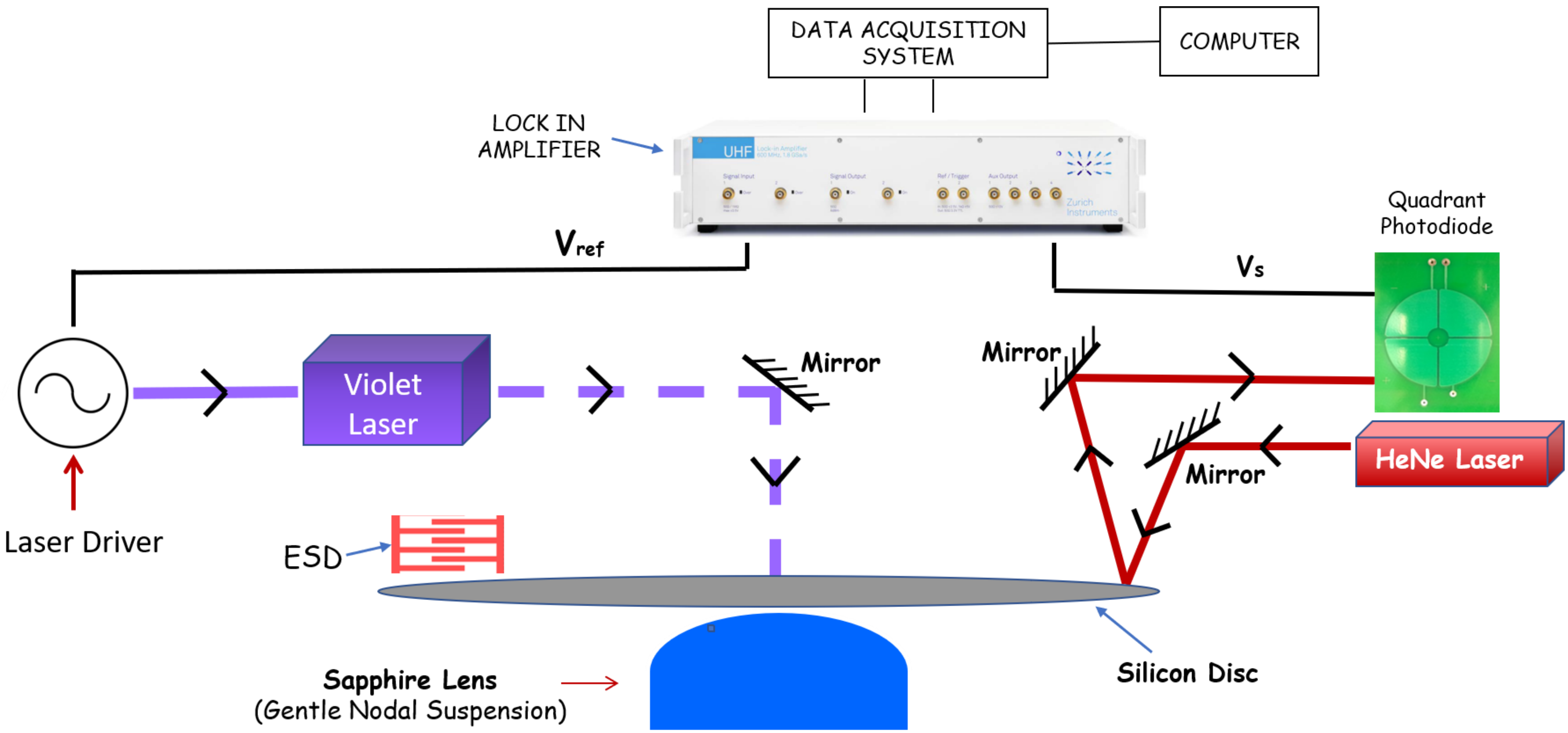


Non – Contact Temperature Probe

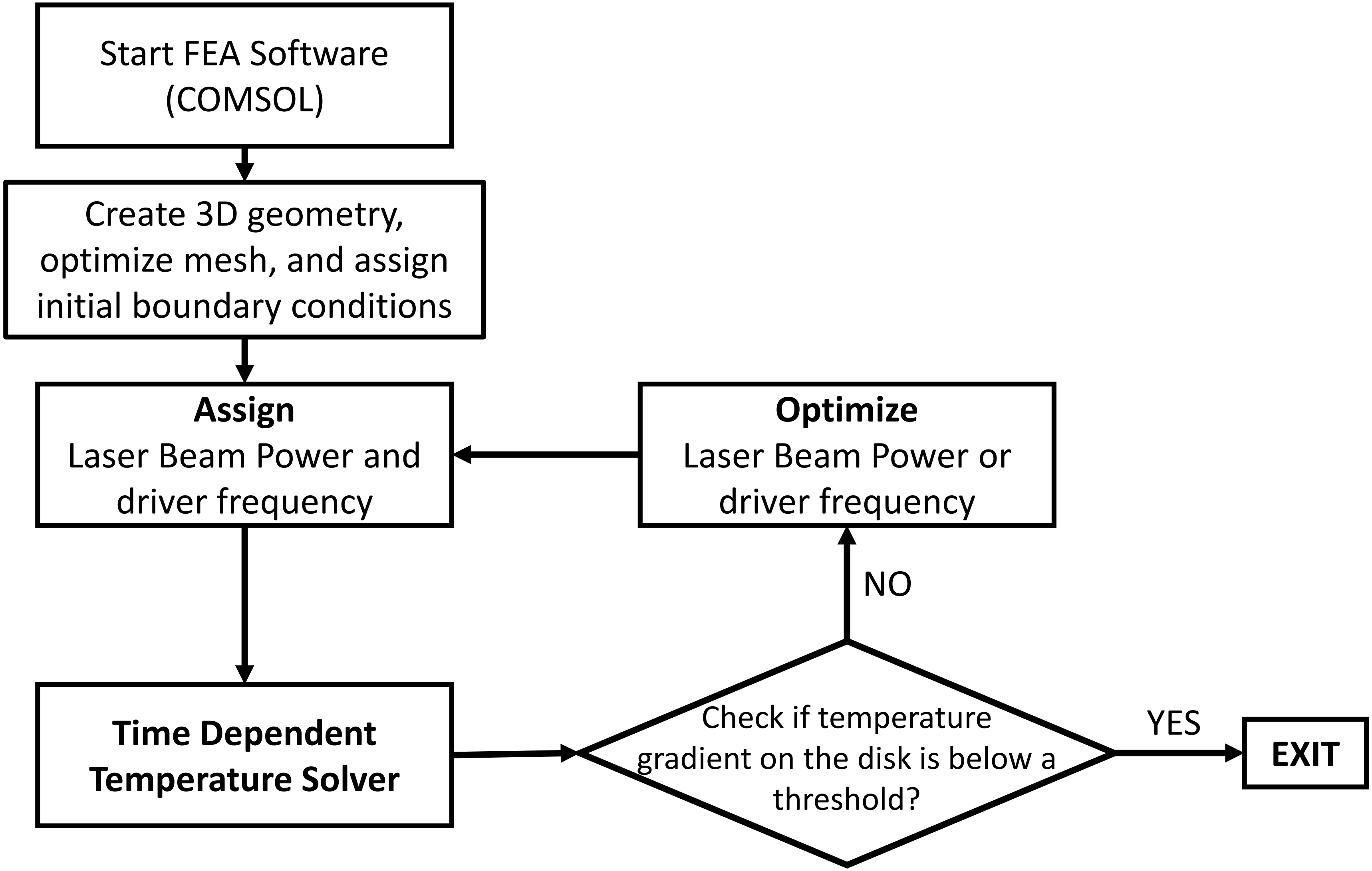




Modified Setup

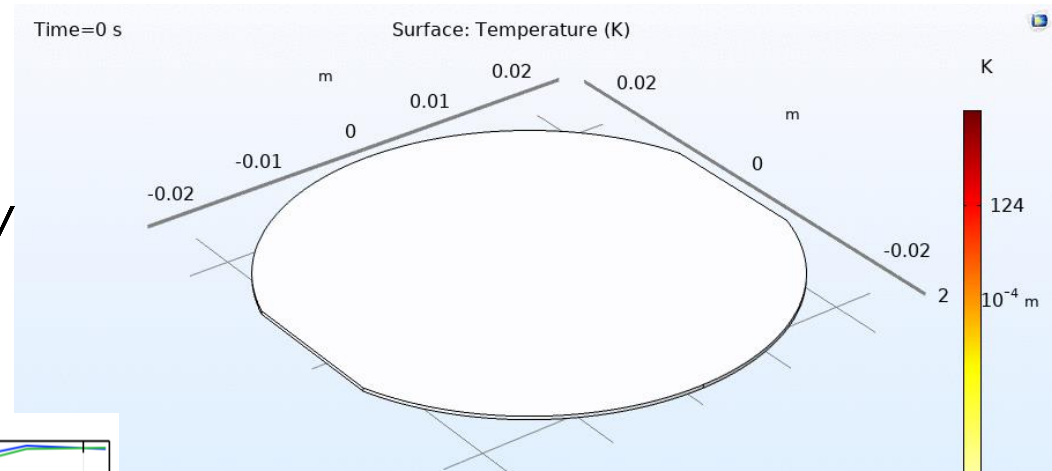


FEA Modelling

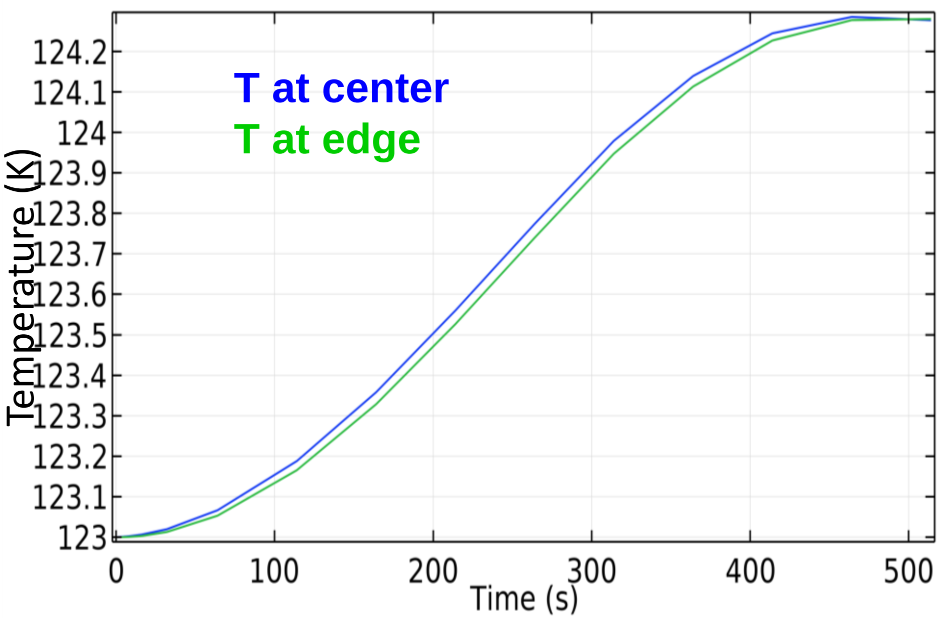


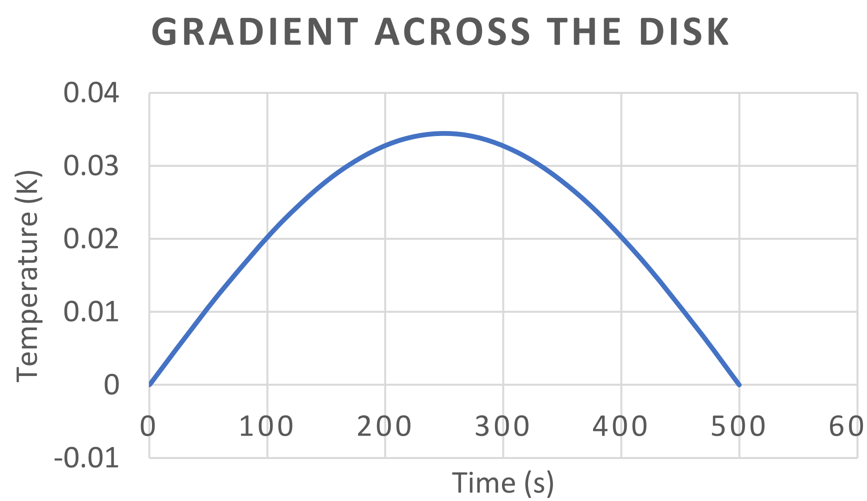
FEA Analysis

Gaussian Beam
Laser Power : $5\sin(2\pi \times 0.001 \times t)$ *mW*
Standard Deviation : *2 mm*
Emissivity of disk : *3e-4*



Temperature profile – Disk





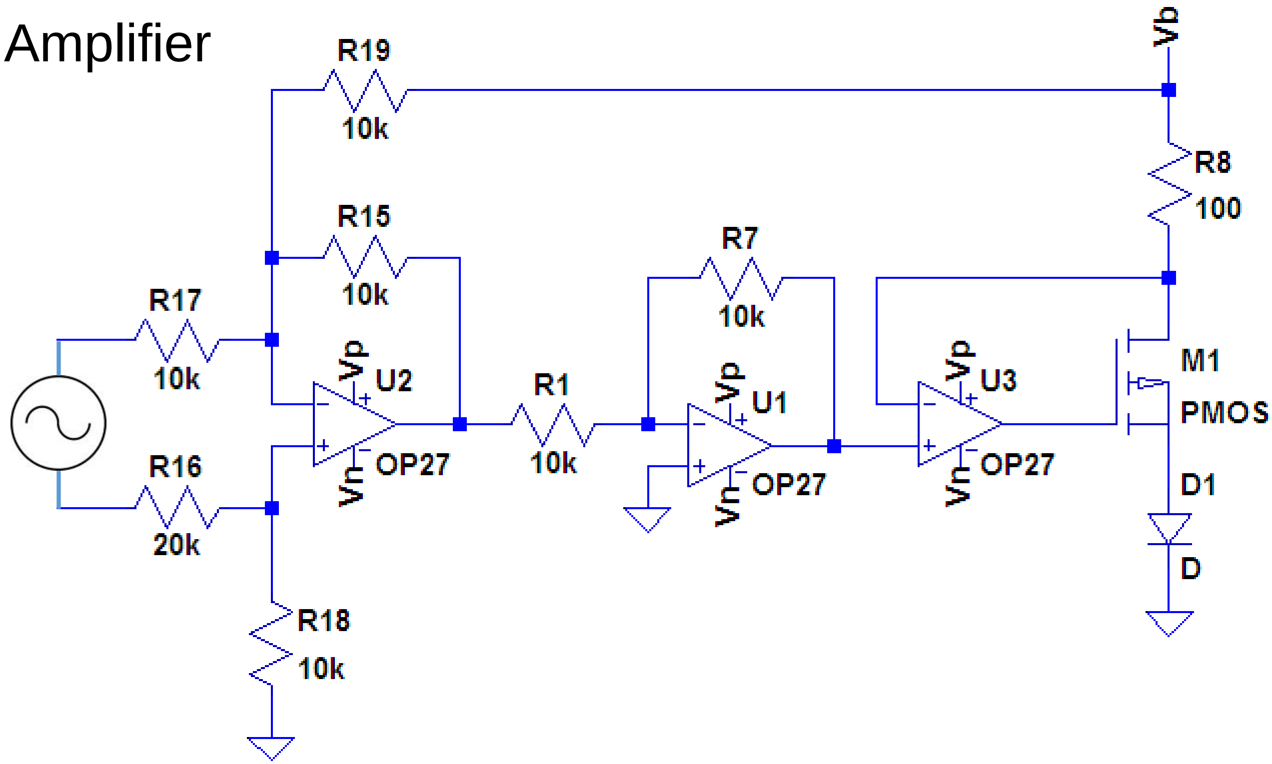
Laser Driver Circuit Analysis

Operating Condition :

U1 : Unity gain Amplifier operating in inverting mode

U2 : Differential Amplifier

U3 : Unity gain Buffer Amplifier



Future Work

- More data points for the temperature probe
- Faster cooling on the go
  - Increase emissivity of the disk (doped Silicon)
  - To develop a thermally contacted but mechanically isolated system
- Cool down below the zero-crossing temperature (123K)

THANK YOU