LIGO

Experiments towards a cryogenic interferometer: From the sublime to the practical

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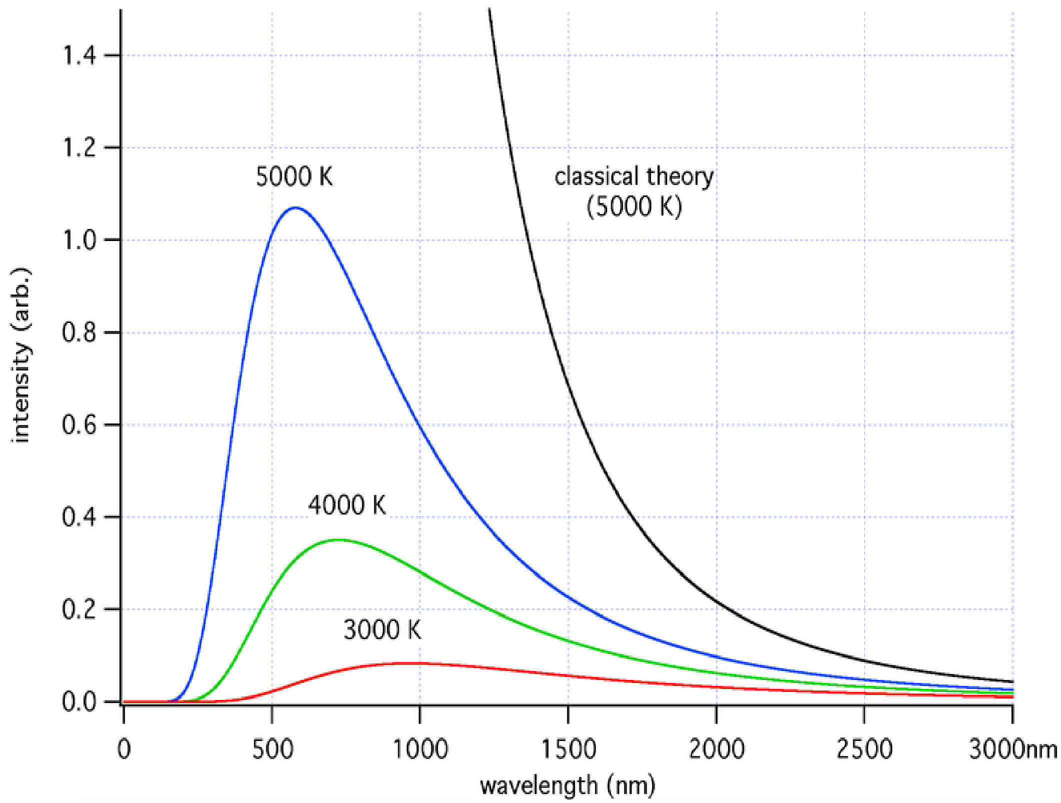
LIGO-G1400565

Black body radiation

- Quantum Theory
  - Planck's Law
    - $B_\nu \propto \nu^3 \frac{1}{e^{\frac{h\nu}{kT}} - 1}$
    - Far-field theory
- Near-Field
  - Casimir force
  - Evanescent-wave heat transfer
  - * Rytov, Polder/van Hove Loomis/Maris



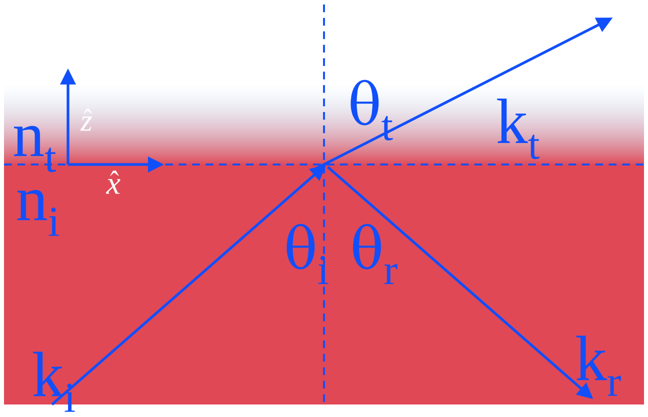
http://en.wikipedia.org/wiki/File:Blackbody-lg.png

Theory

- Exponentially decaying field
- Produced by total internal reflection
- If a wave propagates in vacuum,
  - » k_{tx} and k_{tz} found from Snell's law.
  - » Total internal reflection:

    ($\sin\theta_i > n_t/n_i$)
- If total reflection,

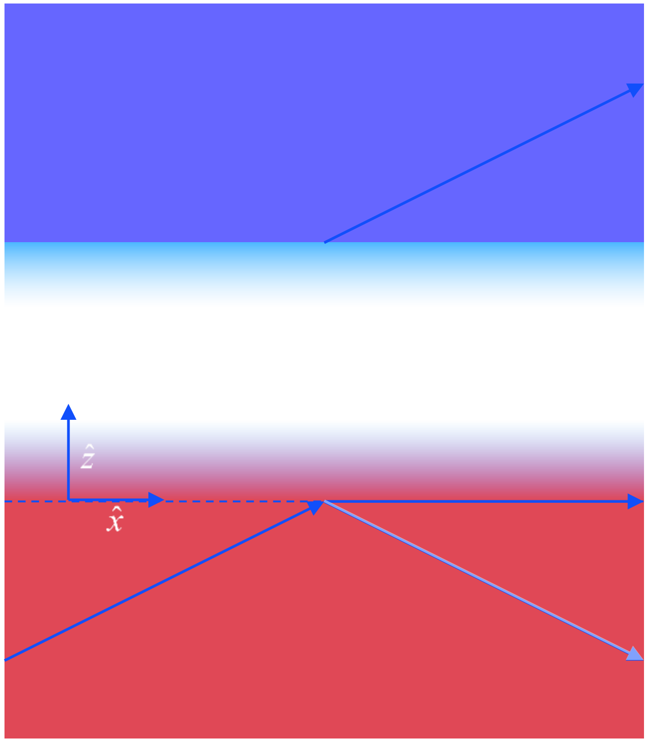
$$\vec{E}_t = \vec{E}_{t0} e^{ik_t x \frac{n_i}{n_t}\sin\theta_i} e^{-k_t z\sqrt{\frac{n_i^2}{n_t^2}\sin^2\theta_i - 1}} e^{-i\omega t}$$



- E_{tz} is exponentially decaying

Theory 2

- Bring 2nd medium near the interface
- Energy propagates into the 2nd material
- "Frustrated total internal reflection" (photon tunneling)



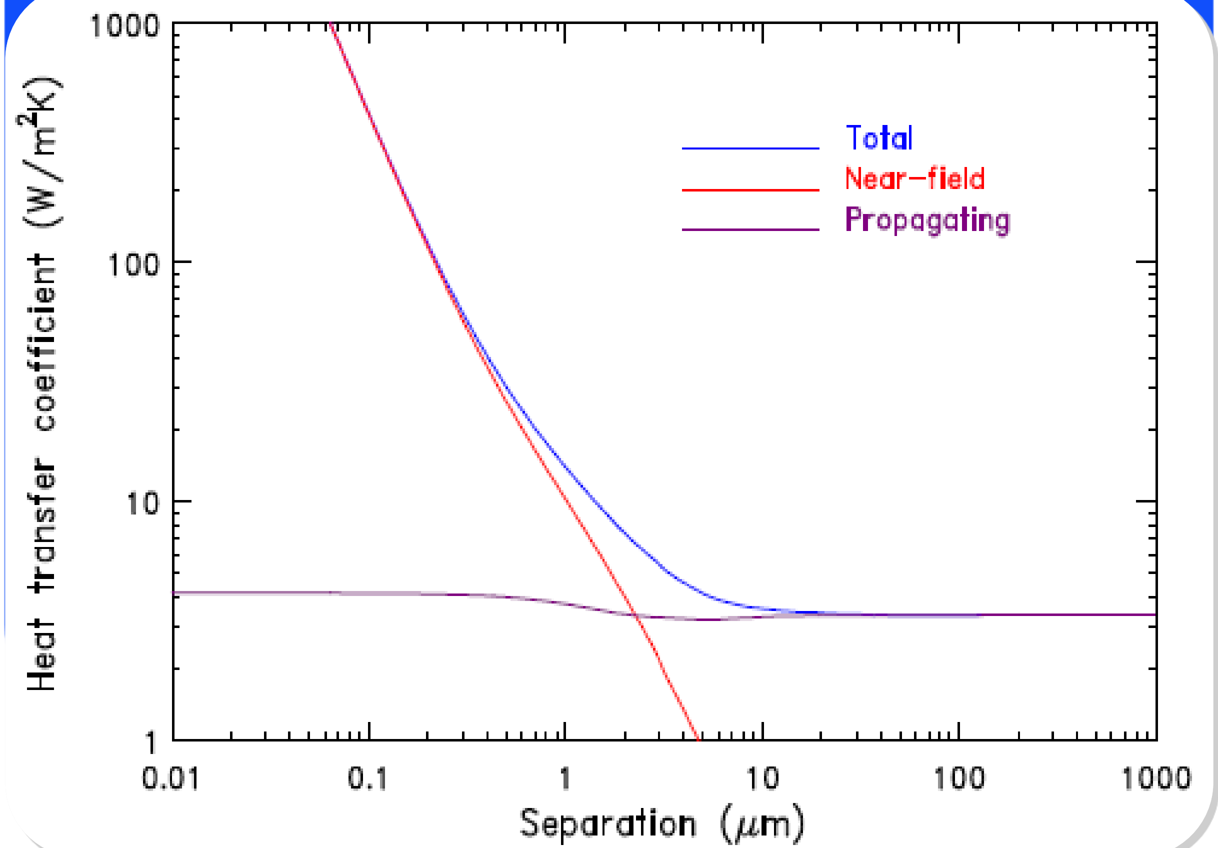
Theory 3

- Propagating part (almost) constant with separation
- Near-field becomes dominant at distances below the thermal wavelength

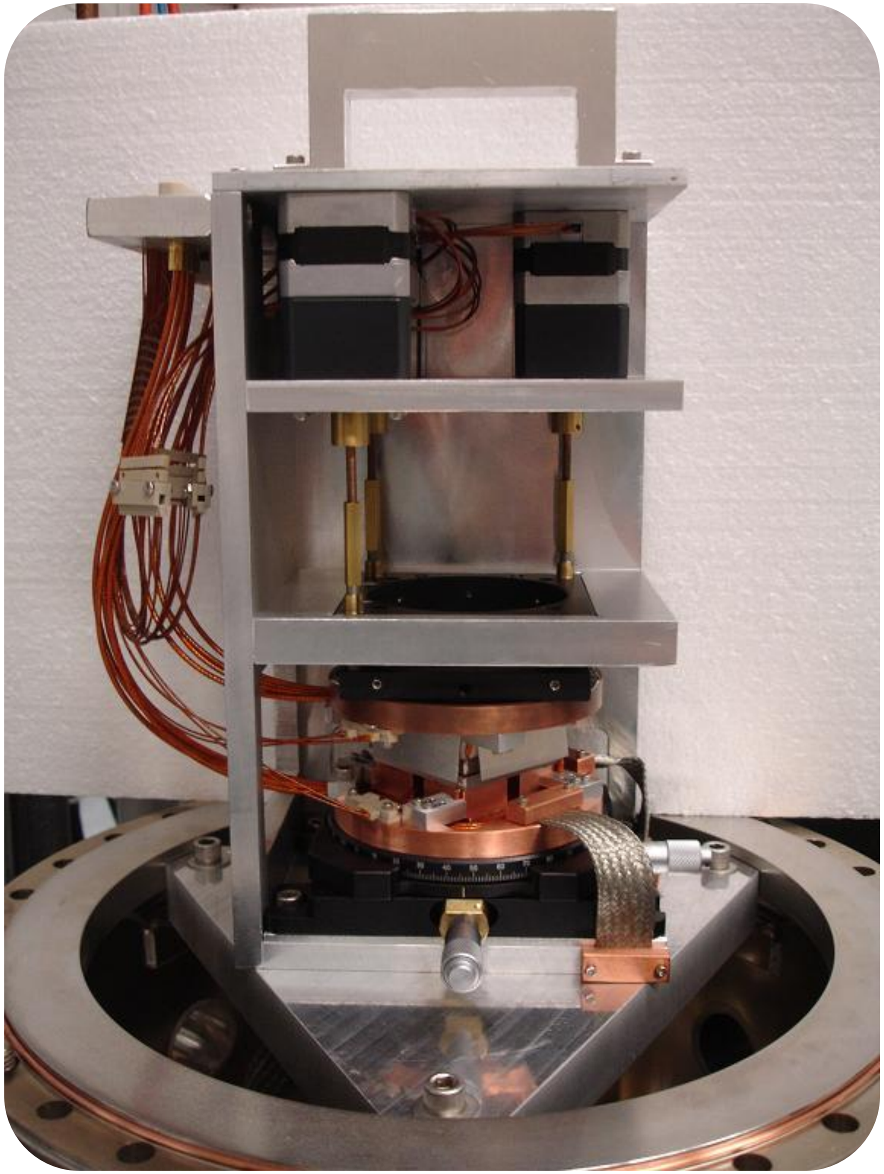
$$\Lambda = \frac{ch}{2\pi^{1/3}kT}$$

- Λ = 10 μm at 300 K

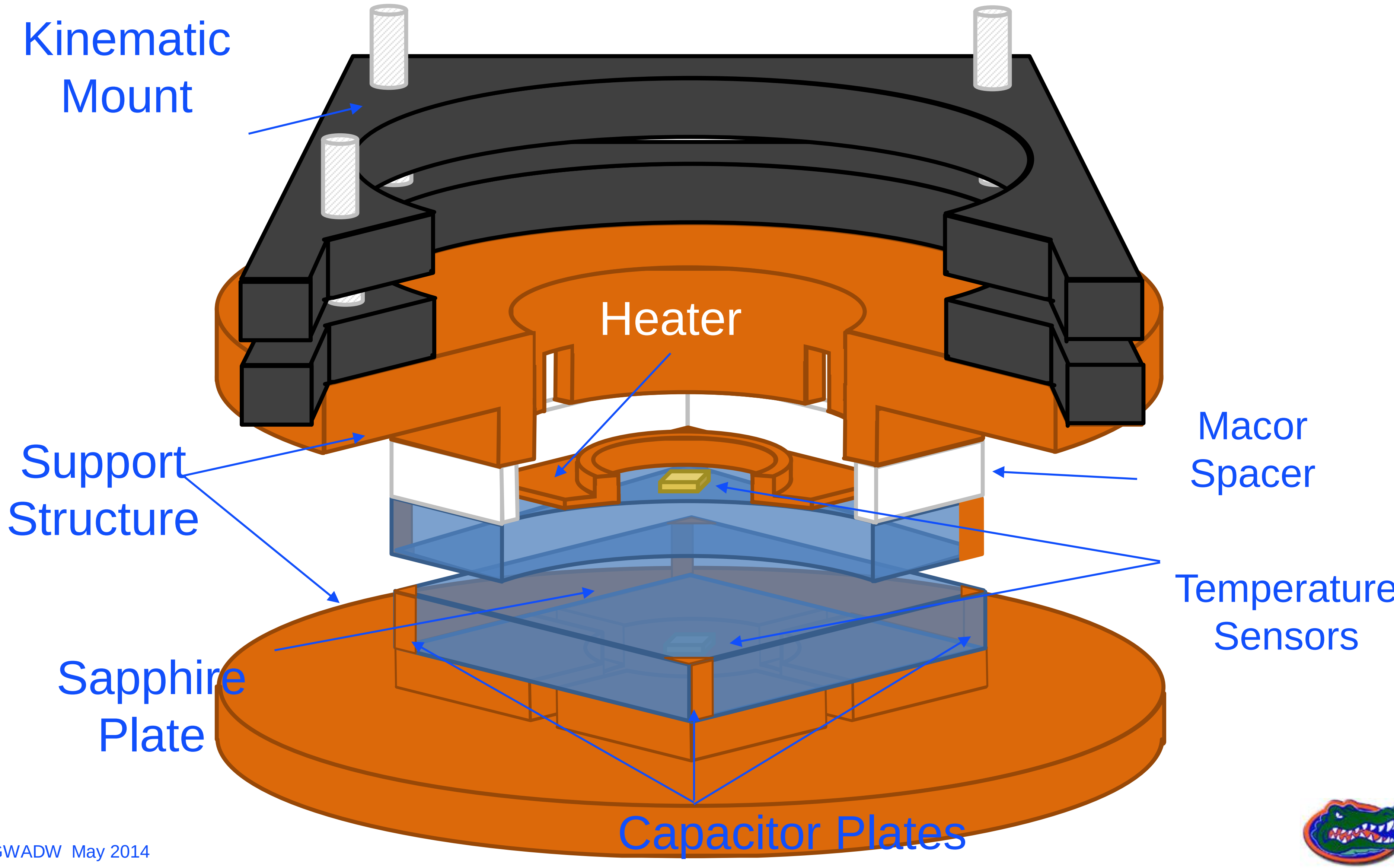
Heat transfer components
(T_1 = 300K T_2 = 310K)



Experimental Setup



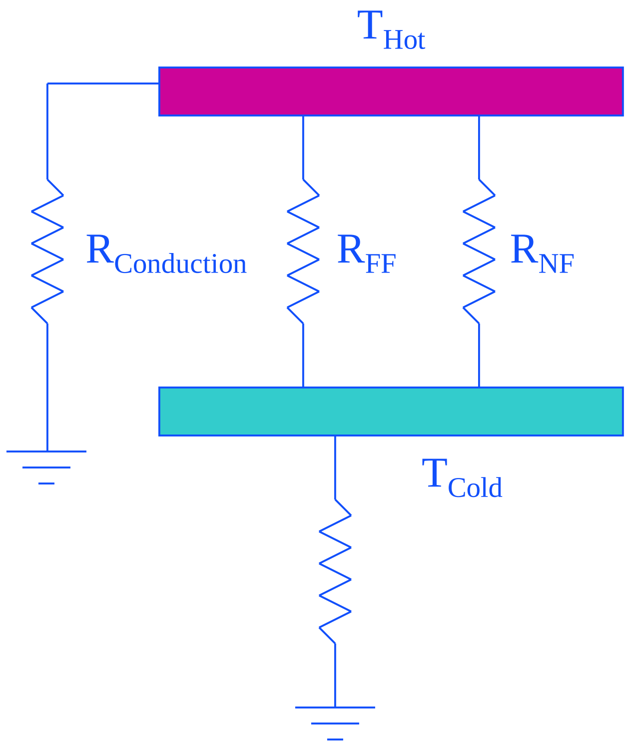
Cutaway


Kinematic Mount
Heater
Macor Spacer
Support Structure
Temperature Sensors
Sapphire Plate
Capacitor Plates

Heat Transfer Measurements

The heat transfer is the ratio of heater power to (area * temperature difference)

$$w = \frac{P}{A \cdot \Delta T}$$



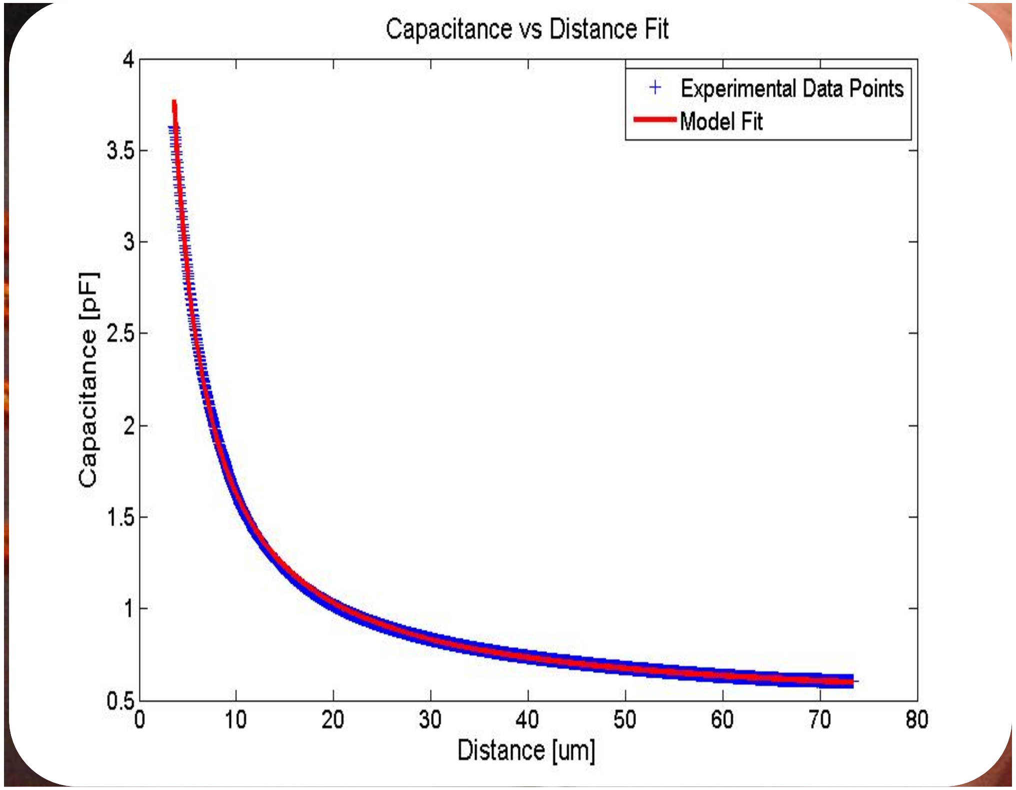
Move the plates closer; heater power increases

Distance Measurements

- Use 4 capacitors
  - » On corners
- Capacitors follow

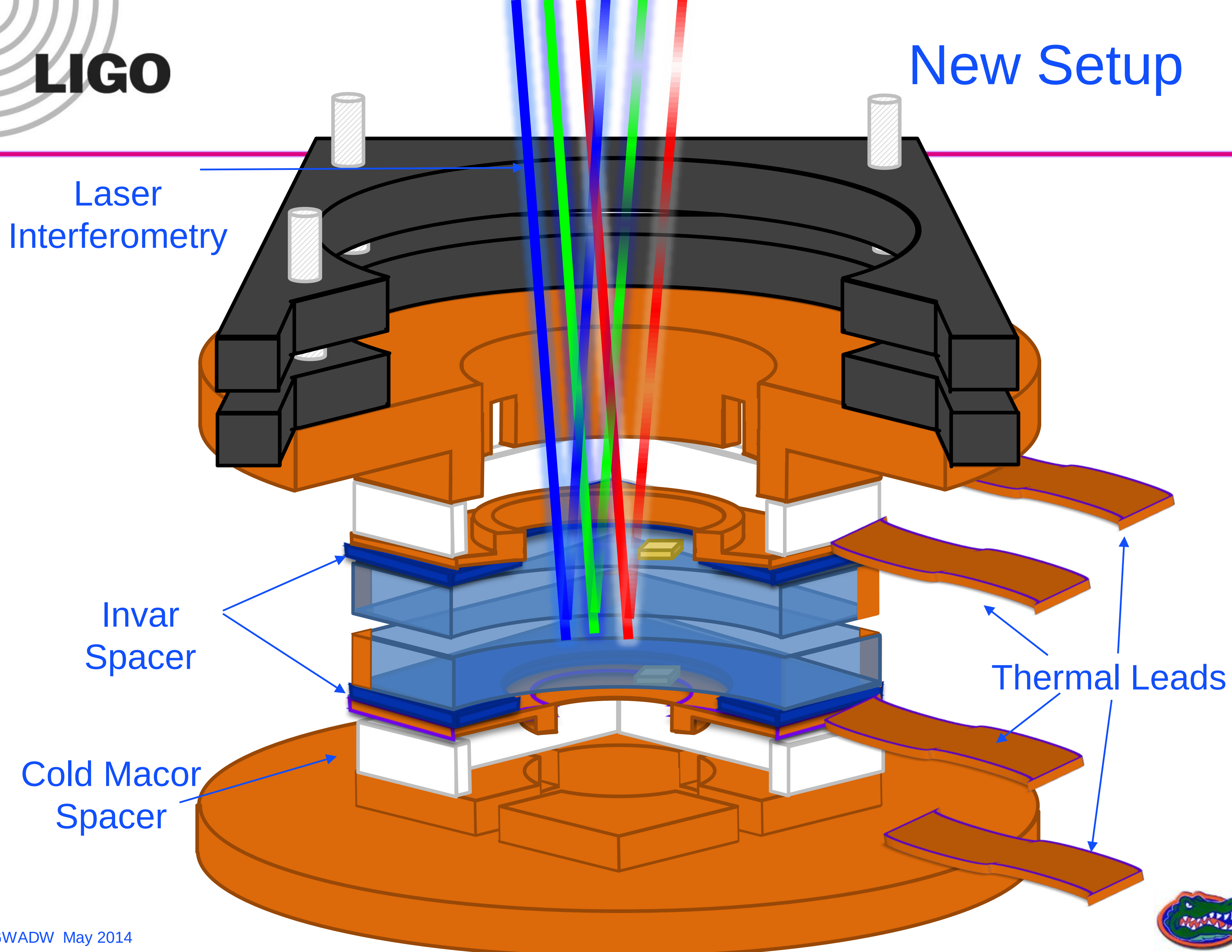
$$C = \frac{\gamma}{d + d_0} + \delta$$

- γ, d_0, and δ found experimentally



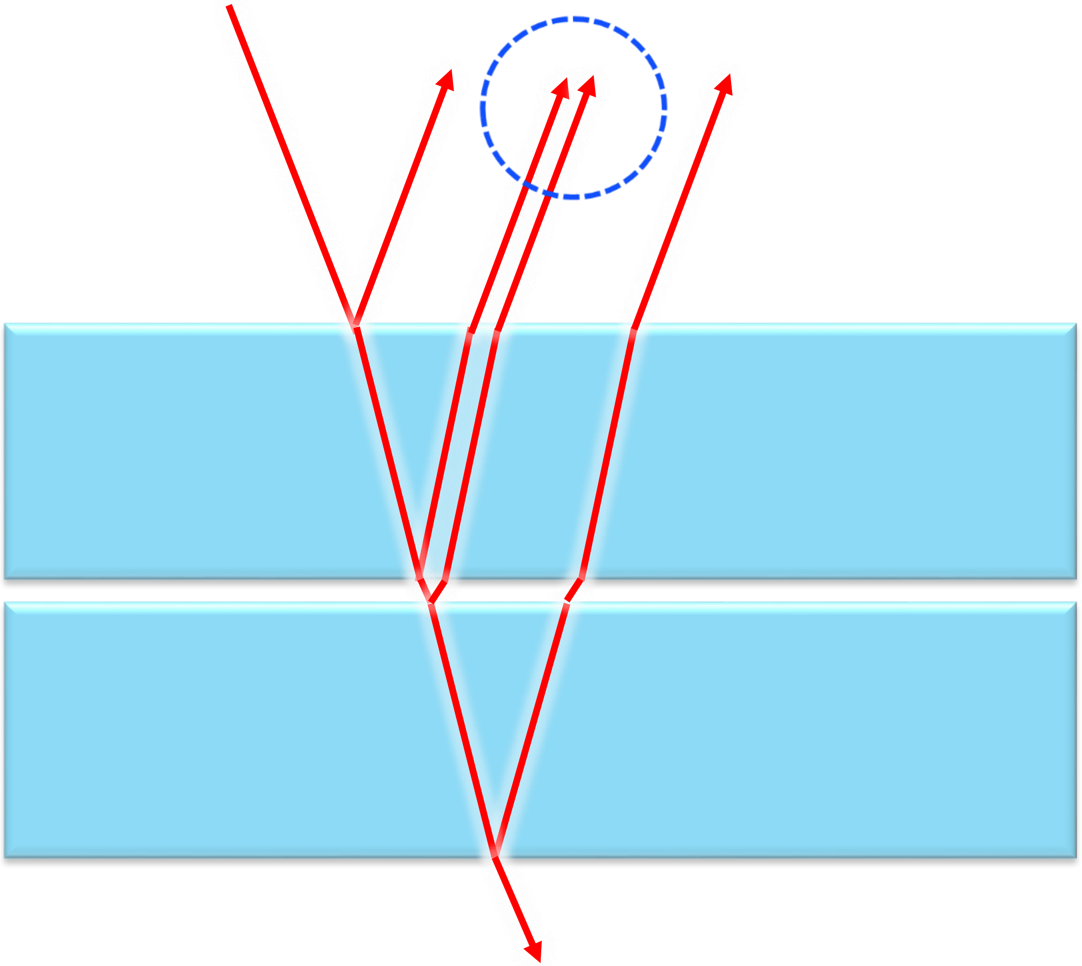
LIGO

New Setup



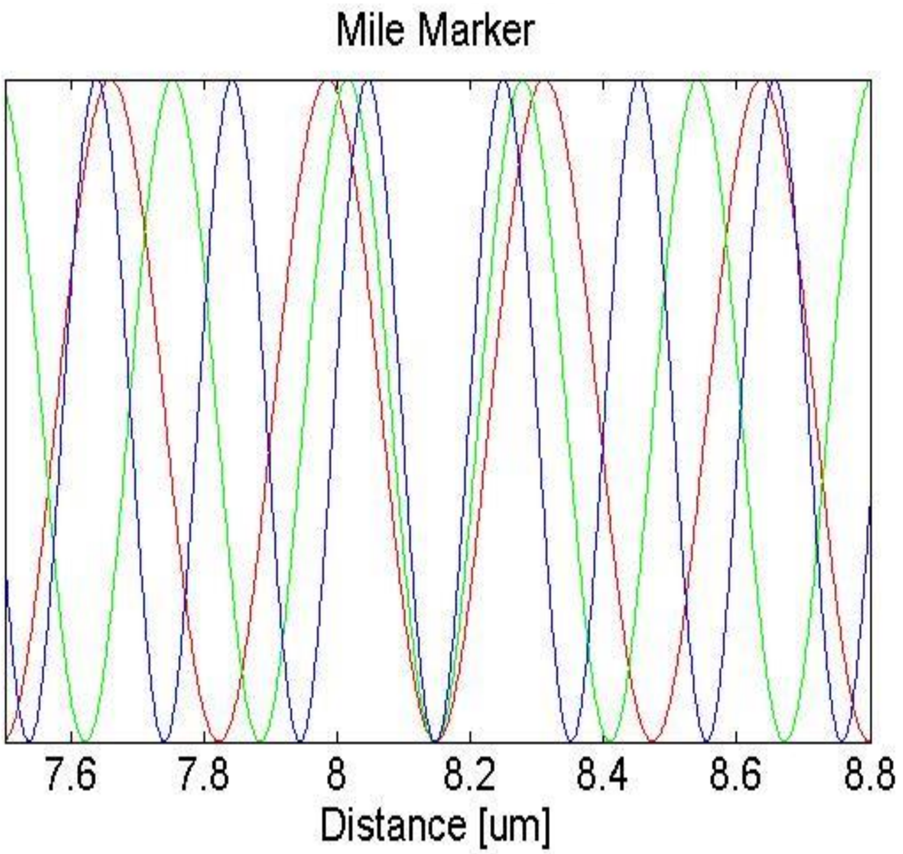
Laser Interferometry

- Laser light interferes with reflections off the two gap surfaces
- Angling beam separates reflected light off of undesired surfaces



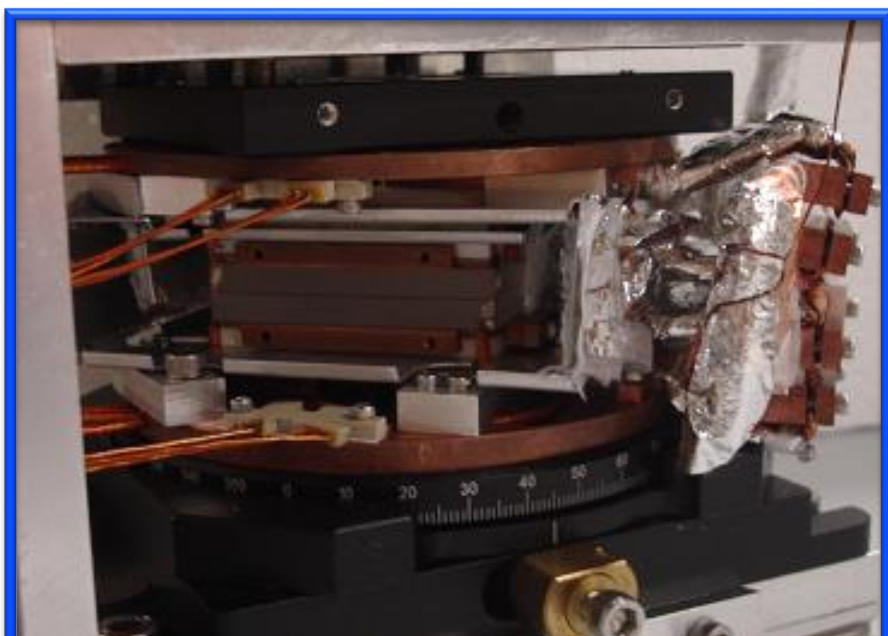
Laser Interferometry

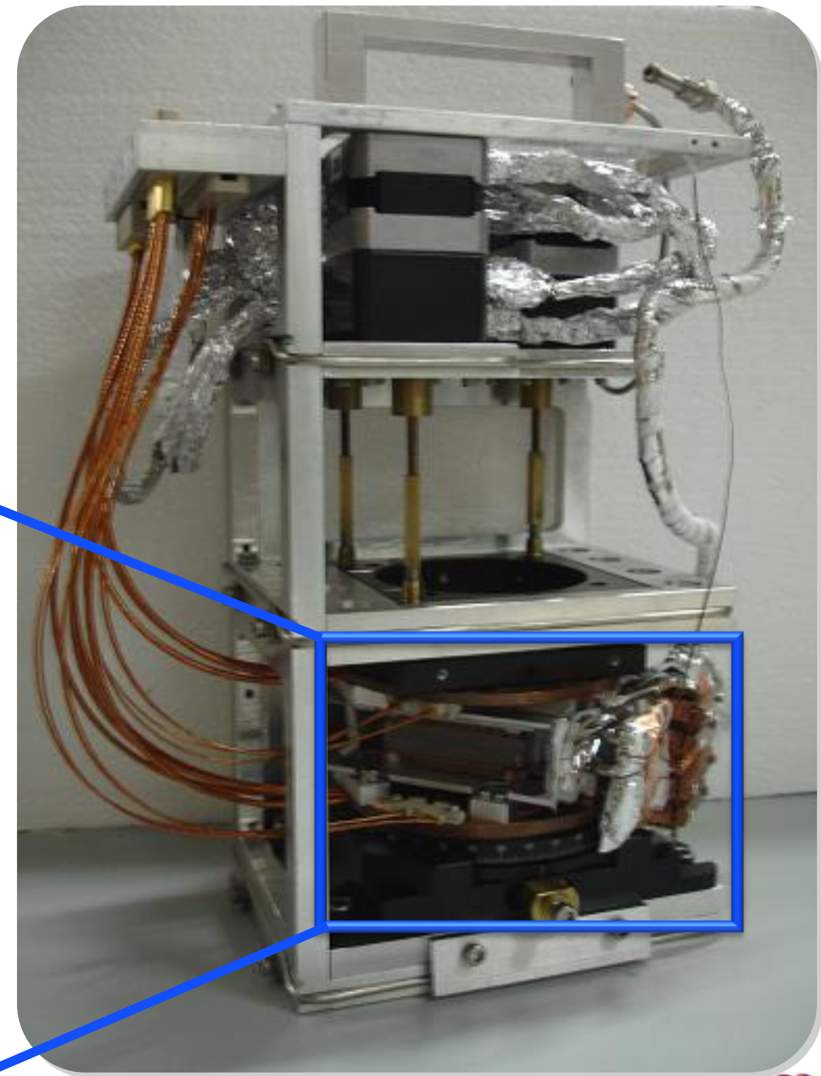
- Laser interference between the two plates produce fringes
  - Gives relative distance
- Minima realign about every 8.1 μm
  - Use as mile markers
- Capacitors are sufficient to determine the proper 8.1 μm window
  - Gives absolute distance



New Setup

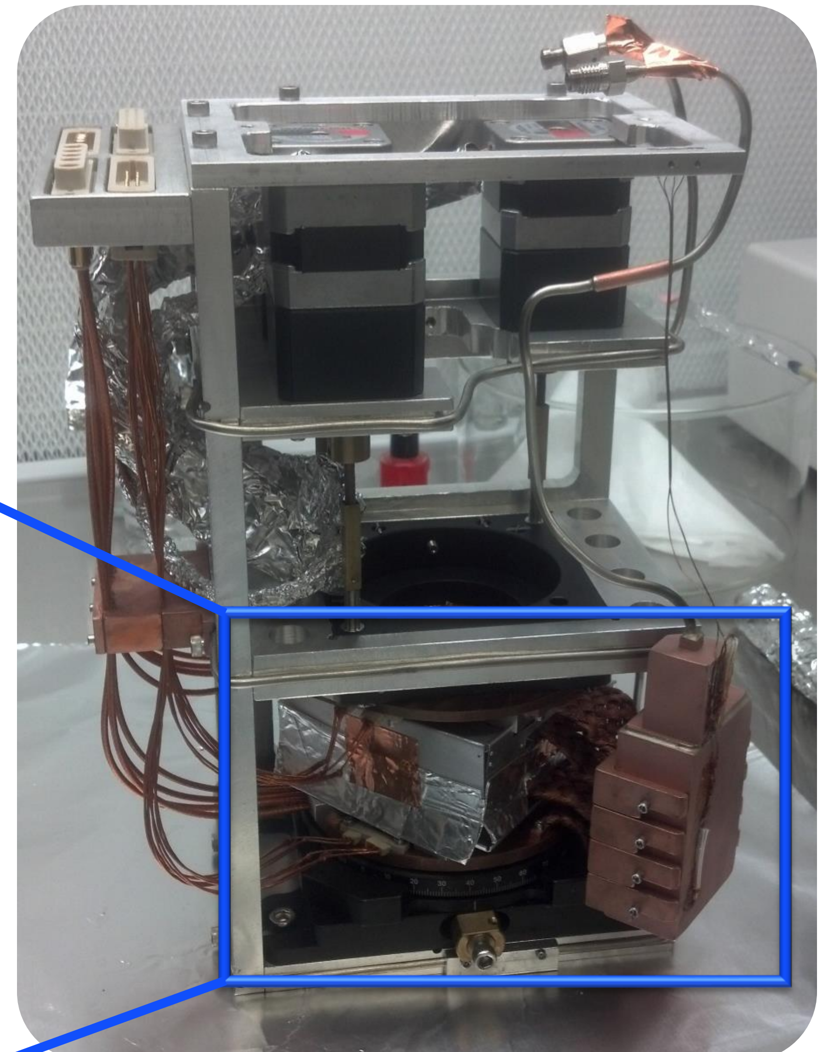
- Both sapphire plates thermally controlled
- Better thermal controller

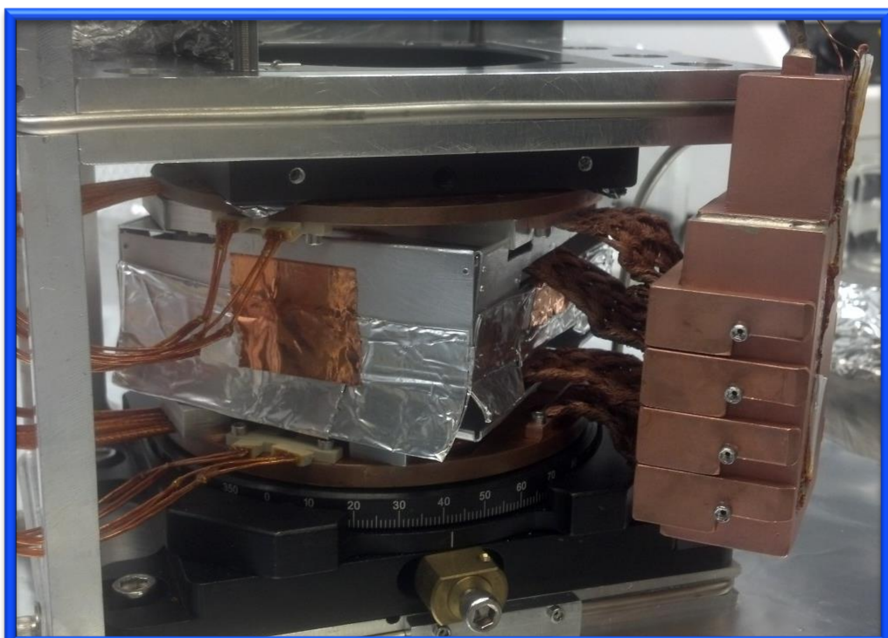




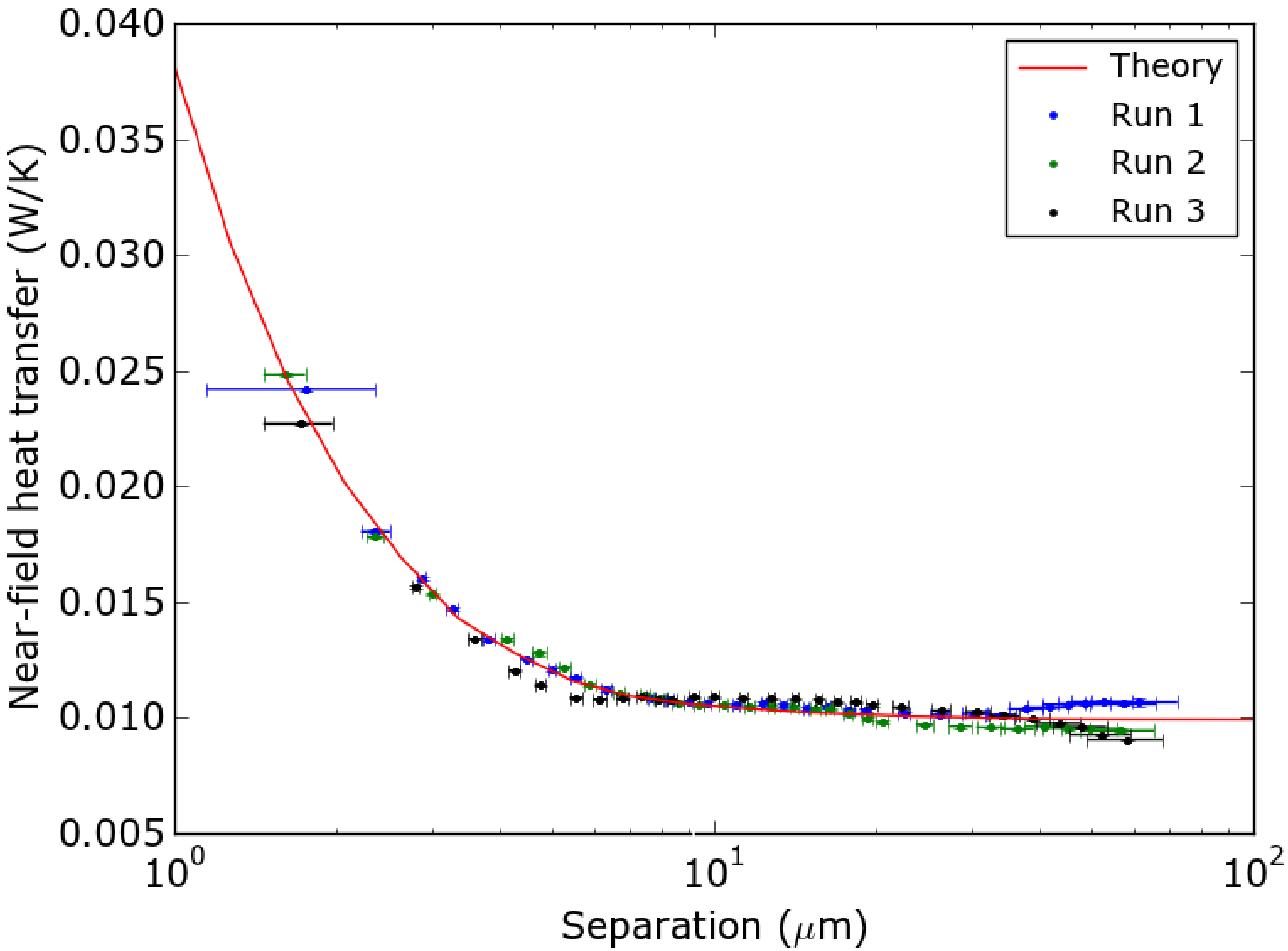
New Setup

- Modified heat exchanger
  - Reduce thermal noise
  - Improved thermal link

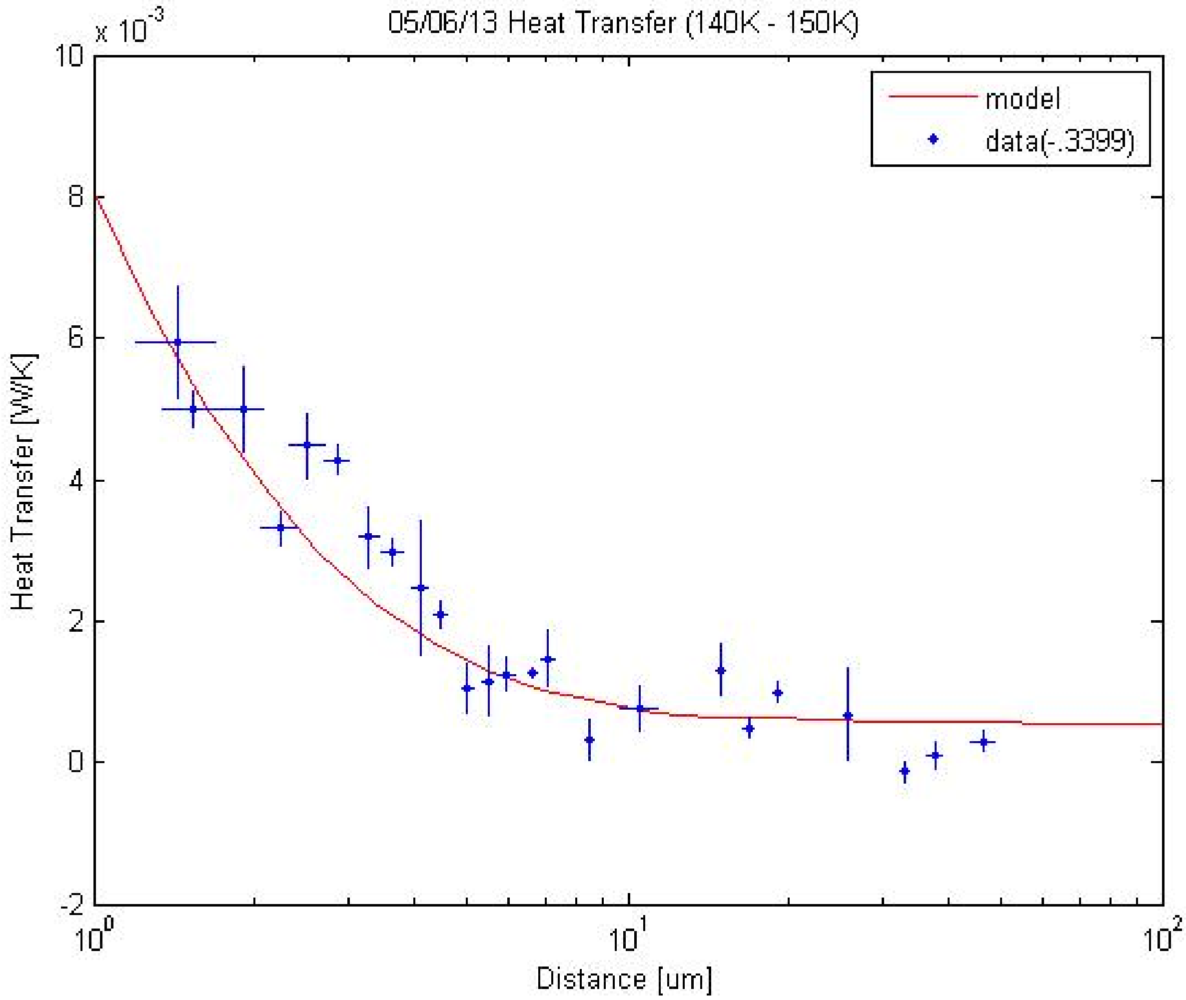




Best Results at Room Temperature



~100 K



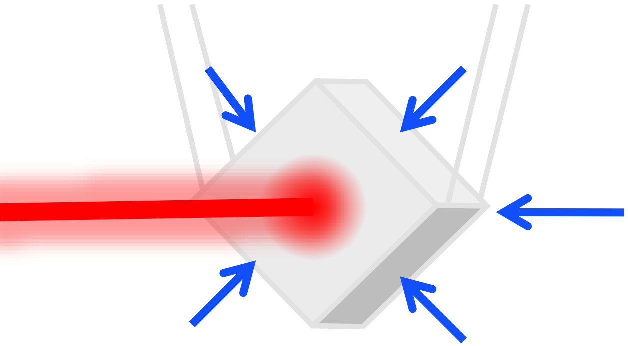
05/06/13 Heat Transfer (140K - 150K)
x 10^-3
Heat Transfer [W/K]
Distance [um]
model
data(-.3399)
10
8
6
4
2
0
-2
10^0
10^1
10^2

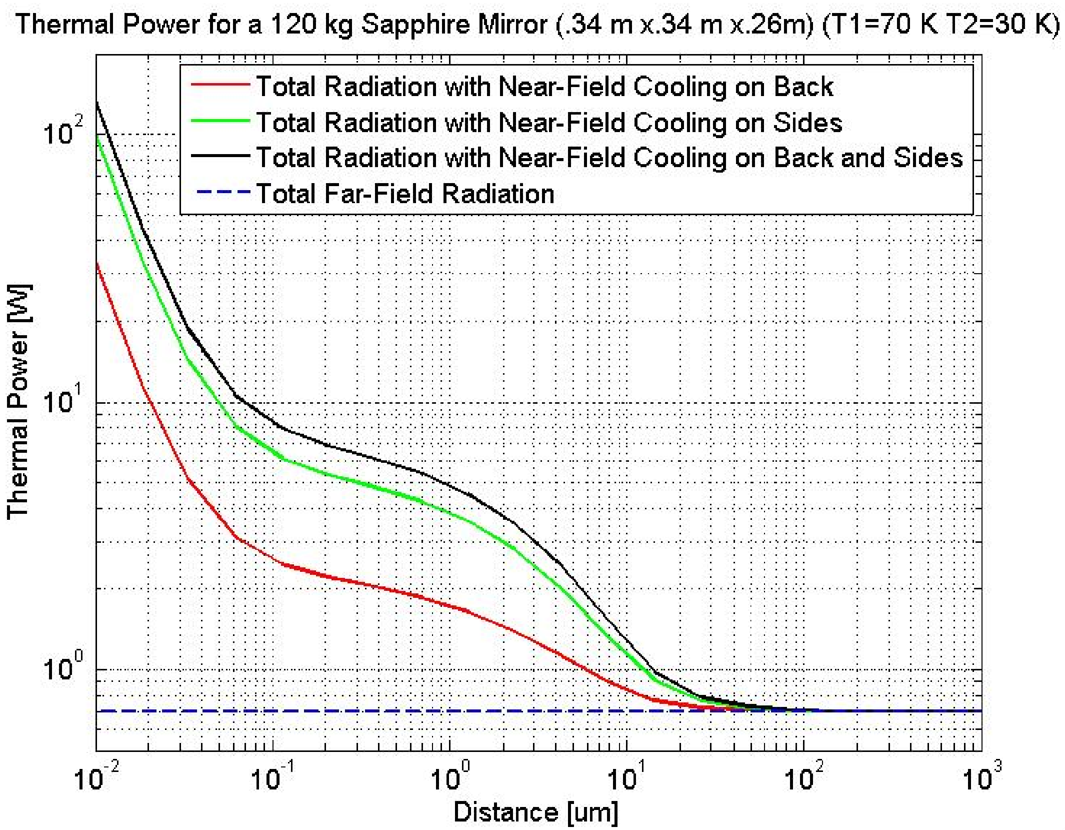
Implementation in LIGO

Back
- Only one surface
- Noise due to charging
- And Casimir force

Sides
- Multiple surfaces
- Reduced noise coupling

Back and Sides

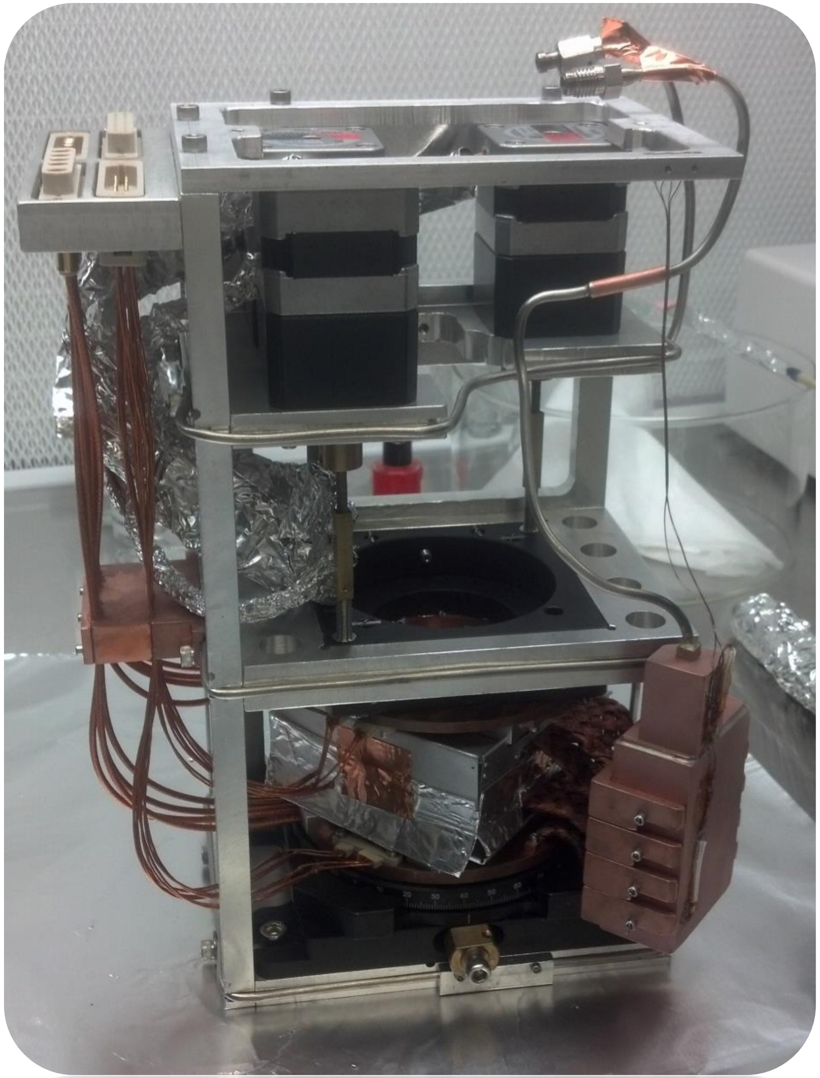




Conduction through the fibers: 4.4×10^{-6} W/K (<< far field radiation)

Near-field summary

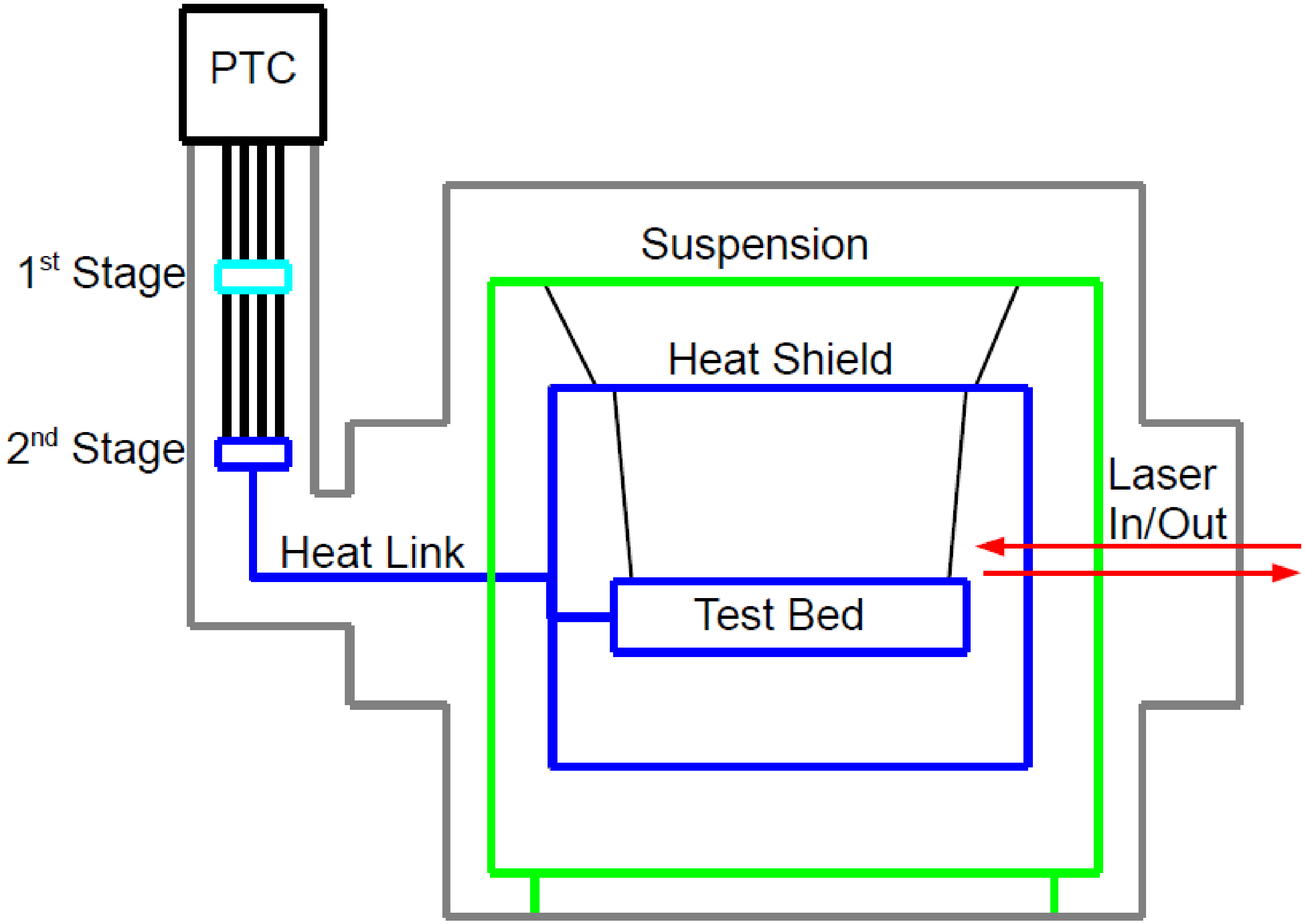
- Measured evanescent-wave heat transfer across a small gap
- Agrees with theory
- Can potentially be used to take excess heat from mirrors in LIGO
- Starting to get cryogenic results



Cryogenic gadgets

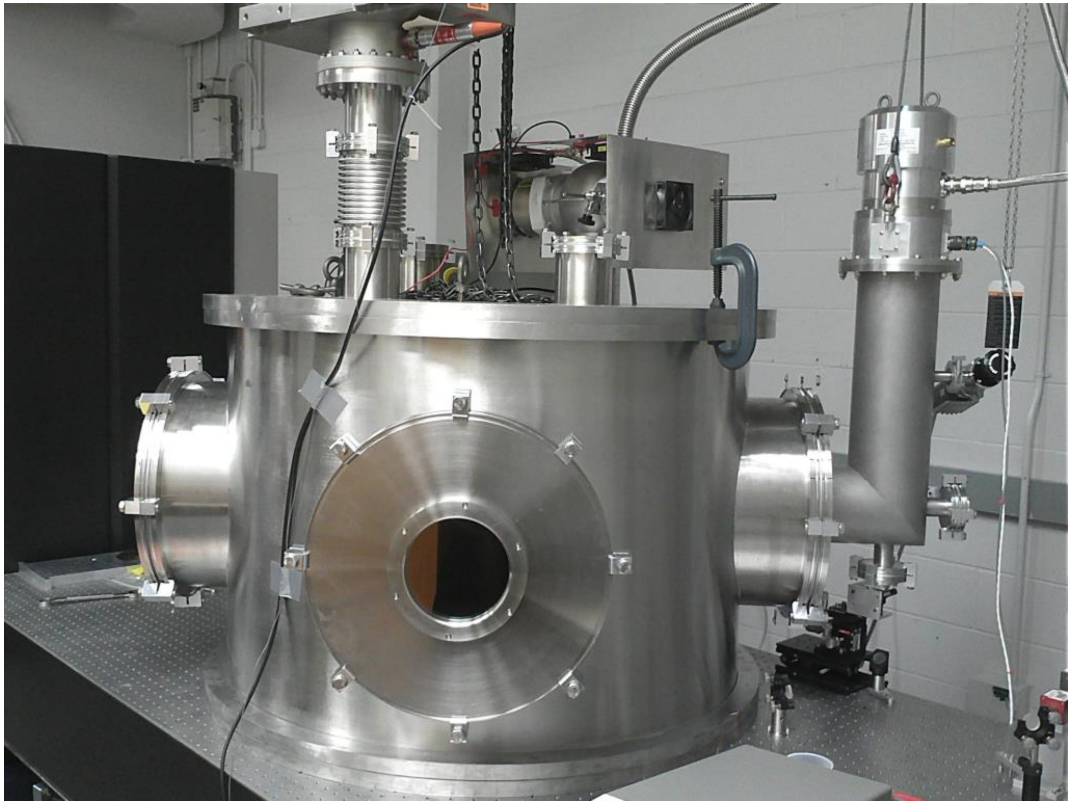
- Ryan Goetz poster in GWADW13
- Many different gadgets used in the vacuum systems of GW detectors
- Would need to work in a cryogenic environment in future detectors

Cryogenic test facility



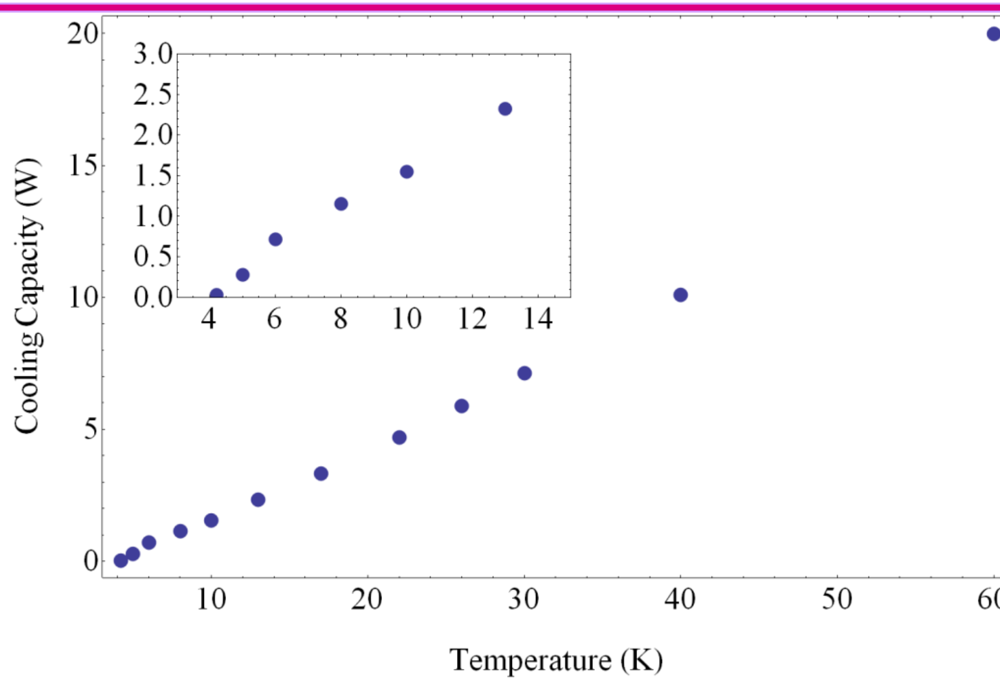
Cooler and chamber

- 0.6 m^3 main vacuum tank along with an attached Sumitomo cryocooler

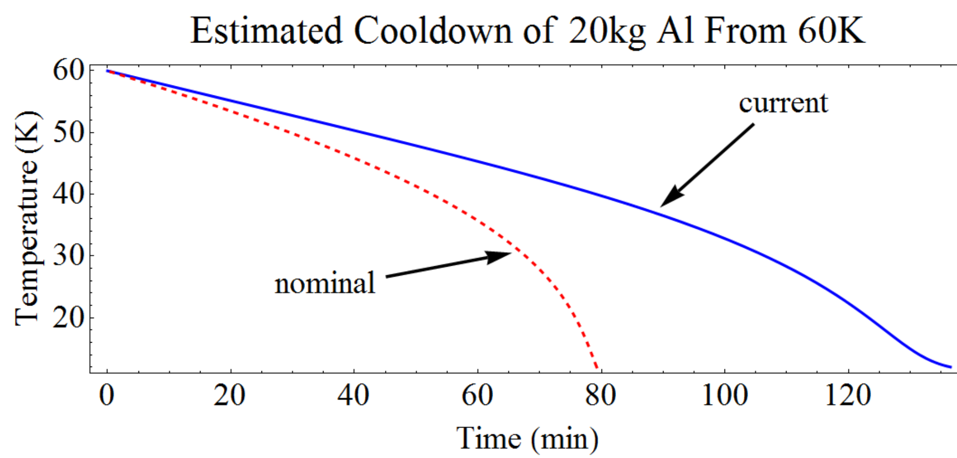


Performance

- More than 1 W at 7 K; 10 W at 40 K
- Base temperature below 4 K.

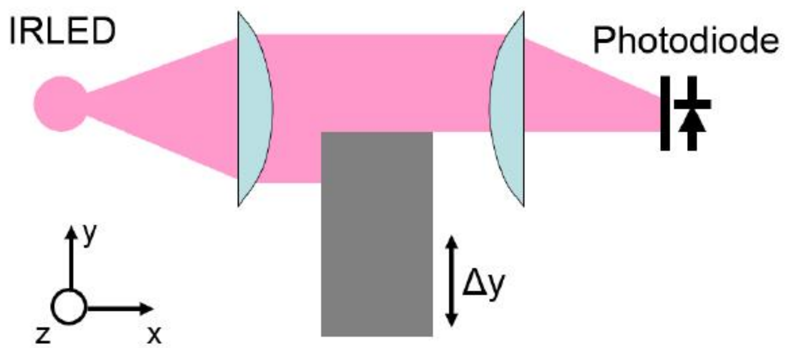


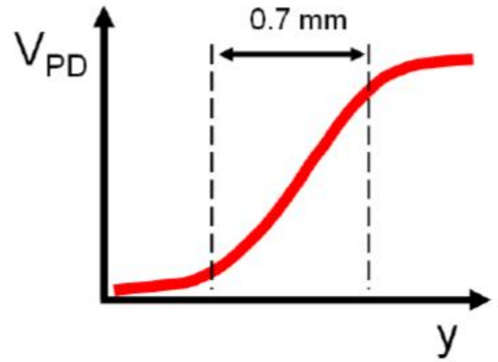
- If thermal link is good, cooldown is quick

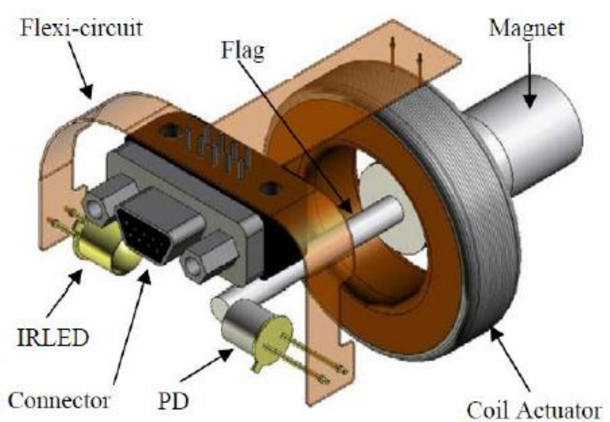


BOSEM

- BOSEM used in aLIGO
- Would need to work at low T in future detectors







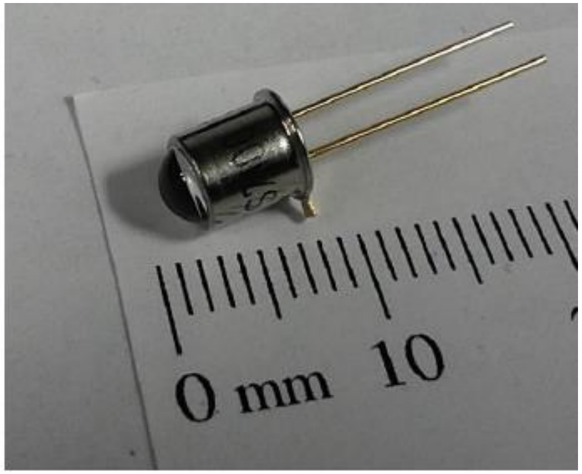
S Aston, LIGO-T0900496

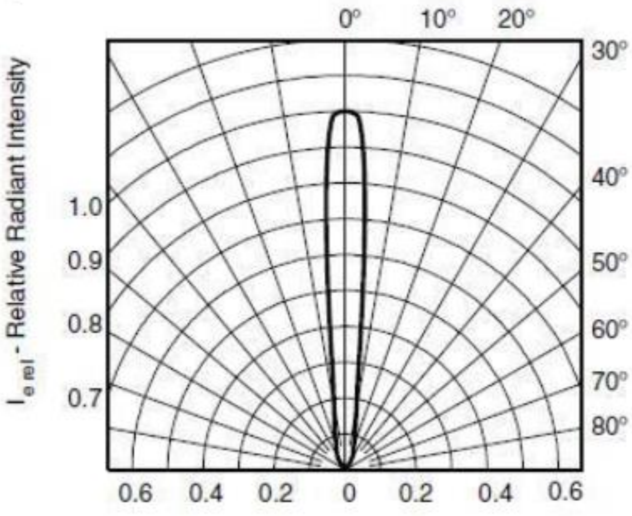
- Shadow detectors and actuators throughout LIGO suspensions
- Displacement of flag read as change in photocurrent:
  - sensitivity of ~10^{-10} m/$Hz^{1/2}$ at 10 Hz†
- Current through coil actuates on flag magnet

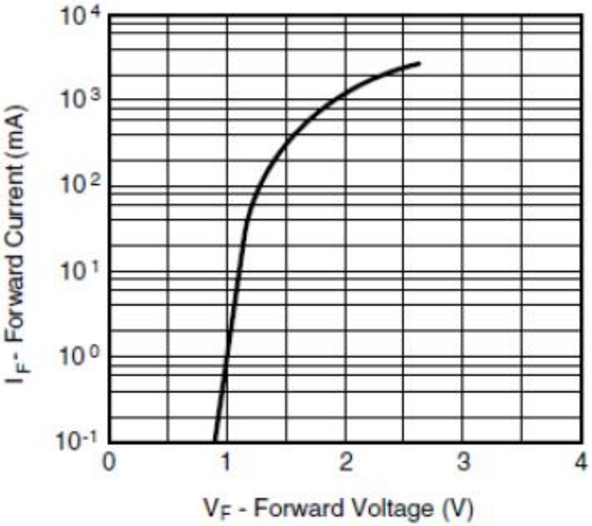
†S Aston, LIGO-P1300051

Vishay TSTS7100

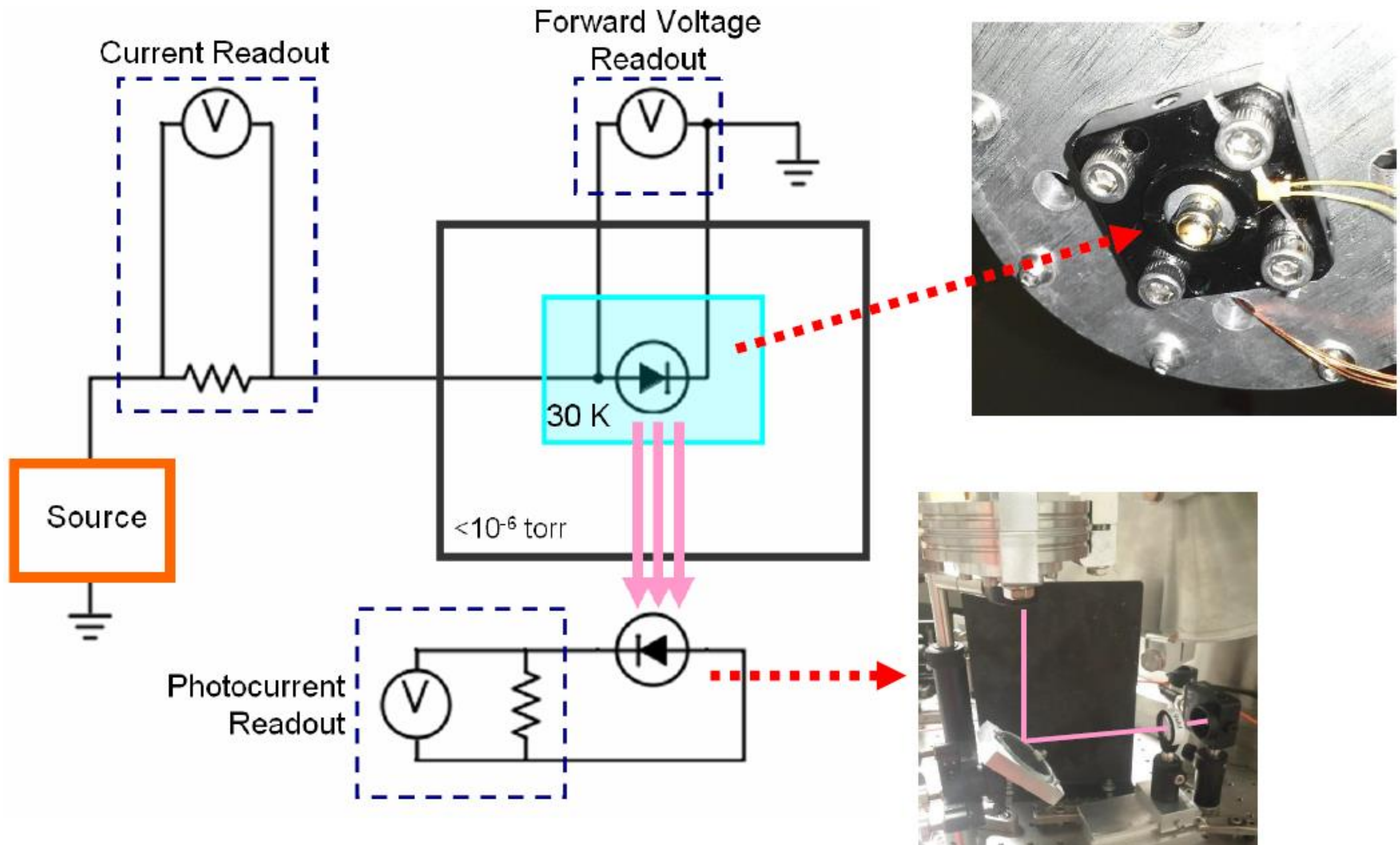
- GaAs (III-V) IRLED
- Used in BOSEM:
  - 950 nm
  - Narrow intensity profile
  - Good noise performance
  - Relatively low forward voltage at 35 mA
- Cryogenic concerns: noise, efficiency, lifetime, profile, spectrum





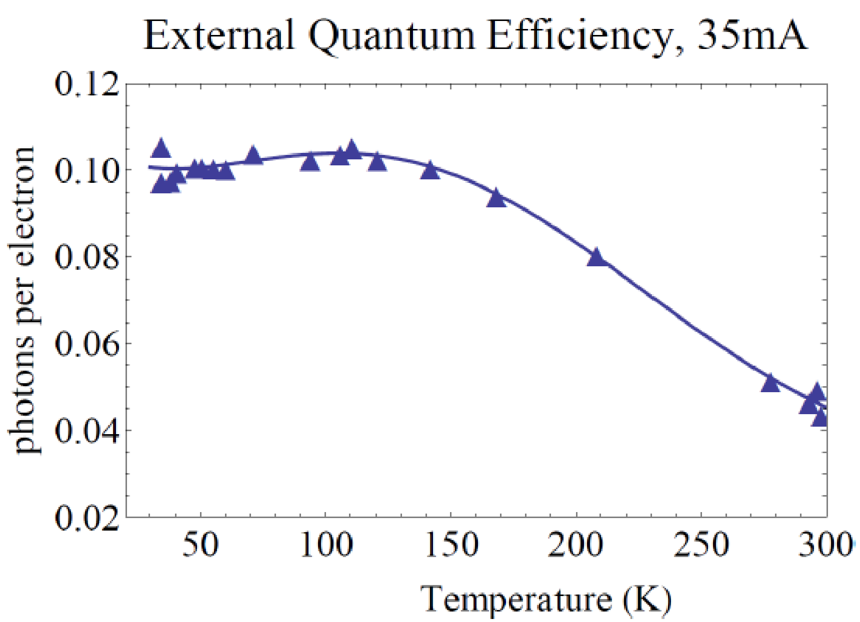


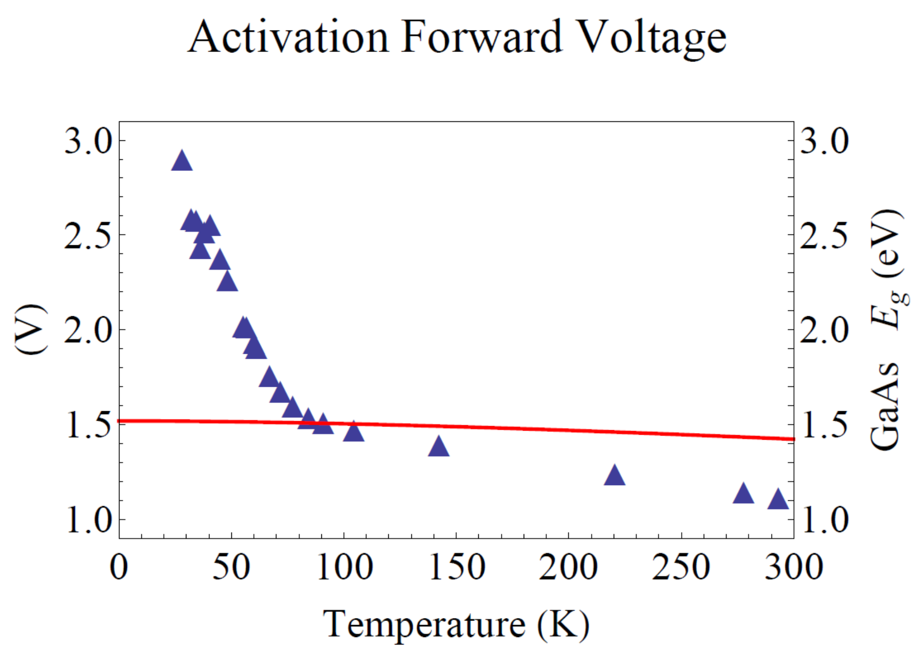
Measure *i, v, T, I*



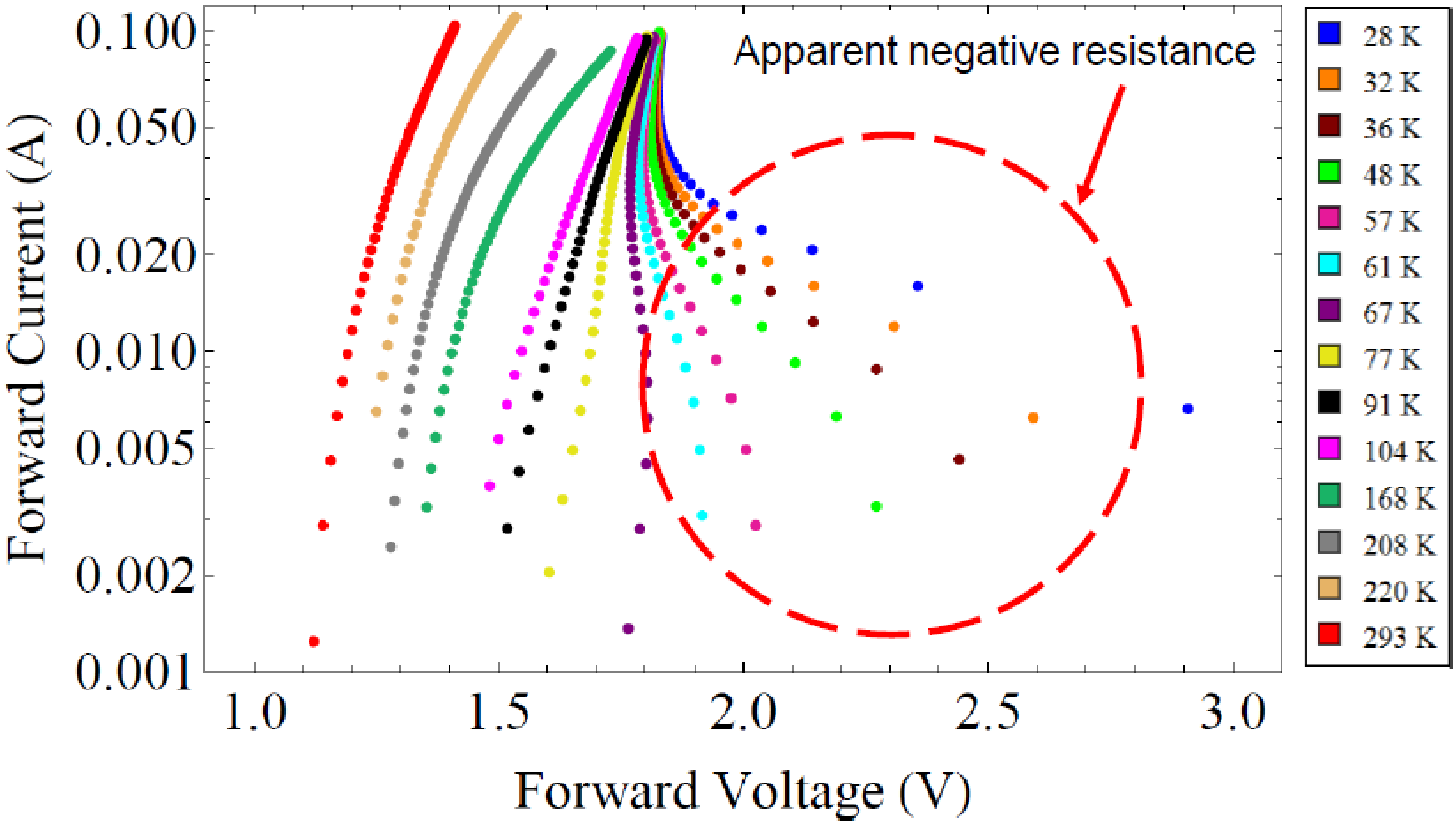
Efficiency, power

- Both external quantum efficiency and heating from the diode at 35 mA increase from 300 K to 30 K
- Not accounting for possible profile changes

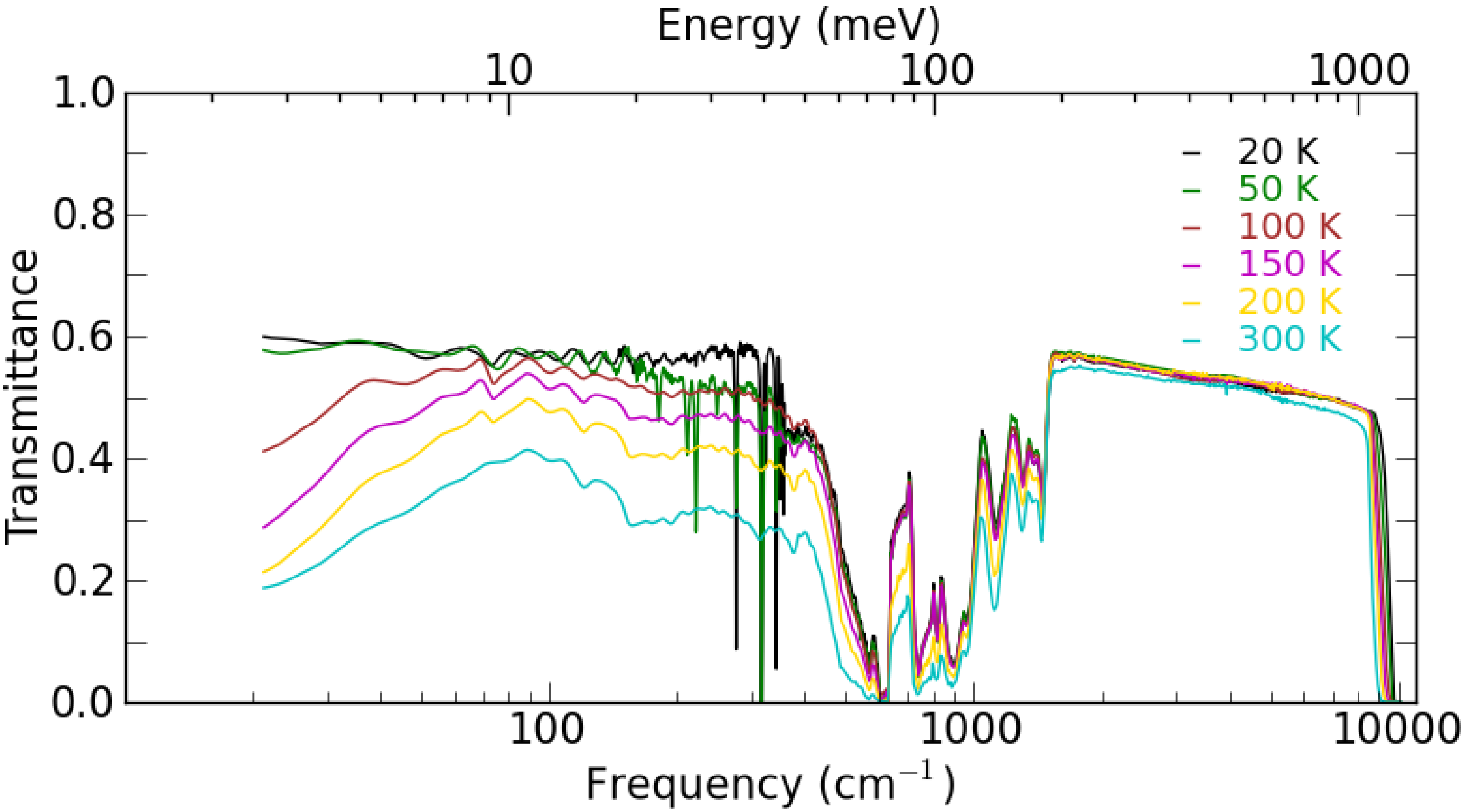




Heating above ambient



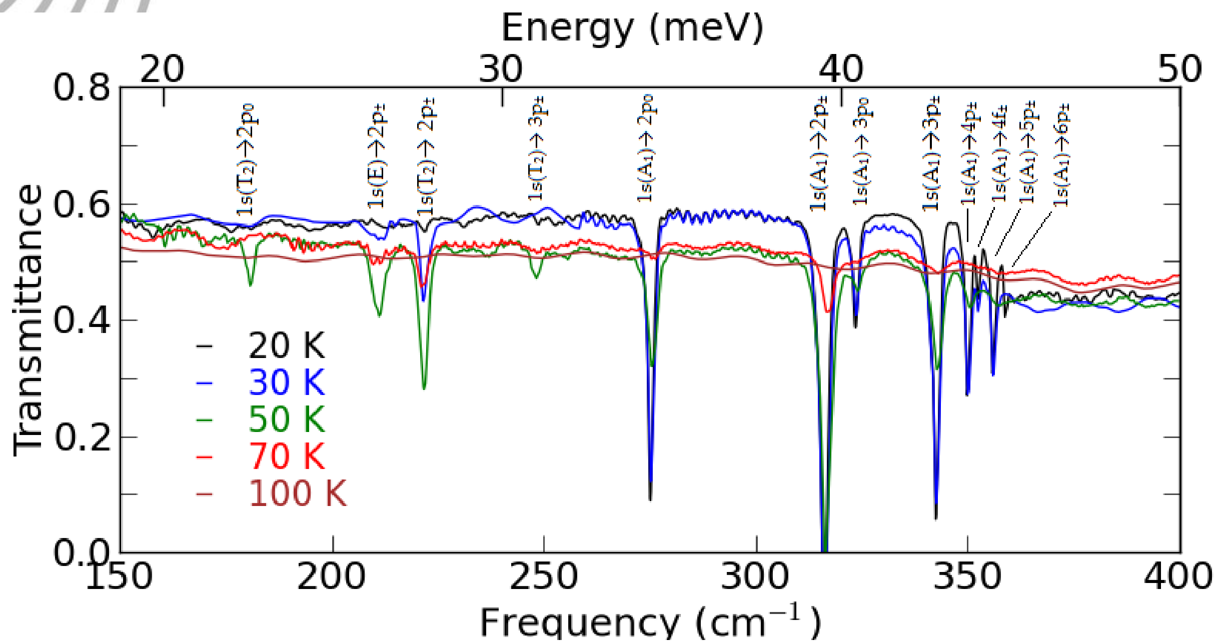
Temperature dependent transmission of 200 Ω-cm Si

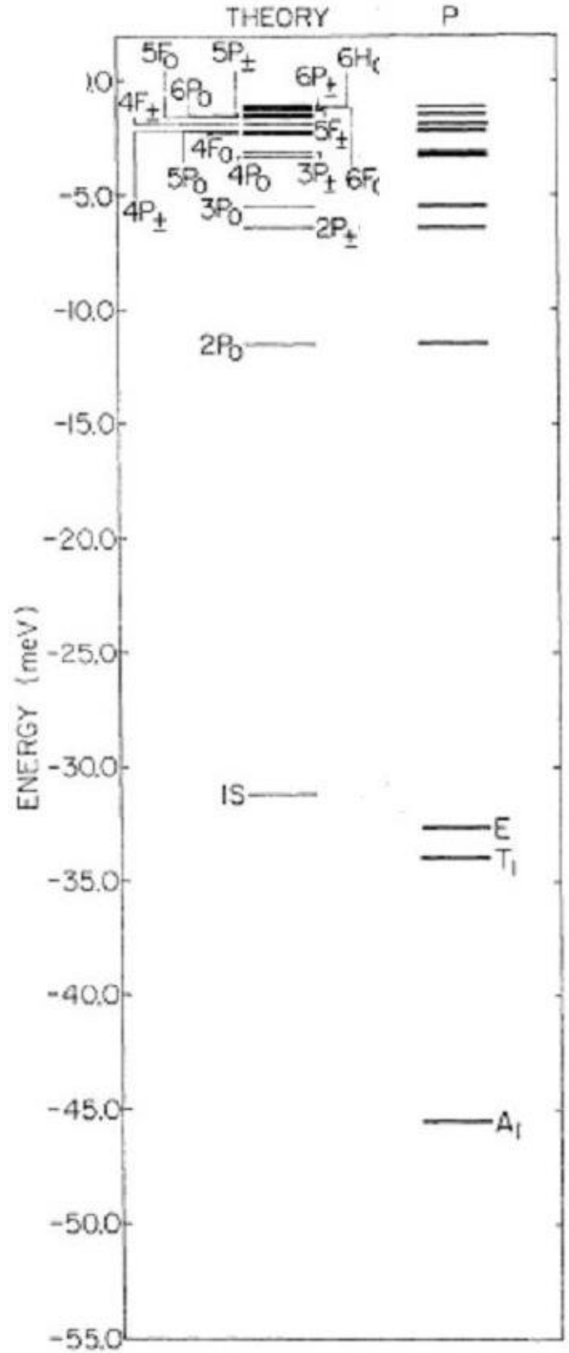


Conclusion

- Much to be done before cryogenic operations are a reality
- My opinion: The gains from low T operations justify the agony of getting there.

The end





- Hydrogen-like spectra of bound electron
- Except ground state is split by intervalley mixing
- P donor
- Agree with theory fairly well
- At intermediate *T*, transitions from thermally occupied levels observed
- Bleached at high *T*

Evanescent-Wave Heat Transfer

Richard S. Ottens

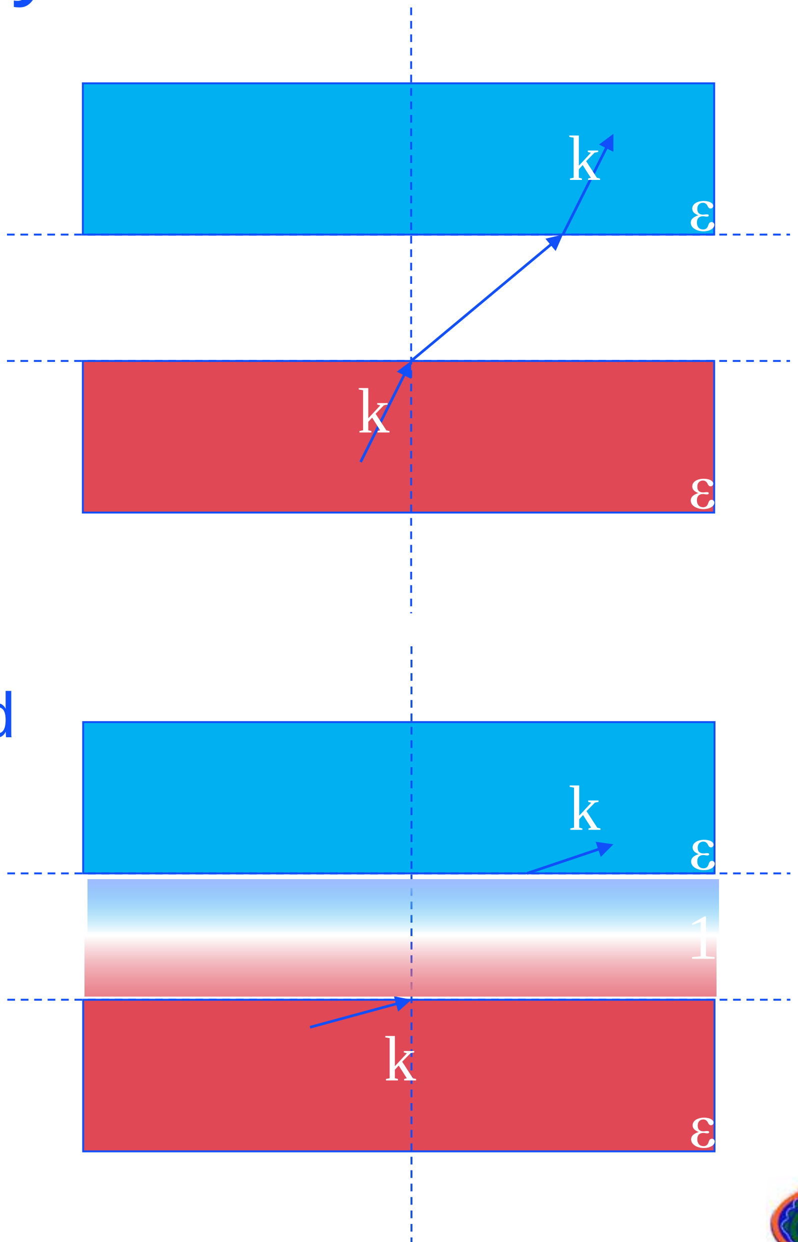
Theory 3

- Heat transfer coefficient w is the sum of two parts w_{sin} and w_{exp}

$$w(d) = \frac{\partial S_z(d)}{\partial T} = w_{sin} + w_{exp}$$

  » w_{sin} is the propagating field

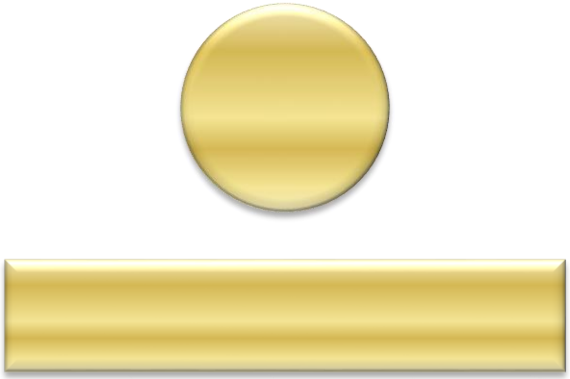
  » w_{exp} is the near-field



Parallel Planes VS Sphere Plane

- Parallel Planes
  - » Simpler theory
  - » The effect occurs <10 µm
  - » Surface topography not important
  - » Engineering problem to keep the planes parallel
  - » Applications in LIGO

- Sphere Plane
  - Complex theory
  - The effect occurs <10 nm
  - Surface topography plays an important role
  - No engineering problem with angular alignment
  - No foreseeable use in LIGO

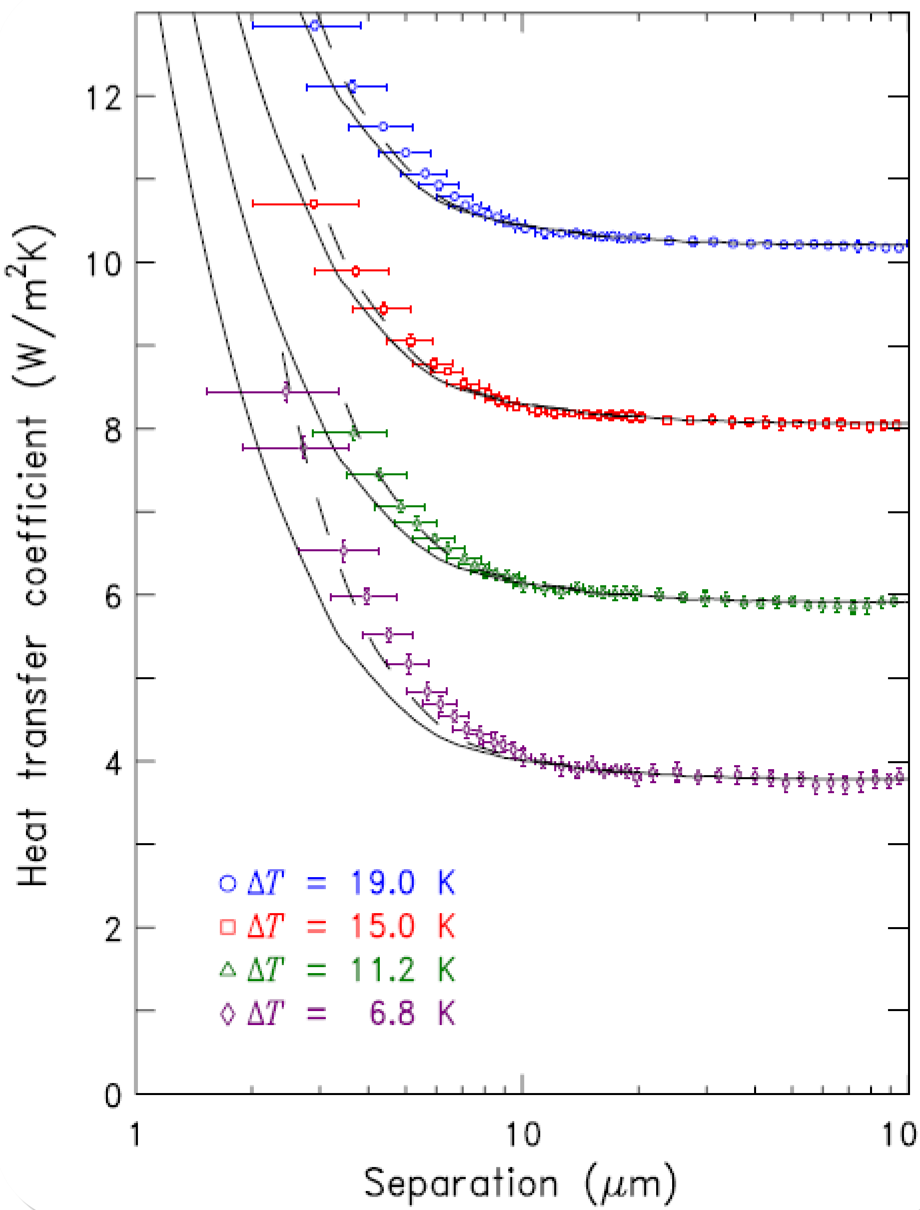


Material Choices

Material	Emissivity	Thermal Conductivity [W/ (m K)]	Index of Refraction
Sapphire	0.16	35	1.76
Fused Silica	0.9	1.4	1.46
Doped Silicon	0.1 to 0.7	150 to 225	3.4
NiChrome	0.9	11	-

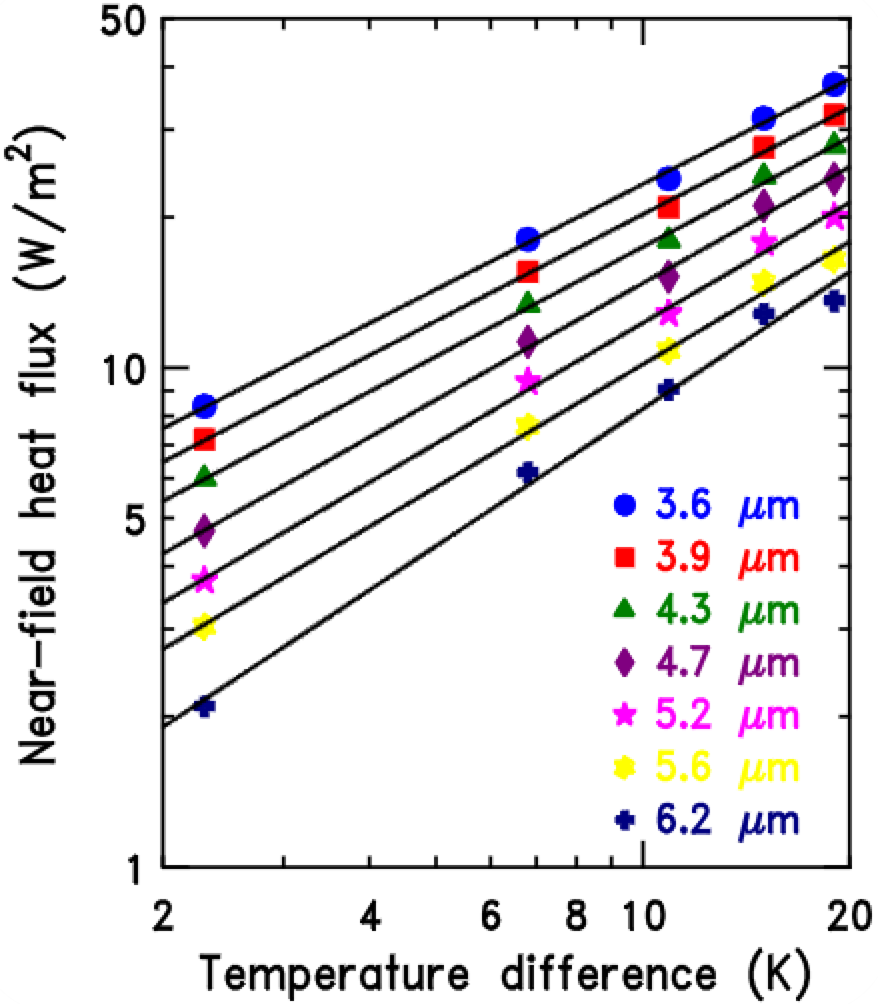
300 K

- Four data runs at four different temperature differences
  - » offset by 2 W/m²K
  - » $T \approx 310$ K
- Model prediction
  - » solid black
- Bend in sapphire plate
  - » dashed black



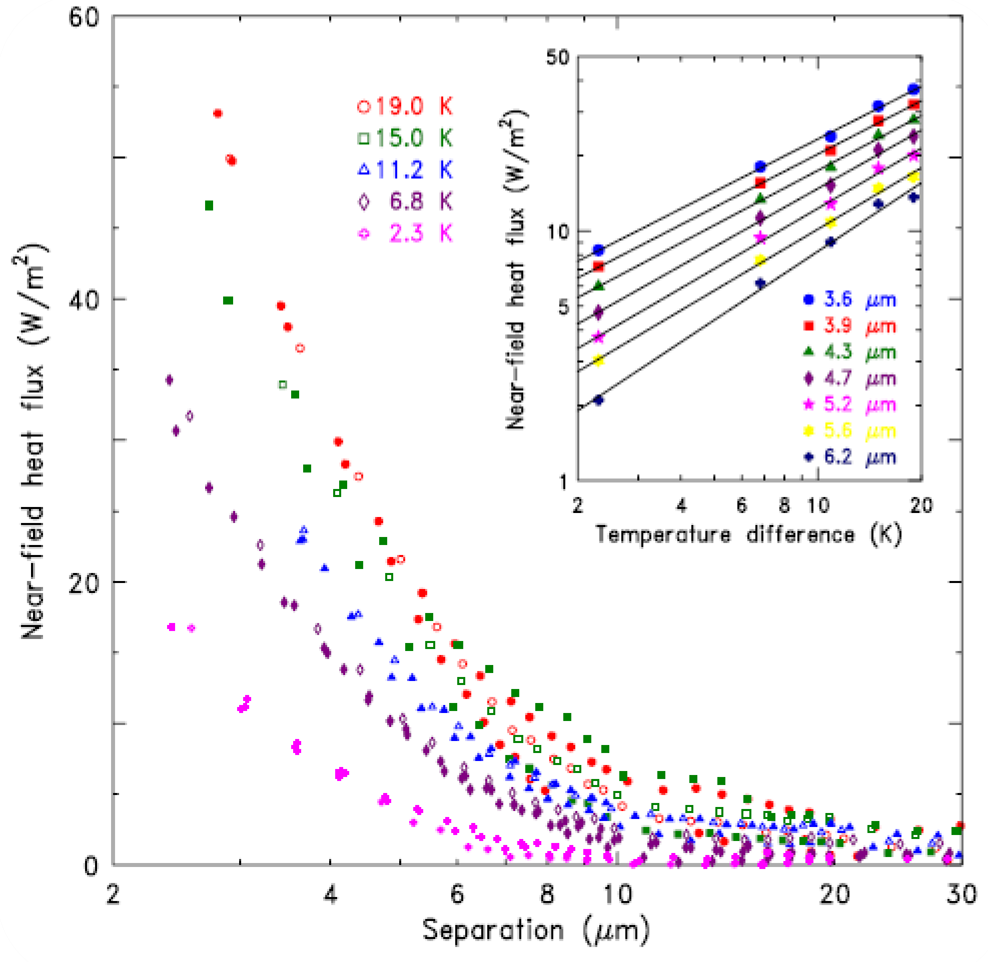
Temperature Dependence

- Near-field regime
  - » heat flux ~ linear with ΔT
- $\varphi(\Delta T, d) = G(d)(\Delta T)^{\alpha(d)}$
- $0.70 \leq \alpha(d) \leq 0.91$

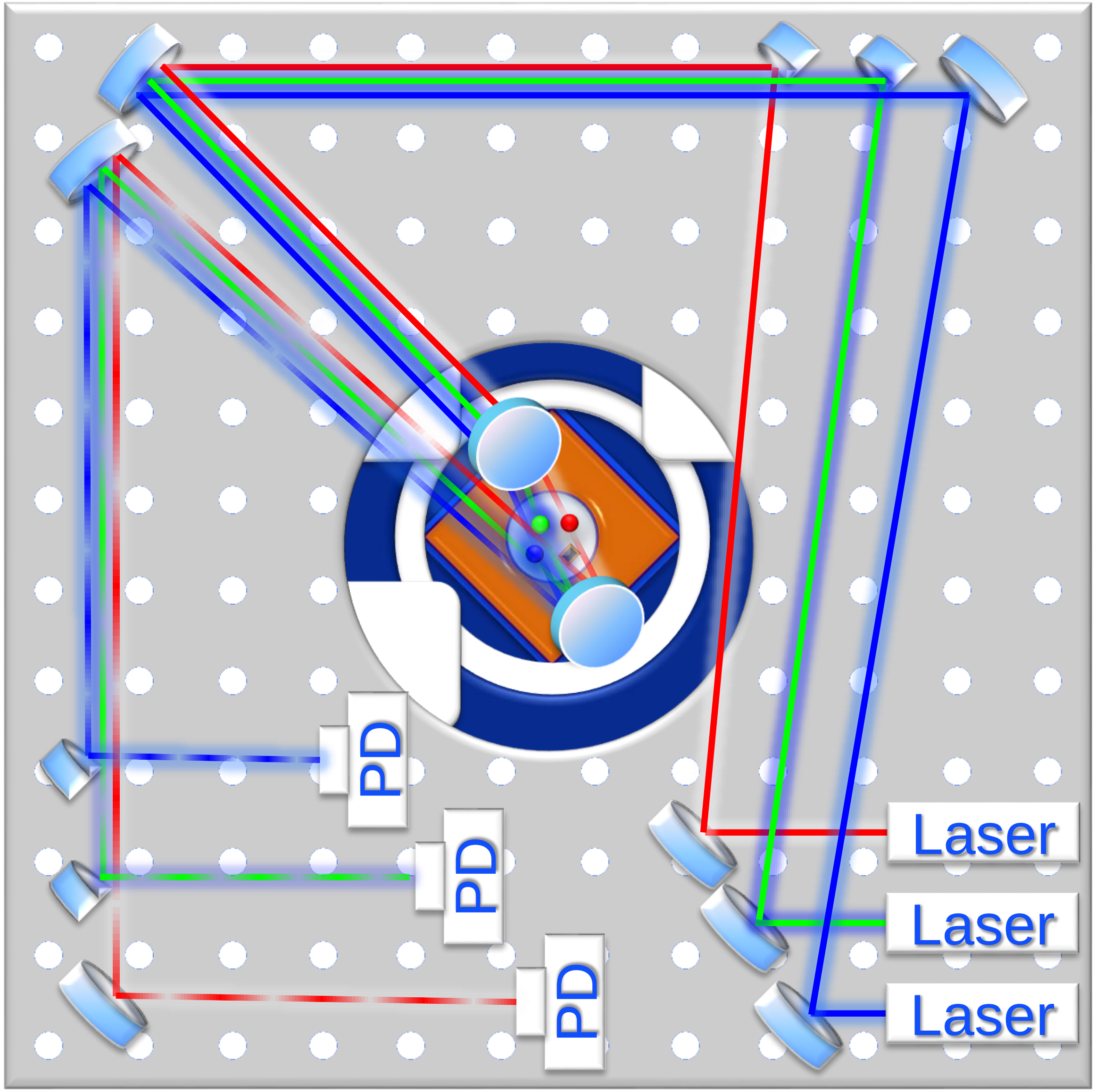


Systematics

- Agreement among runs
- Additional heat transfer with increased ΔT
  - » As much as 50 W/m^2

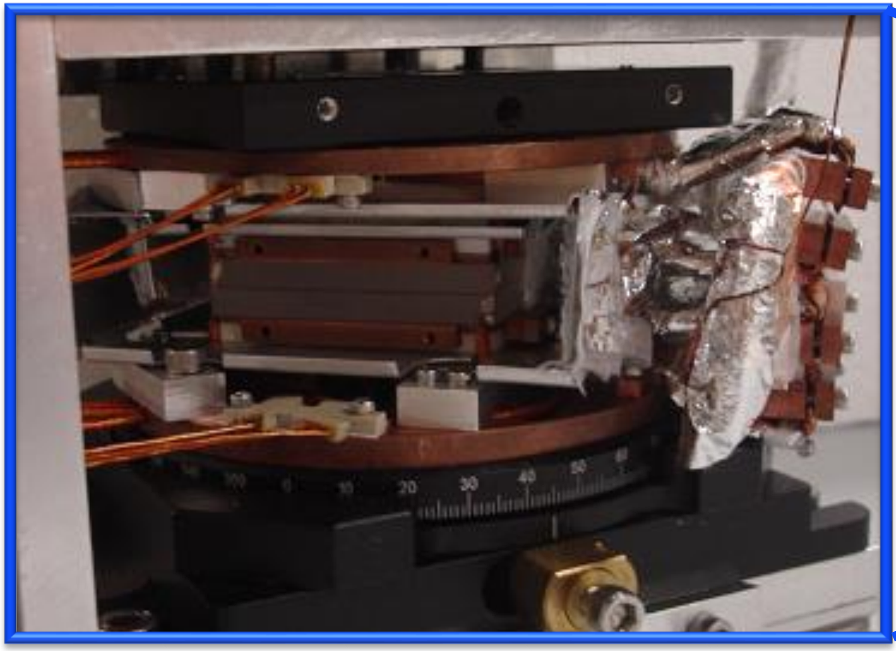


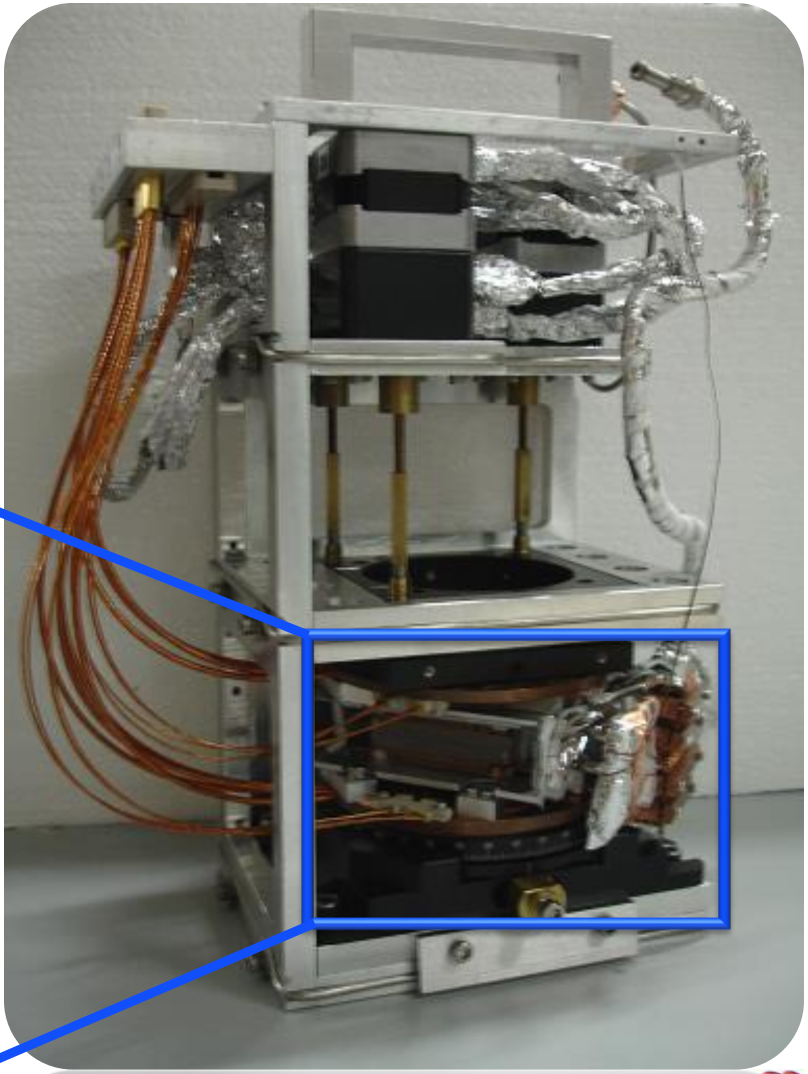
Laser Interferometry



New Setup

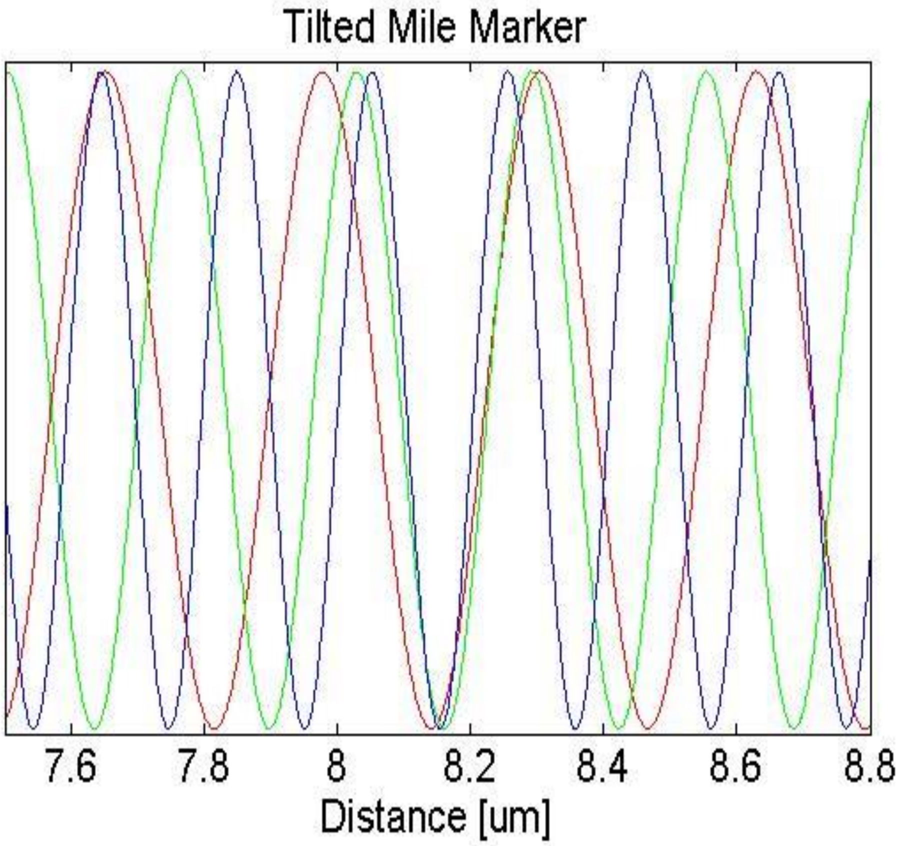
- Modified to work in cryogenic conditions
- Thicker/flatter sapphire plates
- Invar spacer to prevent warping





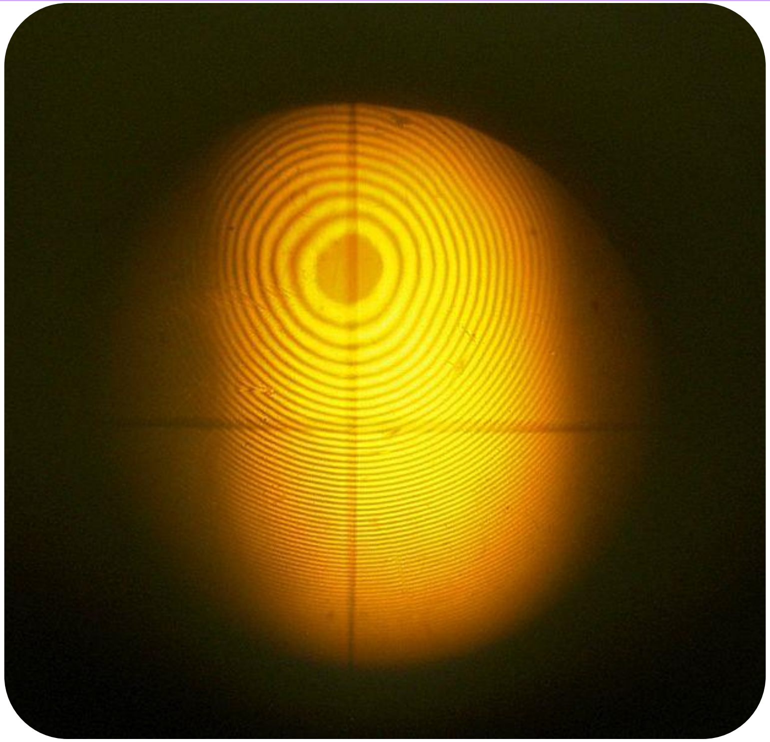
Laser Interferometry

- Triangular pattern
  - Measure tilt
- Must be within a vertical tilt of 12 μm over 2 inches
  - Capacitors have this accuracy
  - To make sure mile marker exists



Bend and Newton's Rings

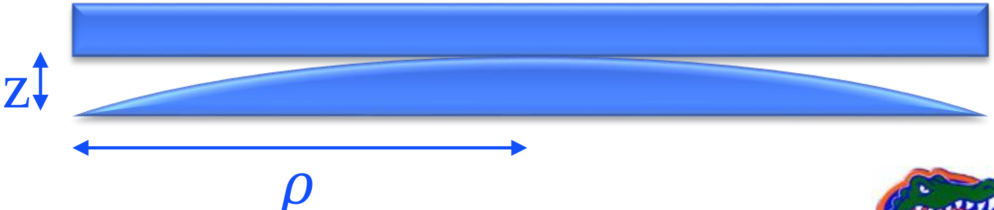
- Interference pattern between the reflections of a flat surface and a curved surface



http://en.wikipedia.org/wiki/Newton's_rings

$$r_N = \sqrt{\left(N - \frac{1}{2}\right)\lambda R}$$

$$Z = R - \sqrt{R^2 - \rho^2}$$

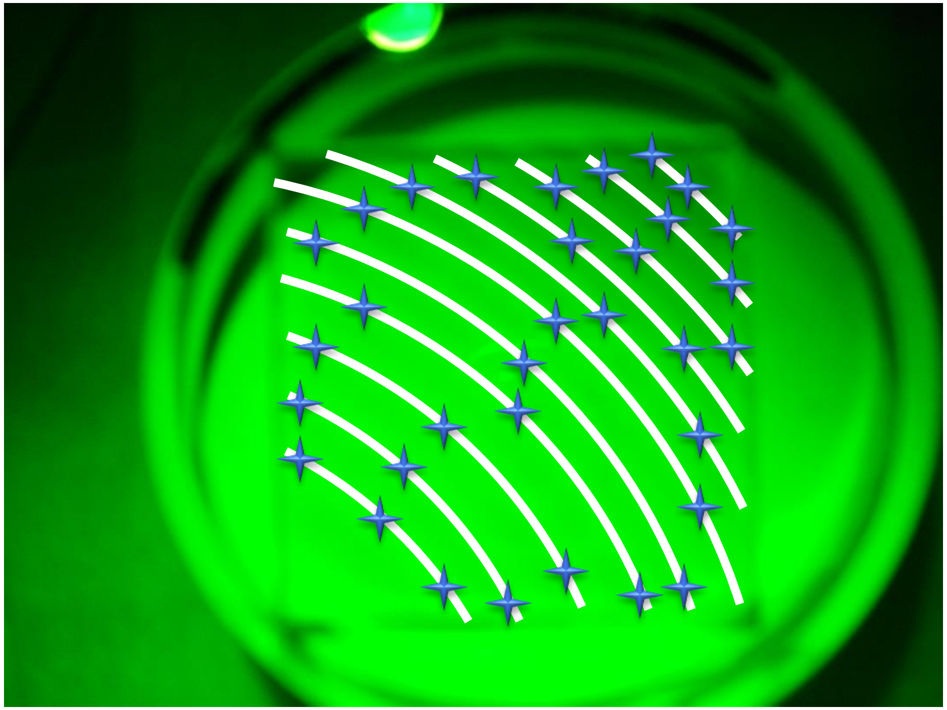


Bend and Newton's Rings

- Measured Radii using 3 points

$$r_N = \sqrt{\left(N - \frac{1}{2}\right)\lambda R}$$

$$Z = R - \sqrt{R^2 - \rho^2}$$



- r_N^2 is linear with N
- Z = 0.1 to 0.6 µm
  - Depending on stresses