# Overview of Coating Research

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On behalf of coating subgroup



LIGO-G070735-00-Z

# Program Overview

- Goal: Get the best coating for Advanced LIGO and still be prepared for future challenges

- **Development for Advanced LIGO – ongoing**

- **Research for future**
  - **Crucial to increase coating sample throughput**
    - **Add vendors beyond CSIRO and LMA**
    - **Existing LSC coating labs prepared for more samples**
    - **Scatter, *Q* measuring, other experiments**
    - **Collaborate with others outside field**

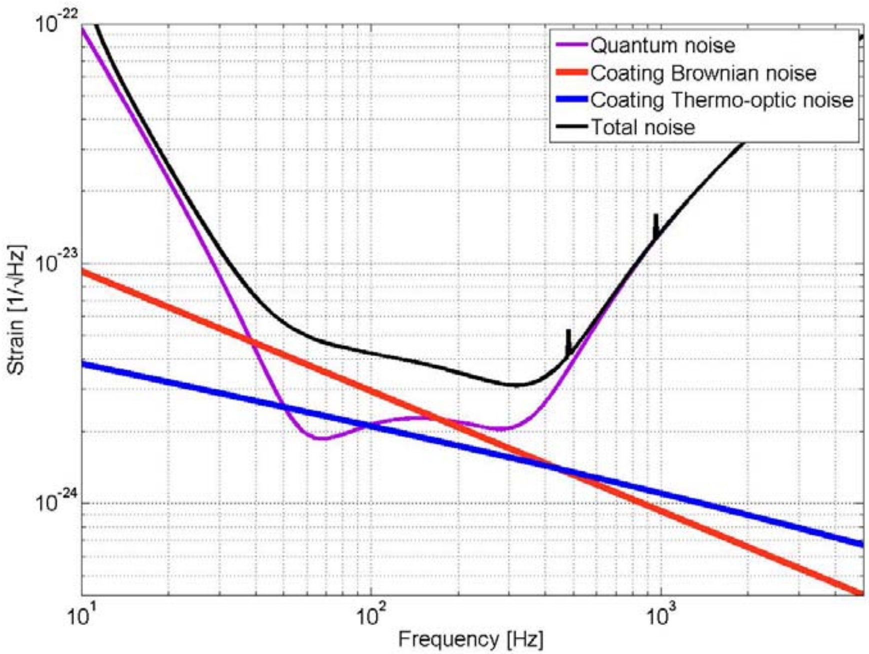
# Coating Sensitivity Impact – Advanced LIGO

## Coating Thermal Noises  Limiting noise source in Adv LIGO

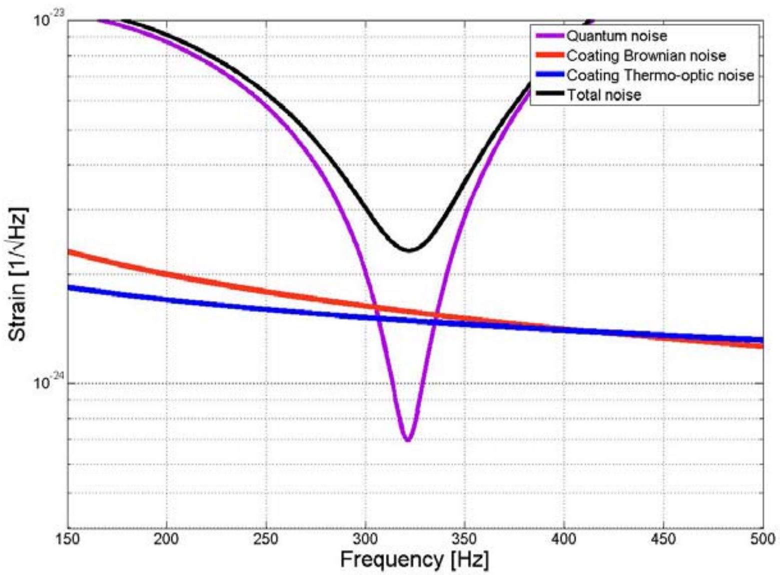
**Multiple noise sources:**

- **Brownian – internal friction**
- **Thermo-optic**
  - *dL/dT* **- thermoelastic**
  - *dn/dT* **- thermorefractive**

**Wideband Advanced LIGO Sensitivity**



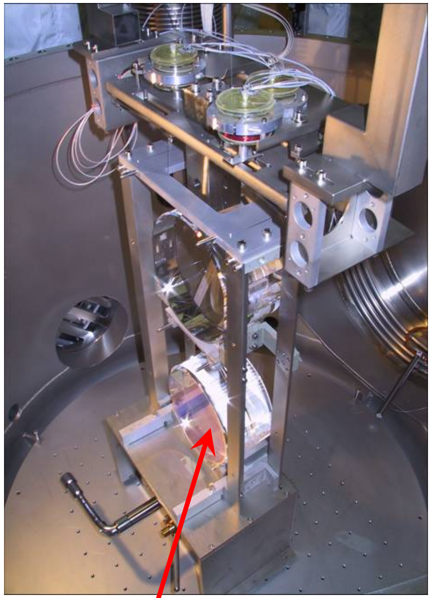

Assuming Advanced LIGO Baseline Values




**Narrowband Advanced LIGO Sensitivity**

# Brownian noise

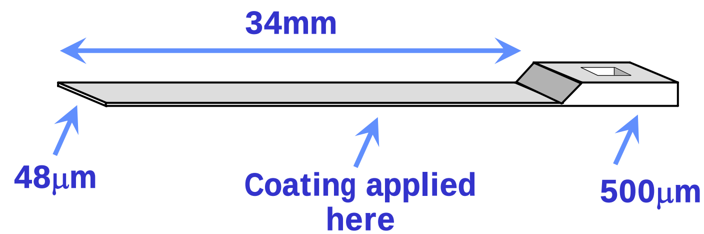
- **Experiments suggest**
  - » **$Ta_2O_5$ is the dominant source of dissipation in current $SiO_2/Ta_2O_5$ coatings**
  - » **Doping the $Ta_2O_5$ with $TiO_2$ can reduce the mechanical dissipation by ~40% for overall coating**
- **Mechanism responsible for the mechanical loss in $Ta_2O_5$ as yet not clearly identified**
- **Research ongoing to:**
  - » **Identify and directly reduce dissipation mechanisms in the coatings**
  - » **'optimise' coating designs by minimising volume of $Ta_2O_5$ present in the coatings**

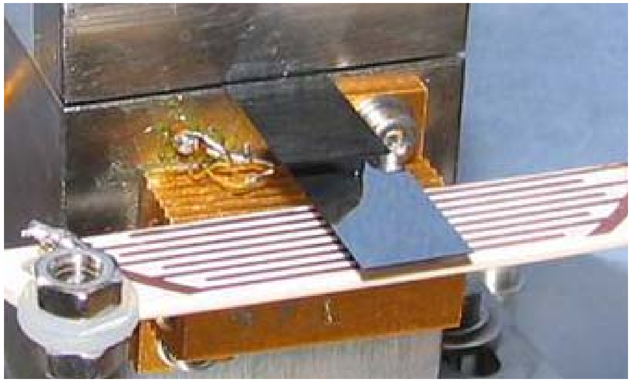


Mirror suspension, with HR coating on front face.

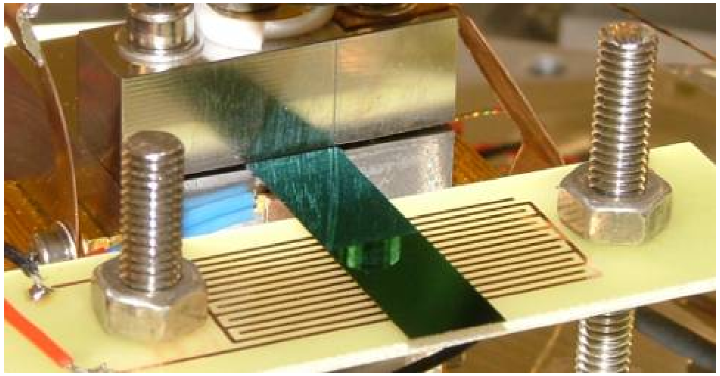
# Single layer coating samples (I. Martin et al)

- 0.5 μm single layer of $Ta_2O_5$ doped with $TiO_2$ ((14.5 ± 1)% by cation) deposited by ion beam sputtering
- Thin silicon substrates used for coating
  - » Loss of silicon decreases at low temperature
  - » Coating will dominate the loss of thin samples



Uncoated silicon cantilever in clamp

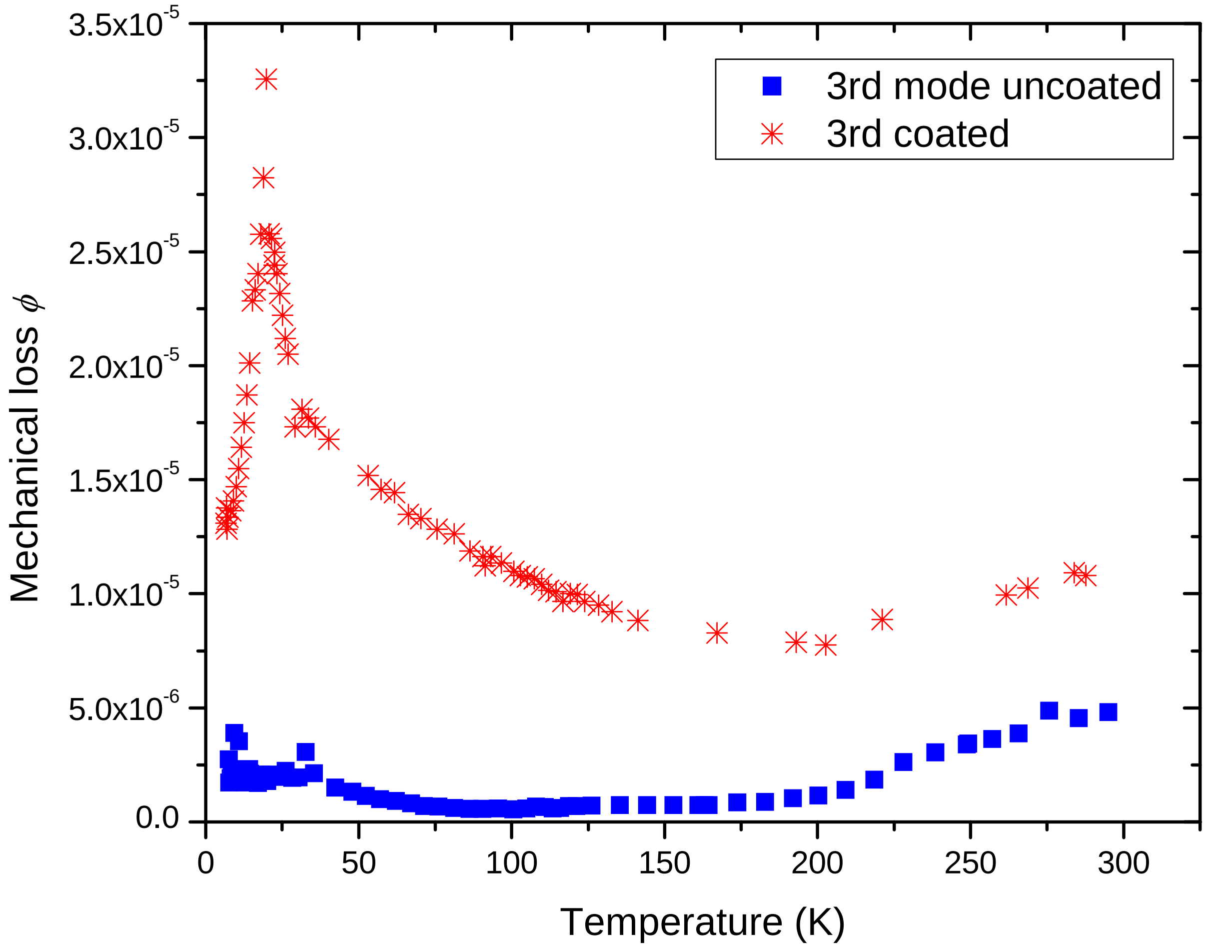


Titania doped tantala coated silicon cantilever in clamp

- Samples etched from silicon wafers (Stanford)

# Mechanical loss of coated and uncoated samples

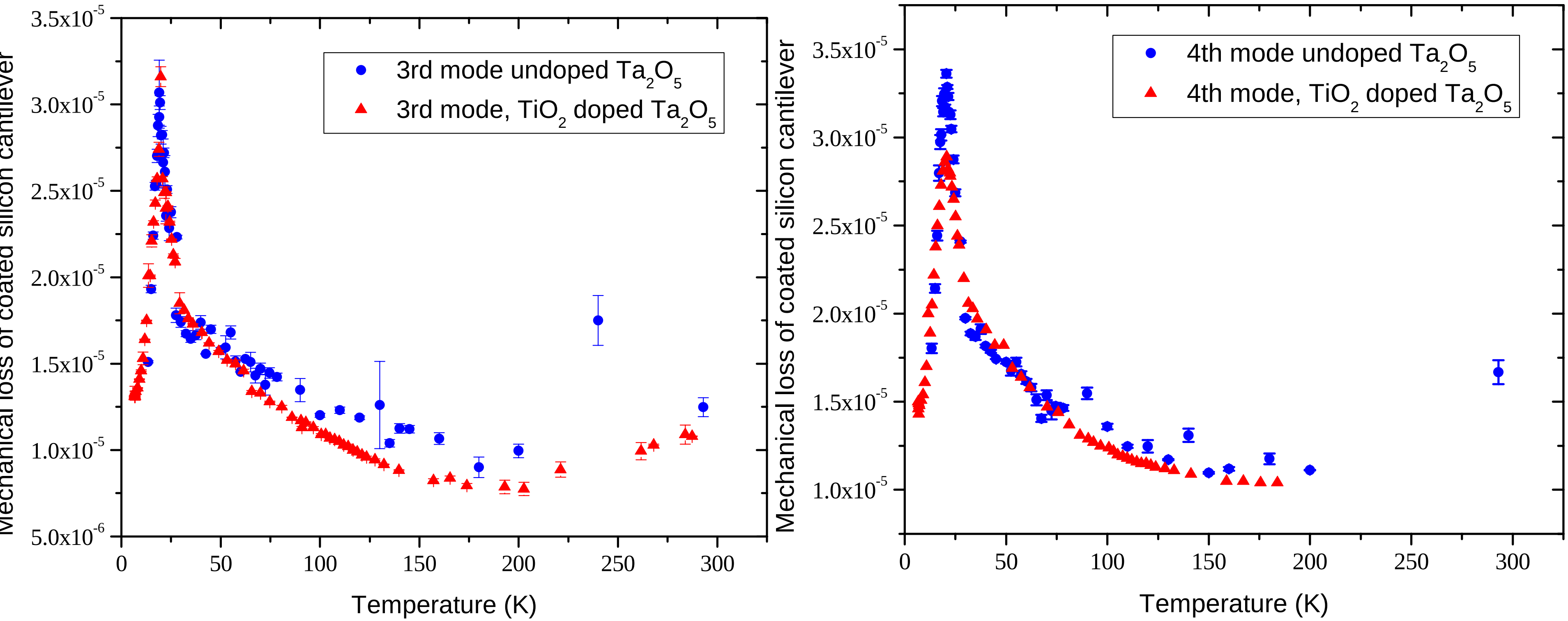
- A clear increase in the measured loss is observed due to the addition of the single-layer of doped tantala coating to the silicon cantilever.




Low T peak present for all modes of sample studied

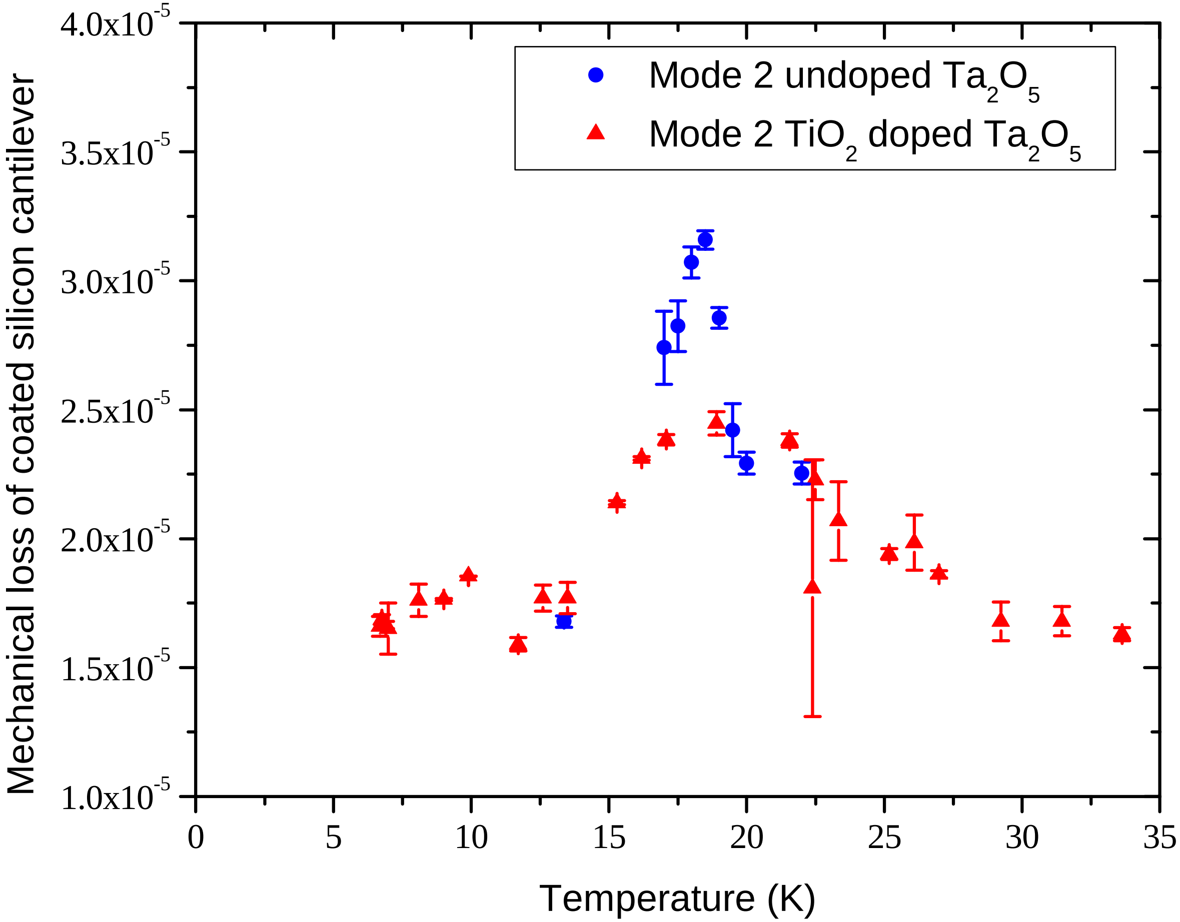
Temperature at which the dissipation peaks is a function of frequency

# Comparison of un-doped $Ta_2O_5$ and $Ta_2O_5$ doped with $TiO_2$ (14.5% by cation)




- Third mode, ~990 Hz. Tail of the peak is higher in un-doped case.
- Fourth mode, ~ 1940 Hz, un-doped peak is higher than doped peak.

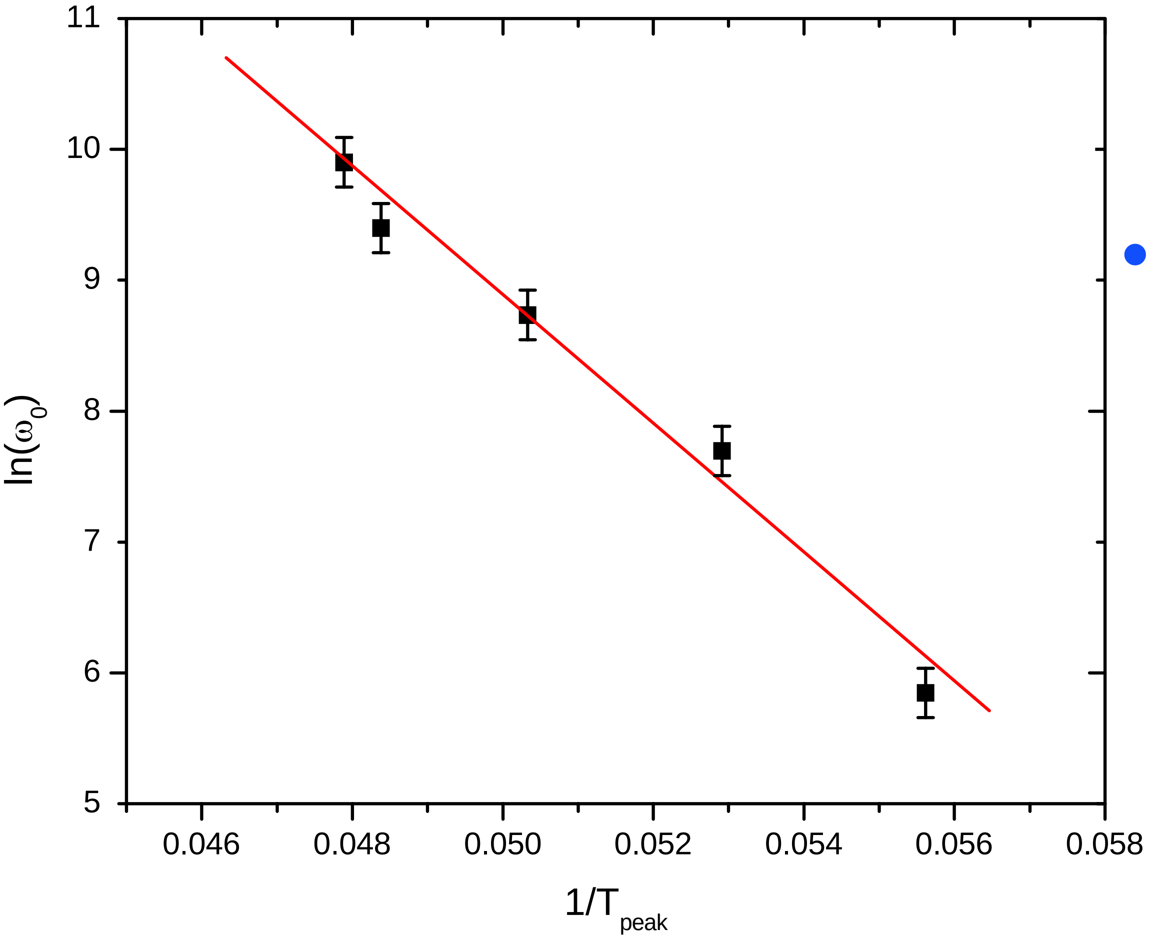
# Comparison of un-doped $Ta_2O_5$ and $Ta_2O_5$ doped with $TiO_2$ (14.5% by cation)




- **Second mode, ~340 Hz.**

- **In 3 of the 4 modes measured, doping has reduced the peak height**

# Relation of mode frequency to temperature at which loss peaks




- Can calculate an activation energy associated with the dissipation peak of (42 ± 2) meV
- The low temperature dissipation peak in fused silica has a similar activation energy (44 meV)
  - » **Oxygen atoms can undergo thermally activated transitions between two possible energy states in a double well potential**
  - » **Results suggest this dissipation mechanism in $Ta_2O_5$ may be similar**

# Work in progress – Brownian noise

- Studies of the underlying material physics by means of high-resolution TEM, Electron Energy Loss Spectroscopy and Electron Energy Loss Near Edge Structure to investigate short and medium range order and bonding in doped and undoped coatings

- Heat treatment of bulk $SiO_2$ can significantly improve its mechanical dissipation :
  - » alters its bonding structure; narrows distribution of potential barrier heights in the double well systems.
  - » effects of heat treatment can be clearly identified through the behaviour of the low temperature dissipation peak,
- Research ongoing at HWS (S. Penn) on effects of heat treatment of single layers of thin film silica (and of multi-layer coatings) – preliminary results show loss decreasing with increasing 'annealing' T.
- Research ongoing at Glasgow on effects of annealing on single layers of $Ta_2O_5$

LIGO

LSC

# Coating Research at Sannio University

- ‘Optimization’ of coating layer thicknesses:
- Goal: lowest noise at prescribed transmittance;

- Preliminary study based on genetic optimization led to focus further study on stacked-doublet (SD) geometries with tweaked end layers;

- MATHEMATICA code for SD coating optimization and characterization developed;

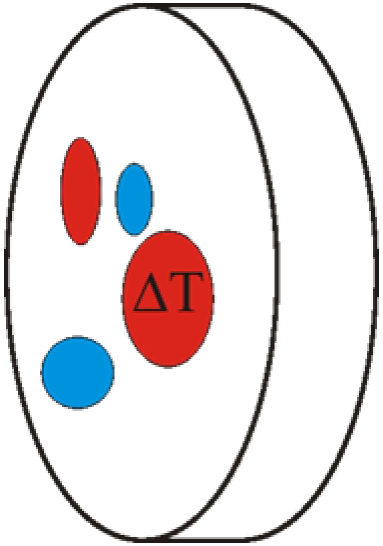
- Plain-tantala-based optimized coating mirror prototypes manufactured at LMA (fall 2006), scheduled for testing at TNI.

# Update on Thermo-optic noise measurements at Embry-Riddle (A. Gretarsson)

- Equilibrium fluctuations of the temperature of the test mass coatings cause fluctuations in physical parameters of the coating. Coupling parameters:
  - » Thermal expansion coefficient, $\alpha \Rightarrow$ Thermoelastic noise.
  - » Thermorefractive coeff. $\beta = dn/dT \Rightarrow$ Thermorefractive noise.

*Thermo-optic noise*

= (coherent) sum of thermoelastic and thermorefractive contributions.



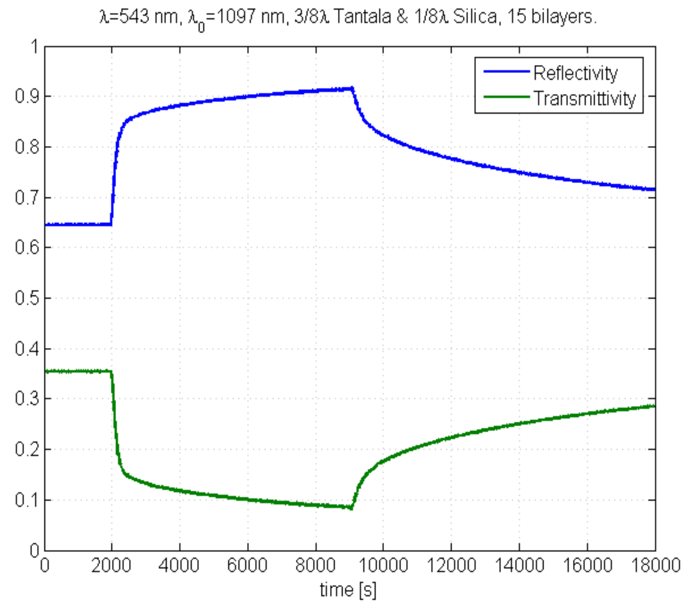

Thermorefractive contribution somewhat higher than thermoelastic contribution but same order of magnitude.

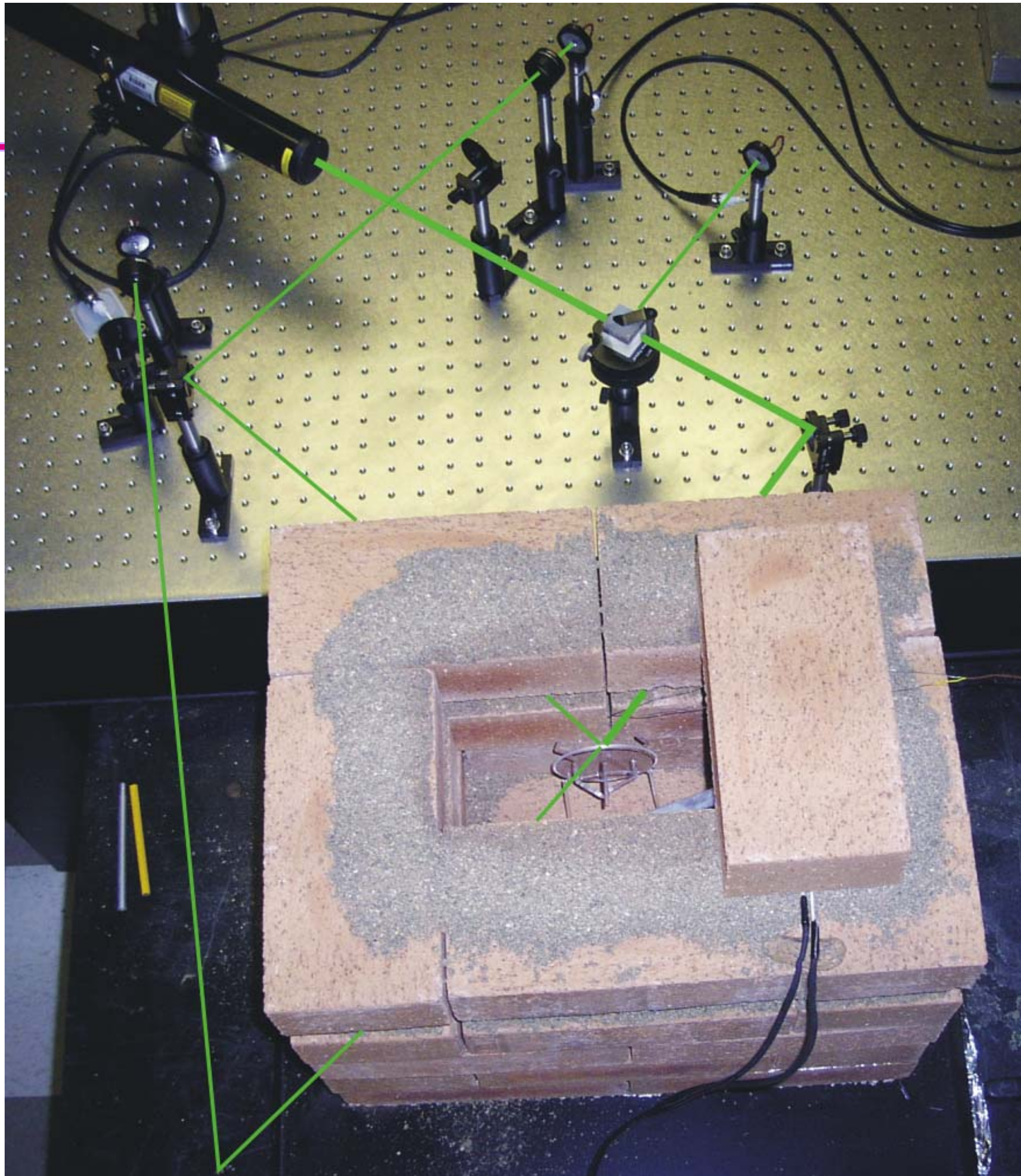
# The setup

Obtain:

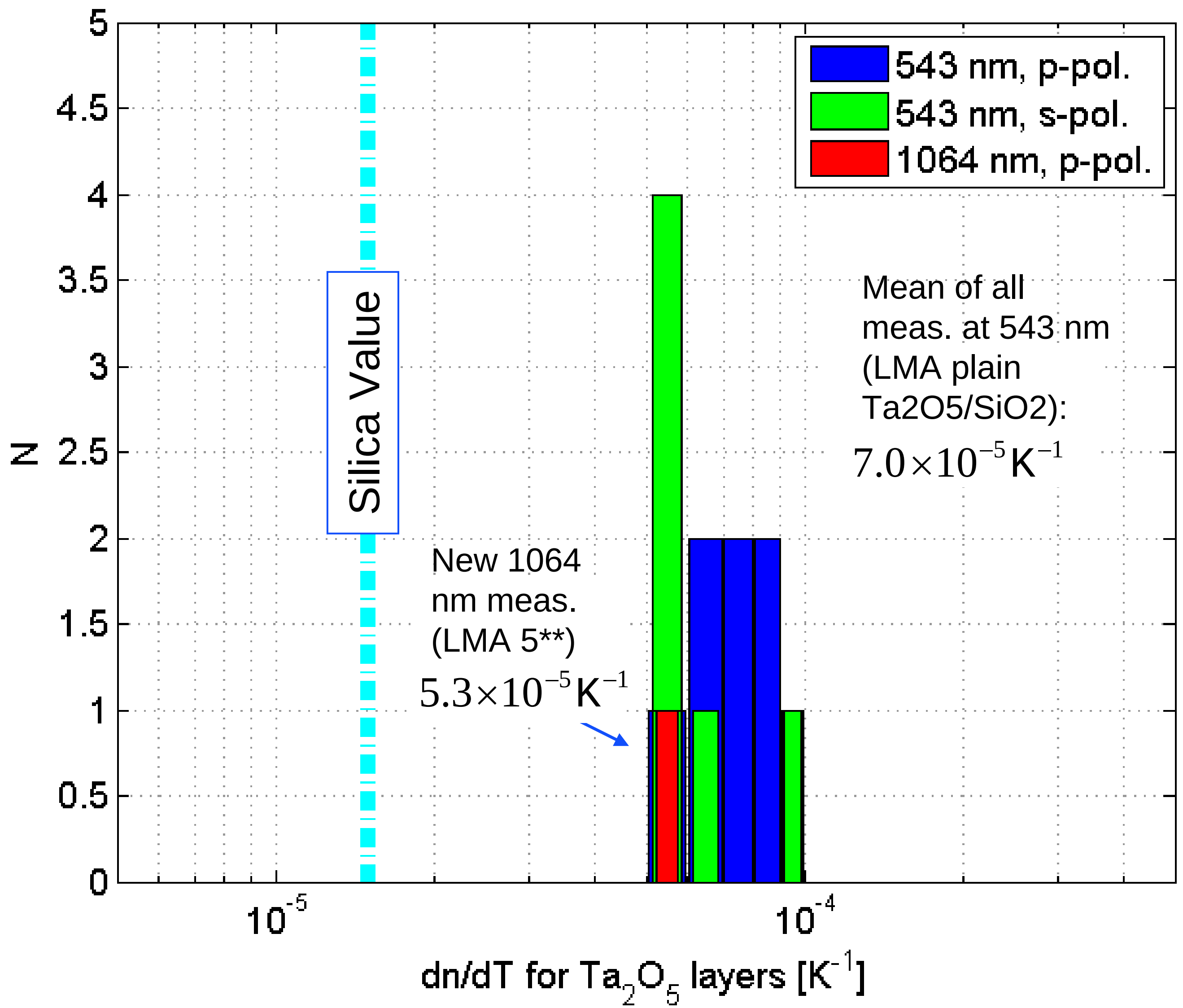
$(P_{trans} / P_{input})$ & $(P_{refl} / P_{input})$

Versus $T_{sample}$



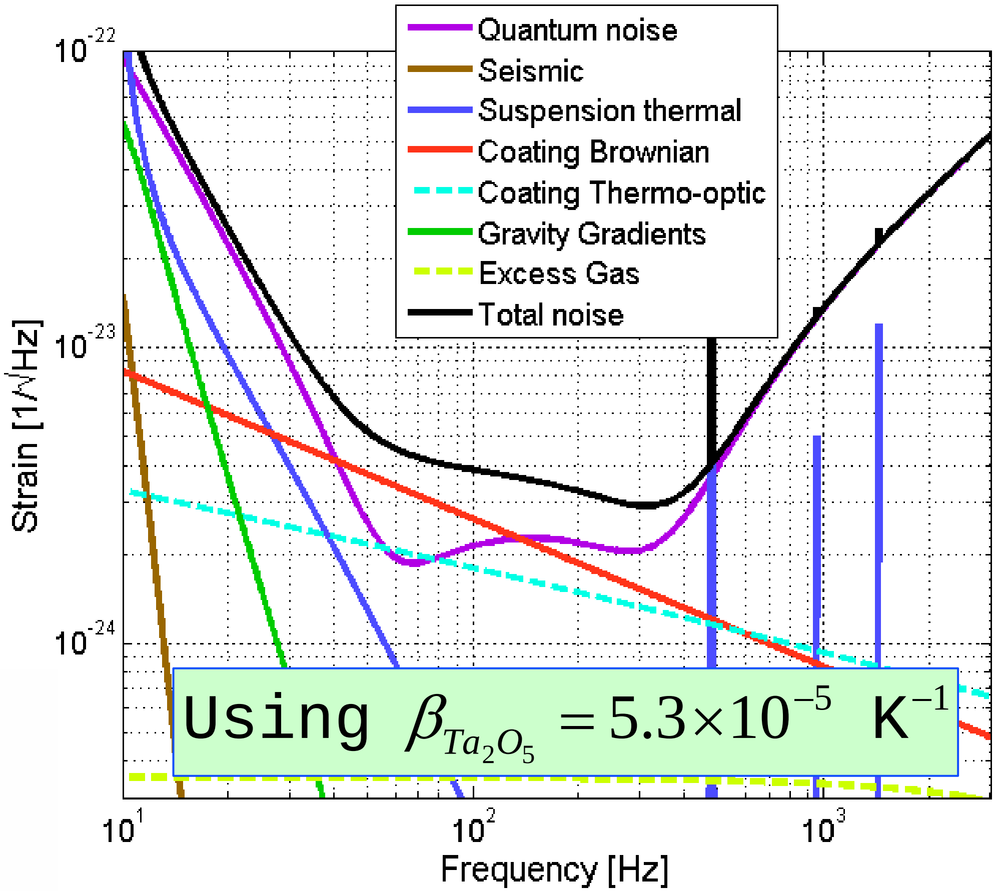



# Result for $\beta_{Ta_2O_5}$



# Thermo-optic noise in Advanced LIGO

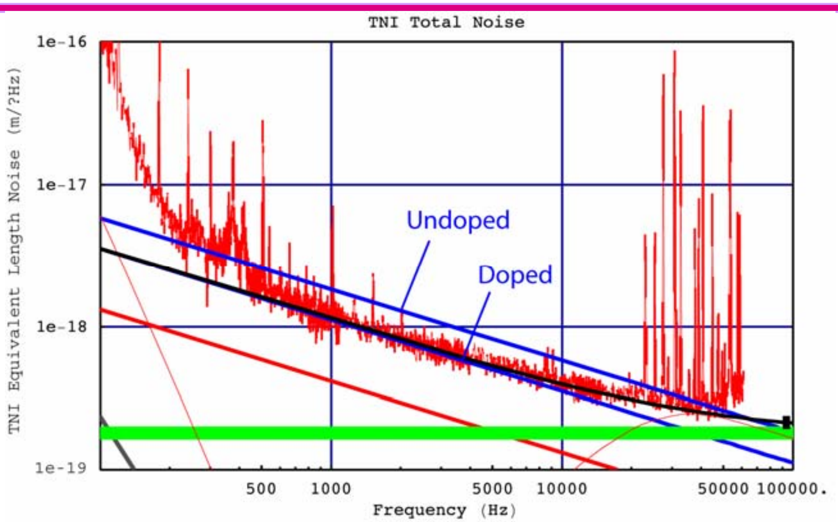
- Contributes 25% of total noise floor in 70-100 Hz region.
- Is the limiting noise source in narrowband mode.
- Measurements are ongoing at ERAU.
- Ellipsometer measurements on single layer recently completed at SOPRA.
- Results fed to Univ Sannio to optimise doped-Tantala coatings - total (B+TR+TE) noise included;
- Porting of optimization code to BENCH scheduled.



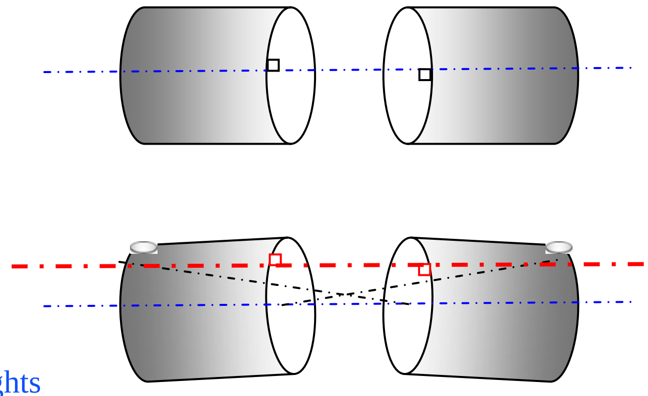

| $\tau = 0.9727\, ppm$ | ER boost @100Hz |
|---|---|
| Plain Tantala, QWL | 1 |
| Plain Tantala, OPT | 1.38 |
| Doped Tantala, QWL | 1.54 |
| Doped Tantala, OPT | 2.05 |

# Thermal Noise Interferometer (TNI): Recent Coating Results (E. Black)

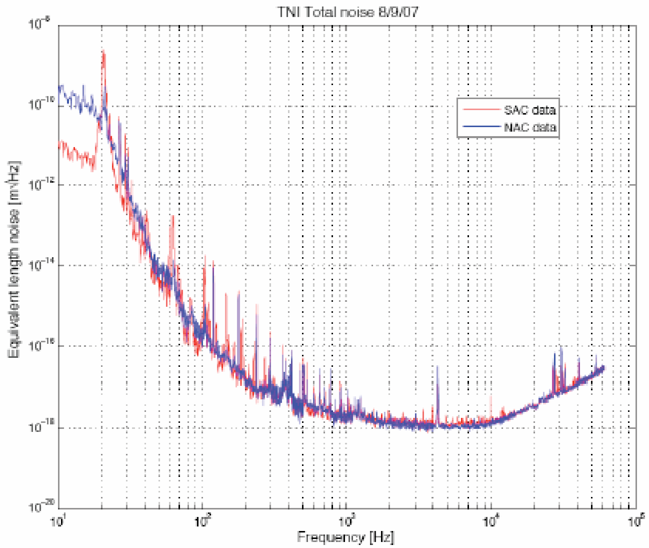
- Broadband measurement of doped-tantala/silica
- Homogeneity experiment: Coating thermal noise vs. spot position
- Lab move:
  - » Reassembly/optical-alignment complete
  - » Servo recommissioning in progress




natural cavity axis

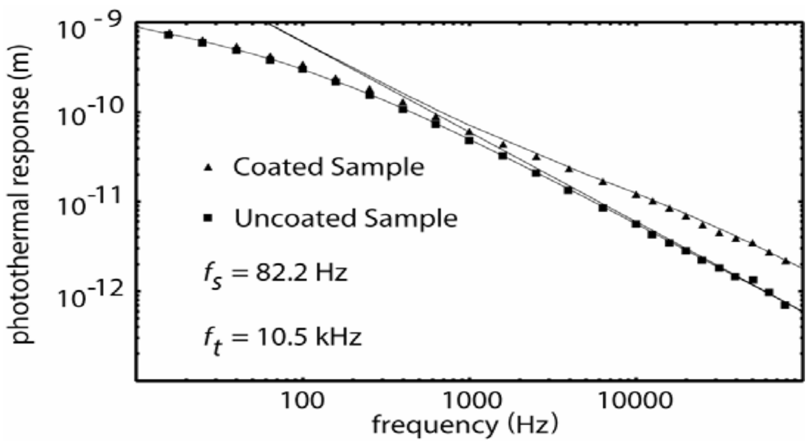


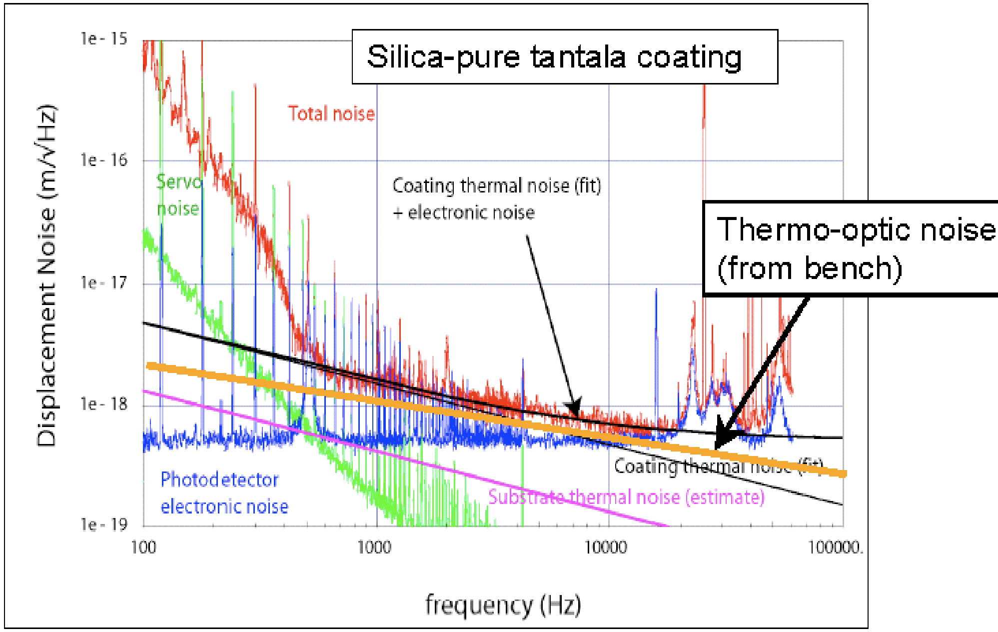
natural cavity axis with weights on



# TNI Future Coating Plans

- Optimized silica/tantala coating measurement
  - » In progress
- Doped, optimized coating measurement
  - » Funding approved, contingent on un-doped, optimized results
- Photo-thermal measurements of thermo-physical properties in advanced coatings
- Direct measurement of thermo-optic noise (image from Andri Gretarsson)

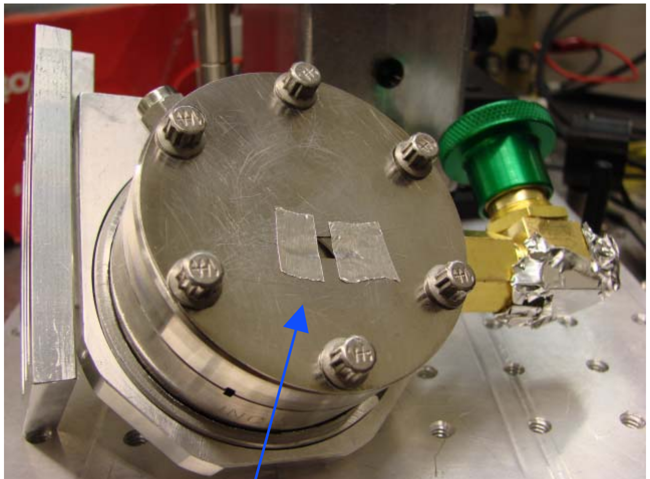


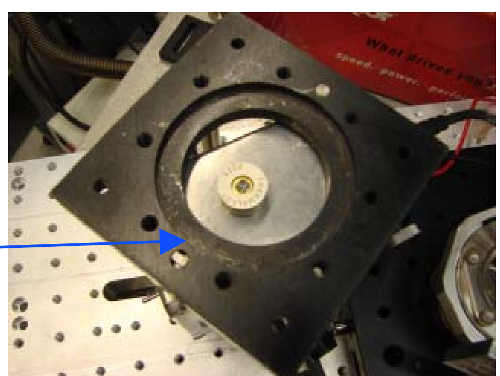
# UV Irradiation Effects on Initial LIGO-type Mirror Coating

Nick Leindecker, Sei Higuchi, Ashot Markosyan, Ke-Xun Sun, Bob Byer, Sacha Buchman, Marty Fejer, Roger Route, Stanford
In Collaboration with LIGO Charging Work Group

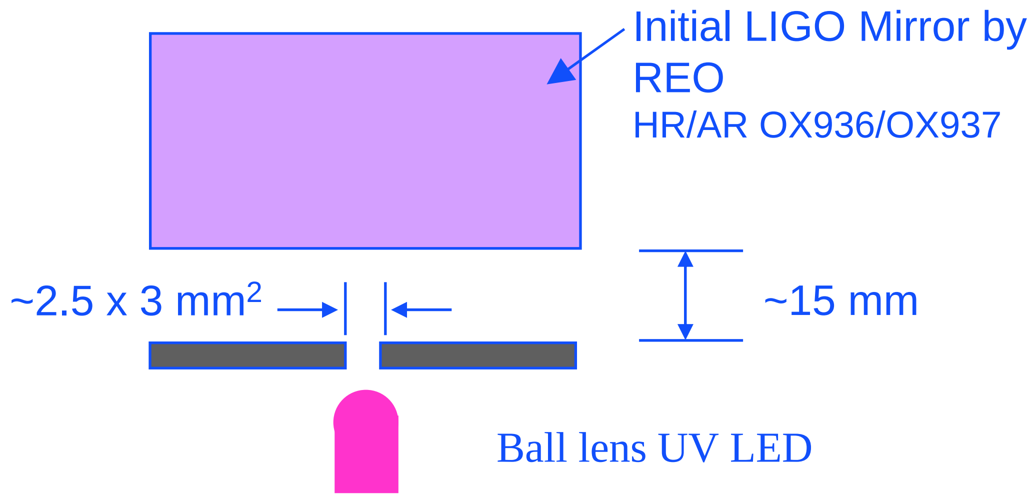
# UV Irradiation Geometry



Removable mask forms a small aperture



UV LED with a Ball Lens




Irradiation by UV LED at 255 nm
Operated with average power 3.3 $\mu$W
Irradiation intensity 15 $\mu W/cm^2$
Irradiation for 48 hours
Total UV energy deposition ~2.6 $J/cm^2$

# Optical Loss Measurement Results

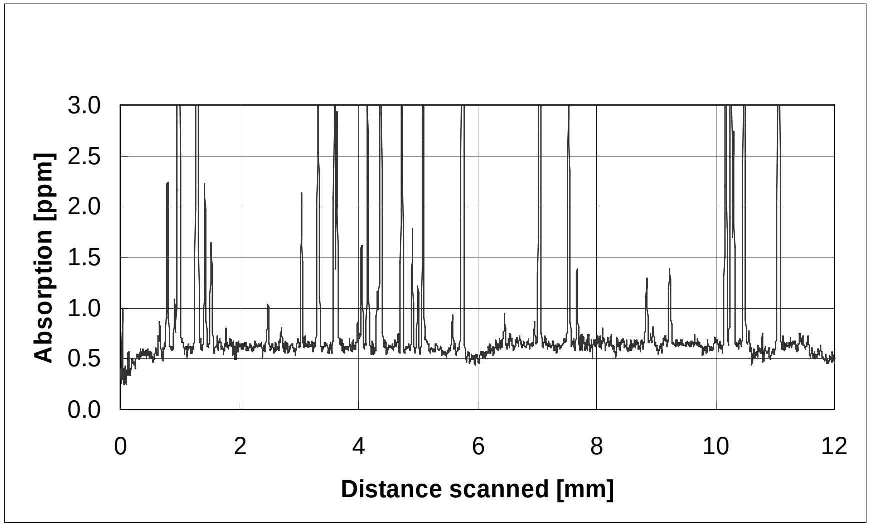



Fig. 1. Loss measurement prior to UV irradiation. A transversal scan across the surface over 12 mm length. The average value of $\alpha \sim 0.6$ ppm.

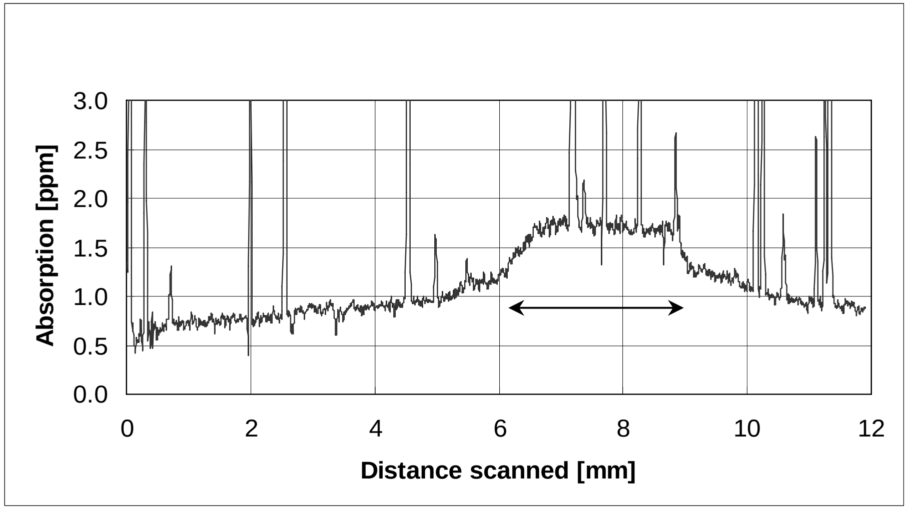



Fig. 2. In the exposed area (~2.5 mm window) $\alpha$ = 1.7- 1.8 ppm. continuous increase of $\alpha$ while approaching the exposed area.

- **Possibility that loss increase is due to contaminants? (which may become worse in the UV region because of disassociation?)**
- **Plan to increase the dose of UV irradiation and try to parameterize the phenomena. Meanwhile continue to check the vacuum cleanliness.**

# Enhanced effort on coatings planned with additional vendors

**Visits by Eric Gustafson/Helena Armandula + others to talk to possible vendors (for R&D)**

MLD (US) - Very Interested in working with us.

OCLI (US) - Very Interested in working with us. Want to concentrate on what causes stress in the coatings. Fabulous measurement capability. They can do any coating technique except for CVD and have any ISB source you can imagine.

REO (US) - Interested but no particular suggestion on what they might work on with us.

ATF (US) - Very interested in working with us. Really want to find ways to improve thermal noise in coatings for frequency standard applications

LMA (France) – Ongoing program on coatings for Advanced LIGO.

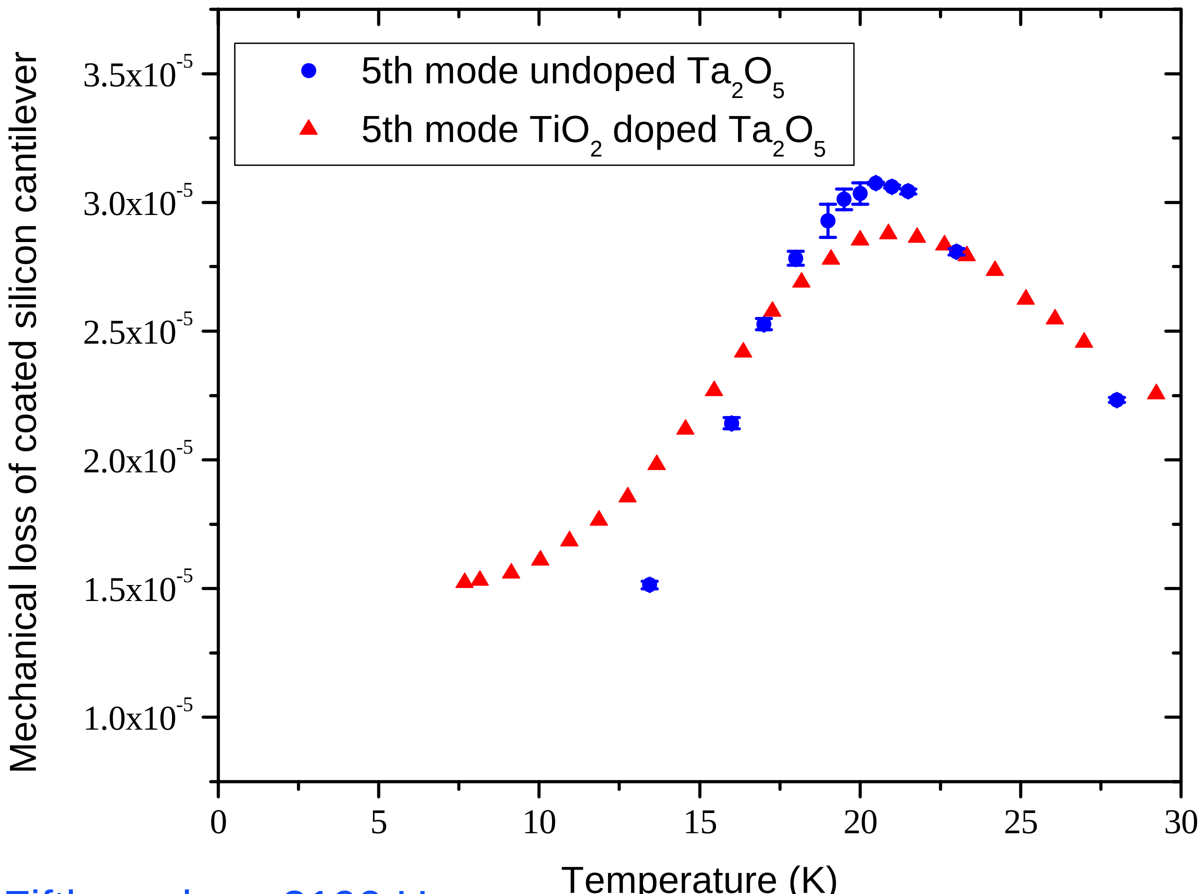
**Solicit formal bids**

**Coating Workshop at December or March LSC Meeting – (Gregg Harry)**

# Summary

- Coating thermal noise crucial limit to gravitational wave detector sensitivity for foreseeable future
- Optical and thermal properties also important and demanding
- Progress has been made in understanding and improving coating thermal noise
  - Titania-doped tantala reduces mechanical loss
  - Optimization of thickness improves thermal noise
  - We have the first handle on a dissipation mechanism through temperature dependence of dissipation
- Need continuing research
  - Development of Advanced LIGO coating
  - Research on improved coating for future detectors
- Plan developed to increase on-going LSC coating research
  - Need to involve more vendors than current research
  - Lab payment of coating costs crucial
  - Existing team (including Virgo) with experience
  - Allows for both Advanced LIGO and beyond work

# Comparison of un-doped $Ta_2O_5$ and $Ta_2O_5$ doped with 14.5% $TiO_2$




- Fifth mode, ~ 3190 Hz.