Overview of coating research

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On behalf of the coating subgroup

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Program Overview

- Goal: To get the best coating for Enhanced and Advanced LIGO and still be prepared for future challenges.

- Development for Advanced LIGO – ongoing
- Coating noise limits Advanced LIGO sensitivity.

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

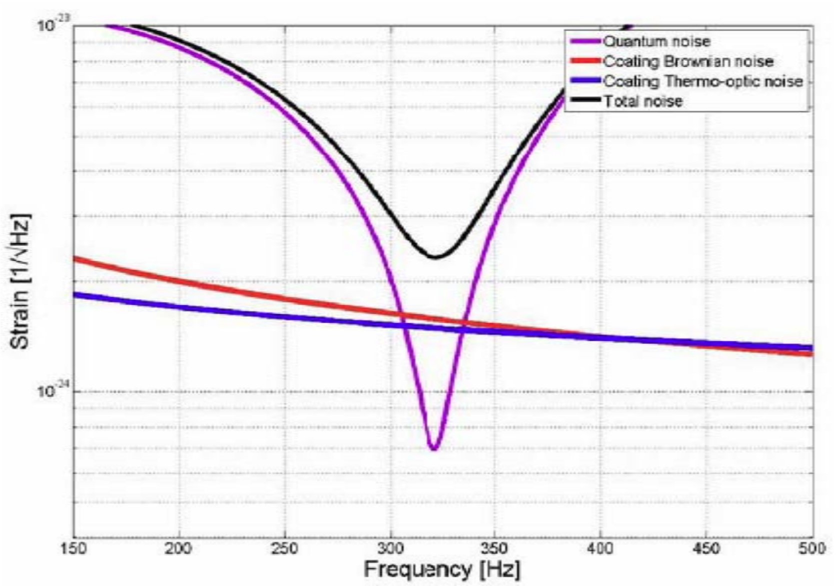
Coating sensitivity impact

- **Coating Thermal Noises – limiting noise source in Advanced LIGO**

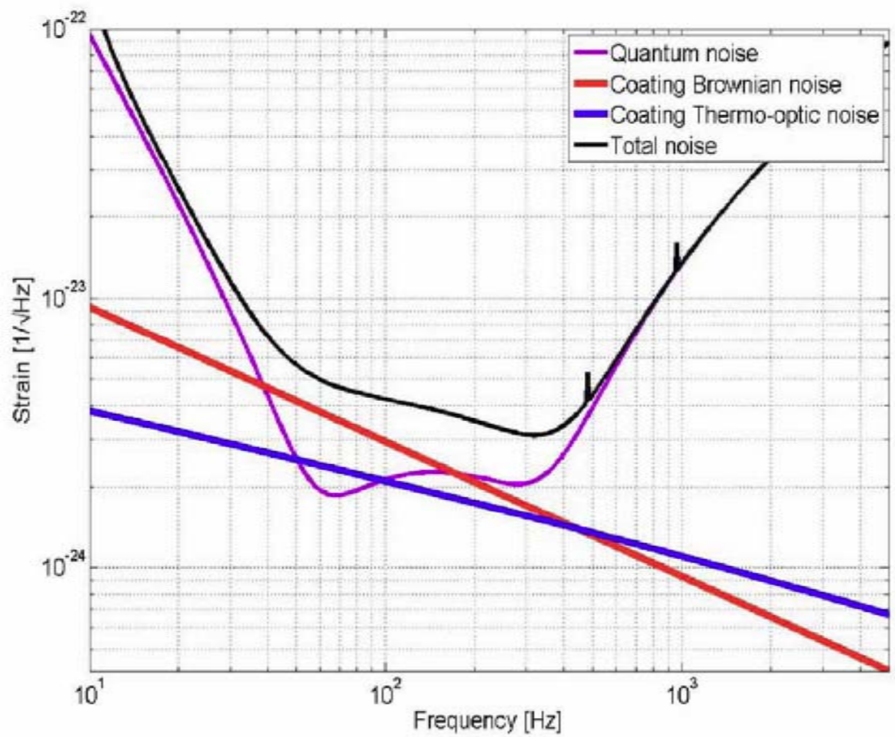
Multiple noise sources:

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

(assuming Advanced LIGO baseline values)



Narrowband Advanced LIGO sensitivity



Wideband Advanced LIGO sensitivity

Advanced LIGO developments

Advanced LIGO:

- Finalise optimisation design (find "best estimates" for all material properties/parameter).
- Transmission at second wavelength (green - for secondary IFO for lock acquisition)
- Testing and verification
  - **Absorption and scatter** (underway – see later slides)
  - **Bubble problems?** (closer studies of Virgo test mirror at LMA)
- Thermorefractive noise less important than previously anticipated.

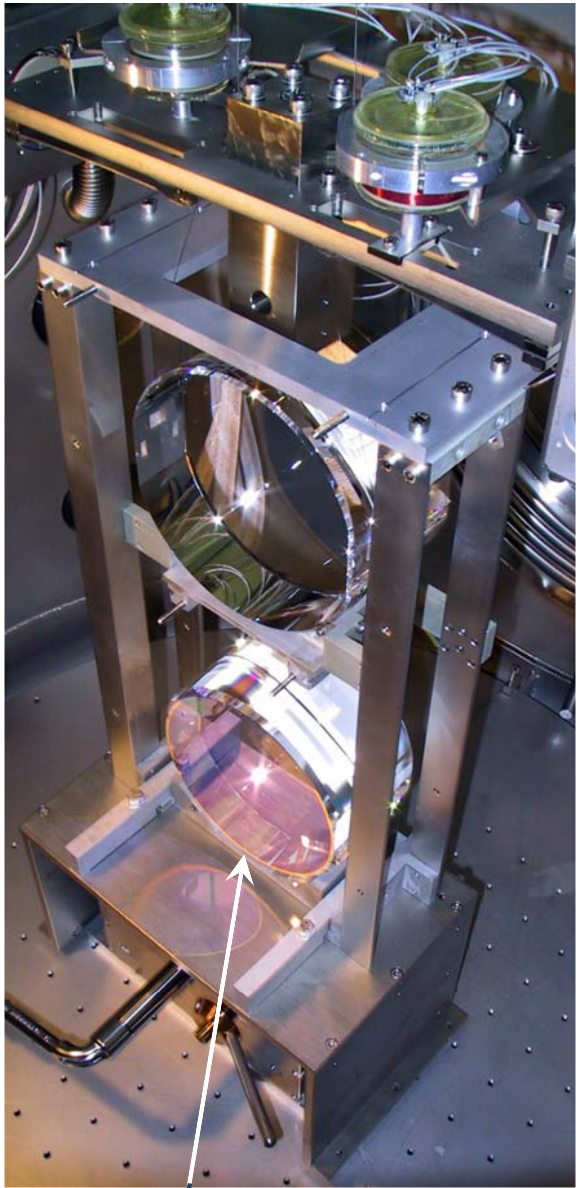
Beyond Advanced LIGO:

- New materials and techniques
  - Two new coating runs: low water (ATF), magnetron (JDSU)
- Better understanding of microscopic mechanisms (+computer modelling)
- Better understanding of material properties (Y, κ, α...)
- High power/thermal loading
- Coating-free technologies
- Low temperatures
- Structure and contamination studies
- Uniformity of ϕ
- Other interactions with detector scheme: scatter, charging and non-gaussian noise...

Brownian noise

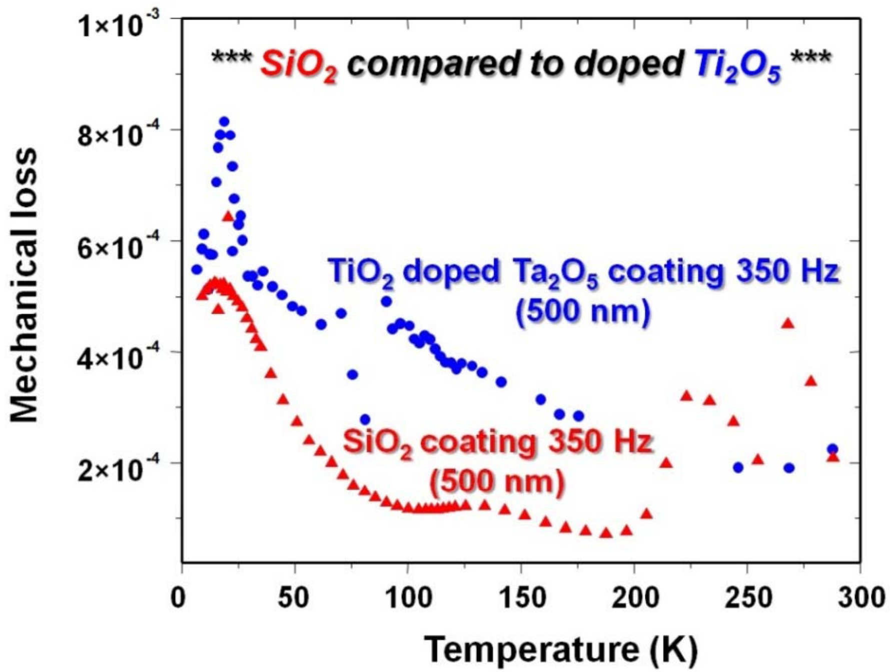
- Experiments suggest:
  - Ta_2O_5 is the dominant source of dissipation in current SiO_2/Ta_2O_5 coatings
  - Doping the Ta_2O_5 with TiO_2can reduce the mechanical dissipation by ~40% for overall coating

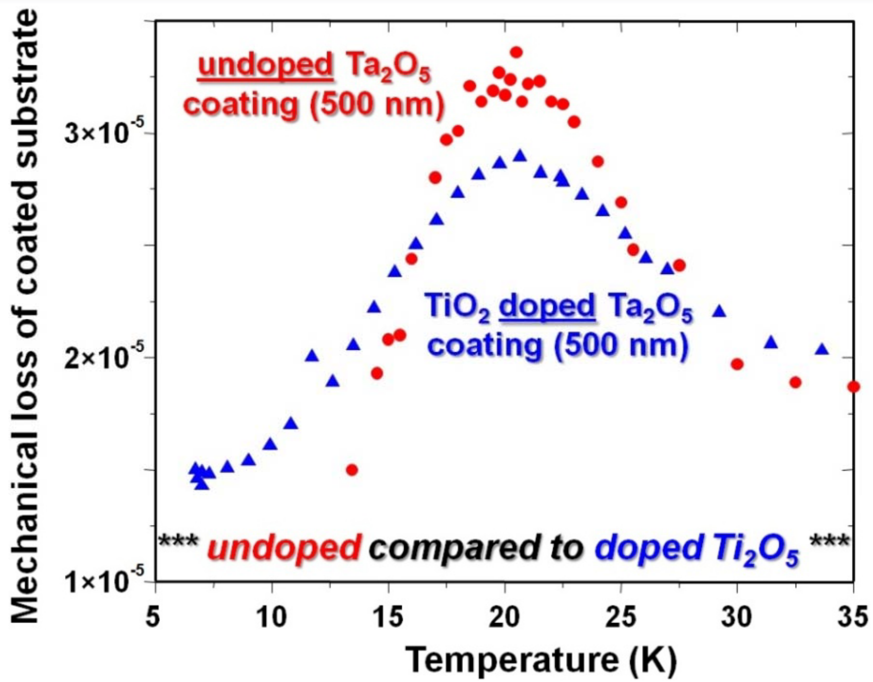
- Research ongoing to:
  - Identify and directly reduce dissipation mechanisms in the coatings
  - 'optimise' coating designs by minimising volume of Ta_2O_5 present in the coatings



Mirror suspension, with HR coating on front face

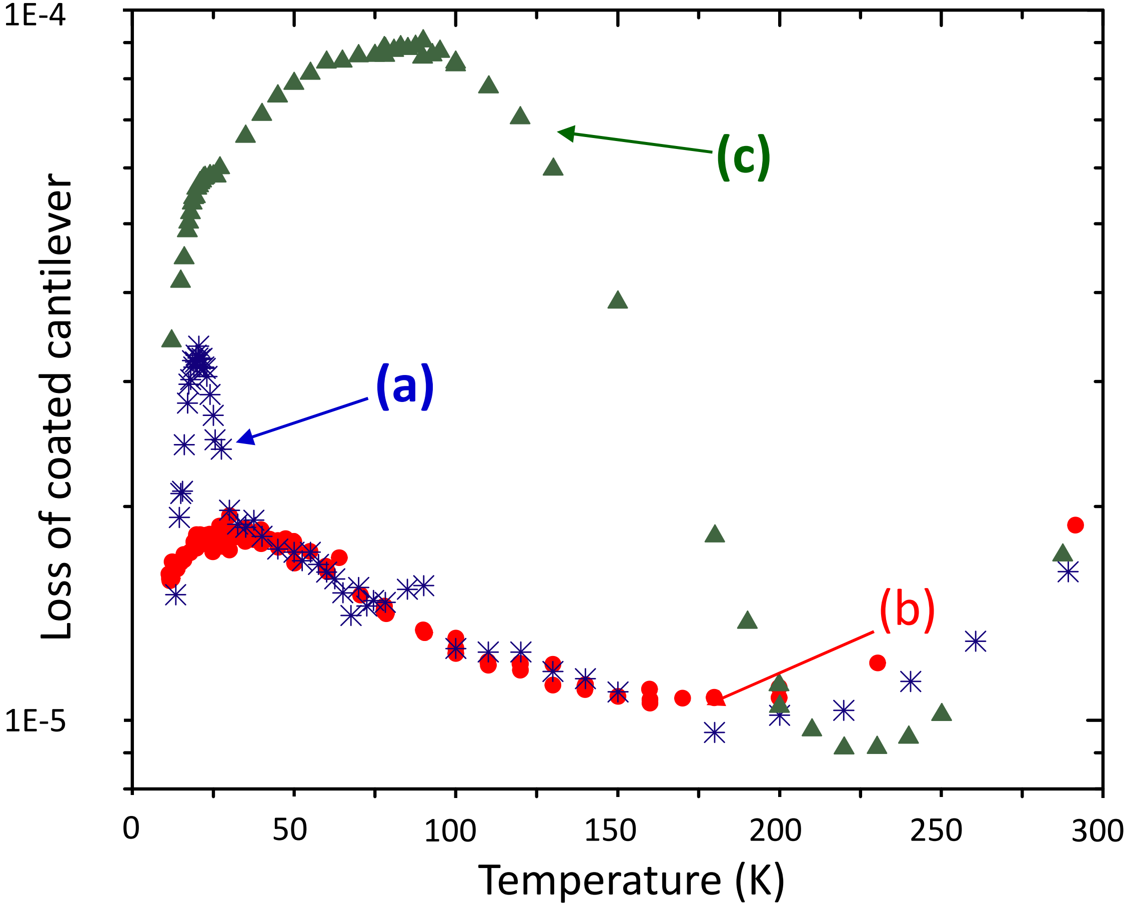
Glasgow (I. Martin et al)
low T dissipation in single-layers Ta_2O_5 and SiO_2

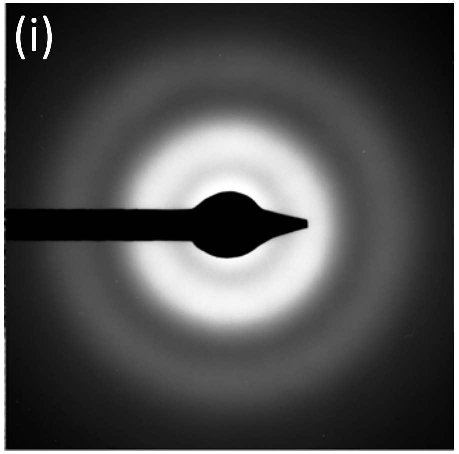


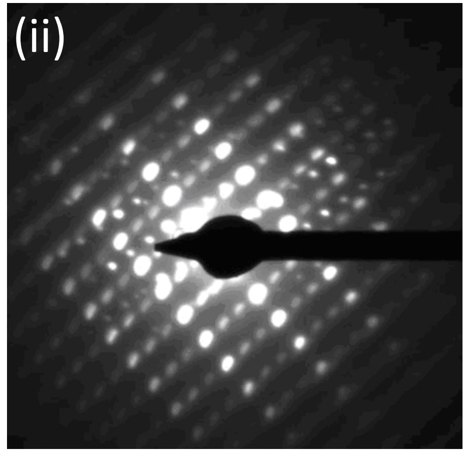


- Dissipation peak observed at ~ 20 K in both pure and TiO_2 doped (14.5%) Ta_2O_5
- Activation energy of 42 meV for dissipation in Ta_2O_5 is similar to that in bulk fused silica i.e. dissipation possibly arises from double well potential corresponding to stable Ta-O bond angles
- Evidence that TiO_2 doping reduces height of peak in addition to reducing loss at room temperature
- Loss of Ta_2O_5 is higher than loss of SiO_2 throughout between 10 and 290 K
  - Scatter close to room temperature due to clamping loss, measurements to be repeated

Glasgow (I. Martin et al)
Heat treatment of un-doped tantala films







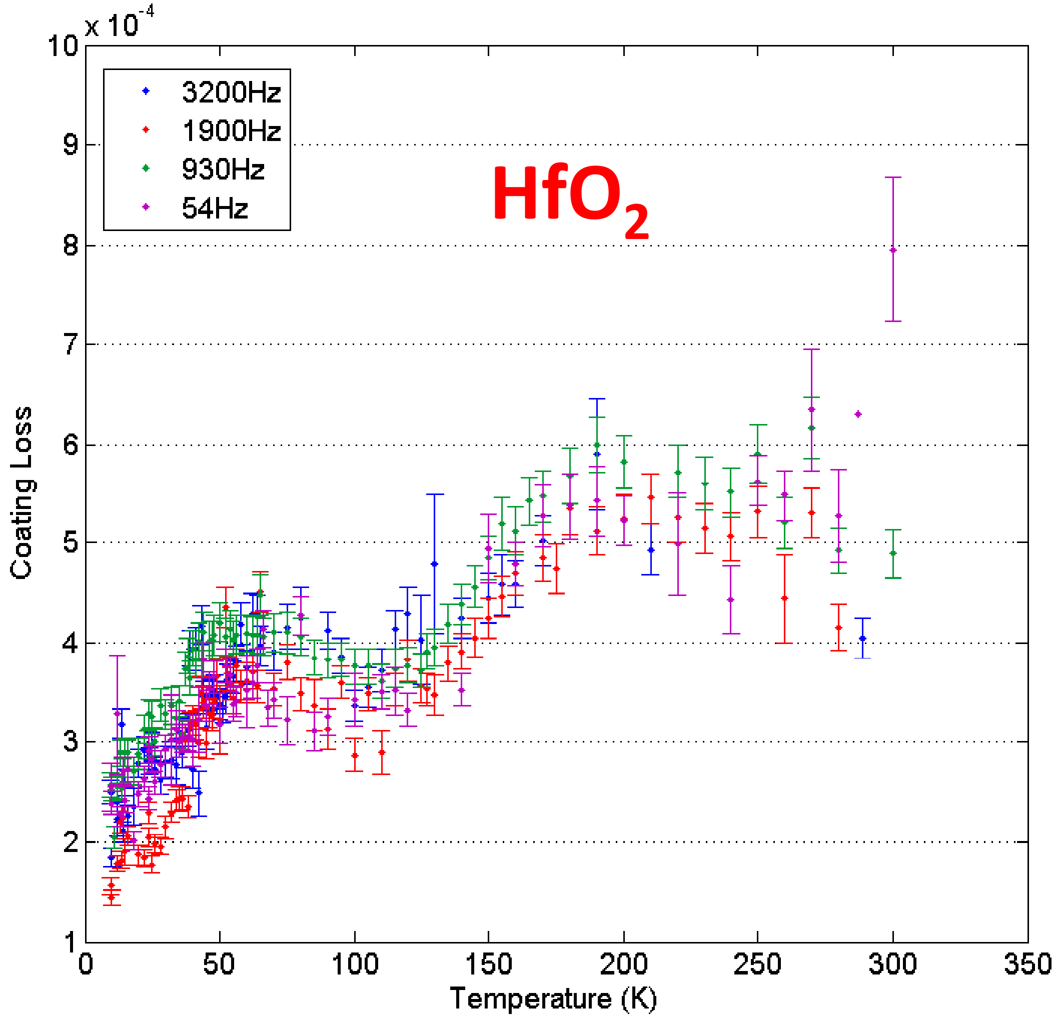
Above: Electron diffraction measurement of Ta_2O_5 heat treated at (i) 600 °C, showing amorphous structure and (ii) 800 °C, showing crystalline structure.

Left: Loss at 1.9 kHz of 0.5 mm Ta_2O_5 coatings heat treated at **(a) 600**, (b) 300 and **(c) 800** °C

- Large loss peak at ~ 80 to 90 K in un-doped Ta_2O_5 coating heat treated at 800 °C, perhaps due to (expected) onset of polycrystalline structure
- Smaller, broader peak at with activation energy of 138 ± 4 meV at ~35 K in un-doped Ta_2O_5 heat treated at 300 °

Glasgow (E. Chalkley et al)
Other ongoing coating R&D

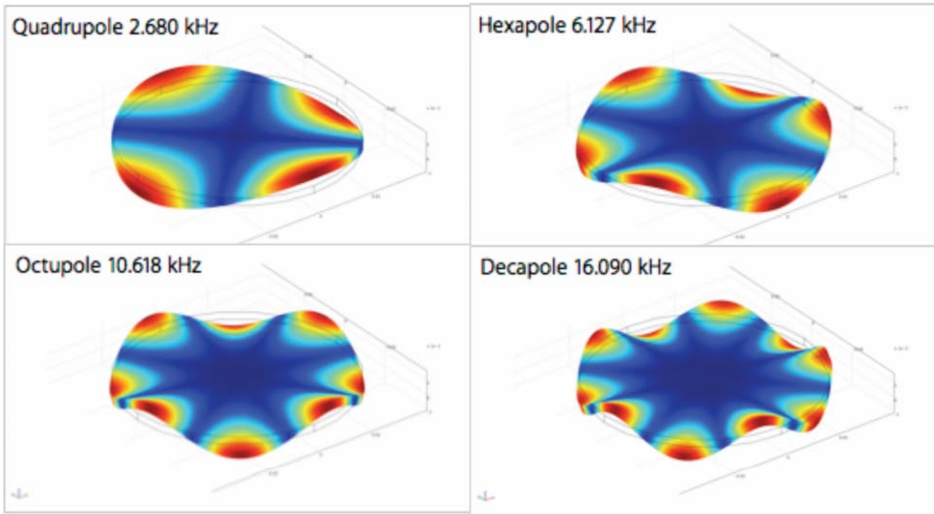
- Investigation of possible alternative high index coating materials
- Preliminary studies of 0.5 μm thick HfO_2 coating, heat treated at 300°C show:
  - a broad dissipation peak at ~ 50 K
  - a plateau, or possibly a second peak, at ~ 200 K.
- Study of the effect of heat treatment on loss of hafnia planned



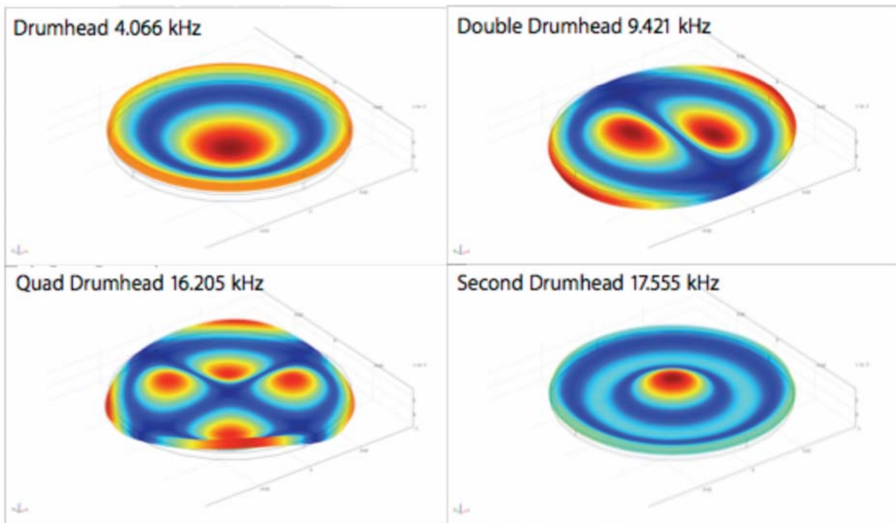
- Collaboration with INFN lab at Legnaro to study the loss of coating materials at ultra-cryogenic temperatures – may yield more information on loss mechanisms.
- ADX Reduced Density Function analysis of TEM images to help quantify structure in amorphous thin-films.

Hobart and William Smith Colleges (S. Penn et al)
Mechanical loss is silica thin-films

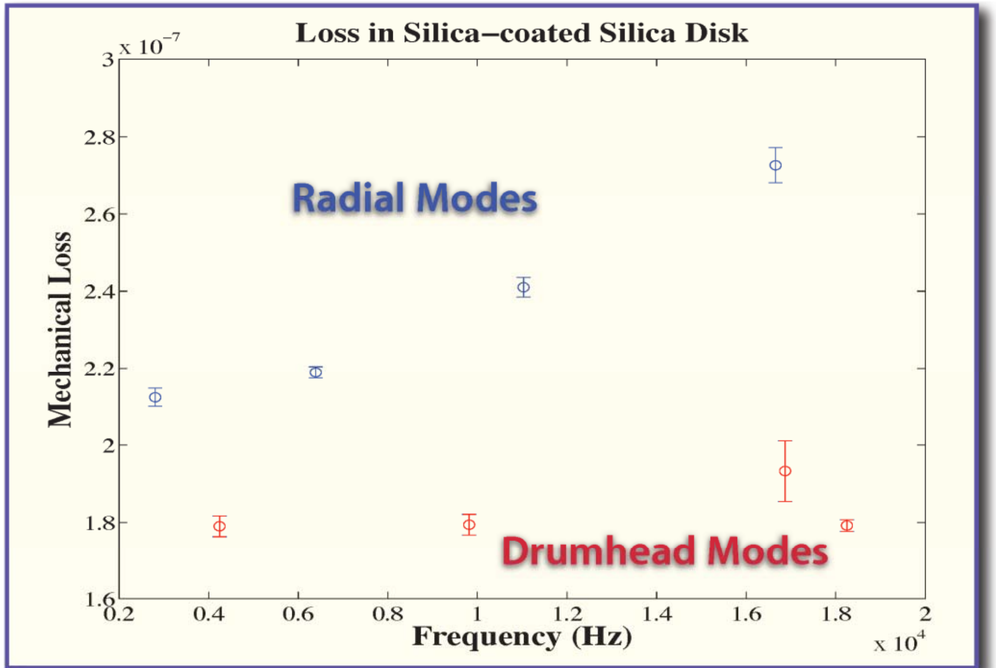
- Loss in Silica Coatings is important for optimizing coating loss.
- Loss vs Annealing temperature yields loss from residual stress in silica
- Comparison with bulk silica reveals the loss due to coating structure.
- Provides data to improve the theoretical modeling of coatings.
- Exploring the Frequency dependence in the loss by mode-type.



Radial Modes

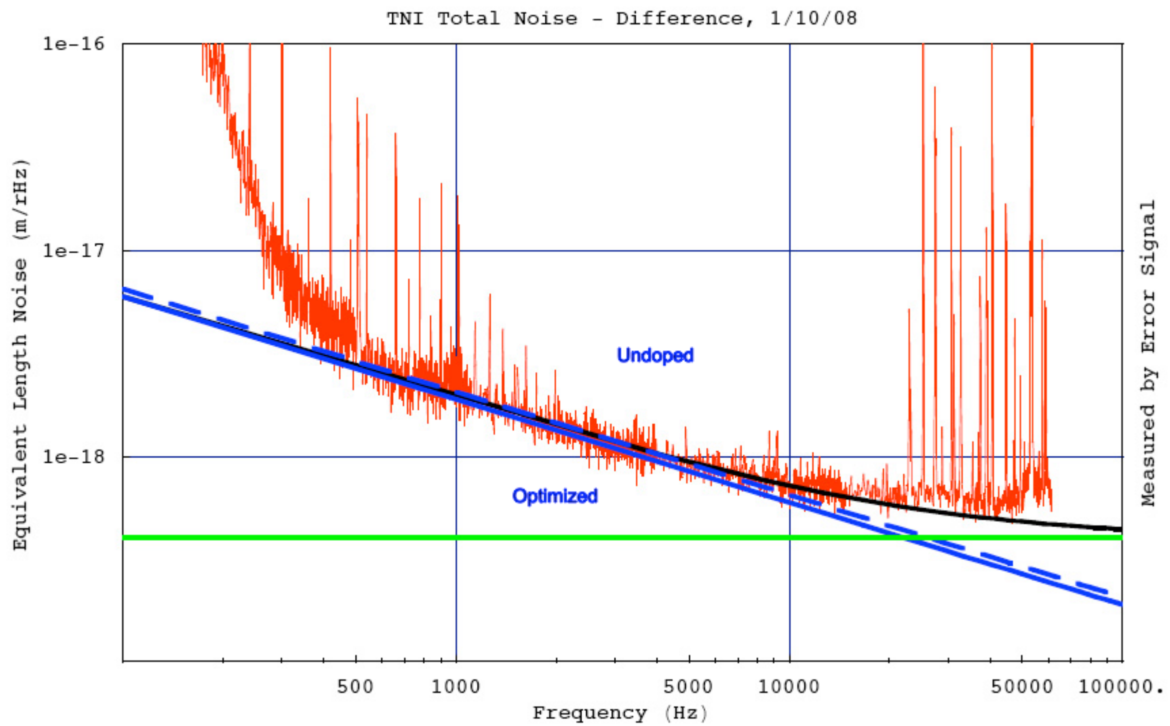


Drumhead Modes



Caltech
TNI update (G. Olgin, E. Black et al)

- Optimized coating measured last fall
- Have substrates for (doped & optimized) coating, waiting for coating fabrication
- Sent undoped optimized coating out for characterization
  - 6 ppm Scatter, Liyuan Zhang
  - 0.57 ppm absorption measurements, Ashot Markosyan
  - Within error bars from non-optimized



- 16% reduction in loss angle
- 29% increase in event rate

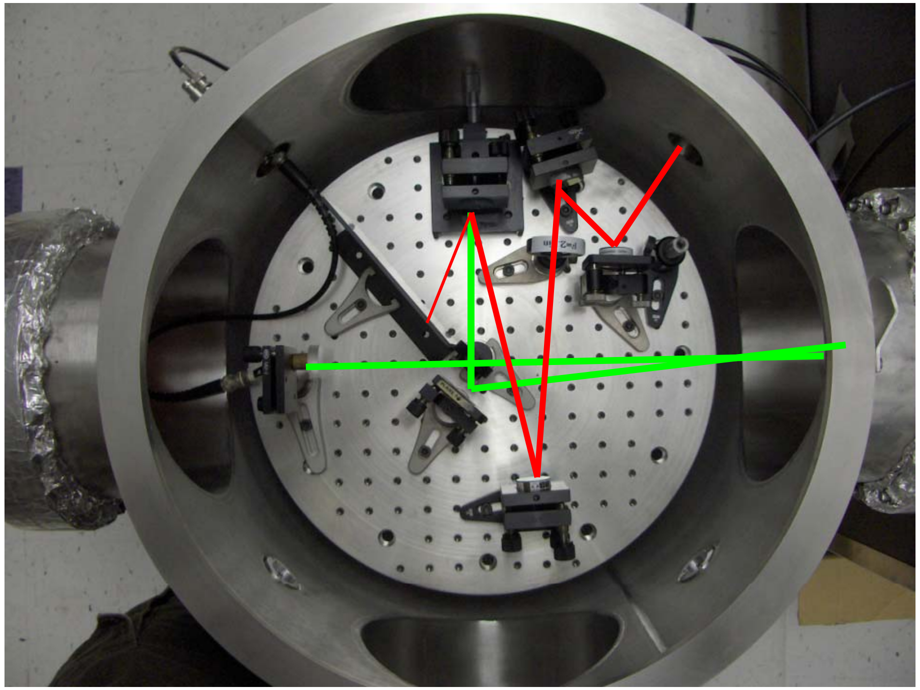
- Experiment constructed to verify relationship between thermo-elastic and thermo-refractive response of mirror

$$\frac{\partial \varphi_{overall}}{\partial T} = \frac{\partial \varphi_{refl}}{\partial T} - \frac{4\pi}{\lambda} \alpha_{eff} d$$

Reflection Phase

Expansion

- Currently in shakedown and debugging phase



Sannio University (I. Pinto et al)
Optimised coatings

- ‘Optimisation’ of coating layer thicknesses
- Goal: lowest noise at a prescribed transmittance

- INFN funding for 2nd generation optimised coating (TNI) prototypes approved
  - Sept. 18th 2008 (35 KEU, INFN panel 5, will be available jan. 2009);

- Vyatchanin calculation of thermoelastic-noise finite-mirror correction factor redone from scratch; MATHEMATICA code written; parametric study under way; accuracy of generalized Braginsky’s formula confirmed;

- Plain tantala-based optimised coating mirror prototypes manufactured at LMA,
  - testing has been carried out at TNI, Caltech and Stanford.

- Study of sub-wavelength-layer based “meta”-materials for coatings initiated;
- Can we do any better than Ti-doped Tantala ?

(Sannio Coating Team: Giuseppe Castaldi, Vincenzo Galdi, Vincenzo Pierro, Innocenzo M. Pinto, Maria Principe)

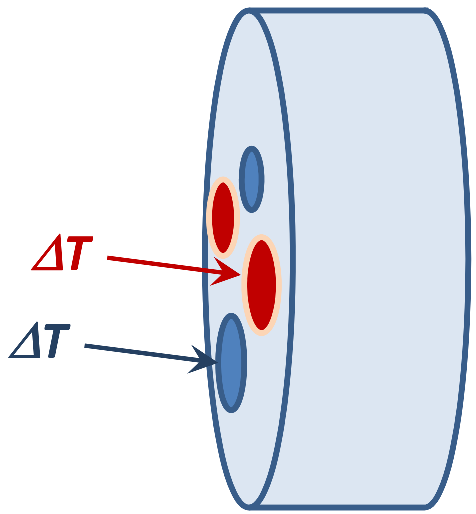
Thermo-optic noise - update

- Equilibrium fluctuation of the temperature of the test mass coatings cause fluctuations in physical parameters of the coating. Coupling due to:
- Thermo-elastic expansion of the coating - where **α=dL/dT**
- Thermo-refractive change in the coating optical thickness - where ***β*=dn/dT**

$\alpha = dL/dT$ » **thermoelastic noise**

$\beta = dn/dT$ » **thermorefractive noise**

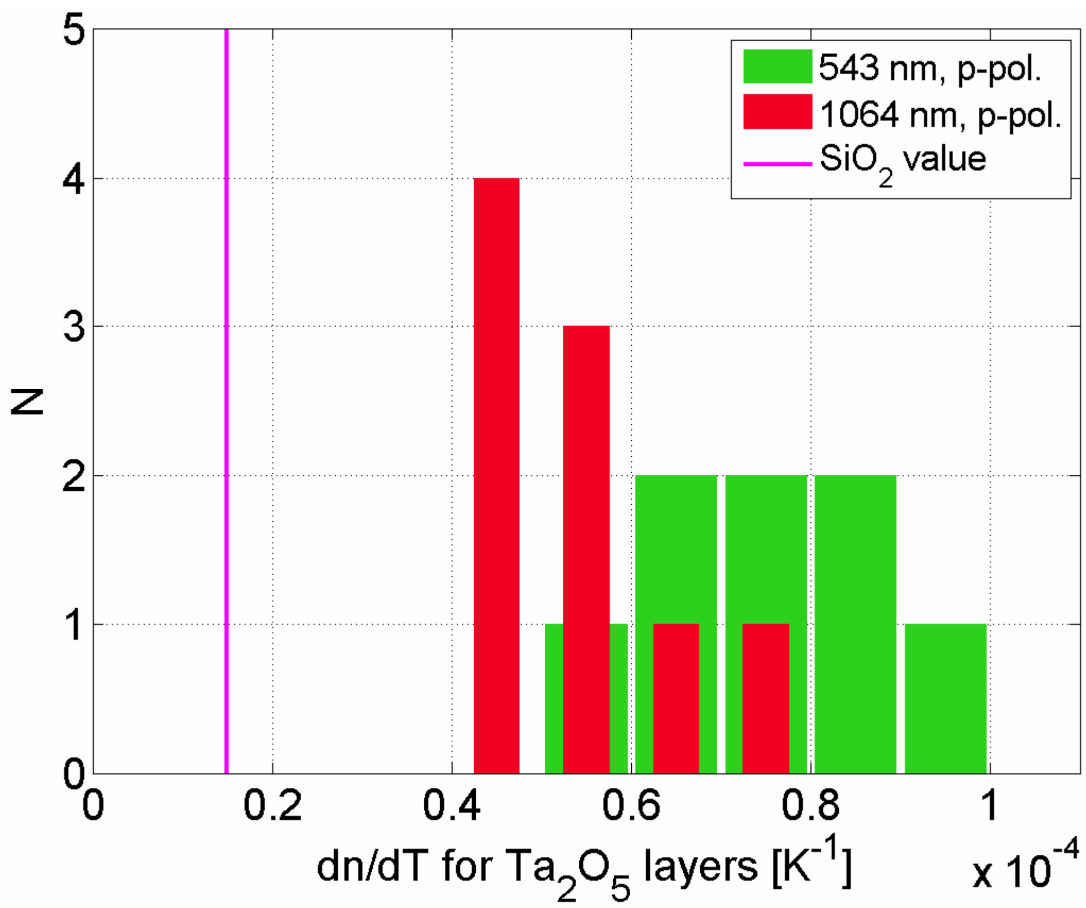
- Thermo-optic noise:
  = (coherent) sum of thermoelastic and thermorefractive contributions



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

Embry-Riddle - Thermo-optic noise
(A. Gretarsson, G. Ogin et al)

- Aim: direct measurement of β=**dn/dT**.



- ERAU (1064 nm):

$$\beta = (5.3 \pm 1) \times 10^{-6}$$

- Using

$$\alpha = (3.6 \pm 1) \times 10^{-6}$$

- Ellipsometry:
  - SOPRA data being analysed by Gregg Ogin

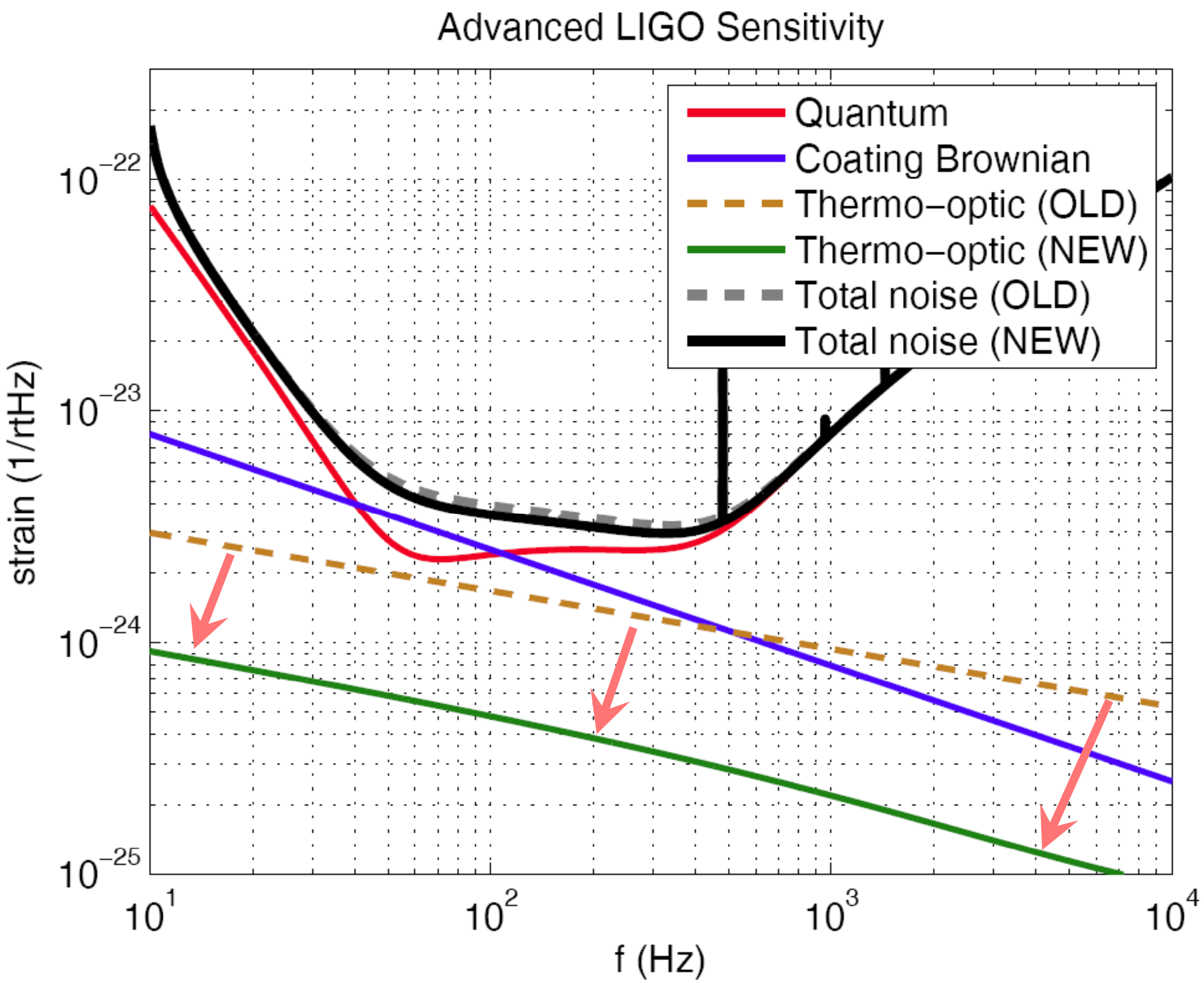
- Need to confirm previous measurements of α.

MIT - Cancellation of thermo-optic noises? (M. Evans et al)

- Recent studies carried out my Matt Evans, investigate whether the coherent sum of thermo-elastic and thermo-refractive can be made to cancel.
- The thermo-optic effects are coherent, if the thermal diffusion length is long compared to the coating thickness.
  (diffusion length at 100Hz is ~40 µm, coating thickness ~4.5 µm)
  see http://arxiv.org/abs/0807.4774v1
- The thermo-elastic effect involves the whole coating.
- The thermo-refractive effect is dominated by the first few doublet layers.
- Most materials have the same sign for their thermal expansion coefficient and dn/dT (α and β), the thermo-optic effects have opposite sign.
- Both SiO_2 and Ta_2O_5 appear to have positive α and β.
- The relative minus sign between TE and TR effects reduces their impact.
- For plausible Advanced LIGO coatings, Brownian noise (due to mechanical loss) dominates.

MIT - Cancellation of thermo-optic noises? (M. Evans et al) *contd*

- Current values of α and β are not well-quantified, however the level of thermo-optic noise now appears to be insignificant compared to that of Brownian thermal noise.
- Advanced LIGO noise curve, illustrating updated thermo-optic noise:



Stanford - Effect of First Contact & UV (A. Markosyan, K. Sun et al)

Effect of First Contact application to UV exposure was studied on a 1" LIGO mirror with baseline absorption value ≈ 0.3 ppm.

Measurements were carried out along the red line (2 mm above center) at ambient atmosphere.

Areas 1 and 2 were subjected to the following procedures

i) *Absorption measurement*

ii) Area 2 was covered by FC, left for 48 hours

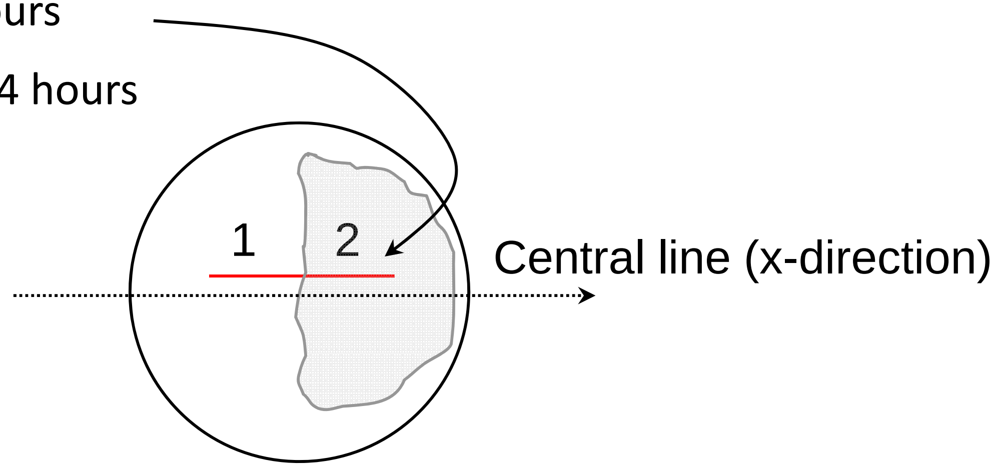
iii) Areas 1 and 2 were UV illuminated for 24 hours

iv) FC was peeled off

v) *Absorption measurement*

vi) Annealed for 2 hour at c.a. 350°C

vii) *Absorption measurement*



UV source: λ = 255nm with several nm FWHM, $\varnothing \approx$ 3.5 mm.

Power density is ~6 μW / cm^2, so 24 hours gives total irradiation flux of ~0.5 J /cm^2

Stanford - Effect of First Contact & UV *contd*
(A. Markosyan, K. Sun et al)

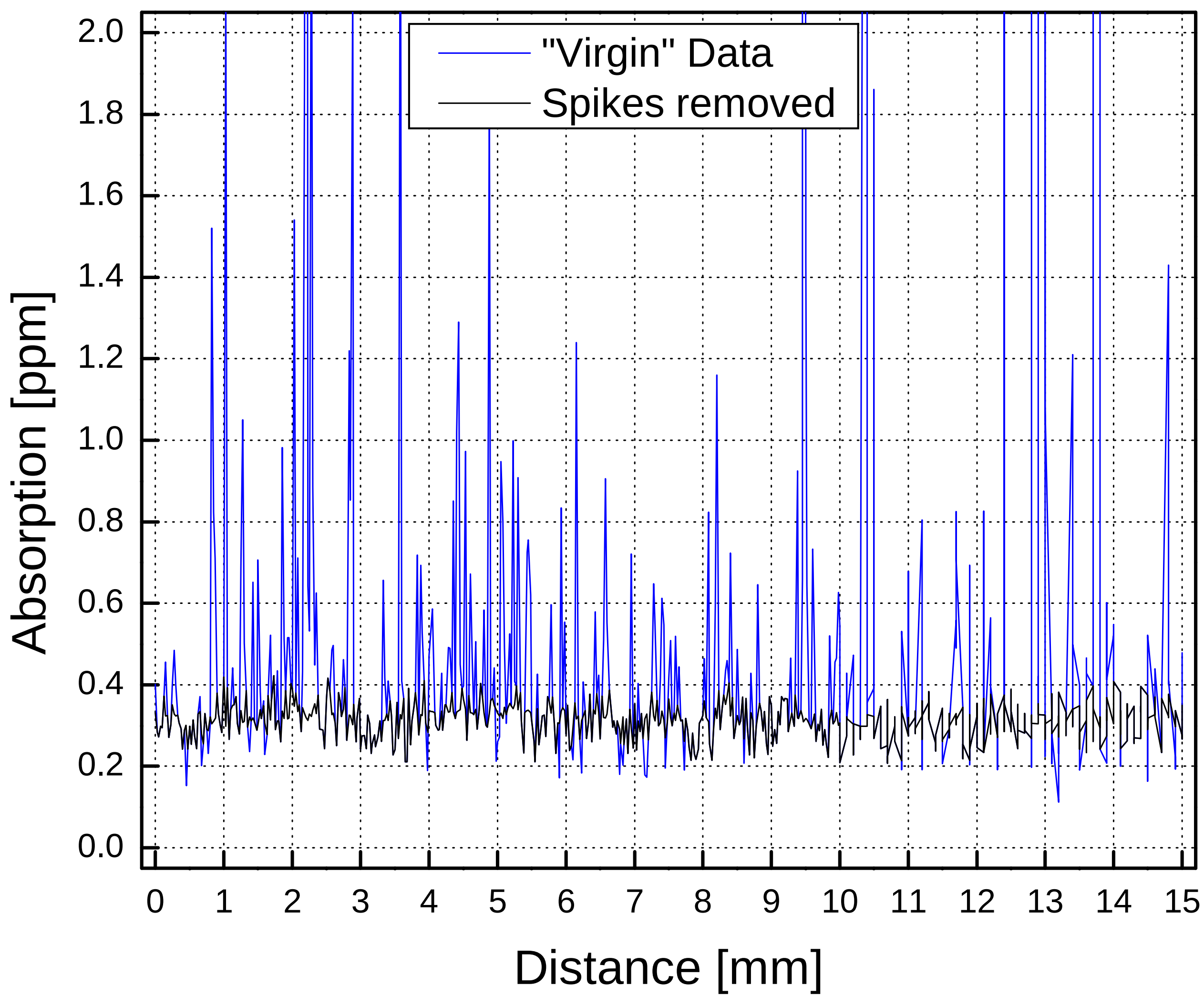


Fig. 1. A reference scan over the sample surface (blue): **<u>Alpha = 0.32 ppm</u>**

The black line shows the same data with spikes removed (for the sake of clarity)

Stanford - Effect of First Contact & UV *contd*
(A. Markosyan, K. Sun et al)

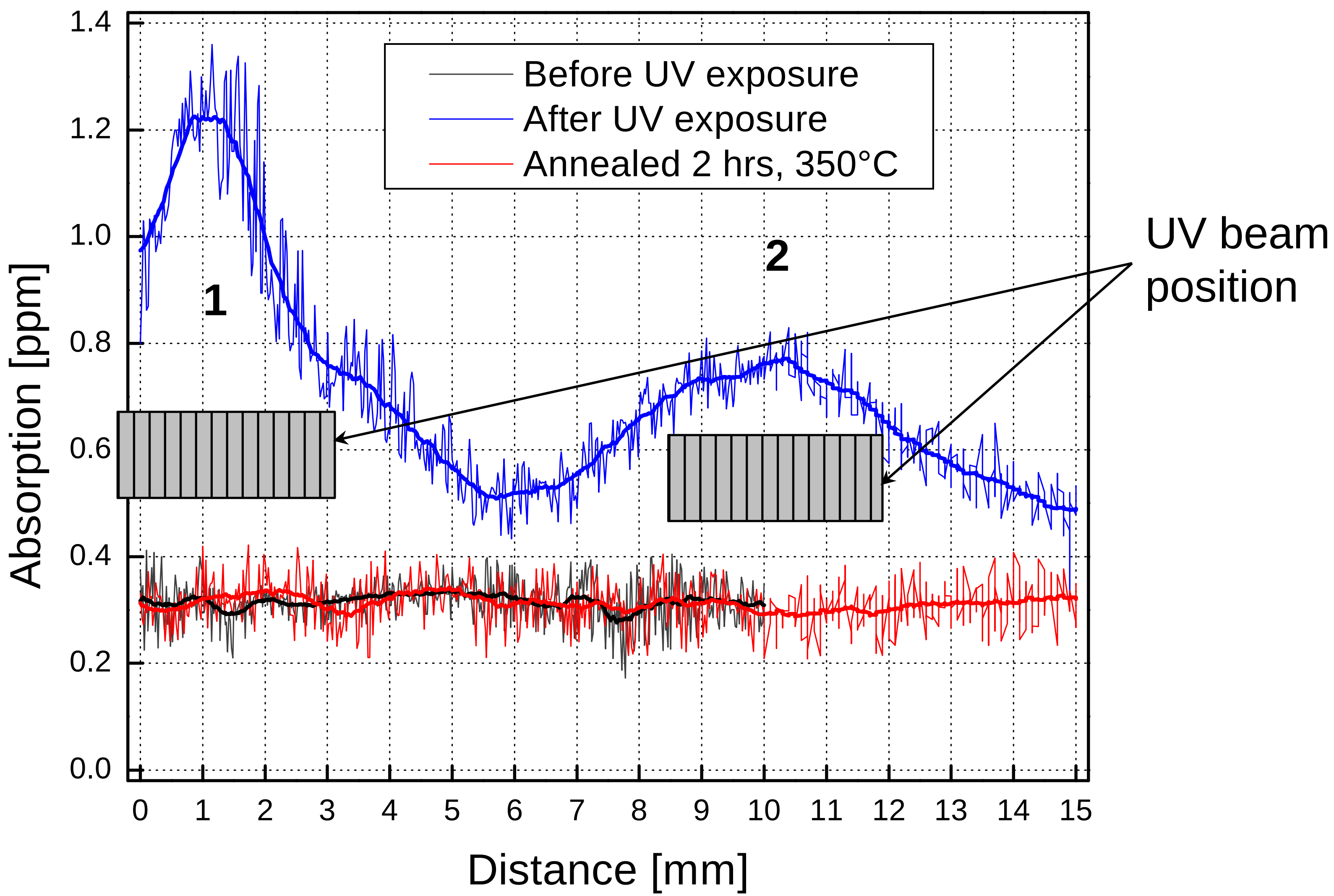
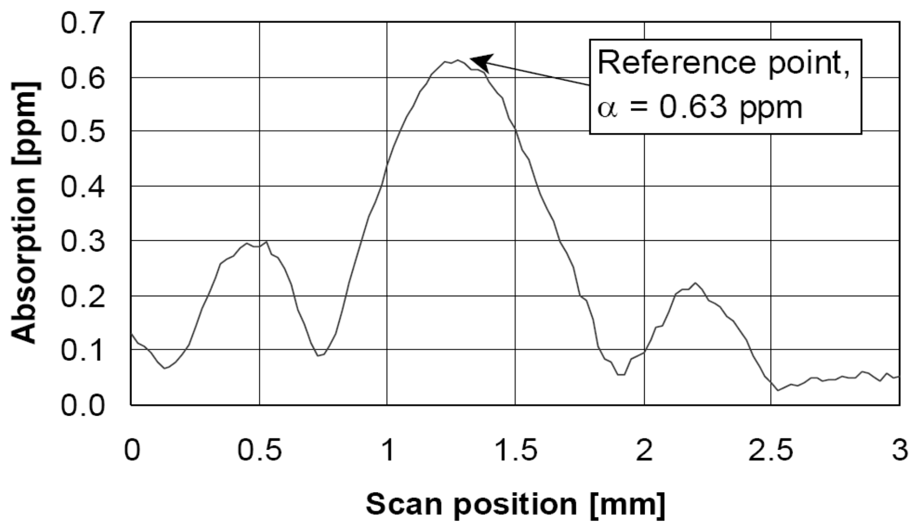


Fig. 2. Comparison between three different scans (all spikes are removed in order to simplify the presentation): before UV exposure (black line), after UV exposure (blue), after heat treatment (red).
Area 2 shows smaller increase presumably because of protection by FC.
The excess absorption caused by UV exposure is totally **reversible** by **annealing** 2 hrs@350°C

Stanford - absorption of TNI optic (optimised coating)
(A. Markosyan, K. Sun et al)

- **LIGO mirror (Δ= 4”, Ø = 4”) 09/07/08.**
- **Coated surface had a curvature with R = 1 m.**
- **Optimised coating**
  (non-periodic coating layer thickness)

- **Average absorption: α = 0.57 ppm.**

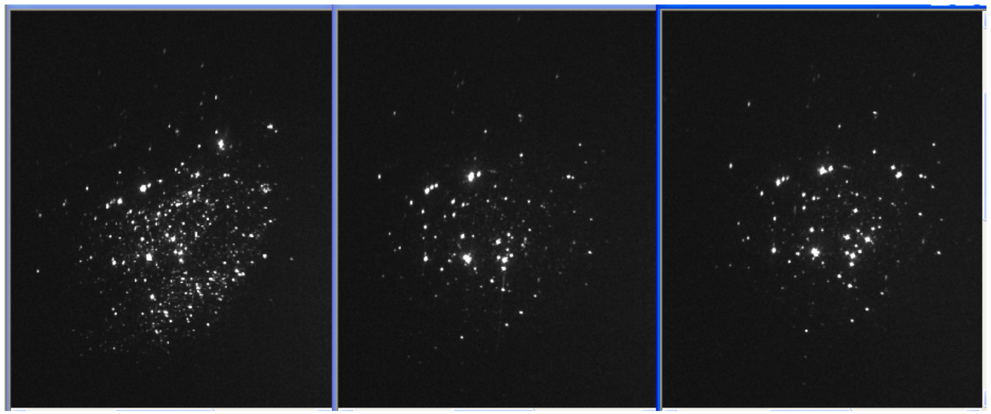


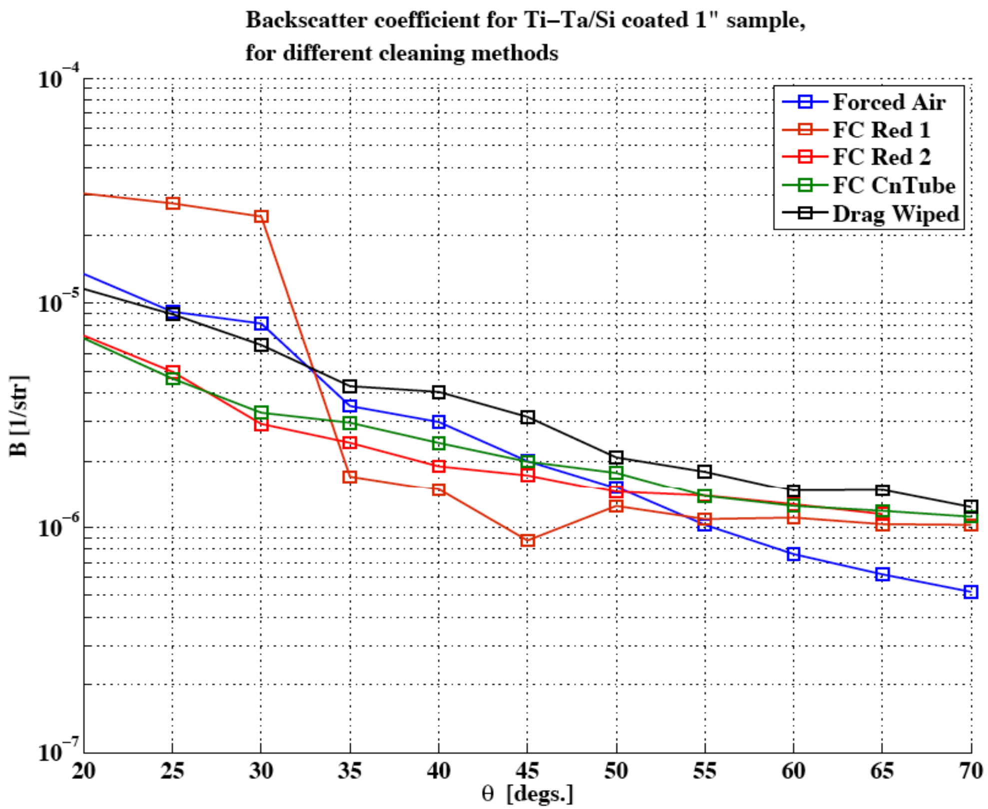
- **This is the expected result – however it is important to note that the optical absorption was not adversely affected by moving to non-periodic coatings.**

Syracuse - Scatter studies after different cleaning techniques (J. Smith et al)

- 1” TiO_2 doped Ta_2O_5/SiO_2 multilayer (Advanced LIGO coating) cleaned using different methods.
- First Contact^{TM} removes some scattering points with respect to the drag-wiped case, but most of the strongest points are still present. The red and FC images are virtually identical.
- The scatter of this optic does not differ significantly based on the cleaning method.
- There is no noticeable increase in scatter from using First Contact Carbon Nanotube.
- Neither FC CNT or Red seem to drastically reduce the number of point scatterers in the images - maybe meaning that most are not due to removable surface particles?

Drag wiped | **Std First Contact** | **Carbon Nano Tube First Contact**

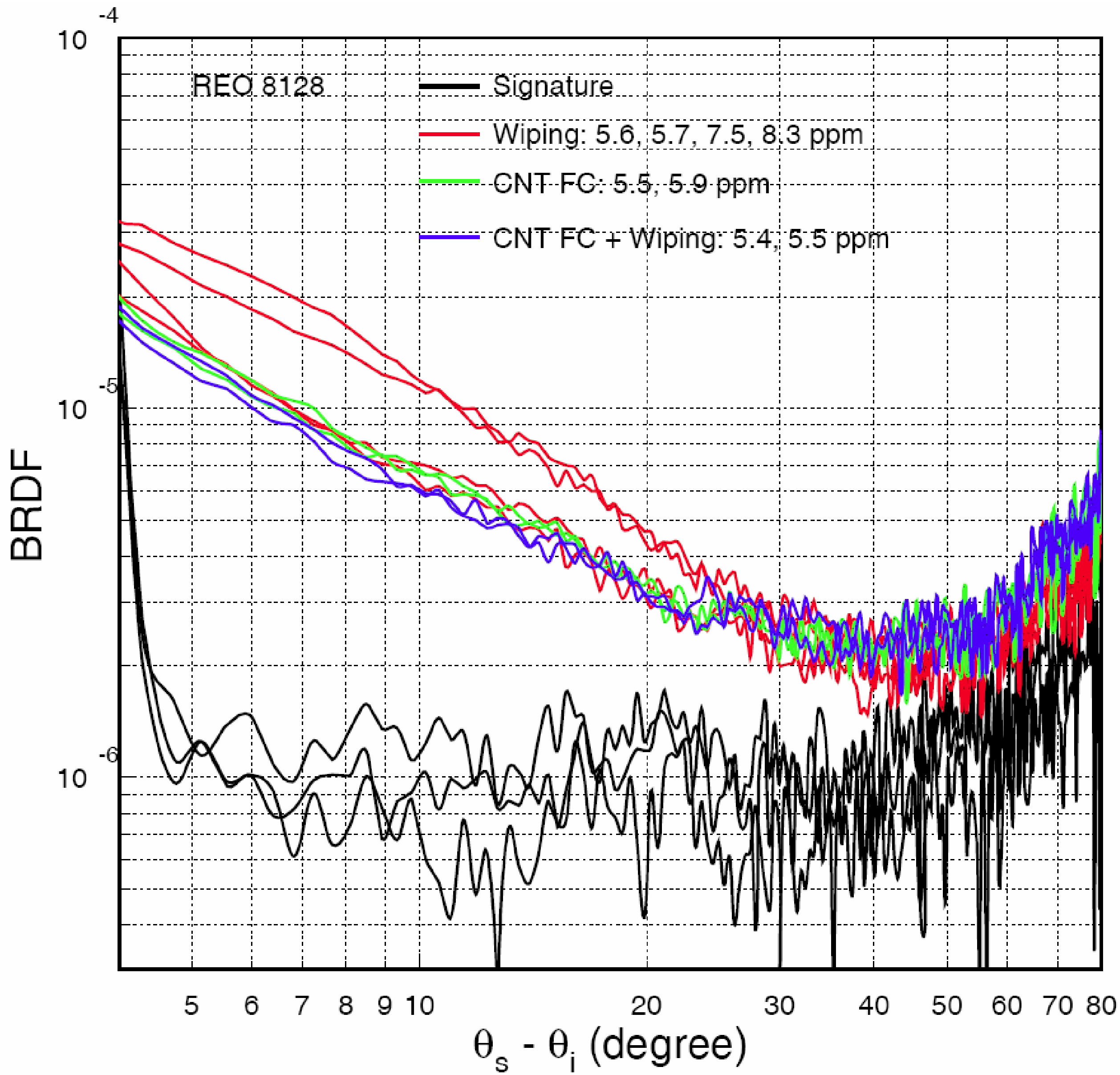




As part of the overall coating plan, we also intend to study scatter vs annealing.

Caltech - Scatter *contd* (Liyuan Zhang)

- Studies carried out by Liyuan Zhang show very comparable results.

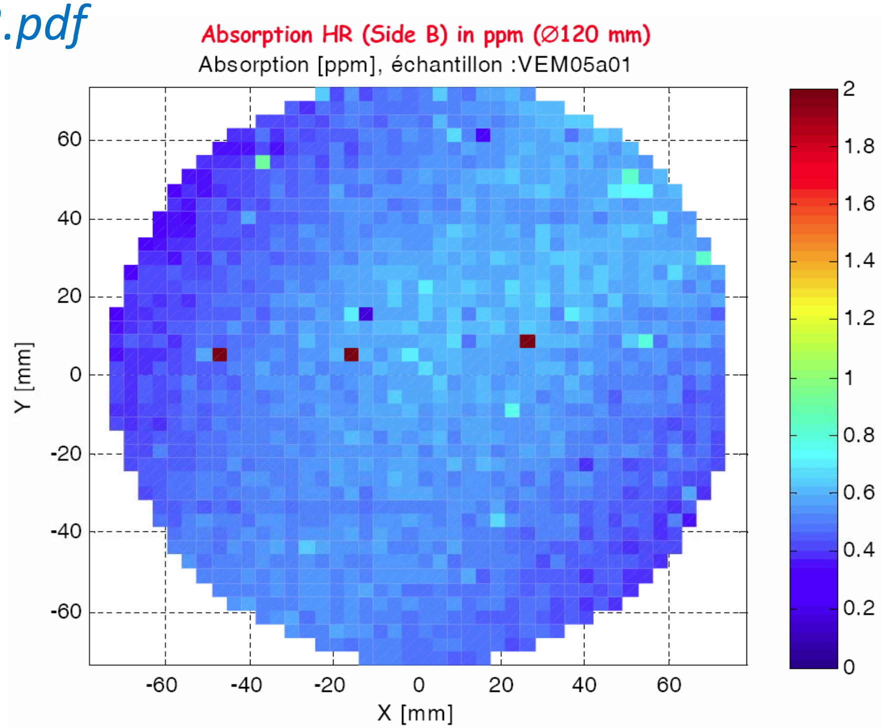


Other developments

- AdvLIGO coating plan to have a coating that is HR at 1064, with some transmittance at green to allow for a secondary IFO for lock acquisition. This coating will be lower in thermal noise than the regular 1/4 wave stack at 1064 but not completely optimised. (differences are very minor)

- Bubbles observed in the LASTI coatings.
- It is important to check that suitable coatings for Adv. LIGO do not have bubbles.
- Detailed characterisation carried out at LMA on a test VIRGO end mirror, see: *http://mm.ligo.caltech.edu/aligo_coc/pdf00012.pdf*
  - *no bubbles observed in these coatings*
  - *scatter <5.5 ppm (good, improvement over Initial LIGO)*
  - *Absorption 0.52 ppm*

  (albeit an undoped, un-optimised coating)



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 (in progress)
  - Existing team (including Virgo) with experience
  - Allows for both Advanced LIGO and beyond work