Overview of LSC Coatings Research

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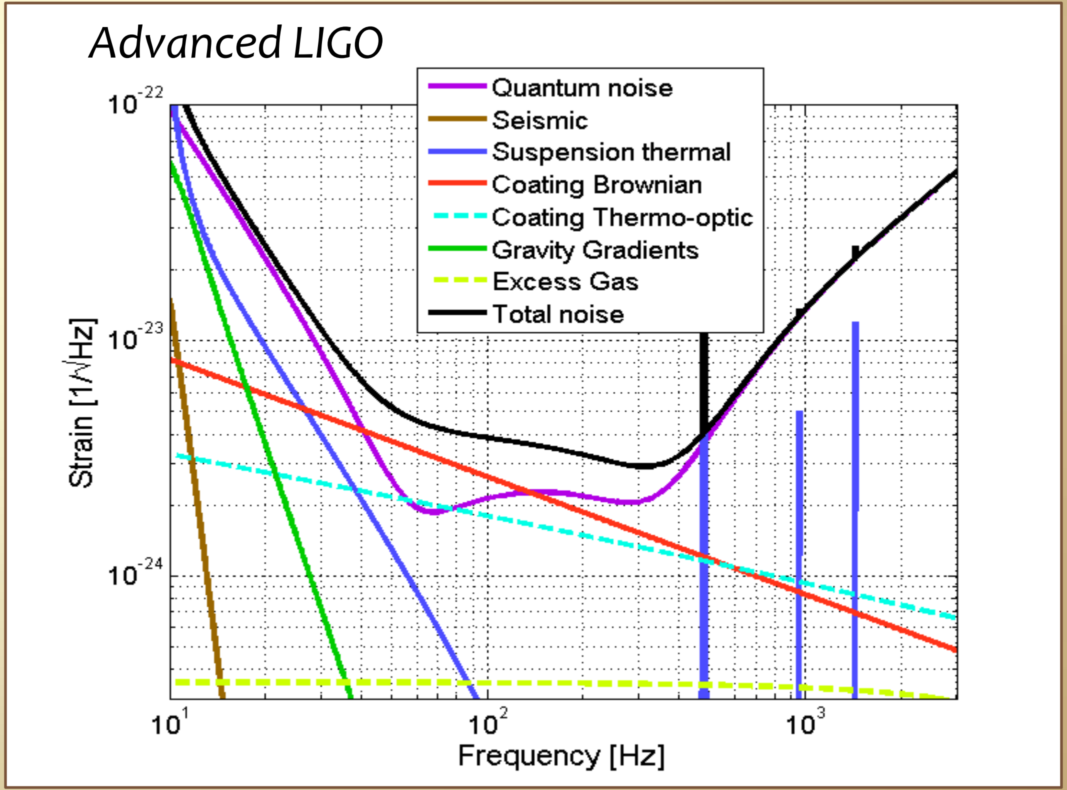
...on behalf of the LSC coatings research group.

Coating Noise Reduces the Advanced LIGO Detection Rate

- "Thermal noises" from coatings
  - Brownian
  - Thermo-elastic
  - Thermo-refractive
- Astron. reach depends on material parameters
  - ϕ, α, β, Y
- Thermal lensing from absorption
- Other important parameters
  - *Scatter*
  - *Stability*
  - *Reflectivity at other λ's.*
  - Uniformity
  - Reflectivity matching



Coating Research Program

- Measured coating loss angles of around 90-100 samples since coating program started in 1999. (See G.Harry workshop talk)
  - Silica, Tantala, Titania, Niobia, Hafnia, Alumina, and alloys
  - Poor Stoichiometry, Xenon bombardment, Substrate polish, Annealing, Proprietary methods
  - Interface layer effects
  - Temperature dependence

- TNI has measured coating thermal noise directly for three prototype coatings
  - Pure Ti_2O_5 / SiO_2, (TiO_2-doped Ti_2O_5)/ SiO_2, optimized coating.

- Layer thickness variation to reduce coating noise while retaining optical properties: “Optimized coatings.”

Coating Research Program

- Other important parameters have been measured for a subset of the coatings
  - α, β, Y, scatter, optical loss, effect of UV
- Measured loss at cryogenic temperatures to understand loss mechanisms
- Microscopic models of the substrate and coating are in progress.
- Barrel coatings
  - Gold for thermal compensation – Thermal noise looks good (See Phil Willems' talk next)
  - Parametric instability reduction

Current Status

- Coating mechanical loss reduced by a factor of 2.5 beyond initial LIGO:
  - For a signal in the coating thermal noise limited band near 100 Hz factor of 6 improvement in detection rate after optimization.
- Thermo-optic noise from coatings is significant.
- Thickness optimization reduces thermo-optic+brownian noise by 15% or more depending on exact material param's.
- TNI results are encouraging and in agreement with coating parameter measurements (ϕ, β, …)
- Low temperature loss-peaks providing clues to the microscopic source of the primary loss mechanisms in metal oxide coatings.
- Problems with uniformity (bubbles) in LASTI coatings

To do…

Advanced LIGO

- Finalize optimization design (need to settle on "best-estimates" for all the material parameters)
- Transmission at 2nd wavelength
- Bubbles (Virgo-plus optics)
- Testing and verification

Beyond Advanced LIGO

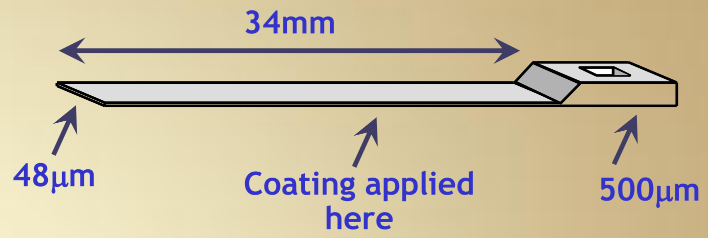
- New materials & techniques
- Better understanding of microscopic mechanisms
- Coating-free technologies
- Low temperatures
- Structure and contamination meas.
- Verification of thermo-optic noise theory
- Uniformity of ϕ
- Better measurements of β, Y.
- High-power issues
- Interaction with interferometry:
  - Scatter, non-gaussian noise, charging, etc.

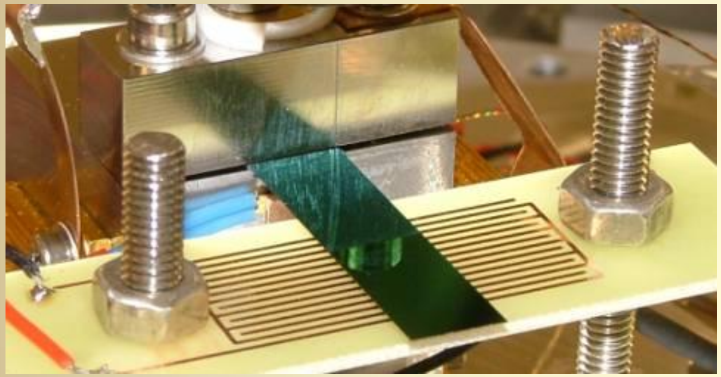
Recent Results

… mainly since the Hannover Meeting

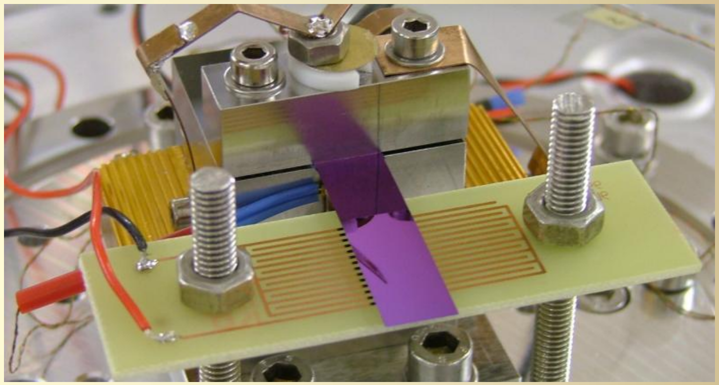
Cryogenic loss of single layer coatings (Glasgow)

- Temperature dependence of mechanical dissipation in coating materials studied using silicon cantilever substrates, fabricated at Stanford





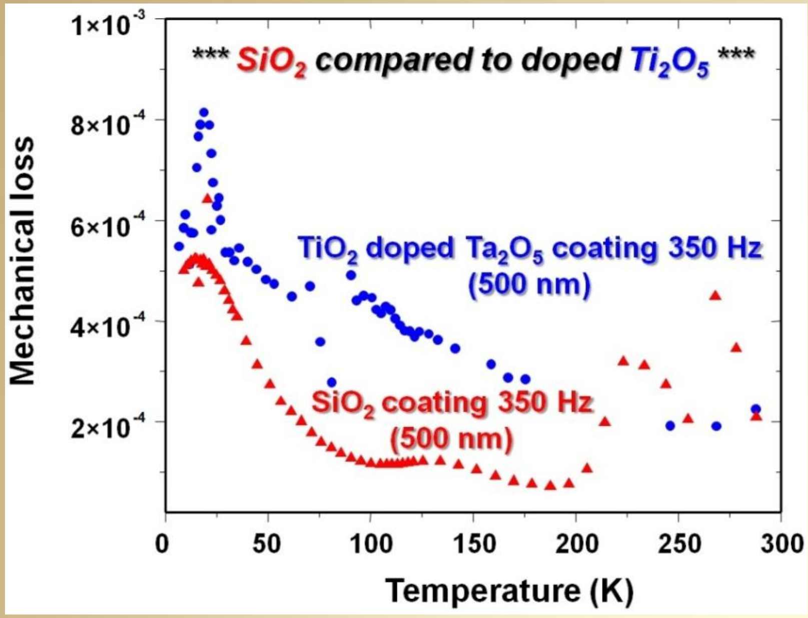
Titania doped tantala (LMA) coated silicon cantilever in clamp

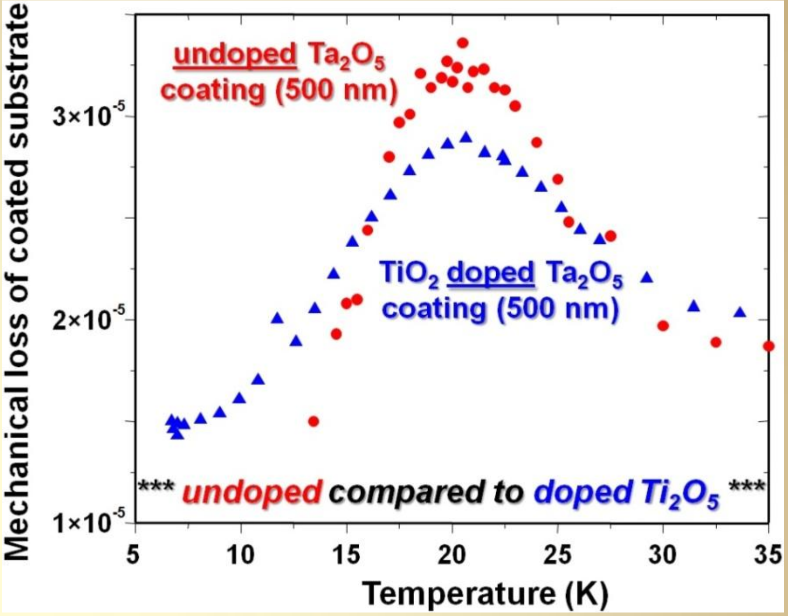


Silica (LMA) coated silicon cantilever in clamp

- Studying dissipation as a function of temperature of interest to:
  - Determine dissipation mechanisms in the coatings, possibly allowing dissipation to be reduced
  - Evaluate coatings for possible use in proposed cryogenic gravitational wave detectors
- Measurements of doped Ta_2O_5 and SiO_2 made in collaboration with Jena University

Low temperature dissipation in Ta_2O_5 and SiO_2





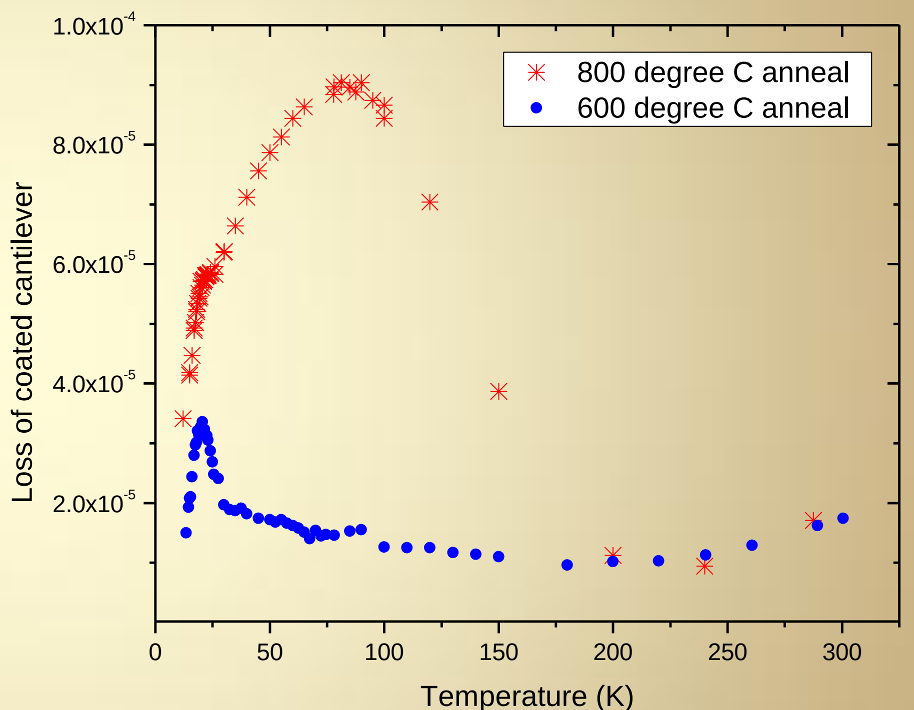
- Dissipation peak observed at ~ 20 K in both pure and TiO_2 doped (14.5%) Ta_2O_5
- Activation energy of 42 meV for dissipation in Ta_2O_5 is similar to that in bulk fused silica i.e. dissipation possibly arises from double well potential corresponding to stable Ta-O bond angles
- Evidence that TiO_2 doping reduces height of peak and reduces 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 300 K due to clamping loss, measurements being repeated

Ongoing coating R&D in Glasgow

- Studies of the underlying material physics using high resolution TEM and Electron Energy Loss Spectroscopy to investigate short and medium range order and bond structure in coatings

- Measurements of the effect of annealing on loss and structure in Ta_2O_5
  - Initial results show large dissipation peak in Ta_2O_5 annealed to 800 º C, possibly due to crystallisation of coating

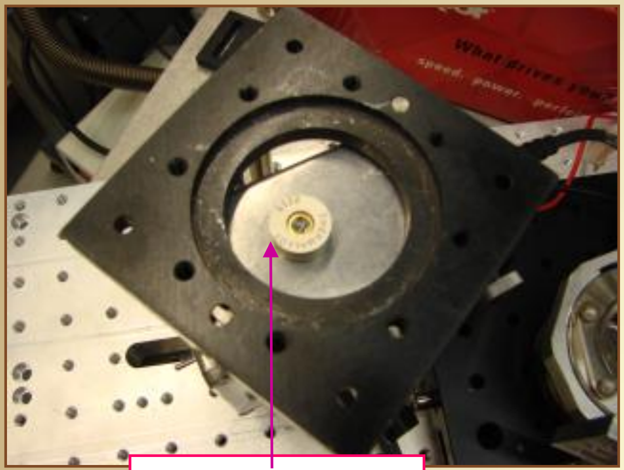
- Investigation of other possible high index coating materials
  - Preliminary studies of hafnia show no dissipation peak and dissipation at 20 K of ~ 3×10^{-4} c.f. ~ 8×10^{-4} for Ta_2O_5.



Comparison of two undoped Ta_2O_5 coatings (from CSIRO) annealed to 600 º C and 800º C

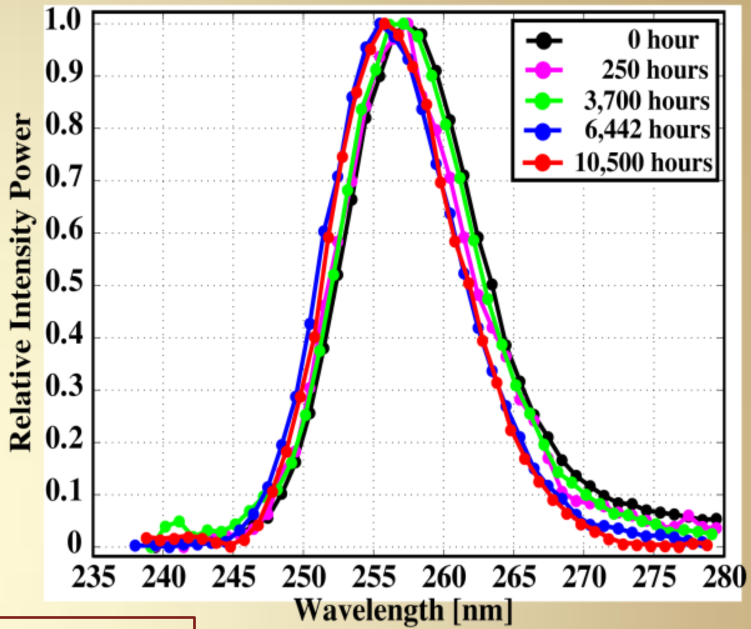
- Collaboration with INFN lab at Legnaro to study the loss of silica films (ion beam sputtered and thermal oxide) at ultra-cryogenic temperatures – may yield more information on loss mechanisms.

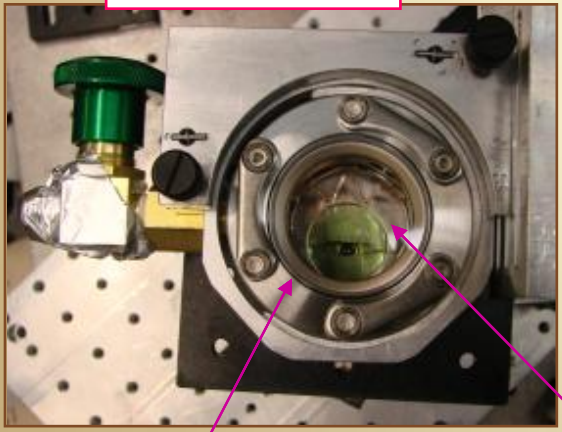
UV Irradiation of Coatings (Stanford)

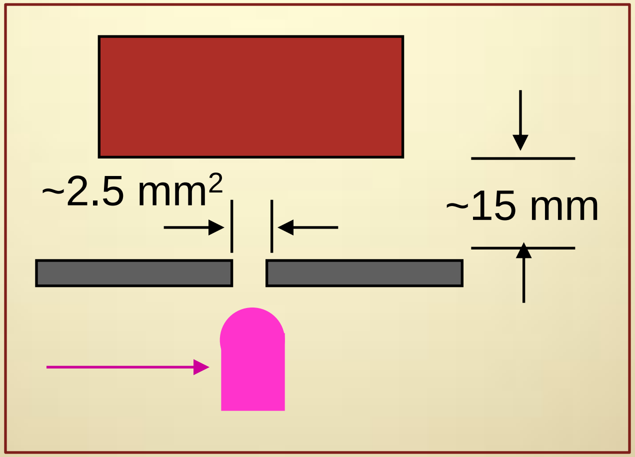


UV LED with a Ball Lens

Initial LIGO Ta2O5/SiO2 recipe coated by REO.





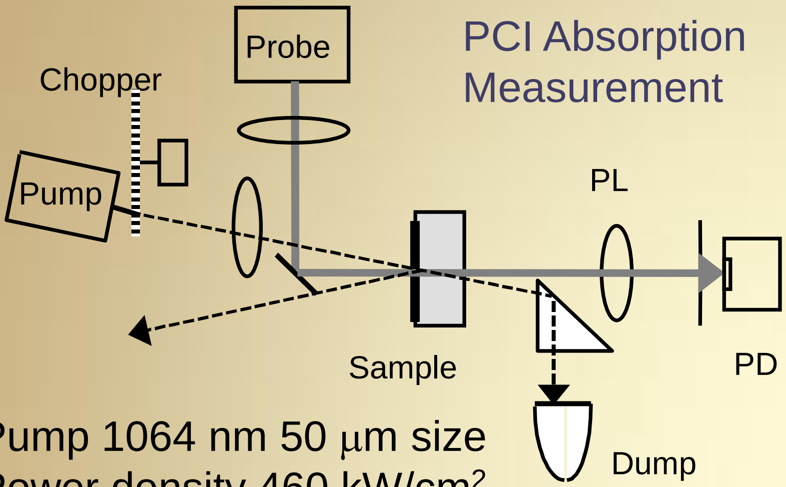


Irradiation by UV LED at 255 nm. Operated with average power 3.3 mW Irradiation intensity ~15 mW/cm^2 .Irradiation for 260 hours. Total UV energy deposition ~16 J/cm^2. (> 1J/cm^2 recommended by Dennis Ugolini)

Small aperture localizes irradiation

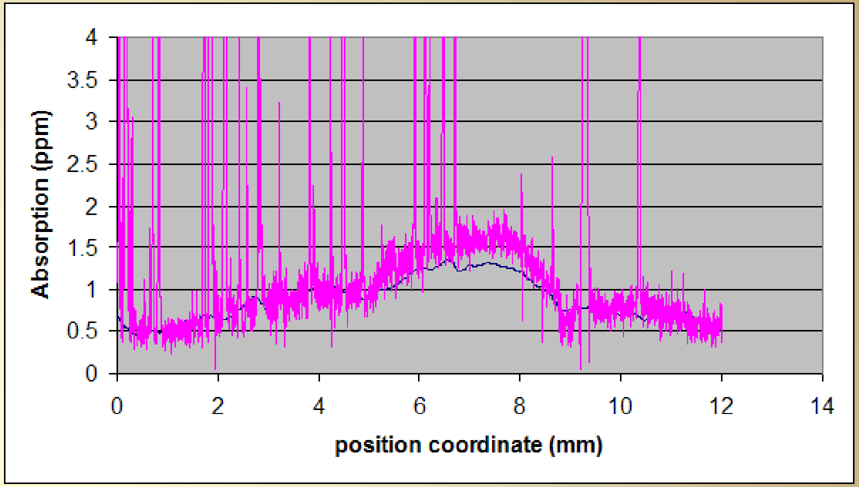
Fused silica window with 93% UV Transmission

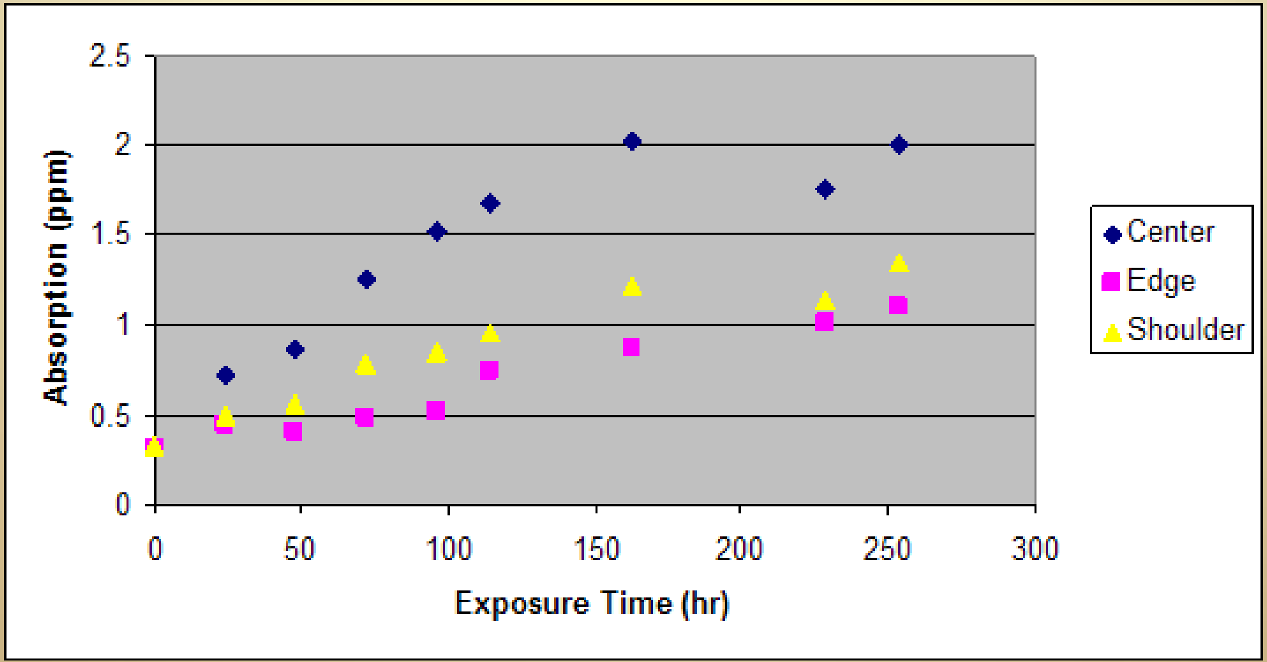
UV Effect Measurement (Stanford)



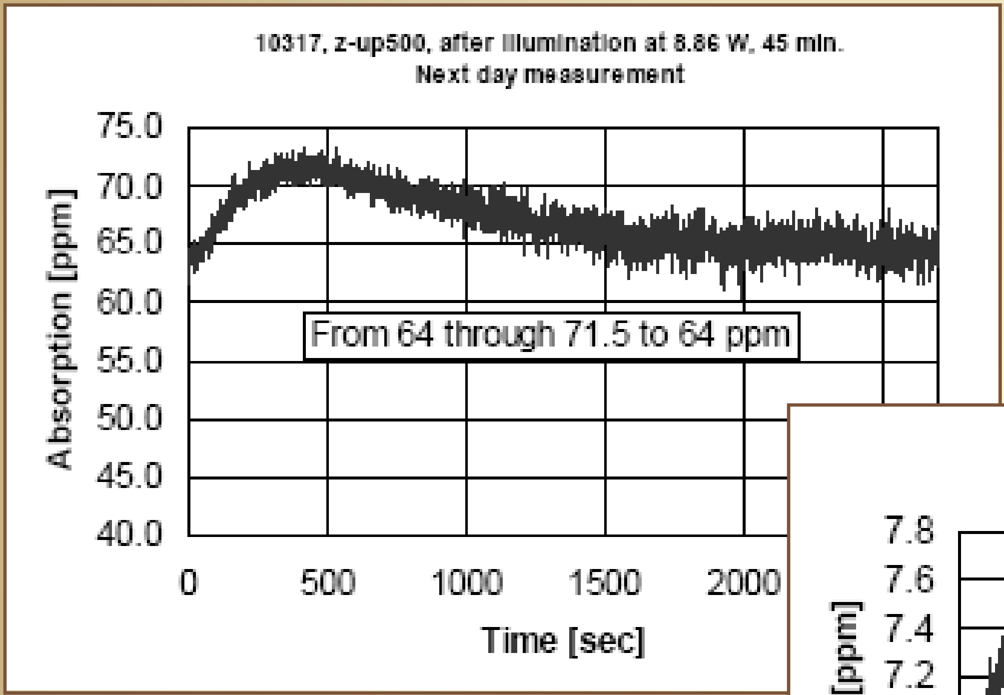
Pump 1064 nm 50 μm size
Power density 460 kW/cm^2

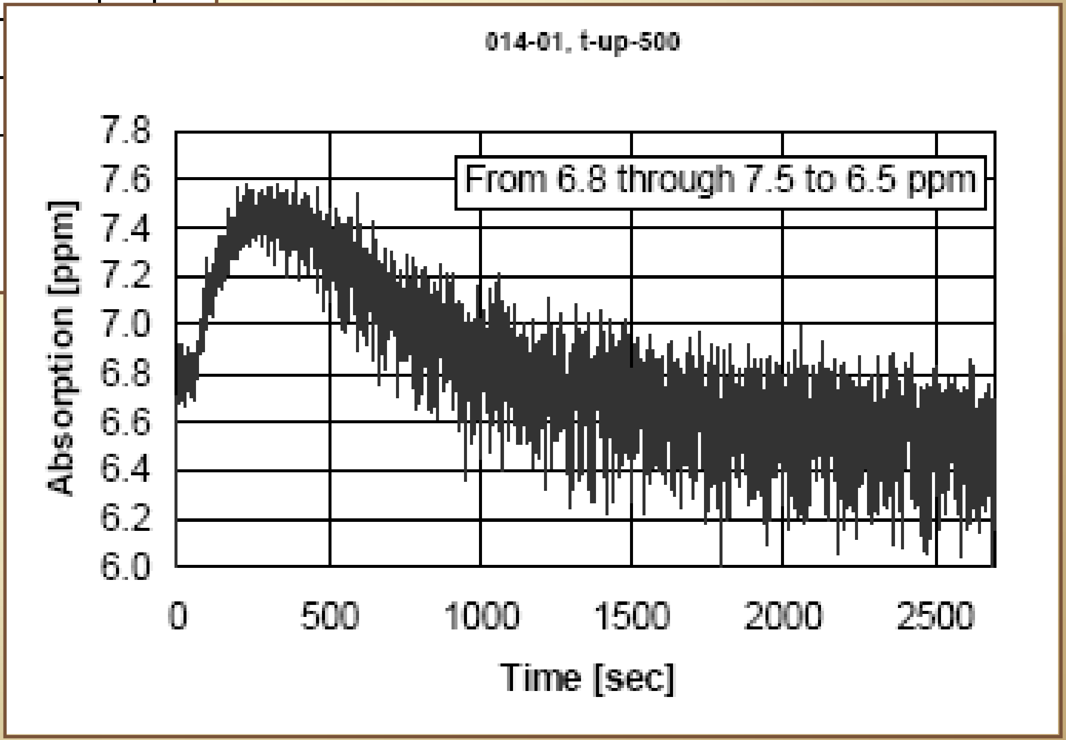
72 hour exposure data sample





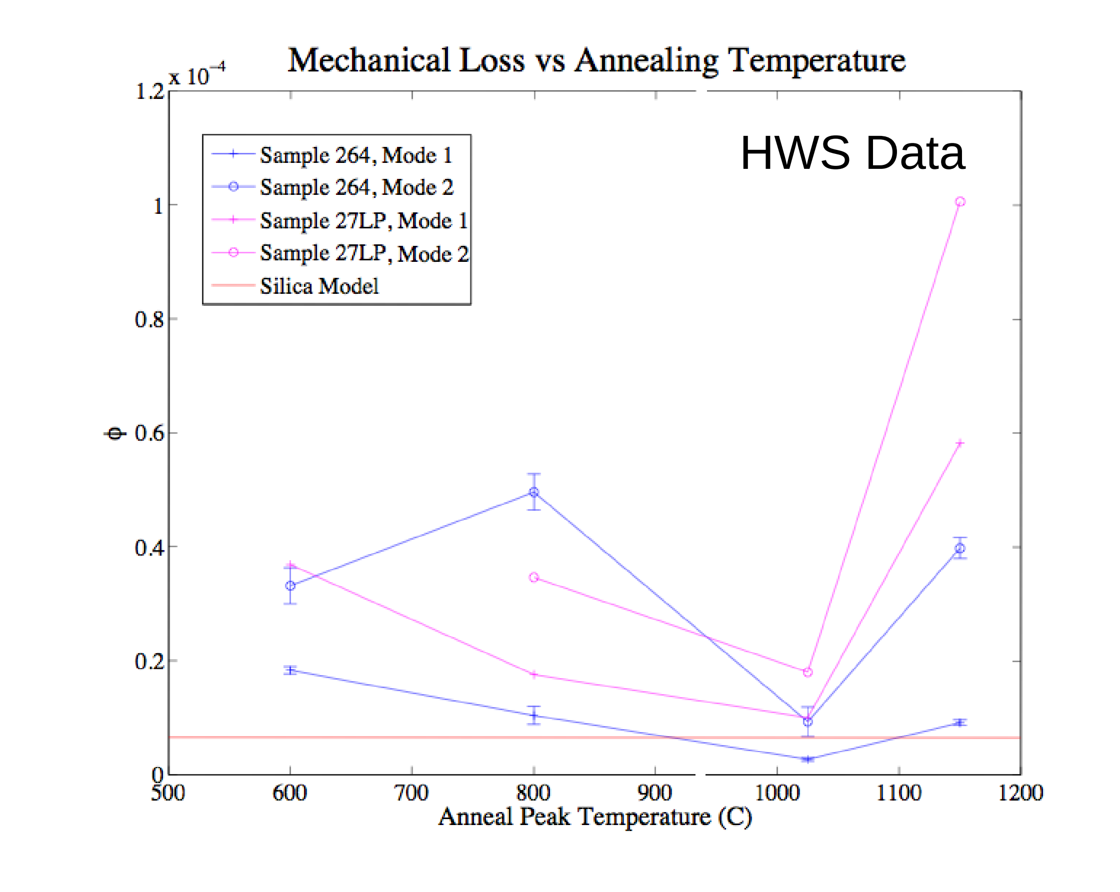
Hafnia Absorbtion is High (Stanford)





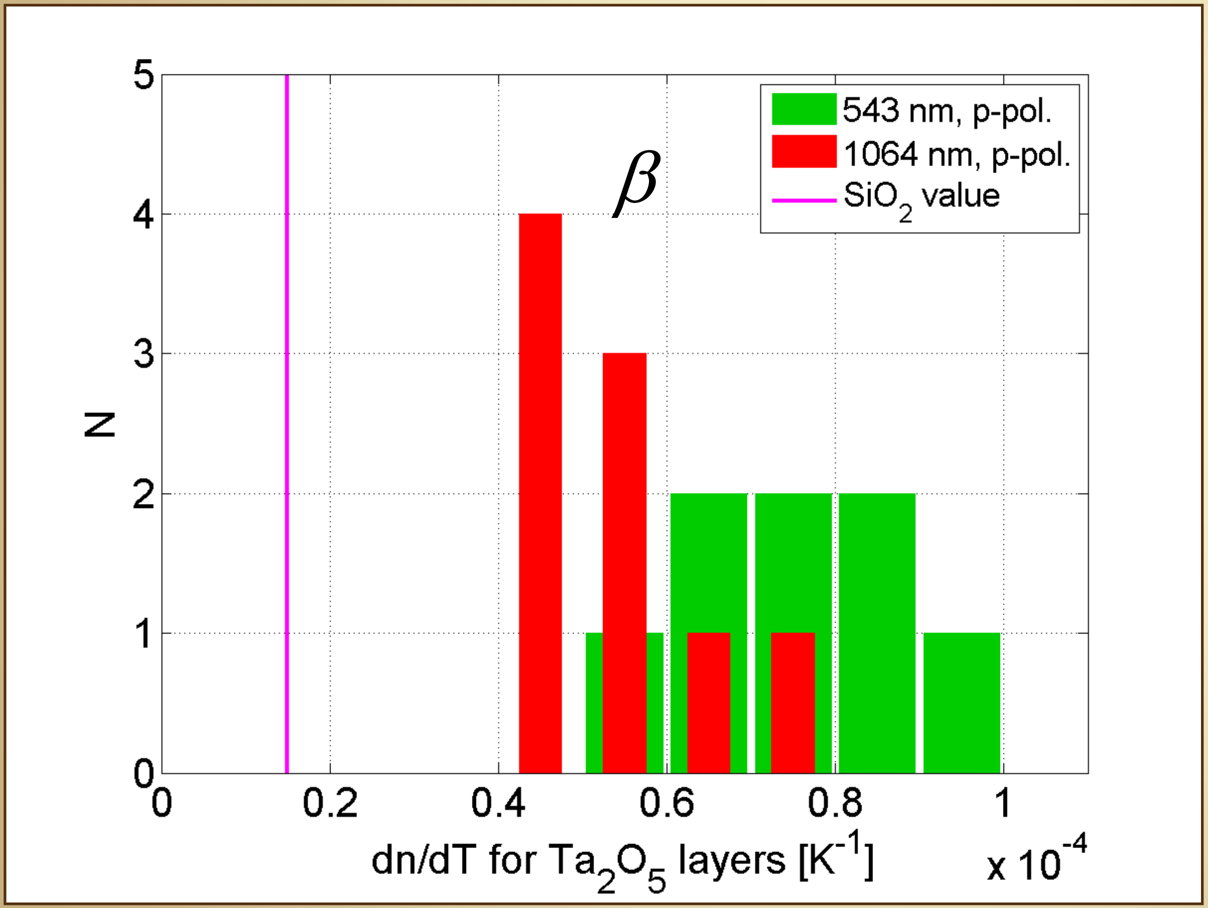
Mechanical Loss in Silica Thin Films
(HWS, Glasgow)

- Silica loss in bulk samples well characterized. Silica coating loss measurements reveal how coating structure affects loss.
- Silica loss crucial to fine tuning the optimized coating.
- Helps in defining expectation of theory models for coating loss.
- Coating loss in annealed silica coating matches loss model for bulk samples.



Above 1025 C, coating likely damaged by breakdown of adhesion to substrate.

Thermo-optic noise (ERAU and G. Ogin)



- ERAU (1064 nm):

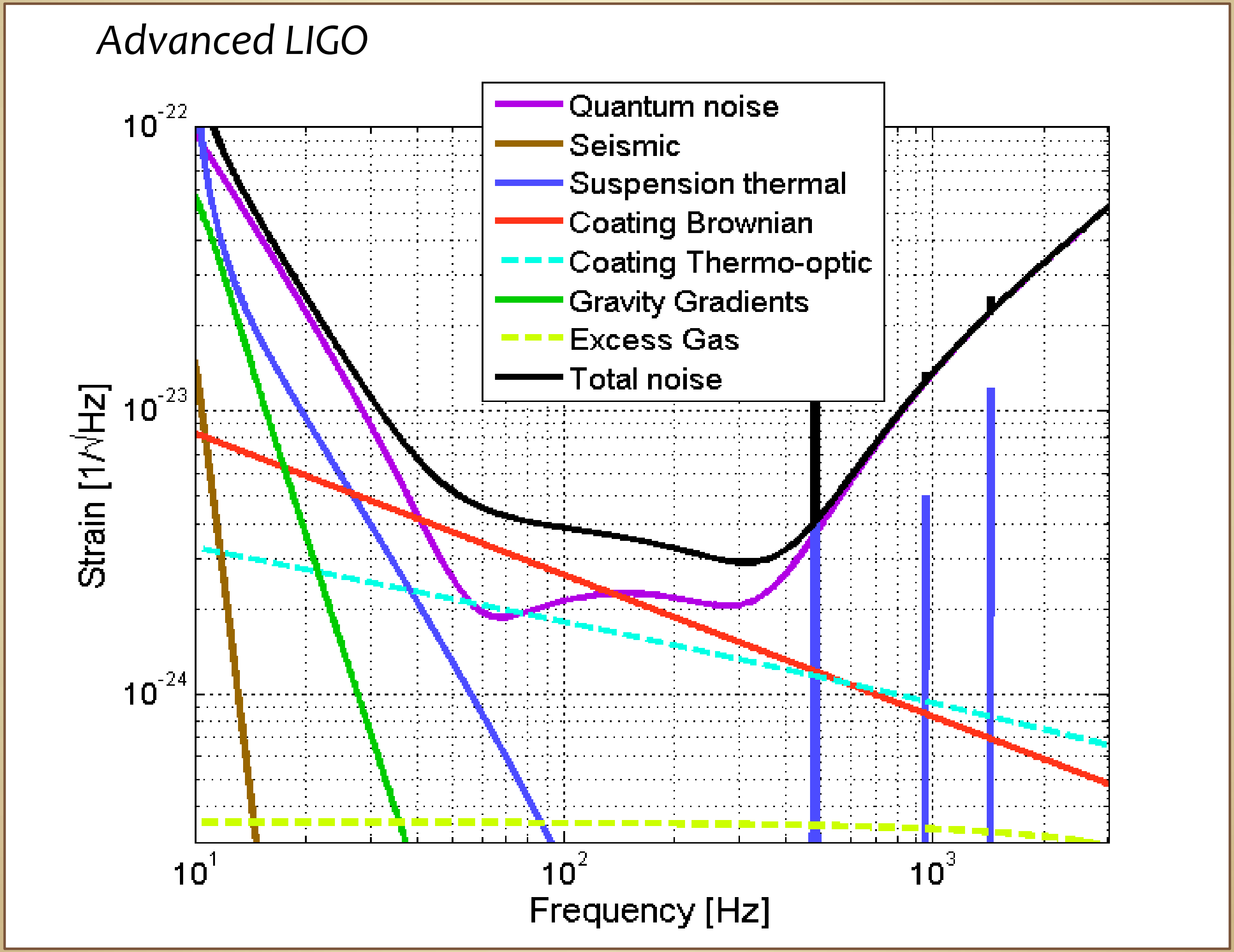
  $$\beta = (5.3 \pm 1) \times 10^{-6}$$

using

$$\alpha = 3.6 \times 10^{-6}$$

- Ellipsometry
  - SOPRA data being analyzed by Greg Ogin.
- Need to confirm prev. meas. of α.

Thermo-optic Noise in AdLIGO



Coating Related Work at the University of Sannio (Italy)

The Waves Group

Università degli Studi del Sannio

Working group: I.M. Pinto (PI), G. Castaldi, V. Galdi, V. Pierro, M. Principe.

- Braginsky's (first) formula for coating thermorefractive noise generalized to non - QWL coatings; result reproduced by in-dependent calculation [I.M. Pinto et al., LIGO T070159-00-Z].

- Mirrors w. optimized coatings (plain Tantala) tested success-fully at TNI in december 2007 , collaboration with Caltech TNI, [Akira's talk, Coating WS, this Meeting].

- Porting of coating optimization code to BENCH (january 2008), collaboration with MIT OWG and Caltech TNI [Clare Bayley's talk, Coating WS, this Meeting];

- TiO_2 doped Tantala based minimum noise mirror prototype for TNI designed (thermoelastic and thermorefractive noises in-cluded); funding requested to INFN gr. V (february 2008);

Coating Related Work at the University of Sannio (Italy)

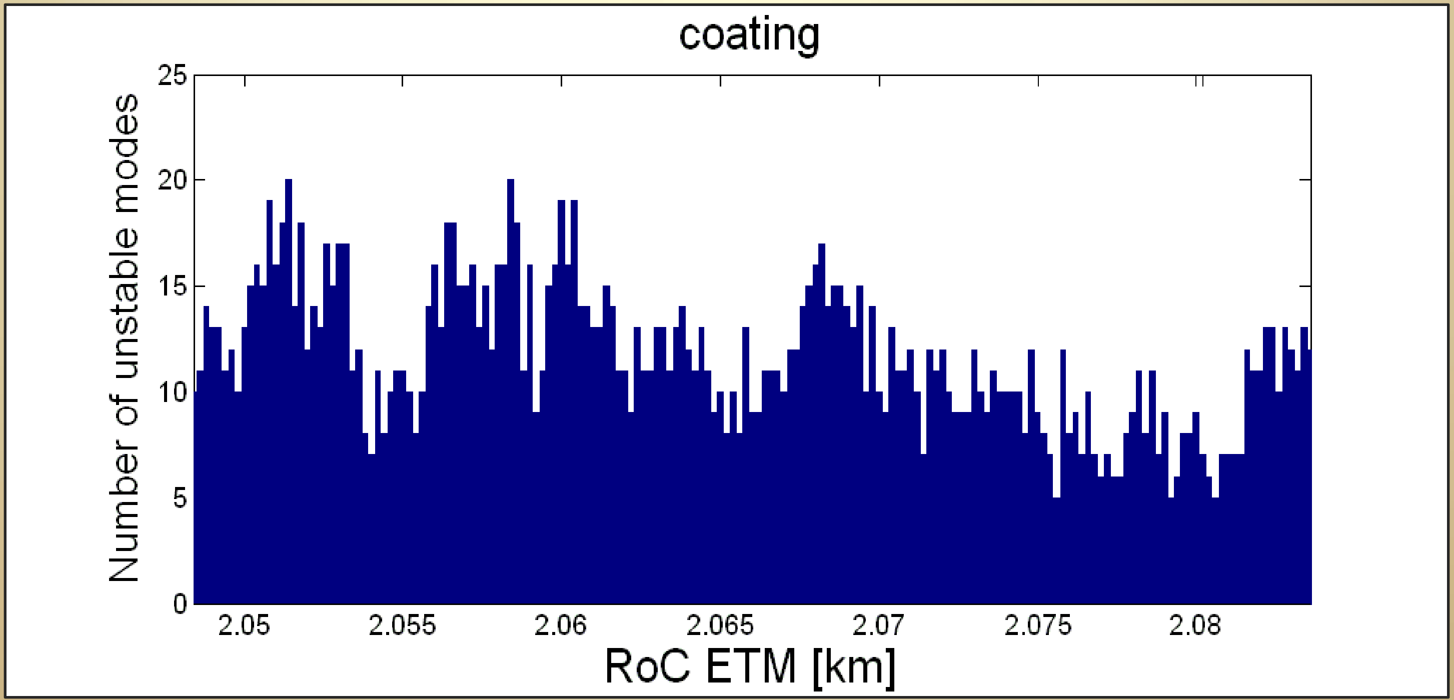
- Preliminary results on optimized mirror reflectance at different out-of-band laser frequencies [Pinto's talk, Coating WS, this Meeting];

- Preliminary investigation of m-dielectric ($m \geq 3$), non-uniform and band-gap engineered (regular non-periodic) coatings start-ed [Pinto's talk, Coating WS, this Meeting];

- Full paper on noise reduction margins from beam profile opt-imization (LIGO P-07006-01-Z) published [V. Pierro et al., Phys. Rev. D76 (2007) 122003];

- Preliminary results on constructive approaches to beam optimiz-ation beyond the Mexican-Hat / Mesa-beam including stability constraints (three MA theses, 2007-2008).

Gold coatings for taming parametric instabilities (UWA)



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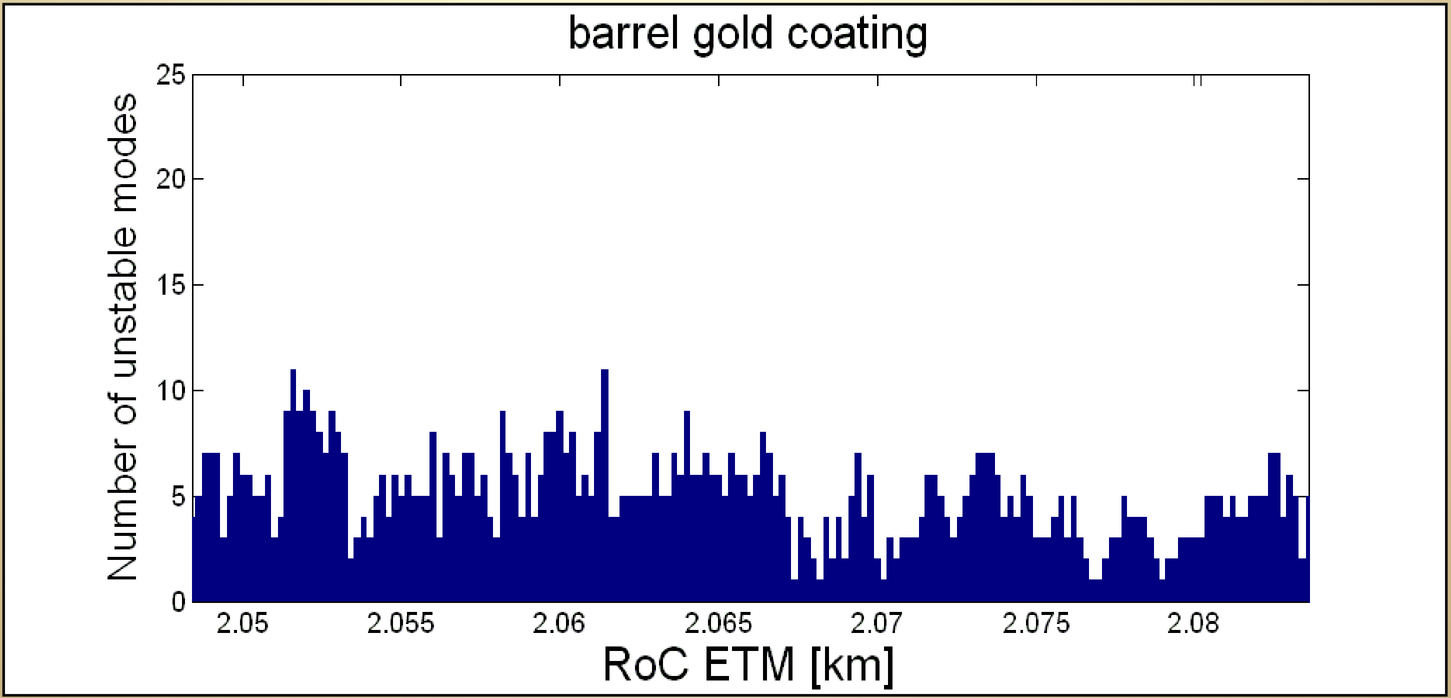

Progress in Materials Simulations (Florida)

- Quantum mechanical calculations of Ta_2O_5

    Young's modulus, Poisson ratio of ground state structure vs. high-T structure

- Characterization of energy barriers in amorphous silica relating barrier distribution to thermal noise

    Bottle neck: fast searching algorithm is needed to locate barriers effectively.

Summary

- Coating improvements are needed
  - Coatings limit: AdLIGO, AdLIGO upgrades and probably 3rd generation ground-based interferometers .
  - Coating thermal noise is now limiting other fields too.
- Overall change in emphasis is in progress
  - From low-risk development back to higher risk/gain research
  - More than one path likely – which ones and how many is a subject of discussion
  - The need to make the right decisions about future directions is an important reason for the coating workshop starting later today.