Progress in LIGO Coating Development

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Theory of Coating Thermal Noise

Levin's Theorem (1997)

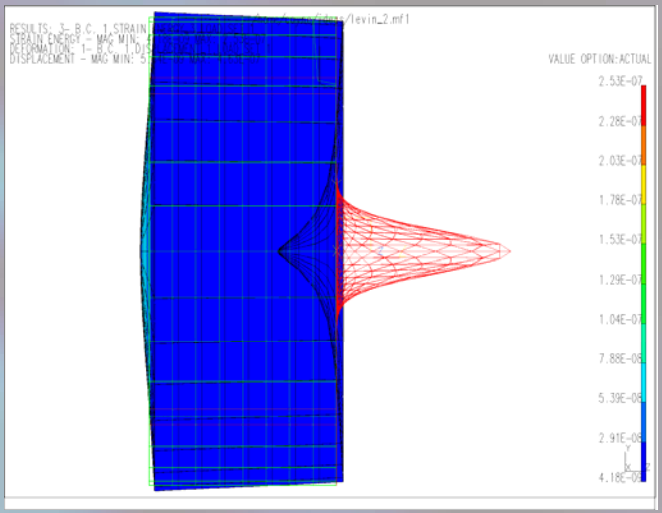
- Direct application of Fluct. Diss. Them.
- Crucial for inhomogeneous loss – coatings, magnets, attachments, etc.
- Replaced modal-based calculation

$$S_x(f) = 2\,k_B T / (\pi^2\ f^2)\ W_{diss}/F_0^2$$

Brownian Thermal Noise (2000)

- Key Parameters – Mechanical loss ϕ, Young's Modulus Y, beam spot size and shape

$$\phi\ = 1/\sqrt{\pi}\ (d/w)\ (Y_{coat}/Y_{sub}\ \phi_{coat\,\|} + Y_{sub}/Y_{coat}\ \phi_{coat\perp})$$



Other Thermal Noises

- Thermo-optic
  - Thermorefractive (2000)
  - Thermoelastic (2004)
  - See A. Gretarsson talk

Yu. Levin, *Physical Review D* 57 (1997) 659.
M. M. Fejer, *et al. Physical Review D* 70 (2004) 082003.
V. Braginsky, *et al. Physics Letters A* (2000) 303.

Brief History of Coating Mechanical Loss Measuring I

Stage 0 – Syracuse, Glasgow, Stanford

- 1999
- Q of two disks, single mode
- Determine whether mechanical loss was significant
- REO tantala/silica coating
- YES!

Stage 1 – MIT, Syracuse, Glasgow, Stanford

- 2001
- Q's at multiple frequencies
- Determine source of loss
  - Rubbing friction between layers
  - Rubbing friction between coating / substrate
  - Internal friction in silica or tantala
- Internal friction in tantala

Coating Mechanical Loss

Coating	Loss Angle (ϕ)
30 layer $\lambda/4$ SiO_2 – $\lambda/4$ Ta_2O_5	$2.7\ 10^{-4}$
60 layer $\lambda/8$ SiO_2 – $\lambda/8$ Ta_2O_5	$2.7\ 10^{-4}$
2 layer $\lambda/4$ SiO_2 – $\lambda/4$ Ta_2O_5	$2.7\ 10^{-4}$
30 layer $\lambda/8$ SiO_2 – $3\lambda/8$ Ta_2O_5	$3.8\ 10^{-4}$
30 layer $3\lambda/8$ SiO_2 – $\lambda/8$ Ta_2O_5	$1.7\ 10^{-4}$

G. M. Harry, *et al*. *Classical and Quantum Gravity* 19 (2002) 897.

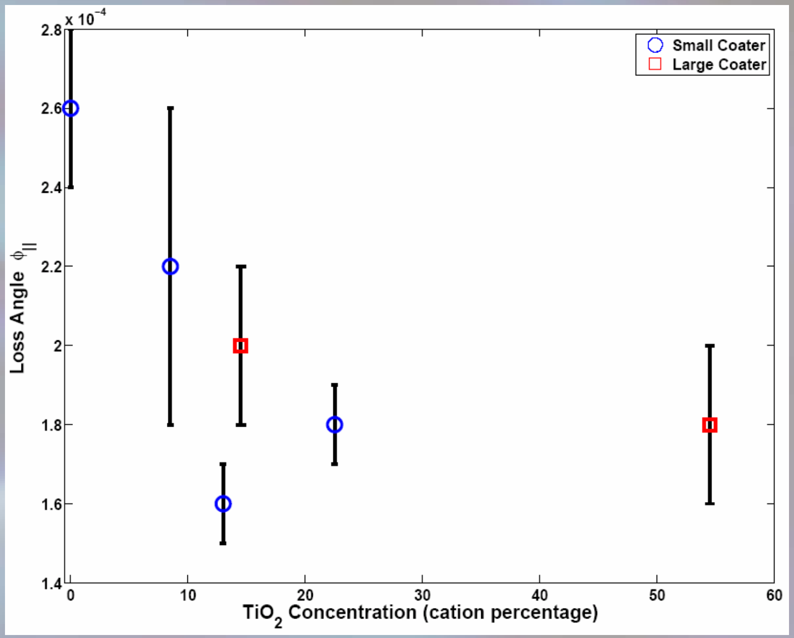
D. R. M. Crooks, *et al*. *Classical and Quantum Gravity* 19 (2002) 883.

Brief History of Coating Mechanical Loss Measuring II

Stage 2 – LIGO Coating Group

- **Improving mechanical loss**
- **Two vendors – LMA and CSIRO**
- **Many materials and techniques**
- **Titania doped into Tantala (2002)**
  - Improves mechanical loss
  - Developed at LMA
  - *Y* mostly unchanged
  - *n* increases with [Ti], less thickness
  - Absorption is excellent
  - Duplicated at CSIRO
- **Silica doped into Titania (2005)**
  - Mechanical loss better Ta/Si
  - Developed at CSIRO
  - High index, good *Y* match to silica, absorption good
  - Not fully optimized yet

ϕ vs $[TiO_2]$ in Ti-Ta/Si



S. D. Penn, *et al. Classical and Quantum Gravity* 20 (2003) 2917.

R. P. Netterfield, *et al. Technical Digest of Optical Interference Coatings* (Optical Society of America, 2007).

A. M. Gretarsson *et al. ibid.*

Other Coating Improvements Tried

Different Materials (2000-2008)

- **Niobia as high index material**
  - Similar to tantala
- **Alumina as low index material**
  - Similar to silica (good)
  - Young's modulus unmeasured
- **Hafnia as high index material**
  - 1st attempt did not adhere well
  - See E. Chalkley talk
- **Lutetium doped tantala**
  - No improvement in ϕ
  - Poor (10 ppm) absorption
- **Silica doped tantala**
  - No improvement in ϕ
- **Cobalt doped tantala**
  - Done in Perugia
  - Possible improvement in ϕ
  - High (1000s of ppm) absorption

Different Techniques (2004-2007)

- **Xenon (instead of Argon) as sputtering ion**
  - Mechanical loss got worse
- **Poor stoichiometry**
  - Tried in various annealing states
  - All gave worse ϕ
- **Secondary ion-beam bombardment with oxygen**
  - Different masks showed different ϕ's
  - No improvement
- **Annealing in different ways**
  - Includes correlation with stress
  - Minimal effect on ϕ
- **Effects of substrate polish**
  - No effect seen

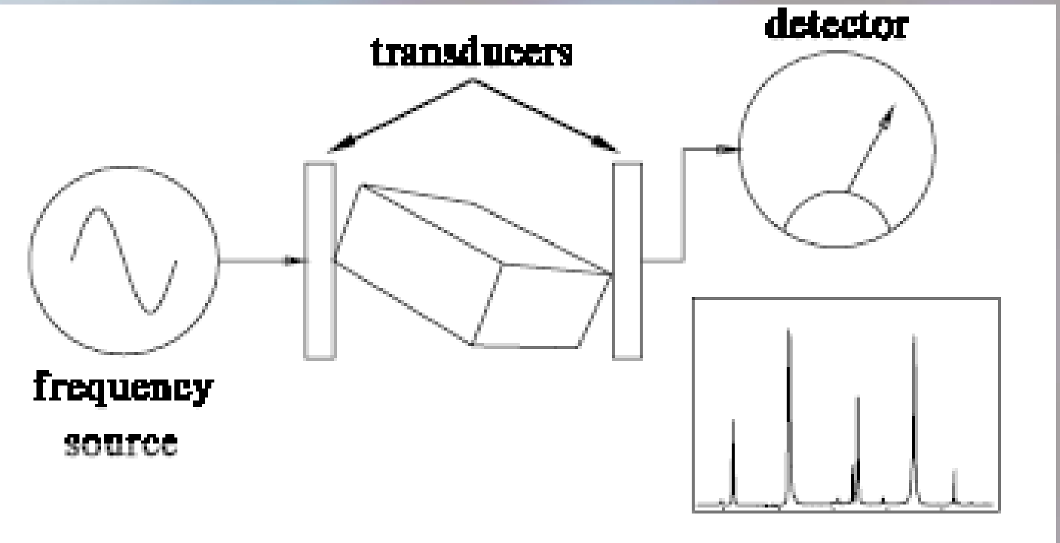
Other Coating Properties

Titania doped Tantala

- **Absorption (< 0.3 ppm)**
  - -Crucial to reduce thermal lensing
  - -See A. Markosyan talk
- **Thermorefraction (significant)**
  - - See A. Gretarsson talk
- **Large area coating**
  - - 34 cm diameter mirrors
  - - Transmission holes due to bubbles
- **Index (As high as 2.18: Ta is 2.07)**
  - - Reduces needed thickness
- **Scatter (preliminary)**
  - - See J. Smith, I. Bilenko, L. Zhang talks
- **High power handling (preliminary)**
  - - See D. Tanner talk
- **Charging (possible problems)**
  - - See K. X. Sun talk

Young's Modulus

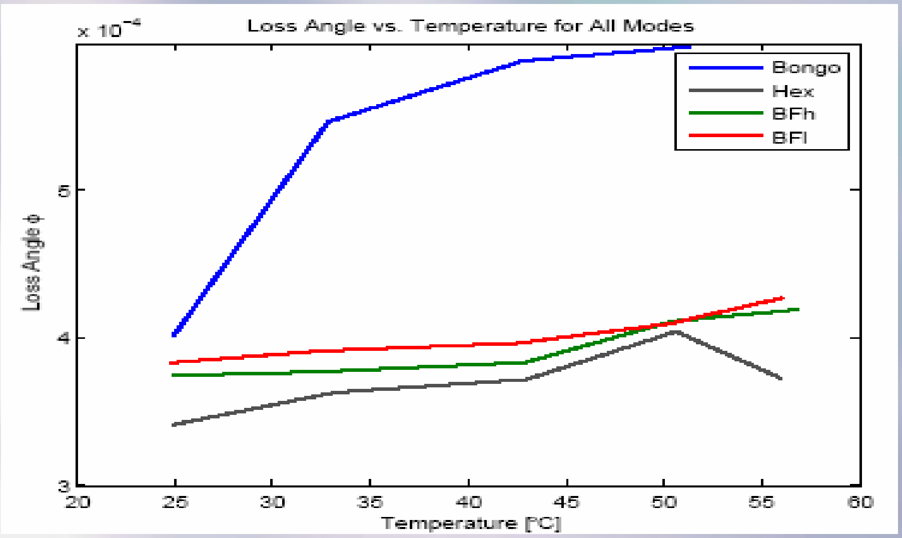
- **As important as ϕ**
- **Measured at Stanford with acoustic reflection technique**
  - - Ta, Al
- **New collaborator Josh Gladden**
  - - University of Mississippi
  - - Measurement of changed transfer function
  - - Resonant ultrasound spectroscopy



Resonant Ultrasound Spectroscopy Apparatus

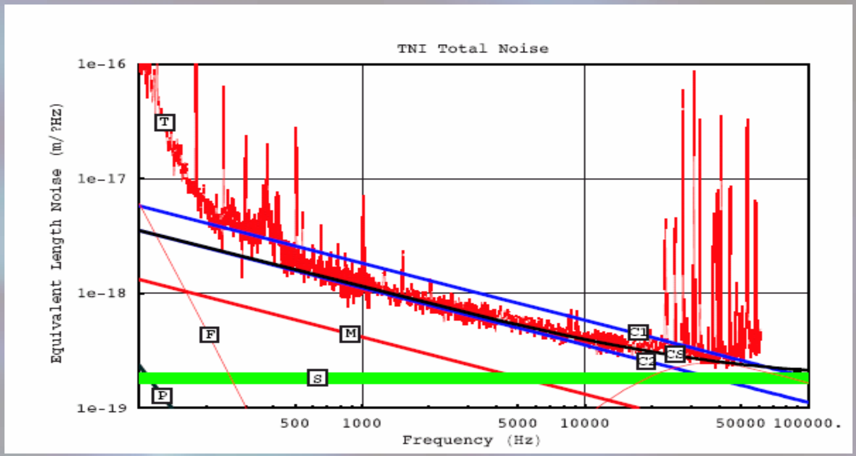
Highlights of Recent LIGO Coating Research

- **Beam Shaping (2000)**
  - -See talk by V. Galdi
- **Thermal Noise Interferometer**
  - - Direct measurement of thermal noise
    - -2003 tantala/silica
    - -2006 titania-tantala/silica
    - -2007 optimized tantala/silica
  - - See A. Villar talk
- **Optimization of layers (2005)**
  - -See I. Pinto, A. Villar talks



Increased Temperature on Tantala/Silica

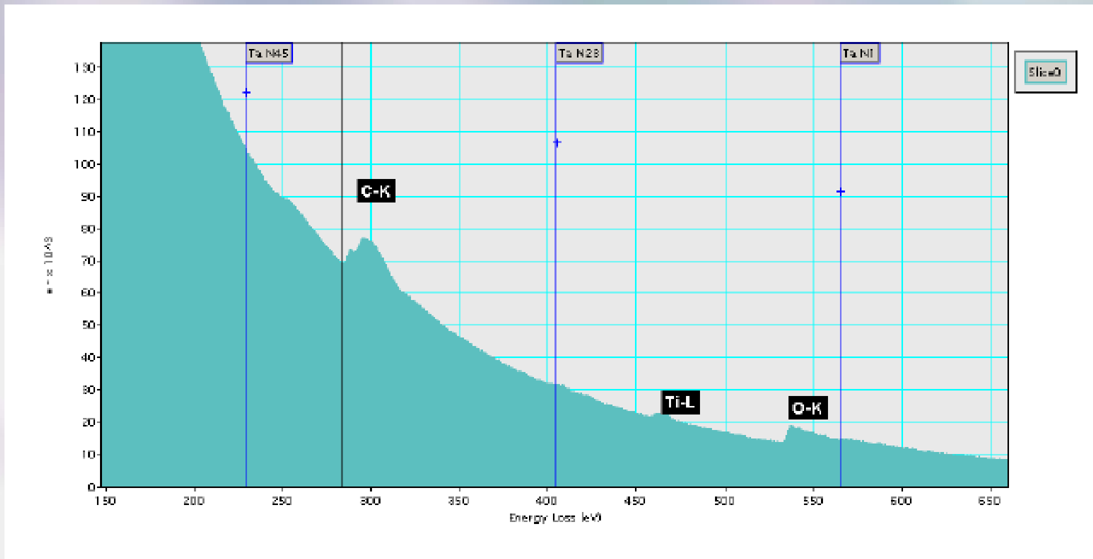
TNI Titania-Tantala/Silica Thermal Noise



- **Modeling (2005)**
  - -See H. Cheng talk
- **Loss mechanisms (2006)**
  - -First appreciated in silica
  - -Now getting results with tantala and titania-tantala
  - -See I. Martin talk
- **Increased temperature (2006)**
  - -Advanced LIGO will be ~ 40 C
  - -Mechanical loss mostly unchanged in tantala/silica
  - -Work needed on titania-tantala and others

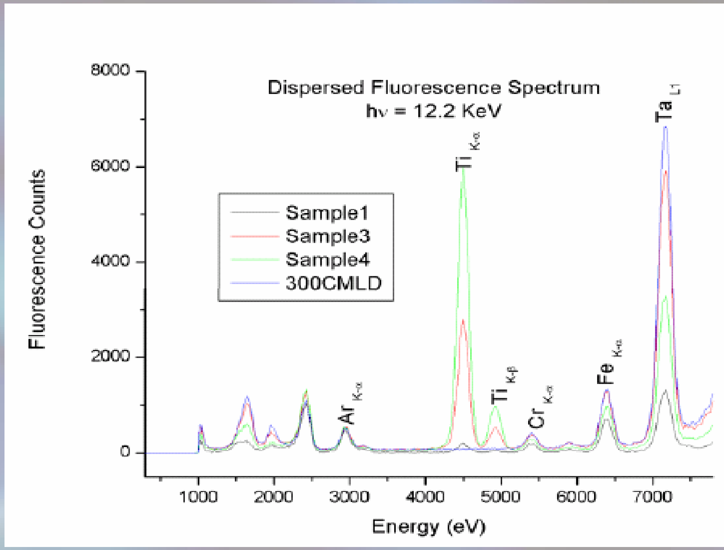
Material Analysis

- **X-ray techniques (2005)**
  - Southern University
  - Fluorescence
  - X-ray absorption near edge structure (xanes)
- **Electron energy loss spectroscopy (2005)**
  - Glasgow
- **Titania concentrations**
- **Identify contaminants (Ce, Ar, Cr, Fe)**



Electron energy loss spectroscopy

X-ray fluorescence of Ti-Ta/Si coating

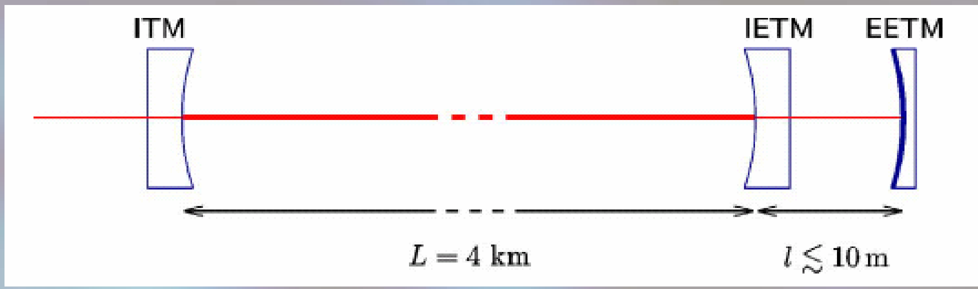


Future work

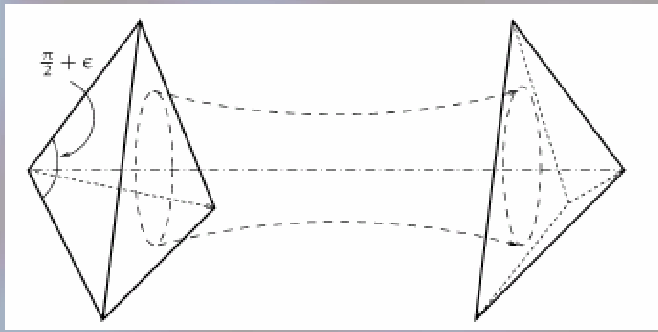
- **Silica**
  - Measure bond angle distribution
- **Correlate with properties**
  - Absorption
  - Scatter
  - Mechanical loss, *dn/dT*, others?
- **Look at structure issues**
  - Mechanical properties (Y, ϕ)
  - Stability - annealing

Next Generation Ideas

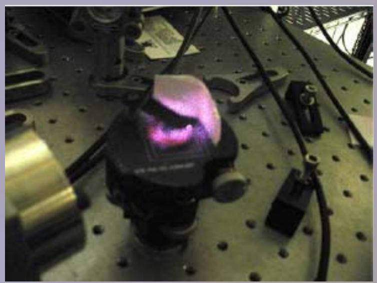
- **New coating materials**
  - -Need modeling and experimental work
  - -See E. Chalkley, I. Martin, S. Penn, F. Travasso talks
- **Short cavities as reflectors**
  - -Significant added complexity
- **Corner reflectors**
  - -Practical concerns (scatter, finesse, angular stability)
  - -Experiment at Australian National University
- **Lower temperatures**
  - -See K. Yamamoto talk
- **New substrate materials**
  - -Sapphire, silicon
  - -Will require new coatings
- **Change in beam shapes**
  - -Mesa beams – better averaging of fluctuations
  - -See V. Galdi, J. Miller talks



Cavity as End Mirror



Corner Reflector



ANU Brewster Angle Experiment

Next Generation Materials Research

- **Fully explore silica**
  - -Dependence on thickness
  - -Effects of annealing
  - -Correlate Q measuring, modelling, material analysis
- **Materials and dopants**
  - -Titania-Tantala-Silica
  - -More with Silica-Titania
  - -Alumina, Beryllia as a dopants
  - -Small atom (N, B) dopants
  - -Fluorides, selenides, others?

Silica Research

- **Processes**
  - -Neon as bombardment ion
  - -More on secondary ion beam bombardment with oxygen
  - -New coating techniques, magnetron, etc.
- **Changed temperatures**
  - -Fully explore loss mechanisms
  - -Low temperature – loss peak
  - -High temperature – heating from laser

Cooled Mirrors

Conclusions

- **Good handle on theory of coating thermal noise**
- **Empirical understanding of mechanical loss in coatings**
  - » Internal friction of materials, independent of layers
- **Titania doped into tantala reduces mechanical loss**
  - » Other properties unchanged or improved as well
- **Other materials/processes tried with limited success**
  - » Silica doped into titania improvement over tantala
- **Progress on understanding coating mechanical loss**
  - » Loss peak indentified at low frequency
  - » Some materials studies and modeling
- **Ideas for next generation coating improvements**
  - » Many a challenge for interferometry more than materials
- **Plan for research on next generation coating materials**