LIGO Coating Project

Gregory Harry
LIGO/MIT
- On Behalf of the Coating Working Group -

LIGO / Virgo Thermal Noise Workshop
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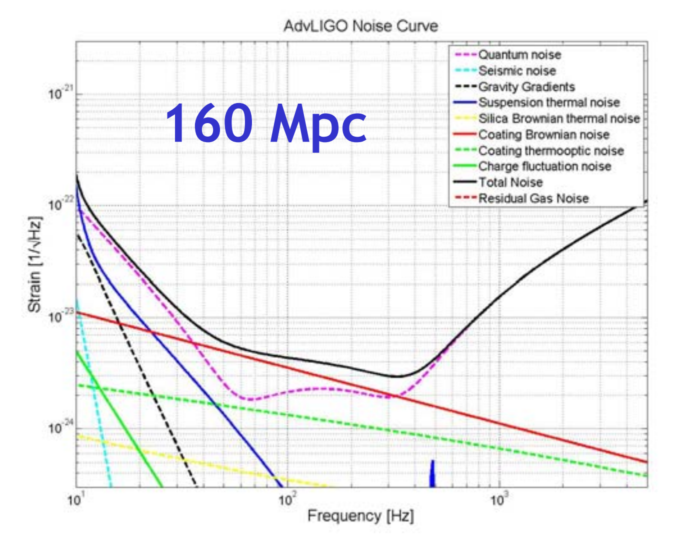
LIGO-G060504-00-R

Advanced LIGO Sensitivity

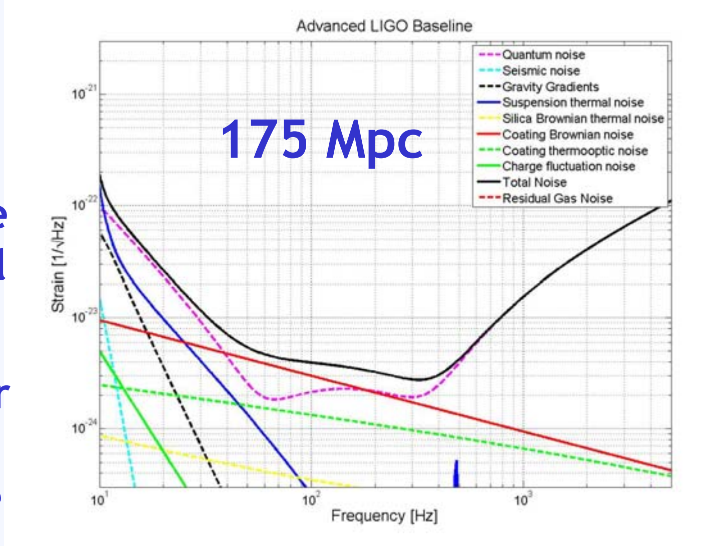


Initial LIGO Coating

Need a lower thermal noise coating

Not much in literature on coating mechanical loss

Current state is better but improvement is possible and desirable

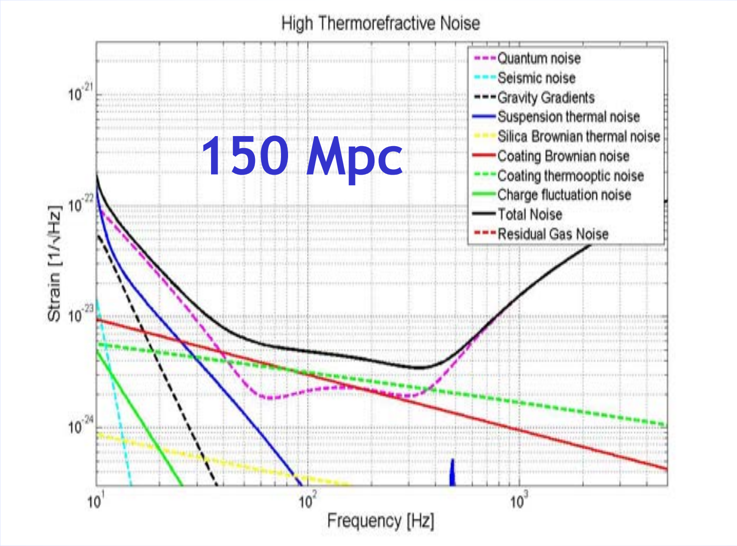


Advanced LIGO Baseline

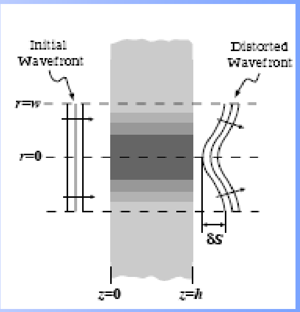
Best number in literature indicates very high thermorefractive noise from tantala: $\beta = 1.2\ 10^{-4}$

Not seen in TNI

Almost certainly wrong, but what is the right value?



High Thermorefractive Noise

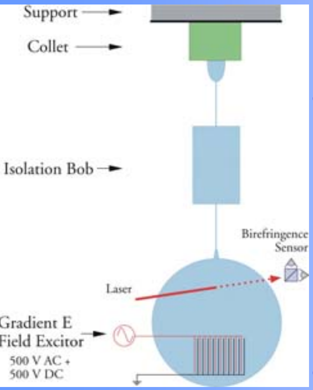


Coating optical absorption also crucial

Thermal lensing a large effect in Adv LIGO

Need absorption < 0.5 ppm

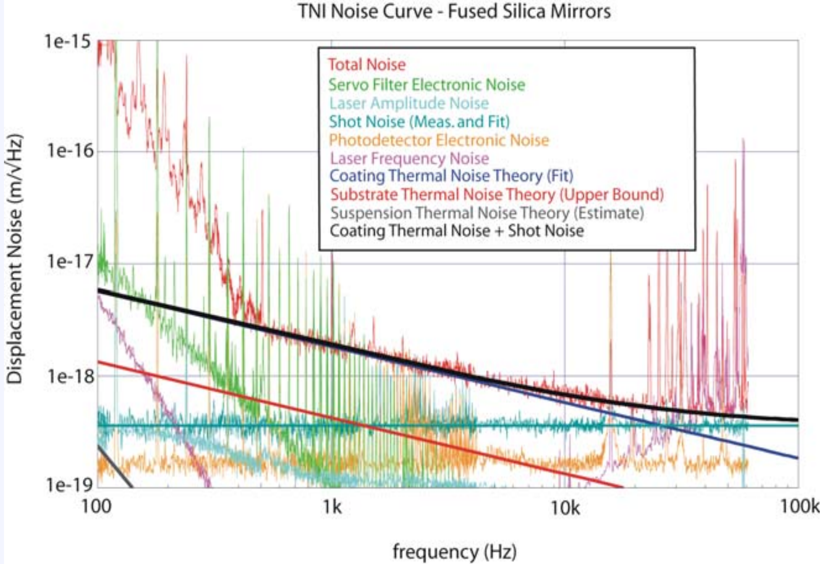
Measurement Techniques



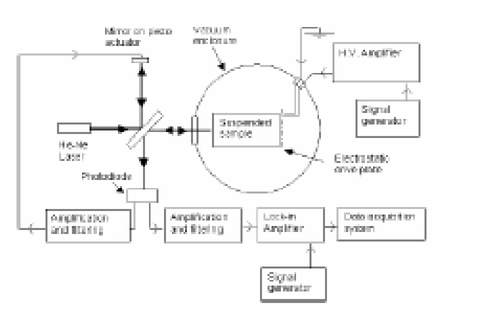
Thin Sample

Coating Thermal Noise

- Q measuring on coated disks
  - Can test many candidate coatings
    - Thin - low freq - MIT, HWS, ERAU
    - Thick - high freq - Glasgow
    - Cantilevers - very low freq - LMA, Glasgow
- Direct thermal noise measurements at the TNI (see talk by E Black)

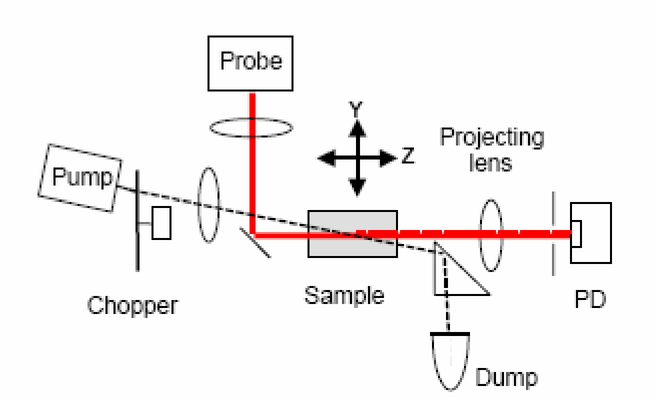


TNI Result of Tantala/Silica Coating



Thick Sample

PCPI Setup



Optical Performance

- Absorption measurements using photothermal common path interferometry (Stanford, LMA)
- Developments with initial LIGO optics
  - High Scatter
  - High Absorption

Initial LIGO Tantala/Silica Coating

Coating Mechanical Loss

Layers	Materials	Loss Angle
30	[a] $\lambda/4\ SiO_2 - \lambda/4\ Ta_2O_5$	$2.7\ 10^{-4}$
60	[a] $\lambda/8\ SiO_2 - \lambda/8\ Ta_2O_5$	$2.7\ 10^{-4}$
2	[a] $\lambda/4\ SiO_2 - \lambda/4\ Ta_2O_5$	$2.7\ 10^{-4}$
30	[a] $\lambda/8\ SiO_2 - 3\lambda/8\ Ta_2O_5$	$3.8\ 10^{-4}$
30	[a] $3\lambda/8\ SiO_2 - \lambda/8\ Ta_2O_5$	$1.7\ 10^{-4}$
30	[b] $\lambda/4\ SiO_2 - \lambda/4\ Ta_2O_5$	$3.1\ 10^{-4}$
30	[c] $\lambda/4\ SiO_2 - \lambda/4\ Ta_2O_5$	$4.1\ 10^{-4}$
30	[d] $\lambda/4\ SiO_2 - \lambda/4\ Ta_2O_5$	$5.2\ 10^{-4}$

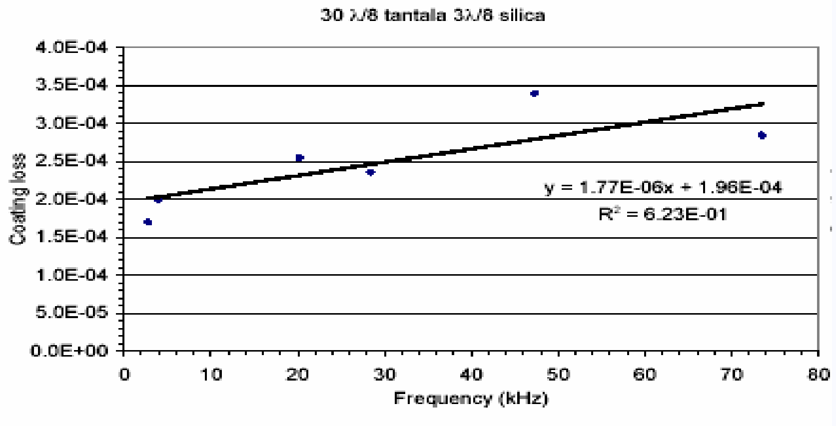
[a] LMA/Virgo, Lyon, France

[b] MLD Technologies, Mountain View, CA

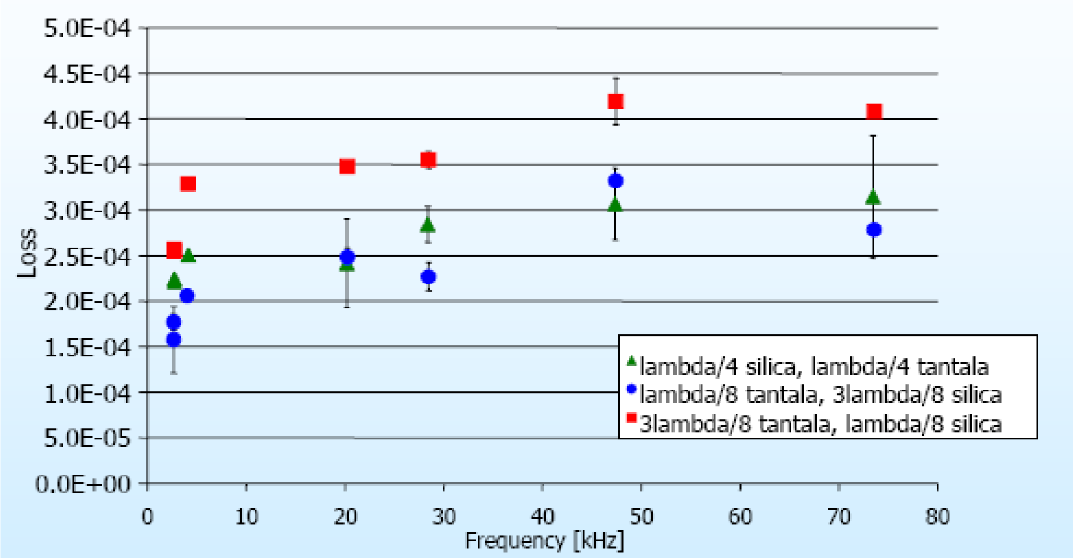
[c] CSIRO Telecommunications and Industrial Physics, Sydney, Australia

[d] Research-Electro Optics, Boulder, CO

Frequency Dependence of Tantala/Silica



Tantala/Silica Coating Mechanical Loss



No effect from from interfaces between layers nor substrate-coating

Internal friction of materials seems to dominate, with tantala having higher mechanical loss

Noticeable differences between vendors

ϕ - Ta_2O_5 $(3.8 \pm 0.2)\ 10^{-4} + f(1.1\pm0.5)10^{-9}$

ϕ - SiO_2 $(1.0\pm 0.2)\ 10^{-4} + f(1.8\pm0.5)10^{-9}$

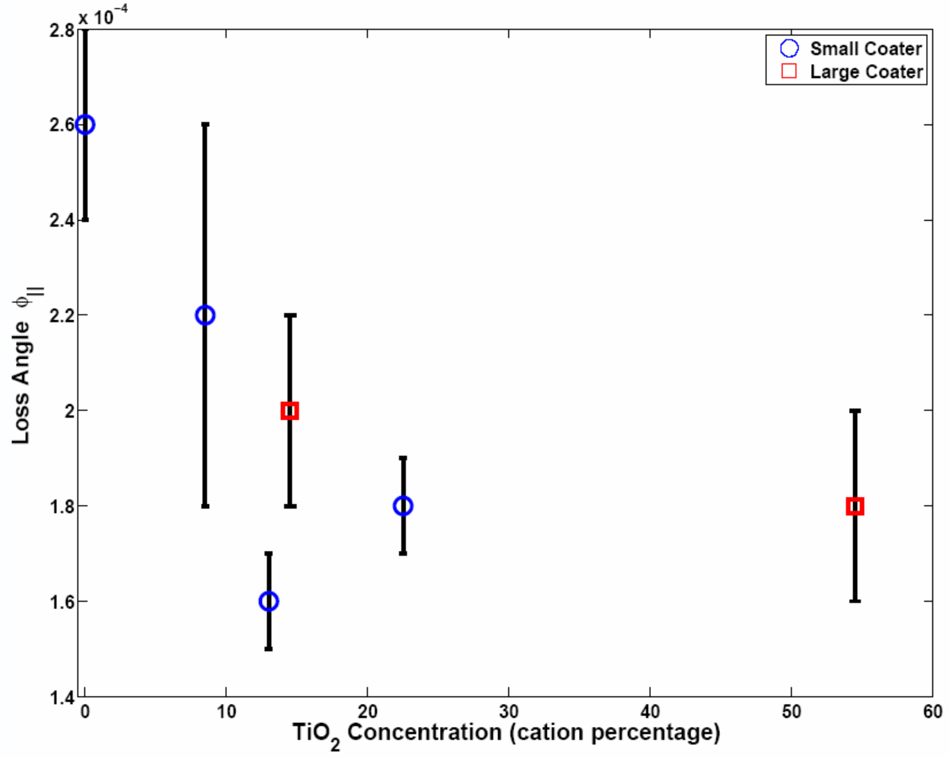
TiO_2-doped Ta_2O_5

Examined titania as a dopant into tantala to try to lower mechanical loss

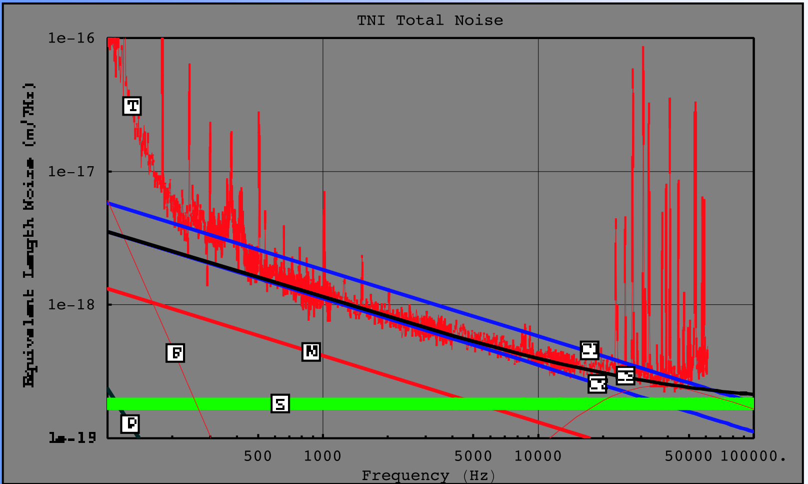
$$\phi_1 = (2.2\pm0.4)10^{-4} + f(1.2\pm0.6)\ 10^{-9}$$
$$\phi_2 = (1.6\pm0.1)10^{-4} + f(1.4\pm0.3)\ 10^{-9}$$
$$\phi_3 = (1.8\pm0.1)10^{-4} + f(-0.2\pm0.4)10^{-9}$$
$$\phi_4 = (1.8\pm0.2)10^{-4} + f(1.7\pm0.6)\ 10^{-9}$$
$$\phi_5 = (2.0\pm0.2)10^{-4} + f(0.1\pm0.4)\ 10^{-9}$$

G. M. Harry *et al*, Submitted to *Classical and Quantum Gravity*, gr-qc/0610004

Titania-doped Tantala/Silica Coatings



TNI Noise from Titania doped Tantala/Silica



Young's modulus and index of refraction nearly unchanged from undoped tantala

Optical absorption accceptable ≈ 0.5 ppm

Other Coatings Explored

Silica doped Titania/Silica
-Backup Coating-

	Ratio(Si:Ti)	Absorption	Index	Y
Run 1	50/50	1.5 ppm	2.15	87 GPa
Run 2	65/35	0.5 ppm	1.85	73 GPa

Thick Sample - Run 1
$\phi = (2.4 +/- 0.9)\ 10^{-4}$

Thin Sample
Run 1* $\phi = (3.1 +/- 0.2)\ 10^{-4}$
Run 2 $\phi = (1.9 +/- 0.3)\ 10^{-4}$

- Low Young's Modulus
- Low Index (Thicker Coating)
- Good Mechanical Loss
- Good Optical Absorption

Less Successful Coating Attempts

Niobia/Silica - high ϕ
Hafnia/Silica - poor adhesion
Alumina/Silica - thick coating
Dual ion beam (oxygen) - interesting, shows differences but not improvement
Oxygen poor - high ϕ, waiting on annealing, high absorption
Xenon ion beam - increased ϕ
Lutetium doped Tantala/Silica - high ϕ
Differing annealings - inconclusive, no major improvements, absorption issues
Effect of substrate polishing - no effect on mechanical loss

Most of these do not have Young's modulus measurements or optical absorption

New Coating Materials

Ozone annealing - improve stoichiometry

Helium ion beam - xenon made things worse

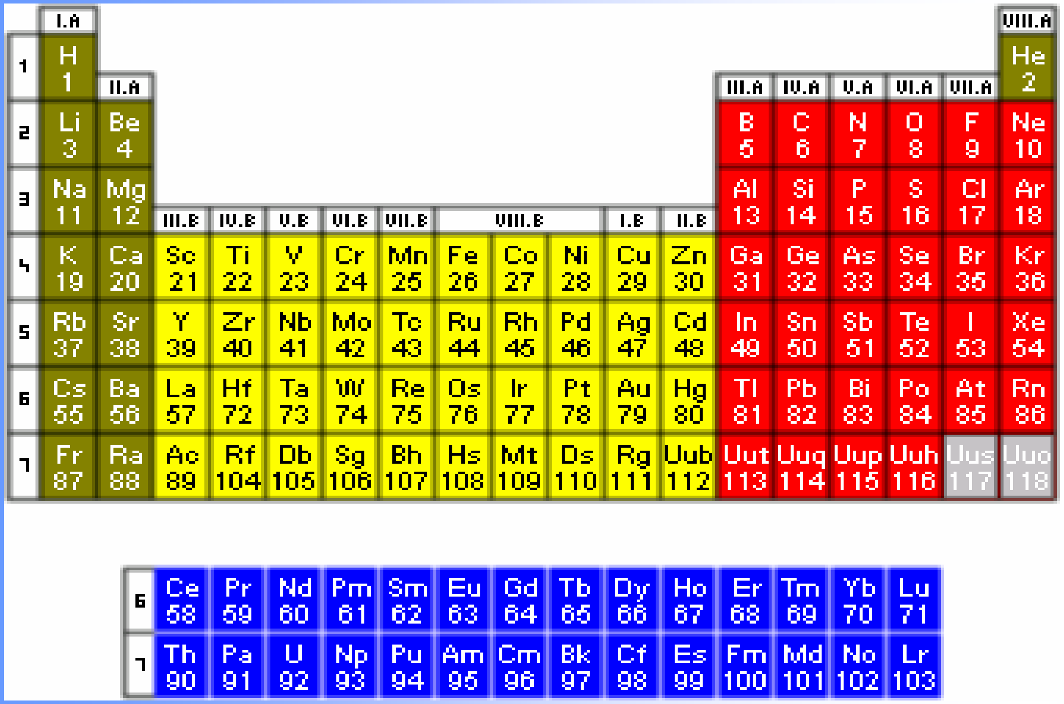
Alumina as dopant into Ta, Ti, or Si

Tungsten dopant into Ta (and Ti, Nb, Hf, etc)

Zirconia

Hafnia - solve adhesion problem

Cobalt as dopant - only layers near substrate



	I.A	II.A	III.B	IV.B	V.B	VI.B	VII.B	VIII.B			I.B	II.B	III.A	IV.A	V.A	VI.A	VII.A	VIII.A
1	H 1																	He 2
2	Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
3	Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
4	K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
5	Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
6	Cs 55	Ba 56	La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
7	Fr 87	Ra 88	Ac 89	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	Rg 111	Uub 112	Uut 113	Uuq 114	Uup 115	Uuh 116	Uus 117	Uuo 118

6	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
7	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

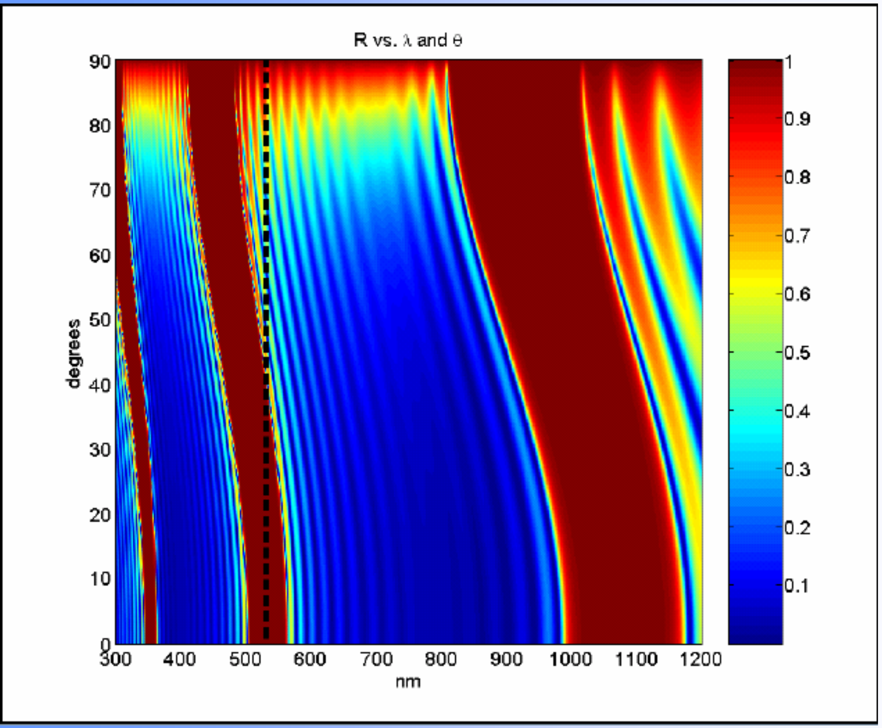
Dopants:high index-high index
- Hf-Ta
- Nb-Ti
- Hf-Nb, etc

Trinary alloys
- Ta-Ti-Si
- Ni-Ta-Ti-Zr-Hf-Si-Al
- Si-O-N

Other nitrides

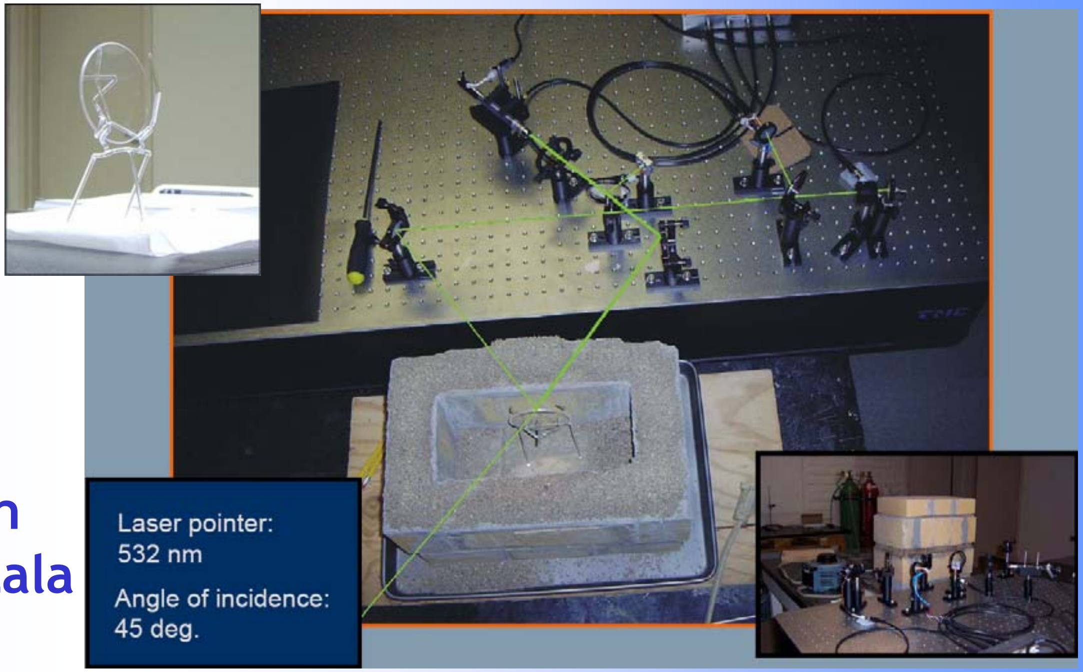
See talk by C Comtet

Thermo-optic Noise



- Thermorefractive(β=dn/dT)/coating thermoelastic noise(α=dL/dT) noise correlated
- β from literature (Inci *J Phys D:Appl Phys*, 37 (2004) 3151) 1.2×10^{-4}
- This value makes combined noise an AdvLIGO limiting noise source
- Limits from TNI encouraging that β is lower
- Need a good value for tantala, titania doped tantala, and other promising coatings

- Experiment at Embry-Riddle Aeronautical University
- Measure change in reflectivity versus temperature
- Use green He-Ne laser at 45 degrees
- 100 C change in temperature enough to verify/rule out Inci result for tantala



Young’s Modulus of Coatings

Coating Young’s modulus just as important to thermal noise as mechanical loss

Acoustic reflection technique used to measure coating impedance in collaboration with Stanford (I Wygant)

MLD alumina/tantala	176 +/- 1.1 GPa
MLD silica/tantala	91 +/- 7.0 GPa
WP alumina/tantala	156 +/- 20 GPa

Uses assumed values for material densities

Infer material Young’s moduli

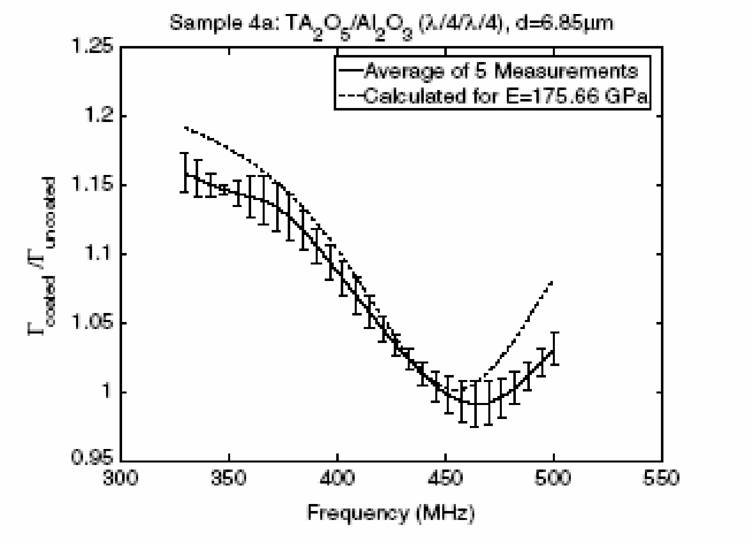
Y_{Ta2O5} = 140 +/- 30 GPa

Y_{Al2O3} = 210 +/- 30 GPa (MLD)

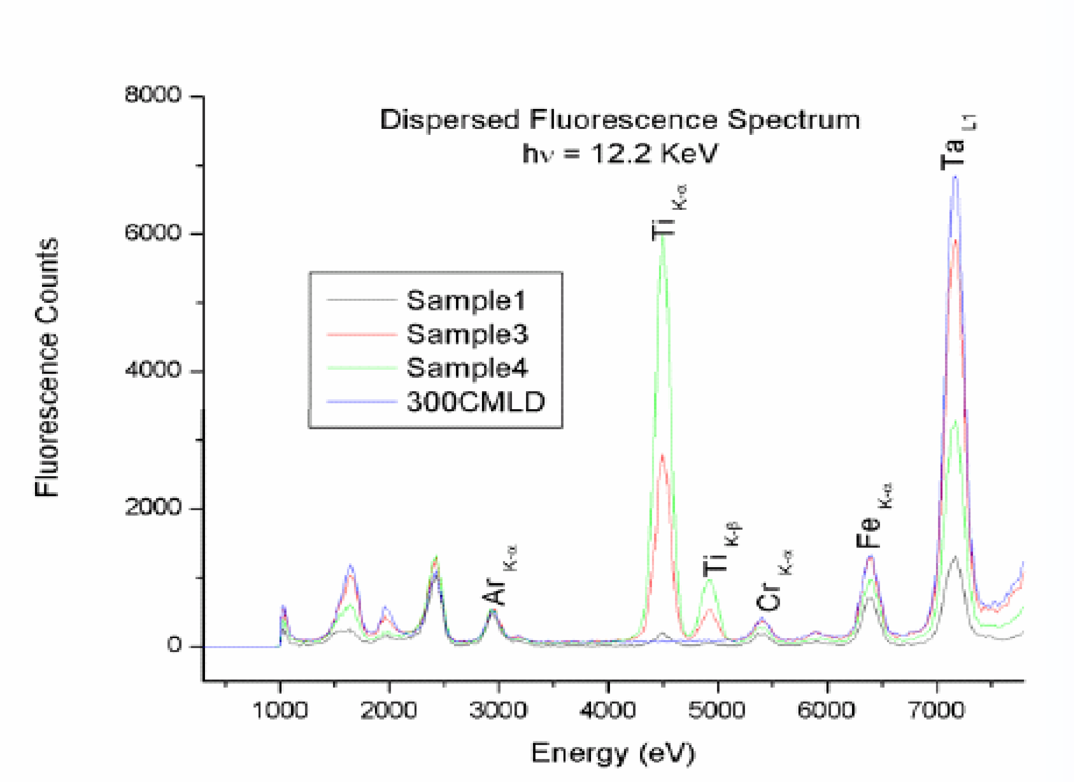
Y_{Al2O3} = 170 +/- 30 GPa (WP)

Large errors problematic when propagated

Fit of Young’s Modulus of Tantala/Alumina

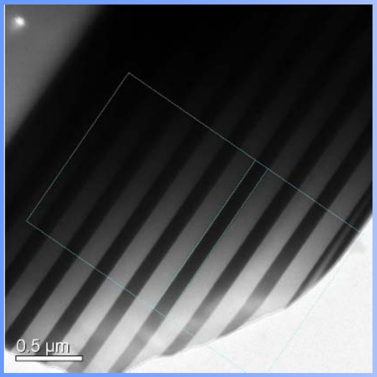


Study of Materials

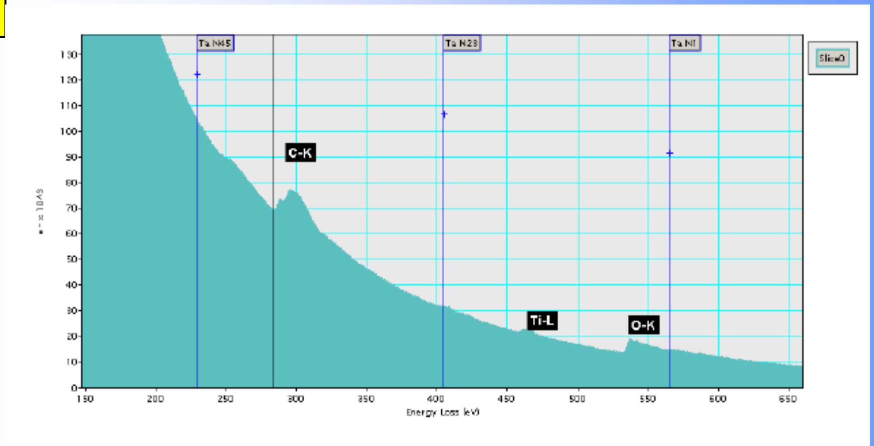


X-Ray Florescence Results from Southern University / CAMD

- Measurements being made at Glasgow, Southern, and Caltech
- Titania concentrations in titania-doped tantala consistent – LMA/SU/UG
- Southern finding titania using XRF, XANES, EXAFS
- Plans for AFM and GIXAFS at Southern
- Hopes for further insights into coating makeup and structure from studying contaminants

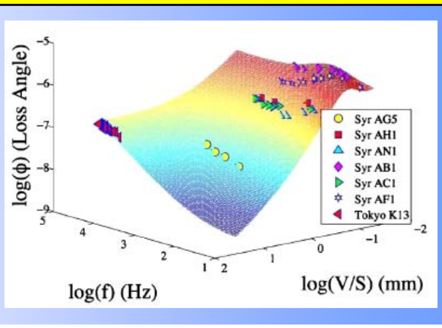


Electron Energy Loss Spectroscopy results from Glasgow



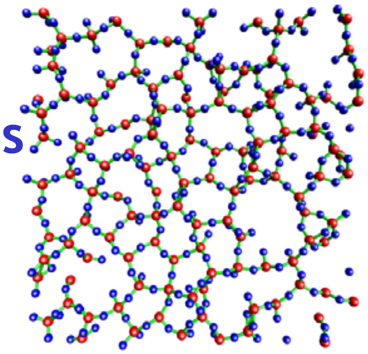
Modeling and Molecular Cause of Mechanical Loss

Goal: A description of mechanical loss in thin film amorphous oxides from basic principles

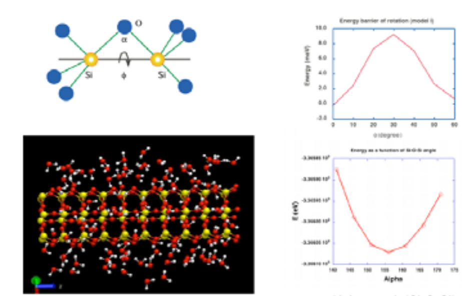


Molecular dynamics calculations beginning at University of Florida

- Have a working semi-empirical model of loss in fused silica
  - Frequency dependence from two level systems
  - Surface loss as observed phenomenon
  - See talks by L Gammaitoni and S Penn
- Develop full molecular description of silica loss
  - Surface loss caused by two member rings
- Generalize to other amorphous oxides
  - Analogous two level systems

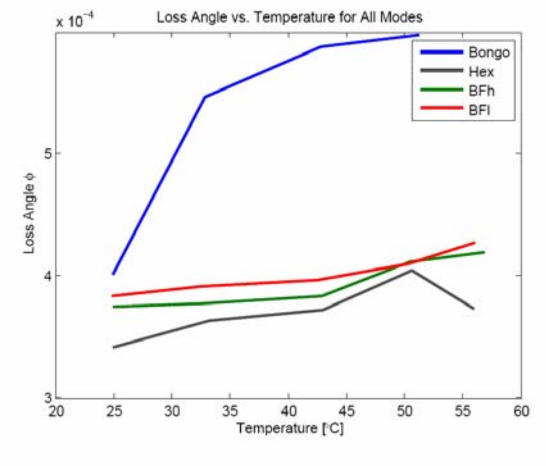


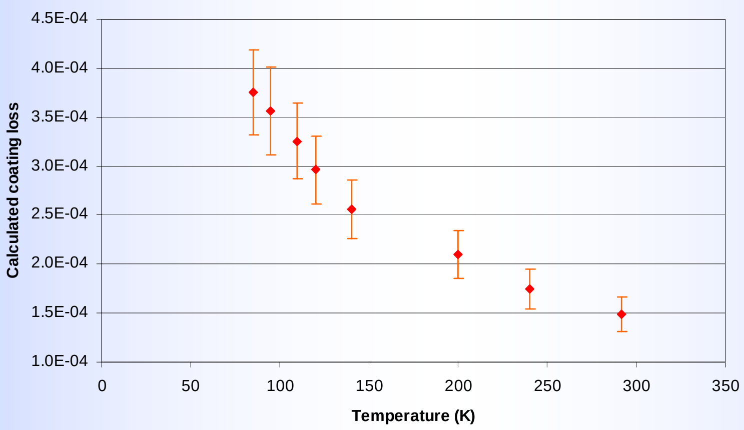
Quantum calculations of silica



A snapshot of SiO_2 rod-water interaction

Alpha=angle(Si-O-Si)





Mechanical loss data at different temperatures

- Tantala/Silica T>300 C
- Ti doped Tantala/Silica T<300 C
- With frequency dependence, start to fit to modeling
- See talk by S Reid and F Travasso

Theory

$$S_x(f) = d(1-\sigma^2)/(\pi\, w^2)((1/(Y_{perp}\,(1-\sigma^2))-2\,\sigma_2{}^2 Y_{para}/(Y_{perp}{}^2\,(1-\sigma^2)(1-\sigma_1)))\,\phi_{perp}+ Y_{para}\sigma_2(1-2\sigma)/(Y_{perp}Y(1-\sigma_1)(1-\sigma))(\phi_{para}-\phi_{perp})+Y_{para}(1+\sigma)(1-2\sigma)^2/(Y^2(1-\sigma_1{}^2)(1-\sigma))\phi_{para})$$

What we have

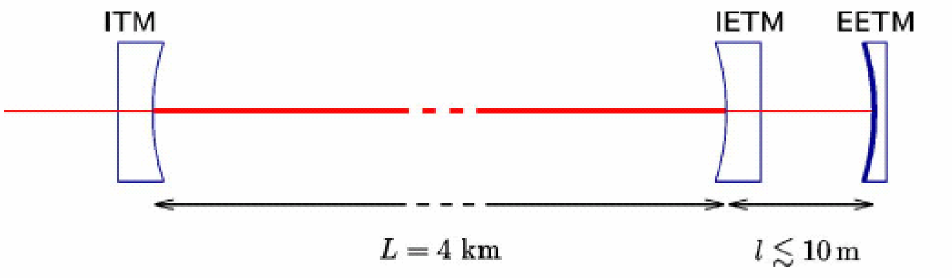
- Complete theory of infinite mirror from Levin’s theorem
- Anisotropic coatings including Young’s modulus, loss angles, and Poisson ratios
- Relationship between total anisotropic coating parameters and isotropic individual material parameters
- FEA models of finite mirror effects
- Theory of coating thermoelastic loss
- General theory of coatings and substrates, both Brownian and thermoelastic, for any beam shape for infinite mirrors
- Optimization of coating thicknesses for thermal noise and reflectivity (see talk by V Galdi)

What we need

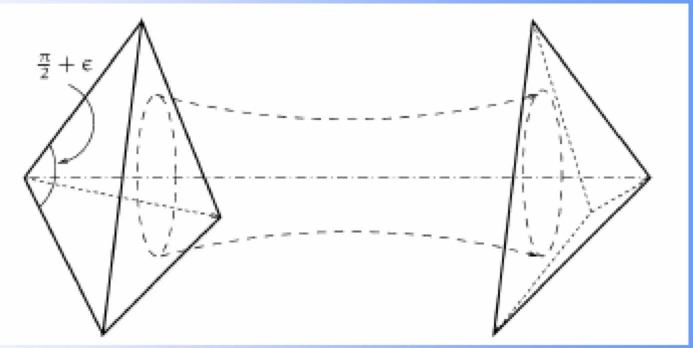
- Empirical formula for finite mirror effects
- Analytical theory of finite mirrors
- Molecular level description of loss angles and other parameters
- Complete optimization over thermal noise, reflectivity, absorption, scatter, etc.

Third Generation Ideas

Crucial to improve beyond Advanced LIGO levels to exploit QND, very low frequency seismic isolation, improved topologies, high laser power, etc



- Short cavities as reflectors
  - Khalili (Phys Lett A 334 (2005) 67)
  - Significant added complexity
  - No experimental work so far
- Corner reflectors
  - Braginsky and Vyatchanin (Phys Lett A 324 (2004) 345)
  - Practical concerns (scatter, finesse, angular stability, etc)
  - Experiments at Australian National University
- Lower temperatures
  - Need to restudy all materials as properties change
  - Some preliminary experimental work
  - See talk by P Puppo
- New substrate materials (sapphire, silicon, etc)
  - Will require new coatings
  - See talk by S Rowan
- Change in beam shapes
  - Mesa beams – better averaging of thermal fluctuations
  - Higher order modes (see talk by J Y Vinet)
  - General theory from O’Shaughnessy/Lovelace
  - Experiments at Caltech (see talks by J Agresti and J Miller)



Conclusions

- Coating thermal noise limiting noise source in Advance LIGO's most sensitive frequency band
- Determined source of coating mechanical loss is internal friction in constituent materials
- High index, typically tantala, is the biggest source of thermal noise
- Doping a means of reducing mechanical loss
    - Titania doped into tantala
    - Silica doped in titania'
- Many other techniques tried to improve thermal noise, many still to be pursued
- Thermo-optic noise a potential problem that is understudied
- Need more information on coating Young's moduli
- Much work to be done with characterizing coating materials and developing thermal noise theory
- New ideas for third generation only beginning to get attention