Optical Coating Development for the Advanced LIGO Gravitational Wave Antennas

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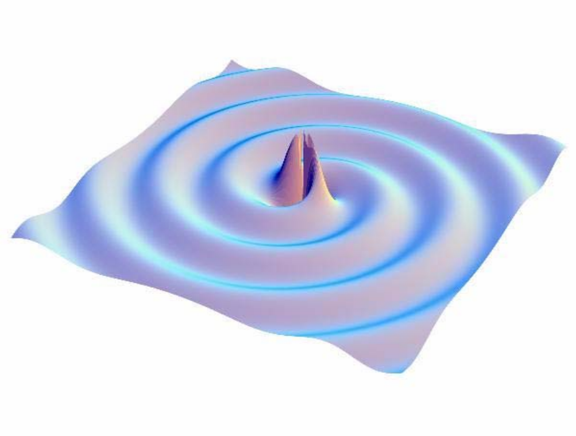
Gravitational Wave Detection

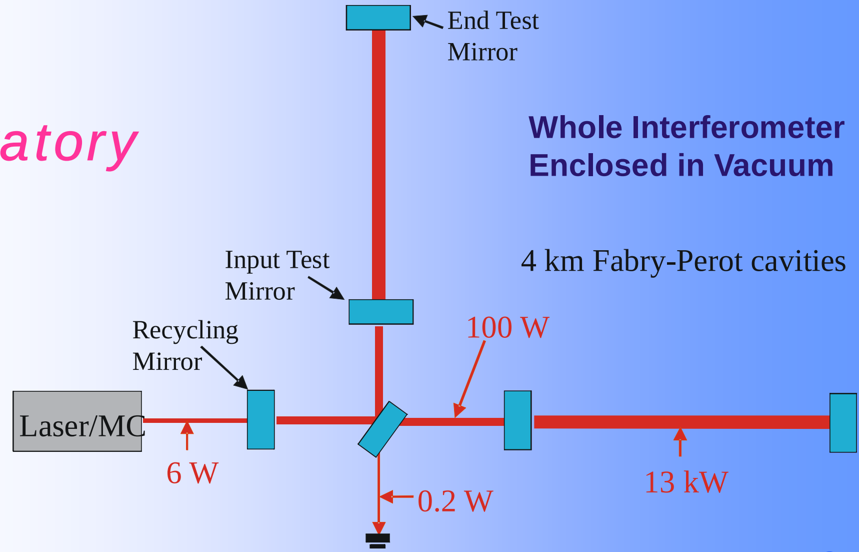


- *Gravitational waves predicted by Einstein*
- *Accelerating masses create ripples in space-time*
- *Need astronomical sized masses moving near speed of light to get detectable effect*

LIGO

Laser Interferometer Gravitational-wave Observatory

- *Two 4 km and one 2 km long interferometers*
- *Two sites in the US, Louisiana and Washington*
- *Similar experiments in Italy, Germany, Japan*
- *Whole optical path enclosed in vacuum*
- *Sensitive to strains around 10^{-21}*



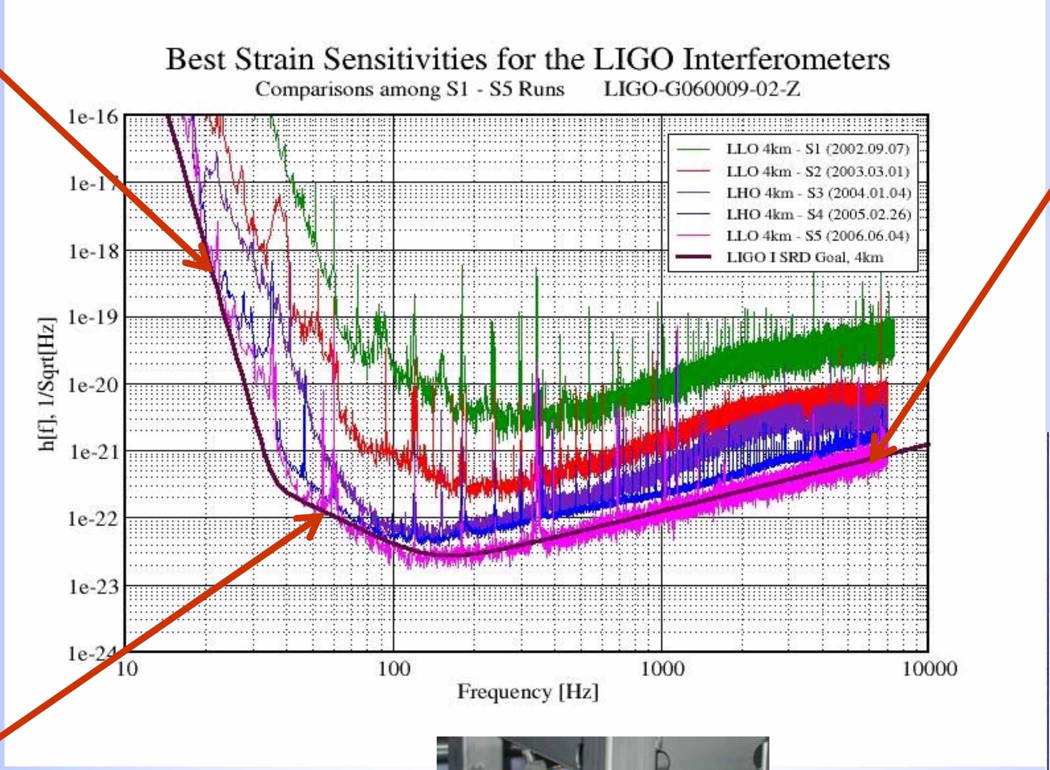
Whole Interferometer Enclosed in Vacuum

LIGO Sensitivity

Measured sensitivity 6/2006

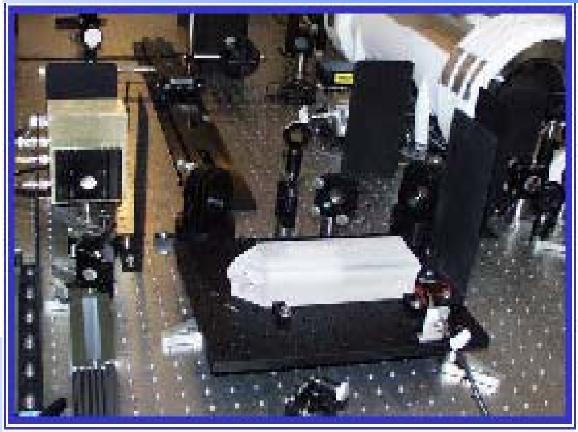
Seismic noise < 40 Hz

Optics sit on multi-stage vibration isolation



Laser shot noise > 200 Hz

10 W frequency and amplitude stabilized laser



Thermal noise 40 Hz < f < 200 Hz

Metal wire pendulum suspensions allow optic to move freely with gravity wave

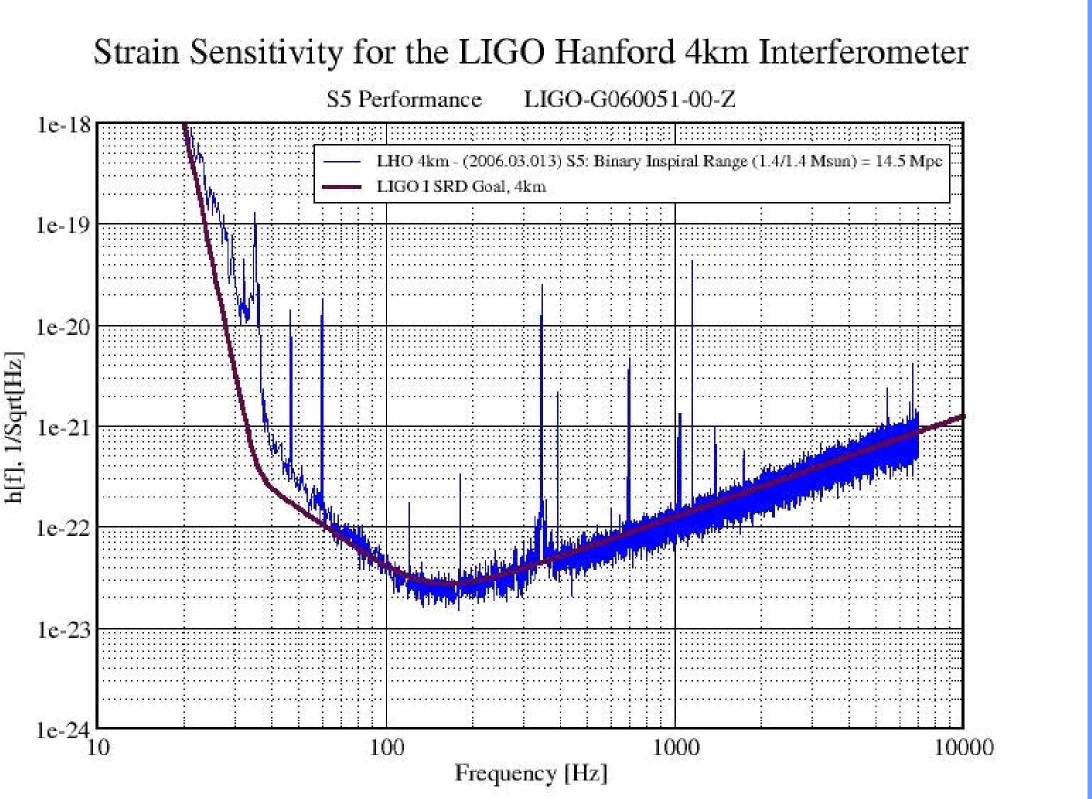
Current LIGO Noise

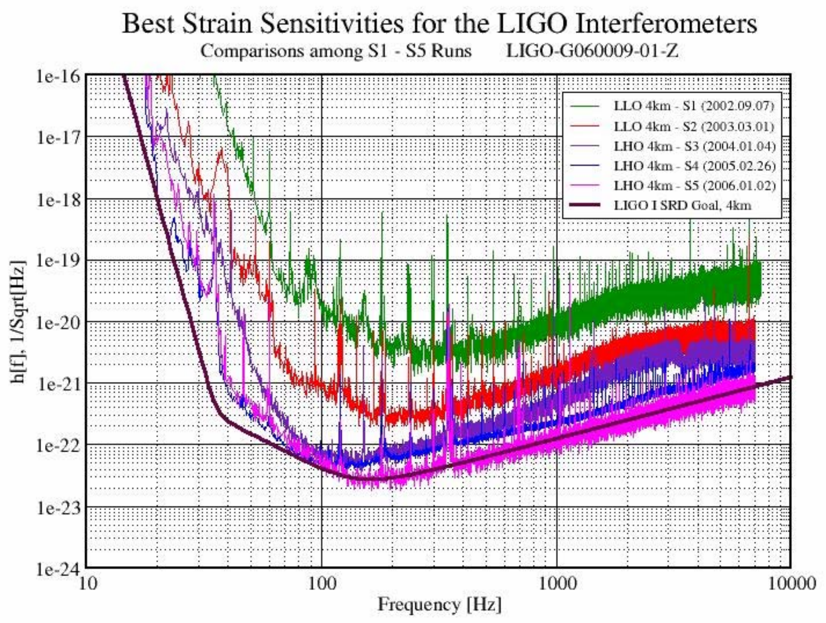
Present noise at design value in all three interferometers

- Some excess noise < 50 Hz
- Noise reduction during breaks

Currently taking data

- Will collect 1 years worth of triple coincidence
- Began in November 2005
- Extensive data analysis ongoing



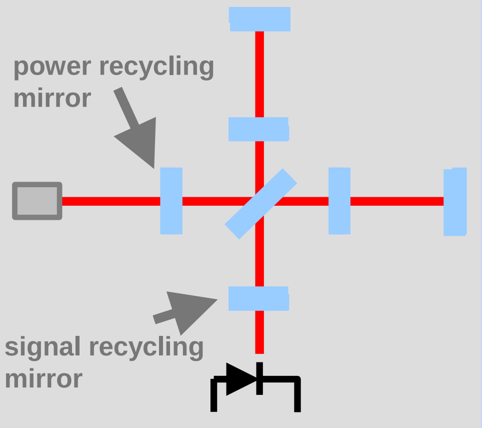


Hanford 4 K sensitivity

- Neutron star inspirals 14.5 Mpc
- 10 M_O black hole inspirals to 50 Mpc
- Stochastic background 7.5 10^{-6}
- Crab pulsar ε 2.8 10^{-5}
- Sco X-1 ε 3.0 10^{-7}

Advanced LIGO

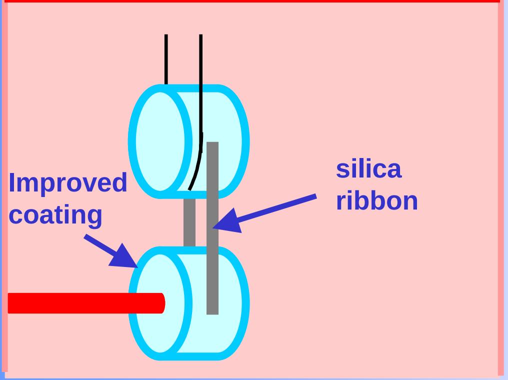
Advanced Configuration



power recycling mirror

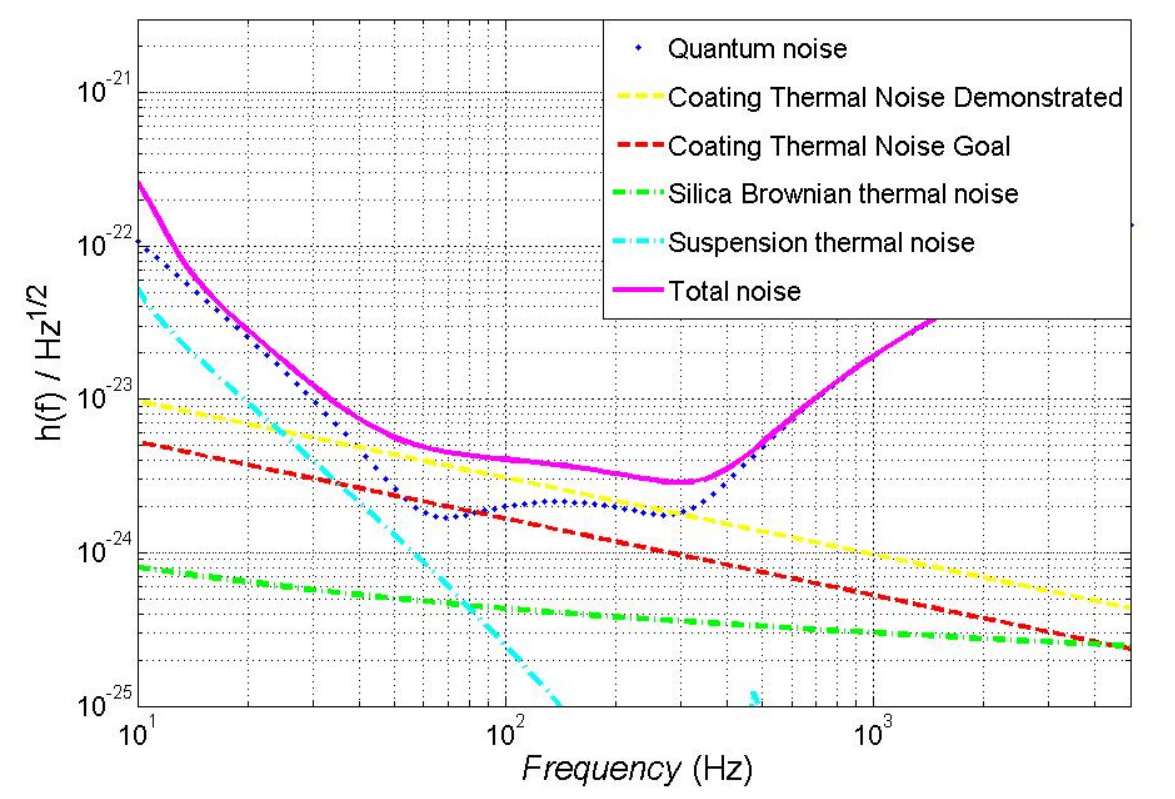
signal recycling mirror

Suspension



Improved coating

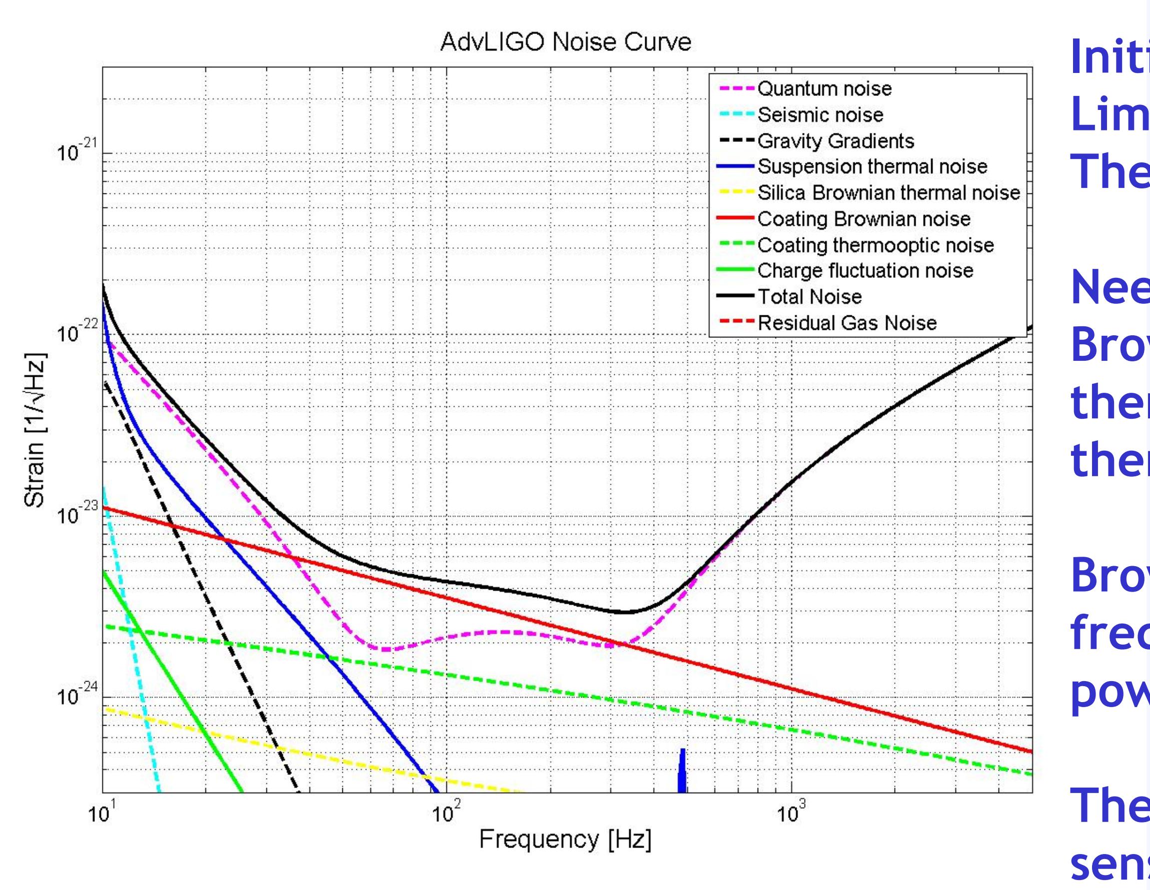
silica ribbon



Proposed Sensitivity

- *Factor of 15 in strain improvement*
- *Seismic isolation down to 10 Hz*
- *180 W of laser power*
- *Larger optics with improved coating*
- *Additional mirror for signal recycling*

Advanced LIGO Sensitivity



Initial LIGO Coating

Initial LIGO Coating – Tantala/Silica
Limits sensitivity 40 Hz - 400 Hz
Thermooptic Noise high in same BW

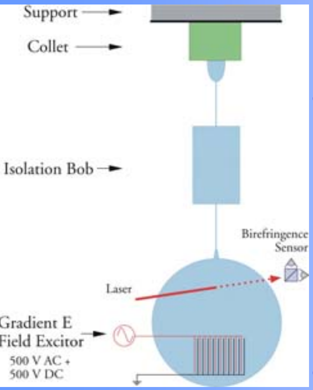
Need improved coating - including Brownian thermal noise, coating thermoelastic noise, and coating thermorefractive noise

Brownian thermal noise limits at low frequency, even with reduced laser power/radiation pressure noise

Thermal noise also limits narrowband sensitivity, sets floor

Binary Neutron Star Inspiral	160 Mpc
Binary Black Hole Inspiral	910 Mpc
Neutron Star/Black Hole Inspiral	360 Mpc
Stochastic Background	$1.3\ 10^{-9}$

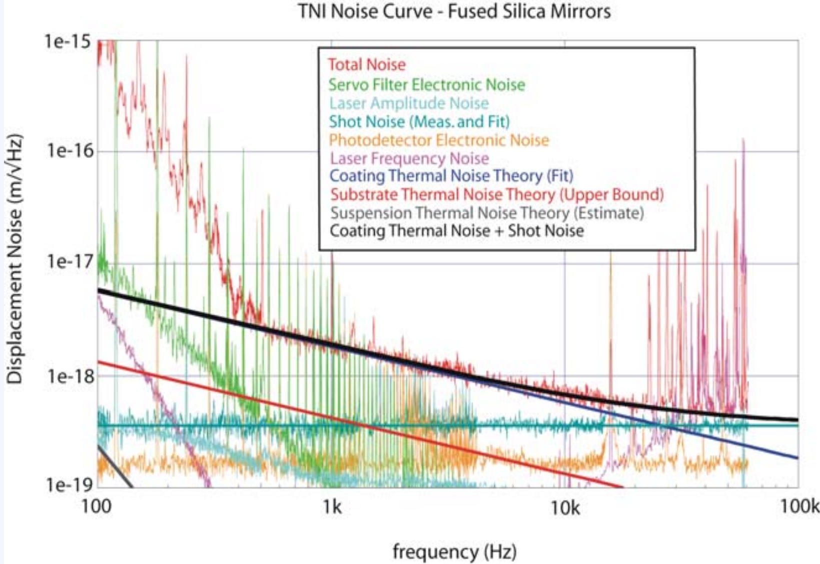
Measurement Techniques



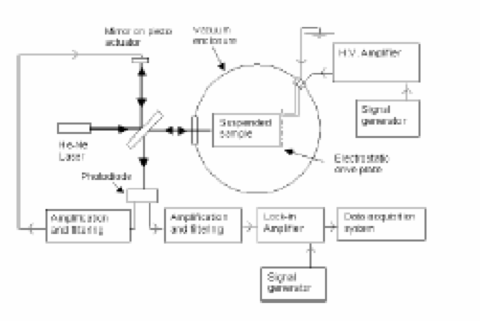
Thin Sample

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



TNI Result of Tantala/Silica Coating

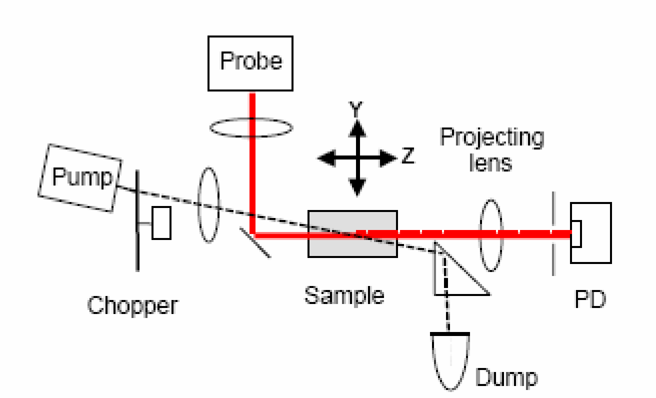


Thick Sample

Optical Performance

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

PCPI Setup



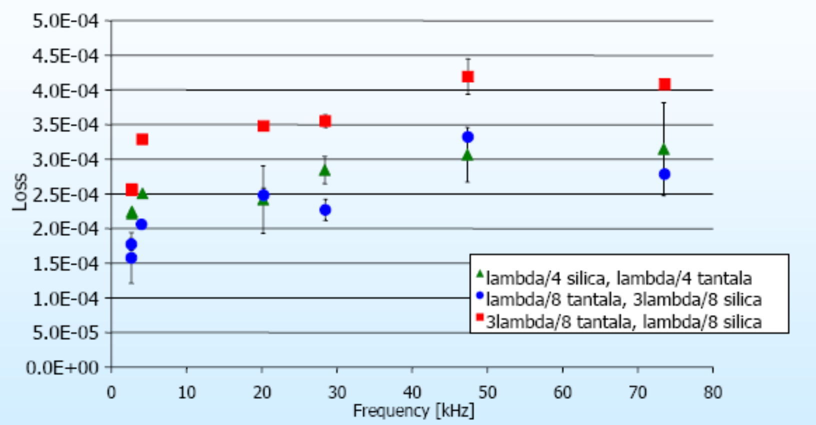
Initial LIGO
Tantala/Silica Coating

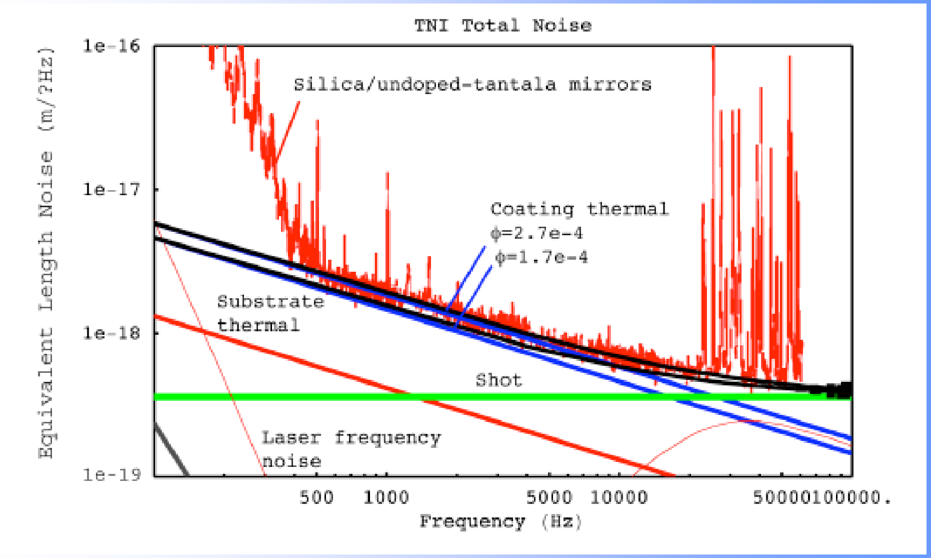
Coating Mechanical Loss

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

Tantala/Silica Coating Mechanical Loss





Direct Coating Thermal Noise Measurement

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

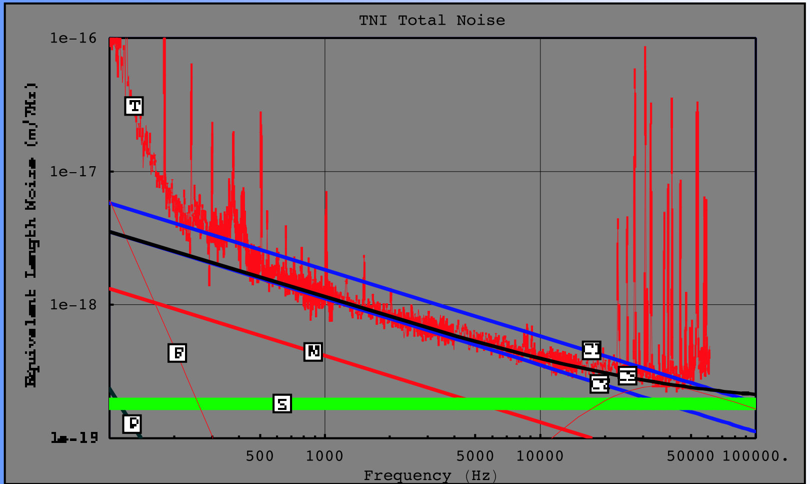
TiO_2-doped Ta_2O_5

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

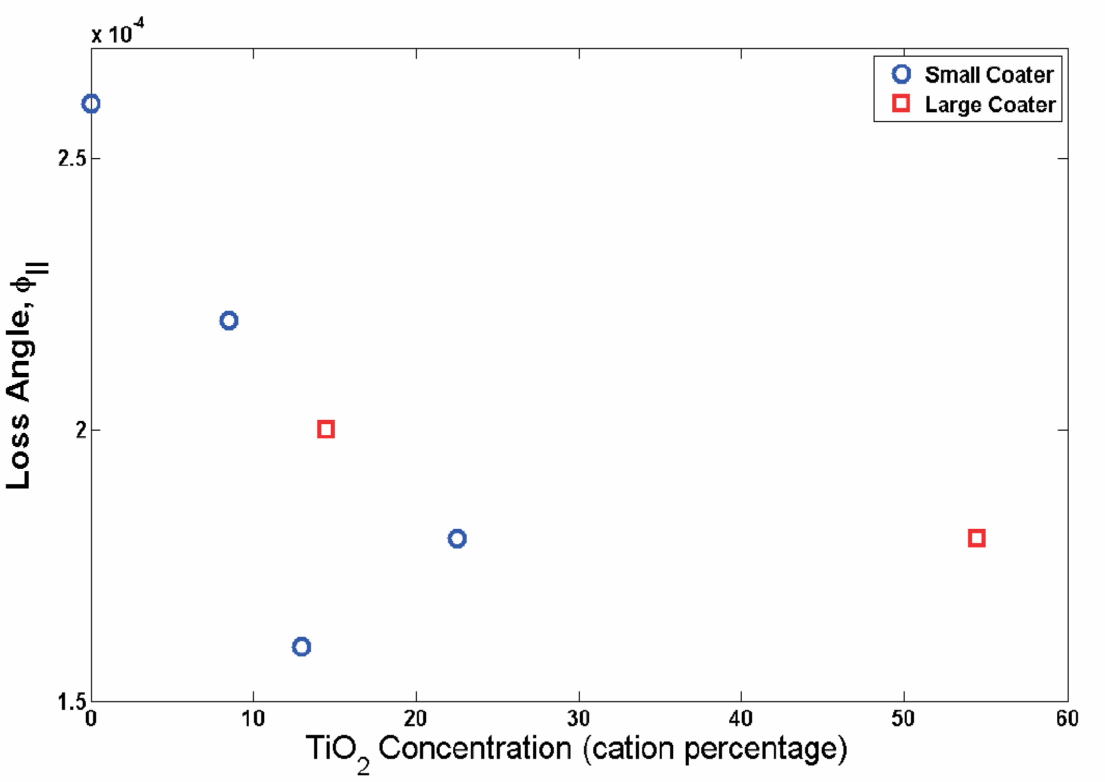
$\phi_1 = (2.2 \pm 0.4)10^{-4} + f(1.2 \pm 0.6)\ 10^{-9}$
$\phi_2 = (1.6 \pm 0.1)10^{-4} + f(1.4 \pm 0.3)\ 10^{-9}$
$\phi_3 = (1.8 \pm 0.1)10^{-4} + f(-0.2 \pm 0.4)10^{-9}$
$\phi_4 = (1.8 \pm 0.2)10^{-4} + f(1.7 \pm 0.6)\ 10^{-9}$
$\phi_5 = (2.0 \pm 0.2)10^{-4} + f(0.1 \pm 0.4)\ 10^{-9}$

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

TNI Noise from Titania doped Tantala/Silica



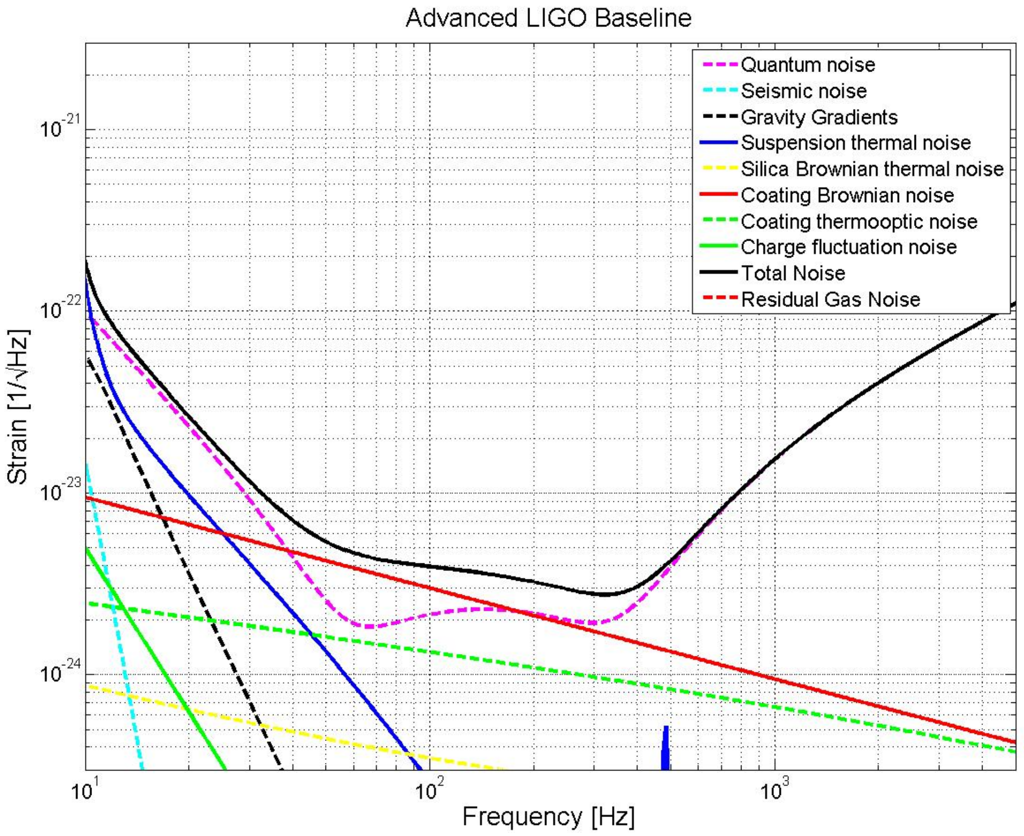
Titania-doped Tantala/Silica Coatings



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

Optical absorption acceptable ≈ 0.5 ppm

Advanced LIGO Baseline Coating



Baseline Advanced LIGO Coating - Titania doped Tantala/Silica

Still not limited by quantum noise

Limits sensitivity 40 Hz - 200 Hz
Thermo-optic Noise high in same BW

Narrowband high frequency configurations still limited by coating thermal noise

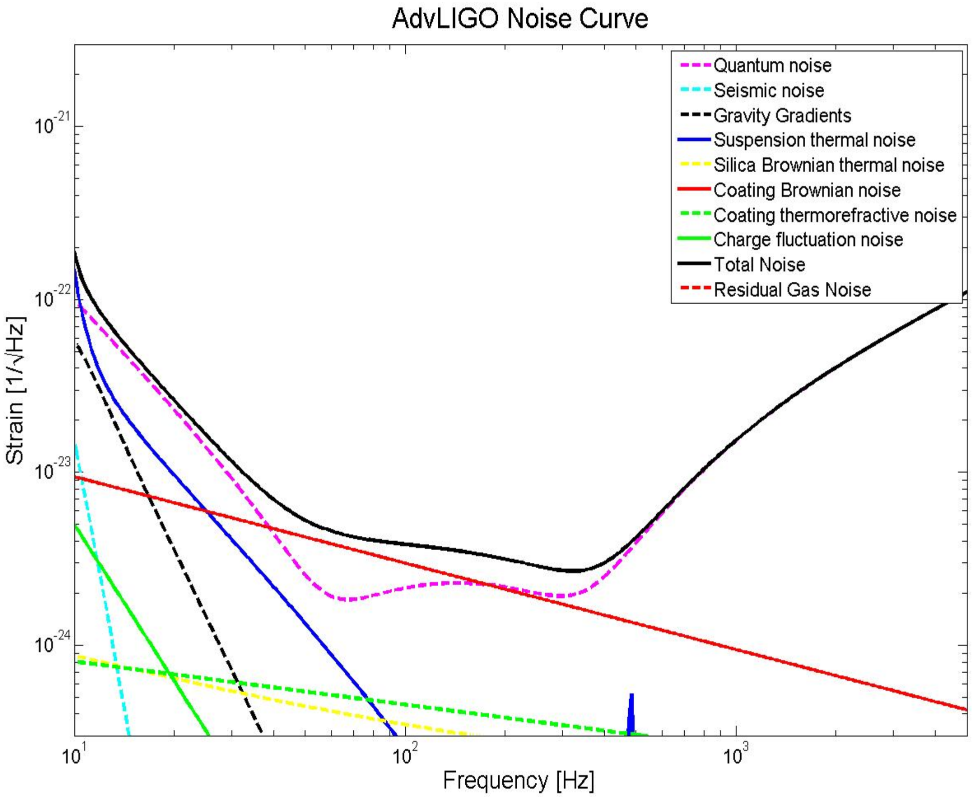
Acceptable impedance match with substrate

Acceptable coating thickness

Advanced LIGO Baseline Titania-doped Tantala/Silica

Binary Neutron Star Inspiral	175 Mpc
Binary Black Hole Inspiral	975 Mpc
Neutron Star/Black Hole Inspiral	390 Mpc
Stochastic Background	$1.2\ 10^{-9}$

Advanced LIGO 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

ϕ= (2.4 +/- 0.9) 10^{-4}

Thin Sample

Run 1* ϕ = (3.1 +/- 0.2) 10^{-4}

Run 2 ϕ = (1.9 +/- 0.3) 10^{-4}

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

Silica doped Titania/Silica
-Backup Coating-

Binary Neutron Star Inspiral	175 Mpc
Binary Black Hole Inspiral	960 Mpc
Neutron Star/Black Hole Inspiral	385 Mpc
Stochastic Background	1.2 10^{-9}

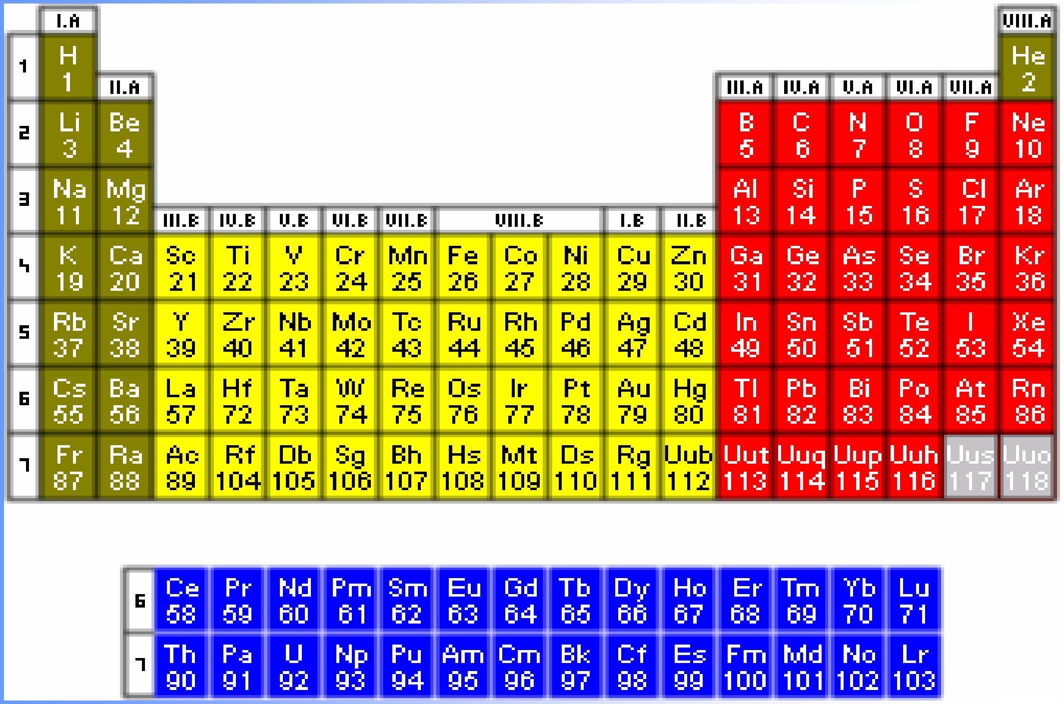
Other Coatings Attempted

- Niobia/Silica – high mechanical loss, unknown optical absorption
- Hafnia/Silica – poor adhesion, poor absorption, never measured for ϕ
- Alumina/Silica – thick coating, good mechanically and optically
- Dual ion beam (oxygen) – interesting, shows differences in mechanical loss between masks but not improvement over baseline
- Oxygen poor – high mechanical loss, waiting on annealing in nitrogen atmosphere, high absorption
- Xenon ion beam - increased mechanical loss
- Lutetium doped Tantala/Silica – no improvement in mechanical loss
- 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
Neon 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

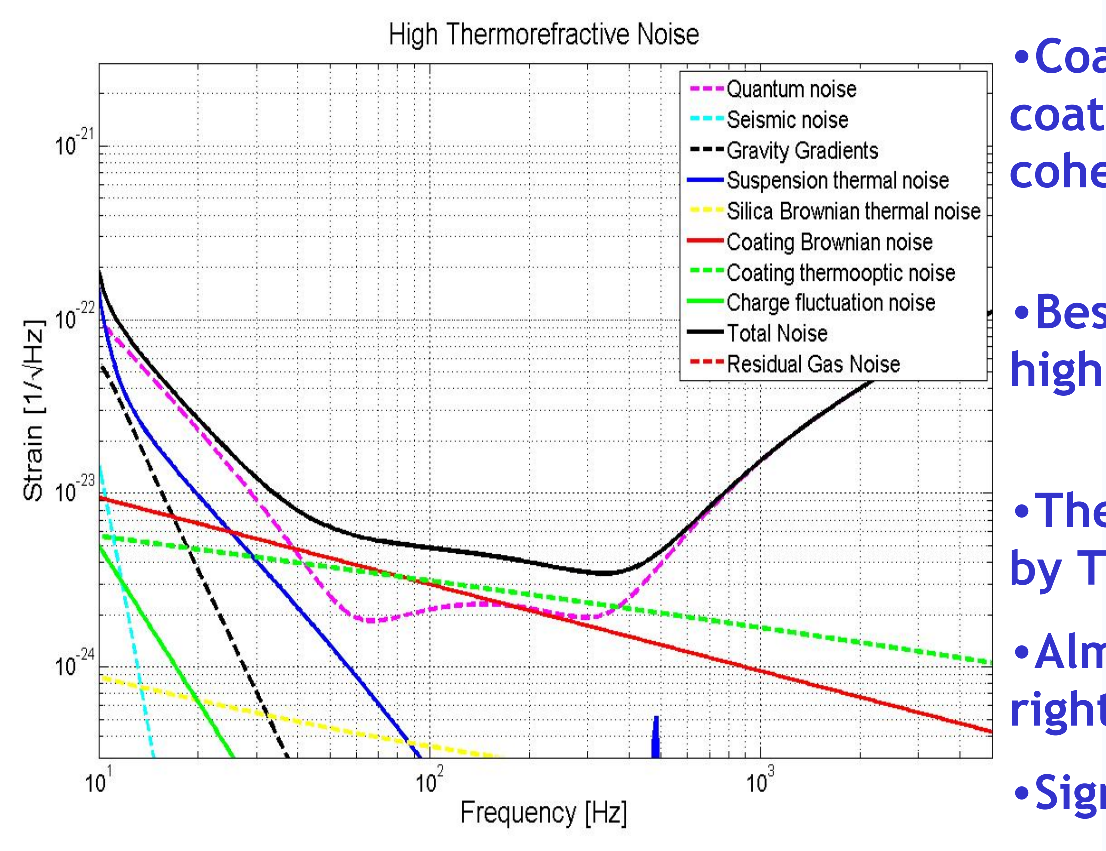
6	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
7	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

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

Thermo-optic Noise



- Coating thermorefractive (β=dn/dT) and coating thermoelastic noise (α=dL/dT) are coherent noise sources
  - Combined noise - Thermo-optic Noise
- Best number in literature indicates very high thermorefractive noise from tantala

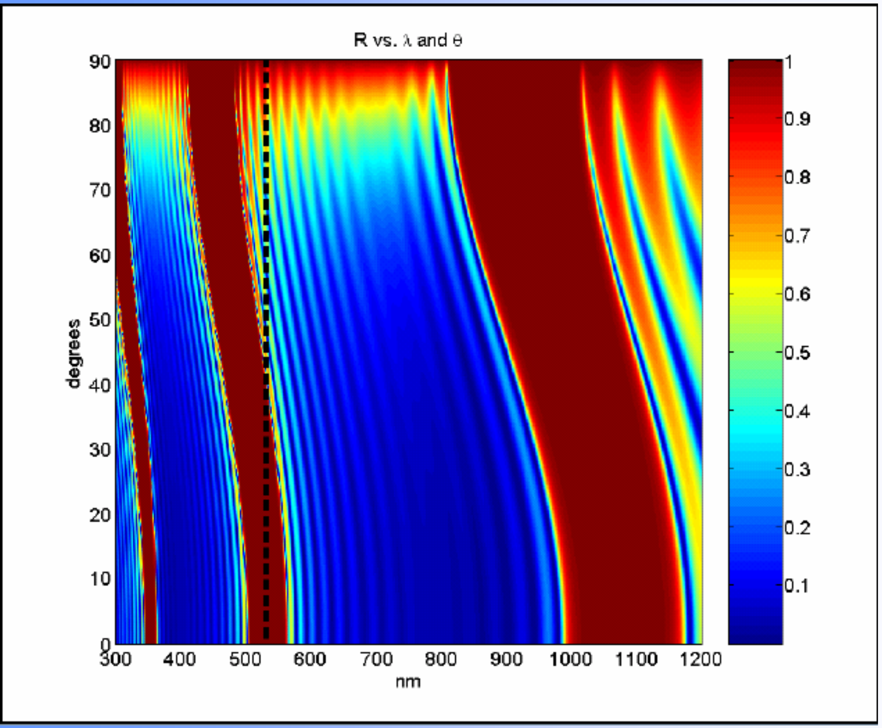
  $\beta = 1.2\ 10^{-4}$
- Thermo-optic noise at this level ruled out by TNI upper limits
- Almost certainly wrong, but what is the right value?
- Significant reduction in sensitivity

Advanced LIGO with High Thermorefractive Noise

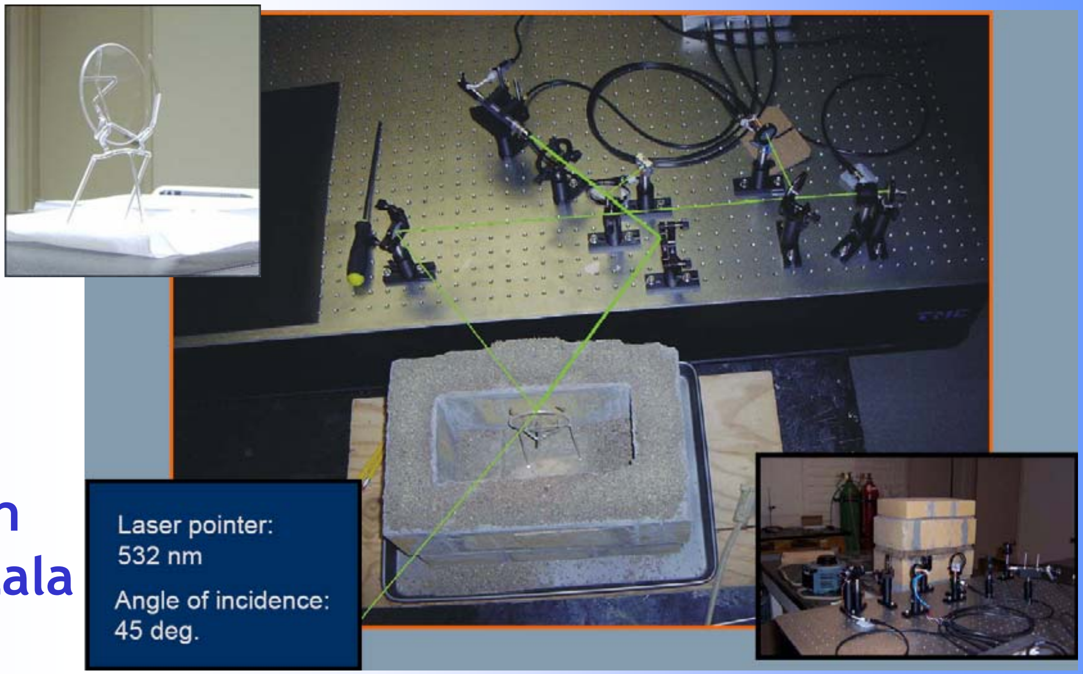
Binary Neutron Star Inspiral	150 Mpc
Binary Black Hole Inspiral	910 Mpc
Neutron Star/Black Hole Inspiral	340 Mpc
Stochastic Background	$1.4\ 10^{-9}$

dn/dT Measurement

- 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 X 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



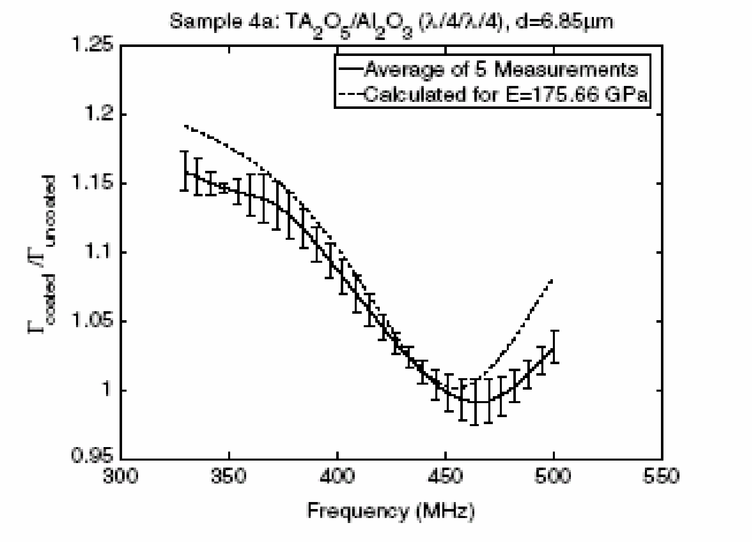
Young's Modulus of Coatings

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 alumina/tantala 167 +/- 1.3 GPa
MLD silica/tantala 91 +/- 7.0 GPa
WP alumina/tantala 156 +/- 20 GPa

Fit of Young's Modulus of Tantala/Alumina



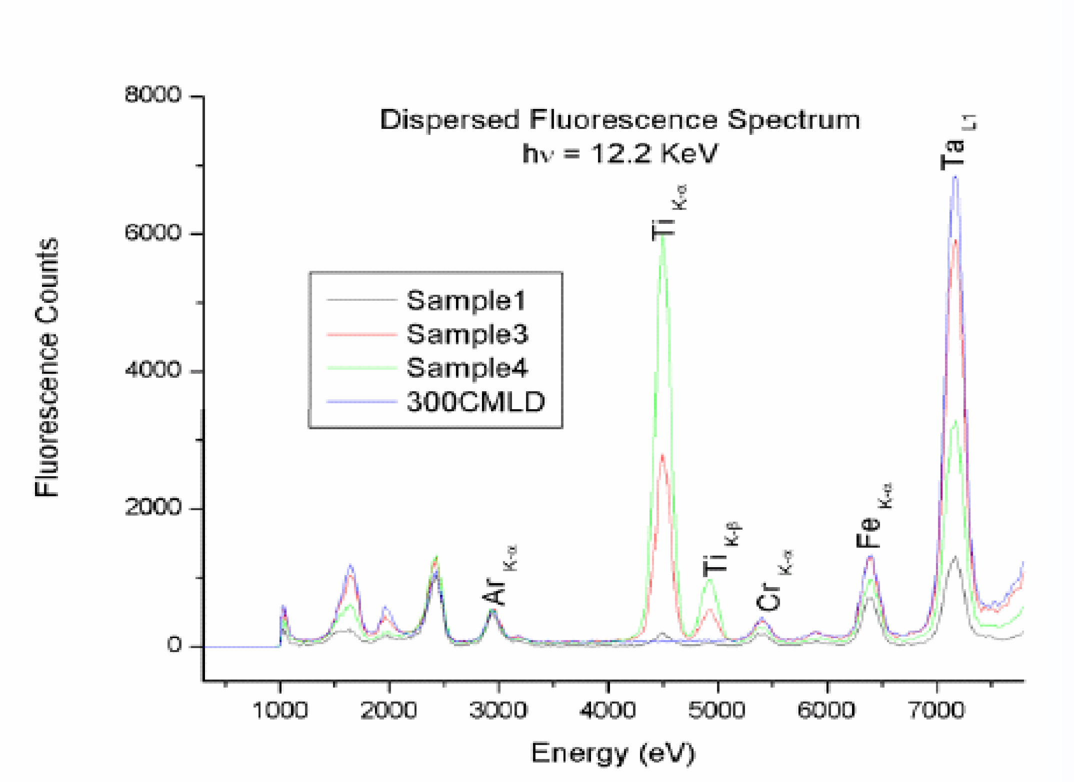
Uses assumed values for material densities

Infer material Young's moduli

Y_{Ta2O5} = 140 +/- 30 GPa
Y_{Al2O3} = 210 +/- 30 GPa (MLD)
Y_{Al2O3} = 170 +/- 30 GPa (WP)

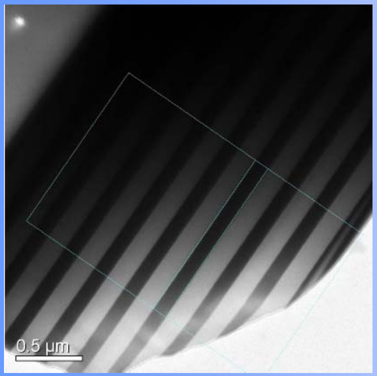
Large errors problematic when propagated

Study of Materials

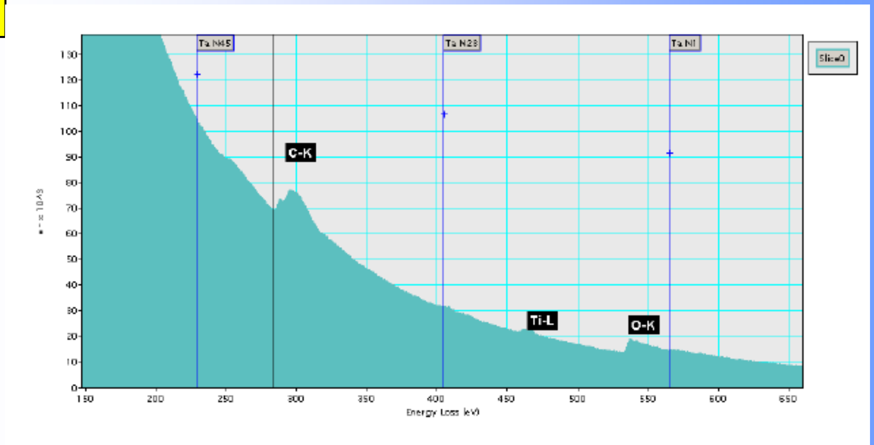


X-Ray Florescence Results from Southern University / CAMD

- 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



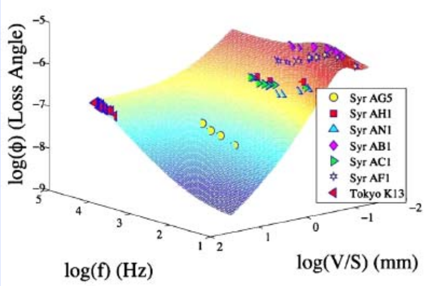
Electron Energy Loss Spectroscopy results from Glasgow



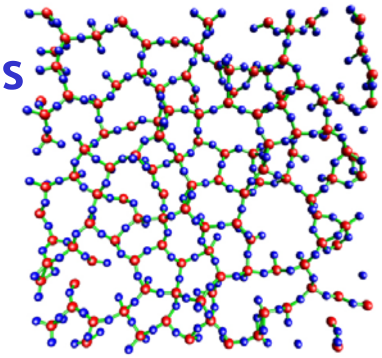
Modeling and Molecular Cause of Mechanical Loss

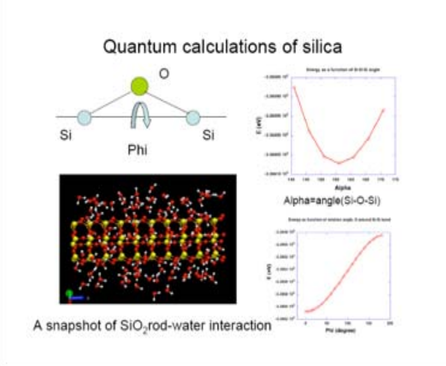
Goal: A description of mechanical loss in thin film amorphous oxides from basic principles

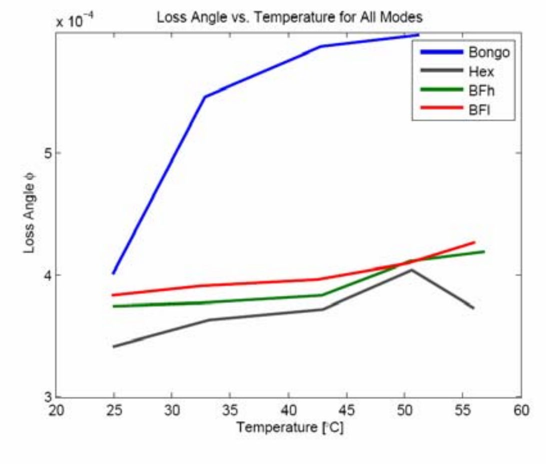
Molecular dynamics calculations beginning at University of Florida

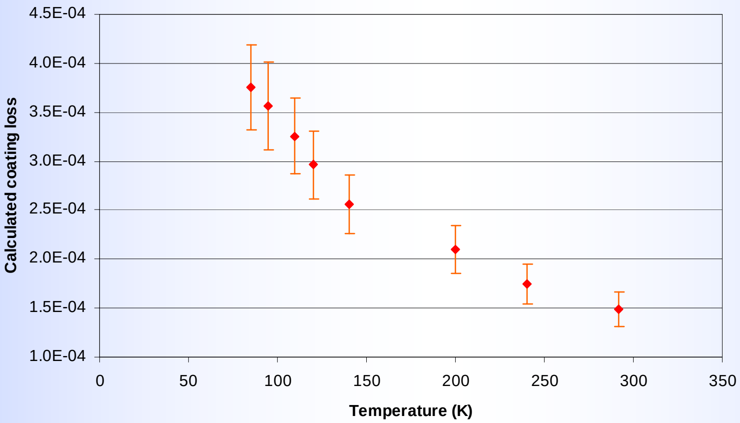


- Have a working semi-empirical model of loss in fused silica
  - Frequency dependence from two level systems
  - Surface loss as observed phenomenon
- Develop full molecular description of silica loss
  - Surface loss caused by two member rings
- Generalize to other amorphous oxides
  - Analogous two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







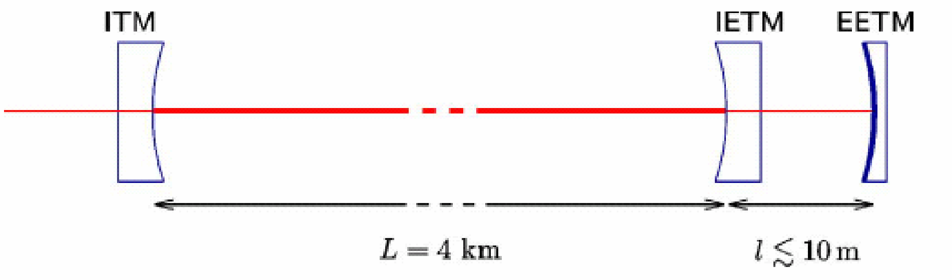


Mechanical loss data at different temperatures

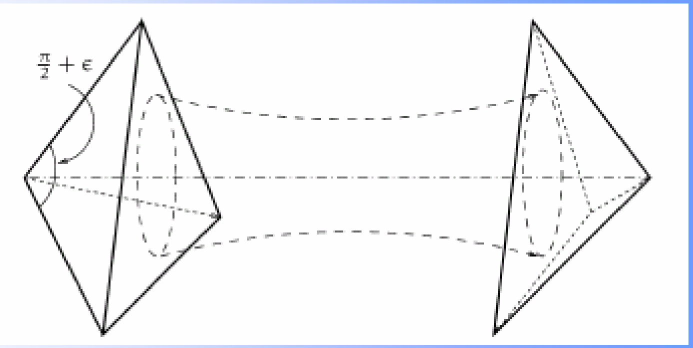
- Tantala/Silica T>300 C
- Ti doped Tantala/Silica T<300 C
- With frequency dependence, start to fit to modeling

Thermal Noise inThird Generation

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

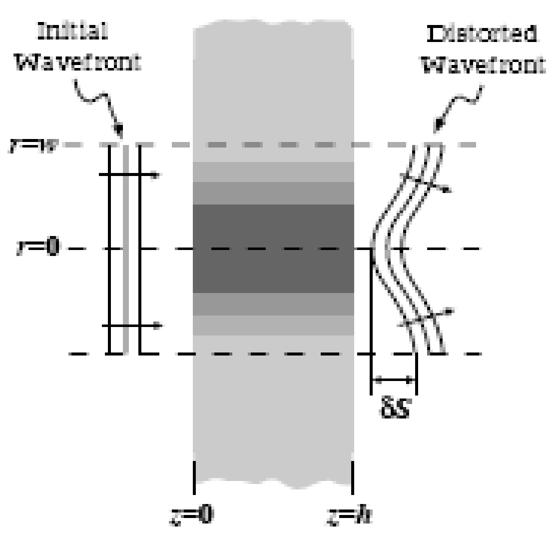


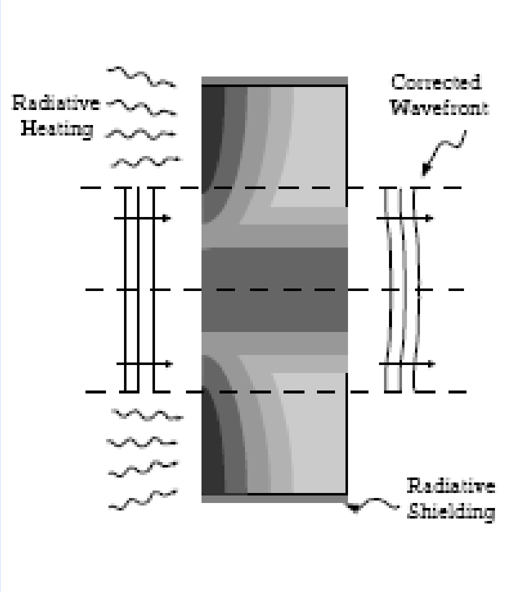
- Short cavities as reflectors
  - Khalili (Phys Lett A 334 (2005) 67)
  - Significant added complexity
  - No experimental work so far
- Corner reflectors
  - Braginsky and Vyatchanin (Phys Lett A 324 (2004) 345)
  - Practical concerns (scatter, finess, angular stability, etc)
  - Experiment at Australian National University -99.89% reflectivity observed
- Lower temperatures
  - Need to restudy all materials as properties change
  - Some preliminary experimental work
- New substrate materials (sapphire, silicon, etc)
  - Will require new coatings
  - Possibly dopants added to substrates
- Change in beam shapes
  - Mesa beams – better averaging of thermal fluctuatio
  - Higher order modes
  - General theory from O'Shaughnessy/Lovelace
  - Experiments at Caltech

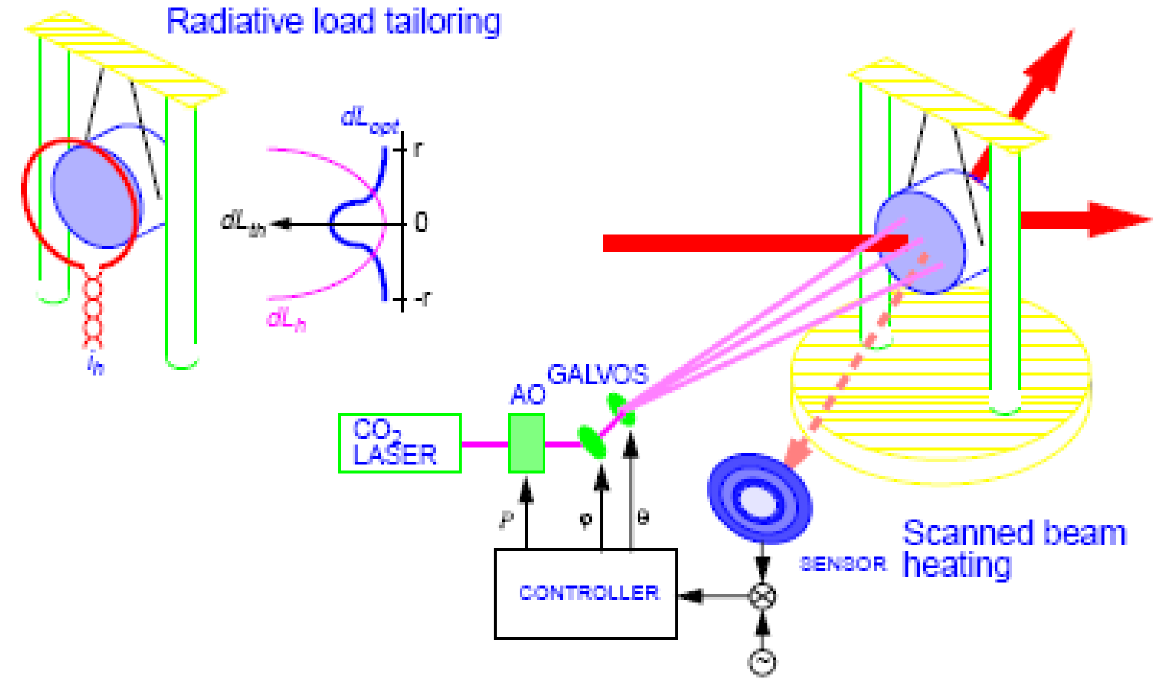


Thermal Lensing

- Absorption of optical power in mirrors causes heating
- Most absorption in coatings because of higher power in the Fabry-Perot cavities
- Heating of optic causes physical distortions and changes in index of refraction
- Optical path length changes distorts wavefront
- Causes poor contrast defect, ultimately increased shot noise and poor sensitivity



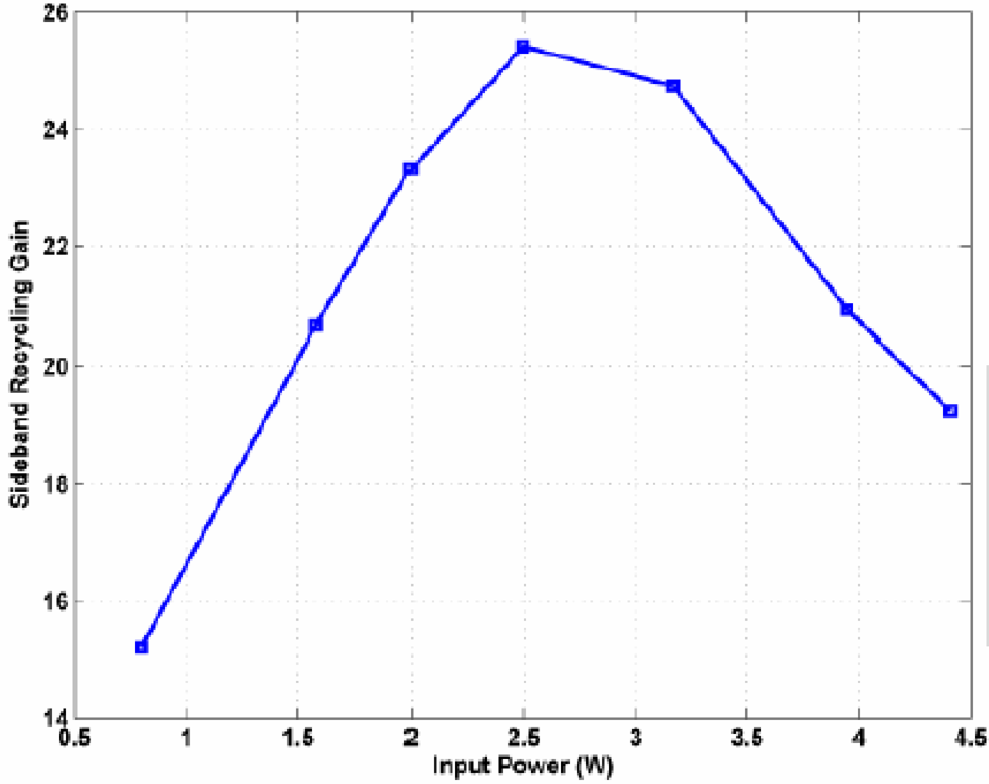




- Thermal lensing can be corrected by adding heat to cold parts of optic
- Use ring heaters or CO_2 lasers
- Limit to how much heat can be provided
- Inhomogeneous absorption requires scanning laser system
  - Increase in rad pressure noise
  - Complicated controls
- Need coatings to have absorption ≤ 0.5 ppm and homogeneous

Excess Absorption at Hanford

- **Input optics curved to match recycling mirror curvature at 8 W**
  - Point design assumes a value for absorption
- **Found best matching at 2.5 W**
  - Additional absorption causes excess thermal lensing
- **Excess absorption has to be in recycling cavity optic**
  - Input mirrors or beamsplitter

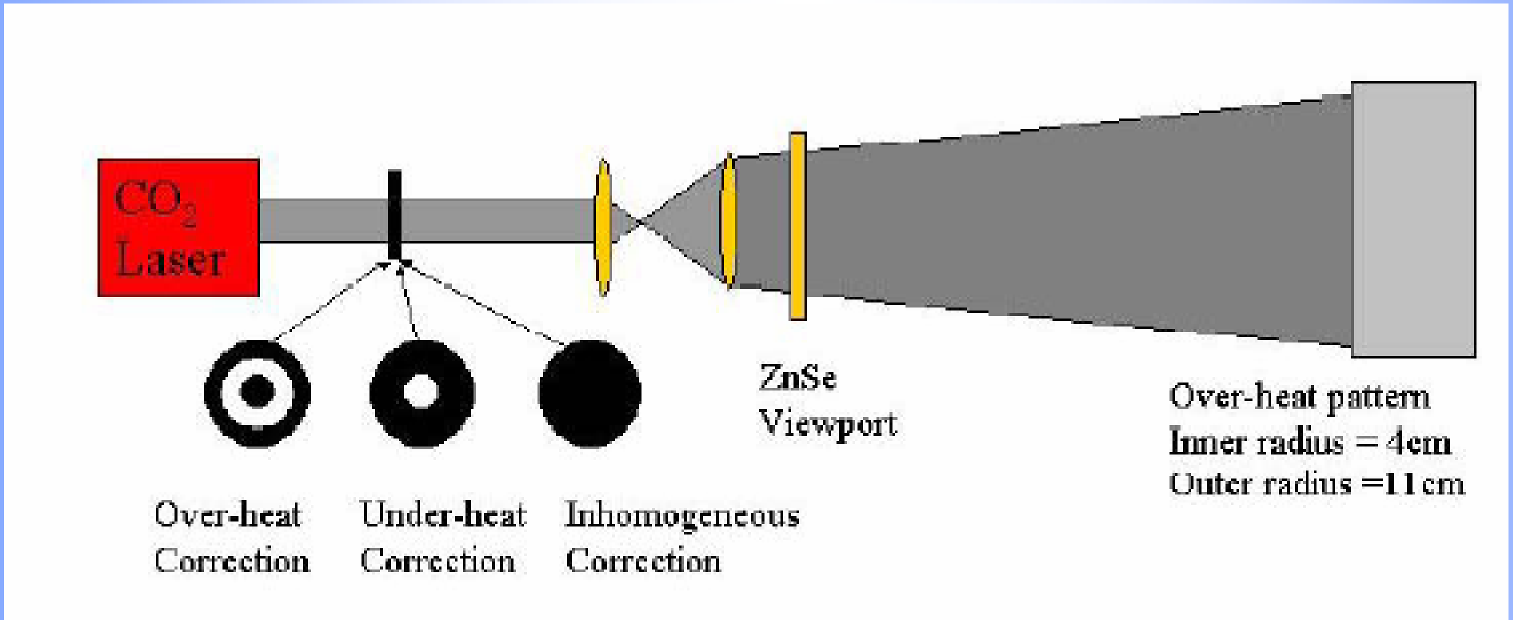


Other interferometers (2 K at Hanford and 4 K at Livingston) found to have much less absorption than expected

Sideband Recycling Gain
LIGO 4K Hanford IFO

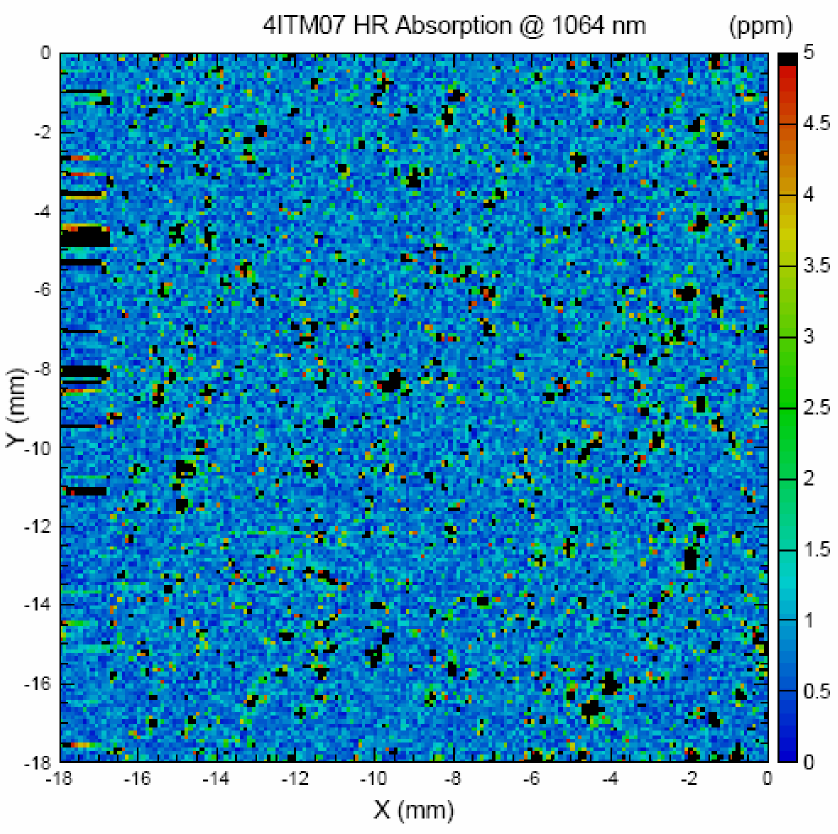
Initial LIGO Thermal Compensation Design

- **8 W CO_2 laser directly projected onto mirrors**
  - Ring heater not used to minimize installation time in vacuum
  - Scanning laser not used to avoid Shack-Hartmann sensors and radiation pressure issues
- **Different masks used to compensate for high or low absorption**
- **Laser power controlled by acousto-optic modulator (H2) and rotating polarization plate (H1, L1)**
- **Power controlled by feedback from IFO channels**



Bench Tests of H1:ITMx

- H1:ITMx shipped to Caltech immediately after removal
- Absorption measured using photothermal common-path interferometry
- Background < 1 ppm
- Significant outliers with absorption > 40 ppm



Dust source of absorption?

- Soot from brush fire in 2000?
- Attracted by charged surface?
- Insufficient cleaning and handling procedures?

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
- Absorption and scatter high in Initial LIGO
    - Both at levels that would not be acceptable in Advanced LIGO

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)

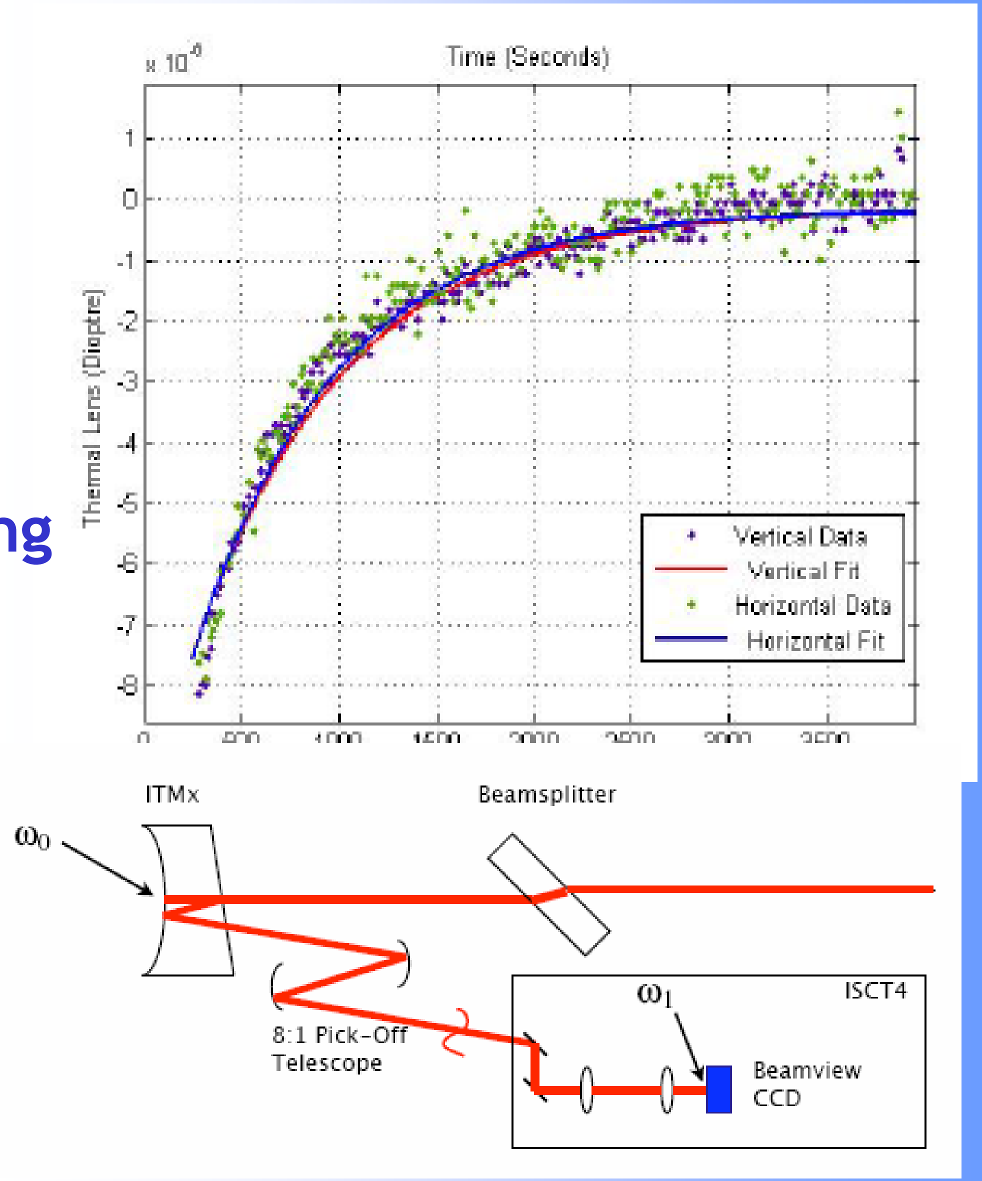
What we need

- 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.

Scatter in Initial LIGO

Excess Absorption at Hanford

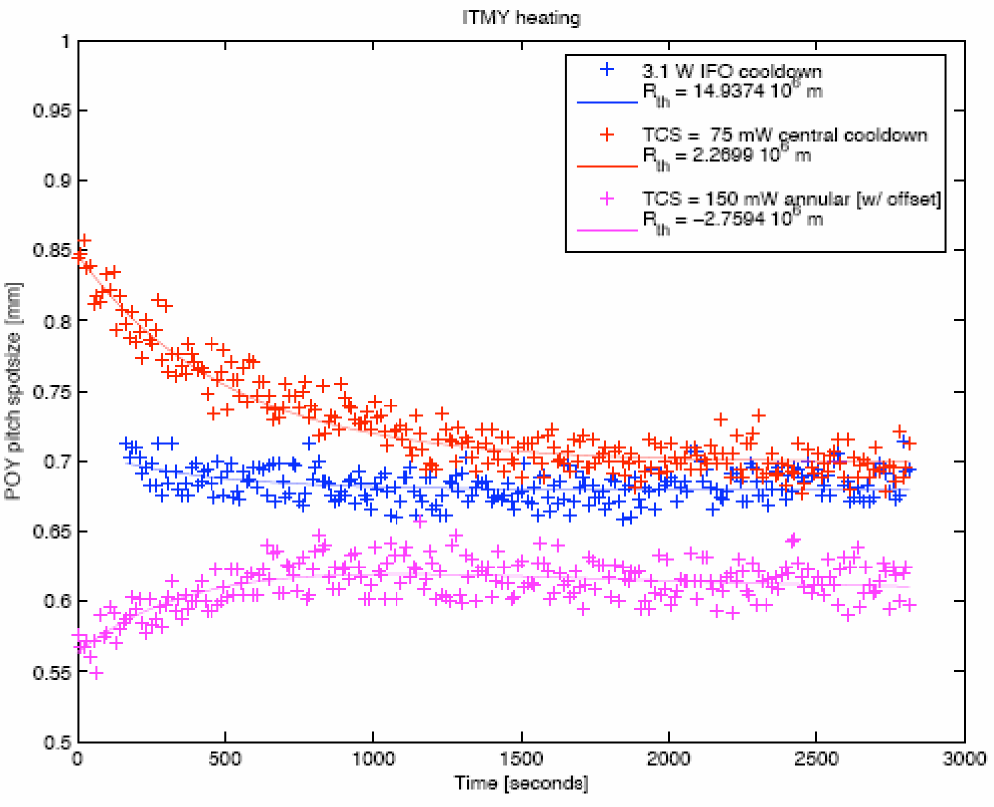
- **Three techniques used to determine source of excess absorption**
    - Change in g factor
    - Thermal compensation power
    - Change in spot size
- **Fairly consistent result (assuming absorption in HR coating)**
    - ITMx 26 ppm
    - IMTy 14 ppm
    - Design 1 ppm
- **Resulting changes**
    - ITMx replaced
    - ITMy drag wiped *in situ*

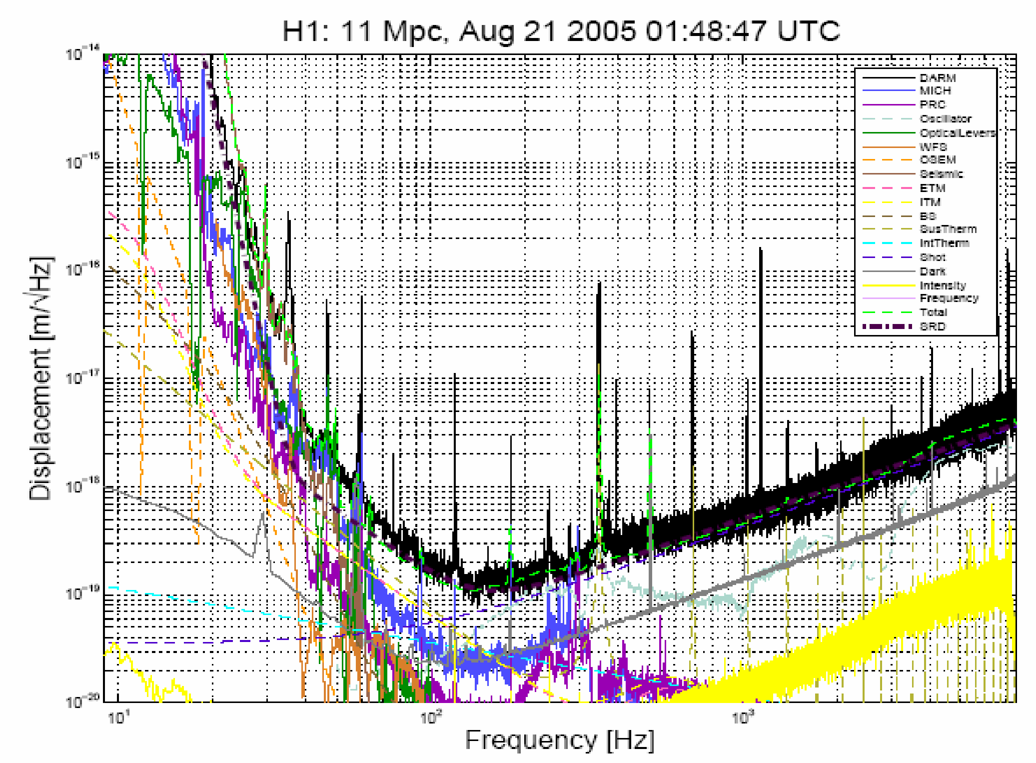


Spot size measurements: Data and technique

Absorption improvement at Hanford

- ITMx replaced with spare optic
- ITMy drag wiped in place
- Both optics (ITMx and ITMy) show improved absorption
    - Both < 3 ppm

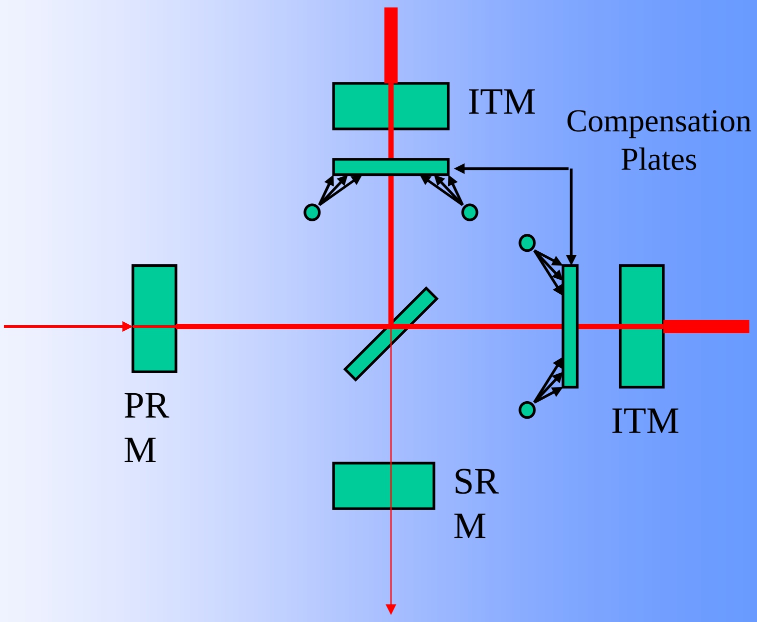




- Power 6.8 W - mode cleaner
- Shot noise at design level
- 15 Mpc binary neutron star inspiral range

Thermal Compensation Upgrades and Challenges

- Initial LIGO compensation effective at 100 mW absorbed
- Advanced LIGO expected to have 350 mW absorbed
- Cleanliness and handling will be crucial
  - Need to keep absorption down
- Potential improvements for advanced detectors
  - Graded absorption masks
  - Scanning laser system
  - Compensation plate in recycling cavity
  - Graded absorbing AR coating
  - DC readout, reducing requirements on RF sidebands
- Challenges
  - Greater sensitivity
  - New materials – sapphire ~ 20 ppm/cm absorption
  - Compensation of arm cavities
  - Inhomogeneous absorption
  - Noise from CO2 laser



Advanced LIGO
Thermal Compensation

- Ring heaters simplest compensation system
  - » Adds a lot of unnecessary heat
  - » Could cause thermal expansion of other parts
- Scanning laser system causes noise
  - » Jumps in location cause step function changes in thermal expansion
  - » Harmonics of jump frequency could be in-band
  - » Could require feedback with Hartmann sensors or similar
- Staring laser system works on Initial LIGO
  - » Could require unique masks for each optic
  - » Unique masks could be inappropriate as system is heating up
  - » CO2 laser noise still a problem