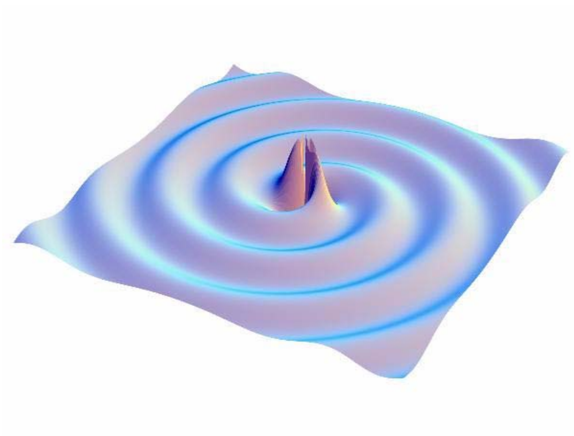
Optical Coatings for Gravitational Wave Detection

Gregory Harry
Massachusetts Institute of Technology
- On Behalf of the LIGO Science Collaboration -

July 2, 2004
Optical Interference Coatings
Conference – Tucson AZ

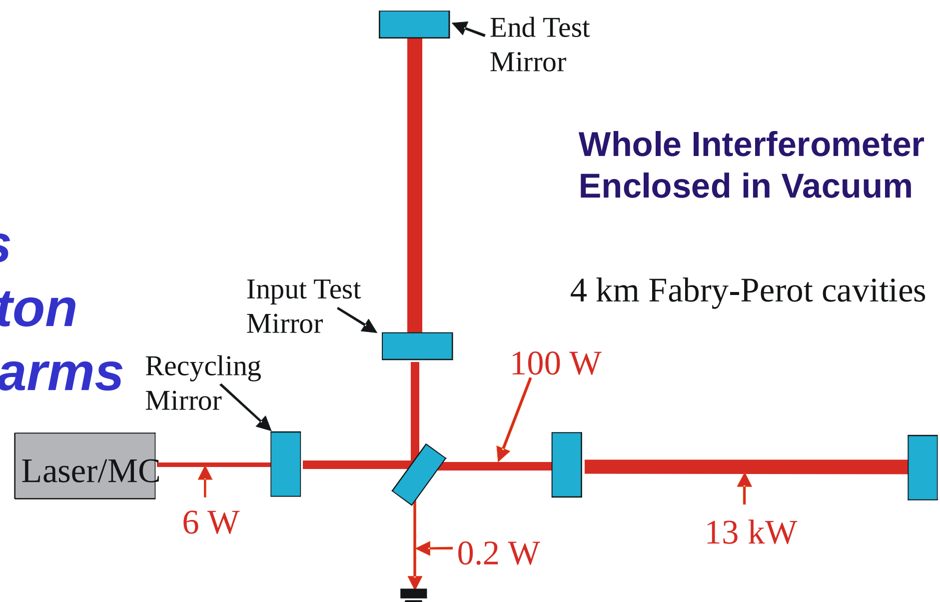
Gravitational Wave Detection



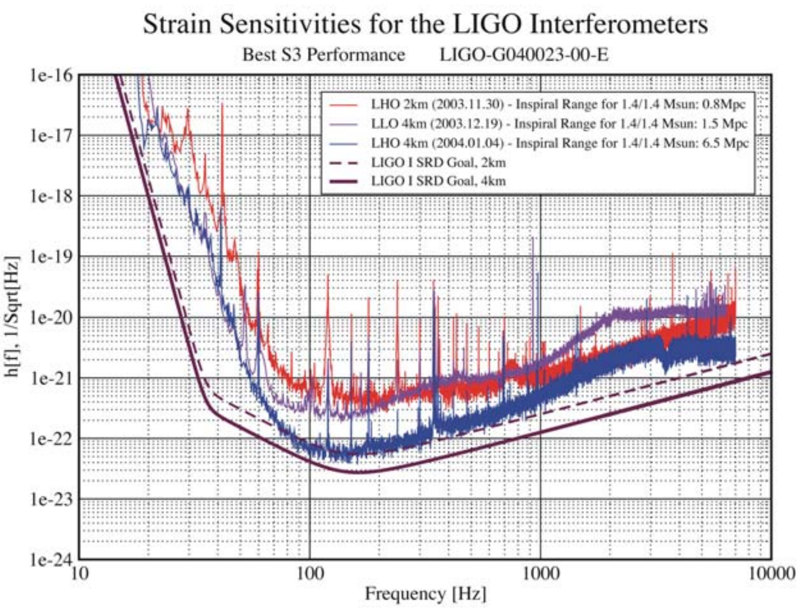
- *Gravitational waves predicted by Einstein*
- *Accelerating masses create ripples in space-time*
- *Need astronomical sized masses moving near speed of light to get detectable effect*

LIGO

- *Two 4 km and one 2 km long interferometers*
- *Two sites in the US, Louisiana and Washington*
- *Michelson interferometers with Fabry-Perot arms*
- *Whole optical path enclosed in vacuum*
- *Sensitive to strains around 10^{-21}*

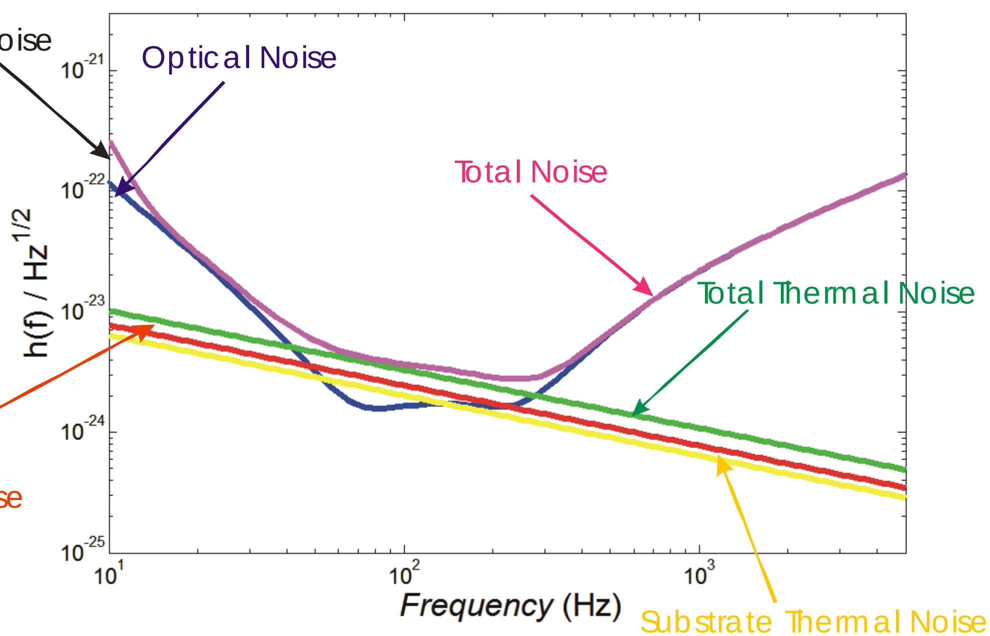


Interferometer Sensitivity



- ***Measured sensitivity of initial LIGO 1/2004***
- ***Nearing design goal***
- ***Hanford 4 km within a factor of 2 near 100 Hz***

- ***Design sensitivity of proposed Advanced LIGO***
- ***Factor of 15 in strain improvement over initial LIGO***
- ***Thermal noise from mirror substrates and coatings sets sensitivity limit***



LIGO-G040254-00-R

Coating Thermal Noise

$$S_F(f) = 4 k_B T \, Re[Z]$$

- *Fluctuation-Dissipation Theorem predicts noise from mechanical loss*
- *Proximity of coating to readout laser means thermal noise from coatings is directly measured*
- *Need low mechanical loss coatings while still preserving low optical loss, low scatter, reflectivity*
- *Initial LIGO has 40 layer silica/tantala dielectric coatings optimized for low optical absorption*

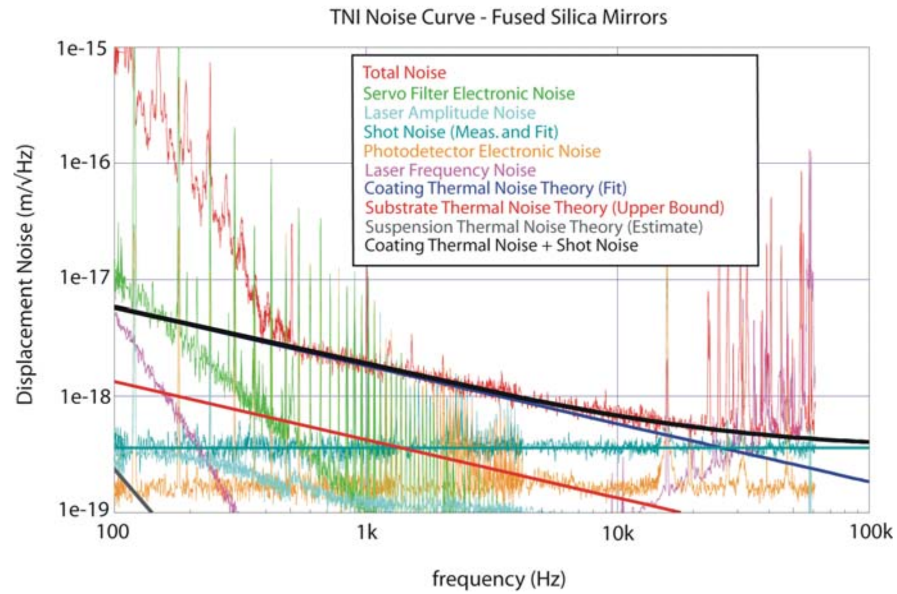
Advanced LIGO Coating Requirements

Parameter	*Requirement*	*Current Value*
Loss Angle ϕ	$5\ 10^{-5}$	$1.5\ 10^{-4}$
Optical Absorption	*0.5 ppm*	*1 ppm*
Scatter	*2 ppm*	*20 ppm*
Transmission	*5 ppm*	*5.5 ppm*

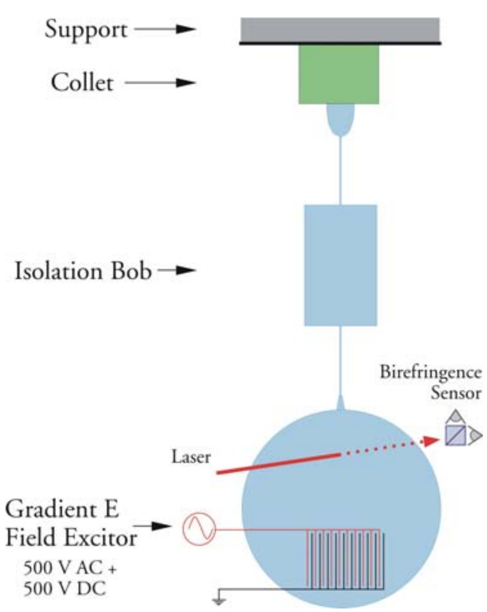
Coating Mechanical Loss Experiments

Direct Measurement of Thermal Noise Using Prototype Interferometer

- ***LIGO/Caltech's Thermal Noise Interferometer***
- ***1 cm long arm cavitites, 0.15 mm laser spot size***
- ***Consistent with ~ 4 10^{-4} coating loss angle***



Measurement of Coating Mechanical Loss From Modal Q Values



- ***Test coatings deposited on silica substrates***
- ***Normal modes (2 kHz to 50 kHz) decay monitored by interferometer/birefringence sensor.***
- ***Coating loss inferred from modal Q and finite element analysis modelling of energy distribution***
- ***Can examine many different coatings fairly quickly***

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Results

Coating Mechanical Loss

Layers	Materials	Loss Angle
30	$\lambda/4\ SiO_2$ - $\lambda/4\ Ta_2O_5$	$2.7\ 10^{-4}$
60	$\lambda/8\ SiO_2$ - $\lambda/8\ Ta_2O_5$	$2.7\ 10^{-4}$
2	$\lambda/4\ SiO_2$ – $\lambda/4\ Ta_2O_5$	$2.7\ 10^{-4}$
30	$\lambda/8\ SiO_2$ – $3\lambda/8\ Ta_2O_5$	$3.8\ 10^{-4}$
30	$3\lambda/8\ SiO_2$ – $\lambda/8\ Ta_2O_5$	$1.7\ 10^{-4}$
30	$\lambda/4\ SiO_2$ – $\lambda/4\ Ta_2O_5$ doped with low [TiO_2]	$1.8\ 10^{-4}$
30	$\lambda/4\ SiO_2$ – $\lambda/4\ Ta_2O_5$ doped with high [TiO_2]	$1.6\ 10^{-4}$

- *Loss is caused by internal friction in materials, not by interface effects*
- *Differing layer thickness allow individual material loss angles to be determined*

ϕ_{Ta2O5} = $4.6\ 10^{-4}$, $2.8\ 10^{-4}$, $2.4\ 10^{-4}$

ϕ_{SiO2} = $0.2\ 10^{-4}$

ϕ_{Al2O3} = $0.1\ 10^{-4}$

ϕ_{Nb2O5} = $6.6\ 10^{-4}$

Goal : $\phi_{coat} = 5\ 10^{-5}$

Future Plans

- *Continue with TiO_2 doped Ta_2O_5 up to stability limit of TiO_2 films*
- *Examine other dopants in Ta_2O_5*
- *Examine other high index materials*
- *Improve stoichiometry of Ta_2O_5, correlate with optical absorption*
- *Examine relationship between annealing and mechanical loss*
- ***Need more input and collaboration with material scientists and optical engineers***

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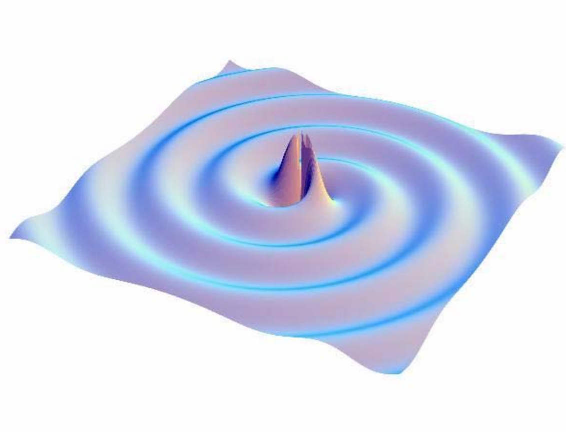

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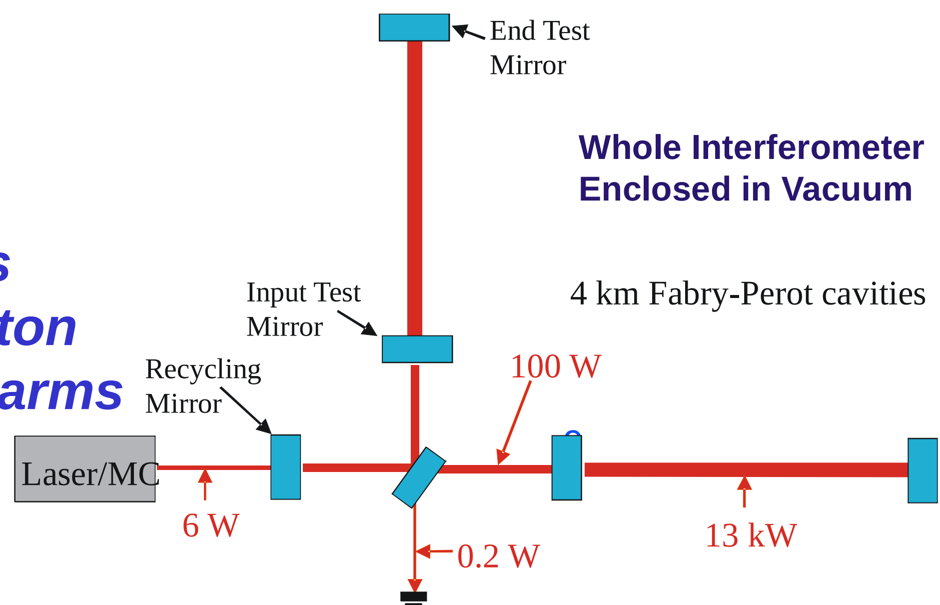

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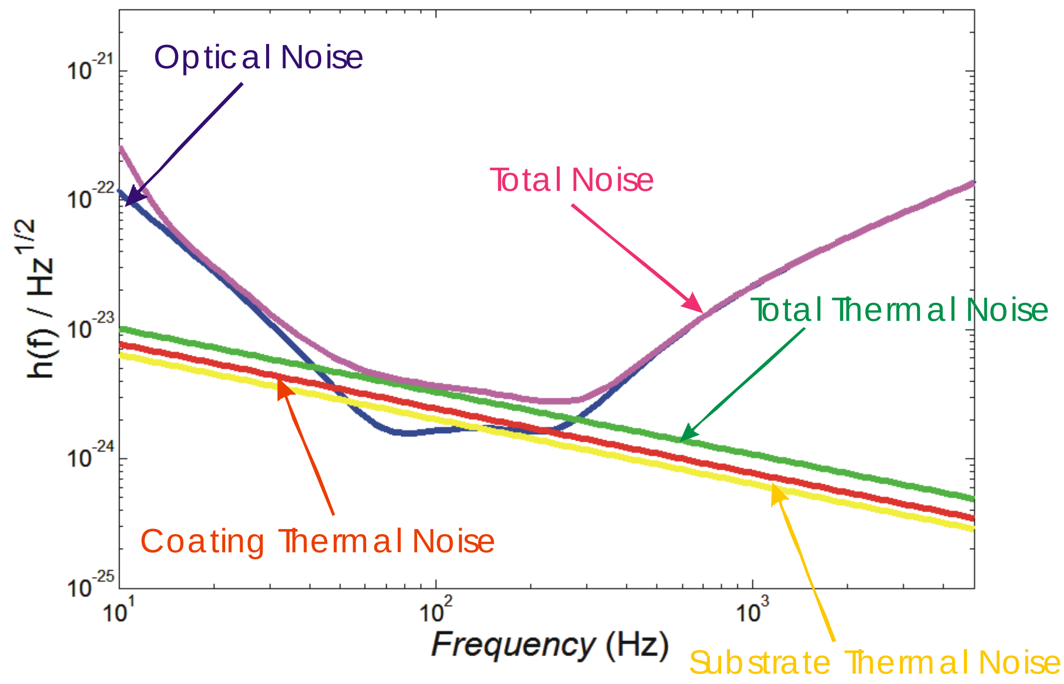
Coating Thermal Noise

- *Mechanical loss causes thermal noise according to FDT*
- *Dielectric optical coating can have high mechanical loss compared to silica substrates*
- *Thermal noise from the mirror coatings will set the sensitivity limit in Advanced LIGO*
- *There is not much data on internal friction in optical thin films, and not much theoretical guidance on reducing it*
- *The coating must also meet strict optical standards, sub ppm absorption, 2 ppm scatter, 5 ppm HR transmission*

Proposed Advanced LIGO sensitivity



Results and Plans

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Future Plans

SMA/Virgo: further TiO_2-doped Ta_2O_5

CSIRO: improving stoichiometry in Ta_2O_5 and effects of annealing