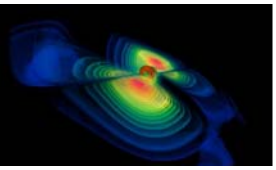
The importance of Coatings for Interferometric Gravitational Wave Observatories

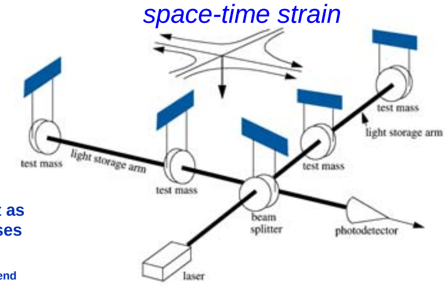
Riccardo DeSalvo for the Coating group riccardo@caltech.edu



Simulation of Gravitational waves emitted by Two inspiralling Black holes

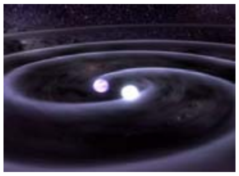
What is a GW observatory: Detecting the space-time strain of Gravitational Waves using laser Interferometry

Power-Recycled Michelson Interferometer with Fabry-Perot Arm Cavities

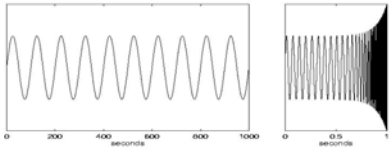


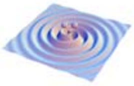
Suspended mirrors act as "free-falling" test masses (in horizontal plane) for frequencies $f >> f_{pend}$

What are Gravitational Waves and how strong they are



Gravitational waves are emitted by orbiting compact bodies (Neutron Stars, Black Holes) and other dense astrophysical objects.
They generate strain in the space-time travelling at the speed of light
The GW strain is measured by the adimensional unit h: $h = \Delta L / L$

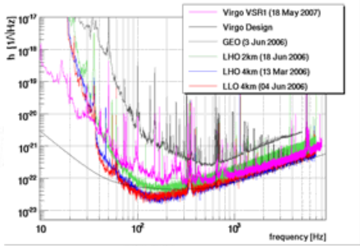




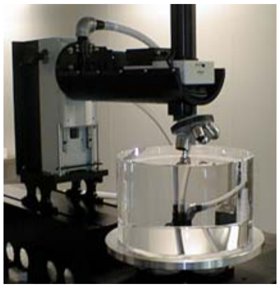
in Terrestrial detector a pair a Neutron Stars inspiralling at a few tens of Megaparsec from Earth generate strain $h \sim 10^{-22} - 10^{-21}$
Which for interferometer arm length
$L \sim 4$ km (LIGO) means a physical length change $\Delta L \sim 10^{-18}$ m

How do we measure 10^{-18} m movements

We measure lengths interferometrically.
With a single photon we can measure with a precision of 1/2 λ (0.5 μm) (indetermination principle)
To measure 1/4 λ (0.25 μm) we need at least 4 photons
To measure 10^{-19}m @ 100 Hz we need 1 MW of standing power on our mirrors.
The mirror coatings need very low losses (<0.25 ppm) not to overheat and deform the mirror
A Thermal Compensation System (heat projected to specific points) is needed to maintain proper optical properties



Strain sensitivity of the interferometers in the present network of GW Observatories



40 cm Fused Silica Mirror substrate Pre-coating inspection at LMA Lyon

Measurement by Australian Center for Precision Optics, a part of CSIRO

Questions for you

- We are looking for other materials and coating techniques, Can you help?
- Can X-ray physics tell us something about the losses in our coatings?
- Why silica in coatings has so much more loss (10^{-4}) than in bulk (10^{-9})
- Is it an intrinsic property of thin layers? Can we make layers less lossy and increase the GW interferometer sensitivity?
- How else can you help us?

LIGO-G080027-00-R

http://www.ligo.caltech.edu/

Your presenter is easy to find, just find the beard!
Please talk with me, your comments and suggestions may help and will be greatly appreciated

How can we pretend to measure 10^{-18} m bouncing photons on the mirror electrons

Atoms are 10^{-10}m
electrons thermal movements are a fraction of that, say 10^{-12}m
To measure 10^{-20} m we must average over a large number of electrons by means of a large laser spot size on the mirror.
Happily Avogadro gave us a large number to play with!

How thermal noise hurts GW detectors

The mirror is an elastic body.
The mirror surface can be regarded as a mechanical oscillator.
The thermally induced and GW induced position fluctuation are indistinguishable.
The interferometer sensitivity is equal to the longitudinal mirror TN / arm length
Thermally induced fluctuations (dissipation) limit the sensitivity and must be minimized.

The advanced detectors will be limited by mirror and suspension thermal fluctuations.

How do we measure losses in materials

We measure ring-down
a- in test masses for the bulk
b- in thin coated cantilevers for the coatings

QuickTime™ and a decompressor are needed to see this picture.

What is thermal noise?

Excite a mechanical oscillator with a stored elastic energy $E = \frac{1}{2} k x^2$
Its motion will decay with a time constant τ
Every τ seconds it will shed into the thermal bath a fraction (1-1/e)*E = 0.63E

typical ring-down curve

Which means that it dissipates a power $W_{diss} = \frac{0.63E}{\tau}$
This process continues forever:
At thermal equilibrium it must be $< E_{thermal} > = K_B T = \frac{1}{2} k < x^2 >$
But the dissipation also continues unhindered

It means that at thermal equilibrium $W_{diss} = \frac{0.63 K_B T}{\tau}$

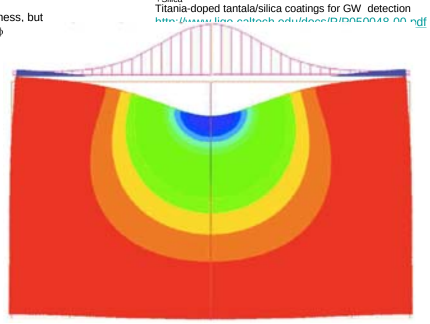
the thermal noise power disturbing the oscillator is inversely proportional to the pendulum Quality factor!
It means that at thermal equilibrium, after a time τ the pendulum will still oscillate with amplitude <x>
but with completely different and random phase.
It will have lost information of its previous position.
Mathematically this is known as Fluctuation-Dissipation theorem.
Fluctuations of the surface are proportional to dissipation in the materials

Why is coating so important?

To calculate the noise we need to calculate the dissipation of the system
Only the dissipation seen by the observable is of importance (in a pendulum all dissipation relevant to its motion is in the flexing points at the hinges. Losses along the pendulum arm that does not bend is unimportant).
How do we calculate what dissipation is "visible" for a beam reflecting on a mirror?
Four steps:
1- Consider the beam profile as a pressure profile applied to the mirror surface
2- Calculate with F.E.M. the deformation and deformation energy in every point of the mirror.
I3- n Each finite element calculate the loss per cycle (multiply the deformation energy X loss angle)
4- Add up the elemental losses and apply the fluctuation-dissipation theorem.

Is the coating loss important?
The coating is only 10~20 μm thick, against the 200 mm mirror thickeness, but
The loss in the substrate $\phi \sim 10^{-9}$ while the loss in the coating layers is ϕ
Also the coating is the part most "compressed" by the light beam.
The coating ends up being the dominant noise source

$\phi_{Tantala} = 4.5\ 10^{-4}$
$\phi_{Titania\text{-}doped\ Tantala} = 2.4\ 10^{-4}$
$\phi_{Silica} = 0.5\ 10^{-4}$
Titania-doped tantala/silica coatings for GW detection
http://www.ligo.caltech.edu/docs/P/P050048-00.pdf



Coating thermal noise measurement in the TNI interferometer

Laser spot "compressive" energy distribution on a mirror test mass - - laser beam sensitivity to material losses

What are the sensitivity limiting factors

Thermal Noise induced by mechanical losses in the mirror coating materials is the main limiting factor of the Interferometer sensitivity.
In the original Silica-Tantala coatings TN was dominated by the dissipation in the Tantala layer.
To reduce the impact of the mirror thermal noise limitation we took the following steps:
- maximize the surface sampled by the beam (large spot size and, in future, flat-top beams)
- LMA developed a Titania doped Tantala, a high refraction material with less mechanical losses
- we redesigned the coating structure different from the traditional 1/4λ-1/4λ to minimize the impact of the (doped) Tantala layers