Discussion of the Advanced LIGO design and sensitivity

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Overview

- LIGO optical design
- Broadband stationary noises
  - Environmental noises
  - Fundamental noise sources
  - Technical noise sources
- Future plans and goals
Michelson interferometer

- Measures differential length of two arms using the detector at the antisymmetric port
Optical layout

Ground motion \(10^{-6}\) m

- 22W laser emitting at 1064 nm
- 45MHz oscillator
- 9MHz oscillator

5 longitudinal degrees of freedom
- differential arm (GW)
- common arm
- Michelson interferometer
- power recycling cavity
- signal recycling cavity

10 km path

100 kW power recycling

800W signal recycling
LIGO optical design

- We need nice, robust and low noise instrument
- Quantum noise
- Resonators
Classical picture of light

\[ P = AA^* = (\bar{A} + a_{cl})(\bar{A}^* + a_{cl}^*) \]
\[ P_{ac} = \bar{A}a_{cl}^* + \bar{A}^*a_{cl} \]

where \( \bar{A} \) is a static DC field

\( a_{cl} \) is an oscillating AC field (signal or noise)
Classical picture of light

\[ P_1 = \frac{1}{2} (\bar{A} a_{cl}^* + \bar{A}^* a_{cl}) \]

\[ P_2 = \frac{1}{2} (\bar{A} a_{cl}^* + \bar{A}^* a_{cl}) \]
Classical picture of light

\[ P_1 = \frac{1}{2} (\bar{A}a_{cl}^* + \bar{A}^* a_{cl}) \]

\[ P_2 = \frac{1}{2} (\bar{A}a_{cl}^* + \bar{A}^* a_{cl}) \]

\[ \text{Magnitude, W/Hz}^{1/2} \]

\[ \text{Frequency, Hz} \]
Classical picture of light

\[ P_1 = \frac{1}{2} (\bar{A} a_{cl}^* + \bar{A}^* a_{cl}) \]

\[ P_2 = \frac{1}{2} (\bar{A} a_{cl}^* + \bar{A}^* a_{cl}) \]

Free running laser
PD1
PD2
Classical picture of light

\[ P_1 = \frac{1}{2} (\bar{A}a_{cl}^* + \bar{A}^* a_{cl}) \]

\[ P_2 = \frac{1}{2} (\bar{A}a_{cl}^* + \bar{A}^* a_{cl}) \]
Quantum picture of light

\[ P_1 = P_{cl,1} + \frac{1}{2} \left( \bar{A}(a_1^* + a_2^*) + \bar{A}^*(a_1 + a_2) \right) \]

\[ P_2 = P_{cl,2} + \frac{1}{2} \left( \bar{A}(a_1^* - a_2^*) + \bar{A}^*(a_1 - a_2) \right) \]
Quantum picture of light

\[ P_1 = P_{cl,1} + \frac{1}{2} \left( \bar{A}(a_1^* + a_2^*) + \bar{A}^*(a_1 + a_2) \right) \]

\[ P_2 = P_{cl,2} + \frac{1}{2} \left( \bar{A}(a_1^* - a_2^*) + \bar{A}^*(a_1 - a_2) \right) \]
Quantum noise in the Michelson interferometer

DC power at the anti-symmetric port

\[ P_{as} = P_{in} \sin^2 \phi, \text{ where} \]

\[ \phi = 2\pi \frac{x_0}{\lambda} \ll 1 \text{ is a small detuning} \]

Optical transfer function

\[ \frac{dP_{as}}{dx} = \frac{P_{in}}{\lambda} 4\pi \sin \phi \cos \phi \]

Shot noise in units of length is

\[ x_{shot} = \frac{\lambda}{2\pi \cos \phi} \sqrt{\frac{h\nu}{2P_{in}}} = 4.34 \times 10^{-18} \sqrt{\frac{125W}{P_{in}}} \frac{m}{\sqrt{\text{Hz}}} \]
Equation of for the intracavity field

\[ \bar{A}_{res} = \sqrt{T_i} \bar{A}_{in} + \sqrt{1 - T_i} \sqrt{1 - T_e} \sqrt{1 - X} \bar{A}_{res} \]

Build-up

\[ b = \frac{\bar{A}_{res}}{\bar{A}_{in}} = \frac{2\sqrt{T_i}}{Y}, \text{ where} \]

\[ Y = T_i + T_e + X \] is the total loss in the cavity
Optimal design

» Maximize power in the arms
» Minimize power going through the substrates
» Filter laser noises
» Optimize response in the frequency range 10Hz-10kHz

Power in the arms is limited by the optical losses

\[
\frac{1}{2} G_{prc} G_{arm} = \frac{1}{X}
\]
Quantum noise
Quantum noise

![Graph showing quantum noise magnitude vs frequency](image)

- **Magnitude, m/Hz**
  - $10^{-17}$
  - $10^{-18}$
  - $10^{-19}$
  - $10^{-20}$
  - $10^{-21}$

- **Frequency, Hz**
  - $10^1$
  - $10^2$
  - $10^3$
  - $10^4$

- **Types**
  - Michelson type
  - Initial LIGO type
Quantum radiation pressure noise

Power fluctuations in the arm

\[ P_m = ? \]
Quantum radiation pressure noise

Power fluctuations

\[ P_m = \sqrt{2h\nu P_{arm} b} \]

vacuum field also resonates and drives suspended mirrors

\[ F_m = \frac{2P_m}{c} \]

\[ x_m = \frac{F_m}{M\omega^2} \]
Quantum noise

Magnitude, m/Hz^{1/2}

Frequency, Hz

Michelson type
Initial LIGO type
Equation for the intracavity field

\[ a_{res}(t) = \sqrt{T_i}a_{in}(t) + \left(1 - \frac{Y}{2}\right)a_{res}(t - \tau) \]

where \( \tau = \frac{2L}{c} \) is the round trip time.

Solution to this equation is

\[ \tau \dot{a}_{res} + \frac{Y}{2}a_{res} = \sqrt{T_i}a_{in} \quad \text{and} \quad a_{res}(\omega) = \frac{\sqrt{T_i}a_{in}(\omega)}{i\omega \tau + \frac{Y}{2}} \]
Advanced LIGO

- Laser: 22W, 1064 nm
- 45MHz oscillator
- 9MHz oscillator
- 800W
- 85mW
- 25mW
- New mirror
- 100 kW
- 4 km
Quantum noise

Magnitude, m/Hz$^{1/2}$

Frequency, Hz

Michelson type
Initial LIGO type
Advanced LIGO type
Noises

- We need to make noises as low as possible
- Environmental noises
- Fundamental noises
- Technical noises
Environmental noises

- Ground vibrations
- Gravity gradients
- Acoustic noise
Ground motion

» the motion of the optical table is actively controlled
» this motion is passively filtered using multistage suspensions
» gravity gradients are caused by the motion of chambers, people and the ground
Ground motion

![Graph showing ground motion data with different lines representing ground motion in summer, ground motion in winter, HAM table in summer, HAM table in winter, BSC table in summer, BSC table in winter, and GS13 noise. The graph plots frequency in Hz on the x-axis and displacement in m/Hz on the y-axis.](image-url)
Suspension transfer function
Light scattered out from the main beam gets modulated in phase and amplitude and partially scatters back into the main beam.
In theory, fundamental noises should limit sensitivity of the instrument

- Fundamental sensing noises:
  - Shot noise
  - Residual gas noise

- Fundamental displacement noises:
  - Thermal noises
  - Quantum radiation pressure noise
Thermal noise

- LIGO operates at room temperature
- Thermal motion is proportional to $\sqrt{kT}$
- Arises from finite losses present in mechanical systems (need high Q)
- Thermal motion of the atoms in suspension fibers moves the mirror
Fundamental noises

![Graph showing fundamental noises and their frequency response.]

- Quantum noise
- Seismic noise
- Gravity Gradients
- Suspension thermal noise
- Coating Brownian noise
- Coating Thermo-optic noise
- Substrate Brownian noise
- Excess Gas
- Total noise
Technical noises

- Technical noises in the arm cavities include:
  - Laser noises
  - Actuator electronics
  - Residual gas in the chambers
  - Angular motion of test masses
  - Charging noise
- Auxiliary longitudinal and angular degrees of freedom
- Input-output port noises
  - Laser phase and amplitude noises
  - Beam jitter
Laser noises

Ideal laser field

\[ A(t) = A_0 \sin(\omega t + \phi_0) \]

Real laser field fluctuates in amplitude and phase

\[ A(t) = A_0 (1 + A_n(t)) \sin(\omega t + \phi_0 + \phi_n(t)) \]

This noise couples to the gravitational wave channel
Auxiliary degrees of freedom

- Longitudinal from the corner station
- Angular from the arm cavities
Low frequency spectrum

![Graph showing various noise sources at low frequencies](graph.png)
High frequency spectrum
Conclusions

☑ Optical design of the Advanced LIGO is optimized for the frequency range 10Hz - 10kHz
☑ There is an unknown noise source at 20Hz - 100Hz
☑ Above 100Hz sensitivity is limited by quantum noise
☑ Future goals include the upgrade of the current facility and construction of a longer facility

https://dspace.mit.edu/handle/1721.1/28646
http://thesis.library.caltech.edu/8899/
LIGO Scientific Collaboration
Extra slides
If mirror surfaces are charged, ambient electric fields couple to gravitational wave channel

Ion gun was developed to discharge the mirrors
Laser noises are filtered at 0.6 Hz by the coupled cavity pole. Extra coupling mechanism comes from high-order modes.
Noise transients

- Electronic failures
- Seismic noise
- Acoustic transients
- Scattered light noise
- Faulty radio frequency modulators
- Dust particles
Noise transients
Beam jitter filtering

Input mode cleaner filters pointing fluctuations
Future

» What do we ultimately need?
» Medium term goals
» Long term goals
Squeezed states of light

- reduce quantum noise
- inject squeezed vacuum state through the AS port
Squeezed states of light

Sub-quantum noise level has been demonstrated

Typical noise without squeezing
Squeezing-enhanced sensitivity

3.5 dB squeezing
(1.5X reduced noise)

2.1 dB squeezing
(1.27X reduced noise)
Long term goals

- Upgrade current facility (LIGO 3)
  - Thermal noise can be reduced by using cryogenic systems
  - Quantum noise can be reduced by increasing optical power and mirror masses
  - Feedforward cancellation algorithms can be applied to gravity-gradient noises

- R&D for a longer facility (Lungo)
Straw man sensitivity curves