Next Generation Interferometers

TeV ‘06
Madison

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Advanced LIGO

- LIGO mission: detect gravitational waves and initiate GW astronomy
- Next detector
  » Should have assured detectability of known sources
  » Should be at the limits of reasonable extrapolations of detector physics and technologies
  » Must be a realizable, practical, reliable instrument
  » Daily gravitational wave detections

→ Advanced LIGO
The next several years

Between now and AdvLIGO, there is some time to improve…

1) ~Few years of hardware improvements +
   1 ½ year of observations.
2) Factor of ~2.5 in noise, factor of ~10 in event rate.
3) 3-6 interferometers running in coincidence!
Initial and Advanced LIGO

- **Factor 10** better amplitude sensitivity
  - \((\text{Reach})^3 = \text{rate}\)
- **Factor 4** lower frequency bound
- **Factor 100** better narrow-band
- **NS Binaries:**
  - Initial LIGO: \(~15\) Mpc
  - Adv LIGO: \(~200\) Mpc
- **BH Binaries:**
  - Initial LIGO: \(10\, M_\odot, 100\) Mpc
  - Adv LIGO: \(50\, M_\odot, z=2\)
- **Known Pulsars:**
  - Initial LIGO: \(\varepsilon \, 3\times10^{-6}\)
  - Adv LIGO: \(\varepsilon \, 2\times10^{-8}\)
- **Stochastic background:**
  - Initial LIGO: \(\Omega \sim 3\times10^{-6}\)
  - Adv LIGO: \(\Omega \sim 3\times10^{-9}\)
- Noise improvements are mainly above 100 Hz
- Requires good control of technical noise
- NS/NS Ranges: 15 Mpc, 30 Mpc, 200 Mpc
Advanced LIGO Design Features

- **180 W Laser, Modulation System**
- **40 KG Fused Silica Test Masses**
- **Active Seismic Isolation**
  - FUSED SILICA, MULTIPLE PENDULUM SUSPENSION
- **Active Thermal Correction**
- **Power Recycling Mirror (PRM)**
  - $T \sim 6\%$
- **Beam Splitter (BS)**
- **Input Test Mass (ITM)**
- **End Test Mass (ETM)**
- **Signal Recycling Mirror (SRM)**
  - $T = 5\%$
- **Photodiode (PD)**
- **Output Mode Cleaner**
- **GW Readout**
Anatomy of the projected Adv LIGO detector performance

- Newtonian background, estimate for LIGO sites
- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning
Advanced LIGO Design Features

- **180 W Laser, Modulation System**
- **40 Kg Fused Silica Test Masses**
- **Active Seismic Isolation**
- **Fused Silica, Multiple Pendulum Suspension**

Diagram labels:
- **PRM** Power Recycling Mirror
- **BS** Beam Splitter
- **ITM** Input Test Mass
- **ETM** End Test Mass
- **SRM** Signal Recycling Mirror
- **PD** Photodiode
- **GW Readout**
Why use Signal Recycling?

Principal advantage of signal recycling is in power handling.
Ultra Stable Laser

- High power laser: 180 Watts

**Front end**
- Master Oscillator

**Alternative front end**
- 12 W
- 35 W

**high power, injection-locked stage**
- 180 W

- Laser power stabilization (relative power fluctuations ~ 2 x 10^{-9})
- Laser frequency stabilization
  » Wideband frequency actuation for further stabilization (~ 10^{-7} Hz/rHz)
- Pre-mode cleaner for spatial clean-up and high-frequency filtering

Work lead by AEI (Hanover) in collaboration with LZH (Laser Zentrum Hanover)
Input Optics, Modulation

- 40 KG SAPPHIRE TEST MASSES
- ACTIVE ISOLATION
- QUAD SILICA SUSPENSION

Diagram showing the layout of the optical system with labels for LASER, MOD., PRM, BS, ITM, ETM, SRM, PD, and GW READOUT.
Input Optics
(Univ. of Florida)

Electro-optic modulators for phase modulation

From PSL

RF Modulation

MC Mode Matching Telescope

Power Control

Mode Matching Telescope

Mode Cleaner

MC Length Actuation

Continuous variable attenuation

Optical isolation & delivery of IFO reflected beam

IFO Control to ISC

Faraday Isolator

PSL Intensity Stabilization

Mode Matching to IFO, remotely adjustable

Spatial filtering of light; reference for secondary level of frequency stabilization

MC Length and Alignment Sensing

Steering Mirrors

MC ASC Actuation

Optical isolation & delivery of IFO reflected beam
Input Optics

- University of Florida leading development effort
  - As for initial LIGO
- High power rubidium tantany phosphate (RTP) electro-optic modulator developed
  - Long-term exposure at Advanced LIGO power densities, with no degradation
- Faraday isolator from IAP-Nizhny Novgorod
  - thermal birefringence compensated
  - Ok to 80 W – more powerful test laser being installed at LIGO Livingston
Test Masses

40 KG SAPPHIRE TEST MASSES

ACTIVE SEISMIC ISOLATION

FUSED SILICA, MULTIPLE PENDULUM SUSPENSION

ACTIVE THERMAL CORRECTION

INPUT MODE CLEANER

200 W LASER, MODULATION SYSTEM

LASER MOD.

125W

PRM T~6%

ACTIVE ISOLATION

T=0.5%

BS ITM

830KW ETM

SRM T=5%

OUTPUT MODE CLEANER

P D

GW READOUT

In-vacuum Seismic Isolation Platform

Quadruple pendulum test mass suspension
Core Interferometer Optics

Challenges:
- Substrate polishing
- Dielectric coatings
- Metrology
- Substrate procurement

Test Masses: 34cm φ x 20cm
Large beam size on test masses (6.0cm radius), to reduce thermal noise

Compensation plates: 34cm φ x 6.5cm

BS: 37cm φ x 6cm
ITM T = 0.5%

PRM T = 7%

SRM T = 7%

Recycling Mirrors: 26.5cm φ x 10cm

Round-trip optical loss: 75 ppm max
- **Substrates**
  - Fused silica: Heraeus (for low absorption) or Corning
  - Specific grade and absorption depends on optics
  - ITMs and BS most critical (need low absorption and good homogeneity)

- **Polishing**
  - Low micro-roughness (< 1 angstrom-rms)
  - Low residual figure distortion (< 1 nm-rms over central 120mm diameter)
  - Accurate matching of radii-of-curvature
  - Surfaces for attachment of suspension fibers

- **Dielectric coatings**
  - Low absorption (0.5 ppm or smaller)
  - Low scatter (< 30 ppm)
  - Low mechanical loss (< 2e-4)

- **In-house Metrology**
  - ROC, figure distortion, scattering, absorption
Mirror coatings

40 KG SAPPHIRE TEST MASSES

ACTIVE ISOLATION

QUAD SILICA SUSPENSION

COATINGS

ACTIVE THERMAL CORRECTION

T=0.5%

200 W LASER, MODULATION SYSTEM

INPUT MODE CLEANER

LASER MOD.

125W

PRM T~6%

BS ITM

SRM T=5%

OUTPUT MODE CLEANER

PD

GW READOUT

830KW ETM
Test Mass Coatings
(Talks by Pinard, Crooks, Rowan)

- Optical absorption (~0.5 ppm), scatter meet requirements for (good) conventional coatings
- Thermal noise due to coating mechanical loss recognized; LSC program put in motion to develop low-loss coatings
  - Series of coating runs – materials, thickness, annealing, vendors
  - Measurements on a variety of samples
- Ta₂O₅ identified as principal source of loss
- Test coatings show somewhat reduced loss
  - Alumina/Tantala
  - Doped Silica/Tantala
- Need ~5x reduction in loss to make compromise to performance minimal
- Expanding the coating development program
  - RFP out to 5 vendors; expect to select 2
- Direct measurement via special purpose TNI interferometer
- First to-be-installed coatings needed in ~2.5 years – sets the time scale
Thermal Compensation

40 KG SAPPHIRE TEST MASSES

ACTIVE ISOLATION

QUAD SILICA SUSPENSION

ACTIVE THERMAL CORRECTION

COATINGS

T=0.5%

T=5%

LASER MOD.

200 W LASER, MODULATION SYSTEM

INPUT MODE CLEANER

125W

PRM T~6%

BS

ITM

830KW

SRM

OUTPUT MODE CLEANER

GW READOUT
Active Thermal Compensation

- Removes excess ‘focus’ due to absorption in coating, substrate
- Allows optics to be used at all input powers
- Initial R&D successfully completed
  - Ryan Lawrence MIT PhD thesis
  - Quasi-static ring-shaped additional heating
  - Scan to complement irregular absorption
- Sophisticated thermal model (‘Melody’) developed to calculate needs and solution
- Gingin facility (ACIGA) readying tests with Lab suspensions, optics
- Application to initial LIGO in preparation
Seismic Isolation

200 W LASER, MODULATION SYSTEM

LIGO – G060489 – 00 - I
Seismic Isolation: Active Platform

<table>
<thead>
<tr>
<th>Requirement</th>
<th>BSC Chamber Value</th>
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<tbody>
<tr>
<td>Payload Mass</td>
<td>800 kg</td>
</tr>
<tr>
<td>Range</td>
<td>± 1 mm, ± 0.5 mrad</td>
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<tr>
<td>Table Noise</td>
<td>$3 \times 10^{-13}$ m/$\sqrt{\text{Hz}}$ @10 Hz</td>
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<tr>
<td>Angular Noise</td>
<td>10 nrad RMS</td>
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Advances in Suspensions

- **Quadruple pendulum:**
  - \( \sim 10^7 \) attenuation @10 Hz
  - Controls applied to upper layers; noise filtered from test masses

- **Seismic isolation and suspension together:**
  - \( 10^{-20} \) m/rtHz at 10 Hz
  - Factor of 10 margin

- Fused silica fiber
  - Welded to 'ears', hydroxy-catalysis bonded to optic
GW Readout

200 W LASER, MODULATION SYSTEM

40 KG SAPPHIRE TEST MASSES

ACTIVE ISOLATION

COATINGS

ACTIVE THERMAL CORRECTION

T = 0.5%

830 KW

OUTPUT MODE CLEANER

GW READOUT

PD

SRM T = 5%

BS

ITM

ETM

125 W

PRM T ~ 6%

MOD.

INPUT MODE CLEANER

LASER
Projected Noise Sources

- Seismic Noise \(10^9\)
- Suspension Thermal Noise \(10^2\)

Quantum Optical Noise is Tunable!
**Opto-mechanical Spring**

Radiation pressure: 
\[ F = \frac{2P}{c} \]

Detuned Cavity \( \Rightarrow \frac{dF}{dx} \)

- \( \frac{1}{2} \) MW in the arms \( \Rightarrow \)
- ‘Optical Bar’ detector
- \( \sim 75 \) Hz unstable opto-mechanical resonance
- High Bandwidth servos

Optical Spring stiffness \( \sim 10^7 \text{ N/m} \)

BMW Z4 \( \sim 10^4 \text{ N/m} \)

Angular spring resonance \( \sim 2 \text{ Hz} \)
Most of the sensitivity comes from a band around 50 Hz.
There's more…

- **Power Recycling** mirror
- Laser
- **End Test Mass**
- **Input Test Mass**
- **Arm Cavity Q**
- **Signal Cavity Q**
- **50/50 beam splitter**
- **GW signal**
- **Signal Recycling** mirror

- 125 W
- 2 kW
- 500 kW
30% Sensitivity Improvement

- For only 1 choice of BH mass
- Ignores tidal disruption important for $M > 2.5$

Vallisneri, PRL (2000)
Advanced LIGO

- Initial instruments, data helping to establish the field of interferometric GW detection
- Advanced LIGO promises exciting astrophysics
- Substantial progress in R&D, design
- Still some meaty problems
- Installation in 2011, Data ~2013-2014
- Steady stream of gravitational wave signals