Future LIGO Interferometers

Moriond 07
La Thuille, Italy

Rana Adhikari
Caltech
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…
  - Few years of hardware improvements + 1 ½ year of observations.
  - Factor of ~2.5 in noise, factor of ~10 in event rate.
  - 3-6 interferometers running in coincidence!

Enhanced LIGO details in “Lessons from LIGO-I” talk on Thursday
Advanced LIGO Sketch

180 W LASER, MODULATION SYSTEM

INPUT MODE CLEANER

40 KG FUSED SILICA TEST MASSES

ACTIVE THERMAL CORRECTION

T ~ 1%

FUSED SILICA, MULTIPLE PENDULUM SUSPENSION

ACTIVE SEISMIC ISOLATION

125W

PRM  T~6%

BS

83 GW

ITM

ETM

SRM  T=5%

OUTPUT MODE CLEANER

PD

GW READOUT

PRM  Power Recycling Mirror
BS  Beam Splitter
ITM  Input Test Mass
ETM  End Test Mass
SRM  Signal Recycling Mirror
PD  Photodiode
<table>
<thead>
<tr>
<th>Parameter</th>
<th>LIGO I</th>
<th>Adv LIGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent strain noise, minimum</td>
<td>3x10^{-23}/rtHz</td>
<td>2x10^{-24}/rtHz</td>
</tr>
<tr>
<td>Neutron star binary inspiral range</td>
<td>15 Mpc</td>
<td>175 Mpc</td>
</tr>
<tr>
<td>Omega GW</td>
<td>3x10^{-6}</td>
<td>1.5-5x10^{-9}</td>
</tr>
<tr>
<td>Interferometer configuration</td>
<td>Power-recycled MI w/ FP</td>
<td>LIGO I, plus signal</td>
</tr>
<tr>
<td></td>
<td>arm cavities</td>
<td>recycling</td>
</tr>
<tr>
<td>Laser Power in Arm Cavities</td>
<td>15 kW</td>
<td>800 kW</td>
</tr>
<tr>
<td>Test masses</td>
<td>Fused silica, 10 kg</td>
<td>Fused Silica, 40 kg</td>
</tr>
<tr>
<td>Seismic wall frequency</td>
<td>40 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Beam size</td>
<td>4 cm</td>
<td>6 cm</td>
</tr>
<tr>
<td>Test mass Q</td>
<td>Few million</td>
<td>200 million</td>
</tr>
<tr>
<td>Suspension fiber Q</td>
<td>Few thousand</td>
<td>~30 million</td>
</tr>
</tbody>
</table>
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

[Diagram showing LIGO's design features with labels for PRM (Power Recycling Mirror), BS (Beam Splitter), ITM (Input Test Mass), ETM (End Test Mass), SRM (Signal Recycling Mirror), and PD (Photodiode).]

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

**Labels:**
- PRM: Power Recycling Mirror
- BS: Beam Splitter
- ITM: Input Test Mass
- ETM: End Test Mass
- SRM: Signal Recycling Mirror
- PD: Photodiode

**Symbols:**
- **Laser**
- **Modulation System**
- **Active Thermal Correction**
- **Output Mode Cleaner**
- **GW Readout**
Why use Signal Recycling?

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

- High power laser: 180 Watts

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)
Test Masses

40 KG SAPPHIRE TEST MASSES

ACTIVE SEISMIC ISOLATION

ACTIVE ISOLATION

FUSED SILICA, MULTIPLE PENDULUM SUSPENSION

830 kW ETM

200 W LASER, MODULATION SYSTEM

INPUT MODE CLEANER

ACTIVE THERMAL CORRECTION

T=0.5%

T=5%

PRM

125W

BS

ITM

SRM

OUTPUT MODE CLEANER

PD

GW READOUT
Core Interferometer Optics

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

Test Masses: 34 cm φ x 20 cm

Large beam size on test masses (6.0 cm radius), to reduce thermal noise

Compensation plates: 34 cm φ x 6.5 cm

Round-trip optical loss: 75 ppm max

BS: 37 cm φ x 6 cm

ITM T = 0.5%

SRM T = 7%

Recycling Mirrors: 26.5 cm φ x 10 cm

PRM T = 7%
Core Optics

Compensation Polish

- **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
Seismic Isolation

40 KG SAPPHIRE TEST MASSES
ACTIVE ISOLATION
QUAD SILICA SUSPENSION

200 W LASER, MODULATION SYSTEM

INPUT MODE CLEANER

COATINGS
ACTIVE THERMAL CORRECTION

125W

PRM T~6%

BS

T=0.5%

ITM

830KW

SRM T=5%

OUTPUT MODE CLEANER

PD

GW READOUT
Seismic Isolation: Active Platform

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

- **Quadruple pendulum:**
  - ~$10^7$ attenuation @10 Hz
  - Controls applied to upper layers; noise filtered from test masses

- **Seismic isolation and suspension together:**
  - $10^{-19}$ m/rtHz at 10 Hz

- **Fused silica fiber**
  - Welded to ‘ears’, hydroxy-catalysis bonded to optic

- **Magnets**

- **Electrostatic**
GW Readout

200 W LASER, MODULATION SYSTEM

40 KG SAPPHIRE TEST MASSES

ACTIVE ISOLATION

QUAD SILICA SUSPENSION

ACTIVE THERMAL CORRECTION

COATINGS

INPUT MODE CLEANER

125W

PRM T=6%

BS

T=0.5%

SRM T=5%

OUTPUT MODE CLEANER

PD

GW READOUT

ETM

830KW
@ the Caltech 40m Lab
Controls and Noise Characterization Prototype

DC Readout Beamline

@ the Caltech 40m Lab
Projected Noise Sources

- **Seismic Noise**: $10^9$
- **Suspension Thermal Noise**: $10^2$

Quantum Optical Noise is Tunable!
Opto-mechanical Spring

- Radiation pressure:
  \[ F = \frac{2 P}{c} \]
- Detuned Cavity \( \Rightarrow \) \( dF/dx \)
  - \( \frac{1}{2} \) MW in the arms \( \Rightarrow \)
  - ‘Optical Bar’ detector
  - \( \sim 75 \) Hz unstable opto-mechanical resonance
  - High Bandwidth servos

**Measured Transfer Functions from the 40m prototype**

**Optical Spring stiffness** \( \sim 10^7 \) N/m

**BMW Z4** \( \sim 10^4 \) N/m

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

- **Power Recycling mirror**
- **Input Test Mass**
- **End Test Mass**
- **Arm Cavity Q**
- **Laser**
- **125 W**
- **2 kW**
- **500 kW**
- **50/50 beam splitter**
- **GW signal**
- **Signal Recycling mirror**
- **Signal Cavity Q**
30% Sensitivity Improvement

Low laser power!
Lower Arm Cavity finesse
Lower SRC finesse
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
- Enhanced LIGO starts now!!
- Installation in 2011, Data ~2013-2014
- Steady stream of gravitational wave signals