Material and components for third generation interferometers: the cryogenic challenges

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Suspension systems and thermal noise

Thermal noise power spectral density (Saulson 1990):

\[ x^2(\omega) = \frac{4k_B Tk\phi(\omega)}{\omega[(k - m\omega^2)^2 + k^2\phi^2]} \]

Materials with low mechanical loss
Operation at low temperatures

Materials, components and systems → UHV and cryogenic compatible

Different cryogenic regimes → 4K, 20K, 120 K

3G: Einstein Telescope, Voyager, Cosmic Explorer

2.5G: KAGRA
<table>
<thead>
<tr>
<th></th>
<th>aLIGO / AdV</th>
<th>A+/V+</th>
<th>KAGRA</th>
<th>CE 1</th>
<th>CE 2</th>
<th>ET-LF</th>
<th>ET-HF</th>
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</thead>
<tbody>
<tr>
<td>Arm Length [km]</td>
<td>4 / 3</td>
<td>4</td>
<td>3</td>
<td>40</td>
<td>40</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Mirror Mass [kg]</td>
<td>40 / 42</td>
<td>40</td>
<td>23</td>
<td>320</td>
<td>320</td>
<td>211</td>
<td>200</td>
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<td>Mirror Material</td>
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<td>sapphire</td>
<td>silica</td>
<td>silica</td>
<td>silicon</td>
<td>silicon</td>
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<tr>
<td>Mirror Temp [K]</td>
<td>295</td>
<td>295</td>
<td>20</td>
<td>295</td>
<td>123</td>
<td>10</td>
<td>290</td>
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<tr>
<td>Suspension Fiber</td>
<td>0.6m/0.7m SiO2</td>
<td>0.6m</td>
<td>0.35m Al2O3</td>
<td>1.2m</td>
<td>1.2m</td>
<td>2m</td>
<td>0.6m SiO2</td>
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<td>Fiber Type</td>
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<td>Fiber</td>
<td>Ribbon</td>
<td>Fiber</td>
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<td>Input Power [W]</td>
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<td>125</td>
<td>70</td>
<td>150</td>
<td>220</td>
<td>3</td>
<td>500</td>
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<td>Arm Power [kW]</td>
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<td>750</td>
<td>350</td>
<td>1400</td>
<td>2000</td>
<td>18</td>
<td>3000</td>
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<td>Wavelength [nm]</td>
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<td>1064</td>
<td>1064</td>
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<td>1550</td>
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<td>NN Suppression</td>
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<td>1</td>
<td>10</td>
<td>10</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Beam Size [cm]</td>
<td>(5.5/6.2) / 6</td>
<td>5.5/6.2</td>
<td>3.5/3.5</td>
<td>12/12</td>
<td>14/14</td>
<td>9/9</td>
<td>12/12</td>
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<tr>
<td>SQZ Factor [dB]</td>
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<td>6</td>
<td>foresee</td>
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<td>10</td>
<td>10</td>
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<tr>
<td>F. C. Length [m]</td>
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<td>unknown</td>
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</tbody>
</table>

Einstein Telescope Pathfinder

40 m Caltech interferometer
Mechanical losses at low temperatures

Hofmann GWADW2013
Mirrors and coatings

Bulk thermal noise: Brownian noise, thermoelastic noise

Coating thermal noise: Brownian, thermo-refractive, thermoelastic

Several coating solutions under investigation (several talks at this conference):
  - Amorphous oxides
  - a-Si, Si
  - AlGaAs/GaAs
  - GaP/AlGaP
Suspension systems: pendulums, cantilevers, actuators, coils, magnets, cabling...
Thermometry

Yeager & Courts 2001
Fundamental properties of materials

Thermal expansion: mechanical stress, different expansion of bonded components

Thermal conductivity: crucial for heat extraction, involving fibers and bonds

Yamada, KIW 2019

Tomaru 2002
Cabling

Requirements: low thermal conductivity, low electrical resistivity, high flexibility, low contamination, robustness against thermal cycling

Conductors

Insulation: Kapton, Pyre-ML, Gore-Tex, alumina..

Optimization of conductor size

\[
\frac{L}{A} = \int_{T_L}^{T_H} \frac{k(T)dT}{\sqrt{Q_H^2 + I^2 \int_T^{T_H} 2\rho(\tau)k(\tau)d\tau}}
\]

Mechanical modeling necessary, as in T0900627

Also: Coils, LVDT, accelerometers
Magnets

Coil-magnet actuators

Barkhausen noise

Candidate material: SmCo (ET-0004A-11)

Strnat+ 1985

Uehara+ 1986
Adhesives

Requirements: bond strength, differential thermal expansion, contamination, robustness against thermal cycling, aging

Ceramic (Ceramabond 571): used down to a few Kelvin (Lee+ 2005, Gerstl+ 2014)

Epoxies: bonding strength increases after degassing, cure temperature and time relevant; tested down to LN2 temperature (Silvera+ 2001)

Suggested: measurement of thermal expansion coefficient; long term testing for aging
Actuation

Technical solutions available down to a few Kelvin:
- Stepper motors
- Piezoelectric motors
- Superconducting film actuators

Solid state lubrication

Sato 2003
Creep at cryogenic temperatures

Suspension wires, cantilever blades...

Candidate materials: steel, CuBe

Generally transient creep investigated in literature

Long term testing suggested
Creep at cryogenic temperatures

Suspension wires, cantilever blades: steel, sapphire, CuBe

310S, Ogata 1990

18-10, Mugnier 1963

Wagner 1991
Contamination

LCGT approach: 4.2 K cryogenic area around mirrors, 300 K vacuum system and 40 K radiation shielding

Miyoki+ 2000: 10 K mirror reflectance constant within ±5 ppm over 1 mo

Miyoki+ 2001: 10 K mirror reflectance decreasing at 0.12 ppm/day over 2 mo

Hasegawa+ 2019: molecular adsorbed layer formation → H₂O

Miyoki+ 2001

Hasegawa+ 2019
Baffles

Stray light reduction

Surface finishing should have low reflectance and low outgassing

Akutsu+ 2016, electroless NiPW plating
Conclusions

• Several ongoing R&D efforts for 3G detectors
• Suspensions operating at cryogenic temperatures topics: materials and solutions
• Investigations needed on some topics