Helium-based cooling concept of the ET-LF interferometer

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Gravitational Wave
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Test mass temperature limitation

Last-stage suspension scheme:

Heat sink at $T_{\text{HeatSink}}$

$T_{\text{Fiber}}(x)$

$Q_{\text{total}} = 200 \text{ mW}$

Analytical calculations

$T_{\text{HeatSink}} \rightarrow 2 \text{ K offers } T_{\text{Mirror}} \leq 10 \text{ K potential}$

4x High-purity fibers ($\varnothing = 3 \text{ mm}$)

$T_{\text{Fiber}}(x) / K$

$16 \text{ K}$

$10 \text{ K}$

$2 \text{ K}$

Silicon (TPRC 1970)

Sapphire (TPRC 1971)

$x / m$

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OU Refrigeration and Cryogenics
He-II: payload heat extraction

Two liquid phases of $^4$He:

- **He-I** (classical liquid helium)
  - Behaviour: ~ideal gas
  
  \[ T_\lambda (1 \text{ atm}) \approx 2.17 \text{ K} \quad \text{if} \quad T > T_\lambda \]
  \[ T < T_\lambda \]

- **He-II** ("two fluid model" [1][2])
  - Normal component
  - Superfluid component
  
  \[ \text{Bose-Einstein condensate} \]

He-II: enhanced heat transfer properties

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TM cryostat cooling: temperature levels

TM-cryostat scheme:

To upper super attenuator

Outer shield

Duct shield

Inner shield

Three temperature stages:

<table>
<thead>
<tr>
<th>Part(s)</th>
<th>Temp. level</th>
<th>Estimated cooling power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer thermal shield</td>
<td>50…80 K</td>
<td>$x\ldots10^3$ W</td>
</tr>
<tr>
<td>Inner thermal shield</td>
<td>5 K</td>
<td>$x\ldots10^2$ W</td>
</tr>
<tr>
<td>Payload heat sink</td>
<td>2 K</td>
<td>$x\ldots1$ W</td>
</tr>
</tbody>
</table>

$T_{\text{InnerShield}} < T_{\text{Mirror}} (~10 \text{ K})$ possible
Helium-based cooling power provision

Basis: He-refrigerator + subcooler

Example: Linde L-Series

He-supplies:
- 50...80 K (HP)
- 5 K (LP)
- 2 K (VLP)

Single refrigerator: large cooling power at three temperature levels

Basic layout: complete cryostat cooling

1. Outer shield cooldown
2. Inner shield cooldown
3. Payload preliminary cooldown
4. Payload link $\rightarrow \sim 5$ K
5. Payload link $\rightarrow \sim 3$ K
6. He-II formation
7. Steady-state (no flow)
Payload thermal link: He-II capillaries

Key boundary conditions:

- Operating pressure: 0.1 MPa
- Capillary length: 30 m
- Capillary cold end temp. (He-II): 1.80 K
- Capillary warm end temp. (He-II): 1.90 K

Dimensioning example (approx.):
10 capillaries with $d_i = 1.8$ mm can extract 200 mW from a payload at 1.9 K over 30 m distance with a $\Delta T$ of only 0.1 K.
1.8 K unit positioning possibilities

Corner cavern scheme:

1.8 K Unit main components:
- Vacuum vessel
- Low-pressure heat exchanger
- Vacuum pumps

Long capillaries offer low-noise cooling potential and flexible positioning of the 1.8 K units.

Vibration propagation via He-II hollow heat links
KAGRA experience on vibration transmission into payload

Sources:

He-II hollow capillaries as heatlinks of ET-LF payload

Payload thermal link operation 1.7…1.9 K

Lower thermal dissipations
- Cryogenic temperatures
- Dissipation-free superfluid component in He-II

![Graph showing thermal conductivity vs temperature for different materials: Silicon, high purity, Sapphire, high purity, 6N-Aluminum, 4He at 0.1 MPa.](image)
Integration of He-II filled capillary into payload

- He-II filled capillary ($\varnothing \leq 3 \text{ mm}$)
- Hollow capillary as suspension fiber
  - Marionette
  - Mirror (?)
- Hollow capillary as external heat links

Source: [1] Payload design from P. Rapagnani: ET LF-Main Features and Constrains (26.04.21)
Prospects

Theoretical description of thermal dissipation in He-II capillaries

Vibrational Noise into payload
- He-II capillaries → suspension fibers and/or heat links
- Cooling system noise

Experimental Proof of Concept
- Ultra-low noise He-cooling system
Thank you for your attention!

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