Helium-based cooling concept of the ET-LF interferometer

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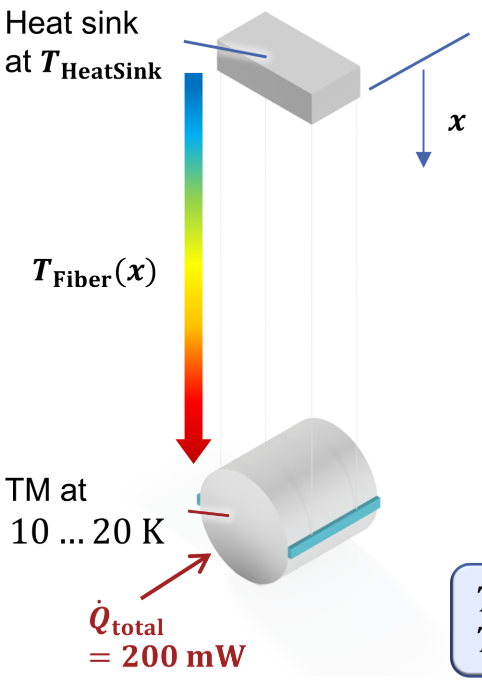
Gravitational Wave
Advanced Detector Workshop
17-21 May 2021

Test mass temperature limitation

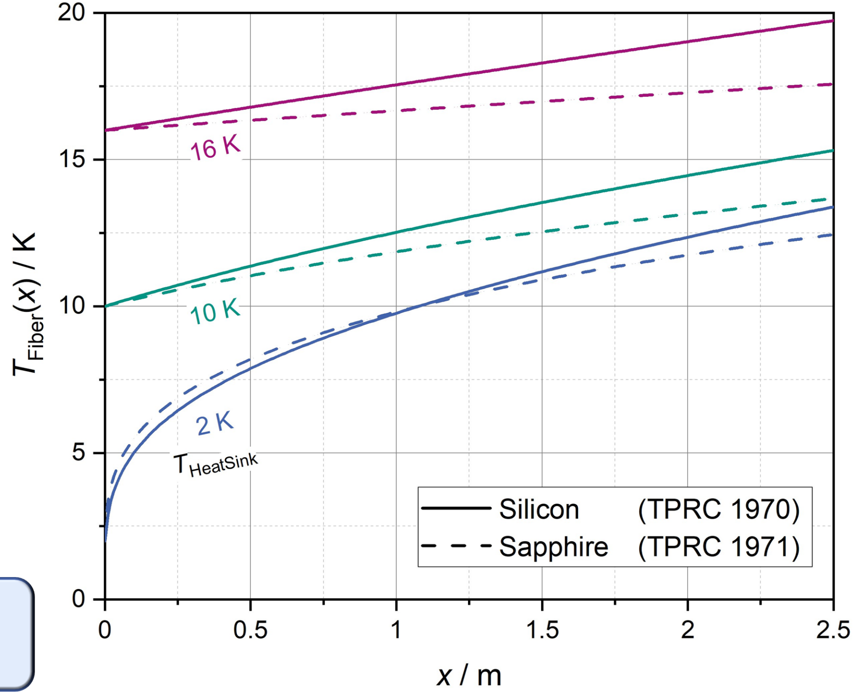
Last-stage suspension scheme:



Analytical calculations

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

4x High-purity fibers ($Ø = 3$ mm)



He-II: payload heat extraction

Two liquid phases of ^{4}He:

- <u>He-I</u> (classical liquid helium)
  - ➢ Behaviour: ~ideal gas

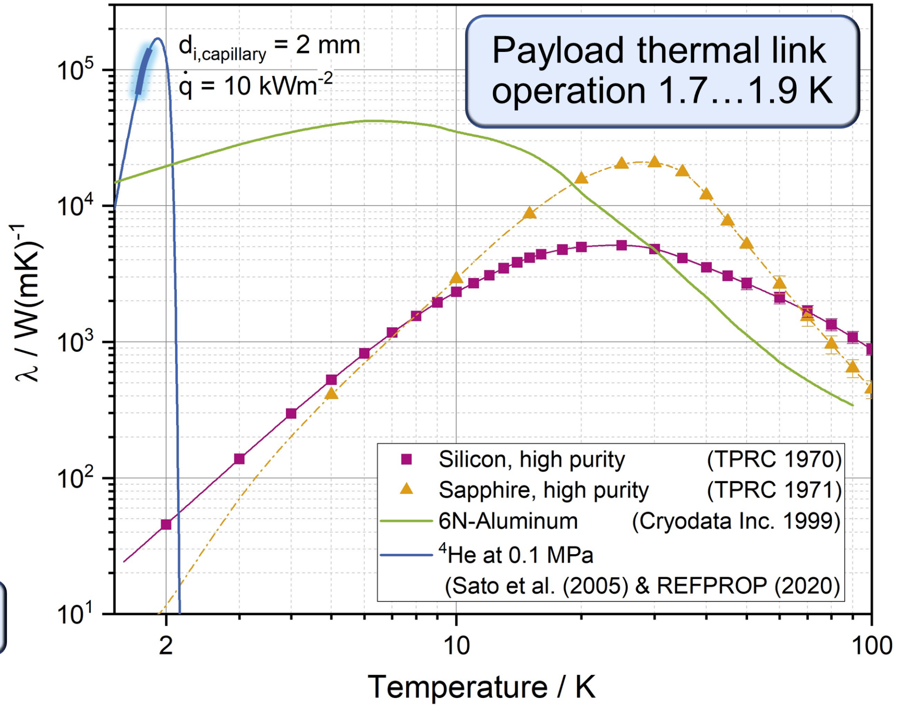
$T > T_\lambda$

$T_\lambda(1\,\text{atm}) \approx 2.17\,\text{K}$

$T < T_\lambda$

- <u>He-II</u> (“*two fluid model*” [1][2])
  - Normal component
  - Superfluid component
    - ➢ Bose-Einstein condensate

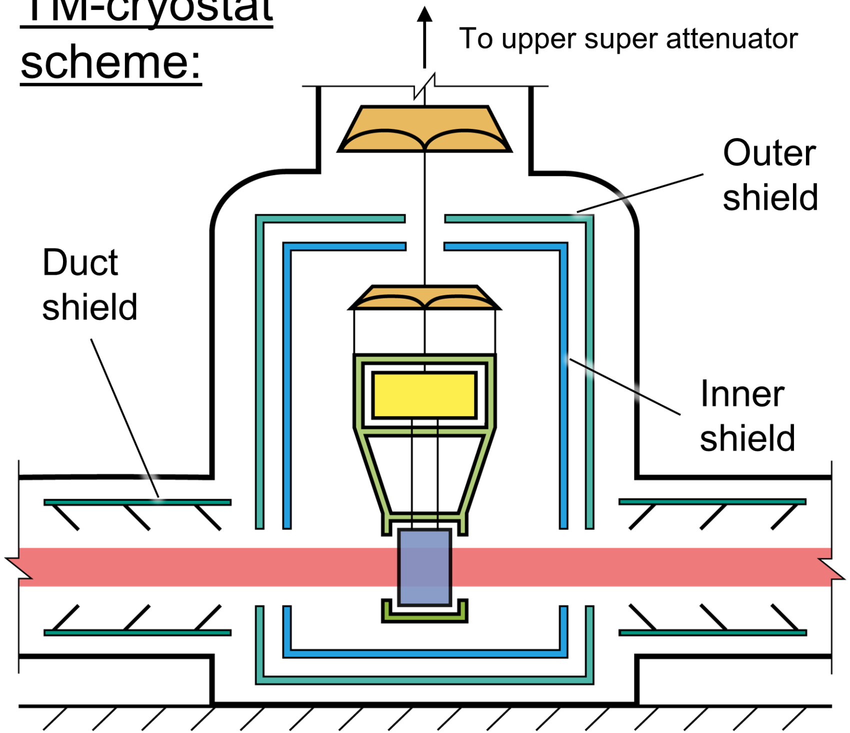
He-II: enhanced heat transfer properties



Sources: [1] Tisza, L. Transport Phenomena in Helium II. Nature 141, 913 (1938).
[2] Landau, L. Theory of the Superfluidity of Helium II. Phys. Rev. 60, 356-358 (1941).

TM cryostat cooling: temperature levels

TM-cryostat scheme:



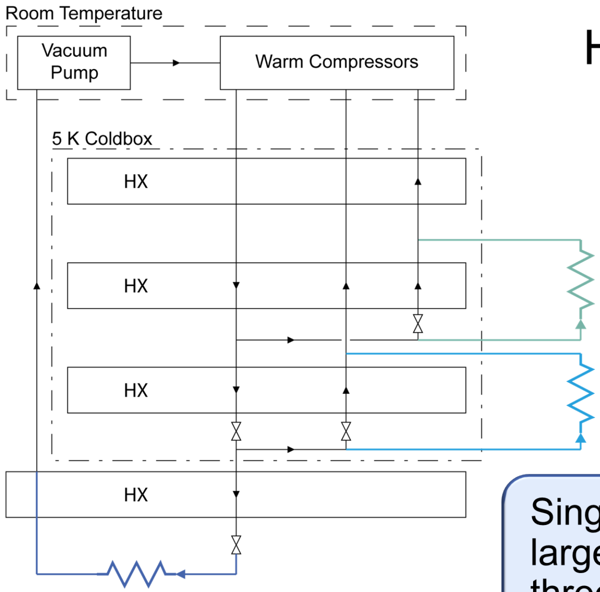
Three temperature stages:

Part(s)	Temp. level	Estimated cooling power
Outer thermal shield	50…80 K	x…10^3 W
Inner thermal shield	5 K	x…10^2 W
Payload heat sink	2 K	x…1 W

$T_{\mathrm{InnerShield}} < T_{\mathrm{Mirror}} (\sim 10\ \mathrm{K})$ possible

Helium-based cooling power provision

Basis: He-refrigerator + subcooler



He-supplies:

- 50…80 K (HP)
- 5 K (LP)
- 2 K (VLP)

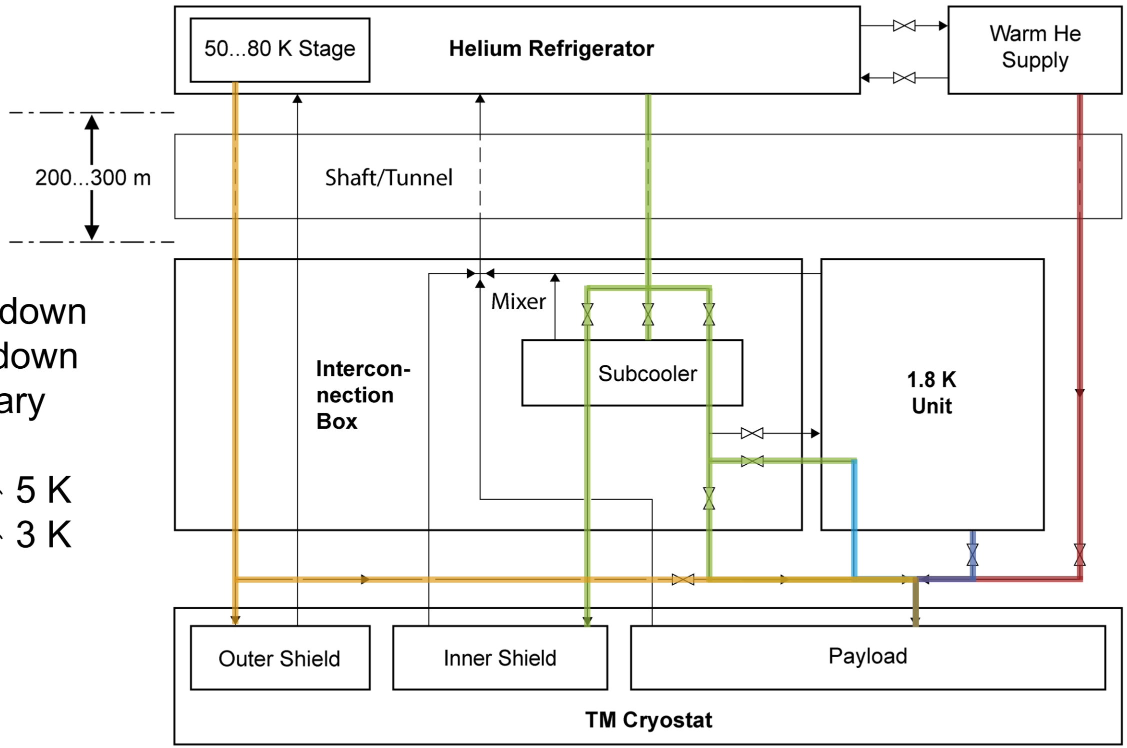
Single refrigerator: large cooling power at three temperature levels

Example: Linde L-Series

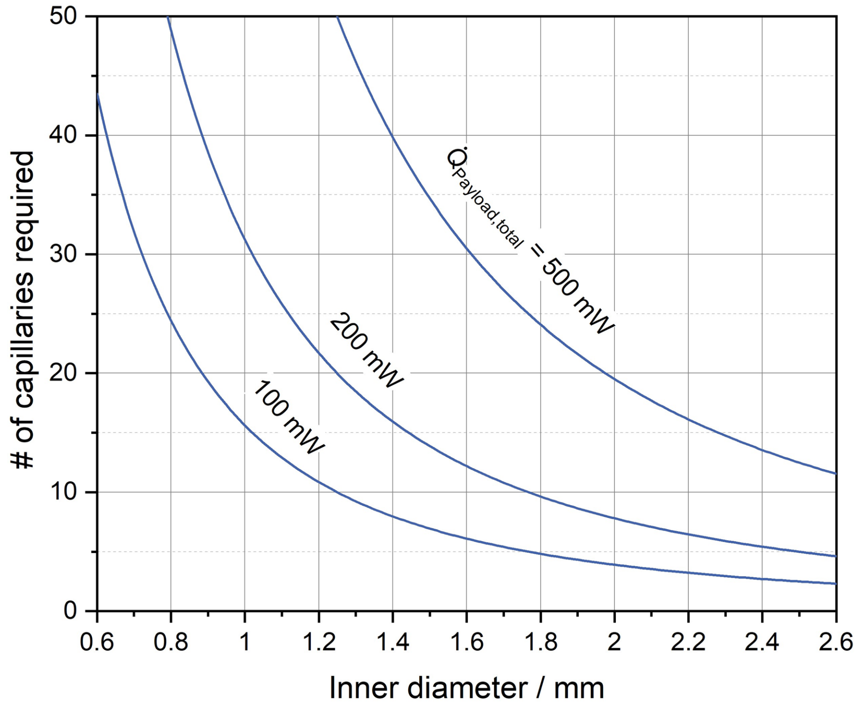
Image: L-Series - Standard Helium Liquefiers / Refrigerators, Linde Kryotechnik AG, 2021.

Basic layout: complete cryostat cooling

1. Outer shield cooldown
2. Inner shield cooldown
3. Payload preliminary cooldown
4. Payload link → ∽ 5 K
5. Payload link → ∽ 3 K
6. He-II formation
7. Steady-state (no flow)



Payload thermal link: He-II capillaries



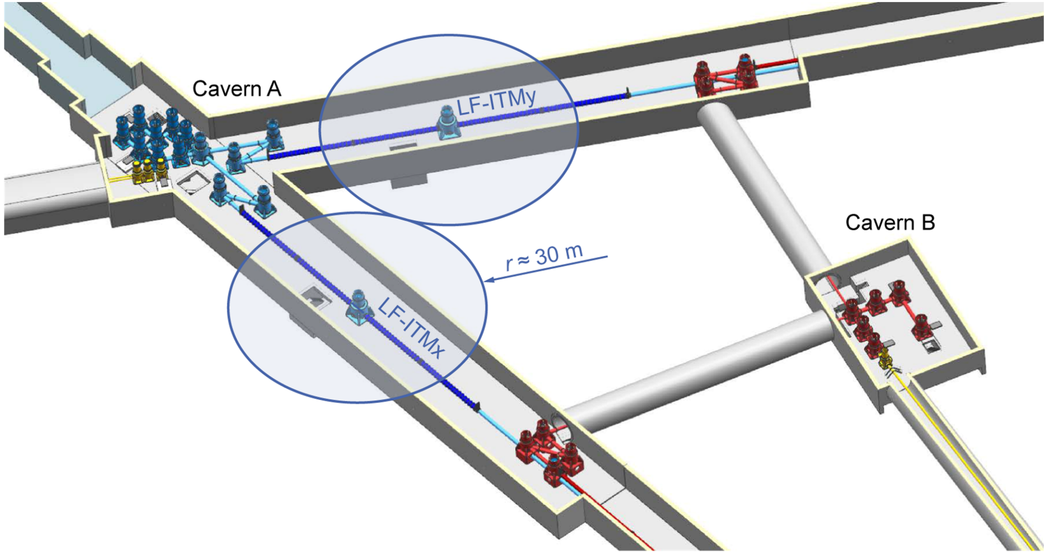
Key boundary conditions:

- 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 $d_\mathrm{i} = 1.8\ \mathrm{mm}$ can extract 200 mW from a payload at 1.9 K over 30 m distance with a ΔT of only 0.1 K.

1.8 K unit positioning possibilities

Corner cavern scheme:



1.8 K Unit main components:

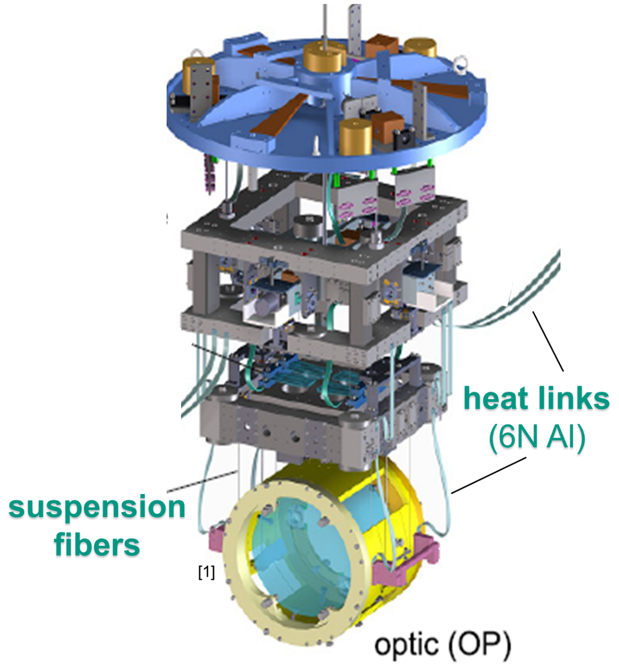
- Vacuum vessel
- Low-pressure heat exchanger
- Vacuum pumps

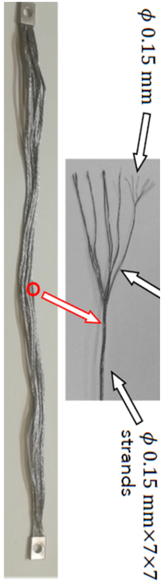
Long capillaries offer low-noise cooling potential and flexible positioning of the 1.8 K units.

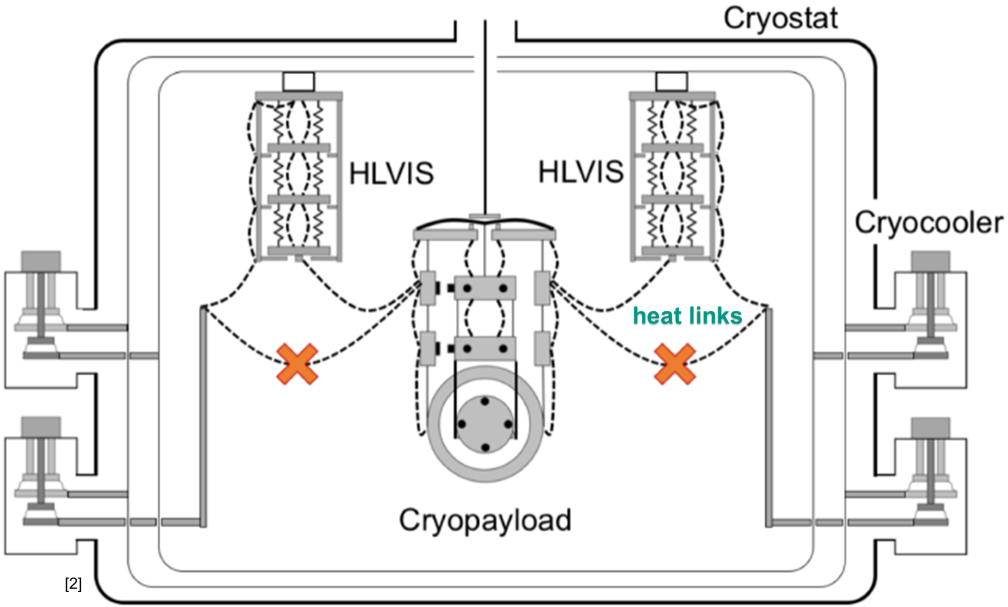
Image: ET Steering Committee Editorial Team. Design Report Update for the Einstein Telescope. Technical report, ET-0007B-20, 2020 (altered)

Vibration propagation via He-II hollow heat links

KAGRA experience on vibration transmission into payload

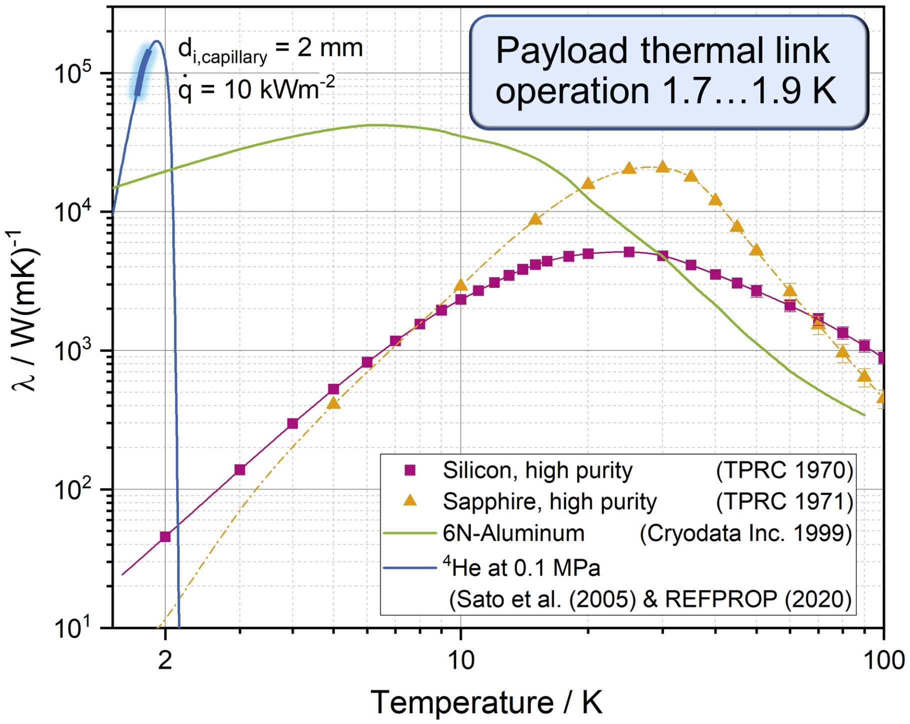






Sources: [1] Akutsu et al (2019) – First cryogenic test operation of underground km-scale GW Observatory KAGRA
[2] T.Yamada (2020) – Low-Vibration Conductive Cooling of KAGRA Cryogenic Mirror Suspension

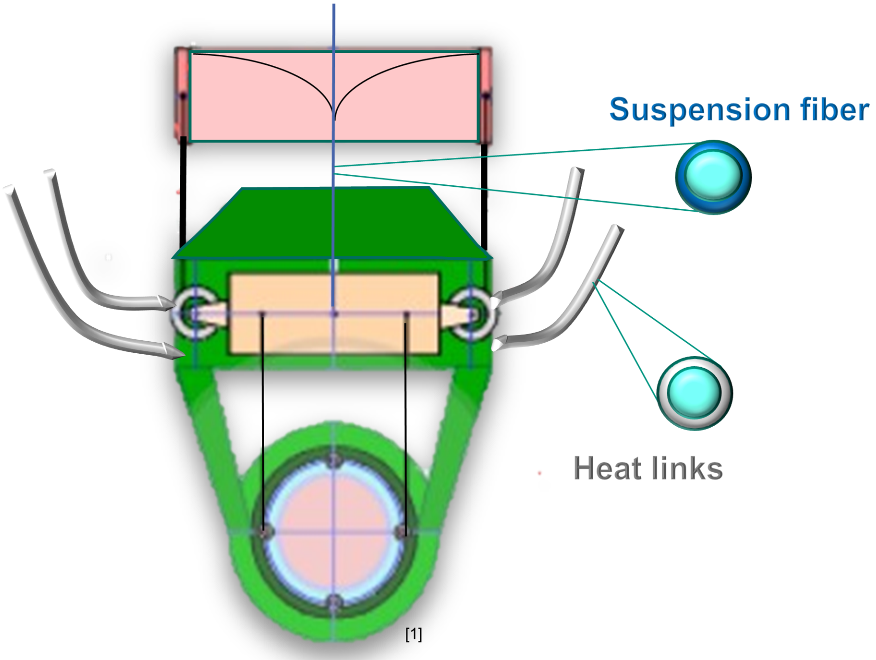
He-II hollow capillaries as heatlinks of ET-LF payload



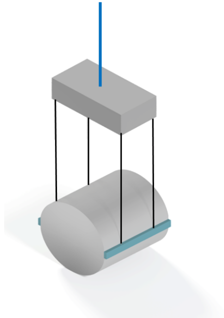
Lower thermal dissipations

- Cryogenic temperatures
- Dissipation-free superfluid component in He-II

Integration of He-II filled capillary into payload



- He-II filled capillary ($\varnothing \leq 3\ mm$)
- 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

Karlsruhe Institute of Technology

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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