Low-noise thermal shielding around the cryogenic payloads in the Einstein Telescope

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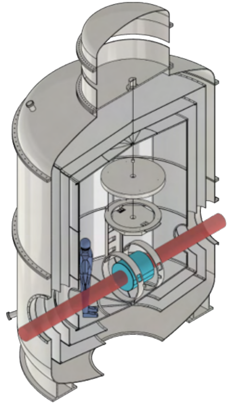
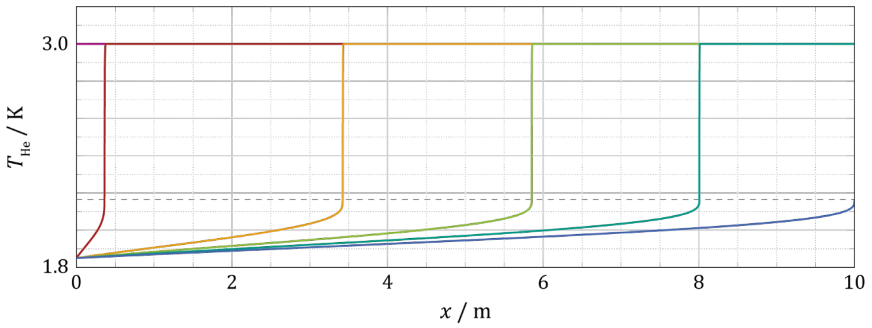
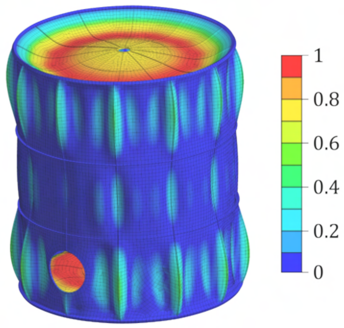






The Einstein Telescope (ET)

The Einstein Telescope (1/2)

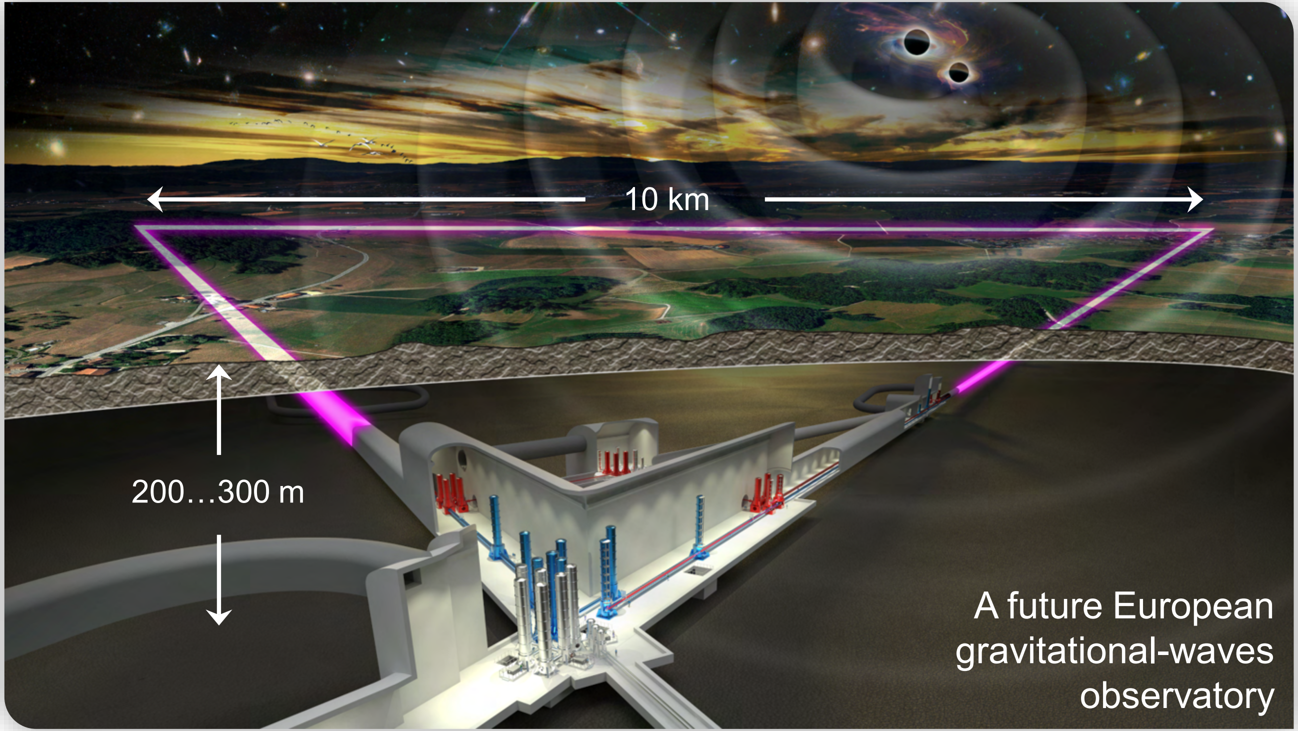


Image: Nikhef (annotated)

The Einstein Telescope (2/2)

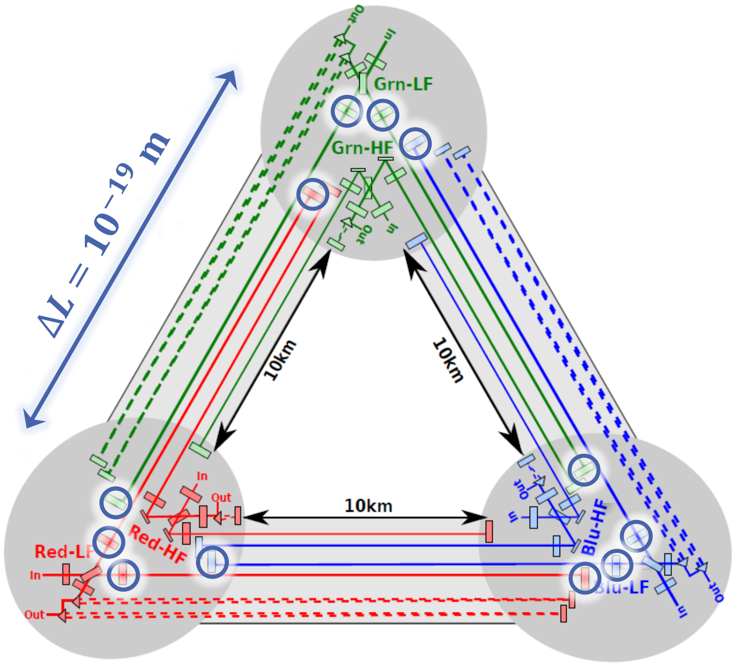
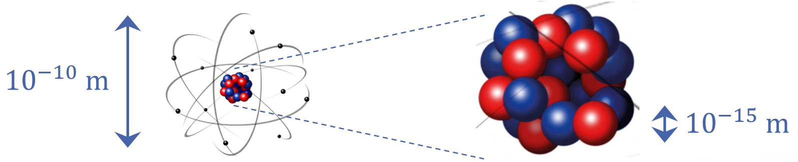


Figure: Hild et al., 2012

- Nested detectors
  - 3x LF-interferometer ($f \approx 3$ Hz to 30 Hz)
  - 3x HF-interferometer ($f \approx 30$ Hz to 10 kHz)
- Sensitivity improvement $\Delta S < 10^{-3}$ @ 3 Hz compared to 2.5G detector (KAGRA)
  - ➢ Strain target c. $10^{-23}\ \mathrm{Hz}^{-0.5}$



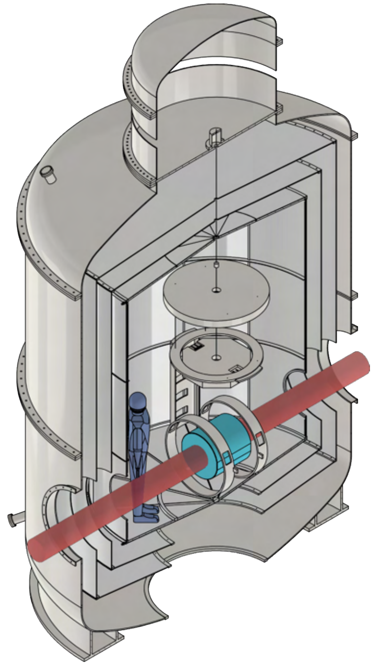
Each ET-corner:

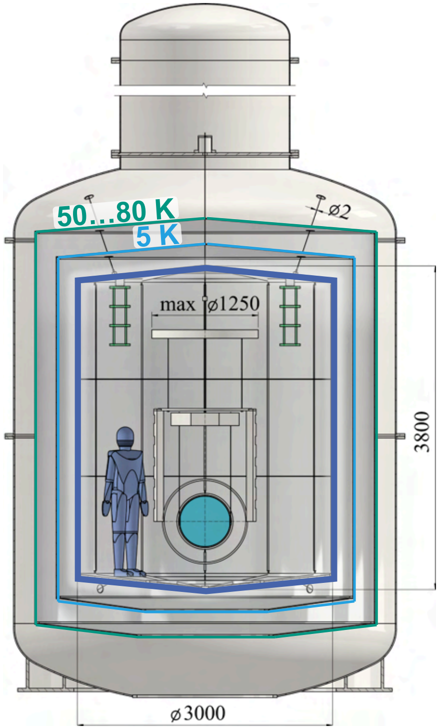
4 sensitive mirrors to be cooled at 10 ... 20 K

➢ Stringent constraints on thermal shield vibrations

ET-LF cryostat shielding structure

ET-LF cryostat structure



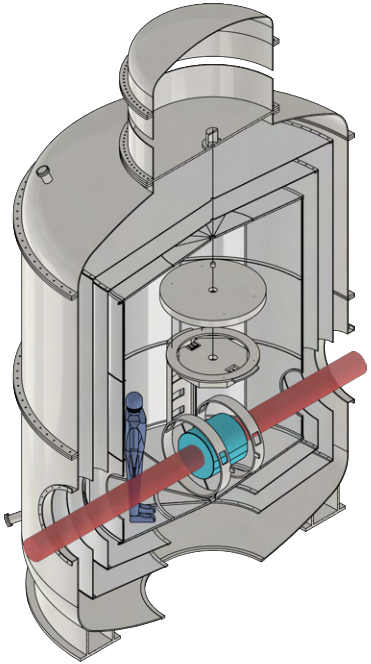


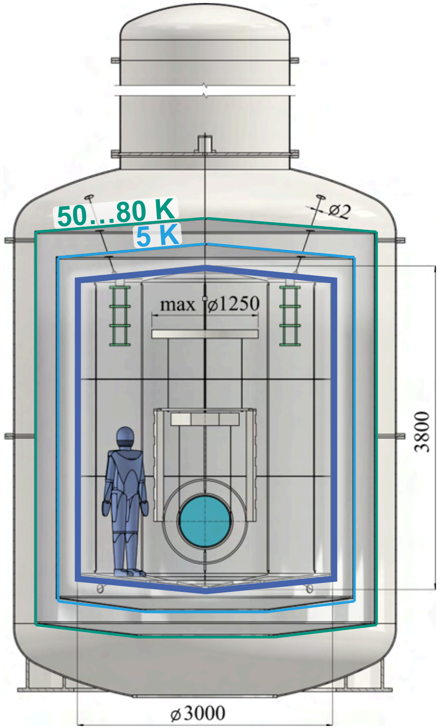
- ≥ 3 thermal shields (active + passive)
- Inner shield hosts:
  - ⌀ Mirror: up to 600 mm
  - ⌀ Payload: up to 1250 mm
  - Total payload length: c. 2.5 m [1]
  - Payload heat link vibration isolation system

> ➢ Min. dimensions of innermost shield:
> ⌀ 3.0 m, c. 3.8 m height

[1] Koroveshi X *et al.*, 2023.
Cryogenic payloads for the Einstein Telescope (arXiv:2305.01419 [astro-ph.IM])

ET-LF cryostat structure





Cooling of inner shield with **He-II**:

- ✓ Quiet cooling at **2 K** via conduction in steady-state
- ✓ Sufficient cooling power provision by integration in **helium infrastructure** [2]

[2] Busch L and Grohmann S, 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1240**(1) p. 012095

ET-LF 2 K-shield geometry concept

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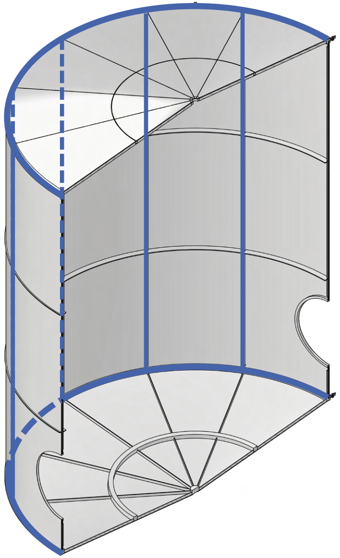
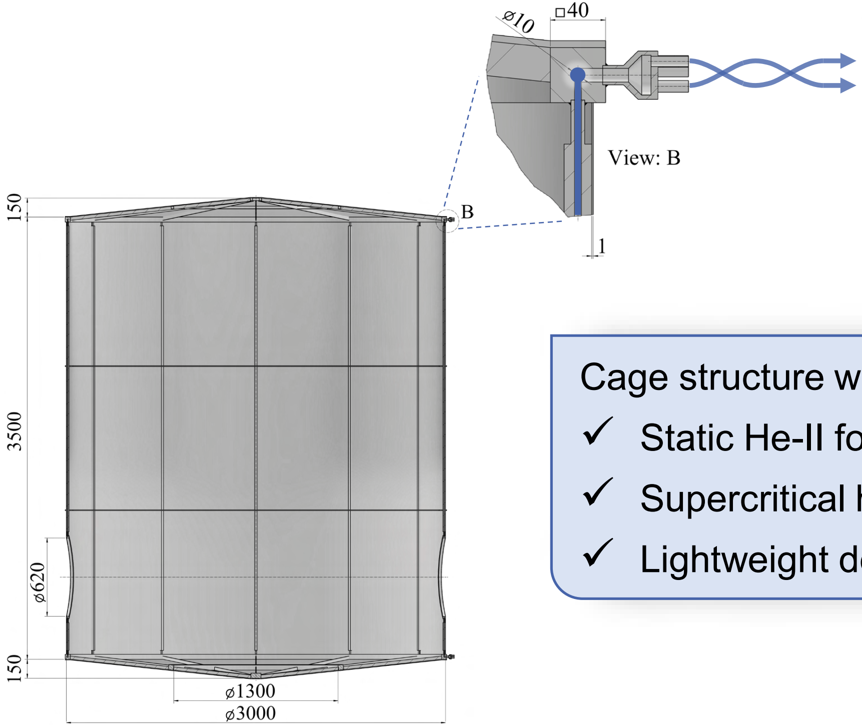




Attenuated cooling system connection

Cage structure with **hollow** profiles:

- ✓ Static He-II for steady-state heat extraction
- ✓ Supercritical helium flow for rapid cool-down
- ✓ Lightweight design (Al 1000, $m_{\text{total}} \approx 450\ \text{kg}$)

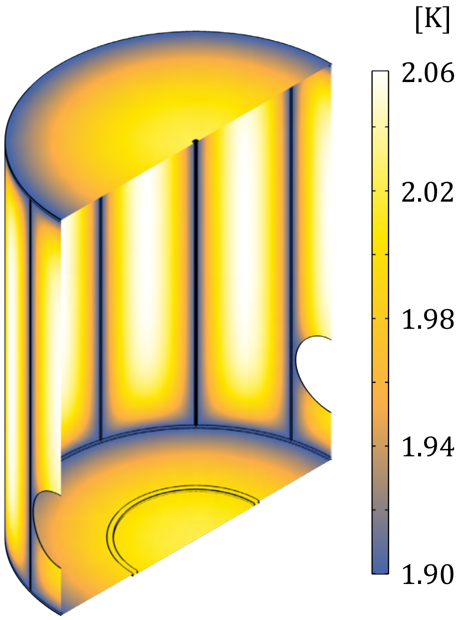
Steady-state thermal modelling

Steady-state thermal modelling

<u>FEM results:</u>

$\dot{Q}_{\text{total}} = 2.0\ \text{W}$
(full shield)

- Viewports
- Beam pipe
- Scattered light
- Shield suspensions



- $\Delta T_{\text{shield,max}} < 100\ \text{mK}$
- $\dot{Q}_{\text{total}}$ distribution to thermal reservoir:
  - c. $^5/_8$ to vertical profiles
  - c. $^3/_8$ to header profiles

Analytical approximation of static 1D temperature profiles in He-II channels:

$$\frac{\mathrm{d}T}{\mathrm{d}x} = \frac{-\dot{q}_{\text{HeII}}(x)^m}{k_{\text{eff}}(T(x), p)}$$

- Example:
  $d_{\text{i,He-channels}} = 5 \ldots 10\ \text{mm}$:
  $\rightarrow T_{\text{HeII}} \approx 1.85 \ldots 1.87\ \text{K}$ ✓
  supply...farthest point

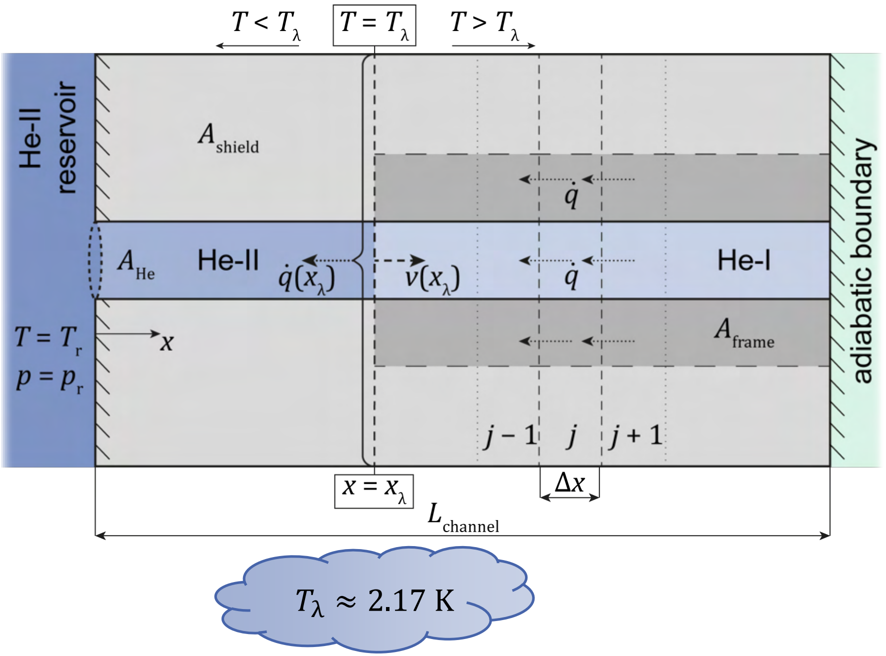
Transient cool-down:

Pre-cooling: forced convection with sc. helium

He-II condensation into pre-cooled shield

He-II condensation into the pre-cooled shield

1D-model:



Model aim:

Approximate He-I → He-II conversion velocity incl. temperature profile evolution

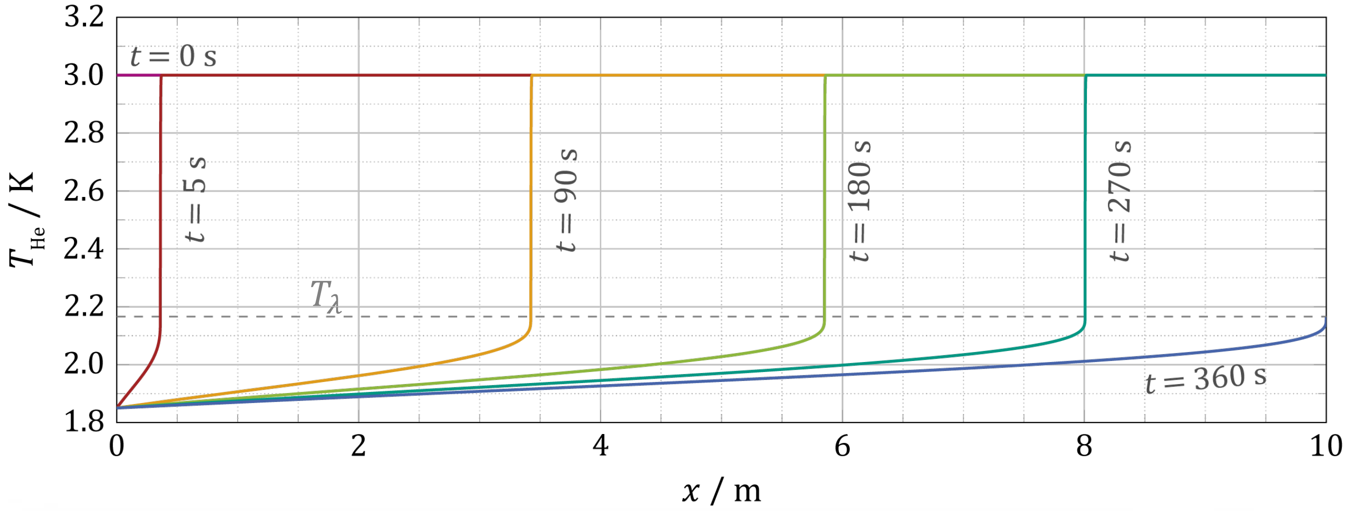
Key characteristics:

$T < T_\lambda$

- Differential equation-based
- Conduction of heat to reservoir through A_{He} only
- Thermal mass of shield considered via A_{shield}
- Ideal solid-to-liquid heat transfer
- Implicit numerical scheme (Crank-Nicolson)
- Conduction of heat through A_{He} and A_{frame}
- $x_\lambda(t)$ implemented via moving boundary condition

$T > T_\lambda$

He-II/He-I temperature profile results



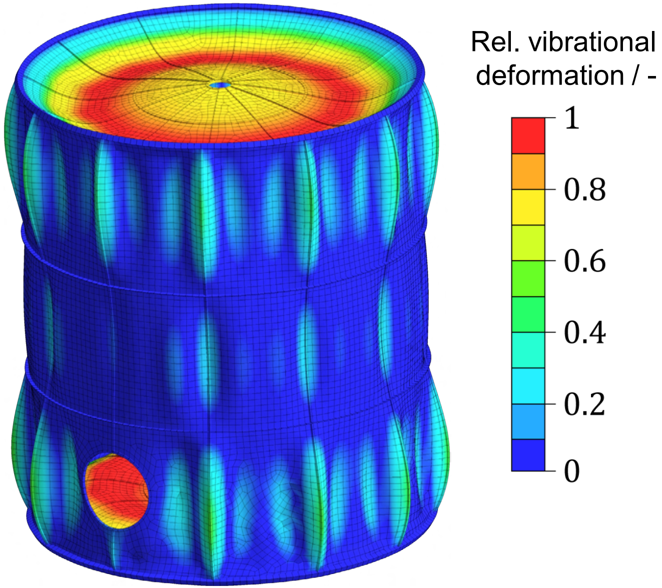
- He-II phase front propagates through the shield frame ($L_{channel} \approx 6$ m) in c. 200 s
- Complete temperature gradients in He-I region occurs within only around 10 mm
- Significant gradients in He-II region only in phase front vicinity

Modal and harmonic response analysis

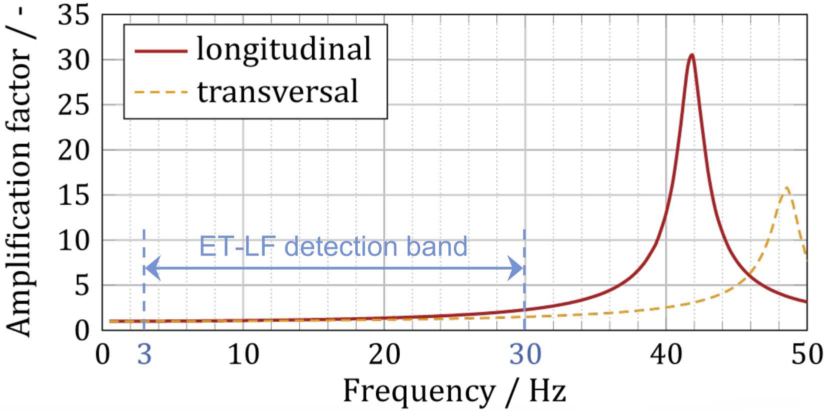
Modal and harmonic response analysis

Free modal analysis results

($f \approx 42$ Hz)



Harmonic response results



- First resonant modes:
  c. 42 Hz (longitudinal), c. 48 Hz (transversal)
- Below 30 Hz: very low amplification factors achieveable

Summary and prospects

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- Conceptual structure of the 2 K inner shield for ET-LF cryogenic payloads
- Approximation of the steady-state thermal behavior of the shield
- Detailed investigation and theoretical validation of the He-II condensation process
- Structural shield reinforcements
  - Box mode frequencies significantly above ET-LF detection band and
  - Low vibrational amplification factors within detection band achievable

- Detailed shield suspension development
- Evaluation of phase noise levels and mechanical coupling with payload
- Experimental investigation of low-noise He-II supply

Thank you for your attention!

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