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)

A future European gravitational-waves observatory

Image: Nikhef (annotated)
The Einstein Telescope (2/2)

- 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. $10^{-23}$ Hz$^{-0.5}$

- Each ET-corner:
  - 4 sensitive mirrors to be cooled at 10 ... 20 K
  - Stringent constraints on thermal shield vibrations

Figure: Hild et al., 2012

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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

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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]

ET-LF 2 K-shield geometry concept

Cage structure with hollow profiles:
- Static He-II for steady-state heat extraction
- Supercritical helium flow for rapid cool-down
- Lightweight design (Al 1000, $m_{\text{total}} \approx 450$ kg)
Steady-state thermal modelling
Steady-state thermal modelling

- $\Delta T_{\text{shield,max}} < 100 \text{ mK}$
- $\dot{Q}_{\text{total}}$ distribution to thermal reservoir:
  - c. $\frac{5}{8}$ to vertical profiles
  - c. $\frac{3}{8}$ to header profiles

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

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

Example:

$d_{i,\text{He--channels}} = 5 \ldots 10 \text{ mm}$:

$$T_{\text{HeII}} \approx 1.85 \ldots 1.87 \text{ K}$$

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 $\rightarrow$ He-II conversion velocity incl. temperature profile evolution

Key characteristics:
- 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
He-II/He-I temperature profile results

- He-II phase front propagates through the shield frame \((L_{\text{channel}} \approx 6 \text{ m})\) 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 ≈ 42 Hz)

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

Harmonic response results

ET-LF detection band

- longitudinal
- transversal
Summary and prospects
Summary and prospects

- 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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