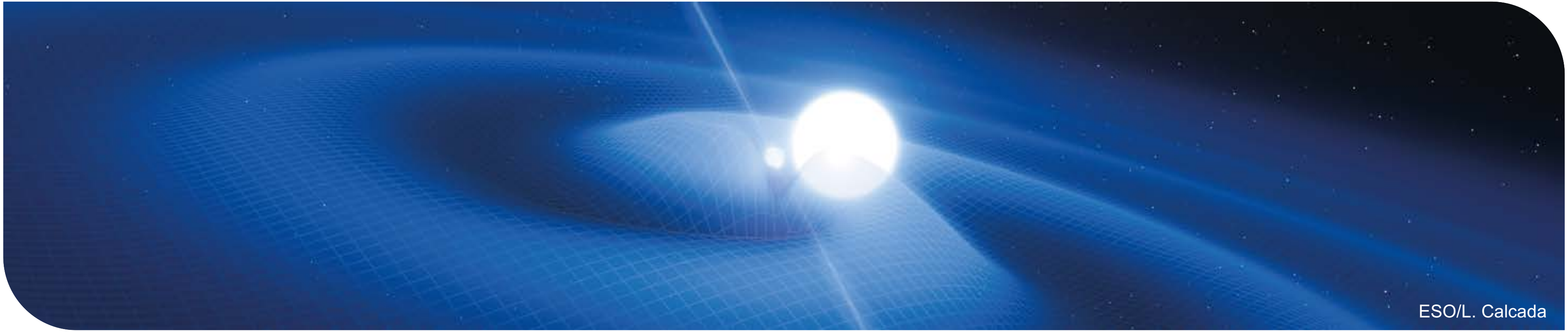
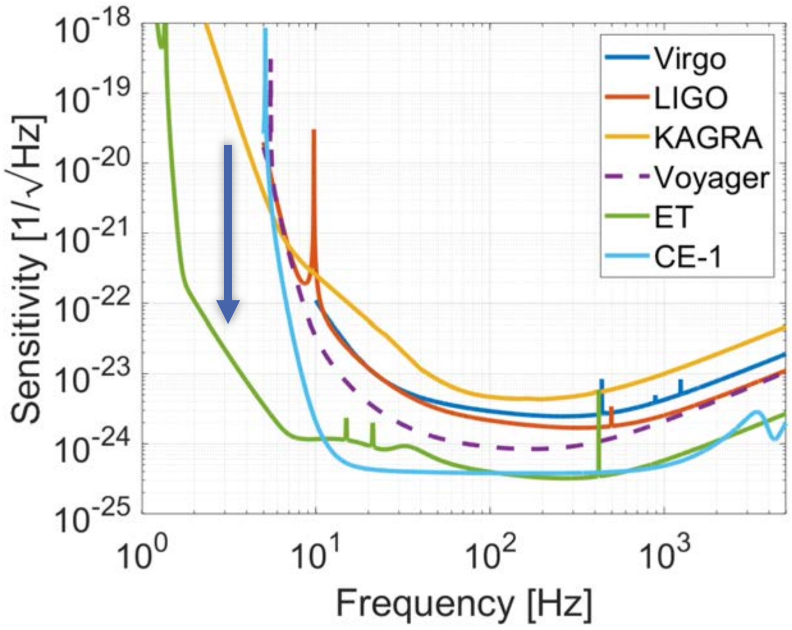
Challenges in ET cryogenics

Steffen Grohmann
Lennard Busch
Xhesika Koroveshi

22.04.2022
Einstein Telescope / Virgo @ KIT Workshop



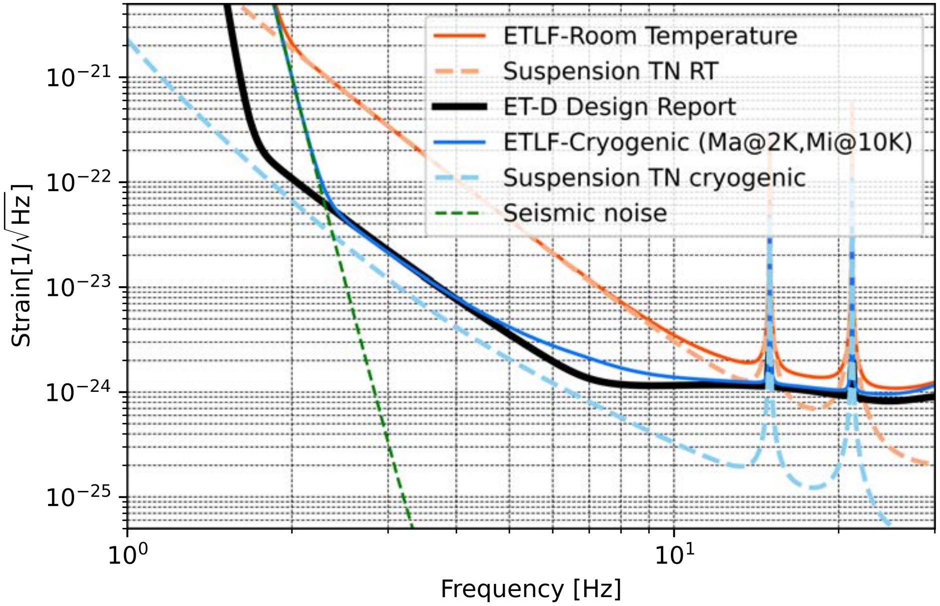
Motivation for ET-LF

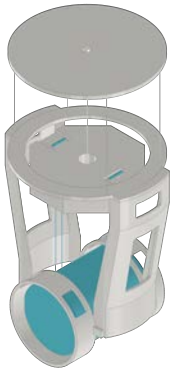


- ET-LF Interferometer (3…30 Hz)
  - Sensitivity improvement $\Delta S < 10^{-3}$ @ 3 Hz compared to 2.5G detector (KAGRA)
  - Laser power ~ 18 kW
  - Cryogenic optics at $T \sim 10 \ldots 20$ K essential

ET-LF core technology: Cryogenics

- ET-LF noises: Cryogenic vs. room-temperature (RT) operation





- Suspension thermal noise (STN) dominant @ $3 \ldots 30$ Hz frequency range
- Cryogenic payload @ $T \sim 2 \ldots 20$ K essential for sensitivity goal!
- Low-noise cooling method required

KIT @ ET: Key positions

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System Design Office

Co-Chairs:
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Gianluca Gemme (INFN, Genova, IT)

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Co-Chairs:
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- WP I.2: Payload LF
- WP I.3: Payload HF
- WP I.4: Seismic Isolation Platform
- WP I.5: Small Suspensions

Optics Division

Co-Chairs:
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Stuart Reid (University of Strathclyde, UK)

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- WP II.2: Core Optics HF
- WP II.3: Lasers
- WP II.4: Input Optics
- WP II.5: Squeezed Light
- WP II.6: Output Optics
- WP II.7: Wavefront Sensing and Control
- WP II.8: Scattered Light

Interferometer Division

Co-Chairs:
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- WP III.2: Optical Layout Sensing and Control Scheme LF
- WP III.3: Optical Layout Sensing and Control Scheme HF
- WP III.4: Data Acquisition and Real Time Control
- WP III.5: Detector Characterization and Calibration

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Co-Chairs:
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- WP IV.2: Pipe Arm Vacuum
- WP IV.3: Cryostats and Cryo-pumps
- WP IV.4: Cryogenic Infrastructure
- WP IV.5: Detector Cooling

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Co-Chairs:
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- WP V.3: Magnetic Noise
- WP V.4: Inter-platform Motion
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- WP VI.2: Survace Civil Infrastruc-tures
- WP VI.3: Safety
- WP VI.4: Low Environmental Noise Design
- WP VI.5: Civil and Mechanical Services
- WP VI.6: Electrical and Communi-cation Services

He-II suspension capillary concept for ET-LF

Payload heat extraction via He-II

Two liquid phases of ^{4}He:

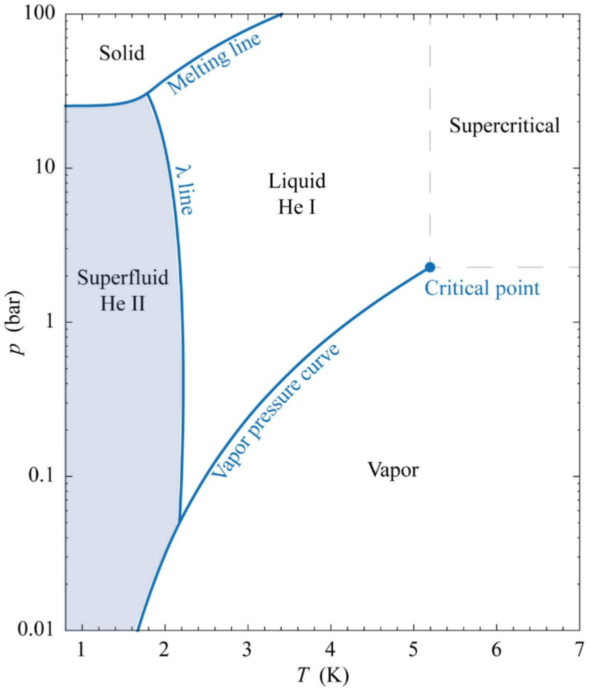
- He-I (classical liquid helium)
  - ➢ Behaviour: ~ideal gas

$T_\lambda(1\ \mathrm{atm}) \approx 2.17\ \mathrm{K}$ — $T > T_\lambda$ / $T < T_\lambda$

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

He-II: exceptional heat transfer properties

^{4}He phase diagram:



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).

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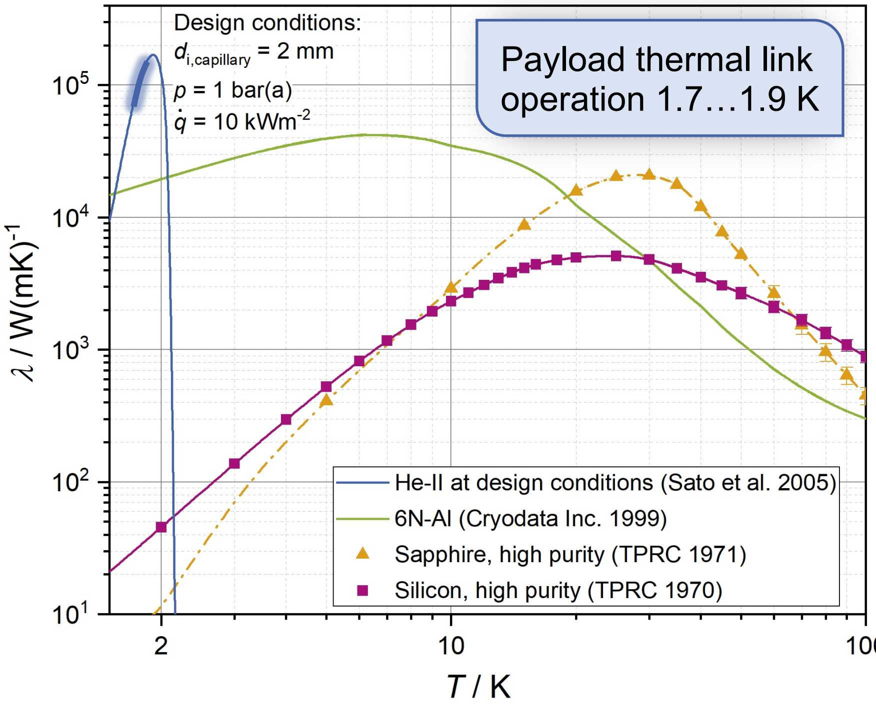

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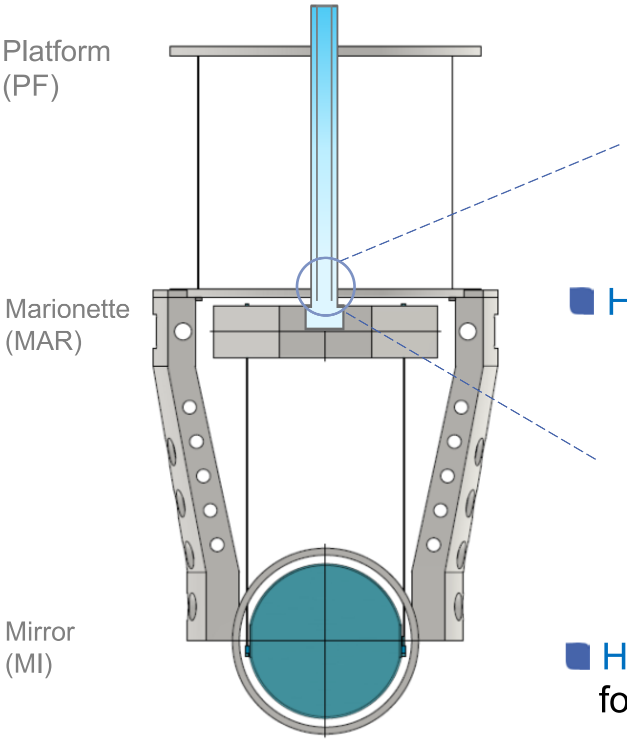
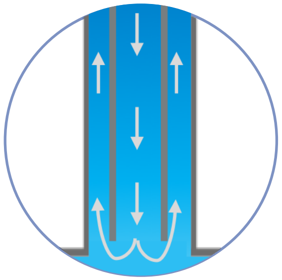
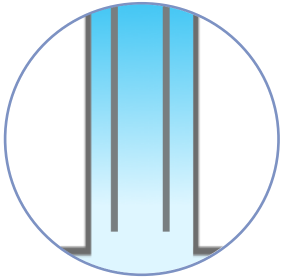
Cooling via He-II suspension capillary

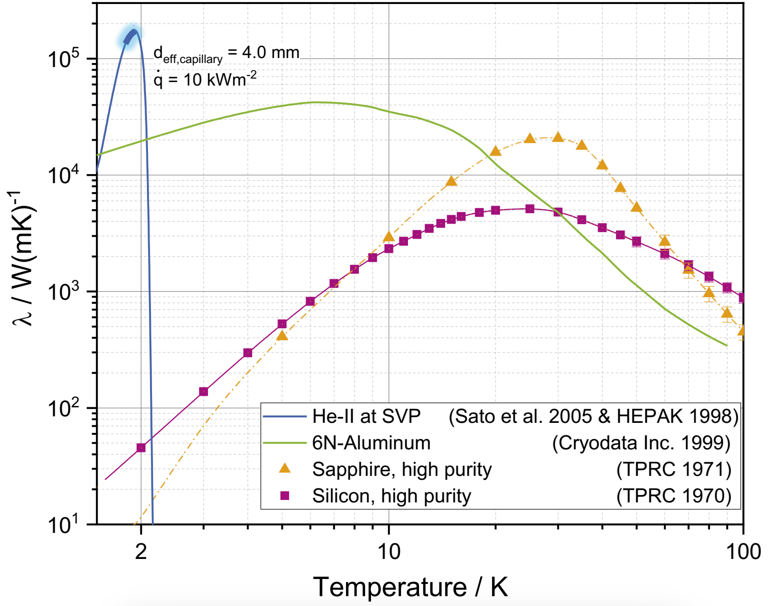




- He-I flow for cool-down



- He-II (no macroscopic flow) for steady-state operation



He-II = Ultra-quiet,
thermally efficient liquid phase!

Courtesy of M Stamm (2021)

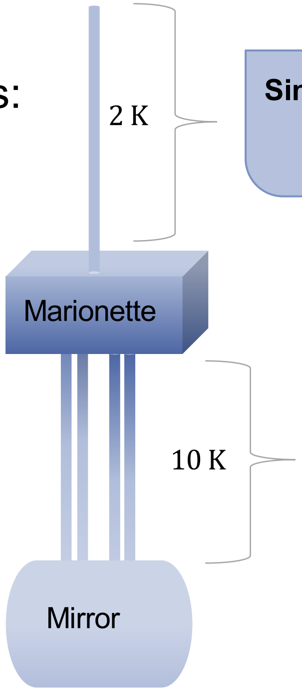
Suspension thermal noise model

Suspension thermal noise (STN) model includes:

- **Discrete FDT model [1]** for inhomogeneous stage temperatures $\boldsymbol{T}$ **@ Ma: 2 K – Mi: 10 K**
- Energy dissipations via **loss angle $\boldsymbol{\Phi}$**

$$\Phi_{fiber}(\omega) = \Phi_{thermoelastic}(\omega) + \Phi_{bulk} + \Phi_{surface}$$

- Design parameter variation, low-temperature physical properties…



Simple Pendulum model

- ❑ $k = k_0 \cdot (1 + i \cdot \boldsymbol{\Phi}_{fiber}(\boldsymbol{\omega}) * \boldsymbol{D})$

Pendulum model with elastic beam fiber

- ❑ $E = E_0 \cdot (1 + i \cdot \boldsymbol{\Phi}_{fiber}(\boldsymbol{\omega}))$

[1] Concept based on Komori et al. (2018)

Conclusions from feasibility analysis

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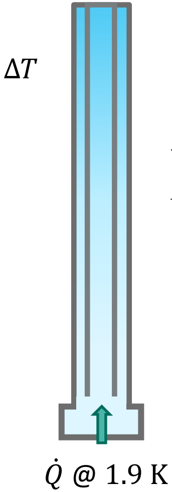
- Thermal & mechanical dimensioning
  - Cooling capacities up to $0.5\ \mathrm{W}$, or even up to $1.0\ \mathrm{W}$, are feasible
  - $T_{marionette}$@ $2\ \mathrm{K}$ and T_{mirror}@ $14-20\ \mathrm{K}$, with $\Delta T \approx 50\ \mathrm{mK}$

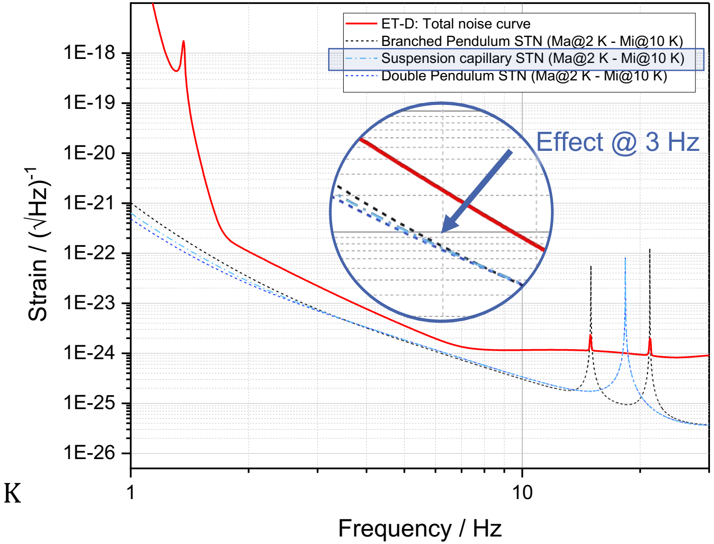
- Suspension thermal noise
  - Effect of suspension capillary on STN marginal @ $f > 3\ \mathrm{Hz}$ for both scenarios !

Suspension capillary scenario:

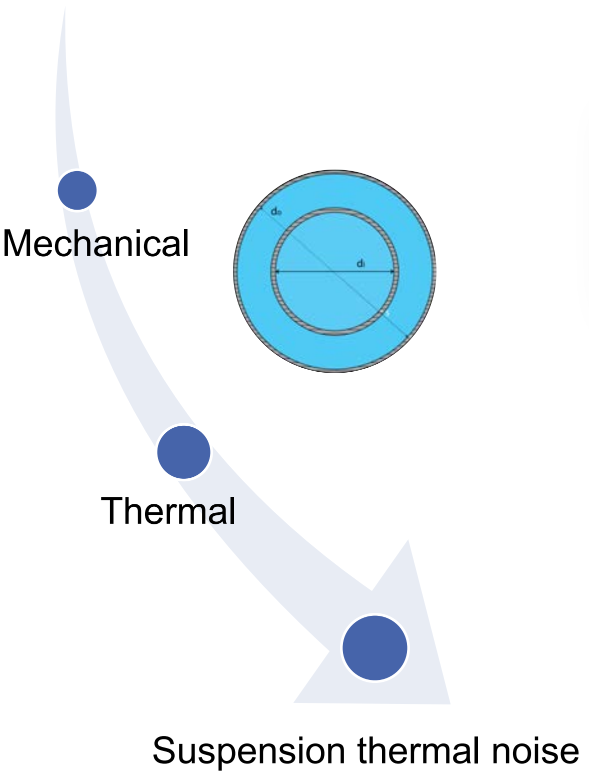
✓ @ $\dot{Q} = 0.5\ \mathrm{W},\ \Delta T = 0.05\ \mathrm{K}$

✓ @ $\dot{Q} = 1.0\ \mathrm{W},\ \Delta T = 0.05\ \mathrm{K}$

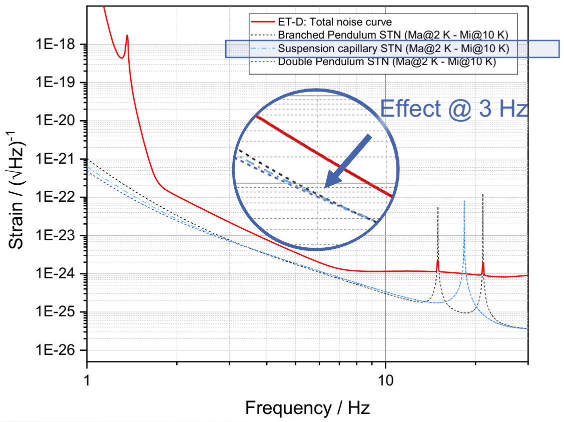


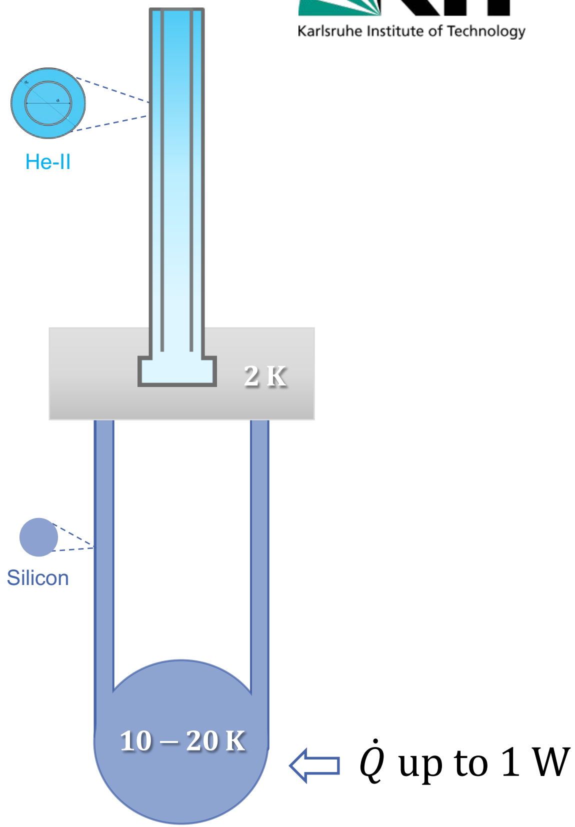


Status of He-II suspension concept



- Feasibility shown theoretically
- Experimental proof of concept required





He-based cooling concept for ET-LF

ET-LF test mass cryostat cooling

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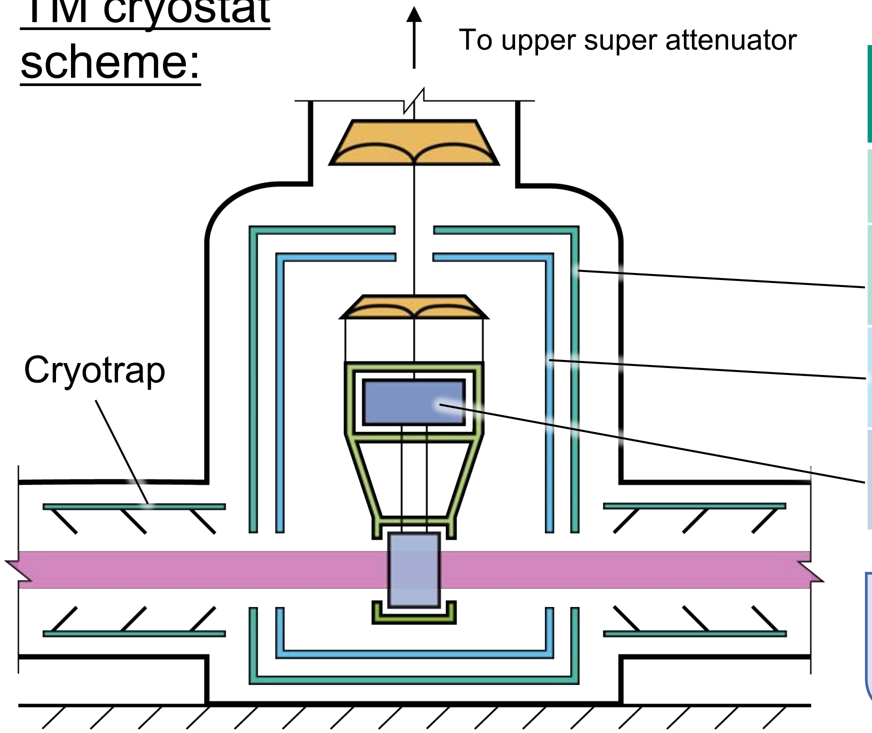
TM cryostat scheme:

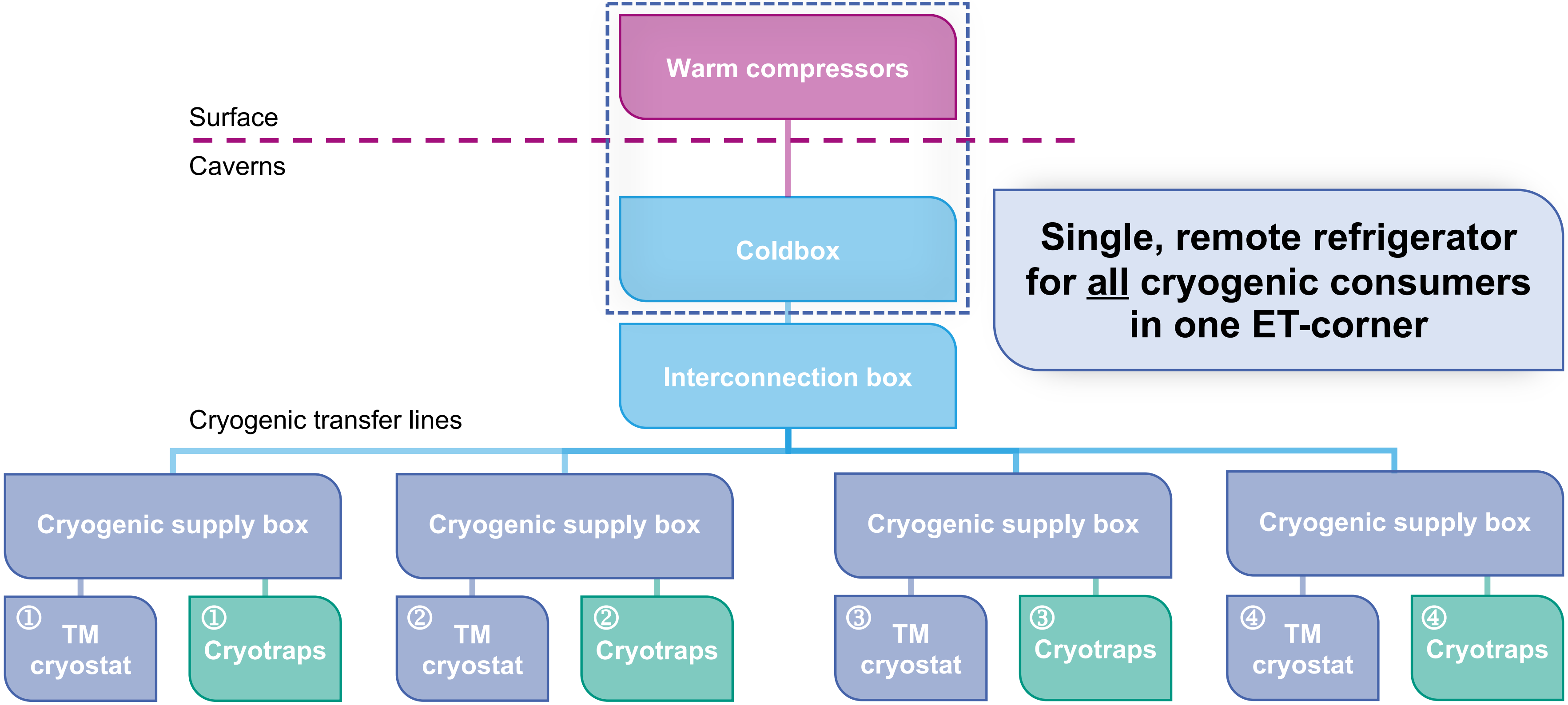


Temperature stages:

Part(s)	Temp. level	Est. cooling power
HF & LF cryotraps	≤ 20…80 K	x…10^4 W
Outer thermal shield	≤ 20…80 K	x…10^3 W
Inner thermal shield	5 K	x…10^2 W
Payload interface	2 K	x…10^0 W

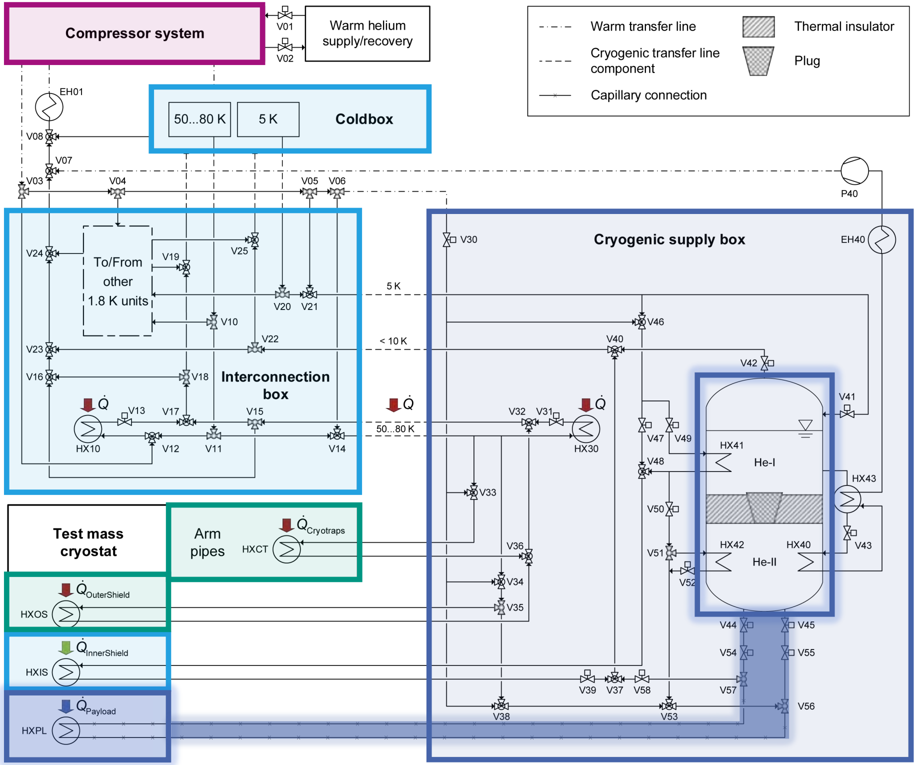
Helium system: remote cooling power generation
→ distribution to cryogenic consumers

Helium cooling system: structure



Single, remote refrigerator for all cryogenic consumers in one ET-corner

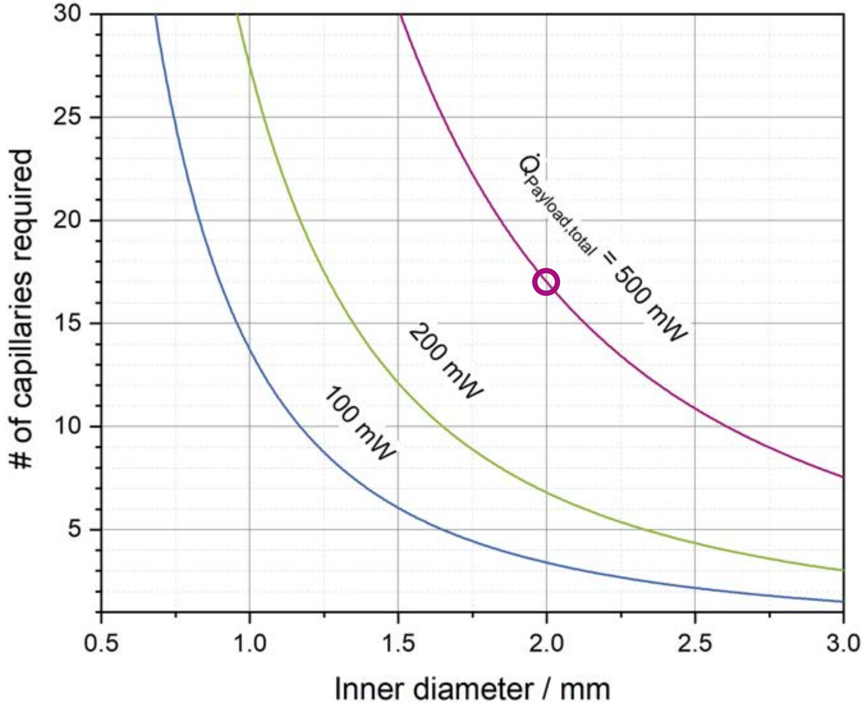
Helium cooling system: Conceptual PFD



Process flow diagram (PFD):

- Will be published in *Advances in Cryogenic Engineering 2021*
- Extensive explanatory project note uploaded to TDS (07/2021)
  → https://apps.et-gw.eu/tds/?content=3&r=17648
- Particular focus:
  cooling power generation for payload at 2 K
  - Creation of **He-II bath**
  - Connection to payload interface via **long supply capillaries**

Cryogenic supply capillaries



Key boundary conditions:

- Operating pressure: 0.12 MPa
- Capillary length: 15 m
- Capillary cold end temp.: 1.75 K
- Payload interface temp.: 1.85 K

Configuration example:
17 capillaries with d_i **= 2.0 mm** can extract **500 mW** from a payload interface at **1.85 K** over **15 m** distance with a ΔT of only **0.1 K**.

Plans for ET development infrastructure at KIT

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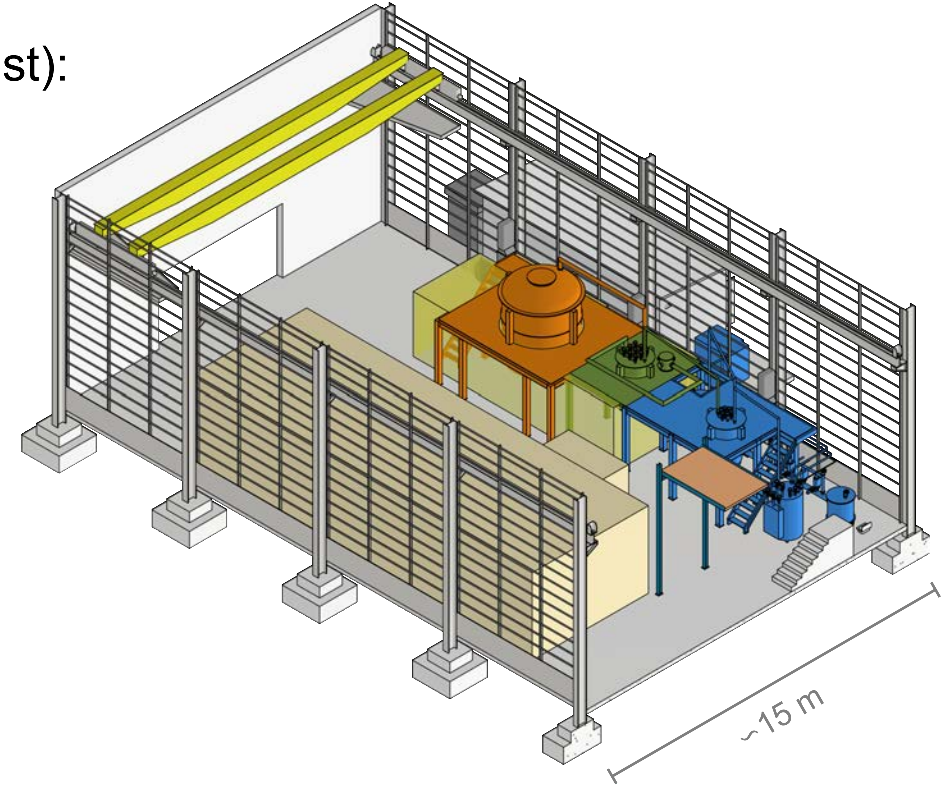
CN, bldg. 245 (west):



Plans for ET development infrastructure at KIT

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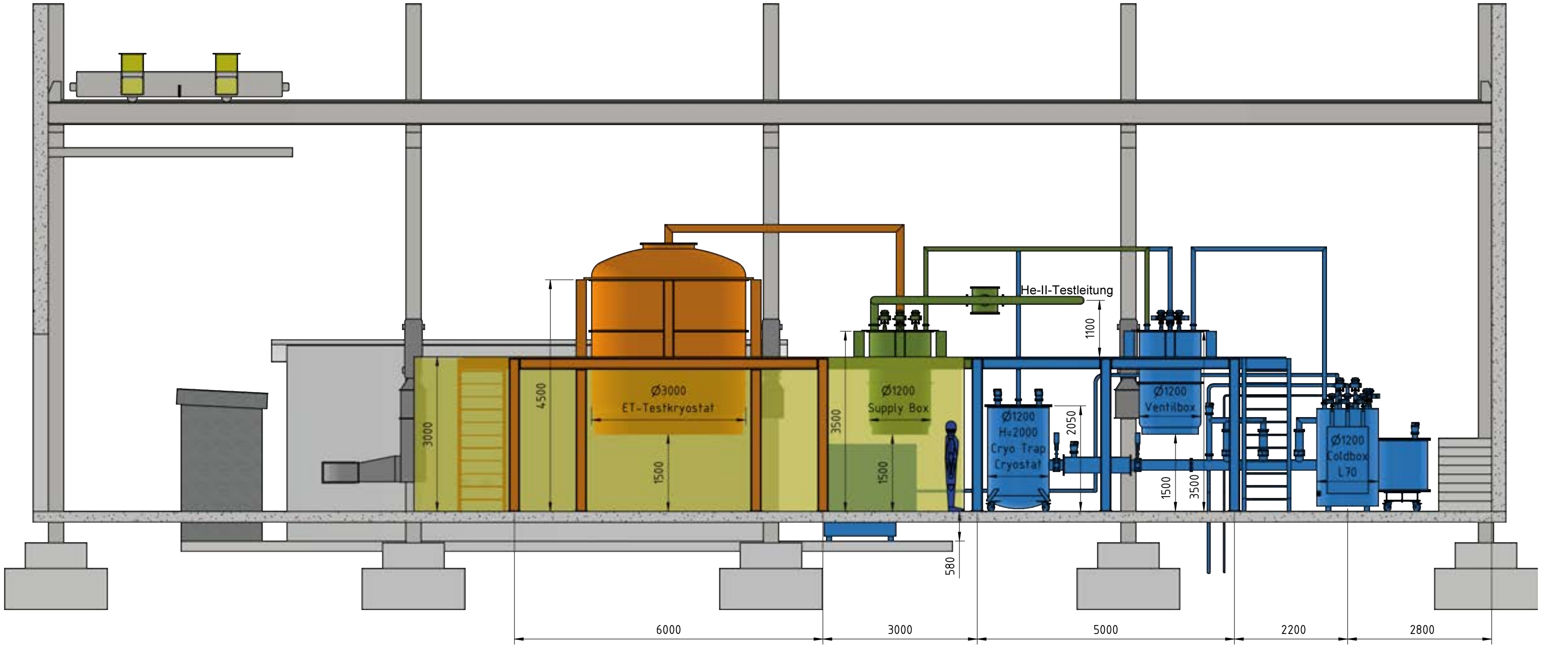

Phase III
- ET test cryostat

Phase II
- He-II supply

Phase I
- He-refrigerator
- Cryotrap test cryostat

Thank you for your attention!