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Conceptual layout of a helium cooling system for the Einstein Telescope

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Abstract. The Einstein Telescope (ET) is a 3$^{\mathrm{rd}}$ generation gravitational-wave detector planned in triangular shape with 10 km arm lengths in an underground installation at a depth of 200 m to 300 m. While 2$^{\mathrm{nd}}$ generation detectors and the ET high-frequency interferometer are operated at room-temperature, the ET low-frequency (LF) interferometer shall be operated at cryogenic mirror temperatures of 10 K to 20 K in order to reduce the thermal noise. Considering thermal dissipation limits in the heat extraction path from the mirror to the heat sink, He-II provides ultra-low-noise cooling to allow for an interferometer sensitivity at levels below $1\times10^{-20}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ in the detection band. In order to limit particle adsorption on the cold mirror surface, the total pressure in the cryostat must be reduced to $p \leq 1\times10^{-10}$ mbar, i.e. partial pressures of water and heavier components $p_i \leq 1\times10^{-14}$ mbar, respectively, using a cryopump/shield around the mirror that is cooled with supercritical helium to $T \approx 5$ K.

We present the conceptual layout of a helium cooling system that can provide cooling power for several ET-LF cryostats and their corresponding cryotraps, including mirror cooling at 2 K as well as thermal shielding at 5 K and at 50 K to 80 K. A process flow diagram focuses on the cooling system's key components with their locations and their interconnections. On the diagram's basis, we explain the cooldown process and steady-state operation, ranging from outer shield and cryotrap cooling to the formation of He-II in the mirror heat extraction path.

1. Introduction

The thermal noise goals of the Einstein Telescope's (ET) low-frequency (LF) detector are ambitious. They have been declared in the ET conceptual design study in 2011 [1] and in the design report update in 2020 [2]. In order to achieve these goals, a test mass (TM) temperature between 10 K and 20 K is anticipated in [1, 2]. The heat extraction from the TMs is restricted by thin suspension fibers in the last mirror suspension stage ("payload"). At expected total heat loads on a TM in the order of 1×10^2 mW [1, 2], the temperature at the payload heat sink is required to be kept at 10 K or below to extract sufficient heat via conduction to maintain TM temperatures of $T \leq 20$ K [3]. In order to reach a TM temperature of 10 K, where thermal noise benefits are expected to increase [2], the heat sink is required to be at 2 K with a heat load of $\dot{Q} \leq 100$ mW. The difference between the 2 K and higher-temperature heat sink cooling options and the corresponding TM temperatures is largest at heat loads of $\dot{Q} \leq 100$ mW and becomes less significant at higher heat loads.

The decrease of the payload heat sink temperature to 2 K, however, is not only motivated by the lower resulting TM temperature, but rather by the properties of superfluid helium. Its steady-state thermal conductivity is typically one order of magnitude larger compared to the peak values of the best solids, and hence there is no need for macroscopic He-II flow for payload cooling. He-II is generated by pumping on a normal ^{4}He bath (He-I), which is supplied by a cryoplant. The second order phase transition from liquid He-I to superfluid He-II can be described by Bose-Einstein condensation, whereby ^{4}He atoms successively condense into their ground state. This implies that thermal noise is switched off in the condensed phase, presumably yielding very low or even negligible thermal dissipation among the condensed and the excited states in He-II. Moreover, there is no cooling power limit with regard to ET requirements and state-of-the-art helium technology. One helium cryoplant can provide sufficient cooling capacity for all cryostats located in an ET detector vertex, including thermal shielding.

2. System layout

Our conceptual layout of the ET-LF helium cooling system is guided by the design principle of the LHC refrigeration system [4], where the coldbox is split in two parts. At CERN, the main coldbox supplying supercritical helium at 4.6 K/3 bar(a) is located above ground and satellite coldboxes for liquefaction and final refrigeration are placed underground [5]. This concept is limited by the hydrostatic pressure head in the vertical helium return line, which increases the saturation pressure and temperature in the underground installations. The return gas in the LHC cooling system is therefore heated to 20 K by mixing with warm return streams, which reduces the pressure head by lowering the gas density [4]. This necessity, however, impairs the cryoplant efficiency [6].

Since ET is planned to be installed at −200 m to −300 m depth compared to the −100 m of the LHC, we propose to install the coldbox in an underground auxiliary cavern. This requires only warm helium transfer lines to the compressor system, which must be installed remotely above ground due to noise emission. This configuration considerably reduces the return line pressure head as well as the thermodynamic losses in the vertical transfer lines, both having a positive impact on the cooling system efficiency. Smaller 1.8 K units for liquefaction and final refrigeration are placed in the main underground caverns of ET close to the TM cryostats and cryotraps.

In our conceptual design, one helium refrigerator at each of the 3 detector vertices of ET provides refrigeration capacity to all cryostats and the adjacent arm pipe cryotraps. There are 2 input test masses and 2 end test masses, i.e. 4 cryostats in total per vertex. Each cryostat comprises the payload and 2 separately cooled thermal shields. Due to the temperature gradient in the suspension fibers, the inner thermal shield surrounding the payload can be operated at a lower temperature compared to the test mass, which is a strategy to avoid or limit frost formation on the cold mirror surface. The helium cooling system hence provides cooling power

Table 1. Temperature levels and estimated cooling capacities (orders of magnitude) required for each of the 4 TM cryostats and adjacent cryotraps in one of the 3 ET detector vertices during steady-state operation.

Component	Temperature level / K	Cooling power / W
Arm pipe cryotraps	50...80	x . . . 10^4
Outer thermal shield	50...80	x . . . 10^3
Inner thermal shield	5	x . . . 10^2
Payload heat sink	2	x . . . 10^0

at 3 different temperature levels as indicated in table 1. The temperature level of the cryotraps and outer thermal shield in the range of 50 K to 80 K depends on the final cryoplant design. The cooling capacities are present estimates, not including transfer line losses and additional capacity required for the cool-down process. In any case, commercial helium refrigerator technology is available to cover the requirements of this concept.

The ET-LF helium cooling system consists of the following 5 main components that are connected by helium transfer lines:

1. the compressor system,
2. the coldbox,
3. the interconnection box,
4. the 1.8 K units and
5. the test mass cryostats.

The interconnection box is placed close to the coldbox in an underground auxiliary cavern, distributing helium supply and merging helium return flows. Horizontal transfer lines link the interconnection box with the individual 1.8 K units. A subcooler in the 1.8 K units enables the reconditioning of the 5 K helium flow after passing the up to c. 500 m long transfer lines to the ET-LF cryostat locations.

3. System working principle

Figure 1 shows our conceptual process flow diagram of the cooling system in order to visualize the working principle of both, the cool-down process and the steady-state operation. It highlights the same 5 main components stated in section 2. The coldbox, which is shown as a black box, is separated from the warm compressor system by means of warm helium transfer lines. The supply line provides the coldbox with helium at pressures around 12 bar(a). The return line operated above atmospheric pressure joins the warm helium header in valve V08[1].

Further, the coldbox incorporates 2 supply outlets to and 2 return connections from the interconnection box. The first coldbox outlet used for outer shield and cryotrap cooling is drawn from a stage of the implemented Collins process in which the helium reaches temperatures between 50 K and 80 K at pressures between 6 bar(a) and 12 bar(a). A corresponding return at slightly higher temperature is fed back into the coldbox, passing through an internal heat exchanger before entering the warm return line to the compressor system. The second outlet used both for the inner shield and the detector cooling comes from the cold end of the Collins process that supplies supercritical helium, typically at 5 K/5 bar(a). The particular operating parameters of the helium cryoplant will be fine-tuned later in a detailed process optimization.

After commissioning, the entire helium circuit is evacuated, purged and filled with pure ^{4}He, ensuring an over-pressure during warm standby, while connecting the system to the warm He supply/recovery system via valves V01, V02 and V03. The functional principle of the transient cool-down procedure and the steady-state operation is explained in the following sub-sections on the basis of figure 1.

3.1. *Outer thermal shield and cryotrap cooling*

The green circuit in figure 1 shows the cooling process of the outer thermal shields installed in the cryogenic transfer lines, the interconnection box, the 1.8 K units and the TM cryostats, as well as the cryotraps in the arm pipes next to the cryostats. To start the cool-down process, warm helium is supplied from the reservoir to the compressor system via valve V01, providing sufficient helium to pressurize the system. During transient cool-down of the entire cryogenic

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[1] General remark: Valves on the low-pressure side of the process may be executed as check valves rather than control valves, depending on the final safety concept.

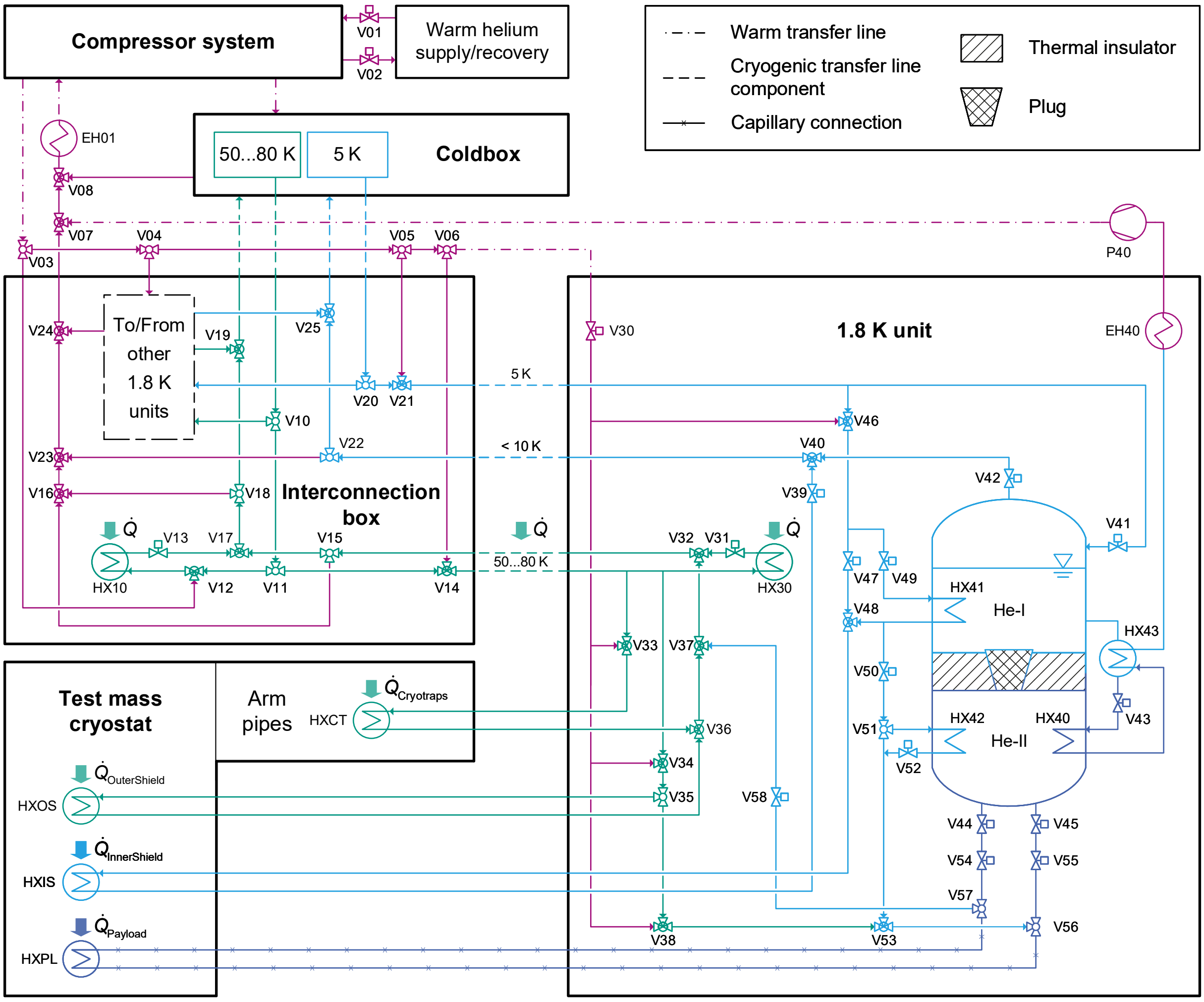

Figure 1. Process flow diagram of a helium cooling system for ET-LF with valves ("V"), heat exchangers ("HX"), electric heaters ("EH") and vacuum pumps ("P"). The $\dot{Q}_i$ represent heat loads absorbed by the cooling system at different temperature levels. Colors indicate different helium temperature levels, ranging from **blue** ($T \approx 2\,\mathrm{K}$) over **cyan** ($T \approx 5\,\mathrm{K}$) and **green** ($T = 50\,\mathrm{K}$ to $80\,\mathrm{K}$) to **purple** ($T = 80\,\mathrm{K}$ to $300\,\mathrm{K}$). For interpretation of the references to color in this figure, the reader is referred to the web version of this paper.

system or of individual cryostats, supercritical helium is supplied at $p = 6\,\mathrm{bar(a)}$ to $12\,\mathrm{bar(a)}$ and $T = 50\,\mathrm{K}$ to $80\,\mathrm{K}$ (depending on the final cryoplant design) through the first coldbox outlet. In order to control the cool-down speed, the cold 50 K to 80 K streams are mixed with room-temperature helium. The return flows from the individual components have higher temperatures compared to steady-state operation and cannot be used for heat recovery in the coldbox. Therefore, these helium returns are warmed up to room-temperature and fed back in the return line to the compressor, bypassing the coldbox. When transient cool-down is completed, the 50 K to 80 K supercritical helium flow is supplied continuously at constant temperature and pressure, while the flow rate can be reduced compared to the cool-down mode.

Valve V10 allows flow distribution among the 1.8 K units (only one 1.8 K unit and test mass cryostat is shown in figure 1). Valve V11 serves to split the flow into two parts. One part is used to cool the thermal shield of the interconnection box by means of HX10. The other part is directed towards the 1.8 K unit, passing the horizontal transfer line in the cavern. Inside the 1.8 K unit, the 50 K to 80 K header distributes helium towards 3 HXs. One flow cools the 1.8 K unit thermal shield via HX30. The 2 others are directed towards the cryotrap heat exchanger (HXCT) in the arm pipes and the outer thermal shield heat exchanger (HXOS) in the TM cryostat. Valves V33 and V34 allow mixing the supply streams to HXOS and HXCT with warm helium from the header via V30 for controlled, independent cool-down of the TM outer shield and the cryotraps. The return flows are joined with the HX30 return in V32, passing the cryogenic transfer line to the interconnection box and being mixed with the HX10 return in V17. Downstream of V17, the return flow is either diverted to the warm header during cool-down via V18 and V16, or led to the cold return line towards V19 during steady-state operation. Valve V15 serves as a separate return bypass for independent cool-down of the depicted 1.8 K unit from the interconnection box. While valves V13, V31, V33 and V35 serve for flow control in HX10, HX30, HXCT and HXOS, valves V36, V37, V32, V17 and V19 may be executed as check valves or simple piping joints[1].

The return flow passing V32 towards the interconnection box and V19 towards the coldbox is used to thermally shield the colder supply and return lines to/from the 1.8 K units and from/to the coldbox in the corresponding cryogenic transfer lines.

In the warm helium recovery line, warm returns from outer shield cooling are mixed in V23 with the warm return from the depicted 1.8 K unit operation, and with the corresponding flows from the other 1.8 K units in V24 (simplified illustration). Before being returned to the compressor system, the merged streams are warmed up to room-temperature in EH01 to avoid temperatures below the dew point in the warm vertical transfer line. Once the return flows have reached sufficiently low temperatures during the cool-down process, the cold streams are redirected in V18 to be used in the coldbox. Downstream, V19 allows the addition of cold returns from the other 1.8 K units (simplified).

3.2. 1.8 K unit operation

After completion of the outer shield cool-down process described in section 3.1, the refrigerator provides a stream of supercritical helium at 5 K/5 bar(a) via the second coldbox outlet. V20 allows flow distribution among the four 1.8 K units. The cold streams may be mixed with warm helium again to enable gradual cool-down of this circuit via V05 and V21.

Downstream of the transfer line connecting the interconnection box with the depicted 1.8 K unit, the 5 K/5 bar(a) helium flow is expanded through the Joule-Thomson valve V41 into a vessel, with valves V43, V44 and V45 being closed. Valve V42 controls the vessel pressure to $p \approx 1.2\,\mathrm{bar(a)}$ corresponding to a saturated He-I bath temperature of $T \approx 4.4\,\mathrm{K}$. The vessel is divided into two sections by means of a so-called λ-plate which thermally separates the liquid He-I from the superfluid He-II phase in the lower part of the vessel. In steady-state operation, the λ-plate's central orifice is closed by a plug. This plug can be lifted externally, enabling the initial filling of the complete vessel with liquid He-I. Additionally, the plug serves as an exhaust valve for the He-II section in case of incidents, opening into the upper vessel which incorporates a pressure relief device to the atmosphere.

During the cool-down phase, the helium exhaust from V42 returns to the warm recovery header via V23. Once this return flow reaches a sufficiently low temperature, it is fed back into the coldbox by means of V22. As soon as the liquid level in the vessel is sufficiently high, the plug in the λ-plate is closed.

Subsequently, the vacuum pumping system P40 and the electric heater EH40 are started. The Joule-Thomson valve V43 is opened, expanding a liquid flow drawn from the He-I bath to $p \approx 11\,\mathrm{mbar(a)}$, corresponding to a saturation temperature of 1.7 K. The low-pressure two-phase flow passes HX40, cooling the lower bath section in the vessel. At a temperature of c. 2.17 K, the liquid in the lower section is transformed into the superfluid He-II by second-order phase transition. With further cooling until steady-state operation, the temperature of the He-II phase is controlled to $T \approx 1.8\,\mathrm{K}$. The λ-plate separating the two liquid phases includes minimal leaks in order to allow for pressure compensation. Exposed to the vessel pressure of $1.2\,\mathrm{bar(a)}$, the He-II phase is in a sub-cooled state.

The low-pressure exhaust flow from HX40 pre-cools the He-I in HX43, increasing the liquid phase yield downstream of V43. It is warmed up in EH40 in order to enable room-temperature compression to the return line pressure by means of roots or rotary-vane pumps used for P40[2] [8]. The warm exhaust flow from P40 is directly returned into the warm helium header via V07.

3.3. Inner shield cooling

The inner thermal shield of the TM cryostat is operated at $T \approx 5\,\mathrm{K}$ and is cooled prior to the payload in order to provide cold surfaces for cryopumping close to the mirrors, avoiding or limiting frost build-up on the optics. The respective cooling power is provided by a supercritical helium flow through HXIS, which represents the inner shield heat exchanger as shown in figure 1. The corresponding flow at $5\,\mathrm{K}/5\,\mathrm{bar(a)}$ is drawn from the header inside the $1.8\,\mathrm{K}$ unit. A separate warm helium supply is implemented for mixing in order to control gradual cool-down via V46.

In steady-state operation, the supercritical helium supply passes V49 for further cooling in HX41 by means of the He-I bath, enabling inner shield temperatures for cryopumping as low as possible. Valve V39 is used to expand the yet supercritical return flow to the lower pressure of the He-I bath return line, which it joins in V40. This configuration is implemented to ensure single-phase flow through HXIS, substantially reducing vibrational noise in the inner shield as compared to two-phase flow [9]. Noise damping in the inner shield is necessary, as Shapiro et al. [10] report on noise coupling between the inner thermal shield and the interferometer optics due to scattered laser light.

3.4. Pre-cooling of the payload

The cooling system is designed such that the cool-down speed of the payload can be controlled across the whole temperature range between $300\,\mathrm{K}$ and $2\,\mathrm{K}$. This is foreseen to ensure minimal thermal stress in the sensitive last suspension stage. The pipework connections indicated in figure 1 between the payload heat exchanger HXPL and valves V56 and V57 are implemented in form of multiple parallel thin-wall capillaries. This improves the performance of the He-II cooling as well as the seismic vibration attenuation compared to rigid pipes or solid thermal links[3].

In the cool-down phase, helium streams of different temperatures are mixed so that the helium temperature through V56, the supply capillaries, the payload heat sink HXPL, the return capillaries and V57 are controllable at supercritical pressure. Hence, the helium flow through this circuit is single-phase, limiting the vibrational noise induced in the payload interface during cool-down, analogously to the inner thermal shield cooling. At the beginning of cool-down, V38 is the defining mixing valve. A flow of room-temperature helium from V30 joins a flow at $50\,\mathrm{K}$ to $80\,\mathrm{K}$ from V35. The resulting stream passes V53 and is fed into the capillary loop via V56. The warm exhaust is directed back to the compressor system via V37, where it joins the HXOS/HXCT return.

Once HXPL reaches temperatures of $50\,\mathrm{K}$ to $80\,\mathrm{K}$, a colder flow drawn from the $5\,\mathrm{K}$ header via V46 can be added by opening the second inlet of V53. Upstream, this flow is further cooled in HX41 and the flow rate towards V53 is adjusted by V50. The other part of the flow is used

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[2] The usage of *cold* or *mixed* compression as suggested in [7] to pump on the helium at $11\,\mathrm{mbar(a)}$ is not an option, due to the low expected flow rates and the lack of commercial equipment in this capacity range.

[3] Solid thermal links have proved to be a limiting factor for the interferometer sensitivity in the past [11], requiring substantial efforts for noise attenuation.

for the inner shield cooling (cf. section 3.3). While supply temperatures of $T \geq 5\,\mathrm{K}$ are desired, HX42 is bypassed using V51.

Below 5 K, all the helium flowing through HXPL is pre-cooled by the He-II bath to $T \approx 3\,\mathrm{K}$ via HX42, with V52 controlling the flow rate, while keeping the upstream pressure supercritical. With a closed inlet from V38 into V53, valves V50, V52 and V58 allow for pressure control inside the capillary pipework and HXPL. At temperatures $T < 4.4\,\mathrm{K}$, these valves are used to match the capillary pressure with the He-II bath pressure. Hence, at this point of the cool-down, there is sub-cooled He-I located between valves V52 and V58. In-between valves V54 and V44 as well as V55 and V45, there is an insulating vacuum that serves to limit the parasitic heat leak into the He-II bath during capillary cool-down.

3.5. Steady-state payload cooling

The prerequisite for initiating the last cool-down step is the presence of sub-cooled He-I at $T \approx 3\,\mathrm{K}$ and $p \approx 1.2\,\mathrm{bar(a)}$ between V56 and V57. The subsequent formation of He-II inside the entire capillary connection length between the 1.8 K unit and the payload marks the end of the TM cryostat cool-down process. The superfluid transition temperature at the capillary steady-state operational pressure of $p = 1.2\,\mathrm{bar(a)}$ is $T_\lambda = 2.17\,\mathrm{K}$. Thus, due to the preceding capillary cool-down to $T \approx 3\,\mathrm{K}$, only a small temperature reduction of $\Delta T \approx -0.83\,\mathrm{K}$ needs to be achieved. Therefore, the inlet into valve V56 from V53 and the outlet from V57 to V58 are first closed, stopping the flow of sub-cooled He-I through the capillaries and HXPL. Next, valves V54 and V44 as well as V55 and V45 are opened, so that the superfluid He-II phase extends down to V56 and V57. Finally, V56 and V57 are opened, connecting the capillaries directly to the He-II bath in the vessel. Hence, a He-II condensation front forms, gradually progressing from the vessel through the stationary liquid in the capillaries towards HXPL, with HX40 being the heat sink of the He-II process. This requires sufficient thermal insulation of the capillaries, which is provided by thermal shields cooled with the returns from HXIS and HXOS.

At the end of the cool-down process, the supply and return capillaries to/from HXPL are both filled with stationary He-II connected to the bath, enabling efficient low-noise heat extraction from the payload. This represents the steady-state system operation for the 2 K-cooling of the payload interface.

4. Summary and prospects

Our conceptual helium cooling system design for ET-LF covers all cooling requirements with one cooling system in each of the three ET detector vertices. It enables full flexibility in terms of cool-down and warm-up of the arm pipe cryotraps, the TM cryostat's outer shields, the inner shields and the payload. This is typically required to provide experimental flexibility and to limit the installed cooling capacity for a subsequent cool-down of components, as compared to synchronous cool-down and warm-up of the entire cryogenic system. In steady-state operation, minimum noise input is guaranteed by stationary sub-cooled He-II heat extraction trough thin capillaries from the payload to the 1.8 K units, and by single-phase supercritical flow through the inner shield heat exchangers. The temperature of the inner shield can be as low as 5 K, enabling efficient cryopumping closely around the somewhat warmer optics.

The general concept proposed in this document leaves room for further system development and optimization. For a more detailed engineering of the cryoplant and the underground cryogenic infrastructure, estimates of the heat loads in steady-state operation and during cool-down need to be refined, depending on advancements in the ET system design.

As a next step, our investigations will focus on the design of the capillary connections between the 1.8 K units and the payload heat exchangers. In this context, we will develop a thermally consistent capillary configuration and transfer line design, which at the same time offers minimal noise introduction into the payload via the cooling system interface.

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