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Conceptual cryostat design for cryogenic payload suspension studies for the Einstein Telescope

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Abstract. The Einstein Telescope (ET) is a third generation gravitational wave detector, combining a low-frequency (LF) and a high-frequency (HF) laser interferometer. Cryogenic operation of ET-LF in the temperature range of 10 K to 20 K is essential to suppress the suspension thermal noise, which dominates the detection sensitivity at frequencies below 10 Hz. This requires suspension materials with high thermal conductivity and low mechanical dissipation at cryogenic temperatures. Two possible suspension concepts are currently considered, using either monocrystalline suspension fibers made of silicon or sapphire, or titanium suspension tubes filled with static He-II. The dissipative behavior of these suspensions is characterized by the mechanical Q-factor. It can be measured by the ring-down method, exciting the suspensions to resonance vibrations on the nanometer scale and analyzing the decay time. For this purpose, a new cryogenic test facility is being planned, allowing the investigation of cryogenic payload suspensions for third-generation gravitational wave detectors. The test cryostat is equipped with a cryocooler and enables real-size studies with various suspension materials and geometries. The future integration of He-II is foreseen to enable He-II filled suspension studies. We describe the scope of experiments and the conceptual design of the test cryostat.

1. Introduction

The Einstein Telescope (ET) is a third generation gravitational wave detector that includes a room-temperature high-frequency (ET-HF) and a cryogenic low-frequency (ET-LF) laser interferometer. The sensitivity range of the LF interferometer lies between 3 Hz to 30 Hz and requires cryogenic operation in order to reduce one of the dominant noise sources in this application, i.e. the thermal noise. Especially, the suspension thermal noise (STN) of the optics system is a fundamental noise source in the low frequency range [1, 2].

In order to reduce the STN, not only suspension and optics temperatures of 10 K to 20 K are needed, but also suspension materials with low mechanical dissipation. In addition, the suspension material must also have a high thermal conductivity to achieve the target temperatures. A baseline design of cryogenic payloads for ET-LF that addresses these requirements has been proposed recently [3]. It includes two possible concepts, based on a monolithic silicon or sapphire suspension and a titanium suspension tube filled with superfluid helium (He-II), respectively. The mechanical dissipation in these structures can not be simulated with the required accuracy and therefore requires measurements [4, 5] for more reliable STN modelling and suspension design optimization. The conceptual design of the test cryostat presented in this paper enables the investigation of full-size suspensions for future cryogenic gravitational wave detectors. The cryostat provides the flexibility to test different types of suspension geometries and cooling concepts including the clamping designs. Future experiments will contribute to R&D efforts related to suspension surface quality, suspension design, suspension clamping and cooling interface design.

2. Methodology of suspension studies

The mechanical dissipation of a material or system can be quantified with the quality factor Q or the loss angle ϕ, where Q equals the inverse of the loss angle at resonance [4]. Hereby, the loss angle of the suspension is a crucial parameter in modelling the STN. The determination of the quality factor Q is performed via the usual ring-down method, whose procedure is described in Section 4.2. The measurement is based on the fact that the ring-down of the vibration amplitude at resonance frequency f_0 follows an exponential law as function of the characteristic ring-down time τ [6], which correlates to Q as:

$$Q \equiv \frac{1}{\phi(f_0)} = \pi f_0 \tau \quad (1)$$

The measured Q of a suspension results from a combination of various dissipative mechanisms, which can generally be classified into: intrinsic losses and extrinsic losses.

- **Intrinsic dissipative mechanisms** result from the properties of the sample material, the sample surface quality and the mechanical load, yielding the bulk losses, the surface losses and the thermoelastic losses, respectively. The bulk losses are typically obtained from Q measurements on substrate samples and are usually assumed to be only temperature-dependent [6]. In suspensions, surface and thermoelastic losses usually constitute the dominant dissipative mechanism compared to the bulk losses [7]. These depend strongly on the temperature, mechanical load and geometry [8, 9].
- **Extrinsic dissipative mechanisms** include gas damping losses, eddy current damping losses, recoil losses and clamping losses, and can be minimized via careful experimental technique implementation [8, 10]. Gas damping is avoided by ultra-high vacuum conditions, whereas eddy currents by a careful design of actuation and sensing transducers. Recoil and clamping losses in the sample support system require particular attention and experimental validation. Especially the clamping losses are deemed to be the main dissipative source in suspensions [10, 11, 12].

The identification of each contribution is non-trivial and at times not even possible to assess [12]. Thus, despite being a straightforward experimental procedure, the conditions at which the measurements are performed must be considered thoroughly in order to be able to discriminate the various loss contributions and inhibit the impact of the extrinsic dissipative sources on the measured data. For this reason, a step-by-step complexity increase within different experimental campaigns is foreseen in the test facility, as discussed in Section 3.

3. Experimental scope of the test facility

In the new test facility, two major experimental campaigns are planned as depicted in Figure 1. The first campaign involves the investigation of monolithic suspension fibers and empty suspension tubes, whereas the second campaign focuses on investigating He-II filled suspension tubes. The experimental campaigns enable the identification of individual dissipative mechanisms, whereby the first campaign is a prerequisite for the second. The loss mechanisms are investigated in the following way:

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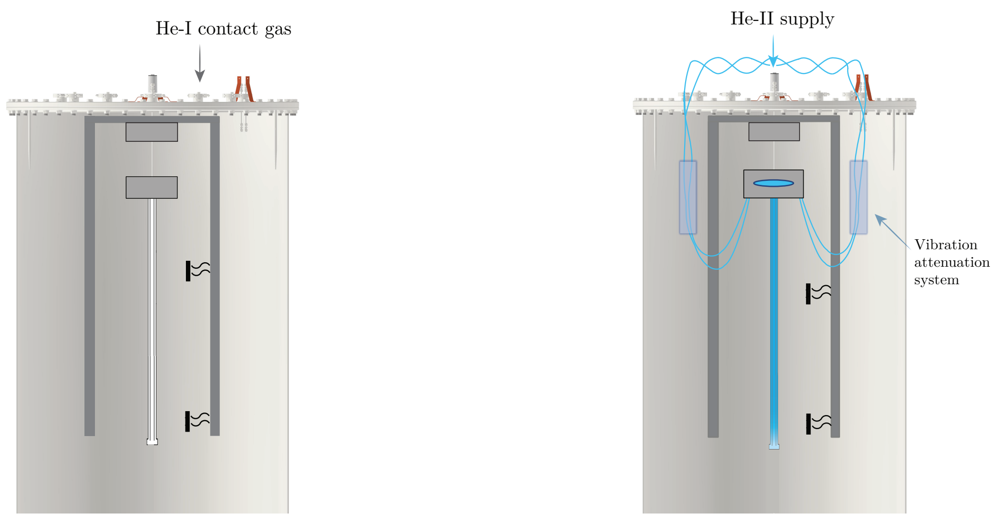
- the temperature dependence of suspension fibers and empty suspension tubes is investigated by measurements between room-temperature and 3 K;
- the influence of the surface losses is investigated by measurements with different fiber/tube diameters (surface-to-volume ratios) via extrapolation [7, 8];
- the influence of thermoelastic losses is investigated by measurements with different mechanical load (at constant temperature);
- the bulk losses in the He-II phase in filled suspension tubes are studied by variations of the heat flux and the operating temperature; and
- the interface losses between the He-II phase and the suspension tube wall may be discriminated from the bulk losses by different surface-to-volume ratios, i.e. different suspension tube diameters.

3.1. Campaigns with suspension fibers and empty suspension tubes
The first campaign with the setup shown in Figure 1a comprises experiments in a cryogen-free test cryostat. First, measurements with silicon and sapphire suspension fibers will be carried out at ambient temperature and compared against literature data, before measurements with the same samples are conducted at cryogenic temperatures. The cryostat thermal shielding and the sample cooling is provided by a cryocooler (cf. Section 4.3). These measurements will provide a validation of the test facility and enrich the literature data, given the wide spread of reported values. Next, Q measurements of empty titanium tubes in the same temperature range will follow. The characterization of losses in empty suspension tubes shall serve as a foundation for the second experimental campaign investigating He-II filled suspension tubes.

3.2. Campaigns with He-II-filled suspension tubes
The second experimental campaign follows the availability and the integration of a He-II supply system, which exceeds the scope of this paper. A compact system is currently being developed, using cryocoolers in combination with a Joule-Thomson cycle for achieving temperatures below the superfluid transition of 2.17 K. This system must be well isolated from the cryostat in order not to spoil the sensitive measurements. The application of static He-II in cryogenic suspensions provides an ultra-low-noise cooling option due to the exceptionally high thermal conductivity and potentially low dissipation in



(a) Suspension fibers and tubes campaigns **(b)** He-II-filled suspensions campaigns

Figure 1: Test chamber scheme during He-II free campaigns (left) and He-II campaigns (right).

the superfluid liquid column [3]. The latter aspect is a new field of research and requires experimental investigation via the quality factor. Q measurements of He-II filled suspension tubes schematically shown in Figure 1b will investigate the behavior of the quantum fluid He-II in suspensions of gravitational wave detectors for the first time, and hence the feasibility of the He-II-based cooling concept that has been validated theoretically and presented in detail in [3].

The suspension tube is cooled down to 1.9 K via the static He-II liquid column, whereas the thermal shielding is cooled to 3 K to 4 K by the cryocooler. Mechanical loading is not necessary in this campaign, because the influence is already investigated in the first campaign with the empty tubes and the He-II liquid column does not carry any load. The operating temperature range and the maximum heat load/flux depend on the He-II cooling capacity. The He-II supply to the suspension tube is planned by capillaries connected to the sample holder via a specially designed vibration attenuation system. The optimization of this cooling interface design is part of the experimental program.

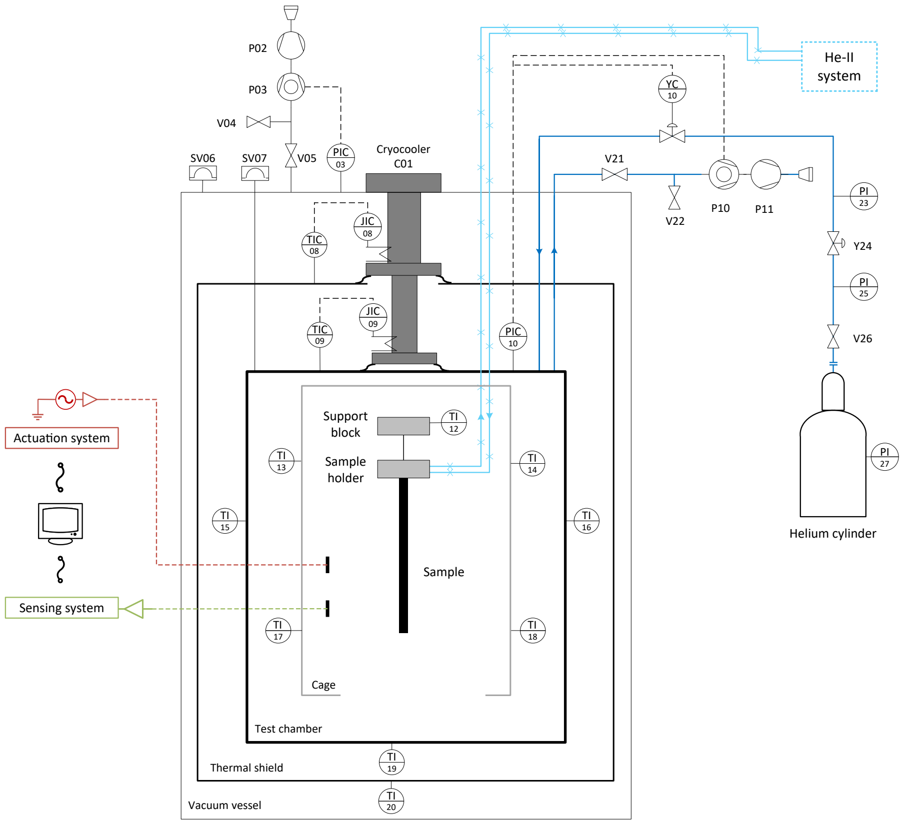
4. Conceptual cryostat design

The P&I diagram and the mechanical design concept of the test cryostat are shown in Figure 2. The cryostat comprises a stainless steel vacuum vessel of 1.5 m diameter and 3 m height, where all internal components are suspended from the top flange via hollow suspensions for reduced thermal conduction. The upper part of the cryostat is fixed via noise damping elements to a solid upper platform in the laboratory, so that the vacuum vessel can be removed downwards to the floor. An aluminium thermal radiation shield reduces the heat load via thermal radiation from the ambience. The Q measurements are performed in a helium-tight test chamber. The test chamber dimensions of 1.2 m diameter and 2 m height allow the investigation of full-size suspensions for ET-LF cryogenic payloads, which have a maximum length of 1.2 m in the present baseline design [3]. This includes also suspended dummy masses of up to 400 kg that can be attached to the lower suspension ends to investigate the thermoelastic dissipation term and the suspension mechanical strength. The sample is surrounded by a separate robust structure, called the cage, used for instrumentation mounting to avoid a direct sample contact that would compromise the Q measurements. A mechanical safety system (not depicted in Figure 2) will also be implemented to catch the dummy mass in case of mechanical suspension failure. This is necessary, because the suspensions will be loaded close to their yield/breaking strengths, which are nearly identical for brittle materials such as silicon and sapphire. The lateral integration of the He-II supply and return lines into the sample holder is visualized in Figure 2 only schematically. The development of a capillary vibration attenuation system is planned within a future project. Sufficient space is foreseen in the test chamber for this system and for future additional equipment installations.

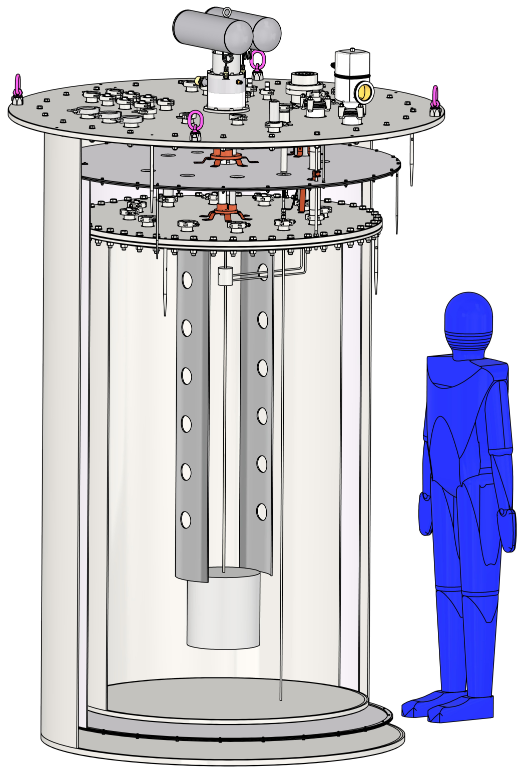
4.1. Sample support system design

The design of the sample support system is crucial in Q measurements of suspensions, due to the potential influence of clamping and recoil losses. The sample support systems will therefore be designed in close collaboration with expert groups in the field. It will consist of a support block and a sample holder, as visualized in Figure 2a. The sample holder for the suspension tube will include the He-II interface. The clamping losses are minimised by applying massive blocks as the clamping system, whose main faces are polished and precision-aligned [11]. To compensate differences in thermal dilatation, constant clamping forces during assembly and cryogenic operation are achieved by a combination of stress bolts and plate springs.

Recoil losses are minimised by a double-pendulum structure, which reduces the vibration transmission induced from the sample excitation to the upper part of the highly dissipative sample support system, inhibiting a coupling of the sample resonances with the support system resonances [8]. The current conceptual design will be validated by a combination of finite element analyses and modal measurements to exclude unwanted coupling between the sample and the surrounding structure.



(a) Piping and instrumentation diagram



(b) Cryostat mechanical design

Figure 2: Conceptual design of the test cryostat.

4.2. Ring-down method instrumentation

The ring-down method involves the excitation of the sample to resonance vibrations by means of an inhomogeneous sinusoidal electric field. Based on the electric properties of the suspension materials used in the experimental campaigns, a simple capacitor plate or a comb capacitor will be implemented as exciter (actuation transducer). Once amplitudes in the range of some nanometres are achieved, the exciter is turned off and the subsequent decay time of the oscillation is recorded. The oscillation of the sample is detected by an optical system known as shadow sensor, involving the detection of a differential photocurrent in two photodiodes, which arises from the vibrating shadow casted by illuminating the sample with a bright LED [11]. The heat dissipation of the Q measurement instrumentation is on the order of 0.1 W. The actuation and sensing transducers are mounted on the cage surrounding the sample. The compatibility with the cryogenic test environment is achieved by placing the transducers inside and the electronics outside of the cryostat. Electrical shielding of the cabling is implemented to prevent noise transmission.

4.3. Cryostat operation

Cryogenic temperatures are provided by a two-stage pulse-tube cryocooler of type Cryomech PT425, delivering 0.75 W at 3 K and 2.7 W at 4.2 K [13]. The first stage cools the thermal radiation shield to temperatures between 50 K and 30 K, while the second stage cools the internal test chamber to temperatures as low as 3 K. This is necessary to provide sufficiently low cooling and shielding temperatures in both campaigns. The temperature distribution in the thermal shield and in the test chamber is monitored via several Cernox® sensors (TIC, TI) shown in the P&I diagram in Figure 2a. The required temperature of the test chamber between 300 K and 3 K in the first experimental campaign is adjusted by the compensation heaters JIC 08 and JIC 09 controlled by the respective temperature measurements.

The vibrations from the cryocooler cold head lie at frequencies around 1 Hz to 5 Hz, whereas the sample resonant frequencies are expected in the range of 20 Hz to 1000 Hz. Thus, the Q measurements should not be affected by the cryocooler vibrations. If necessary, vibration mitigation strategies such as soft dampeners may be implemented.

The cooldown of the sample and the suspended mass is provided via a few pascals of helium injected as a contact gas in the leak-tight test chamber, which is pumped out after cooldown to provide ultra-high vacuum before the start of the Q measurements. The conduction-cooled sample holder and the vacuum chamber provide isothermal conditions around the suspension system throughout the ring-down measurements. A direct mounting of a temperature sensor onto the sample is not possible due to induced mechanical dissipation that distorts the Q measurement. Therefore, the sample temperature measurement is based on a well-established procedure, relying on the close dependence between the resonance frequency and the temperature, i.e. the sample becomes its own thermometer via the measured shift in the resonance frequency as a function of temperature [14]. The sample support block is equipped with the Cernox® sensor TI 12 as the nearest mounting position to the sample. Furthermore, the temperature of the cage is measured with four sensors (TI) distributed around the structure.

The pressure in the vacuum vessel and in the test chamber is monitored with the vacuum gauges PIC 03 and PIC 10, respectively. Ultra-high vacuum conditions in the test cryostat are provided by two vacuum pump systems, each consisting of a turbo pump and a scroll backing pump. The cryostat is protected at $p_{\text{burst}} < 0.5$ bar overpressure with regard to atmosphere via the bursting discs SV 06 and SV 07.

5. Summary and Outlook

A new cryogenic test facility is presented, which enables essential studies for the suspension thermal noise in cryogenic payloads of third-generation gravitational wave detectors. It enables measurements of the loss angle in full-size suspensions being developed for the low-frequency interferometer of the Einstein Telescope. The conceptual design of the cryogen-free test cryostat enables the investigation of the loss mechanisms via Q measurements. The first experimental campaign focuses on monolithic suspension fibers and empty tubes, investigating the impact of material, geometry, surface quality,

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temperature and mechanical load on the dissipation mechanisms. This will increase the data base and the confidence interval of available literature data for monolithic suspension losses. The experience gained in the first campaign including new data for empty suspension tubes will be essential for the second experimental campaign with He-II, which follows the integration of a He-II supply system. In this campaign, fundamental studies are planned on dissipation mechanisms in superfluid helium and its possible application in cryogenic gravitational wave detectors. The design of the He-II supply system for the second campaign is the scope of future work. The test cryostat fulfills the main requirements for suspension Q measurements and offers a wide investigation flexibility. Thus, this test facility will provide essential data for the development and design optimization of cryogenic payloads for the Einstein Telescope.

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