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Studies on the cooling systems of the Einstein Telescope cryogenic payloads(*)

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Summary. — Einstein Telescope (ET) is a third-generation gravitational wave detector that will cover a wide spectrum of frequencies measurable on the Earth's surface, paying specific attention to low frequencies from a few Hz up to 10 Hz (ET-LF). At these frequencies, to achieve a sensitivity at least ten times better than that of current detectors, ET will have to develop innovative technologies that will make the reduction of noise sources possible, especially those of a thermal nature. Therefore, it will be necessary to cool the ET main optics and their suspensions (payload) at cryogenic temperature (10 - 20 K). This will require the development of new cooling techniques, low vibration noise of the cryogenic system and the study of high thermal conductivity and low mechanical dissipation materials. It is extremely important to not only ensure an efficient thermal connection between the payload and the cooling system, but also preserve the mechanical isolation and, therefore, avoid introducing excessive vibrations to the entire system. Here some preliminary studies carried on how to test cryogenic payloads using a test cryostat cooled by means of pulse tube refrigerators and how to cool the payload using superfluid helium-4 are presented.

1. – Gravitational waves and second-generation interferometric detectors

Gravitational waves (GWs) are ripples in the fabric of space-time, a phenomenon anticipated by the theory of General Relativity [1]. They occur when massive and asymmetric objects undergo acceleration and propagate undisturbed in the universe at the speed of light. These waves can be produced from various sources, including merging binary systems of black holes and/or neutron stars, supernovae explosions, spinning neutron stars (pulsars), GWs stochastic background (incoherent sum of numerous GWs which cannot be distinguished individually) and unexpected sources. Currently, there are four operational detectors dedicated to the exploration of GWs, Virgo [2] in Italy, Hanford and Livingston LIGO [3] in the United States, and KAGRA in Japan [4]. These are modified Michelson laser interferometers, which operate in the frequency range from 10 Hz to 1 kHz. In each of the two perpendicular arms of the interferometer, there is a

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(*) IFAE 2023 - "New Technologies" session pair of input and end mirrors positioned 3 or 4 km apart. These mirrors are suspended as the final stage of a quadruple pendulum system to dampen seismic noise and, thus, behave as freely falling test masses within the detector bandwidth above the pendulum resonance frequencies. Laser interferometry is employed to detect the passage of a gravitational wave by observing the variation along the optical axis of the relative length of the interferometer arms formed by these freely suspended test masses. To attain the required sensitivity for detecting GWs, the sources of noise have to be reduced as much as possible. Various noises limit the sensitivity of current interferometers such as Advanced Virgo: seismic noise at low frequencies (below 3 Hz); thermal noise of the suspensions and mirrors and radiation pressure noise at medium frequencies (between 10 Hz and 300 Hz); shot noise at high frequencies (above 200 Hz). The increased sensitivity resulting from the upgrade of the GWs detectors Virgo and LIGO, moving from their first to the second (advanced) generation, not only led to the first direct detection of a gravitational wave [5] but also enabled the discovery of many coalescing binary systems during the O1, O2 and O3 observation runs [6-8]. At present, the level of sensitivity allows for the detection of weekly GWs originating from binary black holes. However, the observation rate of interesting sources, such as neutron star mergers or supernovae, remains relatively low within the current detection range. The sensitivity achievable in the existing interferometers cannot be significantly improved due to the limitations dictated by the site and infrastructure, including factors such as the length of the arms, local seismic noise, the lack of flexibility to accommodate new technologies, and so on. Therefore, to build a third-generation gravitational wave observatory with significantly improved sensitivity, the limitations imposed by the technologies employed in the current interferometers have to be overcome. When dealing with a single interferometer, a strategy aimed at mitigating a noise source in a specific frequency band may worsen the sensitivity in another frequency range and/or conflict with other noise reduction strategies. For instance, because shot noise inversely scales with optical power, whereas photon radiation pressure noise increases with optical power, achieving an enhanced sensitivity curve across the entire frequency range will be challenging with a single detector [9, 10]. Moreover, using high optical power for high-frequency sensitivity and, at the same time, maintaining cryogenically cooled test masses to reduce thermal noise for low-frequency sensitivity within one interferometer also presents a formidable challenge [9, 10].

2. – Einstein Telescope, the third-generation gravitational wave observatory in Europe

Einstein Telescope (ET) [9, 10], a forthcoming third-generation underground gravitational wave observatory to be built in Europe, will achieve a sensitivity level that surpasses current advanced detectors by a factor of at least ten. It will cover a broader detection frequency band, extending down to frequencies below 10 Hz (from 3 Hz to several kHz). This remarkable improvement will be achieved through the extension of the interferometer's arm length from 3/4 km to 10 km and the integration of a series of innovative technologies. ET will consist of three detectors in a triangular arrangement, with each detector featuring two interferometers (xylophone configuration). The low-frequency interferometer (ET-LF), designed to operate within the temperature range of 10 to 20 K, will be optimised for detecting gravitational waves in the frequency range spanning from 3 Hz to 30 Hz. It will employ a light power of 18 kW within its interferometer arms and silicon mirrors with a diameter of approximately 45 cm, each weighing around 200 kg. The second interferometer dedicated to detecting high-frequency gravitational waves (ET-HF), ranging from approximately 30 Hz to several kHz, will operate at room temperature (290 K). It will utilise fused silica optics with a diameter of about 60 cm and a mass of approximately 200 kg each, along with a substantial light power of around 3 MW in the interferometer arms. The separation into two distinct and parallel systems allows for the mitigation of opposing noise sources, such as shot and radiation pressure noises, and facilitates the simultaneous application of contrasting strategies, such as high-power lasers and cryogenic temperatures.

3. – A facility for testing the payload cooling down

A straightforward approach to mitigate the impact of suspension thermal noise, which is dominant in the frequency range from 2 to 30 Hz, on the sensitivity curve of the second-generation detectors is to maintain the mirrors at cryogenic temperatures (between 10 and 20 K) [9,10]. Managing cryogenic optics at high light power poses a significant technological challenge that exceeds the capabilities of currently available technologies. The heat produced by laser light and absorbed by the mirror surfaces must be extracted from the mirror via thermal conduction along the suspension fibres, without compromising the performance of the seismic isolation system. In KAGRA cryogenic temperatures are achieved by using a large battery of cryocooler, mainly based on the pulse tube technology. The presence of cryocoolers near the optics poses a risk to the low-frequency sensitivity: they should introduce extra vibration noise well below the ultimate barrier of the suspension thermal noise [11]. Thus, the need for low-noise cooling methods arises as a critical requirement. It implies a careful selection and design of cooling techniques and equipment to minimise any adverse effects on the interferometer's overall sensitivity. Whatever will be the cooling system, the payload will be inserted in the innermost volume of a cryostat [9, 10] at a temperature of ~ 4 K. This 4 K container will be surrounded by a ~ 80 K shield and the cryostat will be completed by an external vacuum chamber on top of which a vacuum tower housing the superattenuators, responsible for reducing seismic noise up to a few hertz, is mechanically connected. Ensuring an effective thermal connection between the payload and the cooling system while preserving mechanical isolation and preventing the introduction of extra vibrations to the entire system is a challenge. To study this problem a test facility is being developed to cool down the payload drawing inspiration from a proven model validated by KAGRA [12]. In a payload, the cryogenic mirror is suspended using thin wires, which are attached at the opposite end to a marionette used for mirror positioning. An actuation cage acts as a reaction mass for the mirror and the marionette. Both the marionette and the cage are suspended from a platform that is hung from the superattenuator [11]. The suspension of the mirror employs a high-conductivity monolithic design, where the heat is drawn out from the mirror via the sapphire or silicon suspension fibres, and remains independent of the cooling solution. In contrast, there are two possible approaches for suspending the marionette that depend on the cooling method chosen [11]. In the cooling system designed for the test facility developed in Rome, which relies on pulse tube technology like KAGRA [13-15], the sapphire or silicon suspensions are employed. The cooling system is connected to the actuation cage and platform using heat links that are highly flexible to minimise vibrations and exhibit high thermal conductivity. This arrangement is implemented to minimise the transmission of vibrations generated by the system. For the cooling system based on cryogenic fluids, the marionette is suspended using a tube filled with static He-II (detailed in sect. **4**). A pair of pulse tube cryocoolers, operating in phase opposition to self-cancel the vibrations of their cold stages [16], supply the refrigeration power needed to maintain the mirror at cryogenic temperatures, while a second pair will be used to keep cold the cryostat shields. These cryocoolers are positioned far from the cryostat to prevent vibrations generated by the refrigeration cycles from introducing noise that could impact the dynamics of mirror positions. They are connected to the cryostat via a suspended pure aluminium bar, with the connection made possible using soft heat links. This configuration, where the refrigeration power units are separate from the payload cryostat, offers several advantages. Not only does it allow for the isolation of vibrations generated by the refrigeration unit from the payload, but it also enables maintenance without accessing the payload cryostat and facilitates the potential implementation of more efficient and quieter cooling units in the future, such as those based on superfluid helium.

3·1. *Amaldi Research Center*. – As part of Italy's Recovery and Resilience Plan(1), the Einstein Telescope Infrastructure Consortium (ETIC) is responsible for the preparation, planning and execution of feasibility and characterisation studies for the abandoned Sos Enattos mine in Sardinia (Italy). This mine is one of the European candidate sites for hosting ET [17]. One of the primary objectives of ETIC is to identify, study, and develop the necessary technologies to achieve the sensitivity expected by ET. This involves strengthening or creating a network of dedicated laboratories and facilities at universities and institutions. Sapienza University and INFN(2) in Rome are actively involved in the project, with research and development focused on cryogenics and payload technologies. The first prototype of the cooling system [18, 19] will be hosted and tested in one of the laboratories of the Amaldi Research Center(3) at Sapienza dedicated to GWs science. This system consists of a cryostat and a full-scale cryogenic payload, equipped with two low-vibration cooling lines based on pulse tubes. The approach chosen for both the cryostat and payload involves the utilisation of solid conduction for heat extraction. While the test mass in this payload will be dummy, the main components involved in heat extraction and the last suspension stages will accurately represent the real system. The infrastructure where the cryostat is being developed cannot accommodate a seismic isolation system. The costs for these cooling lines are shared between ETIC and Amaldi Research Center. The prototype system is being designed to closely match the requirements of ET-LF, making it suitable for a future integration into the ET detector. Each cooling line has two pulse tubes operating in counterphase. Their second stages are connected to the head of a hammer-shaped bar via heat links. The pure 5N aluminium bar was assembled at CERN: head and cylindrical rod were jointed using the Electron Beam Welding technique in vacuum. It is mechanically suspended and vibrationally decoupled from the cryostat by heat links. The cryogenic payload and cryostat are currently in the study phase. As a result, the cooling line will be tested using a simple cubic test chamber instead of the cryostat (fig. 1), where various test masses can be placed within it for studying cooling times and vibration transmission. The entire system is protected by a shield made of Al1080, which is connected to the first stages of pulse tubes through heat links. The shield serves to diminish the radiation coming from the room-temperature vacuum chamber into the inner heat path. Finally, the vacuum chamber consists of four

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(1) `https://commission.europa.eu/business-economy-euro/economic-recovery/recovery-and-resilience-facility/italys-recovery-and-resilience-plan_en`.

(2) `https://home.infn.it/en/`.

(3) `https://www.phys.uniroma1.it/fisica/arc_amaldi_research_center`.

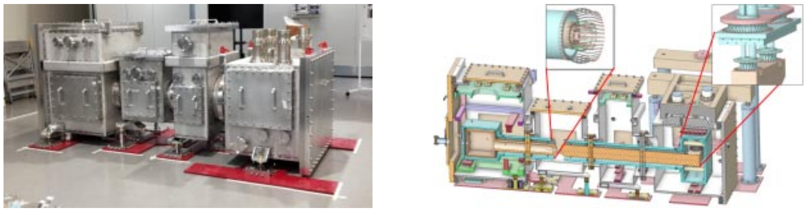

Fig. 1. – The cooling line prototype installed in the Amaldi Research Center laboratory (left) and the corresponding drawing with the soft heat links highlighted (right).

distinct chambers assembled using flanges. One contains the test chamber, two support the entire cooling bar and cover the section where it is vibrationally decoupled from the test chamber, and the fourth houses the pulse tubes. Heat links form connections between the end of the bar and the shield of the cooling line with the test chamber or cryostat, and between the first and second stages of the pulse tubes with, respectively, the shield and the head of the bar. These connections have to vibrationally decouple the different components and, at the same time, thermally connect all of them efficiently. KAGRA was among the pioneers in implementing such heat links [13, 20]. Differently from the Japanese model, the heat links used in the cooling lines in the Amaldi Research Center laboratory will be composed of terminal heads made of 5N copper, used as joints connecting various parts, and three/five soft foils constructed from 6N aluminium. The thickness of each foil will vary between 50 μm and 100 μm, and the length will range from 90 mm to 160 mm, depending on where it will be used. The refrigeration lines will undergo testing at low temperatures, during which both the refrigeration power generated by two pulse tube units and the spectrum of the residual vibrations at the end of the line will be measured. This data will serve as a crucial benchmark for evaluating the reliability of thermo-mechanical simulations.

4. – Cooling system based on He-II

As an alternative to the cooling of ET-LF payloads relying on pulse tube technology, a system based on superfluid helium (He-II) is being studied [11, 21]. He-II is a quantum fluid with zero viscosity and can transport heat with extremely high thermal conductivity, providing more cooling power and leading to a significant reduction of thermal noise. The marionette will be cooled to 2 K using a double-walled titanium suspension tube filled with He-II. The superfluid helium will reach the platform, to which the tube will be anchored, via a system of thin capillaries connected to a cryogenic supply unit. This helium tank will be placed far from the system to minimise any mechanical impact on the payload. During the cooling process, supercritical helium (He-I) will circulate in counterflow through the double-walled tube to cool the marionette. In steady-state operation, He-I will be transformed into stationary He-II, which will fill the suspension tube entirely. The marionette will achieve a temperature of 2 K through contact with the He-II suspension, allowing a silicon mirror to reach an approximate temperature of 15 K. This temperature variation is due to factors such as heat load and temperature gradients within the monocrystalline mirror suspensions. Various silicon suspension elements, including fibres [22] and ribbon-like structures [23], are currently being investigated as integral components of the payload. This payload is essential for achieving mechanical isolation and features meticulously designed crystalline silicon vertical spring blades optimised for demanding cryogenic conditions [9, 10]. These blades serve a dual purpose:

ensuring efficient thermal conduction and maintaining crucial mechanical isolation. The synergy between cryogenic methods, precision-crafted crystalline silicon vertical spring blades, and other suspension elements, such as the mirror, rods, and flexures, exemplifies ET's pioneering efforts to enhance sensitivity.

5. – Conclusion

The field of gravitational wave astronomy has made substantial progress with second-generation detectors, and the upcoming Einstein Telescope represents a groundbreaking leap forward in sensitivity and discovery potential. Overcoming the current limitations and challenges (such as the delicate balance between reducing thermal noise and optimising cooling technology, as well as ensuring optimal performance of payload suspensions) is crucial to acquire insightful knowledge and enhance understanding of the universe's composition and evolution. The cooling system designed for ET-LF faces the dual challenge of simultaneously maintaining mechanical isolation while also ensuring an efficient thermal link between the payload and the cooling system. The options under consideration, pulse tube and He-II technology, represent innovative solutions to these complex requirements. Their successful implementation is essential for the Einstein Telescope's mission.

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