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RESEARCH ARTICLE

Cryogenics and Einstein Telescope

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Abstract The dominant noises which limit the present sensitivity of the gravitational wave detectors are the thermal noise of the suspended mirrors and the shot noise. For the third generation of gravitational wave detectors as the Einstein Telescope (ET), the reduction of the shot noise implies to increase the power stored in the detector at 1 MW level and, at the same time, to compensate the huge optic distortion due to induced thermal lensing. At low temperature it is possible to reduce both these effects. However, lowering the temperature of the test masses without injecting vibration noise from the cooling system is a technological challenge. We review here the thermal noise impact on the ultimate ET sensitivity limit and we discuss possible cryogenic configurations to cool the mirror.

Keywords Gravitational wave · Cryogenics

1 Introduction

The sensitivity that the interferometers will reach in the near future, although high enough to hope for the detection of a few events per year, could be improved by more than an order of magnitude in average, at all frequencies. This upgrade will be needed, in the long term, to step from a "detector" level to an "observatory" level. Recently a new generation of gravitational wave detectors is under study aiming to extend the sight horizon for coalescent binary events of 1.4 solar masses up to 1 GPc and

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consequently increasing the possibility to detect the gravitational waves up to tenth events per day. The fundamental limitations of the sensitivity of the second generation of gravitational wave detectors at low frequency are given by the seismic noise, the related gravitational gradient noise (so-called Newtonian noise) and the thermal noise of the suspension last stage and of the test masses. To circumvent these limitations new infrastructures are necessary: an underground site for the detector, to limit the effect of the seismic noise, and cryogenic facilities to cool down the mirrors to directly reduce the thermal vibration of the test masses. The Einstein Telescope design study is addressing the basic questions how to realize this new instrument.

The suspensions of the optical elements of the interferometer must provide the necessary attenuation from seismic and acoustic noise. In particular the last stage of the suspension must be designed not to degrade the intrinsic mechanical losses of the mirror because of the well known relation between mechanical dissipations and thermal motion in macroscopic systems. At present the thermal noise has been reduced by developing sophisticated suspension systems with materials with low mechanical dissipation and low friction mechanical clamps. However, at the goal sensitivity of third generation detectors, the only way to have a further reduction of thermal noise will be the use of cryogenics. This choice is quite natural considering also the large amount of power which will be stored in the F-P cavities: it could be found indeed that cryogenics will be the only method available to further reduce the thermal lensing effects at the incident power of third generation interferometers.

Low temperature thermodynamics and experimental Gravitation are branches of Physics crossing each other since many years. In the past, much work has been already done to cool resonant gravitational wave detectors by using cryogenic fluids. Fairbank proposed this marriage in 1971 and the first cryogenic antenna of 20 kg was successfully cooled down to 4.2 K by the group headed by Edoardo Amaldi and Guido Pizzella in 1974 [1]. Then we were able to run the first network of gravitational wave antennas based on the detectors of Stanford, Louisiana and Rome Sapienza universities [2]. The last antenna EXPLORER, installed at CERN, was operated with superfluid helium [3] during several years and it is still in operation. Later in 1991 during the first cooling of the NAUTILUS detector performed at CERN we were able to achieve the record temperature of 95 mK on a 2,100 kg test mass [4].

The use of cryogenics required a great effort for filtering the extra mechanical noise associated to the use of cryogenic fluids [5,6]. However, the increase in the complexity of the detector was compensated by the advantage of using the low noise technologies available in the liquid helium temperature range.

In the case of the interferometric detector the compensation of the extra noise generated by the fluid is even more difficult because we need to operate a broad frequency band which is extended down to few Hz. This implies to design carefully the last stage suspension system screened to the extra vibration providing at the same time an efficient thermal path for the propagation of the refrigeration power. Assuming for ET an optic configuration with mirror losses of the order of 10^{-6} and a stored light power of $\sim$1 MW, we deal with the need to implement a cryogenic system able to extract $\sim$1 W of heat from the mirror. This requirement is compatible both by defining a cooling strategy based on closed loop cryo-coolers [7] or by setting up a dedicated liquid helium plant.

In the following we will review the ET sensitivity limit due to the thermal noise of the suspension and then we discuss two alternative approaches for the mirror cooling.

2 The suspension thermal noise at cryogenic temperature

In a homogenous universe an improvement of an order of magnitude in sensitivity implies three orders of magnitude in the number of observable sources. Thus, the sensitivity goal of a third generation interferometer is to go down of more than a factor 10 in average and to extend down to 1 Hz the bandwidth with respect to the advanced gravitational wave interferometers. The present effort in designing such a sensitive detector is relying on the more challenging known technologies which can be employed to reduce all the noise contributions below the aimed goal.

It is well understood that the suspension thermal noise is one of the main sources limiting in the low frequency range the sensitivity curve of a ground based g.w. detector. The mechanical losses of the wires suspending the mirrors depends on the clamps geometry and squeezing force of the wire against the mirror body. A good clamping technique has been developed for the VIRGO interferometer [8]. However, to improve its performances few groups are trying to improve a monolithic configuration for mirror and suspension that, in principle, should be the ultimate low noise limit. Indeed the choice of the monolithic suspensions made of the same low dissipative material of the mirror is the solution studied since several years [9,10] and adopted in the design of the advanced interferometers.

At cryogenic temperatures the use of monolithic suspensions will be the first option for designing the new interferometer payload, the mirror and its steering system the marionette. Moreover the recent new evaluation [11] of the thermal noise limit of the advanced detectors has shown that as soon as we are dealing with low losses mirror pendulum, the role of the upper suspension stage losses starts to contribute and must be included in the computation of the whole thermal noise. For this reason to derive a realistic limit we have to deal with the whole last stage suspension of the test masses.

In Fig. 1a, the thermal noise curves for a possible mirror cryogenic suspension have been compared with the ET goal sensitivity curve [12]. The mirror is made of silicon having a mass of 150 kg and suspended with monolithic suspensions. The materials used for making the suspension wires have a loss angle of 10^{-8} (silicon) for the mirror and the RM and 10^{-5} (Ti6Al4V alloy [13]) for the marionette. Both the cases at 10 K (cyan curve) and at 2 K (green curve) are compatible with the goal noise curve. However if a viscous loss is present on the marionette pendulum stage, the mechanical quality factor of the must be greater 10^6 at 2 K , in order not to spoil the sensitivity curve in the band below 10 Hz (see the light blue curve). This results is a strong indication that also the Q of the marionette suspension stage can play an important role and must be an issue in the design of a cryogenic suspension. Moreover, the continuous power absorbed by the mirror during the interferometer operation gives rise to a temperature gradient between the marionette and the test mass, which must be taken into account in the thermal noise computation and consequently influences the optimization of the mirror last stage suspension design (see the reference [14]). In Fig. 1b, the thermal noise of a last stage having the marionette at 2 K and the mirror

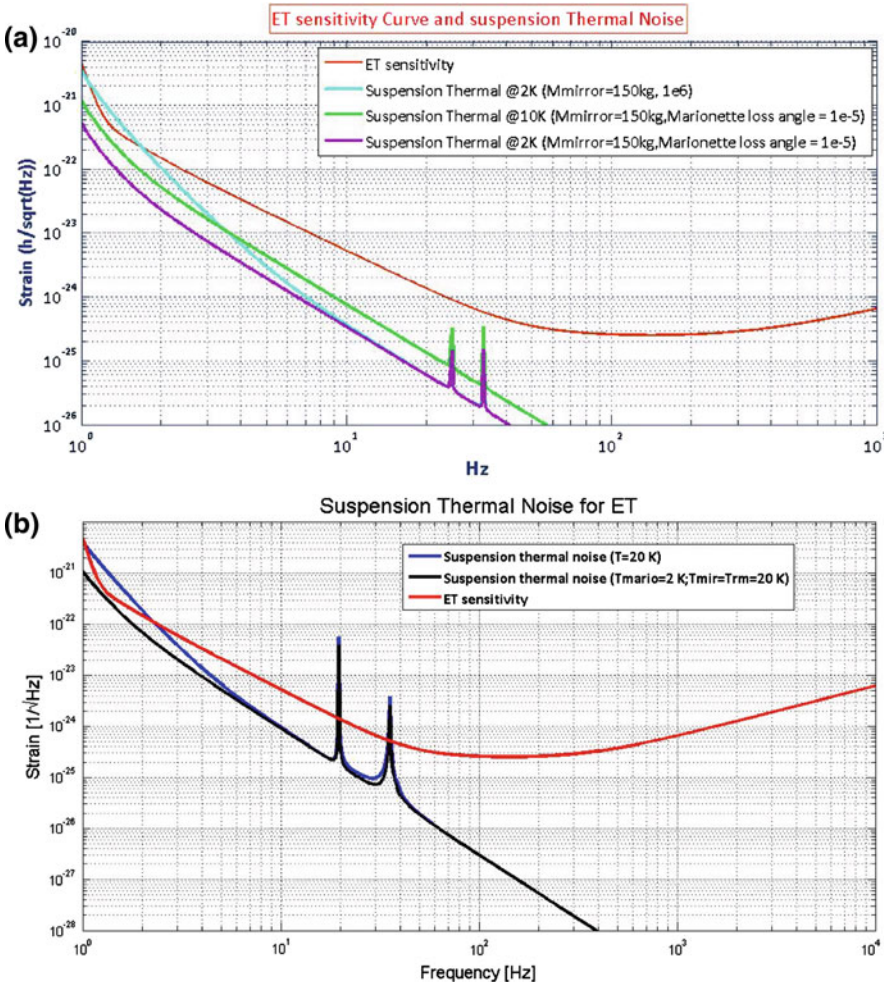

Fig. 1 ET sensitivity curve compared with the suspension thermal noise computed with different viscous losses of the marionette suspension (**a**) and different temperatures of the stages (**b**)

and recoil mass at 20 K is shown and compared with the payload thermal noise at an homogeneous temperature 20 K. The difference between the curves is evident in the low frequency range, which the zone of interest for the optimization of the suspension design.

Between 30 Hz and 1 kHz the sensitivity of the interferometer will be limited by the internal thermal noise of the mirrors and their coatings. At low frequency, this noise is actually more limiting than what we expected some years ago, for two reasons:

- it looks like the proper model for internal damping is not a viscous damping, but rather the so-called structural damping model provided by the loss angle $\Phi(\omega)$ which, for the intrinsic dissipation mechanisms is constants and provides a noise spectrum in $\nu^{-1/2}$ instead of a white spectrum.

– the high reflective coatings present the mirror surfaces dominate in the loss mechanisms for the evaluation of the mirror overall thermal noise, and contribute in a non-negligible way to the overall loss factor of the mirror.

On the other way, there is a good chance to get better qualities of silica, better polishing and lower loss coatings, providing a higher Q than the one VIRGO measured ($Q = 1 \times 10^6$). Presently, LIGO has measured up to $Q = 5 \times 10^6$, for some modes of a high quality polished mirror, and VIRGO is also getting very encouraging results with its first full size beam splitter ($Q = 2.5 \times 10^6$).

By lowering the temperature and by choosing the appropriate materials, the Q values of both suspension and mirror itself can be drastically improved. In view of the design of a cryogenic payload, we need to replace the amorphous silica fiber by crystalline material: in this way both the Q and the thermal conductivity will be higher. The choice of the mirrors material and temperature depends mainly on optical criteria. Tests performed by experimental groups working with super mirrors cooled at liquid helium temperatures, have shown that the performances of the coating does not change dramatically. The silicon seems compatible with the use of cryogenic techniques which can be applied in the future to cool the suspended mirror.

Moreover, the result of a thermal simulation shows as the compensation of the thermal lensing effect at cryogenic temperatures with silicon is easier even with stored light power in the Mw range at it is shown in Fig. 2. Refraction index variation with temperature is very small at low temperature and the thermal lensing is likely to be zero because the thermal expansion coefficients tend to zero at cryogenic temperatures. The simulation, performed using the ANSYS thermal software package shows thermal gradients 10^{-2} times those of the VIRGO silica mirror operating at room temperature with an impinging power 20 times lower.

In conclusion, the set up of low losses cryogenic suspension is a challenge: it requires the selection of new materials and the deployment of all the best known technologies to set up the new payloads. Moreover a strong research and development program devoted to new methods for building quiet and reliable cooling systems must

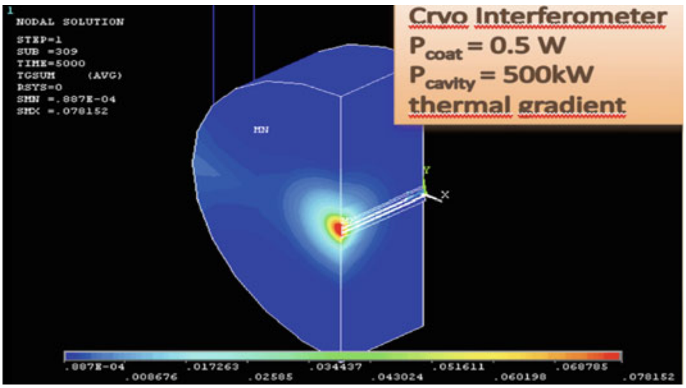

Fig. 2 ANSYS simulation of the thermal deformation of a silicon plate at cryogenic temperatures. We assumed a laser beam of 0.5 MW impinging at its center

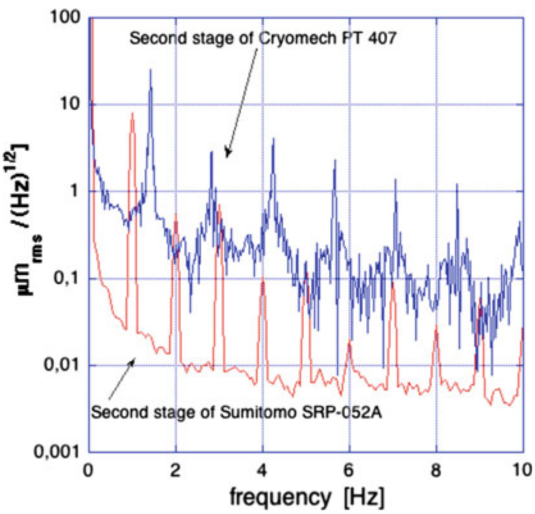

Fig. 3 The displacement noise spectrum of the second stage cold point of the CRYOMECH PT407 and of the Sumitomo SRP-052A as function of the frequency

be pursued and in the next paragraph we will try to sketch a possible solution to this challenging problem (Fig. 3).

3 Achieving cryogenic temperature with cryo-coolers

The crucial requirement for a gravitational wave cryogenic system is to preserve the system from the vibration generated by the cooling devices and at the same time to provide sufficient refrigeration power to compensate the thermal loads due to light absorption by the mirrors. A simple approach to cool down the mirrors is based on the use of cryo-coolers [7]. For instance, Gifford-McMahon (GM) refrigerators have been developed since a long time and are widely used in various fields of science and industries because of their convenient handling. However, their cooling power is provided by the motion of a displacer which causes large vibrations at the cold head, an aspect which makes them not suitable for all applications where a low acoustic noise level is necessary.

In more recent times, the pulse tube (PT) cryo-coolers have been developed. The particular thermal cycle of PT refrigerators gives them a two or three times higher efficiency than GM cryo-coolers for loads temperatures between 55 and 120 K, and requires no moving elements at low temperature. This latter characteristic is quite important: because of it, we expect PT refrigerators to be intrinsically more reliable and less noisy than classic GM coolers [15]. Thus, a pulse tube cryo-cooler seems to be an interesting option for our purposes. However, because of the gas pulse flowing in its cold head, also this kind of refrigerator injects mechanical noise in the cooled sample, at a level which is still far too high for the elements of a gravitational antenna. Indeed, in order to detect gravitational waves, current detectors have reached displacement sensitivities of the order of 10^{-18} m$/\sqrt{(\text{Hz})}$ and an increase by at least two orders of magnitude is foreseen for ET, where we have to implement the use of low temperatures.

To cool the mirrors we should position the cold finger of the refrigerator along the vibration isolation chain in such a way that the extra noise coming from the refrigeration cycle is attenuated to a level lower than the aimed ET sensitivity curve i.e. 2×10^{-18} m/$\sqrt{(\mathrm{Hz})}$ at 2 Hz for a 10 km interferometer arm. On the other hand, such a solution has the disadvantage to absorb a part of the refrigeration power and to increase the length of the heat link, increasing the overall cooling time and the final thermal gradient between the cold finger and the mirror. In order to overcome these difficulties, the plan is to apply the vibration insulation technologies developed for gravitational interferometers and to reduce the vibrations of the cold finger of a PT cryo-cooler by an active control system. This approach will permit us to reduce the length of the passive attenuator system , which is composed in VIRGO by a series of five pendula, providing a ∼100 attenuation factor at 2 Hz for each stage.

We compared two different models of cryo-coolers, the Cryomech PT 407 and the Sumitomo SRP-052A. For both systems, we measured the acceleration of the 4 K cold head.

Our data show that the vibration noise level generated by the Sumitomo is lower by a factor ∼10 than that by the Cryomech. The displacement noise spectrum results to be $\sim 10^{-5}$ m/$\sqrt{\mathrm{Hz}}$ at the frequency of the helium gas wave of the cryo-cooler and $\sim 10^{-7}$ m/$\sqrt{\mathrm{Hz}}$ out of these peaks.

Moreover, our model of Sumitomo has the additional advantage of having the room temperature throttle valve separated from the main body of the refrigerator, with the possibility to keep it far from the cryostat obtaining a further attenuation of the noise produced by this element.

This implies that we need an extra attenuation factor of $\sim 10^{-4}$ at the PT frequency in addition to that provided by a VIRGO-like super attenuator. Thus, on the base of the level of the vibration noise generated by the cooling machine, we have selected the Sumitomo SRP-052A, though its nominal cooling power is slightly lower than for the Cryomech. However, also the noise produced by this refrigerator is still too high noisy for our purposes and for this reason it has been necessary to design a cooling system which can attenuate the PT cryo-cooler vibrations. The vibration free cryostat (VFC) [16] we have designed is suitable for coupling such a system to a mirror, according to the issues discussed above.

The cryostat scheme is sketched in Fig. 4. It is based on the idea to attenuate the cryo-cooler vibrations by directly acting on it. We monitor the cold head vibration by an optic bundle fiber, which is acting as low temperature displacement sensor, while the actuation is based on three piezoelectric stacks set at room temperature outside the cryostat vacuum. The cryo-cooler cold head is clamped to a platform placed on dampers and it is connected to the cryostat by a soft bellow designed to mechanically decouple it from the cryostat. The feedback correction signal is sent to the three piezo-actuators which are loaded by the platform and can push the cold head platform elastically coupled to cryostat mechanical structure.

The cryostat is equipped with a first thermal screen connected to the first cold stage while an inner vacuum chamber made of aluminum and hosting the payload is thermally connected to the second cold stage. The heat links are 99.999% pure aluminum

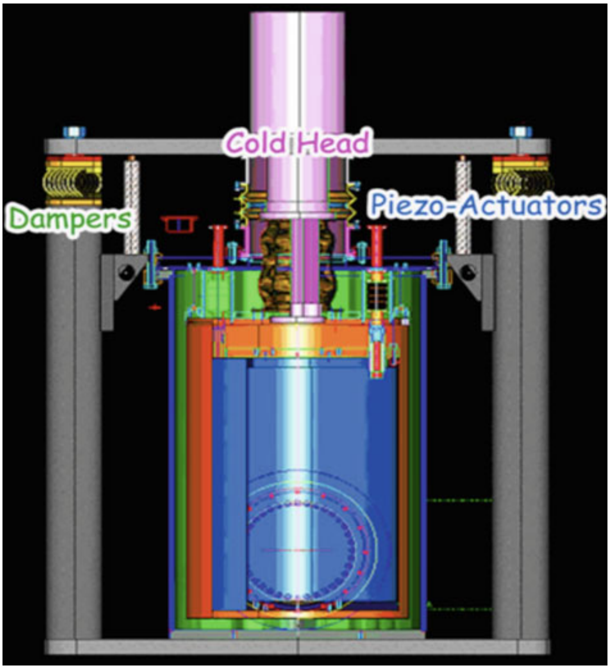

Fig. 4 A simplified scheme of the vibration free cryostat

stripes arranged on a ring. They are chosen to reduce the link stiffness and provide a mechanical decoupling with the system to be cooled. Indeed the main attenuation factor of the cryo-cooler vibrations is obtained by applying the active control system. At present the attenuation achieved controlling just the vertical degree of freedom is of the order of 3×10^{-3}. A further improvement is expected by controlling the horizontal degrees of freedom and by reducing the recoil effect on the structure holding the monitor sensor of the 4 K stage.

We note that in parallel to this R&D effort other industrial studies are under way to reduce the vibration level of the cryo-coolers [17] and already several new ideas and interesting proposal have been presented [18].

4 A cryogenic plant based on Helium II

The use of the liquid Helium II (He II) appears to be an alternative way to cool at low temperature the mirrors. It limits the vibration noise associated to the other cryogenic fluids [3] and it provides a powerful way for extracting the heat from the mirrors. Modern large engineering projects for high-energy physics require thermostatic control of working components at the level of 1.8–2 K and are constructed with lengths of channels containing He II. The uniqueness of He II is that it contains a superfluid component with zero entropy, which moves through other liquids and solids with zero friction to an extent dependent on the temperature of the liquid. He II is a liquid of extremely low viscosity and very high heat capacity, which prevents small transient temperature fluctuations. Moreover, thanks to its very high thermal conductivity is able to conduct away heat a thousand times better than any metallic conductor like copper.

In He II, the heat from a hot surface is carried away by the superfluid component, so in any design with complicated geometry and helium flows, the entire heat load acts on the phase interface. The boiling mechanism involves evaporation from surfaces. In a flow of ordinary boiling liquid, the heat influx is uniformly distributed in unit volume of the two-phase mixture. In stratified He II, the heat influx is associated with the interface between the phases, so the He II evaporation rate is increased by a substantial factor. A major feature of boiling in He II is that the evaporation of the superfluid component predominates. The heat load is transported by convection in the superfluid component, and this consequently evaporates more rapidly than does the normal component.

When a two-phase flow of He II moves in a heated channel, a droplet structure or mist is formed in the vapor space as the amount of liquid in the stratified flow decreases. In a stratified flow of an ordinary liquid in a large-diameter tube, an increase in the bulk vapor content leads to the vapor becoming superheated and the liquid evaporating completely. In He II one prevents the vapor becoming superheated by encouraging the spontaneous formation of a droplet structure with a large heat-transfer surface, which provides a constant temperature over the channel cross section.

An efficient and quiet configuration for cooling the mirror by He II is the *bain de Claudet* sketched in Fig. 5. Here the idea is to provide superfluid helium at atmospheric pressure and to insure continuous refilling from the container of the helium in the normal state. In this way the He II bath is kept in a quiet hydrodynamic status well far from the boiling point.

The transmission of the refrigeration power to the mirror can be granted by the thermal conduction via solid, i.e. by the suspension of the mirror, which in the present gravitational wave detectors are four fibers connecting the mirror to the marionette. A suspension made of pure aluminum (99.9999%) will be extremely effective in extracting from the mirror up to 1 W of a heat power, but if we want take advantages of the monolithic technique of the advanced detectors, as we cited in the previous section, we have to develop a crystal growing technique to realize the silicon fiber for the

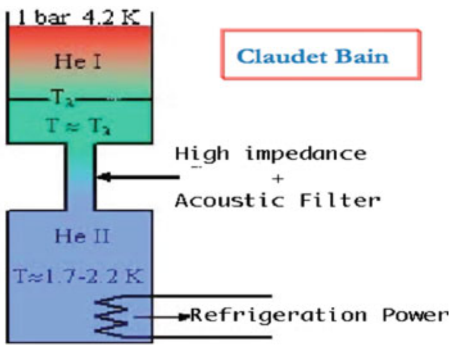

Fig. 5 A scheme of Claudet bain permitting to use no boiling superfluid helium at atmospheric pressure

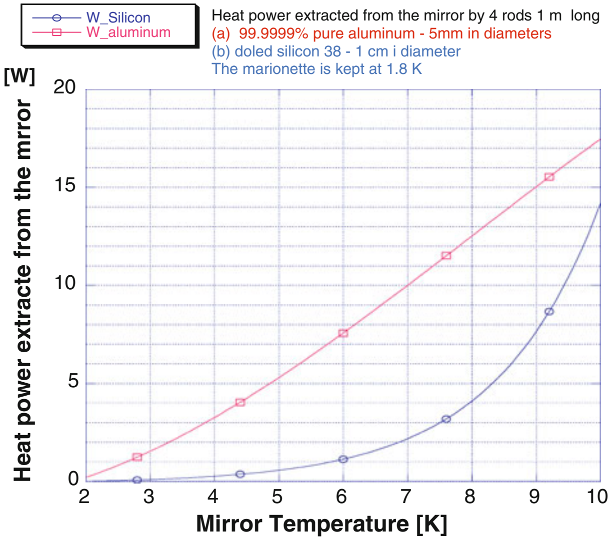

Fig. 6 Plot of the heat power extracted from the mirror versus the mirror temperature in the case of a suspension made of four rods, 1 m long, 5 mm in diameter in the case of pure Al 99.9999% and 10 mm in the case of doped Si 38

cryogenic payload. From the thermal point of view, the solution based on the use of the doped Silicon 38 appears to be less efficient than that of the pure aluminum, but it should be characterized by lower acoustic losses. In both cases, i.e. aluminum or silicon, if the marionette is kept in thermal contact with the He II bath at 1.8 K by, it is possible to extract watts of heat power from a mirror kept at a temperature below 10 K (see Fig. 6).

Moreover, it is possible to conceive also new suspensions made of silicon micro-tubes. It can play also the role of heat exchanger filled by superfluid helium at atmospheric pressure and operating in the stationary condition of zero mass flow, which implies $\rho_s v_s = -\rho_n v_n$ in absence of the vapor phase, where ρ and v are the density and the velocity of the normal (n) and superfluid (s) components.

However the evaluation of the surface extension of the heat exchanger providing a sufficient refrigeration power is not straightforward. In general there are two regimes of surface heat transfer in He II [19] depending on the temperature difference ΔT between the solid object and the He II bath. At high ΔT and for heat fluxes q greater than a critical value, the surface is covered by a film of He I or by vapor or both and primarily the properties of this film determine the heat transfer process. At low ΔT the heat transfer is controlled by a phenomenon called Kapitza conductance h_K [20]:

$$h_K = \frac{q}{\Delta T_s} \tag{1}$$

where the subscript s of the quantity ΔT of the Eq. (1) is used to note the temperature discontinuity at the interface.

h_K refers to the interfacial thermal boundary conductance which occurs between any two dissimilar materials where electronic transport does not contribute. The Kapitza conductance can change of a few orders of magnitude depending both on the status of the solid surface and the liquid pressure. To evaluate it, first of all we refer to the acoustic mismatch theory of Khalatnikov [21], based on the analogy with the classical acoustic condition at the boundary of two media. It results the following numerical formula:

$$h_K{}^{(s)} \simeq 5.5 \times 10^7 \left(\frac{T^3}{M {\Theta_D}^3} \right) \quad (\mathrm{kW/m^2\,K}) \tag{2}$$

where M and Θ_D are the molecular weight (in units of g/mol) and the Debye temperature of the solid. This theoretical approach overestimate the dependence of the Debye temperature which results to be from various experiments $h_K \sim {\Theta_D}^{-n}$, $n \approx 1$. Several improvements of this theory can be found in the literature. They include new interface phenomena as the existence of a helium high-density layer due to the tight bound of the fluid molecules to the surface by van der Walls interaction. However, still the $h_K{}^{(s)}$ formula is useful to define a lower limit of the Kapitza conductance.

An overestimate of the true Kapitza conductance can be derived by solving the problem of the heat flux radiation between the two media:

$$h_K{}^{(R)} = 4T^3 \frac{\pi^4}{10\hbar} \left(\frac{k_B}{\Theta_D} \right)^2 \left(\frac{3N}{4\pi V} \right)^{2/3} \tag{3}$$

where k_b and $\hbar$ are the Boltzman and the reduced Planck constants, N/V the number of particles per unit volume of solid and T is the temperature of the colder media. $h_K{}^{(R)}$ is called the phonon radiation limit and for a silicon heat exchanger in contact with He II at 1.9 K we have $h_K{}^{(R)} \simeq 6.4\ \mathrm{kW/m^2\,K}$. This value appears to be in better agreement with an experimental value obtained at 1.9 K $h_K(T = 1.9\ \mathrm{K}) \simeq 4.2\ \mathrm{kW/m^2\,K}$.

In conclusion, although h_K depends on the status of the solid surface and of liquid hydrodynamic status, we can infer that by setting up an exchange surface of the order of $\sim$10 cm^2 we are able to insure several watts of refrigeration power for cooling the mirror.

The evaluation of the residual vibration level induced by the cryogenic fluid system is not straightforward. The acoustic noise due to the fluid boiling depends on the residual thermal input and on the geometry of the liquid container. We can infer the order of magnitude of the vibration noise by looking at the old data taken by the cryogenic detector EXPLORER. In this specific case the noise due to the boiling of the liquid helium was evaluated in the range 10^{-13} to 10^{-14} m/$\sqrt{\mathrm{Hz}}$ at 900 Hz with an evaporation rate of the liquid helium $\sim$60 l/day, which corresponds to a thermal input on the bath of $\sim$1.8 W.

Assuming this noise figure we should conclude that an attenuation of 10^{12} at 900 Hz is needed to fulfill the E.T. requirement. However, using the same detector EXPLORER it has been shown that below the λ transition, the boiling noise source disappeared. I follows that the E.T. attenuation requirements can be relaxed significantly.

The He II mirror cooling approach requires also a deeper analysis of the impact of the acoustic losses of the fluid to the dynamic behavior of the suspended test masses. This effect should depend on the hydrodynamic regime of the Helium II. In particular we need to consider the interaction mechanism between the two liquids (normal and superfluid), which determines the heat transport. In the case of a superfluid helium vortex formation this is described by the Gorter-Mellink force per unit length, which results a function of the velocity difference $|\mathbf{v}_n - \mathbf{v}_s|$. For a one dimensional helium flow f can be written as

$$f = \frac{\rho_n \rho_s}{(\rho_+ \rho_s)^2} \eta_n |\mathbf{v}_n - \mathbf{v}_s| \tag{4}$$

where η_n the viscosity of the normal fluid. However, the velocity difference depends strongly on the geometry of the heat exchanger, the nature of the material in contact with the fluid and the status of the contact surfaces. Thus a quantitative estimation of this effect should be postponed once the study of the helium exchanger configuration is fully defined. On the other hand in order to assess the validity of the cooling approach for the cryogenic design of the ET detector, we need also to develop a complete hydrodynamic model, which includes the vapor phase and the extra interaction terms.

5 Conclusion

The low temperature techniques can play again a crucial role in the future of the gravitational wave detectors. The difficult task to cool at liquid helium temperatures the test mass of a gravitational wave interferometer must be pursued both by developing a cryogenic system based on low vibration cryo-coolers or a quiet superfluid helium bath kept at atmospheric pressure far from the boiling point. In both cases it is necessary to continue the design study and to carry on in parallel a robust R&D program and set up dedicated payload prototypes.

References

1. Amaldi, E., Cosmelli, C., Bordoni, F., Bonifazi, P., Giovanardi, U., Modena, I., Pallottino, G.V., Pizzella, G., Vannaroni, G.: Measurements at 4.2 K of the Brownian noise in a 20 kg gravitational wave antenna and upper limit for gravitational wave radiation at 8580 Hz. Lett. Nuovo Cimento **18**, 425 (1977)
2. Amaldi, E., Aguiar, O., Bassan, M., Bonifazi, P., Carelli, P., Castellano, M.G., Cavallari, G., Coccia, E., Cosmelli, C., Fairbank, W.M., Frasca, S., Foglietti, V., Habel, R., Hamilton, W.O., Henderson, J., Johnson, W., Mann, A.G., McAshan, M.S., Michelson, P.F., Modena, I., Moskowitz, B.E., Pallottino, G.V., Pizzella, G., Price, J., Rapagnani, P., Ricci, F., Solomonson, N., Stevenson, T., Taber, R.C., Xu, B.S.: First gravity wave coincidence experiment between three cryogenic resonant-mass detectors: Lousiana–Rome–Stanford. Astron. Astrophys. **216**, 325 (1989)
3. Astone, P., Bassan, M., Bonifazi, P., Coccia, E., Cosmelli, C., Frasca, S., Majorana, E., Modena, I., Pallottino, G.V., Pizzella, G., Rapagnani, P., Ricci, F., Visco, M.: Noise behavior of the EXPLORER gravitational wave antenna during the l transition to superfluid phase. Cryogenics **32**, 668 (1992)
4. Astone, P., Bassan, M., Bonifazi, P., Bronzini, F., Castellano, M.G., Coccia, E., Cosmelli, C., Fafone, V., Frasca, S., Majorana, E., Modena, I., Pallottino, G.V., Pizzella, G., Rapagnani, P.,

Ricci, F., Visco, M.: First cooling below 0.1 K of the new gravitational wave antenna of the Rome group. Europhys. Lett. **16**, 231 (1991)
5. Amaldi, E., Bonifazi, P., Bordoni, F., Cosmelli, C., Ferrrari, V., Frasca, S., Giovanardi, U., Iafolla, V., Modena, I., Pallottino, G.V., Pavan, B., Pizzella, G., Ricci, F., Ugazio, S., Vannaroni, G.: Il Nuovo Cimento **1C**, 497 (1978)
6. Fuligni, F., Ricci, F.: A study on the external-noise input in weber-type gravitational-wave antenna. Il Nuovo Cimento C **4**, 93 (1981)
7. Kuroda, K., Ohashi, M., Miyoki, S., et al.: Large-scale cryogenic gravitational wave telescope. Int. J. Mod. Phys. D **8**, 557–579 (1999)
8. Cagnoli, G., Gammaitoni, L., Kovalik, J., Marchesoni, F., Punturo, M.: Suspension losses in low-frequency mechanical pendulums. Phys. Lett. A **213**, 245 (1996)
9. Logan, J.E., Hough, J., Thomson, R.D.: Thermal motion associated with monolithic fused silica cradle suspensions for gravitational wave detectors. Phys. Lett. A **218**, 181 (1996)
10. Traeger, S., Willke, B., Danzmann, K.: Monolithically suspended fused silica substrates with very high mechanical Q. Phys. Lett. A **225**, 39 (1997)
11. Piergiovanni, F., Punturo, M., Puppo, P.: The thermal noise of the Virgo+ and Virgo Advanced Last Stage Suspension (The PPP effect). Virgo Internal Note, VIR-015C-09 (2009)
12. Hild, S., Chelkowski, S., Freise, A.: Pushing towards the ET sensitivity using ‘conventional’ technology. http://arxiv.org/abs/0810.0604
13. Amadori, S., et al.: Low temperature anelasticity in Ti6Al4V alloy and Ti6Al4SiCf composite. doi:10.1016/j.msea.2008.09.156
14. Puppo, P.: A thermal noise model for a branched system of harmonic oscillators. In: Proceedings of 8th Edoardo Amaldi Conference on Gravitational Waves, New York city, June 21–26, 2009, Journal of Physics, Special Conference issue
15. Tomaru, T., et al.: Cryogenics **44**, 309 (2004)
16. Capparelli, S., Majorana, E., Moscatelli, V., Pascucci, E., Perciballi, M., Puppo, P., Papagnani, P., Ricci, F.: Vibration Free Cryostat for low noise applications of a pulse tube cryocooler. Rev. Scientific Instrum. **77**, 0951020 (2006)
17. Riabzev, S.V., Veprik, A.M., Vilenchik, H.S., Pundak, N.: Vibration generation in a pulse tube refrigerator. Cryogenics **49**, 1 (2009)
18. Suzuki, T., Tomaru, T., Haruyama, T., Sato, N., Yamamoto, A., Shintomi, T., Ikushima, Y., Li, R.: Pulse tube cryocooler with self-cancellation of cold stage vibration. http://www.citebase.org/abstract?id=oai:arXiv.org:physics/0611031 (2006)
19. Van Sciver, S.W.: Helium Cryogenics. Plenum Press, New York (1986)
20. Kapitza, P.L.: The study of heat transfer on Helium II. J. Phys. (USSR) **4**, 181 (1941)
21. Khalatnikov, I.M.: Introduction to the Theory of Superfluidity, Ch. III. Benjamin, New York (1965)