Vibration Free Cryostat for cooling suspended mirrors

E. Majorana\textsuperscript{2}, M. Perciballi \textsuperscript{2}, P. Puppo\textsuperscript{2}, P. Papagnani\textsuperscript{1,2}, F.Ricci\textsuperscript{1,2}

\textsuperscript{1} Dipartimento di Fisica dell’Università di Roma - “La Sapienza”
\textsuperscript{2} Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1
Piazza A. Moro 2, 00185 Roma, Italy

E-mail: fulvio.ricci@roma1.infn.it

Abstract. A new generation of gravitational wave interferometers is under study with the main goal to improve the sensitivity of the present detectors which are taking data now. Two of the dominant noises which limit the actual sensitivity of the interferometers are the thermal noise of the suspended optics and the thermal lensing process. At low temperature it is possible to reduce both the effects. However, lowering the temperature of the test masses without injecting vibration noise from the cooling system is a technological challenge. We present the first results on a new active system to dampen the vibrations from a pulse tube refrigerator coupled to a suspended mirror.

P.A.C.S.: 04.80.Nn, 07.20.Mc

1. Introduction

One of the most challenging goals in the construction of an advanced generation gravitational wave interferometer is cooling the mirrors at low temperature. In developing a cooling system for the interferometer mirrors, some important issues both in the design of the cryogenic apparatus as well as in the choice of the materials of the mirror suspensions must be taken into account. One of the main requirements is that the mechanical noise injected during the refrigeration procedure must be negligible. As a consequence a good mechanical isolation between the mirror and the cooler is necessary. Another important element in a cryogenic system is the thermal link with the refrigerator. Taking care of having short thermal links and good thermal couplings is important in order to have low refrigeration power losses. For instance, the use of a mechanical attenuator as a heat link is a good solution to dampen the vibrations of the cooler, but it has the disadvantage to absorb a part of the refrigeration power. On the other hand the mirror suspension itself must have the required thermal conductivity to reduce thermal gradients and to optimize the cooling time. The requirements we have just described suggest that the overall design of the mirror suspension and control system will be very different from what it is currently used in interferometric antennas. The new system will be the result of a trade off on one side to have a strong thermal contact with the refrigeration apparatus and on the other side the need to reduce any dissipation source due to the coupling of the suspension with the mirror. Much work has been already done to cool resonant gravitational wave detectors by using cryogenic fluids. The first cryogenic antenna of 20 kg was successfully cooled down to 4 K by the group headed by Edoardo Amaldi and Guido Pizzella in 1974. The cooling runs were very useful to
understand the cryogenic techniques and the behavior of material properties in the range of low
temperatures [1]. A second important result was reached when the antenna Explorer, having a
mass of 2400 kg was cooled at the temperature of liquid helium in 1982. In this experiment the
noise injected by the boiling cryofluid was reduced thanks to the suspension system. However
a further improvement of the sensitivity was reached when the boiling of the liquid helium was
reduced drastically by bringing below the $\lambda$ point [2] a large fraction of the three-thousand liters
of fluid stored in the cryostat. On the other hand from the experience with cryogenic resonant
antennas we learned that the maintenance of such a big cryogenic apparatus is difficult and
requires a heavy work. For instance, typically a liquid helium refilling is necessary once per
month, with a consequent stop of a few days of the data taking. A cryogenic interferometer
would have a similar problem with the added complication of the increased number of systems
to be cooled down, four at least. Indeed it must be taken into account that to maximize the
duty cycle, all the cryogenic operations should be performed at the same time on all the systems,
with an increased need of facilities and manpower.

2. The cryocoolers.
An alternative approach to cryofluids is the use of a Gifford-McMahon (GM) cryocooler which is
widely used in various fields of science and industries because of its convenient handling. However
it provides large vibrations due to the displacer motion in its cold head. The alternative solution
is the pulse tube (PT) cryocooler which is expected to be less noisy because it has no moving
parts in its cold head. Moreover, it is more reliable and has a 2 to 3 times higher efficiency than
GM cryocoolers for loads temperatures between 55 and 120 K. A pulse tube cryocooler seems to
be suitable for our purposes. However also this kind of refrigeration system injects mechanical
noise because of the gas pulse flowing in its cold head.

3. Finite element simulation of cooling a mirror using a pulse tube.
We have performed a cooling test of a CaF$_2$ mirror sample using the cryostat equipped with
a double stage cryocooler model PT 407 from the US company Cryomec. The test was done
in order to study the thermal behavior of a system cooled by a pulse tube. The experimental
apparatus is shown in figure 1. The mirror has a diameter of 100 mm and is 30 mm thick, it
is suspended by two copper wires of 0.5 mm diameter wrapped around its lateral surface and
acting also as thermal links. This payload was set inside a thermal shield made of copper which
was connected to the cold point of the second stage of the refrigerator. The cryostat includes
also an external shield thermally linked to the first stage of the pulse tube. We have monitored
the temperatures of the thermal shields of the cryostat, the mirror suspension clamp and the
center of the CaF$_2$ sample surface.

To better understand the thermal behavior of this system, we have compared the
measurements with the finite element model developed using ANSYS software. The simulation
includes the two thermal screens of the cryostat and the suspended mirror. Moreover, the
dependency on temperature of the thermal properties of the materials and of the cooling power
of the refrigerator stages were included in the computation. We simulated the thermal evolution
of the system during the 10 hour cooling process. We report on the left side of figure 2 the
comparison between measurements and the simulation results.

The computation of the behavior of the thermal shields in the cryostat provided us useful
results to infer if unaccounted thermal losses were present. We were also able to correlate the
temperature curves to the thermal conductivities dependence with temperature for the copper
shield. In the right side of the same figure we plot the temperature of the internal shield and
the related time evolution of the thermal conductivity of the copper. The strong variation of
the slope of the temperature is clearly correlated with the approach to the maximum value
**Figure 1.** The payload including the suspended sample of CaF$_2$ cooled at low temperature.

**Figure 2.** Typical output of the thermal gradient simulation of the cooling procedure.

**Figure 3.** The temperature vs. times of the cooled system. The lines are measurements, the dots are simulation results.

**Figure 4.** Plot of the time evolution of the temperature of the internal copper shield compared with the thermal conductivity variation with time. The slope change of the temperature curves is associated to the approach of the maximum of the conductivity functions of the copper thermal conductivity. The finite element model is useful also for predicting the mechanical stress induced by the cooling process in particular at the mirror level.

**4. The Vibration Free Cryostat.**

On the basis of the experiment results reported in the previous section and using the simulation tool, we designed a new cryostat for cooling mirrors. During the previous experiment we measured the acceleration of the 4 K cold head of the Cryomec refrigerator, both in vertical and
in the horizontal directions. (see figure 5).

Figure 5. Displacement noise of the Cryomec PT 407 coldest point, measured at 4 K in the low frequency range.

Figure 6. Displacement noise of the Cryomec PT 407 coldest point, measured at 4 K in the high frequency range.

On the basis of the level of the vibration noise generated by the cooling machine, we have selected another pulse tube refrigerator, the Sumitomo SRP-052A. However, also the noise produced by this refrigerator is still too high for our purposes and for this reason it has been necessary to design a cooling system which can attenuate the PT cryocooler vibrations. The vibration free cryostat (VFC) we have designed is suitable for coupling such a system to a mirror, according to the issues discussed in the introduction.

The cryostat scheme is sketched in figure 7. It is based on the idea to attenuate the cryocooler vibrations by directly acting on it and consequently allowing a shorter heat link between the cryocooler and the mirror, without using any other attenuation system. This solution permits to preserve the refrigeration power. The active control on the cold head vibration is performed by a digital feedback system in which the displacement is monitored by a tri-axial accelerometer placed on the second stage and the correction is performed by piezoelectric actuators.

The cryocooler cold head is clamped to a platform placed on dampers. The cryocooler is connected to the cryostat by a soft silicon bellows designed to mechanically decouple it from the cryostat. The feedback correction signal is sent to three piezo-actuators which are loaded by the platform and can act on it from below. The platform can be moved along mechanical guides in order to inhibit its rotation degrees of freedom.

In the cryostat, a first thermal shield is connected to the first 30 K cold stage while a second shield is thermally connected to the second 4 K cold stage. The heat links shown in figure 8 are copper strips arranged on a ring. They are thermally treated before the assembly to reduce the stiffness and provide a mechanical decoupling with the system to be cooled.

The VFC has been already cooled at low temperature and we have taken data of the vibration noise transmitted from the cold head to the inner vacuum chamber. In figure 9 we report the noise spectrum of the displacement measured at low temperature on the vertical direction, on the second stage cold head and on top of the flange. Recently we discovered that the mechanical characteristics of the selected copper for the thermal links, change drastically during the thermal
Figure 7. Scheme of the free vibration cryostat. We notice the location of the piezoelectric actuators and of the supporting springs.

Figure 8. Picture of the copper links assembled in the free vibration cryostat. In the middle it is possible to see also the accelerometers used to monitor the vibrations of the coldest point of the refrigerator.

Figure 9. Displacement noise of the Sumitomo PT measured at the coldest point (red line) and on the top flange of the vacuum chamber (blue line). The green and the black lines are related to the voltage noise spectrum of the two sensors. The chamber is connected to the coldest point through the heat links shown in the figure 8. The feedback control is still inactive.
cycle of our apparatus. As a consequence, at each run we observed changes in the mechanical transfer function between the cold point of the PT refrigerator and the inner vacuum chamber of the cryostat. This implies an increase of the cut-off frequency of the thermal links. The data reported on the plot have been taken during a run done after several thermal cycle of the VFC. We notice that at higher frequencies the noise generated by the pulse tube is attenuated more than an order of magnitude on top of the inner vacuum chamber. Once in operation, we expect to have a noise reduction also at low frequencies by canceling the extra noise generated by the pulse tube up to the level of the local seismic noise. The active control will be active up to 30 Hz, although in the present configuration we can go up to 150 Hz, i.e. the cut-off frequency of the high voltage drivers of the piezoelectric actuators.

5. Conclusion
We have designed a cryostat which can actively attenuate the vibrations of a pulse tube cryocooler. The system is suitable for applications in the advanced interferometric gravitational wave detectors. The system is equipped with a 4K pulse tube of the Japanese industries Sumitomo which seems to be the less noisy among the same kind cryocoolers. We developed a finite element simulation, for the design of the vibration free cryostat. Such a cryostat will be used to develop a new mirror cryogenic suspension, to study the thermal properties of the materials candidates for the mirrors of a cryogenic interferometer and to set up the new electromagnetic actuators which can be used at low temperatures.

References
[1] E. Amaldi, C. Cosmelli, F. Bordoni, P. Bonifazi, U. Giovanardi, I. Modena, G. V. Pallottino, G. Pizzella and G. Vannaroni, 1977 Lettere al Nuovo Cimento, 18, 13
[2] F. Bronzini, E. Coccia, I. Modena, P. Rapagnani, F. Ricci, 1985 Cryogenics, 25

Acknowledgments
We wish to thank M. Martinelli and E. Serrani that provided us with their technical support during the last twenty years of our experimental activity and are going to retire in a short time. We also gratefully acknowledge M. Ciaccafava for the helpful technical assistance; we hope that their skills and enthusiasm will assist us in the experimental challenges of next years.