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MiniGRAIL progress report 2001: the first cooldown

A de Waard, L Gottardi and G Frossati

Kamerlingh Onnes Laboratory, Leiden University, Leiden, The Netherlands

E-mail: arlette@minigrail.nl

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Abstract
The results of the first cooldown of MiniGRAIL are presented. MiniGRAIL is a 65 cm diameter spherical gravitational wave detector made of CuAl6%, having a mass of 1150 kg. The sphere is suspended from a seven-stage vibration isolation system with a total weight of about 950 kg. The sphere should be cooled to below 20 mK. During the first run the sphere was cooled down to 1.8 K. A forced helium flow was used to cool the sphere down to 4 K, which took only two days. Further cooling to 1.8 K was done using a 1 K pot. We measured the temperature dependence of the mechanical quality factor and made an evaluation of the heat leaks (for more details see www.minigrail.nl).

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1. Introduction

MiniGRAIL is the first spherical gravitational wave detector. It is being built in the Kamerlingh Onnes Laboratory at Leiden University in the Netherlands [1]. The antenna has a diameter of 65 cm and a resonant frequency of around 3.1 kHz. It should operate at a temperature lower than 20 mK and is expected to have a quantum-limited strain sensitivity $h = \Delta L/L$ of about 4×10^{-21} for bursts, with a bandwidth larger that 220 Hz. MiniGRAIL is the first of three (Brazil [2], Italy [3]) similar spherical gravitational wave detectors that will operate in coincidence. The goal of the first cooldown of the MiniGRAIL was to test the experimental set-up for the forced helium flow and to measure the mechanical quality factor.

2. Suspension

The suspension system of MiniGRAIL consists of four CuAl6% masses and three copper masses. The upper CuAl mass is suspended from the top flange of the cryostat with three stainless steel cables, hanging from three helical coils. The rest of the CuAl masses are connected with three stainless steel rods (length = 30 cm, diameter = 8 mm) and rounded

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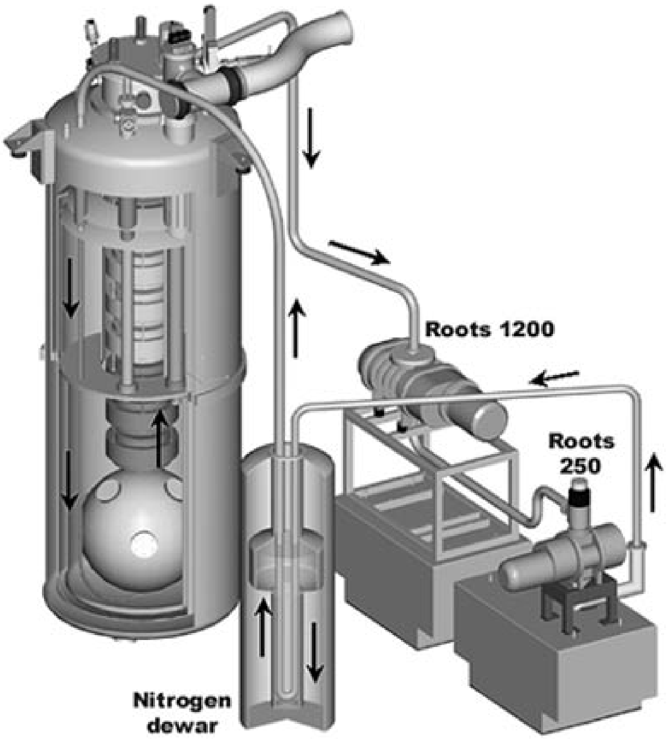

Figure 1. Experimental set-up for forced helium flow used for cooling the sphere to 80 K.

conical nuts, 60° shifted for each mass. The copper masses are suspended from three gold-plated copper rods (length = 30 cm, diameter = 8 mm). To increase the attenuation, the rods of the suspension system will later be replaced with rods having a ring in the middle that will work as a double c-spring. The sphere is suspended from the centre with a copper rod of 20 mm diameter and 48 cm long. The attenuation between the last two copper masses at room temperature, in air was about 20 dB around the resonant frequency of the sphere.

3. Cooling techniques

3.1. Cooling down to 4 K with a forced helium flow

To cool the sphere helium gas is circulated using two Roots pumps in series, one of 1200 (with hydrokinetic drive) and the other of 250 m^3 s^{-1}, see figure 1. The frequency of the Roots 250 can be changed to control the circulation rate. The gas is pre-cooled using a 3 m flexible tube with a diameter of 40 mm, immersed in liquid nitrogen, as a heat exchanger. From the nitrogen dewar a double-wall tube is inserted into the 19 mm feed through of the MiniGRAIL dewar that goes down to the IVC. Inside the IVC a 13 mm copper tube is mounted to guide the helium gas to the bottom of the sphere. The gas flows along the sphere up through the neck of the dewar thus cooling the seven masses (each about 130 kg) of the suspension. The gas is pumped away from the top flange of the dewar through a 50 mm flexible tube. The average flow of the helium gas between 300 and 100 K was about 400 mmol s^{-1} (figure 2). A temperature of about 100 K was reached within 1.5 days. Below 100 K the forced flow was stopped, leaving 1 bar of helium gas in the IVC. Cooling down to 80 K was done by

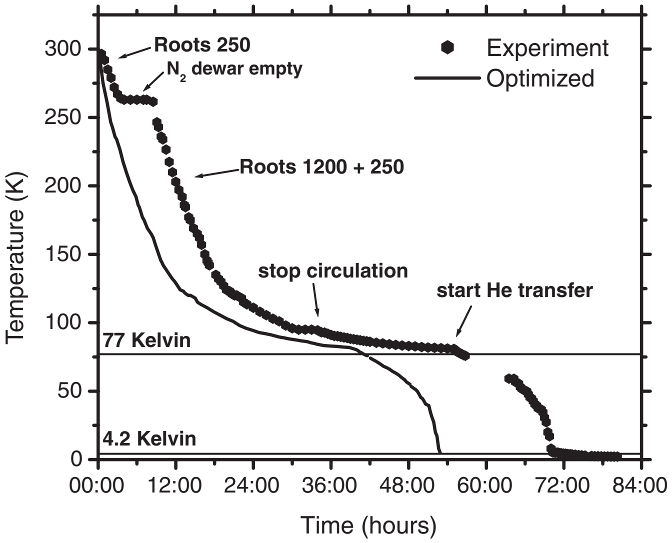

Figure 2. Cooldown of MiniGRAIL using a forced helium flow. The average circulation rate was about 400 mmol s^{-1}. Circulation was stopped after 36 h. Cooling from 100 to 80 K was done by natural convection of 1 bar of helium exchange gas inside the IVC. The total cooldown time to 4 K was 70 h.

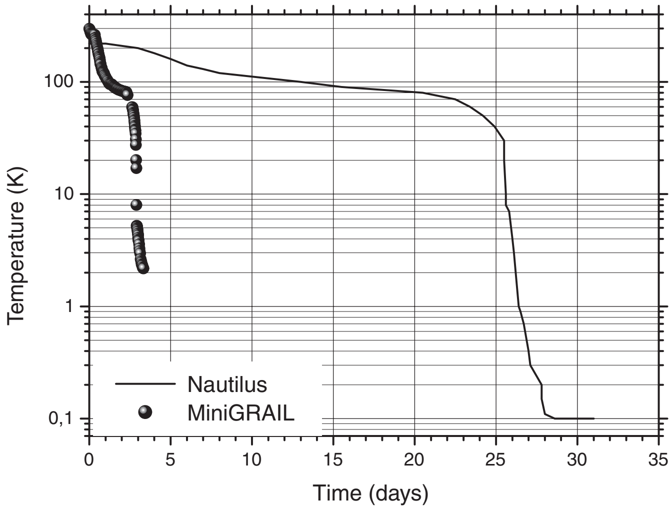

Figure 3. Cooldown of MiniGRAIL compared with a typical cooldown of Nautilus, the Al bar antenna in Rome [4].

natural convection of the gas inside the vacuum can and took about 20 h. The total nitrogen consumption was around 2000 l. Cooling down to 4.2 K was done by transferring liquid helium directly into the IVC. It took 15 h to reach 4.2 K with a total helium consumption of about 600 l. The temperatures were measured with Pt1000 resistance thermometers in the centre of the sphere and at the surface, at the masses of the suspension system and the radiation shields. The cooldown time of MiniGRAIL using a forced flow is almost an order of magnitude faster with respect to the cooling of a bar antenna using the exchange gas (figure 3).

Table 1. Temperatures of the different stages of the suspension system and of the sphere while operating the 1 K pot.

	Temperature (K)
4 K shield	
$Mass1(CuAl6\%)$	7.4
$Mass2(CuAl6\%)$	6.2
$Mass3(CuAl6\%)$	5.7
$Mass4(CuAl6\%)$	4.5
$Mass5(Cu)$	1.87
$Mass6(Cu)$	1.97
$Mass7(Cu)$	2.07
Centre of sphere	2.07
Surface of sphere	2.12
1 K pot (inside)	1.3

3.2. Performance of the 1 K pot

Further cooling was achieved by using a 1 K pot. The sphere was cooled by conduction through the last three stages of the suspension. The first copper mass is thermally anchored to the cold plate of the 1 K pot with copper braid (3 × 30 × 300 mm), later to be replaced with annealed copper ‘spaghetti’. The 1 K pot is suspended from the 4 K flange with stainless steel tubes and slightly mechanically decoupled from the pumping line with a flexible bellows. Vibrations transmitted through the tubes can be taken care of in the future, if necessary. We were able to cool it down to 2.1 K within 10 h. Further cooling down to 1.8 K was achieved by pumping the helium reservoir. The thermal gradient between the centre and the surface of the sphere was about 50 mK at an average temperature of 2.1 K. The temperatures of the different stages of the suspension system and of the sphere are given in table 1.

4. Mechanical quality factor

Without heat treatment the mechanical quality factor of the sphere was about 12 000. A stress-relief annealing of 4 h at 350 °C in a nitrogen atmosphere, with a warming up and cooling down period of 1.5 days each, increased the Q to 14 000. The quality factor measurements were done by exciting the resonant modes of the sphere with a piezoelectric crystal, glued onto the sphere with cyanoacrylate instant glue and measuring the relaxation time t [5]. The mechanical quality factor is then determined by $Q = \pi \tau f_0$, where τ is the relaxation time and f_0 the resonant frequency. The temperature was measured at the centre and on the surface of the sphere using a Pt1000 for temperatures down to 4.2 K and a $\mathrm{RuO_2}\,10\,\mathrm{k\Omega}$ for temperatures below 4 K. We measured the Q-factor of several modes of the sphere that achieved roughly the same values. The Q-factor of the third spheroidal quadrupole mode is plotted as a function of temperature in figure 4 and compared with measurements of a small 17 cm diameter CuAl6% sample, also fabricated by ItalBronze (Brazil). The data show a large peak around 25 K and a smaller one around 11 K. Below 7 K the Q-factor starts to increase rapidly up to a value of 900 000 at 1.8 K, suggesting that below 1 K it could reach 10^7 as the small sphere. Quick warm-up was obtained by circulating helium gas as shown in figure 1, but with the heat exchanger being warmed-up by running a current of 40 A through it.

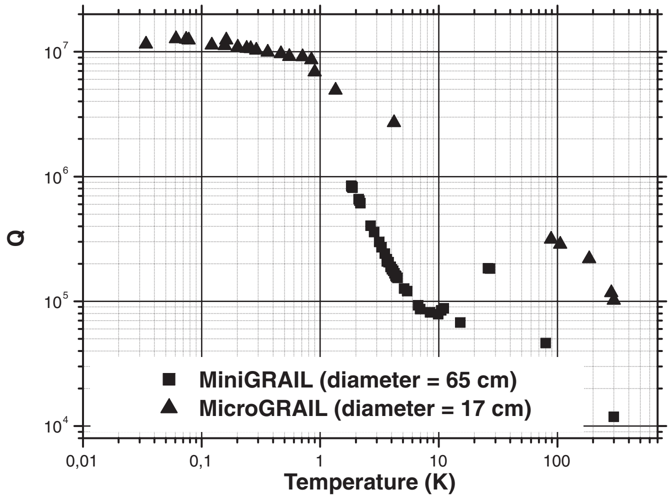

Figure 4. Mechanical quality factor of the third spheroidal mode of MiniGRAIL compared to a small 17 cm diameter CuAl6% sample, also fabricated by ItalBronze (Brazil).

Table 2. Sensitivity for MiniGRAIL for the initial goal, the advanced MiniGRAIL and the quantum limit.

	Initial goal	Advanced	Quantum limit
E_N	$100h\nu$	$10h\nu$	$1h\nu$
T_N	1.6×10^{-5}	1.6×10^{-6}	1.6×10^{-7}
T_{eff}	4.5×10^{-5}	4.5×10^{-6}	4.5×10^{-7}
β	0.1	0.1	0.1
Δf	224	224	224
h_0	4.3×10^{-20}	1.3×10^{-20}	4.3×10^{-21}
$\sqrt{S_h(f_0)}$	4.7×10^{-22}	1.5×10^{-22}	4.7×10^{-23}

5. Expected sensitivity

Table 2 shows the strain sensitivity and the spectral amplitude for a noise energy of $100h\nu$—the initial goal, $10h\nu$—the advanced MiniGRAIL and the quantum limit. The calculations were done for the case of one transducer being coupled to the sphere. Eventually, six transducers will be installed, using the TIGA configuration [6]. The noise energy is given by $E_N = k_B T_N$, with T_N the noise temperature of the SQUID. The minimum detectable energy for this is given by the effective temperature T_{eff}:

$$T_{\mathrm{eff}} = 2\sqrt{2}T_N\left(1 + \frac{k_{\mathrm{B}}T}{\beta Q T_N}\right)^{\frac{1}{2}} \tag{1}$$

where T is the thermodynamic temperature of the detector, β is the ratio of gravitational energy deposited in the antenna to that converted into electromagnetic energy in the transducer and Q is the mechanical quality factor of the sphere. The strain sensitivity is calculated for a gravitational wave burst with a duration of 0.3 s and a SNR = 1 from:

$$h_0 = \frac{2H_0}{\tau_g} \tag{2}$$

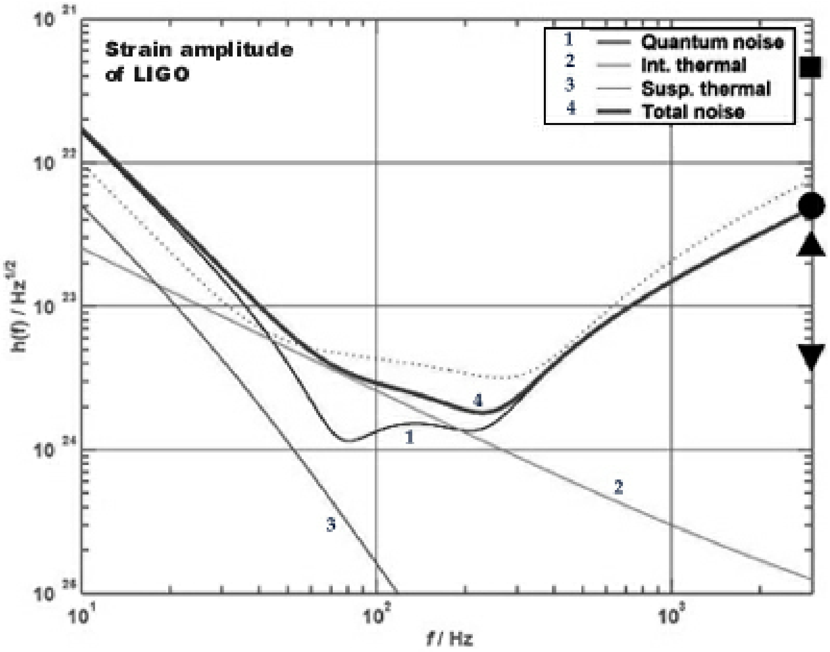

Figure 5. Strain amplitude of LIGO II for optimal orientation and polarization of the gravitational wave, compared to the (omnidirectional) spherical detectors. Square: MiniGRAIL initial goal, circle: MiniGRAIL quantum limit, up-triangle: quantum limit of three spheres (MiniGRAIL–Schenberg–Sfera), down-triangle: beryllium sphere ∅2 m.

with

$$H_0^{\min} = \left(\frac{k_B T_{\text{eff}}}{\frac{1}{2} M l^2 (2\pi f_0)^4} \right)^{\frac{1}{2}} \tag{3}$$

where H_0 is the Fourier transform of $h(t)$, M is the mass and $l = 0.6R$, where R is the radius of the sphere. With a $\beta \sim 0.1$, we can achieve a bandwidth of more than 220 Hz.

Figure 5 shows the spectral amplitude of MiniGRAIL for the initial goal, which is at the same level as LIGO I (not shown in the figure) and in the quantum limit compared to that of the LIGO II [7] for optimal orientation and polarization of the gravitational wave. The up-triangle represents the quantum limited sensitivity of three spheres (MiniGRAIL—Netherlands, Schenberg—Brazil, Sfera—Italy) operating in coincidence. The down-triangle gives the strain amplitude of a beryllium sphere with a diameter of 2 m. Since the antenna cross section is proportional to the square of the sound velocity, a beryllium antenna could reach a sensitivity of about one order of magnitude more than the LIGO II broadband. The LIGO sensitivity could be improved by narrowing the band around, for instance, 3 kHz, but clearly this would only be done if a reasonable chance of finding sources at that frequency exists, since this would cause a significant decrease in sensitivity at lower frequencies.

6. Summary

We have built and cooled a 1.15 ton spherical GW detector to 1.8 K in two days, using a forced helium flow, and measured the mechanical quality factor. The quick turnaround time of less than five days will allow for experiments to be done in much shorter time than with the present antennae.

Acknowledgments

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