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Cooling down MiniGRAIL to milli-Kelvin temperatures

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Abstract

The latest developments in the construction of the ultra-cryogenic spherical detector MiniGRAIL are presented. The room temperature part of the vibration isolation system was improved and provided with an attenuation of about 60 dB around 3 kHz. The transfer function of the cryogenic stages gave about 20 dB per stage, at the resonant frequency of the sphere. The latest results of three cryogenic tests at ultra-low temperature of the spherical detector MiniGRAIL, using several thermal anchorings, are presented. Minimum temperatures of 20 mK on the mixing chamber of the dilution refrigerator and 79 mK on the surface of the sphere were reached. During the last cool down, two capacitive transducers were mounted on the sphere. The first was coupled to a room temperature FET amplifier and the second to a transformer and a double stage SQUID amplifier. Unfortunately the SQUID did not work, so only the first resonator could be used. An equivalent temperature of about 20 K was measured during an acquisition run of 7 h, using the first transducer corresponding to the FET white noise.

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1. Introduction

MiniGRAIL is a 1.2 ton spherical gravitational wave antenna made of CuAl6%, having a diameter of 65 cm and resonating at 3.1 kHz [1]. The minimum detectable energy is given by an effective temperature

$$T_{\text{eff}} = \frac{T}{\beta Q} + 2T_N \qquad (1)$$

where T is the thermodynamic temperature, β the coupling of the transducer to the antenna, Q the mechanical quality factor of the antenna and T_N is the amplifier noise. The ultimate goal is to operate the antenna at a thermodynamic temperature of 20 mK, equipped with six two-mode inductive transducers in the TIGA configuration [2], coupled to nearly quantum limited double stage SQUID amplifiers [3], with $\beta \sim 0.1$. The expected strain amplitude h using a SQUID amplifier with an energy resolution of $100\,\hbar$ is about 10^{-20} within a bandwidth of 200 Hz, and a spectral strain amplitude $\tilde{h} \approx 5 \times 10^{-22}$ $\mathrm{Hz}^{-1/2}$. Using a quantum limited SQUID would give $\tilde{h} \approx 4 \times 10^{-23}$ $\mathrm{Hz}^{-1/2}$. MiniGRAIL will operate in coincidence with the two similar spherical detectors SFERA (Rome, Italy) and Mario Schenberg [4] (Sao Paulo, Brazil), which are currently under construction, and also with other existing detectors.

2. The vibration isolation system

The vibration isolation system was improved by replacing the room temperature helical springs with stacks of aluminium and rubber plates. The low pass mechanical filter, consisting of a stack of seven masses and springs, is suspended from the top flange of the cryostat with three stainless steel cables. The cables are thermally anchored to the 77 K and the 4 K shield with soft copper foils. The upper four masses of the stack are made of CuAl6% followed by three copper masses (figure 1, right). The attenuation of the stainless steel cables, measured at room temperature in vacuum, is about 65 dB around the resonant frequency of the sphere (figure 1, top left). The attenuation between masses 1 and 2 was also measured by sweeping the frequency with a PZT. The results are compared with a FEA simulation made with ProMechanica and are also shown in figure 1. The measurements were repeated point by point (manually) around the resonant frequency of the sphere with good agreement. It is clear that the attenuation is being reduced because of a broad resonance around 2.8 kHz, which is probably due to higher-order modes of the springs. The attenuation around 3 kHz is about 20 dB per stage.

3. Cooling down to milli-Kelvin temperatures

We have assembled a dilution refrigerator (dr) with three sintered silver heat exchangers. Mass number 3 was thermally coupled to the still, mass 4 to the 50 mK plate and mass 5 to the mixing chamber. The sphere was cooled through masses 5–7, all made of copper and connected with copper rods. Three ultra-cryogenic ($T < 1$ K) runs were performed, using different thermal anchorings between the suspension system and the dr. During the first run, the refrigerator was tested without the sintered heat exchangers and the thermal anchorings were made of stacks of OFHC copper plates, each of 0.5 mm thickness ($RRR \approx 30$). The run lasted for 2 weeks and the minimum temperature reached at the surface of the sphere was 294 mK with 80 mK on the mixing chamber . For the second run, the dr was equipped with three sintered heat exchangers. The thermal anchorings were made of annealed copper slabs ($RRR \approx 90$), machined with about 18 slits to form separate wires of about 2 × 2 mm. A time-dependent heat leak was observed, which reduced to about 45 μW after 6 weeks (figure 2, left). This was consistent with the heat release expected from ortho–para conversion of molecular hydrogen confined into micro-bubbles in the sphere, if the concentration were about 80 ppm, a typical value for commercial copper. The minimum temperature of the sphere was 79 mK after 7 weeks. The mixing chamber reached 20 mK. During this run, we measured the noise of the fifth quadrupole mode of the sphere using a piezo-electric crystal (PZT), which was glued on the sphere with silver epoxy. The PZT was read out with a low-noise FET amplifier. A minimum equivalent

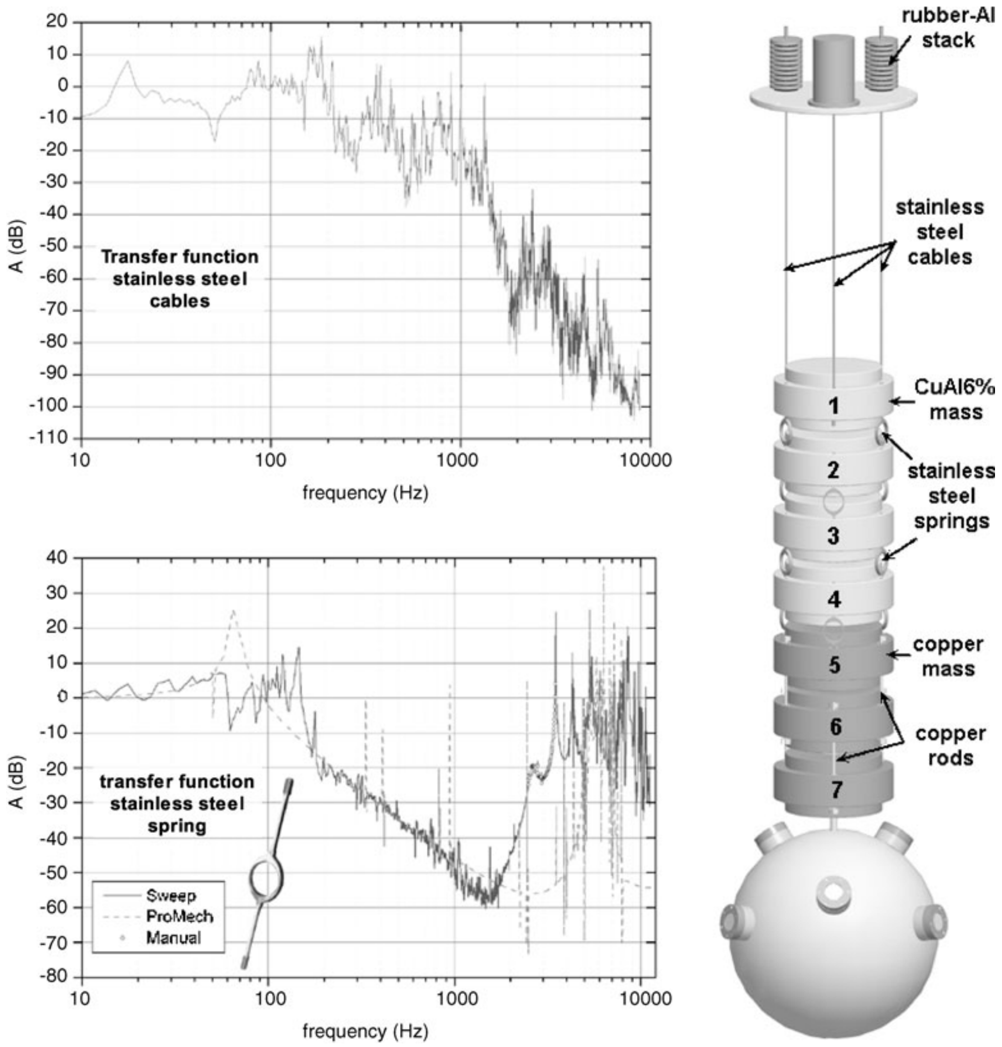

Figure 1. Top left: room temperature transfer function of the stainless steel cables, which suspend the upper CuAl mass of the attenuation system from the top flange of the cryostat. Bottom left: room temperature transfer function between masses 1 and 2, which are connected to stainless steel springs as shown in the picture. Right: a schematic picture of the overall attenuation system of MiniGRAIL.

temperature of 1200 K was measured when the thermodynamic temperature of the sphere was 90 mK. It was clear that the mode of the sphere was excited by non-thermal noise. During the third run, the three copper masses were replaced by ones of high purity (NOSV copper, NA[4]). The copper slabs were replaced by 'jellyfish'-type thermal contacts made of 0.1 mm thick copper plates with $RRR \approx 1700$. During all runs, we saw a time-dependent heat leak coming from the sphere. In each run, the transition from fast cooling to slow cooling occurred at a different temperature, which means that the amount of heat released by the sphere when we started to cool down the dr was different. This could indicate that the heat release at higher

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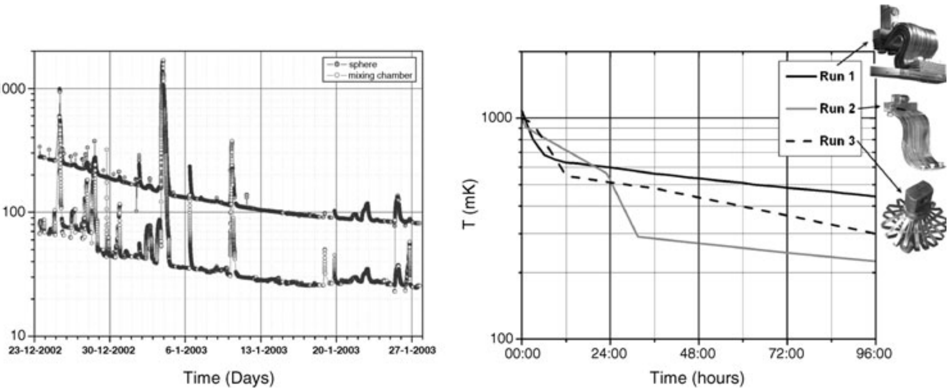

Figure 2. Left: the temperature of the surface of the sphere compared to the temperature of the mixing chamber of the dr are plotted versus the time during run 2. The minimum temperatures that were achieved during this run are 79 mK on the sphere and 20 mK on the mixing chamber. Right: the plot shows a comparison between the temperatures of the sphere during the three ultra-cryogenic runs. The different thermal anchorings used in each run are also shown.

Table 1. It gives a summary of the mode frequencies and compares them with the modes observed with the bare sphere. The quality factor of the spheroidal modes and the coupling factor beta, when the resonator is biased at 200 V, are also reported. All values were measured at a thermodynamic temperature of about 200 mK. The resonator mode of interest was at 3199 Hz.

Bare sphere modes (Hz)	Q	Sphere-resonator modes (Hz)	Q	β
–	–	2904	–	–
2972.1	5.6×10^5	2916	–	–
2982.4	8.1×10^5	2981.5	–	–
2985.6	7.8×10^5	2982.6	–	–
3000.9	13.9×10^5	2993	–	–
3002.9	11.6×10^5	3002	–	–
3158.2	13.7×10^5	3019.1	4.3×10^5	$<10^{-6}$
3159.66	13.6×10^5	3155.79	4.7×10^5	$<10^{-6}$
3168.45	11.5×10^5	3168.0	0.7×10^5	$<10^{-6}$
3170.89	9.3×10^5	3169.84	12×10^5	$<10^{-6}$
3174.32	11.4×10^5	3199.23	1.2×10^5	1.62×10^{-5}
–	–	3226.5	0.3×10^5	8.43×10^{-6}

temperatures determines the cooling rate below 1 K and could be due to relaxations of defects in the alloy.

4. First cryogenic run with two capacitive transducers

For the third run, two capacitive transducers were mounted on the sphere, both 60° from the north pole, 180° apart (see figure 3). They were oriented 44° east, aligned with the Nautilus detector. Both transducers have a 'rosette'-design resonator [5], an electrode and an electrode support. The mass of the resonator is about 450 g. The thickness of the springs is 6 mm. One of the transducers (made in Leiden, $C = 1.2$ nF) was coupled to a FET amplifier ($V_n = 0.7$ nV Hz$^{-1/2}$, $I_n = 4.4$ fA Hz$^{-1/2}$), the other (made in Rome, $C = 0.7$ nF) was coupled to a transformer (also obtained from ROG) and the double stage SQUID consisting of a commercial quantum design SQUID as a first stage and a DROS as a second stage. The SQUID

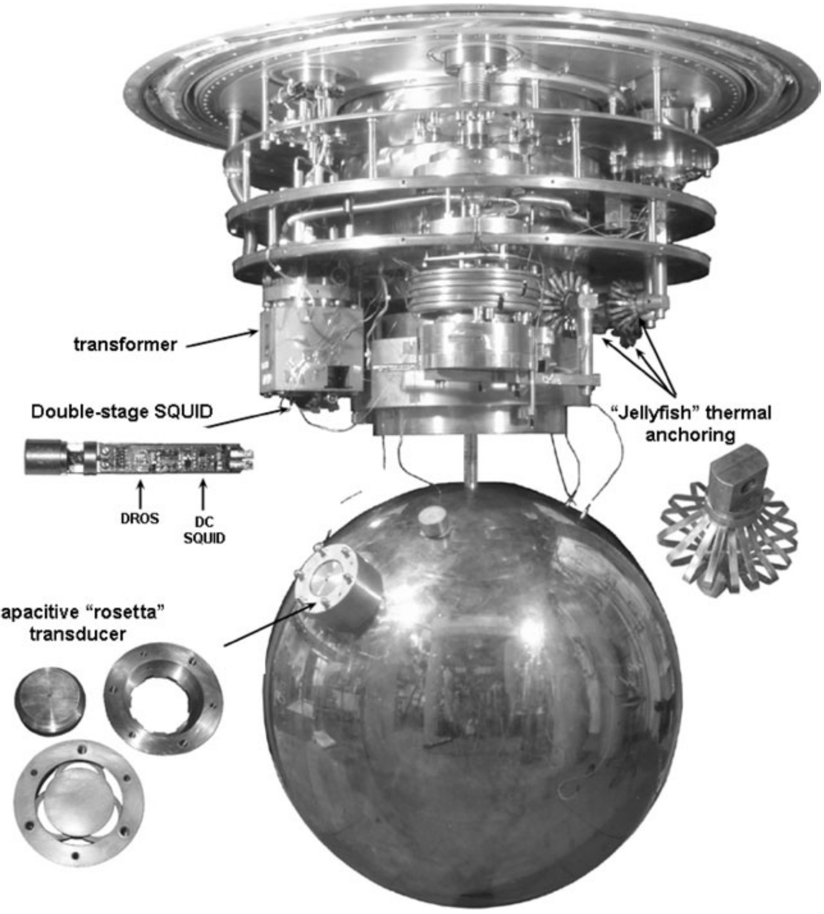

Figure 3. Picture of MiniGRAIL right before the third cryogenic run. Two capacitive transducers were mounted on the sphere 60° from the north pole, 180° apart. One transducer was coupled to a room temperature FET amplifier. The second transducer was coupled to a transformer and a double-stage SQUID amplifier, with a commercial quantum design DC SQUID as a first stage and a DROS as a second stage.

unfortunately did not work. This could be caused by the excess noise from the transformer coil which was attached to the 50 mK shield, whose vibrations were not attenuated. We did not remove the Earth's magnetic field, so it was trapped by the superconducting coating of the coil envelope. Vibrations of the 10 000 turns coil relative to this field could saturate the SQUID.

In table 1 the effect of the transducers on the mechanical Q of the spheroidal modes of the sphere is shown. The first five modes in the column of the bare sphere modes are toroidal quadrupole modes and the last five are the spheroidal quadrupole modes. In the column of the sphere-resonator modes, the first and the last two modes are the coupled modes f_- and f_+, respectively. The second and the fifth spheroidal modes are coupled to the resonators. As we can see, the resonators strongly degraded the Q of some modes, probably due to a bad clamping of the resonator to the sphere. No substantial changes in the Q were observed with lower voltages. The table also shows the coupling of the transducer to the different modes. From the width of the gap (23 μm), the mass (450 gm) and the electric field applied (200 V), a value of about 10^{-4} would be expected. The measured β was at least a

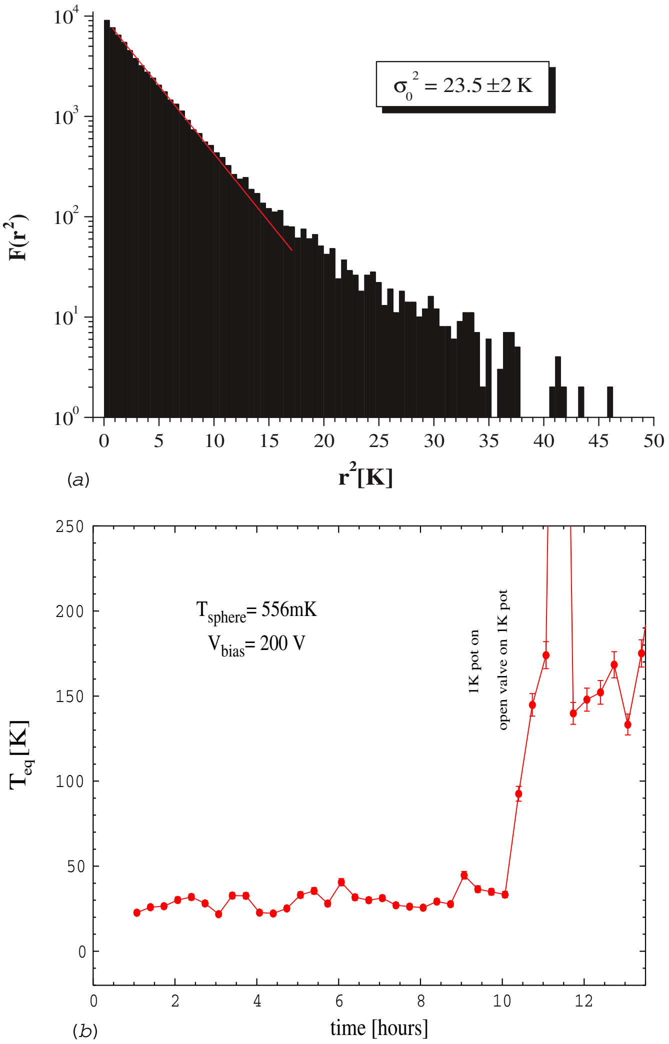

Figure 4. (*a*) The distribution function measured during a 7 h acquisition. (*b*) The equivalent temperature T_{eq} as a function of time, measured for subsets of 20 min. An average T_{eq} of 25 K was measured in the first 7 h of acquisition. This value is also compatible with the white noise contribution from the amplifier.

(This figure is in colour only in the electronic version)

factor of 10 less. During the run we also performed long acquisitions of the modes to evaluate their equivalent temperature and to investigate the performance of the damping system and the 'jelly-fish' thermal anchoring.

The output of the FET amplifier was sent to a lock-in amplifier, where the computer finally acquired the *X* and *Y* components of the signal. The data were elaborated off-line. The time constant of the lock-in amplifier was set to 0.3 s. Due to the low coupling, the mode peak was most of the time lower than the voltage noise of the FET amplifier when the 1 K pot and the dr are switched off. With this time constant, the noise was dominated by the white noise of the FET amplifier. In figure 4 we show the result of a 12 h acquisition of the mode at 3199 Hz. During the first 10 h the 1 K pot and dr were switched off and the noise was dominated by the white noise of the FET amplifier. After about 10 h, the 1 K pot was switched on and the equivalent temperature of the mode increased to about 150 K. In other acquisitions the equivalent temperature stabilized at about 60 K, with the refrigerator fully operating. The mode at 3226 Hz was not affected by the 1 K pot operation, while the other modes had too a low β to give significant information. This is an improvement in sensitivity of a factor of 20 with respect to the previous run, when the dr unit constantly excited the modes to equivalent temperatures of about 1200 K [6].

5. Conclusion

A time-dependent heat leak was observed while cooling the sphere below 1 K. More experiments need to be done to establish the origin of this heat leak. Waiting for about 60 h at 30 K did not help in reducing the heat leak as would be expected if it came from the ortho–para conversion of hydrogen in the copper. The minimum temperatures of the sphere were 79 mK and 20 mK on the mixing chamber of the dr. During the last cryogenic run, the noise was measured using a resonant transducer coupled to a room temperature FET amplifier. When the 1 K pot was not running, the noise was dominated by the white noise of the FET amplifier. With an operating dr an equivalent temperature of about 60 K was measured. To improve the sensitivity of the antenna, the low pass filter of the attenuation stack needs to be improved by at least 40 dB. Mass-to-mass attenuation with rods or springs was measured to be about 50 dB, so the cause of the resonance at about 2.5 kHz, which decreases the attenuation to about 20 dB, should be investigated. Additional improvements of the decoupling of the dilution unit and the attenuation system are required.

Acknowledgments

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