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MiniGRAIL progress report 2004

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Abstract
The MiniGRAIL detector was improved. The sphere was replaced by a slightly larger one, having a diameter of 68 cm (instead of 65 cm), reducing the resonant frequency by about 200 Hz to around 2.9 kHz. The last four masses of the attenuation system were machined to increase their resonant frequency and improve the attenuation around the resonant frequency of the sphere. In the new sphere, six holes were machined on the TIGA positions for easy mounting of the transducers. During the last cryogenic run, two capacitive transducers and a calibrator were mounted on the sphere. The first transducer was coupled to a double-stage SQUID amplifier having a commercial quantum design SQUID as a first stage and a DROS as a second stage. The second transducer was read by a single-stage quantum design SQUID. During the cryogenic run, the sphere was cooled down to 4 K. The two-stage SQUID had a flux noise of about 1.6 $\mu\phi_0$ Hz$^{-1/2}$. The detector was calibrated and the sensitivity curve of MiniGRAIL was determined.

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1. The new sphere

The old MiniGRAIL sphere turned out to have an unexpectedly low quality factor of about 1.5 million below 200 mK [1]. This is about a factor of ten lower than the Q-factor measured in small spherical samples of CuAl6% and of the Brazilian Schenberg detector [2] which was cast from the same material, but with an improved casting process. The reason for the reduced quality of the MiniGRAIL sphere could be the casting process or a crack in the sphere

Table 1. Comparison of the room temperature properties of the old and the new sphere. f_1–f_5 denote the resonant frequencies of the spheroidal quadrupole modes of the bare sphere modes.

Sphere	Diameter (cm)	Mass (kg)	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)	f_4 (Hz)	f_5 (Hz)
Old	65	1150	3033.7	3034.2	3042	3044.4	3047
New	68	1300	2793	2832	2855	2866	2879

Table 2. Properties of the improved vibration isolation system.

Mass number	Material	d_{before} (mm)	f_{before} (Hz)	d_{after} (mm)	f_{after} (Hz)
1, 2	CuAl6%	370	3516	370	3516
3, 4	CuAl6%	370	3516	362	3633
5–7	Cu	370	3397	358	3512

located near the north pole. The crack probably appeared when too much stress was applied to this part during the machining process. We decided to have a new sphere made with the same casting process as the Schenberg detector. The new sphere was also made at ItalBronze [3] (Brazil) and had a diameter of 68 cm, 3 cm larger than the old sphere, and a mass of about 1300 kg. Flat surfaces were machined on the sphere at the TIGA positions [4] allowing for a controlled assembling of the transducers. All flats have a hole in the centre, so different types (larger mass or multi-mode) of transducers can be mounted, without protruding from the sphere surface too much. Because of the larger diameter, the resonant frequencies of the five spheroidal quadrupole modes were about 200 Hz lower than those of the old sphere. Also the splitting of the modes was larger due to the six holes at the transducer locations. A comparison between the most important properties of the old and the new sphere is shown in table 1.

2. Improvements in the vibration isolation system

In order to increase the open window around the resonant frequencies of the sphere and to improve the attenuation of the vibration isolation system, we machined five of the seven masses to increase the resonant frequency of their flexural modes. Previous measurements have shown a resonance peak close to the resonances of the sphere, reducing the aimed attenuation from 50 to 30 dB per stage. The first two masses were not machined, since they also act as radiation shields. Table 2 shows the new diameters of each mass and the resonant frequencies before and after machining. The initial resonant frequencies of the last three masses were lower, since they are made of copper, having a lower sound velocity than CuAl6%.

The attenuation between masses 3 and 4 was measured in a separate room temperature test facility and the result is plotted in figure 1. The combination of the lower resonant frequency of the new sphere and the increased frequency of the flexural modes of the masses of the attenuation system provides an open window of about 1 kHz around the sphere's resonances with an attenuation of about 50 dB. A similar result was achieved for the Cu masses.

3. Cryogenic run 6

Two capacitive transducers and a calibrator were mounted on the new sphere. All of them were made according to the closed membrane transducer design as described in [5]. This time we mounted a 5 mm thick CuAl6% electrode instead of sapphire, because it could hold a bias voltage of about 500 V, five times higher than the much thinner platinum-sputtered sapphire electrode, which would bend and touch the resonant mass. The resonator masses

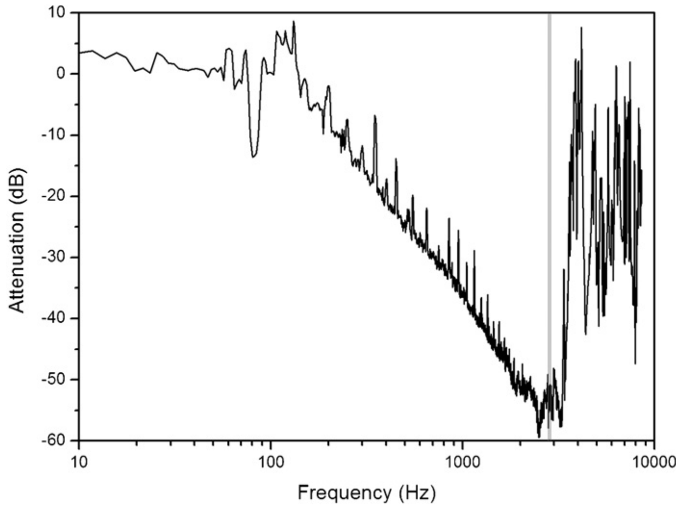

Figure 1. The attenuation between masses 3 and 4 of the vibration isolation system after modification. The grey area indicates the frequency range of the five spheroidal quadrupole modes of the bare sphere. All measurements were done at room temperature in air.

were all about 200 g. Both transducers were tuned to the resonant frequencies of the sphere's quadrupole modes at room temperature. Transducer 1 was assembled with a gap of about 25 μm and had a capacitance of about 1.1 nF measured at room temperature. It was coupled to a double-stage SQUID amplifier through a transformer with an inductance of 0.35 H. The double-stage SQUID has a commercial quantum design SQUID chip as a first stage and a double relaxation oscillation SQUID (DROS) as a second stage, integrated in one module [5, 6]. A cold-damping network, similar to the one developed by the AURIGA group [7], was implemented to increase the stability of the SQUID system. The resonant frequency of the electrical mode was at about 8 kHz. The second transducer was coupled to a single commercial quantum design SQUID via a transformer with an inductance of about 1 H. Both transformers were mounted on the last stage of the vibration isolation stack to minimize the effect of disturbances from external vibrations.

The sixth cryogenic run of MiniGRAIL was performed from April to July 2004. The initial goal was to operate the antenna at a temperature below 100 mK, but because of a leak from the helium reservoir to the vacuum chamber, the experiment was done at 4–5 K. The electrical mode of transducer 2 turned out to be too close to the modes of the sphere, so this transducer was not used during the experiment. All results were obtained with transducer 1. The transducer was biased with a voltage of 200 V and the spectrum was taken with the two-stage SQUID. It looked very clean. There were no unexpected resonances or spurious noise. Eight thermal peaks were visible, five of the sphere modes and three additional resonances from the three coupled resonators. The noise level of the two-stage SQUID outside the frequency band of the resonances was about 1.6 $\mu\phi_0$ $\text{Hz}^{-1/2}$, similar to the noise level measured in a separate cryostat and coupled to a high Q resonator [6]. The system was calibrated as described in [6, 8]. The sensitivity curve was calculated from the spectrum and is plotted in figure 2.

The peak sensitivity was 1.5×10^{-20} $\text{Hz}^{-1/2}$ for the three most coupled modes. The effective temperature for a burst signal was about 70 mK. We could get a good estimate of the peak sensitivity and the bandwidth of the detector using a simple model of one transducer coupled to one mode (like a bar antenna) adding the parameters of MiniGRAIL during this run

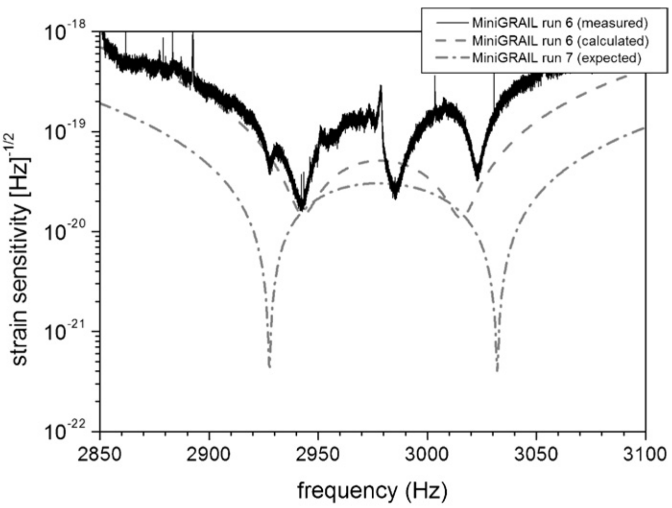

Figure 2. The spectral strain sensitivity of MiniGRAIL as achieved in run 6 at a temperature of 5 K compared to the simulation of a simple two-mode system. The expected sensitivity curve of MiniGRAIL when operated at a temperature of 80 mK is also plotted.

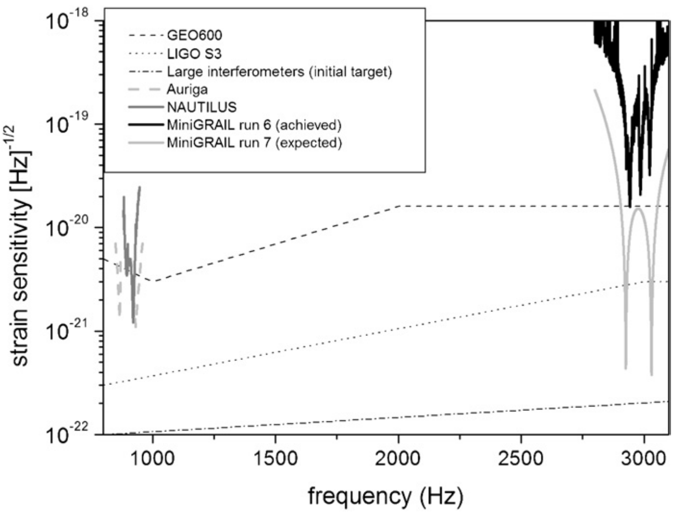

Figure 3. The spectral strain sensitivity of MiniGRAIL compared to the most recent sensitivity curves of some of the other gravitational wave detectors GEO600 [9], LIGO S3 [10], AURIGA [8] and NAUTILUS [11].

(see figure 2). Using this model, we made an estimate of the peak sensitivity and bandwidth which could be reached during the next run when cooling the sphere down to 80 mK. The expected peak sensitivity is a few times 10^{-22} Hz$^{-1/2}$ and the effective temperature for a burst signal is expected to be about 40 μK. The large improvement in peak sensitivity is mainly due to the lower temperature, which will decrease the thermal noise of the antenna (T/Q) by about three orders of magnitude and the SQUID noise with a factor of 7. Also, the coupling will be increased by increasing the bias voltage and the transducer capacitance.

Figure 3 shows the achieved and expected sensitivity curves of MiniGRAIL compared with the most recent sensitivity curves of the other gravitational wave detectors.

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