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MiniGRAIL, the first spherical detector

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Abstract
An overview is given on the possibilities of building low cost omni-directional gravitational wave detectors using resonant spheres. Sensitivity curves of arrays and xylophones of spheres fabricated from different materials show that spherical detectors can be competitive with the large interferometers at frequencies above 1 kHz, with the additional advantage of being omni-directional and being able to determine the direction and polarization of the gravitational wave. MiniGRAIL is the first spherical resonant detector, being built at the Kamerlingh Onnes Laboratory of Leiden University in the Netherlands. The detector is planned to operate at a temperature of about 20 mK and will have a quantum limited strain sensitivity for a burst signal of the order of 4×10^{-21}. We present the progress concerning cryogenics and transducer development.

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1. Introduction

Small spherical detectors can be a good complement to the large interferometers at frequencies above 1 kHz, where the interferometers start to lose sensitivity due to shot noise. Quantum limited sensitivities of spheres operating at frequencies between 1 and 4 kHz could be similar to those planned for the advanced large interferometers. Compared to the traditional resonant bar detectors [1] where the length is about five times the diameter, the cross section of a sphere is about 70 times larger at the same resonant frequency, due to the larger mass (17×) and omni-directionality (4×). Since the cross section is proportional to the square of the sound velocity, high sound velocity materials are being investigated for their suitability as resonant detectors. Table 1 gives the normalized cross sections of several spherical detectors with respect to Al5056, the most commonly used material for resonant bar detectors. The detectors are made of different materials, but all have a resonant frequency of 2 kHz. The mechanical quality factor of the alloy Al5056 is well known [2]. The copper alloys have been tested

Table 1. Normalized cross section of several spheres with resonant frequency at 2 kHz.

Material	Diameter (m)	Density (kg m^{-3})	Sound velocity (m s^{-1})	Normalized cross section
Al5056	1.38	2500	5 400	1
CuAl6%	1.02	8000	4 000	0.7
CuBe5%	1.19	7516	4 668	1.4
CuBe10%	1.38	6537	5 400	2.6
Be	3.06	1800	12 000	38.8

Table 2. MiniGRAIL properties.

Material	CuAl6%
Density	$\rho = 8000$ kg m^{-3}
Diameter	$\varnothing = 0.65$ m
Mass	$M = 1150$ kg
Sound velocity	$v = 4000$ m s^{-1}
Resonant frequency	$f = 3160$ Hz

earlier with respect to their mechanical quality factor [3]. It is clear that beryllium could be a very interesting material for future spherical detectors, due to its high sound velocity. The thermal noise depends mainly on the thermodynamic temperature and the mechanical quality factor. It should not dominate the superconducting quantum interference device (SQUID) noise. Since the mechanical Q of beryllium was not known, we have measured the Q-factor of a beryllium sample, obtained from the Brush Wellman [4] company, and found a maximum value of 2.6 million at about 15 mK [5]. This is high enough to build a spherical resonant detector, which could reach the quantum limit at frequencies above 1 kHz. The fabrication of beryllium spheres with diameters up to 2 m seems possible in both Russia and the USA (Brush Wellman). These detectors would have a resonant frequency of 3 kHz. A beryllium sphere operating at lower frequency would preferably be a hollow [6] sphere. The technique of fabricating large thin features out of beryllium is well established because of their application in telescopes. The possibility of fabricating solid spheres with larger diameter has to be investigated.

The sphere has five spheroidal quadrupole modes of vibration, which interact with a gravitational wave. The direction and polarization of a gravitational wave can be determined by comparing the amplitude of the five modes, which can be measured by putting at least five transducers at certain convenient positions of the sphere. We have chosen the TIGA [7] configuration, where six transducers are placed on the upper hemisphere pentagons of a truncated icosahedron. Merkowitz *et al* [8] have found a mathematical formula to convert the output signal of the six transducers to the amplitude of the five modes. MiniGRAIL is a 65 cm diameter resonant detector (see table 2 and figure 1), with a resonant frequency of 3.1 kHz and is the first of three similar detectors, which will be build in Rome (Italy) and São Paulo (Brazil). The final transducer chain will consist of a three-mode inductive transducer coupled to a nearly quantum limited SQUID. Initially, we will mount a capacitive transducer in collaboration with the ROG group [9] to be able to start data taking as soon as possible. A small sphere like MiniGRAIL has a very short turn-around time and is relatively cheaper, certainly less than 0.5 million euros.

Figure 1. The ultracryogenic antenna MiniGRAIL.

2. MiniGRAIL sensitivity

The minimum detectable energy $k_B T_{\mathrm{eff}}$ of a resonant detector is determined by the effective temperature T_{eff} [10]:

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

where T is the thermodynamic temperature, β^{-1} is the ratio of the energy deposited into the detector and that converted into electromagnetic energy in the transducer, Q is the mechanical quality factor of the antenna and T_N is the noise temperature of the SQUID. The SQUID noise energy in the quantum limit is given by $E_N = k_B T_N = 1h\nu$. So at a resonant frequency of 3.1 kHz, the noise temperature of a quantum limited SQUID is $T_N \cong 1.5 \times 10^{-7}$ K, which sets an upper limit of about 10^{-7} for $T/\beta Q$. The geometry of the three-mode transducer that we are developing for MiniGRAIL has been calculated using numerical analysis to be able to reach a β of 0.1. The bar antennae which are operational today report values for the transducer efficiency β of the order of 0.01 using a two-mode capacitive transducer coupled to a one-stage SQUID. Stevenson [11] has achieved a $\beta \sim 0.5$ with a silicon–niobium thin film transducer and $\beta \sim 0.08$ has been reported by Harry *et al* [12]. For a three-mode system using inductive coupling, the assumption of being able to achieve a β of about 0.1 seems reasonable.

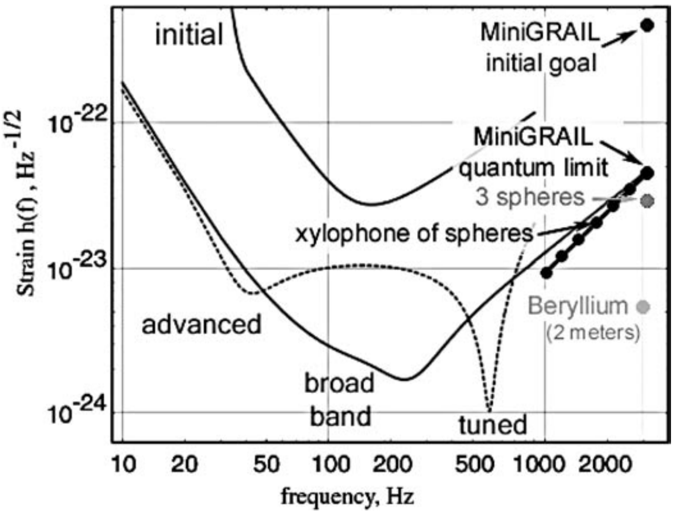

Figure 2. Sensitivity of several spherical detectors compared to LIGO 2. The solid lines give the spectral amplitude of LIGO broadband of the initial phase and for the advanced LIGO. The dotted line gives the spectral amplitude of LIGO narrow-band tuned to about 600 Hz. The bandwidth is comparable to the bandwidth of the spherical detectors. Three spheres are already under construction in Leiden—The Netherlands (MiniGRAIL), Rome—Italy (Sfera) and São Paulo—Brazil (Mario Schenberg). The solid-dotted line gives the sensitivity in the quantum limit of a xylophone of ten spherical detectors, made of CuAl6%, with diameters from 65 cm up to 2 m, covering the frequency band between 1 and 3 kHz. A beryllium sphere with a diameter of 2 m would give a spectral amplitude of about 5×10^{-24} ($Hz^{-0.5}$), which would be comparable to the advanced LIGO operating in the narrow band tuned to that frequency. The figure for the sensitivity curve of LIGO was kindly given to us by David Shoemaker.

Table 3. MiniGRAIL sensitivity.

		Initial goal	Advanced	Quantum limit
SQUID noise energy	E_N	$100h\nu$	$10h\nu$	$1h\nu$
SQUID noise temperature	T_N	1.6×10^{-5}	1.6×10^{-6}	1.6×10^{-7}
Effective temperature	T_{eff}	4.5×10^{-5}	4.5×10^{-6}	4.5×10^{-7}
	β	0.1	0.1	0.1
Band width	Δf	224	224	230
Strain amplitude	h_0	4.3×10^{-20}	1.3×10^{-21}	4.3×10^{-21}
Spectral amplitude	$\tilde{h}\ (\sqrt{\mathrm{Hz}})^{-1}$	4.7×10^{-22}	1.5×10^{-22}	4.7×10^{-23}

We have measured mechanical quality factors of 20 million in CuAl6% samples [3], which implies that an operating temperature of the detector of about 20 mK is necessary for quantum limited operation. Table 3 gives an overview of the important parameters concerning the sensitivity of MiniGRAIL. The strain sensitivity for MiniGRAIL has been calculated for a short burst $h(t)$ of duration τ_g. The Fourier transform $H_0(f)$ of the burst $h(t)$ is considered constant within the bandwidth Δf assuming SNR = 1,

$$H_0^{\mathrm{min}} = \left[\frac{k_B T_{\mathrm{eff}}}{\frac{1}{2} M_s l^2 (2\pi f_0)^4}\right]^{\frac{1}{2}} \approx 1 \times 10^{-24}\,\mathrm{Hz}^{-1} \qquad (2)$$

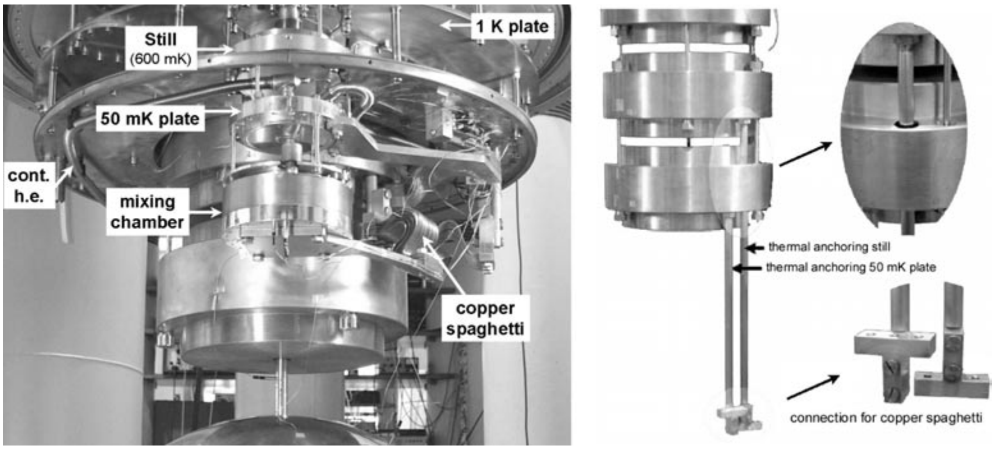

Figure 3. Left: picture of the dilution refrigerator mounted on the MiniGRAIL cryostat. The first sub-Kelvin test will be performed with the continuous heat exchangers only. Radiation shields at 1 K and 600 mK have been assembled. Right: the thermal anchoring masses 3 to 5 of the vibration isolation stage consist of copper rods connected to copper spaghetti.

where $M_s = 1150$ kg is the mass of the sphere, $l = 0.6R_s = 0.195\,\mathrm{m}$ is the effective radius and f_0 is the resonant frequency of the detector. A rough estimate for the strain amplitude of a short burst of 0.3 ms gives

$$h_0(t) \approx \frac{H_0(f)}{\tau} \approx 3 \times 10^{-21}. \tag{3}$$

The spectral amplitude $\tilde{h}$ can be calculated from

$$\tilde{h} = \sqrt{S_h(f_0)} = \sqrt{2\pi \Delta f (H_0)^2}\,(\mathrm{Hz})^{-1/2}. \tag{4}$$

The bandwidth is mainly determined by the efficiency β of the transducer

$$\Delta f = 0.7 f_0 \beta \left(1 + \frac{2T}{\beta Q T_N}\right)^{\frac{1}{2}} \approx 224\,\mathrm{Hz}. \tag{5}$$

3. Cryogenics

We have designed and built a dilution refrigerator for cooling the sphere to a temperature of 20 mK. The sphere is suspended from a cryogenic vibration isolation system, consisting of seven ‘mass-spring’ stages. The attenuation between two masses measured at room temperature is about 40 dB around the resonant frequency of the sphere. The three stainless steel cables, which suspend the upper mass, are thermally anchored to the 4 K plate. Masses 1 and 2 are thermally ‘floating’. Mass 3 is thermally anchored to the still and mass four to the 50 mK plate. The first copper mass (mass 5), is thermally coupled to the mixing chamber of the dilution refrigerator. The thermal anchorings of masses 3, 4 and 5 consist of copper rods (16 mm diameter) screwed into the masses of the suspension on one side and screwed to copper spaghetti on the other. Copper spaghetti is used to create a soft connection for filtering vibrations coming from the dilution refrigerator. The copper spaghetti consist of a stack of copper plates (62 × 140 × 0.5 mm), machined with slits to form a row of copper slabs with a thickness of about 4 mm (figure 3). The dilution refrigerator is equipped with one continuous heat exchanger. The continuous heat exchanger consists of a flexible tube

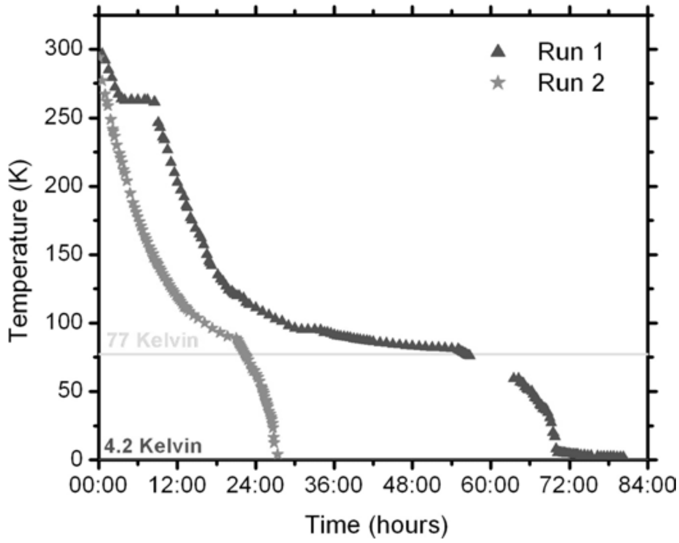

Figure 4. New results on the cool-down time using a forced helium flow obtained in run 2 in 2002.

(10 mm inner diameter, 1.8 m long) for the diluted phase and a 12 m long CuNi capillary (diameter 2.5 × 0.5 mm) for the concentrated phase. A flexible tube was used to avoid high frequency vibrations. With this set-up, we estimate to be able to reach temperatures below 100 mK in the mixing chamber of the dilution refrigerator.

For rapid cooling from room temperature down to 4.2 K we have improved the forced flow system with respect to the first run (see figure 4). The system is a closed circuit which connects the output of the cryostat to a feed-through which goes all the way down to the bottom of the sphere. Helium gas is circulated using two root pumps, through a heat exchanger immersed into liquid nitrogen and injected into the cryostat at the bottom of the sphere. We have increased the size of the nitrogen dewar, so a larger part of the flexible tube heat exchanger is immersed into the nitrogen. We also increased the flow of the circulating helium gas. Now we are able to cool the sphere down to 4.2 K in 27 h, compared to almost 70 h during run 1. Warming up to room temperature now takes about 1.5 days.

4. Transducer development

For the transducer chain we intend to use a three-mode inductive transducer, which is under development [14] (see figure 5). The preliminary design of the three-mode transducer consists of a CuAl6% mass of about 450 g coupled to the sphere through three 'half-moon' shaped springs following the ROG-transducer design [9]. The second mass is a circular plate with a thickness of 0.7 mm made of Al5056, having a mass of about 1.5 g. Four 'S-shaped' springs connect the resonator with the base, which is clamped into a hole of the CuAl mass. A layer of Nb will be deposited on the aluminium disc to increase the critical field. A flat niobium coil, capable of carrying a persistent current of at least 4 A, will be placed in front of the last mass. The support of the coil will be attached to the CuAl mass or to the sphere. When a persistent current is trapped in the Nb coil, movement of the last mass with respect to the coil will add a time-dependent component to the current in the Nb coil. The change in magnetic flux caused by the time-dependent component will be detected by a two-stage SQUID amplifier via a superconductive transformer.

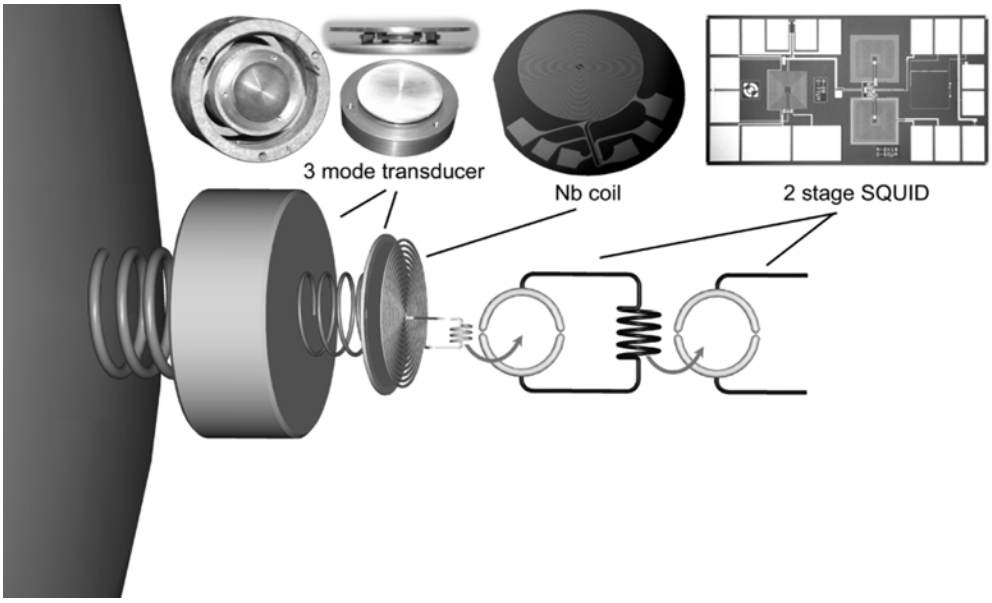

Figure 5. Schematic view of the three-mode inductive transducer chain for MiniGRAIL.

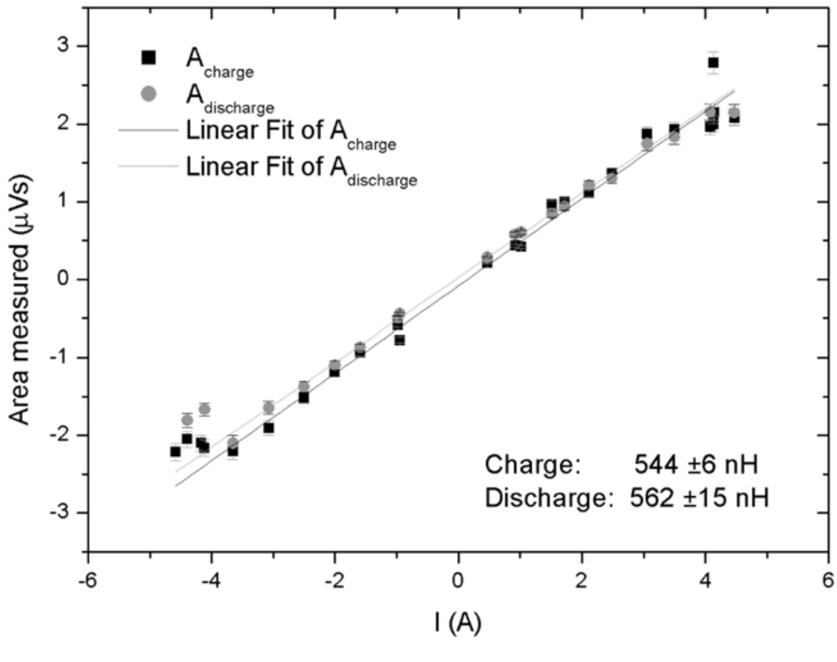

Figure 6. Persistent current trapped in the flat Nb coil.

A flat Nb coil and a superconducting heat switch have been developed and tested. The coil, with a thickness of about 400 nm, was deposited on a silicon disc. To test how much current was stored in the coil in a persistent mode, a dc current was put through the superconducting switch. After applying a short heat pulse to the heater, the current flows through the coil,

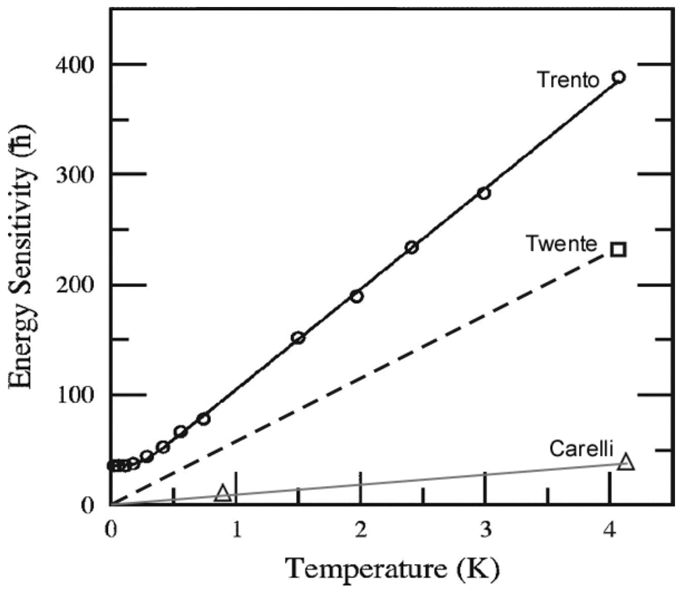

Figure 7. Comparison of the energy sensitivity of several two-stage SQUIDs as a function of temperature. The circles represent the measurements done by the group in Trento [15] with two quantum design SQUIDs coupled. The square gives the sensitivity at 4.2 K of the integrated, double-stage SQUID developed by the Twente group [16], and the up-triangles the multiwasher SQUID of Carelli *et al* [17], which achieved an energy sensitivity of 5.5 $\hbar$ at 0.9 K.

generating a voltage. The current trapped in the Nb coil (I_t) is determined by the integral of the voltage V_c generated across the coil,

$$I_t = \frac{1}{L}\int V_c\,\mathrm{d}t \qquad (6)$$

where L is the inductance of the coil and V_c is the critical voltage. The integral of the voltage is denoted as 'area measured' in figure 6. This graph shows that we were able to trap a current of 4 A in the Nb coil. The development of an ultra-low temperature, nearly quantum limited SQUID is being done in collaboration with the Low Temperature Division of the Technical University of Twente, the Netherlands. A double-stage SQUID was developed and an energy sensitivity of about 240 $\hbar$ was measured at 4.2 K (figure 7).

Acknowledgments

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