Preparing for science run 1 of MiniGRAIL

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Abstract. We report on the 8th cryogenic run of MiniGRAIL, which is planned to be the first science run. Three new capacitive transducers were mounted on the sphere, all coupled to super conducting transformers and a double stage SQUID amplifier. All SQUID modules had a noise level around $1-2\mu\Phi_0/\sqrt{\mathrm{Hz}}$ at 4K in separate test runs. The detector was upgraded with a complete data acquisition and data storage system and a data analysis program for ms burst signals was written using a matched filter. Two cosmic ray detectors were built and installed on the roof above MiniGRAIL as a veto for cosmic rays. A test run was done, but failed because of bad electrical isolation of the transducer-electrode at low temperature. A new cool down is currently going on. With an already obtained sphere temperature of 65 mK and a SQUID noise of $100\hbar$, the expected sensitivity should be $4\times10^{-22}/\sqrt{\mathrm{Hz}}$.

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1. Introduction

In March 2004 we replaced the MinGRAIL sphere 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 [1]. 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 [2] for easy mounting of the transducers. The best sensitivity up to now was $1.5\times10^{-20}/\sqrt{\mathrm{Hz}}$ with a SQUID energy sensitivity of $700\hbar$ and a thermodynamic temperature of the sphere of 5.2 K.

2. Expectations for science run 1

2.1. Cryogenic improvements

Two test runs were performed in the past year(November 2004 and June 2005), mainly to improve the detector read out, but also cryogenic improvements were made.

During run 7, the new sphere was cooled below 4K for the first time. Within two weeks the sphere reached a record temperature of 65 mK, an improvement of 13 mK relative to the 78 mK the old sphere had reached during run 5 in 6 weeks time [3]. This improvement is probably due to a higher annealing temperature of the new sphere which could have decreased the thermally relaxing stresses or the hydrogen impurities, or both, resulting in less heat release by the sphere at low temperatures.

Table 1. Overview of the cryogenic improvements over the last cool downs. We expect to reach a thermodynamic temperature of the sphere below 40 mK for the next run.

cryogenic run	sphere	$T_{annealing}$	T_{min}^{sphere}	T_{min}^{mc}	ΔT	time
run 5	old	450°C	78 mK	20 mK	59 mK	6 weeks
run 7	new	750°C	65 mK	28 mK	37 mK	2 weeks
run 8 (expected)	new	750°C	$<$ 40 mK	$<$ 20 mK	$<$ 20 mK	2 weeks

The thermal contact between the mixing chamber of the dilution refrigerator and the first copper mass was done using the already used jelly-fish [4] but with the 17 copper strips etched to decrease their thickness from 0.18 mm to 0.13 mm so as to further decrease their stiffness. The size of the strips was 0.13x5.2x90 mm. If we assume that the rest of the thermal chain remained the same as in run 5, then the thermal resistance would have increased by 30% (since the other thermal links have a much larger A/L ratio). With a mixing chamber temperature of 26 mK (instead of 20 as previously) and a minimum sphere temperature of 65 mK instead of 78, we can say that the heat leak from the sphere was now reduced by about a factor 2 to 25 μW.

2.2. The improved transducer chain

The transducer design was improved with respect to the one used in the previous successful run (run 6 - 2004) [5]. The new transducer is, like the 'old' design a simple closed membrane transducer, but with a larger mass and a larger surface area. Also the polishing procedure was improved, so a smaller gap could be obtained. Table 2 shows an overview of the improved properties of the new transducer with respect to the old one. During run 6, the most coupled mode had a coupling factor β of 6.6×10^{-4} with a bias voltage of 200V. With the new transducer, the most coupled mode had a β of 2.1×10^{-3} with the same bias voltage, which means an improvement of more than a factor of three.

Table 2. A comparison of the properties of the old transducer, used in run 6 - 2004 and the improved design (new transducer). The coupling β of the new transducer to the 'most coupled mode' was more than a factor of 3 better than the best coupling factor of the old one using the same bias voltage on the transducers.

transducer	mass	area (cm^2)	gap (μm)	C (nF)	β_{max}
old	200	25.5	30	0.8	6.6×10^{-4}
new	700	44.2	20	2	2.1×10^{-3}

MiniGRAIL will be equipped with 3 complete read out chains during the first science run. Three capacitive transducers will be located on position 1, 2 and 5 according the the TIGA configuration. All three will have a similar read out chain consisting of a super-conducting transformer coupled to a double stage SQUID (see figure 1) consisting of a commercial Quantum Design dc SQUID and a DROS (Double Relaxation Oscillation SQUID). The transformer and the SQUID are assembled in separate compartments of a tin-lead plated box. The transformer boxes are hung from the last copper stage of the seismic filter. All polarization cables can be disconnected right above the transformer box, using reed relay switches.

The 2-stage SQUIDs all have a cold damping circuit to improve the stability [6]. The noise level of all SQUIDs was measured in a separate cryostat and all had a similar noise level of about 2 $\mu\Phi_0/\sqrt{\mathrm{HZ}}$ within the bandwidth of the detector. All three circuits have a calibration coil, which is coupled to a small coil in series with the dc SQUID's input coil and the secondary coil of the matching transformer. Using this coil, we plan to use the same calibration procedure as was used for the AURIGA antenna [7]. The properties of the three matching transformers are shown in table 3.

The calibrator is a closed membrane transducer used in a previous run [1], de-tuned to a frequency of ($f_{cal} = 2.4$ kHz at T=300K) and attached to the sphere at position 3. A single PZT was glued to position 4 and a PZT-stack with an additional mass of 15 grams was glued about 60 degrees above position 5. Both PZTs can be used for calibration purposes.

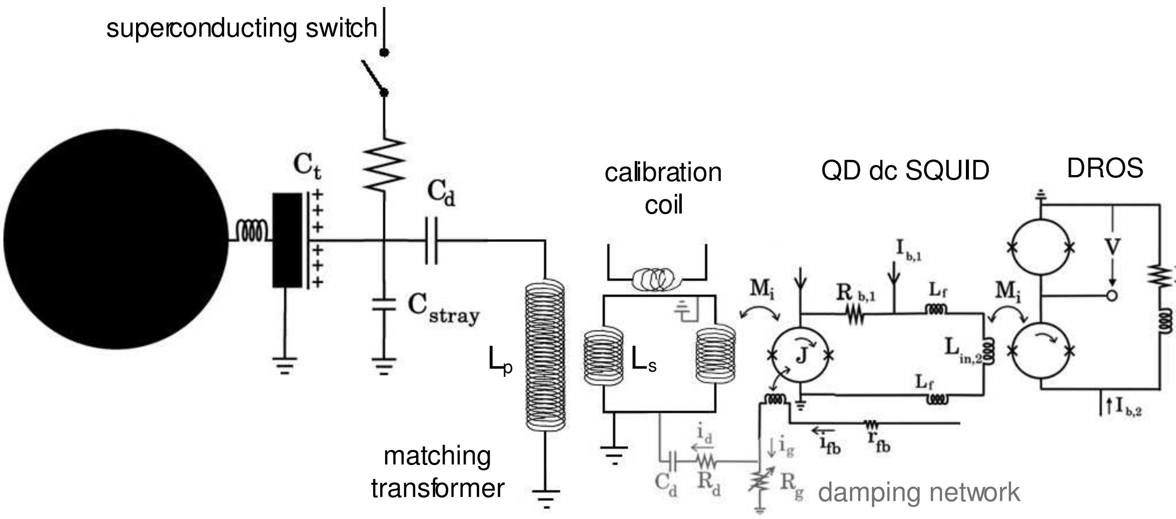

Figure 1. Schematic view of the total read out chain of MiniGRAIL

Table 3. Properties of the three matching transformers of the read out chains. We used transformers with different values of Q and coupling, to test the behavior of the system in various working set-up. C_t is the capacity of the transducer, L_p is the inductance of the primary coil of the transformer, L_s is the inductance of the secondary coil, Q_{el} is the quality factor of the electrical mode and k is the coupling between the primary and secondary coil.

Chain	TIGA position	transducer	C_t (pF)	L_p (H)	L_s(μH)	Q_{el}	f_{el} (kHz)	k
1	1	#1-2	1820	0.4	3.2	1.3×10^6	7.1	0.4
2	2	#1-1	1940	0.4	3.2	3.0×10^5	7.5	0.7
3	5	#1-3	1800	0.32	2.1	2.6×10^5	6.9	0.4

2.3. Data acquisition

A complete data acquisition system was set up, including exact timing with a GPS (figure 2). Two cosmic-ray detectors (scintillator plates coupled to photo multiplier tubes) were built and placed on the roof above MiniGRAIL as a veto for cosmic rays [8]. Besides being a veto for MiniGRAIL, the cosmic ray detectors are a part of the national array of cosmic ray detectors in the Netherlands, called HiSPARC (High-School Project on Astrophysics Research with Cosmics). The data will be stored on a 4TB data storage system. The acquisition rate is 20 kHz and the amount of data about 40-60 GB/day.

The data analysis program for burst signals used by the ROG collaboration was adjusted for MiniGRAIL. The MiniGRAIL data is acquired by a National Instruments PCI-4472 AD converter. This is a sigma-delta converted card, which can acquire 8 channels. Channels are not multiplexed - each channel has its own AD converter. Using the sigma-delta converter greatly decreases aliasing effects - frequencies above 0.55 of the sampling frequency are suppressed by 110 dB by the PCI-4472 AD card. The ADC card has no external clock input, so the internal clock generator is used. With a bandwidth of 10 kHz, we obtain a frequency resolution of 2.4 mHz. Sub-bands are extracted from the spectra, containing resonant modes, calibration, and wide-band noise. Every time the bands are extracted the energy of the modes are calculated. Sub-sampled bands are passed to a Matched filter.

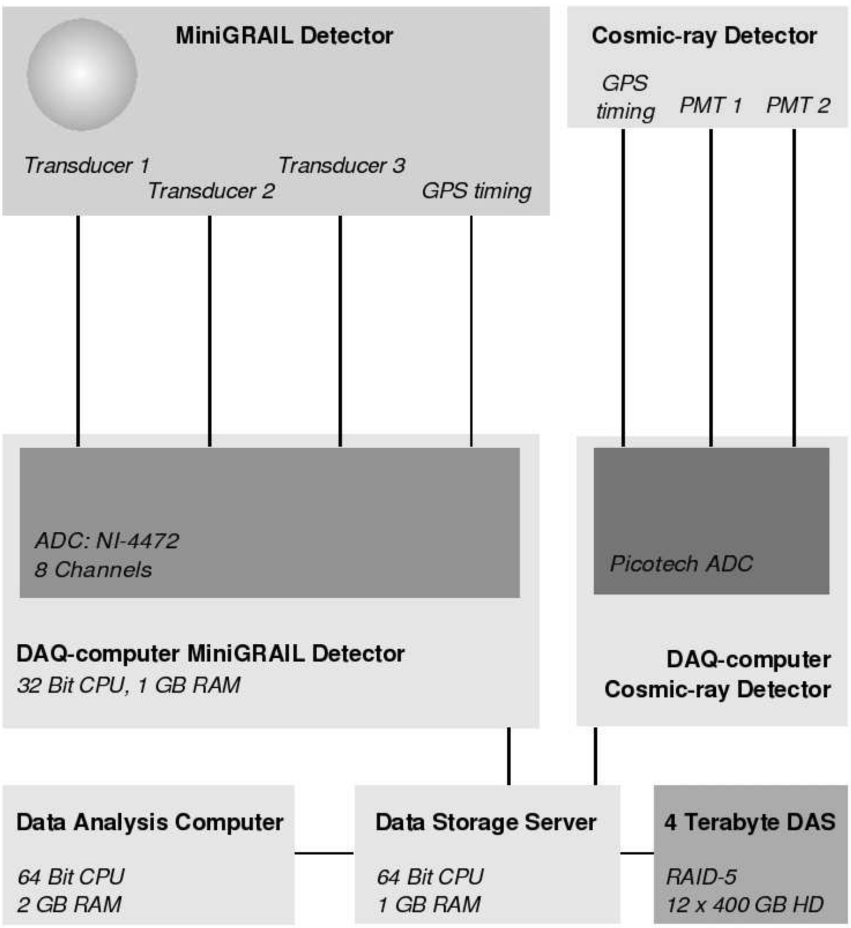

Figure 2. Schematic view of the data acquisition system for MiniGRAIL. The output of the three transducers is acquired by an 8-channel ADC (NI-4472). Other channels will be used to monitor the GPS and possibly a seismic channel. The sampling rate will be 15-20 kHz and the data will be stored on a 4 Terabyte data storage system (RAID-5).

3. Towards the quantum limit

Work is being done in different areas to upgrade MiniGRAIL to a nearly quantum limited detector.

3.1. Advanced transducer design

To further increase the coupling of the transducer to the sphere modes, a new design was made with the main intention of maximizing the surface area and decreasing the gap below $10\mu m$. The resonating mass is clamped into the transducer base by differential contraction. A thin layer of glue (Stycast 2850 FT) isolates the electrode support from the electrode. The surface area is A=85 cm^2, which is a maximum, because of the restriction due to radiation shields. The transducer will be screwed to the sphere by a single bolt, which will minimize the contact area and preserve the quality factor. We expect to achieve a smaller gap, since in this design the mass surface and supports are at the same level, so the surface will be easier to polish flat. The capacitance should be about 8 nF, which is an improvement of a factor of 4 with respect to the current one.

Figure 3. 3D model, simulation and prototype of the advanced transducer.

3.2. Two dimensional super-conducting transformer

To improve the thermalization and electrical quality factor of the transformer, we are developing a two dimensional transformer, consisting of a Nb coil deposited on a silicon wafer. Several flat coils were produced by the Technical University of Twente (the Netherlands) and in Jena (Germany) (figure 4). Table 4 gives an overview of the properties of two types of coils.

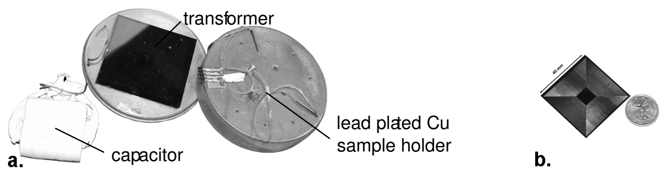

Figure 4. **a.** Picture of the flat transformer coil made at Twente University mounted in the lead-plated copper sample holder. **b.** Flat transformer coil from Jena.

Table 4. Properties of the two types of transformer coils.

Manufactured	line width	line spacing	turns P	L_p (mH)	turns S	$L_s(\mu H)$
Twente University	100 μ m	50 μ m	100	5	-	-
Jena	2 μ m	2 μ m	4000	500	10	2

3.3. Ultra-cryogenic SQUID test facility
In order to test the SQUID noise below 4K, we have set up an ultra-cryogenic SQUID test facility. It consists of a commercial MCK-50-100 plastic dilution refrigerator [9] with a special feed through in the mixing chamber, so the SQUIDs can be tested inside liquid helium to improve the thermal contact (see figure 5). The cool-down time of this type of refrigerator is only 2 hours from room temperature down to the base temperature of about 20 mK. The first test runs have been performed.

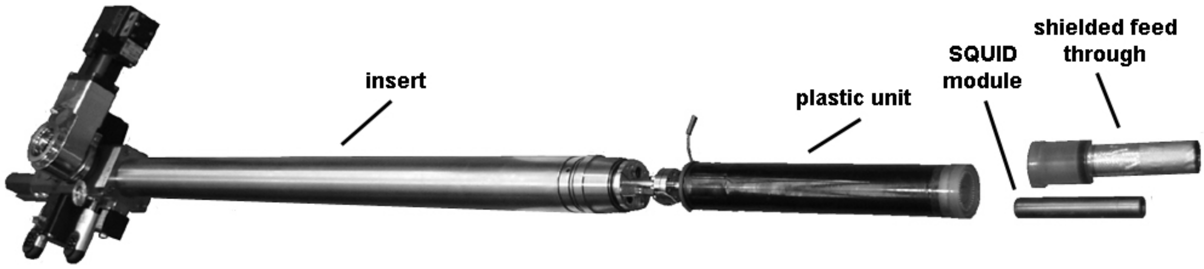

Figure 5. Picture of the ultra-cryogenic SQUID test facility using a MCK-50-100 commercial plastic dilution refrigerator. The fridge was modified with a special shielded feed though to the mixing chamber, so that the SQUID module can be directly inserted in to the liquid.

Acknowledgments
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