Noise measurements and optimization of the high sensitivity capacitive transducer of AURIGA

Andrea Marin†‖, Michele Bignotto†, Michele Bonaldi‡, Massimo Cerdonio†, Paolo Falferi‡, Renato Mezzena§, Giovanni Andrea Prodi§, Gabriele Soranzo†, Luca Taffarello†, Andrea Vinante§, Stefano Vitale§ and Jean-Pierre Zendri†

† Dipartimento di Fisica, Università di Padova and INFN Sezione Padova Via Marzolo 8, I-35100, Padova, Italy

‡ Centro di Fisica degli Stati Aggregati CNR-ITC and INFN Gruppo Coll. Trento I-38050 Povo (Trento), Italy

§Dipartimento di Fisica Università di Trento and INFN Gruppo Coll. Trento, I-38050 Povo (Trento), Italy

Abstract.

Tests of the new AURIGA readout have recently started in the AURIGA Ultracryogenic Test Facility (TF). The most important modifications, with respect to the previous version of the readout, are a new heavier resonant capacitive transducer, the tuning of the electrical mode to the two mechanical ones, and the use of a low noise two-stage SQUID amplifier. Results regarding the quality factor and the noise of the transducer mechanical mode and of the electrical mode are presented.

PACS numbers: 04.80.Nn, 95.55.Ym

1. Introduction

The main goal of the next cryogenic AURIGA run is to increase the detection bandwidth to at least 30 Hz, while keeping a peak strain sensitivity below $10^{-21}/\sqrt{\mathrm{Hz}}$.
In order to obtain this there will be some important modifications on the detector [1]. A new suspension system was designed and is now being tested; a new cryostat will be designed to allow to operate steadily the bar at 1.5 K.
The readout as well will be completely renewed: a heavier capacitive transducer (about 3 Kg of effective mass) will be used; the electrical mode, which is constituted by the transducer capacitance and by the inductance of the primary coil of a low loss superconducting matching transformer, will be tuned to the mechanical modes of bar and transducer. The use of a heavier resonant transducer and the tuning of the high quality factor electrical mode[2] ($Q \sim 10^6$) to the mechanical ones allows to achieve an easier noise matching between the bar and the SQUID amplifier[1, 3], without spoiling the

---

‖ Corresponding author (Andrea.Marin@lnl.infn.it)

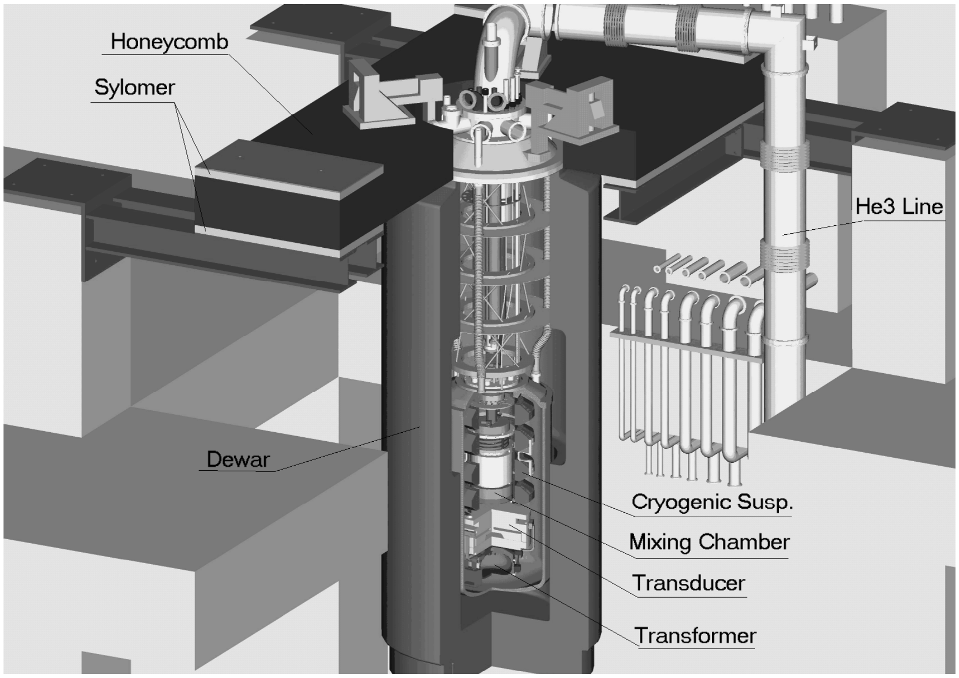

Figure 1. Cross section of the Ultracryogenic Test Facility: 4 reinforced concrete pillars support 4 H-shaped steel beams on which is placed a plane with an Al honeycomb structure; 3 cantilever arms (that provide an attenuation of 65 dB) hold the outer flange, which closes the dewar. All the pumping lines, the cryogenic refilling conduits, the electronic wiring and the Dilution Refrigerator (DR) pass through this flange; a light and torsionally rigid structure holds the Internal Vacuum Chamber (IVC). The IVC houses the cryogenic suspensions: the upper suspension spring is made of stainless steel to reduce the thermal leaks toward the ^{4}He bath. The material of the other springs is a high strength Al alloy (*Ergal 7075*); the last stage is a Cu spring. Thermal link between the transducer and the cold part of the DR is given by this last spring stage which is softly connected to the mixing chamber through annealed OFHC Cu strips.

high mechanical Qs of the system. The last modification of the readout will be the use of a low noise two-stage SQUID system, that showed a noise temperature of 15 μK at 1.5 K[4] as signal amplifier.

2. The Ultracryogenic Test Facilty

In order to optimize the test operations necessary for the AURIGA upgrade, a specific apparatus has been designed, the AURIGA Ultracryogenic Test-Facility (TF)[5].
Using the TF (see figure 1), it is possible to perform frequent ultracryogenics measurements on the complete readout; this fact will allow to find the best readout configuration for the second AURIGA run. The seismic isolation is provided by a multi-stage suspension system, designed for a 200 dB attenuation at 1kHz and with a wide region of the spectrum (from 300 Hz to 1400 Hz) free from internal resonances. All the

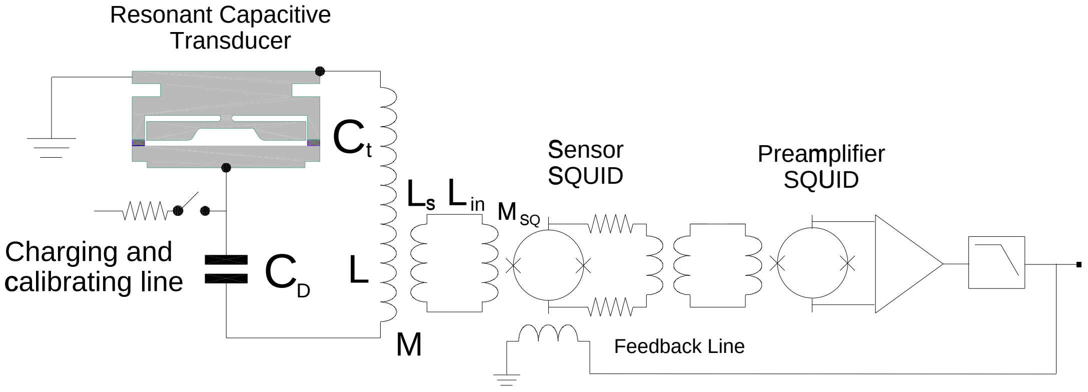

Figure 2. Two-stage SQUID readout scheme: the current flowing into the matching transformer is read by the sensor SQUID whose signal is amplified by the second SQUID. The system is operated in closed loop configuration.

crucial parts of the isolation system were simulated using a FEM simulation program[6]. The 24 resonant frequencies below 200 Hz agree with the calculated ones within 20 %. The transfer function of the various stages of the suspensions were measured (so far only at room temperature) and are well fitted by the simulation data.

A measurement at liquid He temperature was performed, testing the overall attenuation of the suspension system: the excitation was given on the honeycomb plane and the output signal of accelerometers on the top of the dewar flange and the SQUID signal were recorded. The vertical attenuation, measured at the transducer resonant frequency (975 Hz), was 180 dB.

3. Noise Measureraments

In this section we describe some of the tests done in the cryogenic TF runs (1.6 - 4.2 K) on the new AURIGA readout; the goal was to obtain an output signal determined only by the thermal noise sources of the system and of the SQUID amplification stage.

The readout system (see figure 2) is formed by the capacitive resonant transducer[7] (with a capacitance C_t varying from 3.5 to 6 nF), and by the SQUID amplifier (in some cases *two* SQUIDs), which reads the transducer through a low loss superconducting matching tranformer. Thanks to a decoupling capacitor ($C_D \gg C_t$) the transducer can be charged using a charging line. The vibrations of the transducer plate are converted in a current signal in the primary coil of the transformer. The transformer is housed in a superconducting box, without mechanical resonances in the kHz region.

The inductance of the primary coil is 7.9 H and we used two differnt secondary coils: one strongly coupled ¶ (k=0.86) with L_s= 3.2 μH, and one weakly coupled ($k < 0.01$)

¶ If we denote with L and L_s the inductances of the primary and secondary coil of the matching transformer and with M their mutual inductance, then the coupling constant k is defined by $M \equiv k\sqrt{LL_s}$.

with $L_s \simeq 0.1$ μH. The SQUID amplifiers used are manufactured by Quantum Design (Q.D.)[8] and have an input coil of inductance $L_{in}= 1.65$ μH with a mutual inductance between input coil and SQUID loop $M_{SQ}= 10.4$ nH.

The charging line is equipped with a mechanical cryogenic switch, which is placed inside the IVC; when the switch is closed it's possible to charge the transduce or to send, at least at low frequency, a known current to the primary coil of the matching transformer and calibrate the system. In this way it is possible to compare the noise measuraments with the values expected from the theory. On the other hand when the switch is open it is possible to have an optimal insulation from the electromagnetic disturbances and to preserve the high Q of the electrical mode.

In the measuraments described below, the frequencies of the transducer mechanical mode and of the electrical mode were kept apart enough to provide a decoupling of the modes. In this way it was possible to study them separately and to measure their Q and peak noise[9]. We tested three different readout schemes; first of all we used a weakly coupled SQUID ($k < 0.01$). Then we used 2 SQUIDs at the same time, one weakly coupled ($k < 0.01$) and one strongly coupled ($k= 0.86$); finally we used a strongly coupled ($k= 0.86$) two-stage SQUID.

It is well known that the SQUID can affect, in a way depending on the coupling and on the SQUID setting parameters, both the quality factor of the modes, due to its dynamical input impedence[10], and the apparent temperature of the modes, due to its back action noise[11, 12]. In the first test, the coupling was low enough to measure the intrinsic Q but strong enough to allow the measurement the thermal noise[13]. The mechanical mode was at $\nu_m= 974$ Hz with a Q_m of $1.4 \cdot 10^6$ while the electrical mode was at $\nu_e= 886$ Hz with a Q_e of $1.0 \cdot 10^6$. In this configuration, the measured value of the peak noise of the electrical resonator was found in agreement with the value expected from the equipartition theorem. Regarding the mechanical mode, we registered an excess noise, likely due to an excessive leakage curent in the transducer.

In the second series of tests, realized with two SQUIDs, the main difficulty is given by the effect of the real part of the dynamic input impedance of the strongly coupled SQUID, which changes the quality factor of the modes. This effect is present when the SQUID is on and operating in the usual way but also when it is switched off. To get round this problem, the strongly coupled SQUID is biased with a current (few mA) much higher than the optimal one and the quality factors are measured by the weakly coupled SQUID. When the SQUID is biased with a current this high, it no longer works as an active device and its contribution to the quality factor of the modes is reduced to an additive dissipation due to its resistive elements.

During these measurements, performed in the temperature range 1.6 - 4.2 K, the Q of the electrical mode ($\nu_e= 1247$ Hz) was $9 \cdot 10^4$, at all the temperatures. It is not yet clear if this low quality factor is due to the strong coupling with one of the SQUIDs or due to some spurious dissipative element in the LC_t circuit. The Q of the transducer mechanical mode was $1.1 \cdot 10^6$.

In this cryogenic run we have performed also noise measurements of the electrical mode

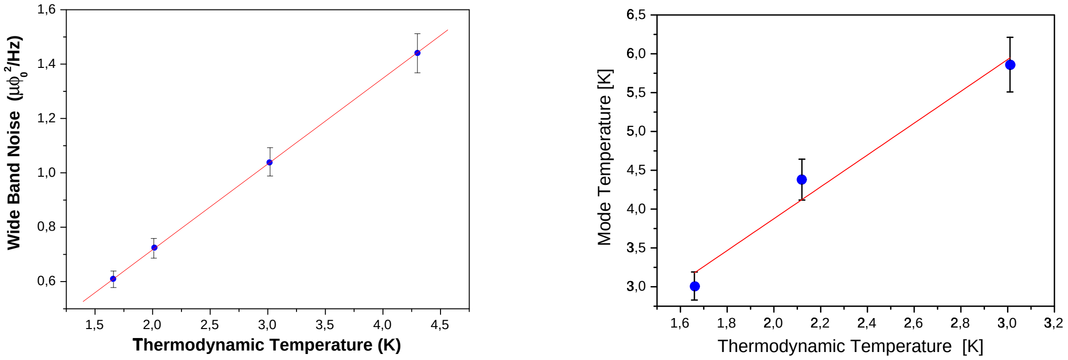

Figure 3. Two-stage SQUID broadband noise (left) and electrical mode temperature as a function of the thermodynamic temperature (right).

with both the SQUIDs. In the measurements with the weakly coupled SQUID (and with the strongly coupled SQUID operated with a high bias current) we have assumed that the Q was not changed by the input impedance of the strongly coupled SQUID (or, if there was a change, this was due to a real dissipation in some element of the SQUID sensor). The behaviour of the mode noise amplitude as a function of the temperature was linear and in agreement with the theory. Also the measurement made with the strongly coupled SQUID produced a result in agreement with the theory but, in this case, it was necessary to consider both the SQUID input impedance effect on the Q and the back action noise. As regards the mechanical mode noise, in this run it was again not thermal.

In the third series of measurements we have employed a two-stage SQUID[14, 15], (see figure 2) based on a modified commercial sensor[8]; this sensor, with respect to the commercial version used in the previous measurements, contains less dissipative elements and shows a lower intrinsic noise. The broadband noise of the two-stage SQUID coupled to the transducer and operated in closed loop mode, is shown in figure 3, left. In this run we made no measurements on the mechanical mode but, as regards the electrical mode (ν_e= 1142 Hz), also in this case, the dynamic input impedance of the SQUID changed the quality factor. By means of a suitable adjustment of the setting parameters (bias, gain, flux offset) of the two-stage SQUID it was possible to operate with an apparent quality factor Q_a of the order of 10^3. The intrinsic quality factor Q_i has been evaluated by strongly biasing the sensor SQUID (up to almost stop its functioning) and by measuring the decay time thanks to a very weak signal detected by the preamplifier SQUID. The result, $Q_i = 3.5 \cdot 10^5$, was not dependent on the temperature in the range 1.6 - 4.2 K. Given the strong coupling, the analysis of the measurements of the mode peak noise has been realized considering both the ratio (Q_a/Q_i) and the SQUID back action.
From the peak noise variance σ^2 it is possible to define the mode temperature T_{mode}:

$$k_B T_{mode} = \frac{\sigma^2 L_r}{\beta^2} \frac{Q_i}{Q_a} \qquad (1)$$

where β is the factor which transforms the current in the primary coil of the matching transformer to the SQUID output voltage and is evaluated with the calibration measurement, $L_r = L - M^2/(L_s + L_{in})$ is the primary inductance reduced by the coupling to the SQUID, and k_B is the Boltzmann constant.

If the only noise sources are the mode thermal noise and the SQUID back action noise, then the expected mode temperature is :

$$k_B T_{mode} = k_B T_{th} + \frac{S_{vv} Q_i}{2\omega_0 L_r} \frac{M^2}{(L_s + L_{in})^2} \tag{2}$$

where T_{th} is the temperature measured by the thermometer fixed on the transformer housing, ω_0 the mode angular frequency, M is the mutual inductance between the coils of the matching transformer, and finally S_{vv} is the spectral density of the SQUID voltage noise responsible for the back action noise.

The measurament of the broadband noise (figure 3, left) allows to calculate the *energy resolution per bandwidth* ε, defined as:

$$\varepsilon = \frac{L_{in}}{2M_{SQ}^2} S_{\phi\phi} = N\hbar \tag{3}$$

For instance, at 1.66 K, we found $\varepsilon \simeq 200\hbar$. The mode temperature as a function of the thermodynamic temperature T_{th} is shown in figure 3, right. From these data, we have estimated S_{vv}= 4.8 $\cdot 10^{-30}$ V^2/Hz at 1.66 K.

This value is greater by a factor of about $\sqrt{3}$ in amplitude than the one obtained in previous measurements performed with an electrical resonator in which the resonant transducer capacitance was substituted by a commercial capacitor[15]; the result is anyway promising, given the preliminarity of the measurements done in the TF with the two-stage SQUID.

References

[1] J. P. Zendri *et al* , in this proc. and references therein.
[2] P. Falferi *et al* , Rev. Sci. Instrum. **65**, 2916 (1994).
[3] J. C. Price, Phys. Rev. D **36**, 3555 (1987).
[4] A. Vinante *et al* , in this proc. and references therein.
[5] J. P. Zendri *et al* , *Advanced readout configurations for the gravitational wave detector AURIGA*, in *Proc. Recent Developements In General Relativity, Genoa 2000*, proceedings of the XIV Congress on General Relativity, Genova, Italy, Sept 2000, in press.
[6] The software is licensed by *Parametric Technology Corporation*, 140 Kendrick Street, MA 02494 Needham (USA).
[7] P. Rapagnani, Nuovo Cimento C **5**, 385 (1982).
[8] Quantum Design, 11578 Sorrento valley Road, Suite 30, San Diego, California 92121.
[9] P. Falferi *et al* , J. Low Temp. Phys. **123**, 275 (2001).
[10] P. Falferi *et al* , Appl. Phys. Lett. **71**, 956 (1997).
[11] P. Falferi *et al* , Appl. Phys. Lett. **73**, 3589 (1998).
[12] J. M. Martinis, J. Clarke, J. Low Temp. Phys. **61**, 227 (1985).
[13] M. Bonaldi *et al* , Rev. Sci. Instrum. **70**, 1851 (1999).
[14] R. Mezzena *et al* , Rev. Sci. Instrum. **72**, 3694 (2001).
[15] A. Vinante *et al* , Appl. Phys. Lett. **79**, 2597 (2001).