STATUS REPORT OF THE GRAVITATIONAL WAVE DETECTOR AURIGA

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The gravitational wave resonant detector AURIGA is about to start its second scientific run. Compared to the first run, the detector has been upgraded significantly in: 1) the readout employs a double stage SQUID amplifier; 2) the matching line between the transducer and the amplifier is resonant and tuned to the bar resonance; 3) the cryogenic suspensions have been modified in order avoid spurious resonances in the relevant frequency range and ensure an attenuation of approximately -300 dB. The sensitivity and the bandwidth at T=1.5 K are expected to be at least one order of magnitude better than in the previous run.

1 Introduction

The gravitational wave (GW) resonant detector AURIGA has already operated for a couple of years reaching the best sensitivity[1] of about $H(\omega) \approx 2.5 \cdot 10^{-22}\ Hz^{-1}$ in terms of the GW Fourier amplitude . The main factors limiting the sensitivity were the broad band noise of the SQUID amplifier and the upper limit on the electric bias field E_0 of the capacitive transducer set by the breakdown limit. Specifically the commercial dc-SQUID[2] had a noise power spectral density dominated by the room temperature preamplifier which partially cancels out the advantage of cooling down the detector at ultra-cryogenic temperatures. In order to avoid this problem, in the next AURIGA run we use a double stage dc-SQUID amplifier. This device, recently developed at the Trento University [3], shows a noise power spectral density which scales linearly with the temperature down to 200 mK where the achieved energy sensitivity per unit bandwidth is about 30 $\hbar$ (more than 100 time lower then the previous AURIGA SQUID amplifier). Thanks to the reduction of the SQUID additive noise a significant improvement on the detector bandwidth is expected in the next AURIGA run. However, even in this situation, the maximum achievable value of the bias field E_0 limits the transduction efficiency to a lower value then that required limit in which the amplifier noise sources dominante[4]. In order to approach this optimal condition it should be noted that for a capacitive transducer the efficiency is proportional to the electric bias field E_0 times a resonant transfer function centered at the natural frequency of the electric oscillator formed by the capacitor and the primary coil of the transformer. Thus to optimize the matching in the next AURIGA run the electric resonant frequency is tuned to the mechanical resonances. The two mechanical resonances plus the electrical one realize a three mode system. The details on the new AURIGA readout will be described in the following section.

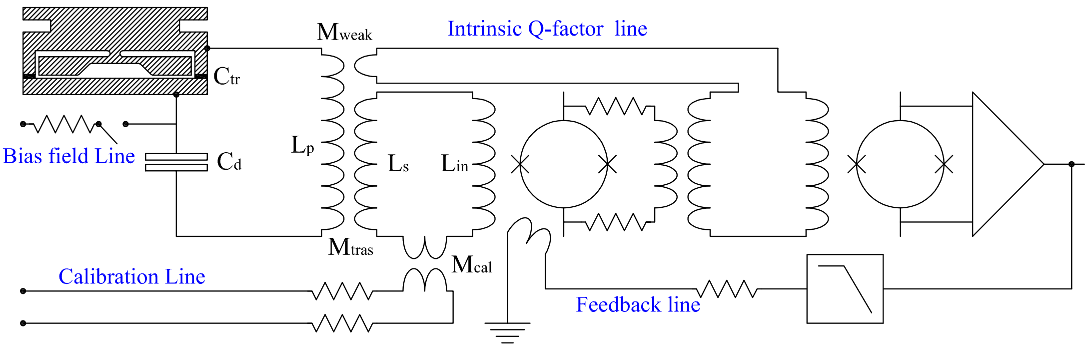

Figure 1: Scheme of the capacitive readout of the second AURIGA.

The GW detection efficiency and reliability require a high detector duty cycle and noise stationarity. During the previous AURIGA run only approximatively 1/3 of the acquisition time produced data with acceptable quality [5]: these have been shared with the other operating detectors within the IGEC [6] collaboration. Half of the vetoed data come from the periods with cryogenic maintenance and calibration operations. The other data have been rejected because of the presence of non-modelled, noise like spurious resonances, strong non gaussian noise and rapidly non stationary noise[5]. A fully satisfactory explanation of the physical mechanisms which origin these phenomena is still missing. Many mechanisms have been proposed as, for instance, the instability of the ultra-cryogenic temperature, the presence of the suspension creep and the electromagnetic interferences. In order to discriminate between these effects we decide to split the next AURIGA run into two phases. In the first one, the detector operates at cryogenic temperature (1.5÷4.2 K) where the temperature can be easily stabilized for long periods and the dilution refrigerator 1K-pot, which is source of acoustic noise, is not present. In the second phase of the run the detector will operates at ultra-cryogenic temperature (50÷100 mK). Moreover the cryogenic suspension of the detector has been renewed completely with the aim of reducing the low frequency rolling of the bar and of reducing the suspension internal stress below 25 % of the Yield stress: this is expected to reduce the creep rate. On the contrary of the previous set-up the suspension has been designed to avoid internal resonances in the relevant frequency window (700÷ 1200 Hz). The new cryogenic suspension and the cryogenic set-up are described respectively in the sections 3 and 4 . Finally section 5 is dedicated to the new data analysis and acquisition system which has been developed taking into account the expected increase in the detector bandwidth.

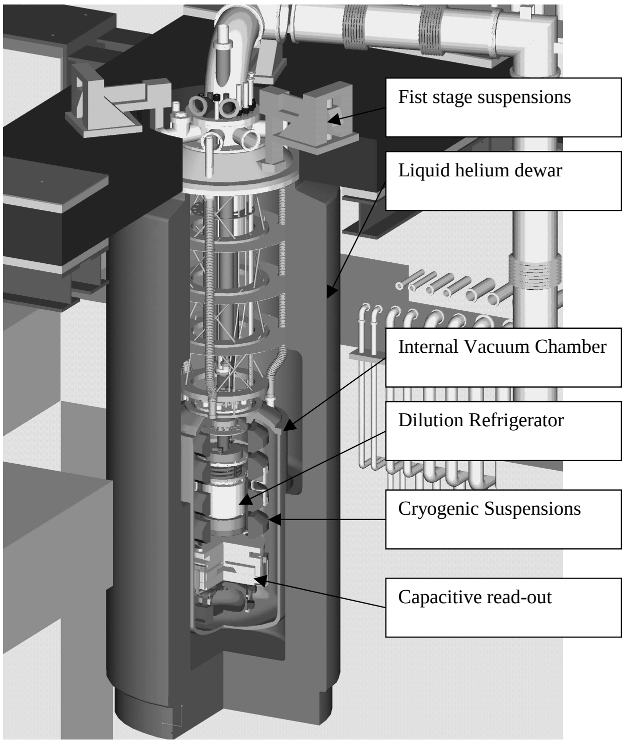

Figure 2: Sketch of the Transducer Test Facility. The liquid helium dewar and the Internal Vacuum Chamber (IVC) are suspended by three stainless steel cantilevers (labelled as 'first suspension stage' in the picture) which provide for the first mechanical attenuation. A stainless steel cylinder, about 10 mm thick, encloses the IVC and is immersed in liquid helium. Inside the IVC the cold insert of the dilution refrigerator is installed and it is embraced by the cryogenic suspensions. Each stage of the cryogenic suspension is composed by three aluminum springs, C-shaped , which are positioned at 120° with respect to each other and hold a toroidal mass. The last spring, which holds the transducer, is made out of OFHC which also provides for the thermal link between the mixing chamber and the readout.

2 The new capacitive readout

2.1 Description

The transducer for the next AURIGA run is a capacitive resonant transducer which is inductively coupled to a double stage dc-SQUID amplifier through the inductance L_{in} (see fig.1). In order to match the impedances between the dc-SQUID amplifier and the capacitive transducer a superconducting transformer is inserted between them. The magnetic flux signal is read by a double stage dc-SQUID amplifier in which the first stage is used as the sensor and the second as the cryogenic preamplifier. In this way the overall SQUID noise scales with the thermodynamic temperature and the energy resolution is $20 \div 30$ times better than of any SQUID amplifier ever used by a GW detector, even at cryogenic temperature. The electronic readout is also equipped by a feedback line which is used to operate the SQUID in closed loop and to allow the cold damping of the resonances. An additional new feature of the readout is that the electric resonant frequency $\nu_{el} = 1/2\pi\sqrt{L_{eff}C}$ (where $L_{eff} = L_p - M_{tr}^2/(L_{in} + L_s)$) is kept at the same value of the mechanical one, thus producing an enhancement of the transduction efficiency. Finally thanks to the improved performance of the SQUID amplifier and to the increased transduction efficiency, a lower mechanical gain is required and thus the transducer optimal mass could be increased from the 0.4 kg of the first AURIGA run to about 3.5 kg: this has the effect of widening the useful band of the detector. Moreover, in order to measure the resonance intrinsic quality factor, which is a very important parameter for the system diagnostic, the circuit is equipped with an inductor which is weakly coupled (M_{weak}) to the primary coil of the transformer. As the effect of the dynamic SQUID dynamic input impedance scales as M_{weak}^2, when the first SQUID is switched off, we can measure the true values of the mode resonance decay time with the SQUID amplifier.

2.2 Transducer Test Facility

The new AURIGA readout incorporates many new features as the resonating matching line and the double stage dc-SQUID amplifier and thus required many optimization runs. As the thermal cycle of the AURIGA cryostat is very long, we have developed a short thermal cycle (few days) facility (the so called Transducer Test Facility, TTF) where to test the whole readout in the same environment as that in the detector. The TTF is equipped with a dilution refrigerator able to cool down the transducer to 100 mK. In order to measure the thermal and back-action noise of the transducer line we have also equipped the TTF with cryogenic suspensions which provide for an attenuation of about -180 dB at about 1kHz. The allowable experimental space for the readout is a cylindrical volume, 40 cm in diameter and 40 cm in height. Figure 2 shows the main features of the TTF.

2.3 Experimental results

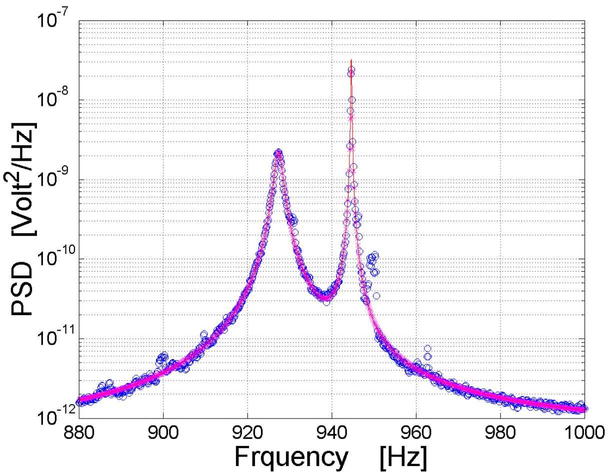

Figure 3: The measured Power Spectral Density (PSD) of the SQUID amplifier output. The fitting function (continuous line) is given in eq.1. When the readout is at liquid helium te fit estimates $T = 4.2 \pm 0.4$ K, in agreement with the thermodynamic temperature.

In the readout circuit a calibration line is available (see fig.**??**) which can be used to apply the voltage $V_{ecc}(\omega) = i\omega I_{cal}(\omega) M_{cal}$ at the SQUID input port, where I_{cal} is the current flowing in the calibration line. The induced SQUID input current $I_{sq}(\omega)$ is then measured using the SQUID amplifier and thus the electromechanical equivalent impedance $Z_{in}(\omega)$ can be estimated as $Z_{in}(\omega) = V_{ecc}(\omega)/I_{sq}(\omega)$. Given the impedance $Z_{in}(\omega)$, the overall noise power spectral density (PSD) at the SQUID input is predicted as

$$S_{II}(\omega) = 2k_B T \Re e\left\{\frac{1}{Z_{in}(\omega)}\right\} + \frac{S_{VV}(\omega)}{|Z_{in}(\omega)|^2} + S_{II}^{ad}(\omega) \tag{1}$$

where the first contribution is the thermal noise, according to the fluctuation-dissipation theorem, the second the amplifier back-action noise and the third the amplifier additive noise. Equation (1) can be used as the fitting function with the three free parameters T, S_{VV} and S_{II}^{ad}.

In this way, after many optimization runs, we have measured the thermal noise of a resonant capacitive readout, for the first time at cryogenic temperature, in which the mechanical mode is tuned to the electrical one (see fig.3). When the SQUID is used in the readout, the measured additive noise at T=1.4 K is $S_{II}^{ad} \sim 8 \cdot 10^{-31}\ A^2/Hz$ corresponding to an energy resolution of about 170 $\hbar$. Moreover, according to the theoretical model [8], the back-action contribution is within the experimental error ($\sim 10\%$).

The capacitive readout for the next AURIGA run is thus commissioned.

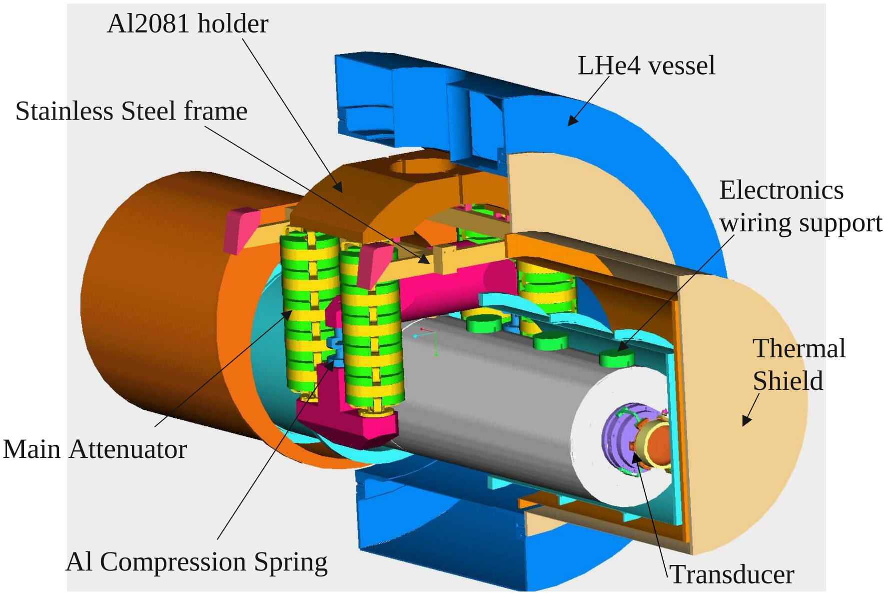

Figure 4: Layout of the new AURIGA cryogenic suspensions. The Al2081 suspension holder is supported by 4 titanium compression springs which are connected to a stainless steel frame bolted to the liquid helium vessel. The holder has a central hole which will fit the cold insert of the dilution refrigerator (in the second phase) and it is thermally anchored to the liquid helium dewar that is inserted centrally from the top (see sec.4). The main attenuators are 4 columns each formed by 5 mass-spring elements which should provide an overall attenuation of about -180 dB at about 1kHz. The main attenuators hold 2 masses that support a transverse mass through 2 Al compression springs; the bar is suspended by a CuBe tube fixed to its center of mass and whose other end is attached to the transverse mass.

3 The suspensions

The AURIGA cryogenic suspension has been fully redesigned, on the basis of the experiences gained with the Transducer Test Facility. The main attenuator is formed by a cascade of 5 mass-spring elements. Each spring is composed by three elements disposed at 120° with respect to each other and C-shaped: thus attenuation is provided along the 6 degrees of freedom. The predicted overall attenuation is about -300 dB at 1kHz, without any internal resonance in the frequency window 700÷1200 Hz. The suspension has been designed to have an internal stress below 25 % of the material Yield stress. An additional new feature is that the bar is suspended by a CuBe tube jointed at the center of mass. The main advantage of this geometry should be an increased rigidity at low frequency. The choice of the tube is motivated by the need to avoid violin modes within the detector frequency band.

A description of the whole suspension system is given in figure 4.

4 Cryogenics

In the first phase of the next AURIGA run we use a conventional liquid helium dewar housed in the upper part of the main cryostat in place of the dilution refrigerator employed in the previous run. This setup will allow to operate the detector in the temperature range 1.5÷4.2 K with just one liquid helium refill approximatively each 10 days. The thermal contact between the dewar and the detector is provided by soft OFHC thermal links with the shape of spaghetti which have already been used satisfactorily in the previous AURIGA run.

Although the 1K-pot and the cold insert of the dilution refrigerator are not installed in the first phase, the liquid helium dewar is equipped nonetheless by pumping lines and copper holders which will be used in the second phase to install and operate a dilution refrigerator.

5 Data analysis and acquisition

The AURIGA detector will take part in an intercontinental network of bar and interferometric GW detectors. To ease the data exchange we have redesigned both the data acquisition and the data analysis and have adopted the FRAME format (developed by VIRGO-LIGO) for the input/output. PC Linux, open source tools and libraries and the C++ programming language have been the natural choice for the development platform.

6 Conclusions

The AURIGA detector has been fully redesigned. The sensitivity and the bandwidth are expected to improve at least one order of magnitude with respect the previous run. For the first cryogenic phase of the next run, the strain sensitivity is expected to stay below $10^{-21}/\sqrt{Hz}$ within a bandwidth of approximatively 40 Hz and to reach the minimum value of about $6 \cdot 10^{-22}/\sqrt{Hz}$. In terms of energy resolution the expected effective temperature is $T_{eff} \sim 65$ μK, 15 times lower than in the previous run. The performances for the ultra-cryogenic phase are expected to improve further: the strain sensitivity will reach a minimum of about $2 \cdot 10^{-22}/\sqrt{Hz}$ and the effective temperature will approach T_{eff} =10 μ K.

7 References

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