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The AURIGA second scientific run and the dual detector of gravitational waves

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For the AURIGA Collaboration

Abstract

We report on the present status of the AURIGA gravitational wave (gw) detector, which is entering its second scientific run: the major changes which it has been subjected to are described along with the expected performance. We also report on a novel kind of acoustic gw detector, named dual detector, which would be broadband; we illustrate the concept of the selective readout, which helps in rejecting thermal and back-action contribution from non-gw sensitive acoustic modes. A SiC dual detector, 2.8 m in diameter and equipped with a wide area selective readout, would reach spectral strain sensitivities below 1×10^{-23} $\mathrm{Hz}^{-1/2}$ between 1.3 and 4 kHz.

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1. Introduction

Direct experimental detection of gravitational waves (gw) is being researched for since the 1960s unsuccessfully. The pioneering work was that of J.Weber of the University of Maryland (USA), who set up several detectors, essentially formed by an elastic body that absorbs energy from the impinging wave resonantly and by displacement sensors: his idea was to discriminate the signal from the noise by correlating the output of far separated detectors. Though unsuccessful as for as detection is concerned, his work developed into a new field of experimental Physics (which is embraced by the gw community from all over the world.) The detection strategy of looking at the output of different detectors has evolved into a more robust technique but the concept is still valid. In the following, as customary in the gw detection field, the sensitivity is quoted as (the square root of) the power spectral density of the total noise expressed in terms of gw amplitude at the detector input, $\sqrt{S_{hh}}$ (units in $\mathrm{Hz}^{-1/2}$).

Modern ground-based gw detectors are usually divided into two classes: the acoustic detectors, which are the direct descendants of Weber's experiments, and the interferometric detectors.

The acoustic detectors, based on suspended cylinders, a few tons heavy, have collected data in the past decades and are still being upgraded (see for instance Section 2). In recent years, from

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1997 to 2000, the five acoustic bar detectors have been operated to search for gw bursts by the time coincidence analysis [1]. The sensitivity of bar detectors is peaked in a narrow frequency range centered on the bar resonance, at about 1 kHz: the maximum useful bandwidth is set by the noise added by the secondary mechanical oscillator resonant with the bar coupled to it (the so-called 'resonant transducer') and which performs a mechanical amplification of the signal before it is converted into an electromagnetic one.

Interferometric detectors have been operated in the past only in small-/medium- scale prototypes but long baseline detectors have now entered the data-taking phase. The sensitivity of these detectors is expected to stay below $1\times10^{-22}/\sqrt{\mathrm{Hz}}$ in a frequency span ranging from a few tens of Hz up to about 1 kHz.

While detection with these more sensitive experiments is usually considered as occasional, plans for the second generation are already being prepared and the related R&D programs have started [2,3]. Also, potentially more sensitive acoustic detectors, based on spherical resonators, are being built in a worldwide network [4,5]: they will be equipped with resonant transducers and therefore the frequency range of sensitivity will be limited to about 10% of the central frequency set by the quadrupolar resonance, at a few kHz.

We have recently proposed a third kind of detector which will be acoustic and sensitive in a broad frequency range: the dual detector [6,7]. The dual detector aims at detection in a frequency range, a few kHz wide, above $\sim$1 kHz: this spectral region is of particular interest as it is that expected for signals from fully relativistic stellar sources [8] but it will be hardly covered by the advanced interferometers.

In the following section (Section 2) we describe the status of the AURIGA bar detector that is entering the second data taking period: to improve the performance with respect to the first run, AURIGA has been subject to major changes which we also account for. In Section 3 we describe the concept and expected performance of the dual detector: the realization of such an advanced detector requires an intense R&D project, which will benefit from the experience we have gained for the upgrading of AURIGA.

2. The second run of the AURIGA detector

The gw bar detector AURIGA has collected data in the past years, reaching the best sensitivity of $\sqrt{S_{hh}} = 5\times10^{-22}/\sqrt{\mathrm{Hz}}$ in a $\sim$1 Hz bandwidth around two well-separated mechanical modes [9] (see Fig. 1). The main limits on the sensitivity were given by the bias electric field of the capacitive transducer and by the poor performance of the following SQUID amplifier (namely, its additive noise).

In order to improve the detector, we have fully re-designed the readout which now employs a double stage SQUID amplifier following the capacitive transducer after a resonant electric matching network. The double-stage amplifier solves the problem of the noise of room temperature electronics, which was prevented in the previous run to gain sensitivity by cooling the detector to ultracryogenic temperatures. The resonant electric circuit overcomes the problem of the bias field limited by the breakdown voltage. The new readout has been fully characterized in a

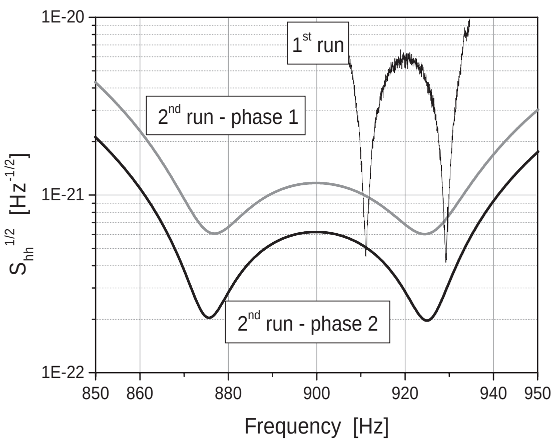

Fig. 1. Expected sensitivity for the next run of AURIGA: the first phase (gray thick line) will be at cryogenic temperatures ($\sim$1 K) while the second phase (black thick line) at ultracryogenic temperatures ($\sim$0.1 K). For comparison we also show the experimental sensitivity obtained in the first run (thin black line).

dedicated cryogenic facility and shows behaviour in agreement with the expectations, with a sensitivity corresponding to an energy resolution of $170\hbar$. The sensitivity predicted for the next AURIGA run is shown in Fig. 1: it is expected to be as good as $6 \times 10^{-22}/\sqrt{\mathrm{Hz}}$ and to stay below $10^{-21}/\sqrt{\mathrm{Hz}}$ within a frequency band about 80 Hz.

The first AURIGA run has also evidenced the need of a higher detector reliability: only approximately one-third of the collected data could be used to search for the gw signal. The other data had to be vetoed half because they were taken while performing experimental activity on the apparatus, as cryogenic liquid refills and calibrations, and half because they were plagued by non-modelled noise. A clear explanation of the origin of this noise is still lacking but the likely culprits are the instability of the ultracryogenic temperature, the creeping of the suspension and the electromagnetic interference. While the latter is minimized by the compact design of the new readout, we have decided to address the other problems in two phases: in the first phase, the detector will run at cryogenic temperatures, without the presence of the dilution refrigerator (a possible noise source) but with the new suspensions, which have been fully redesigned. In the second phase, we will insert the refrigerator and run at ultracryogenic temperatures (50−100 mK) with better expected sensitivity (see Fig. 1).

The new AURIGA suspension, which fit into the same cryostat as the previous run, are designed to work at about 20% of the yield stress of the employed materials (this should reduce the creep problem) and to reduce the low-frequency rolling of the bar, while providing enough insulation. The main components of the suspension are 4 columns which provide for most of the gain (−180 dB at about 1 kHz, without any resonance in the frequency range 400−1400 Hz). The last stage of the suspension is the CuBe cable that supports the bar from its center of mass: this solution should improve the mechanical quality factor of the detector with respect to the previous run, the center of mass being a node of the bar's first longitudinal mode.

The data acquisition and analysis have also been fully renewed and the data format is now the FRAME [10], to allow the exchange of data with other detectors, either interferometers or bars.

3. The dual torus

In the first proposal [6] the new detector was based on two nested spheres, both sensitive to the gw signal and whose differential displacement is measured by a set of optical sensors optimally distributed on the sphere surfaces: the detector was named 'dual sphere'. Recently [7], we have studied a simpler detector configuration of cylindrical symmetry, the 'dual torus', which offers the advantage of naturally hosting the 'selective readout' described in the following but gives up to the omni-directional responsivity assured by the spherical symmetry.

The idea of a dual detector is to have two concentric elastic and massive bodies in free-fall, whose quadrupolar mechanical resonances, which are eventually excited by the passing gw, are at different frequencies: the gw detection is accomplished by reading the differential deformation of the facing surfaces, while the center of mass of the system provides for the rest frame of the measurement.

The basic features of a dual detector can be illustrated by a simple one-dimensional model: the detector is schematized as two independent oscillators of frequencies ν_1 and ν_2, driven by the same gw force. The latter is measured from the measurement of the relative displacement $x_1 - x_2$. The frequency region between ν_1 and ν_2 is of particular interest: here the same force drives one oscillator above and the other below resonance: therefore the displacements are out of phase and thus they sum up in a differential measurement, resulting in a signal enhancement with respect to the single oscillator response. Let us now consider the noise budget: fundamental noise sources come from the thermal noise of the oscillators and from the force and displacement noise of the amplifier used in the differential measurement. As the back-acting force noise is applied with opposite sign on the two oscillators, their response is in-phase and thus is greatly depressed by the differential measurement [7,11].

In the real world, the bodies have internal acoustic modes other than the gw-sensitive ones and whose effect is to add only noise, being excited by the thermal and back-action noise forces. To reduce the sensitivity to these modes, we have envisioned a 'selective' readout: in this scheme, the measured quantity is the sum of the differential displacement averaged over 4 distinct wide areas at 90 from each other and combined so that the signal sums up. Provided the area is large enough, one can cancel the noise contribution from most of the non-sensitive modes: this is true not only for the back-action noise but also from that of thermal origin, which is known to scale inversely with the sensor linear dimension.

In order to obtain satisfactory sensitivity one needs to push the sensor noise figure down to the limit set by the Quantum Mechanics, which is reached when the displacement and the force noises of the sensor amplifier are balanced and the thermal noise is negligible. In Fig. 2 we show the Standard Quantum Limited (SQL) sensitivity of a SiC dual cylinder, along with sensitivity from second generation long-baseline interferometers (LCGT [2] and Advanced-LIGO in both wide- and narrow-band operation [3]) which the dual cylinder can complement. We also show the sensitivity predicted for the first generation of the long baseline interferometers, namely LIGO and VIRGO. The radius of the inner SiC cylinder is 0.82 m while the internal/external radii of the outer SiC cylinder are, respectively, 0.83/1.44 m; the height is 3 m and the total mass amounts to $20.5 + 41.7$ tons. The sensor area is $0.35\ m^2$. The SiC is a ceramic material which has a very high cross-section to the gravitational signal: it also has mechanical and thermal properties of interest here but its dissipation has not been measured at low temperatures so far. As an alternative, we can consider molybdenum, which has a lower cross-section, but is known to reach $Q/T > 2 \times 10^8/\mathrm{K}$ at low temperatures: a Mo detector, 1 m in diameter, would reach spectral sensitivity of $\sim 3 \times 10^{-23}/\sqrt{\mathrm{Hz}}$ between 2 and 6 kHz.

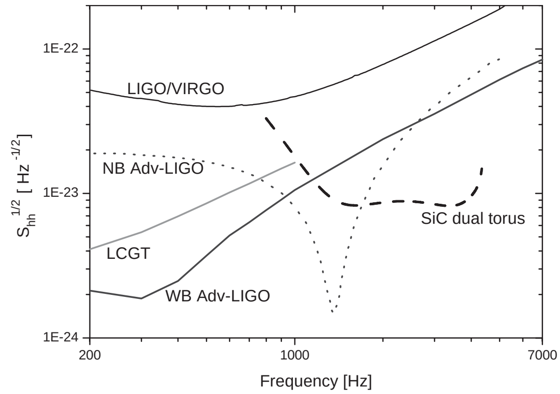

Fig. 2. Expected SQL sensitivity for a SiC dual cylinder (dashed line). For comparison sensitivities predicted for the first generation of long baseline interferometers, namely LIGO and VIRGO (black line), and for the second generation (LCGT (gray line) and Advanced Ligo in both wide-band (WB: dark gray line) and narrow-band (NB; dotted line) operation) are also shown.

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