Available online at www.sciencedirect.com

Nuclear Physics B (Proc. Suppl.) 138 (2005) 443–445

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

www.elsevierphysics.com

Wide bandwidth dual acoustic gravitational wave detectors

M. Bonaldi[a], M. Cerdonio[b], L. Conti[b], G.A. Prodi[c], L.Taffarello[d], and J.P. Zendri[d].

[a]Istituto di Fotonica e Nanotecnonolgie CNR-ITC and INFN Trento, I-38050 Povo (Trento), Italy

[b]INFN Padova Section and Department of Physics, University of Padova, via Marzolo 8, I-35100 Padova, Italy

[c]Department of Physics, University of Trento and INFN Trento, I-38050 Povo (Trento), Italy

[d]INFN Padova Section, via Marzolo 8, I-35100 Padova, Italy

In a "dual" detector a wideband sensitivity is obtained by measuring the differential displacement, driven by the gw wave, of the facing surfaces of two nested massive bodies mechanically resonating at different frequencies. By the use of the recently proposed "selective readout" scheme, capable of specifically selecting the signal contributed by the vibrational modes sensitive to the gravitational waves, a flat spectral strain sensitivity could be obtained. In the case of a 3 m diameter Silicon Carbide dual cylinder, the sensitivity expected at the standard quantum limit is better than 10^{-23} $\mathrm{Hz}^{-1/2}$ in the wide frequency interval 1-4 kHz.

1. INTRODUCTION

Substantial progress has been made over the last forty years in preparing instruments and methods to search for gravitational waves from the universe. Resonant mass "bar" detectors [1], the first historically to come to continuous operation, have been improved by 4 orders of magnitude in energy sensitivity, so that they can detect energy changes of a 2300 kg bar as little as a few thousand of quanta of vibration at about 1 kHz. However it is commonly accepted in the community that, to enter the "observatory phase" and open up a new gw astronomy, a substantial improvement in detector sensitivities should be achieved.

Traditional acoustic detectors are seriously limited in terms of bandwidth (typically to about 10% of the resonant frequency) due to the usage of the resonant transducer, which is needed to reduce the effect of the noise of the final amplifier. A different approach is needed to fully exploit the potential sensitivity of resonant detectors and make them complementary to the advanced versions of interferometric detectors. We are actively investigating a novel detection scheme, the "dual" resonator system [2–4], which can provide both high sensitivity and wide bandwidth.

2. DUAL DETECTORS

In the first proposal 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'. The main advantage of the spherical geometry is the isotropic responsivity assured by the symmetry, once equipped with at least 5 readout channels. Recently, we have studied a simpler detector configuration of cylindrical symmetry, the 'dual cylinder'. This gives up the isotropic sensitivity but offers the advantage of naturally hosting the 'selective readout' described in the following, and it is useful in reducing the detector thermal noise.

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

0920-5632/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.nuclphysbps.2004.11.102

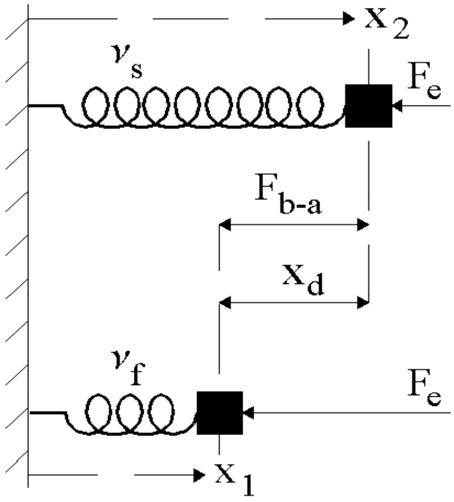

Figure 1. One-dimensional “dual” detector: the same force F_e is measured by the relative displacement x_d of two resonators.

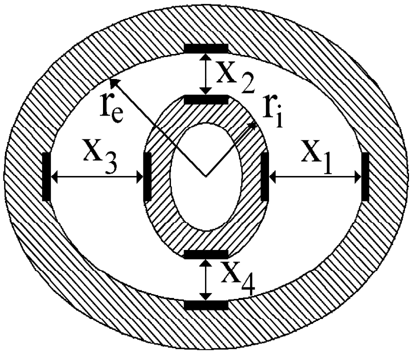

Figure 2. Section of a “dual cylinder” detector showing the signal enhancement obtained when a GW signal drives the external cylinder above resonance and the internal cylinder below resonance.

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 (Fig. 1). The detector is schematized as two independent oscillators of frequencies ν_1 and ν_2, driven by the same force F_e. 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 force F_e 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 F_{ba} noise is applied with opposite sign on the two oscillators, their response is in-phase and thus is greatly depressed by the differential measurement [3,4].

In a real detector, the simple oscillators are replaced by elastic three-dimensional bodies, which possess a variety of acoustic modes of resonance. In the limit of validity of a normal mode expansion, each mode contributes its own (thermal and back-action) noise and the detector output is affected by the sum of such terms; on the contrary, the signal is contributed only by the first few modes with quadrupolar sensitivity. To approach the ideal one-dimensional model which offers signal enhancement and back-action noise reduction, it is necessary to devise the measurement so it is not sensitive to the majority of these modes. This is accomplished by devising the readout that selects the modes geometrically, the so-called ‘selective reading’. We refer to the system of two co-axial cylinders (Fig. 2). The detector response is maximized for a gw signal that propagates parallel to the cylinder axis z. We average the differential displacement over 4 distinct areas x_{1-4} and then combine them into $X_d = x_1 - x_2 + x_3 - x_4$. It can be seen that this combination gives a significant rejection to modes that do not possess the quadrupolar symmetry and thus helps in reducing the total detector noise. It should be noted that in order to measure the two basic polarization states (usually referred to as the + and x polarizations) of the gw signal, two selective readouts

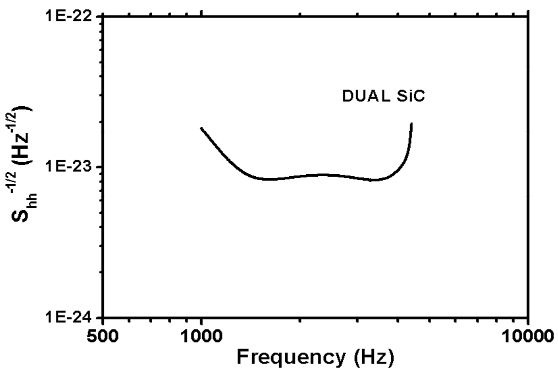

Figure 3. Predicted spectral strain sensitivity of a dual detector configuration at the Standard Quantum Limit. SiC detector, inner cylinder radius 0.82 m, outer cylinder internal-external radius 0.83 - 1.44 m, height 3 m, weight 20.5 - 41.7 tons, $Q/T > 2 \times 10^8$ K^{-1}.

rotated by $\pi/4$ around the z-axis are necessary.

Thanks to the selective readout, an almost flat detector response (Fig. 3) can be achieved between the quadrupolar modes of the cylinders, in spite of the large number of acoustic modes of both masses. In fact, not only the back-action noise is suppressed as described above, but also the large sensed areas guarantee thermal noise reduction as a contribution from high-frequency modes averages to zero. As a net result, we obtain a good convergence of the system response by adding less than 100 modes in the normal mode expansion.

3. READOUT ISSUE

The dual cylinder sensitivity curves are optimized with a quantum limited readout with displacement sensitivity of the order of 3×10^{-23} m/$\sqrt{\text{Hz}}$. This figure is impressive and indeed has not been achieved so far, and we stress that a wide-band readout cannot profit from the displacement amplification at resonance of a conventional transducer. Up to now, the lowest displacement noise we have achieved experimentally is about 5×10^{-20}m/$\sqrt{\text{Hz}}$ in the kHz range. This has been demonstrated by two different kinds of readout that we are developing: the optomechanical one [6], based on Fabry-Perot cavities, and the capacitive one [5], based on SQUID amplifiers. An R&D program is ongoing to improve the performances of both readout schemes.

Another relevant requirement for the transducer system is to sense the deformation of the resonant masses on a wide surface, in order to be less sensitive to the resonant modes of higher frequency, which do not carry any gravitational signal. In this way the thermal noise of the detector is minimized, while preserving the sensitivity to the signal. A practical implementation of the selective reading can be accomplished by a capacitive readout, and evolution of that employed in resonant bar gw detectors. Each polarization channel would be a series of four capacitive transducers, gradiometrically connected and sensed by a single SQUID amplifier. We are also studying the possibility of implementing an optical readout, another evolution of that under development for bar detectors. Here the main problem comes from the difficulty in achieving a sensed area larger than 1 cm^2, as required, but an idea on how to extend the sensed area has already appeared [7] .

REFERENCES

1. Z.A. Allen *et al.*, Phys. Rev. Lett. 85 (2002) 5046.
2. M. Cerdonio *et al.*, Phys. Rev. Lett. 87 (2001) 031101.
3. T. Briant *et al.,* Phys. Rev. D 67 (2003) 102005.
4. M.Bonaldi *et al.,* Phys. Rev. D 68 (2003) 102004.
5. J.P. Zendri *et al.*, Proc. of the XXXVIIIth Rencontres de Moriond - Gravitational Waves and Experimental Gravity, Les Arcs 1800, March 2003, Edition Frontiers, Paris.
6. L. Conti *et al.*, J. Appl. Phys. 93 (2003) 3589.
7. F. Marin *et al.*, Phys. Lett. A 309 (2003) 15.