SCRF DETECTORS FOR GRAVITATIONAL WAVES

G. Gemme*, R. Ballantini, A. Chincarini, S. Cuneo, R. Parodi, A. Podestà, R. Vaccarone
INFN and Università degli Studi di Genova, Genova, Italy
O.Aberle, Ph. Bernard, S. Calatroni, E. Chiaveri, R. Losito, H. Neupert
CERN, Geneva, Switzerland
R.P. Croce, V. Galdi, V. Pierro, I.M. Pinto
INFN, Napoli and Università degli Studi del Sannio, Benevento, Italy
E. Picasso
INFN and Scuola Normale Superiore, Pisa, Italy

Abstract

The basic ideas underlying the use of SCRF cavities for the detection of high frequency gravitational waves are discussed. Experimental results on prototypes are presented. The outline of a possible detector design and its expected sensitivity ae also shown.

INTRODUCTION

In the last decades, several laboratories all around the world have promoted an intense effort devoted to the direct detection of gravitational waves. The detectors, both those in operation and those being developed, belong to two conceptually different families, massive elastic solids (cylinders or spheres) [1] and Michelson interferometers [2]. Both types of detectors are based on the mechanical coupling between the gravitational wave and a test mass, and in both types the electromagnetic field is used as motion transducer.

In a series of papers, since 1978, it has been studied how the energy transfer induced by the gravitational wave between two eigenmodes of an electromagnetic resonator, whose frequencies ω_1 and ω_2 are both much larger than the characteristic angular frequency Ω of the g.w., could be used to detect gravitational waves [3, 4]. The energy transfer is maximum when the resonance condition $|\omega_2 - \omega_1| = \Omega$ is satisfied. This is an example of a frequency converter, i.e. a nonlinear device in which energy is transferred from a reference frequency to a different frequency by an external pump signal.

In the scheme suggested by Bernard et al. the two modes are obtained by coupling two identical high frequency cavities [4]. Each resonant mode of the individual cavity is then split in two modes of the coupled resonator with different spatial field distribution. In the following we shall call them the *symmetric* and the *antisymmetric* mode. The frequency difference of the two modes (the detection frequency) is determined by the coupling, and can be tuned by a careful resonator design. An important feature of this device is that the detection frequency does not depend on its mechanical properties (dimensions, weight and mechanical modes resonant frequencies), though, of course, the detector *can* be tuned so that the mode splitting equals the frequency of a mechanical resonant mode. The sensitivity in this and other experimental situations will be discussed in the following. Since the detector sensitivity is proportional to the electromagnetic quality factor, $\mathcal{Q}$, of the resonator, superconducting cavities should be used for maximum sensitivity.

An R&D effort started in 1998 and will be completed at the end of 2003 (PACO, 1998–2000; PACO–2, 2001–2003) [5, 6, 7, 8, 9]. Its main objective is the development of a *tunable* detector of small harmonic displacements based on two coupled superconducting cavities. Several cavity prototypes (both in copper and in niobium) were built and tested, and finally a design based on two spherical cells was chosen and realized (Fig. 1). The feasibility of a spherical detector based on Nb/Cu technology was also investigated [10].

The detection frequency, i.e. the frequency *difference* between the symmetric and antisymmetric modes, was chosen to be: $\omega_2 - \omega_1 \sim 10$ kHz (the frequency of the modes being $\omega_{1,2} \sim 2$ GHz). An electromagnetic quality factor $\mathcal{Q} \gtrsim 10^{10}$ was measured on a prototype with fixed coupling (Fig. 2).

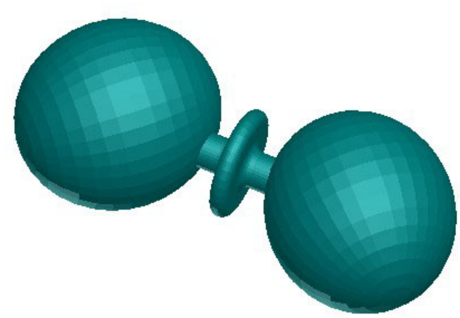

Figure 1: Artistic view of the coupled spherical cavities with the central tuning cell

The tuning system was also carefully studied. The coupling strength, and thus the tuning range, is determined

* gianluca.gemme@ge.infn.it

Figure 2: Niobium spherical cavities (fixed coupling)

by the diameter of the coupling tube and by the distance between the two spherical cells. A central elliptical cell, which can easily be streched and squeezed, was found to provide a tuning range of several kHz (4–20 kHz in the final design). A prototype with the central elliptical cell was built and is now being tested (Fig. 3). A second tunable cavity (two spherical cells and the central cell) will be built by the middle of 2004.

Figure 3: Niobium spherical cavities (variable coupling)

The system was also mechanically characterized, and the mechanical resonant modes in the frequency range of interest were identified. In particular the quadrupolar mode of the sphere was found to be at 4 kHz, in good agreement with finite elements calculations.

The detection electronics was designed. Its main task is to provide the rejection of the symmetric mode component at the detection frequency. A rejection better than 150 dB was obtained in the final system.

Starting from the results obtained in the last six years, we are now planning to design and set up an experiment for the detection of gravitational waves in the 4–10 kHz frequency range (MAGO, Microwave Apparatus for Gravitational waves Observation). Our main task is the design and construction of the refrigerator and of the cryostat (including the suspension system), which houses the coupled cavities. The refrigerator must provide the cryogenic power needed to keep the superconductiong cavities at $T \sim 1.8$ K (approx. 10 Watts) without introducing an excess noise from the external environment. A design based on the use of subcooled superfluid helium is being invesigated. The expected time-scale is four years (2004–2007).

In the following a detailed description of the various issues aforementioned will be given. Expected system sensitivity will also be discussed.

PHYSICS MOTIVATION

The spectrum of gravitational waves of cosmic origin targeted by currently operating or planned detectors spans roughly from 10^{-4} to 10^4 Hz.

The $f \leq 10^{-1}$ Hz region of the gravitational wave (GW) spectrum, including galactic binaries [11], (super)massive black hole (BH) binary inspirals and mergers [12], compact object inspirals and captures by massive BHs [13], will be thoroughly explored by LISA [14], which might be hopefully flown by year 2015. Ground based interferometers and acoustic detectors (bars and spheres) will likewise co–operate in exploring the $f \geq 10^1$ Hz region of the spectrum, including compact binary inspirals and mergers [15], supernovae and newborn black-hole ringings [16], fast-spinning non-axisymmetric neutron stars [17], and stochastic GW background [18].

The whole spectral range from $10^{-4} - 10^4$ Hz, however, is far from being covered with uniform sensitivity, as seen e.g. from Fig. 4, where the fiducial sensitivity curves of LISA and LIGO–II are shown side by side. Plans are being made for small–scale LISA–like space experiments (e.g., DECIGO, [19]) aimed at covering the frequency gap $10^{-1} - 10^1$ Hz between LISA and terrestrial detectors.

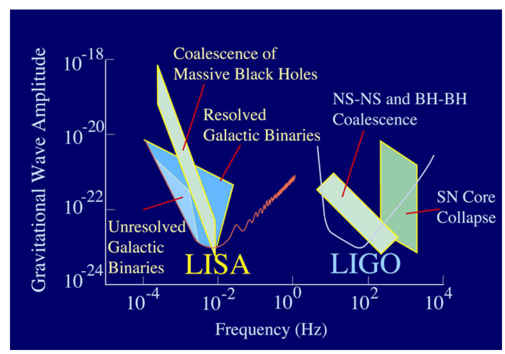

Figure 4: LISA–LIGO comparison

Several cryogenic/ultracryogenic acoustic (bar) detectors are also operational, including ALLEGRO [20], AURIGA [21], EXPLORER [22], NAUTILUS [23], and NIOBE [24]. They are tuned at $\sim 10^3$ Hz, with bandwidths of a few tens of Hz, and minimal noise power spectral densities (PSD) of the order of 10^{-21} $\text{Hz}^{-1/2}$.

Intrinsic factors exist which limit the performance of both interferometers (IFOs) and acoustic detectors in the upper frequency decade ($f \gtrsim 10^3$ Hz) of the spectrum.

The high frequency performance of laser interferometers is limited by the $\propto f^2$ raise of the laser shot-noise floor. While it is possible to operate IFOs in a resonant (dual) light-recycled mode, for narrow-band increased-sensitivity operation the pitch frequency should be kept below the suspension violin-modes [25], typically clustering near and above $\sim 5 \cdot 10^2$ Hz.

Increasing the resonant frequency of acoustic detectors (bars, spheres and TIGAs), on the other hand, requires decreasing their mass M. The high frequency performance of bars and spheres is accordingly limited by the $\propto M^{-1/2}$ dependance of the acoustic detectors' noise PSD.

The next generation of resonant detectors will be probably spheres or TIGAs (Truncated Icosahedral Gravitational Antennas, [26]. The MINIGRAIL [27] spherical prototype experiment under construction at Leiden University (NL), as well as its twins planned by the Rome group [28] and at São Paulo, Brazil [29], is a relatively small (CuAl (6%) alloy, $\emptyset$ 65cm, 1.15ton) spherical ultracryogenic (20mK) detector with a 230Hz bandwidth centered at 3250Hz, and a (quantum limited) strain sensitivity of $h \sim 4{\cdot}10^{-21}$. Spherical (or TIGA) detector might achieve comparable sensitivities up to $f \sim 4 \cdot 10^3$ Hz.

Summing up, the GW spectrum below $f \sim 10^3$ Hz might be adequately covered by ground-based and space-borne interferometers. The range between 10^3 Hz and $\sim 4 \cdot 10^3$ Hz could be sparsely covered by new-generation acoustic detectors. The high frequency part ($f \gtrsim 4{\cdot}10^3$ Hz) of the gravitational wave spectrum of cosmic origin is as yet completely uncovered. Within this band, GW sources might well exist and be observed [1]. Indeed, the ultimate goal of gravitational-wave astronomy is the discovery of *new* physics. In this spirit, the very existence of gravitational wave sources of as yet unknown kind could not be excluded a-priori.

The above brings strong conceptual and practical motivations for the MAGO proposal. The MAGO design is easily scalable, and may be constructed to work at *any* chosen frequency in the range $10^3 - 10^4$ Hz, with uniform (narrow-band) performance. On the other hand, the MAGO instrument appears to be comparatively cheap and lightweigth, thus allowing to build as many detectors as needed to ensure adequate covering of the high frequency ($f \gtrsim 4 \cdot 10^3$ Hz) GW spectrum. In view of their limited cost, MAGOs might also be nice candidates for many–detector networks, to achieve very low false alarm probabilities in coincidence operation. In addition MAGO–like detectors operating at $f \sim 10^3$ Hz might hopefully provide coincident observations with both acoustic detectors and IFOs, based on a *different* working principle.

Before all this might come into reality, it will be necessary to build and operate one or more MAGO prototypes so that some basic issues might be efficiently addressed and solved, viz.:

- efficient decoupling from platform $\rightarrow$ suspensions design;
- efficient and quiet cooling to 1.8K $\rightarrow$ cryostat design;
- efficient readout $\rightarrow$ microwave feeding and tapping networks, and low noise amplifier design.

[1] A well known back-of-an envelope estimate (motion at the speed of light along body-horizon circumference) gives the following upper limit for the spectral content of gravitational waves originated in a process involving an accelerated mass $\sim M$: $f_{sup} \lesssim \frac{c^3}{4\pi G M} \sim 10^4 (M_\odot/M)$ [Hz] .

In parallel, a start–to–end simulation codes should be implemented, in order to tune all design parameters for best operation. In particular, criteria for obtaining the best tradeoff between detector bandwidth and noise levels should be investigated, with specific reference to selected classes of sought signals.

DETECTOR LAYOUT

Electromagnetic Design

In order to build an efficient detector, a suitable cavity shape has to be chosen. According to some general considerations, a detector based on two coupled spherical cavites looks very promising (Fig. 1) [9]. The choice of the spherical geometry is based on several factors. From the point of view of the electromagnetic design the spherical cell has the highest geometric factor G, thus it has the highest electromagnetic quality factor $\mathcal{Q}$, for a given surface resistance R_s ($\mathcal{Q} = G/R_s$). For the TE_{011} mode of a sphere, the geometric factor has a value $G \sim 850\,\Omega$, while for standard elliptical radio-frequency cavities used in particle accelerators, the TM_{010} mode has a value $G \sim 250\,\Omega$. Looking at the best reported values of surface resistance of superconducting accelerating cavities, which typically are in the $10^{-8}\,\Omega$ range, we can extrapolate that the electromagnetic quality factor of the TE_{011} mode of a spherical superconducting cavity can be $\mathcal{Q} \sim 10^{10} - 10^{11}$.

In the first generation of detectors, dedicated to the development of the experimental technique, the internal radius of the spherical cavity will be $r \sim 100$ mm, corresponding to a frequency of the TE_{011} mode $\omega \sim 2$ GHz. The overall system mass and length will be $M \sim 5$ kg (with a wall thickness $w \sim 2$ mm) and $L \sim 0.5$ m. The choice of the wall thickness is made considering both practical and design constraints. On one hand, the wall thickness should be kept small enough to allow an easy fabrication while maintaining sufficient stiffness to withstand the external pressure once the cavity is evacuated. Furthermore, wall thickness was chosen to optimize the cavity cooling process, and to guarantee optimum stability against point–like thermal dissipation due to possible defects present on the cavity inner surface. On the other hand, wall thickness can be used to design a particular mechanical resonant frequency and it is obviously related to the mass of the detector, which plays an important role in the signal to noise ratio.

Since this type of detector is ideally suited to explore the high frequency region of the g.w. spectrum, we plan to build a tunable cavity with 4 kHz$\lesssim \omega_2 - \omega_1 \lesssim 10$ kHz, which is outside the spectral region covered by the resonant and interferometric detectors, both existing and planned, and is still in a frequency region where interesting dynamical mechanisms producing g.w. emission are predicted [30, 31, 32].

The interaction between the g.w. and the detector is characterized by a transfer of energy and angular momentum. Since the helicity of the g.w. (the angular momentum along the direction of propagation) is 2, the g.w. can induce a transition between the two levels provided their angular momenta differ by 2. The optimal field spatial distribution has the field axes in the two cavities which are orthogonal to each other (Fig. 5). Different spatial distributions of the e.m. field (e.g. with the field axes along the resonators' axes) have a smaller effect or no effect at all. This can be achieved by putting the two cavities at right angle or by a suitable polarization of the electromagnetic field inside the resonator. The spherical cells can be easily deformed in order to induce the field polarization suitable for g.w. detection.

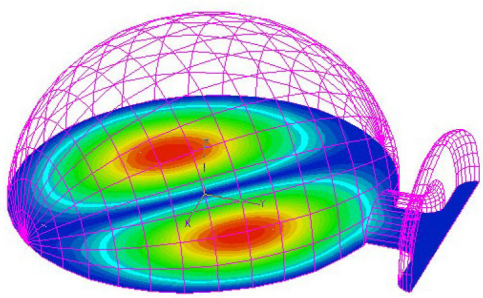

Figure 5: Electric field magnitude of the TE_{011} mode. Note the alignment of the field axis

A tuning cell is inserted in the coupling tube between the two cavities, allowing to tune the coupling strength (i.e. the detection frequency) around the design value. The dependence of the detection frequency on the distance between the two coupled cells is shown in Fig. 6.

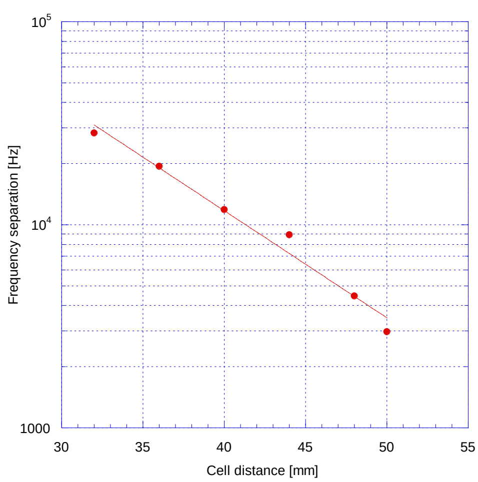

Figure 6: Detection frequency vs. coupled cells distance

A first detector based on two spherical niobium cavities (with fixed coupling) has recently been built and tested at CERN (Fig. 2). A second detector with variable coupling has also been built and is now being tested (Fig. 3).

The first test on the cavity in Fig. 2, showed a quality factor $\mathcal{Q} \gtrsim 10^{10}$ (see Fig. 7). This corresponds to a surface resistance $R_s \sim 50$ nΩ, a factor of ten higher than the best values reported for superconducting accelerating cavities. The obtained result is very satisfactory. In fact, the whole fabrication procedure (including surface treatments) is optimized for the elliptical cavity geometry used for high energy particle acceleration. Some development is still needed to tailor the technique to the spherical shape of our resonator and to obtain a surface quality comparable to that routinely obtained on elliptical cavities that would lead to a quality factor $\mathcal{Q} \sim 10^{11}$.

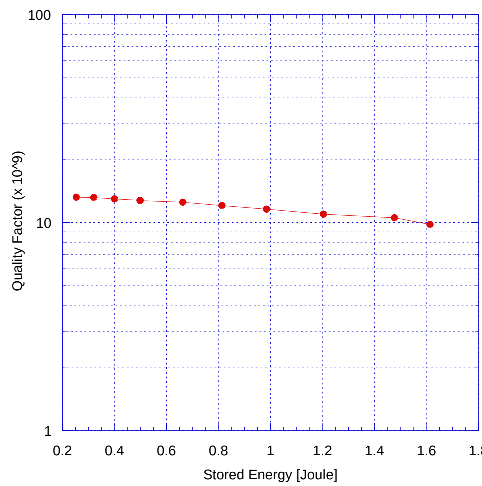

Figure 7: Quality factor vs. stored energy for the fixed–coupling cavity of Fig. 2

A single–cell, seamless, copper cavity was built to investigate the applicability of the Nb/Cu technology in the fabrication of a spherical resonator. The cavity, shown in Fig. 8 was built at INFN–LNL (E. Palmieri). It was then electropolished and tested at CERN [10]. The measured surface resistance, shown in Fig. 9, corresponds to a quality factor $\mathcal{Q} \sim 10^{11}$ at low field and $T = 1.5$ K, and $\mathcal{Q} \gtrsim 10^{10}$ at the maximum magnetic surface field $H_{surf} \sim 120$ mT, at the same temperature.

Figure 8: Single–cell, seamless, copper cavity

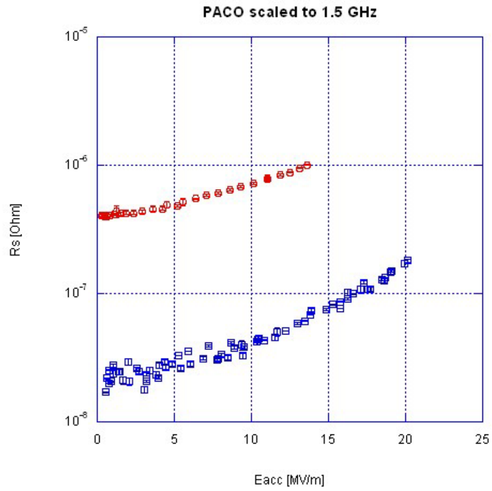

Figure 9: Surface Resistance of the single–cell spherical cavity

Mechanical Design

From the mechanical point of view it is well known that a spherical shell has the highest interaction cross-section with a g.w. and that only the quadrupolar mechanical modes of the sphere do interact with a gravitational wave [33]. The mechanical design is highly simplified if a hollow spherical geometry is used. In this case the deformation of the sphere is given by the superposition of just one or two normal modes of vibration and thus can be easily modeled. In fact, the proposed detector acts essentially as an electro–mechanical transducer; the gravitational perturbation interacts with the mechanical structure of the resonator, deforming it. The e.m. field stored inside the resonator is affected by the time–varying boundary conditions and a small quantity of energy is transferred from an initially excited e.m. mode to the initially empty one. We emphasize that our detector is sensitive to the polarization of the incoming gravitational signal. Once the e.m. axis has been chosen inside the resonator, a g.w. with polarization axes along the direction of the field, will drive the energy transfer between the two modes of the cavity with maximum efficiency. With standard choices for the axes and polar coordinates, the pattern function of the detector is given by $F_\times = -\cos(\theta)\sin(2\phi)$, and is equal to the pattern function of *one* mechanical mode of a spherical resonator.

SENSITIVITY

Let us focus our attention on the system based on two spherical niobium cavities working at $\omega_1 \sim \omega_2 \sim 2$ GHz with a maximum stored energy in the initially excited symmetric mode of $U_1 \sim 10$ J per cell (corresponding to a maximum surface magnetic field $H_{max} = 0.1$ T, half the critical field of niobium). This is a small–scale system with an effective length of 0.1 m and a typical weight of 5 kg. The lowest quadrupolar mechanical mode is at $\omega_m \sim 4$ kHz. In the following, we shall consider an equivalent temperature of the detection electronics $T_{eq} = 1$ K.[2]

A possible design of the detector uses both the mechanical resonance of the structure, and the e.m. resonance. Due to the tuning system, the detection frequency can be made equal to the mechanical mode frequency $\omega_m \sim \omega_2 - \omega_1$. The expected sensitivity of the detector for $\omega_2 - \omega_1 = \omega_m = 4$ kHz is shown in figure 10, for a mechanical quality factor $Q_m = 10^3$ (solid line) and $Q_m = 10^6$ (dashed line). Note that, in the two cases, the optimum sensitivity is obtained with different values of stored energy. In both cases the stored energy has been optimized for maximum detector bandwidth. When the mechanical quality factor is higher ($Q_m = 10^6$) the stored energy has to be maintained much under the maximum allowed value.

When $\omega_2 - \omega_1 = \omega_m$, the detector sensitivity is limited by the walls thermal motion. In this case, a lower T_{eq} would increase the detection bandwidth.

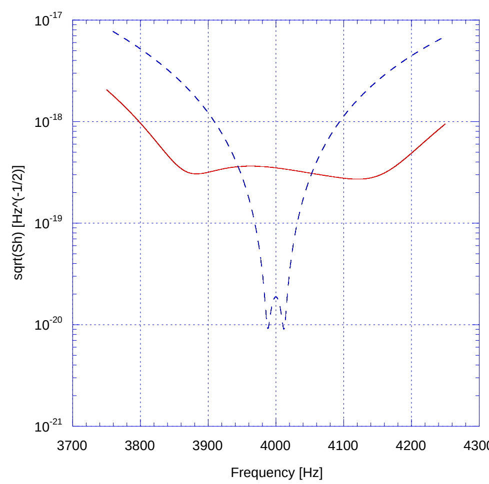

Figure 10: Calculated system sensitivity ($\omega_m \sim \omega_2 - \omega_1 \sim 4$ kHz, $\mathcal{Q} = 10^{10}$, $T = 1.8$ K, $T_{eq} = 1$ K, and a) $Q_m = 10^3$, stored energy $U \sim 10$ J per cavity (solid line); b) $Q_m = 10^6$, stored energy $U \sim 0.1$ J per cavity (dashed line))

Since our detector is based on a double resonant system (the mechanical resonator and the electromagnetic resonator) it can be operated also for frequencies $\omega_2 - \omega_1 \neq \omega_m$. At frequencies $\omega_2 - \omega_1 \leq 1$ kHz the master oscillator phase noise will, in general, completely spoil the system sensitivity, while at frequencies $\omega_2 - \omega_1 \geq 10$ kHz the noise coming from the detection electronics will dominate. The expected sensitivity of the small–scale detector for $\omega_2 - \omega_1 = 10$ kHz is shown in figure 11.

In order to increase the expected sensitivity a large–scale

[2] The equivalent (or noise) temperature of the amplifier is equal to the temperature (in Kelvin) of a 50 ohm termination at the input of an ideal noiseless amplifier with the same gain and generating the same output noise power. It is defined as: $T_{eq} = T\left(10^{N/10} - 1\right)$, where N is the noise figure of the amplifier (in dB) and T is its working temperature.

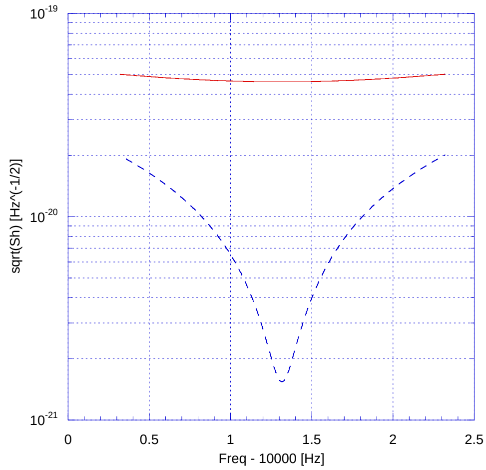

Figure 11: Calculated system sensitivity ($\omega_m \sim 4$ kHz, $\omega_2 - \omega_1 \sim 10$ kHz, $\mathcal{Q} = 10^{10}$, $T = 1.8$ K, $T_{eq} = 1$ K, stored energy $U \sim 10$ J per cavity and a) $Q_m = 10^3$ (solid line); b) $Q_m = 10^6$ (dashed line))

system has to be developed. A possible design could be based on two spherical cavities working at $\omega_1 \sim \omega_2 \sim 500$ MHz, with $\omega_m \sim 1$ kHz. This system could have a maximum stored energy of $U_1 \sim 1200$ J per cell, an effective length of 0.4 m and a typical weight of 2300 kg. With a reasonable choice of system parameters one could obtain the sensitivity shown in figure 12, for the double-resonance case ($\omega_2 - \omega_1 = \omega_m$). As in the previous (small–scale) case the energy store in the initially excite mode has been optimized for maximum bandwidth, and it has to be much less then the maximum allowed. Also in this case lowering T_{eq} corresponds to an increase of the detection bandwidth.

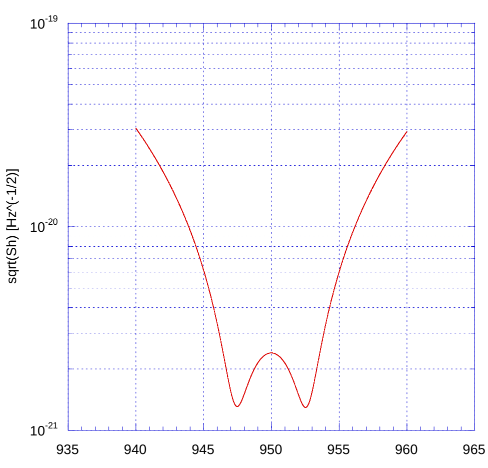

Figure 12: Calculated system sensitivity ($\omega_m \sim \omega_2 - \omega_1 \sim 1$ kHz, $\mathcal{Q} = 10^{10}$, $Q_m = 10^6$, $T = 1.8$ K, $T_{eq} = 1$ K, stored energy $U \sim 1$ J per cavity)

Obviously the large–scale system could also be used at higher frequencies; in this case a good sensitivity can be achieved in a narrow detection bandwidth (see Fig. 13).

It is worth noting that the narrow detection bandwidth is not an unavoidable drawback of the system. Actually its value is determined by the coupling coefficient of the anti-symmetric mode at the Δ port of the output magic–tee, and can be adjusted changing this coupling. This corresponds to changing (lowering) the quality factor of the antisymmetric mode, leaving the quality factor of the symmetric mode unaffected. Of course an increased bandwidth corresponds to a lower sensitivity, since the latter is proportional to the antisymmetric mode quality factor. The possibility to increase the detection bandwidth is also interesting for other possible applications of this detection technique which is based on the parametric frequency conversion between two electromagnetic modes in a cavity (for example, in connection with recently proposed detectors based on the dual resonator concept [34, 35, 36]).

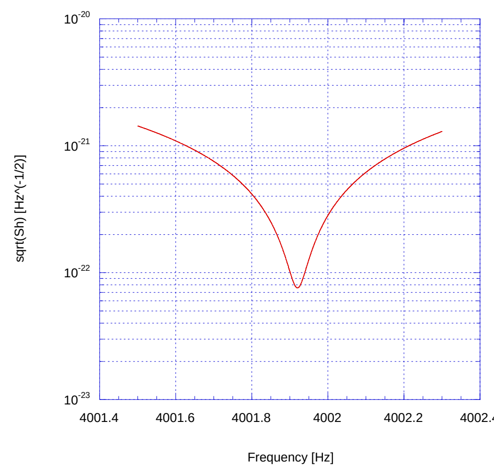

Figure 13: Calculated system sensitivity ($\omega_m \sim 1$ kHz, $\omega_2 - \omega_1 \sim 4$ kHz, $\mathcal{Q} = 10^{10}$, $Q_m = 10^6$, $T = 1.8$ K, $T_{eq} = 1$ K, stored energy $U \sim 1200$ J per cavity)

ACKNOWLEDGMENTS

We wish to thank E. Palmieri, of INFN–LNL, for the construction of the seamless, single–cell, copper cavity.

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