EXPERIMENTAL RESULTS ON SCRF CAVITY PROTOTYPES FOR GRAVITATIONAL WAVE DETECTION

R. Ballantini, A. Chincarini, G. Gemme*, R. Parodi, INFN, Genova, Italy
O. Aberle, Ph. Bernard, S. Calatroni, E. Chiaveri, R. Losito, CERN, Switzerland
E. Picasso, SNS, Pisa, Italy

Abstract

The results of the measurements on the prototypes for a novel gravitational wave detector based on coupled superconducting cavities are presented. The detector, based on the parametric converter scheme, is a tunable narrow band device for the detection of gravitational wave in the frequency ranges over 3-4 kHz. The tests on a double pill box, operating at 3 GHz, allowed to check the operation of the detector, the sensitivity of the system, and behaviour of the related electronics needed to reduce to a minimum the noise coming from the RF energy stored in the detector. Mechanical measurements gave information on the frequency and quality factor of the mechanical modes of the cavity, whose characteristics are relevant to reduce the thermo-mechanical noise (Brownian noise) setting the ultimate limit for the detector sensitivity. Based on the results on the pill-box prototype, a first detector prototype was built and tested. The results of the first measurements are reported and discussed.

INTRODUCTION

Since 1978 superconducting coupled cavities have been proposed as a new possible gravitational wave detector. The knowledge of the mechanic and electromagnetic characteristics of the SRF cavities deputed to this application is extremely important for the evaluation of the detector sensitivity related to the electromagnetic energy stored in the two cells, and the coupling to the gravitational wave. When two identical resonant cavities are coupled, each resonant mode of the single resonator is splitted in two ones with opposite spatial symmetries, and distance in frequency Ω much lower then their resonant one. These modes are labeled as *symmetric* and *antisymmetric* and their angular frequency respectively ω_S and ω_A. According to the parametric conversion principles changes of the e.m. boundary conditions due to small harmonic displacement of the cavity wall, induce energy transfer between the two splitted modes of the two coupled cavity resonator [1]. A flat e.m. field distribution is then required to get the maximum sensitivity of wall displacement revealed by this energy transfer. The correct e.m. field distribution is obtained through a careful mechanic cell tuning. This feature imposes an appropriate polarization of the electromagnetic field axis inside a real detector that can be achieved by a well-defined geometry of the resonator. In fact, the g.w. spatial symmetry implies that the energy released by the g.w. during the interaction with the detector can only be transferred to the mechanical quadrupolar modes of the body. The main goal of the measurements performed is the evaluation of the apparatus sensitivity according to the features of gravitational wave angular momentum, the determination of how to get the best cells tuning, the behaviour of the tuning shifts along the cool down and the changes in cell tuning due to changes in LHe bath. Moreover, the study of the changes in frequency mode distance and the relative amplitude of the e.m. cells field for detuned cells were carefully analysed. The experimental determination of the cavity mechanic modes at 4.2K, compared with the frequencies found through finite elements simulations, allowed to evaluate the mechanic quality factor and to establish the reliability of the simulations themselves.

It must be stressed that a very high sensitivity is reached using superconducting devices, as the sensitivity itself is proportional to the e.m. resonant quality factor of the cavity.

THE PILL-BOX SYSTEM

To check the parametric transfer of energy between two normal modes of a resonator and to develop the detection electronics, a prototype system, made up of two pill box niobium cavities mounted end to end and coupled through a small circular aperture on the axis, was built. The resonant working frequency is 3 GHz and the mode splitting 511 kHz. The energy stored is 1.8 J and the electromagnetic quality factor 2×10^{-9} at 1.8 K.

With this system we obtained a sensitivity to fractional deformations of the cavity wall: $\delta L/L \sim 10^{-20}$ $Hz^{-0.5}$ at 500 KHz [1].

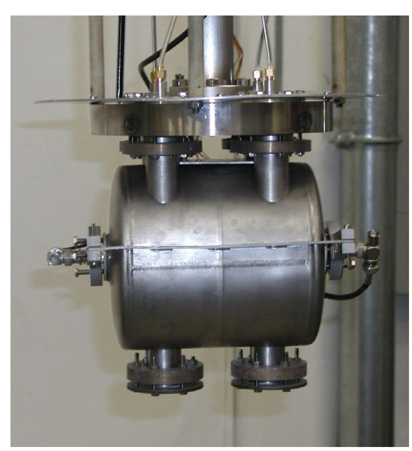


Figure 1: The two cells pill-box cavity.

*gianluca.gemme@ge.infn.it

Two piezoelectric crystals are mounted on the basis to reproduce the effects of an incoming gravitational wave.
An RF circuit feeds the cavity on the first mode (symmetric) and detects at the output only the field components from the second mode (antisymmetric).

The main circuital RF elements are two 180° hybrid rings acting as magic tees.

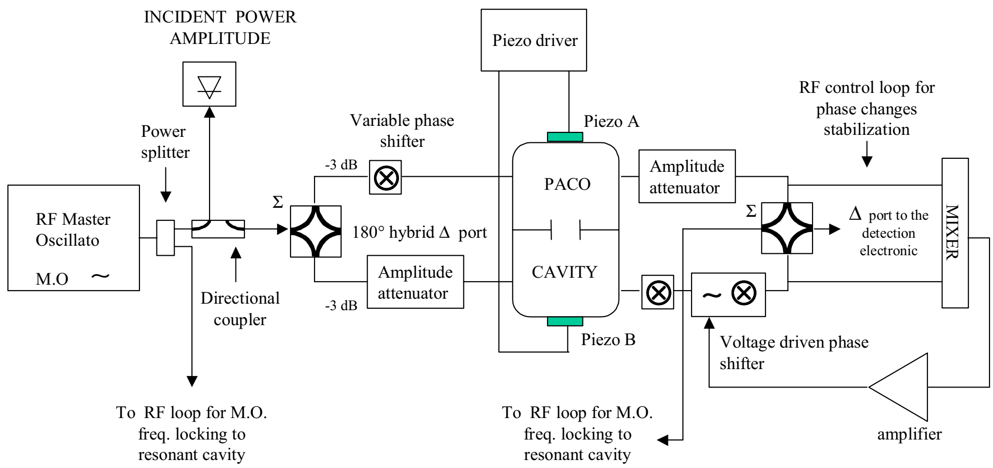


Figure 2: Schematic view of the RF circuit.

PARAMETRIC CONVERSION PRINCIPLES

Generality

When the g.w. interacts with the cavity the RF energy stored in the symmetric RF mode is transferred to the antisymmetric one, due to the wall deformation. The energy transfer is maximum when the g.w. angular frequency Ω equals the frequency spacing of the modes ω_s-ω_a. The g.w. angular momentum imposes the e.m. field polarization. The action of the 2 piezo crystals A and B, driven at Ω frequency is aimed to check excitation of the converted mode. Mechanic perturbation should modify cell frequency in opposite way. One cell should decrease its frequency while the other increases it. According to g.w. quadrupolar feature maximum coupling between the wave and the resonator is for perpendicular axis cell, while for parallel axis the conversion effect is null.
The quadrupolar characteristic of the gravitational wave is simulated, in our simple geometry experimental apparatus, by the combined action of two piezoelectric crystals, placed on the two circular bases of our cavity. The crystals, driven by a synthesized oscillator at the Ω frequency, with a chosen relative phase, provide small harmonic displacements of the cavity's wall. The aim of the measurements reported is to check the maximum excitation of the converted mode according to the theoretical characteristic of the gravitational wave. The perpendicular axis disposition is denominated "L" configuration while the one with parallel axis is named "I" configuration. In the "L" configuration the average value of the whole cavity's resonant frequency doesn't change during the action of the external force on it, and the resulting electromagnetic effect is the parametric conversion of the field. In the "I" configuration the average resonator's frequency changes as the external force acts in phase on the cavity wall operating a frequency modulation that gives rise to side bands. Only a detector with an "L" axis configuration can be coupled to a gravitational wave and reveal it.

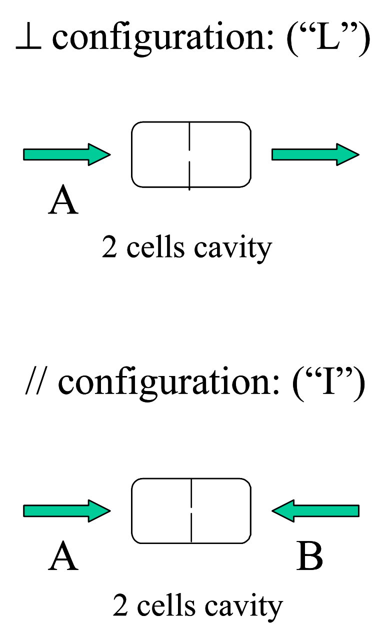


Figure 3: Piezo action on the cavity walls

Parametric Conversion Induced by the Piezo

In our system the first configuration is simulated by driving the piezo with 180º phase difference (A, notB), while the second one driving the piezo in phase (A, B). The converted power is analyzed in relation to the relative phase of the piezo driven at 511.89 KHz by a square wave.

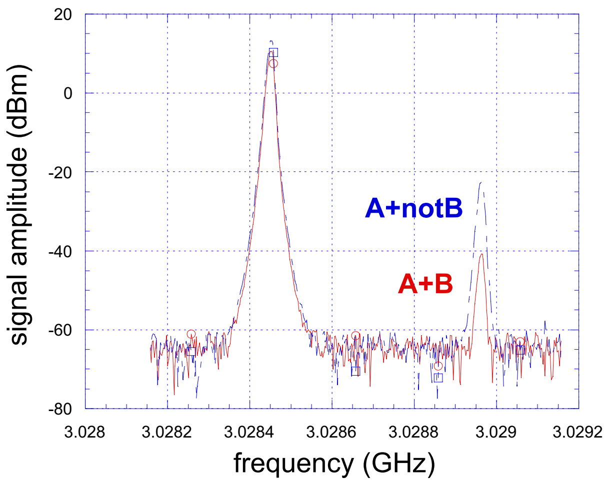


Figure 4: Converted signal due to piezo action

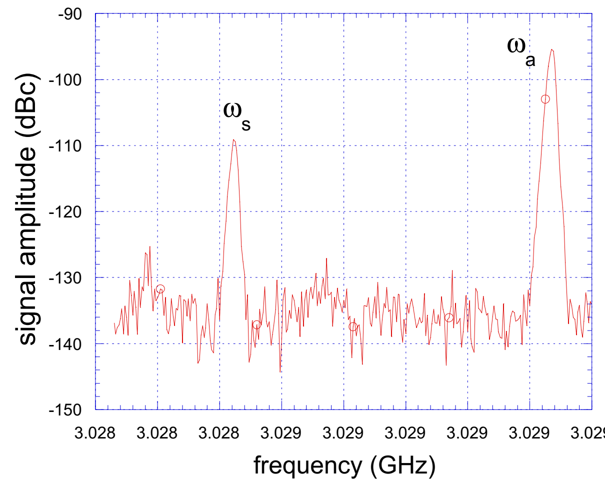
The piezoelectric devices are denoted as: **A** and **B** when driven at the same phase of input signal, while **notA** and **notB** when driven at 180° phase difference respect to the input signal. Configurations with piezo in phase (A, B); (notA, notB) simulate "I" shaped detector, while with piezo acting in phase opposition i.e. (A, notB) simulate "L" shaped detector. As shown in Table 1, the maximum converted signal is for "L" configuration.

Table 1: Converted Signal Measurements

Piezo	Symmetric signal dBm	Antisymm. Signal dBm
A (single piezo)	9.19	-25.19
B (single piezo)	11.63	-28.08
A,B (two piezos in phase)	10.24	-40.62
A,notB (two piezo, opposite phases)	13.03	-22.50

CONTROL LOOP FOR MAXIMUM REJECTION SYMMETRIC MODE

The rejection of symmetric mode component (frequency dependent) at the detection frequency increases the detector sensitivity. Temperature gradient and changes of idrostatic pressure inside cryostat change the operating frequency of the system, impairing the mode rejection on a time scale of few minutes An automatic control loop was added, compensating for the frequency induced phase shift in the detection path.



T

Figure 5: Rejection of the Symmetric mode operated by the control loop

The feedback helps to get a rejection value of 120 dBc on a time period of about one hour.

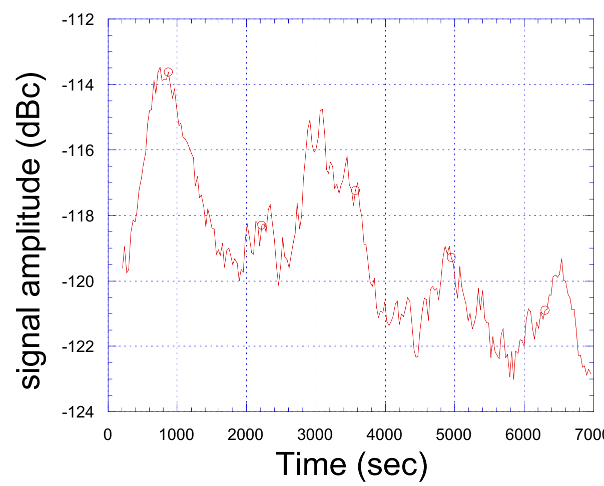


Figure 6: Symmetric peak height variation

MECHANIC MEASUREMENTS

Tuning

As the resonator's cells must be tuned to a flat e.m. field distribution inside to have the maximum detection sensitivity, mechanic unbalance modifies the cell coupling, changes the frequency splitting of the modes and lowers the parametric conversion efficiency.

We tested the cavity behaviour in different experimental situation, determined by temperature and pressure, and compared the results to the solutions of a lumped circuit cavity model. The mechanical modes were also studied and the mechanical quality factor measured at 4.2K.

Our main goals were:

- Find the best way to perform cells tuning
- Evaluate the frequency modes distance for detuned cells, the tuning shifts along the cool-down and the changes in cell tuning due to changes in LHe bath pressure

- Determinate the cavity mechanical modes (frequency and mechanical quality factor)

We found that the maximum unbalance in peak amplitude is measured on the ports belonging to the same cell. Then after a careful tuning we measure equal peak amplitude ($\Delta A \sim 0.02$db) from any couple of ports. The frequency distance of the two peaks is minimum according to the prediction of the lumped parameter circuit model.

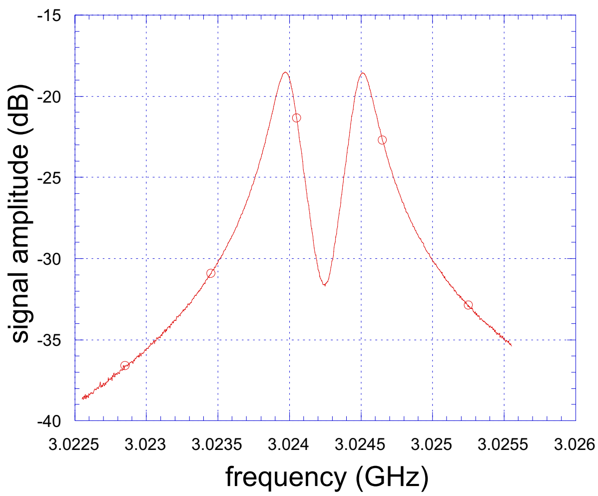


Figure 7: Transmitted signal from ports belonging to the same cell after syntonization at room temperature

Cool Down Effect on the Cell Balance

During cooling, the tuning was checked, measuring, at different cavity temperatures, the difference between peaks heights, both before and after the superconductive transition (see Table 2).

Table 2: Tuning during cool down at atmospheric pressure

Atmospheric pressure		
Temp. (K)	Peak amplitude (dB)	Amplitude difference (dB)
300	-27.01 -27.84	0.83
117	-20.95 -21.90	0.95
83	-19.56 -18.21	1.35
50	-7.35 -6.24	1.11
37	-4.67 -3.46	1.21
20	-4.98 -3.32	1.66
9	-2.28 -0.83	1.45
8	-10.58 -9.13	1.45
7	29.96 30.31	0.35
6	26.85 28.23	1.38

We analysed the signal transmitted through ports belonging to the same cell. Moreover, for some temperature values, the pressure was led to 10 mbar pumping on the helium bath, and the amplitude peaks difference measured in this experimental situation (see Table 3).

Table 3: Tuning during cool down at 10 mbar pressure

Pressure: 10 mbar		
Temp. (K)	Peaks amplitude (dB)	Amplitude difference (dB)
300	-28.39 -25.90	2.49
117	-19.56 -23.40	3.84
83	-20.93 -17.05	3.88
50	-8.82 -4.84	3.98
5	-4.77 -3.32	1.45

Cells unbalance was also measured for different temperatures and pressures: for different temperatures and 1 bar pressure the cells remain tuned while changing pressure at the same temperature the tuning is lost (see Table 4).

Table 4: Tuning in various experimental conditions

Helium NBP (4.2K 1bar)			
ports 0_3	Freq. (GHz)	Amplitude (dB)	Amplitude difference (dB)
Peak1	3.028443	-19.31	0.52
Peak2	3.028953	-19.83	
Saturated Superfluid Helium (2.1 K 50mbar)			
Peak1	3.027713	-15.17	2.92
Peak2	3.028233	-18.09	
Subcooled Helium (2.2K 1 bar)			
Peak1	3.028429	-17.31	0.28
Peak2	3.028940	-17.59	

Mechanic Quality Factor

We measured the mechanic response of the cavity at 4.2 K sweeping the drive signal on the piezo crystal from 350Hz to 1kHz. The peaks found correspond, as shown in figure 8, to the mechanic resonances of the system.
The peak at 650 Hz corresponds to the first mechanical mode of the cavity according to finite elements code analysis (ANSYS®). The peaks at lower frequencies are due to whole apparatus oscillations. The peak curve fit gives a mechanic Q in the range of 1000-5000.

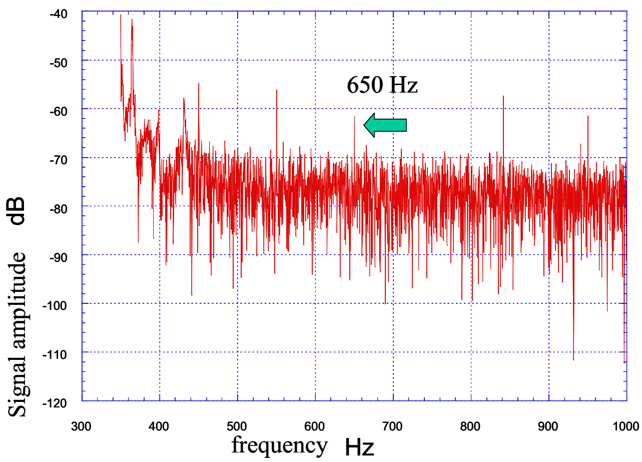


Figure 8: Mechanic resonant modes from 350 Hz to 1 kHz

To evaluate the value of the mechanic quality factor of the proper cavity mode peaks, we fit the peaks curves with a lorentian function with three free parameters: the amplitude A, the frequency F and the mechanic quality factor Q_m. The analytic expression of the fitting curve is

$$y(dB) = 20\log\frac{A^2}{\left(1-\left(\frac{F}{x}\right)^2\right)^2+\left(\frac{F}{Q_m x}\right)^2} \qquad (1)$$

where y is expressed in decibels and the abscissa x is the frequency in Hz. The results obtained from the fits give a mechanic Q in the range of 1000-5000.
In the case of the first mode at 650 Hz, the Q value is about 3000.

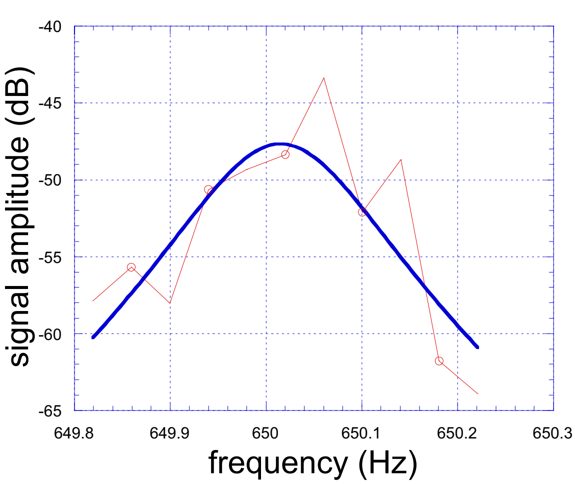


Figure 9: Lorentian fit of the 650 Hz peak. Mechanic quality factor ~ 3000

CONCLUSIONS

The analysis performed with the action of two piezoelectric crystals confirms, as theoretically predicted, that the maximum sensitivity of the parametric conversion is reached when the mechanic perturbation on the detector operates in phase opposition on the cavity's cells. The control loop helps in getting a better rejection of the unwanted mode and makes the signal stable for time periods of the order of hours.
Cells tuning is necessary to obtain a flat field distribution inside the detector and maximum sensitivity. Little geometry deformation leads to e.m. field amplitude unbalance in the cells of many dB. Cells tuning must be checked through measurements between ports belonging to the same cell. After a careful mechanic tuning we measure the transmitted signal peaks difference for various experimental situations changing temperatures and pressures. For different temperatures and 1 bar pressure the cells remain tuned. Changing pressure at the same temperature the tuning is lost. A good tuning is conserved from room temperature (300 K) to superfluid helium (1.8 K) if the pressure on the cavity is kept at 1 bar (amplitude differences ≤ 0.5 dB). Pumping on LHe the system unbalance reach 3-4 dB, the system being sensitive to pressure variations. The lumped circuit model simulations agree with experimental results and are a good tool to relate the cells field distribution to the frequency distance of the splitted peaks. The mechanic quality factors Q_m of the proper detector mechanic modes, at 4.2 K, are in the range 1000-5000, and Q_m~3000 for the fundamental one at 650 Hz.

REFERENCES

[1] Ph. Bernard, G. Gemme. R. Parodi and E. Picasso, Rev. Sci. Instrum. 72 (5), (2001), 2428.