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RAP: thermoacoustic detection at the DAΦNE beam test facility

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Abstract
In order to investigate the anomalous response at ultra-low temperatures of the resonant-mass gravitational wave detector NAUTILUS, the RAP experiment has been planned to measure the vibrations in a small cylindrical aluminium bar when hit by 10^5 510 MeV electrons from the DAΦNE beam test facility, corresponding to the energies released by typical extensive air showers. The results of the measurement at low temperature and in the superconducting regime are crucial to understand the interaction of ionizing particles with bulk superconductors and to confirm the results on the thermoacoustic model of the past experiments. The first run of RAP experiment is scheduled for the end of June. The scheme of operation and the preliminary results at room temperature will be presented.

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1. Experimental motivations

The thermo-acoustic model, first applied to resonant bars in 1983 [1], describes the mechanical vibration induced by the interaction of ionizing particles. This model has been extensively tested (at room temperature) [2, 3], and has been used [4, 5] to evaluate the background due to cosmic rays impinging on gravitational wave antennas. In 1999, NAUTILUS was the first experiment that observed the effect of cosmic rays in a GW detector [6]. Analysis of the NAUTILUS data has shown that, while the results at thermodynamic temperature $T = 1.5$ K [7] are in good agreement with the thermo-acoustic model expectation, in a run at

$T = 0.14$ K [8]—below the transition temperature of the NAUTILUS aluminium bar—large signals were detected at a much higher rate than expected.

In the thermo-acoustic model mechanical vibrations originate from the local thermal expansion caused by warming up due to the energy lost by a particle crossing the material and the relation that accounts for the detectable vibrational energy E in the nth longitudinal mode due to the specific energy loss $\mathrm{d}W/\mathrm{d}x$ of a particle impinging on a cylindrical bar is [4, 9]

$$E \propto \gamma^2 \left(\frac{\mathrm{d}W}{\mathrm{d}x}\right)^2 G_n^2$$

where G_n is a function of the impinging track geometrical parameters, and γ is the Grüneisen adimensional parameter, depending on the elastic and thermodynamic properties of the material.

The NAUTILUS results suggest that a more efficient mechanism for particle energy loss conversion into mechanical energy takes place when the bar is in the superconducting state. In order to clarify these results the RAP[6] experiment [10] aims to measure the effect of the passage in a mechanical oscillator of an electron beam, provided by the beam test facility (BTF) of DAΦNE, the INFN-Laboratori Nazionali di Frascati (LNF) e^+–e^- collider.

The RAP experiment is intended to operate an oscillating test mass either in the normal or in superconducting regime. The measurements will be crucial to understand the interaction of ionizing particles with bulk superconductors and to confirm the results on the thermo-acoustic model obtained by the previous experiments.

2. Experimental setup

The beam and the detector are the main components of the setup.

The DAΦNE BTF can deliver electrons or positrons in pulses made by 1–10^{10} particles of energy varying from 25 to 750 MeV with 1% resolution. The maximum repetition rate is 50 Hz and the pulse duration ranges from 1 to 25 ns.

The oscillating test mass, the suspension system, the cryogenic and vacuum system, the mechanical structure needed to host the cryostat, the readout and the data acquisition system are the components of the detector.

The oscillating test mass is constituted by a cylindrical bar ($2R = 181.7$ mm, $L = 500$ mm) made of AL5056, the same aluminium alloy (5.2% Mg, 0.1% Mn, 0.1% Cr) used in NAUTILUS. The resonance frequency of the first longitudinal mode is about 5.096 kHz at $T = 300$ K.

The suspension system is a cascade of seven attenuation stages (mechanical filters), each consisting of a flexible joint connecting and supporting an inertial mass. The aim of the cascade is to provide the requested level of attenuation inside the working frequency window (−150 dB attenuation). The system also provides a thermal link between the bar and the dilution refrigerator.

The cryogenic and vacuum system is basically composed of a commercial cryostat (height = 3200 mm, diameter = 1016 mm) and a ^{3}He–^{4}He dilution refrigerator (base temperature = 100 mK, cooling power at 120 mK = 1 mW). The assembly minimizes the acoustic interference, since there is no direct contact between cryogenics and detector, except for the weak thermal connections between the refrigerator and the suspension system. A picture of the setup with the open cryostat is shown in figure 1.

The system allows a fast pre-cooling down to liquid-helium temperatures. When a temperature of 6 K has been reached, the pre-cooling phase ends, the inner space of the

[6] Rivelazione Acustica di Particelle.

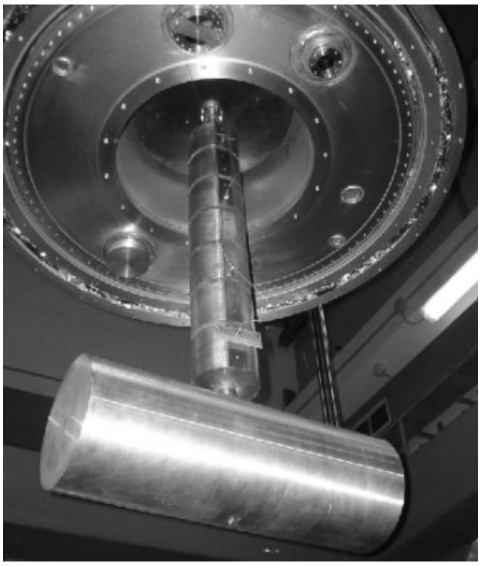

Figure 1. Picture of the bar, suspended from the seven-stage suspension system, in the open cryostat. The piezoelectric ceramic is also visible on the bottom of the bar together with the cryogenic wire for the readout.

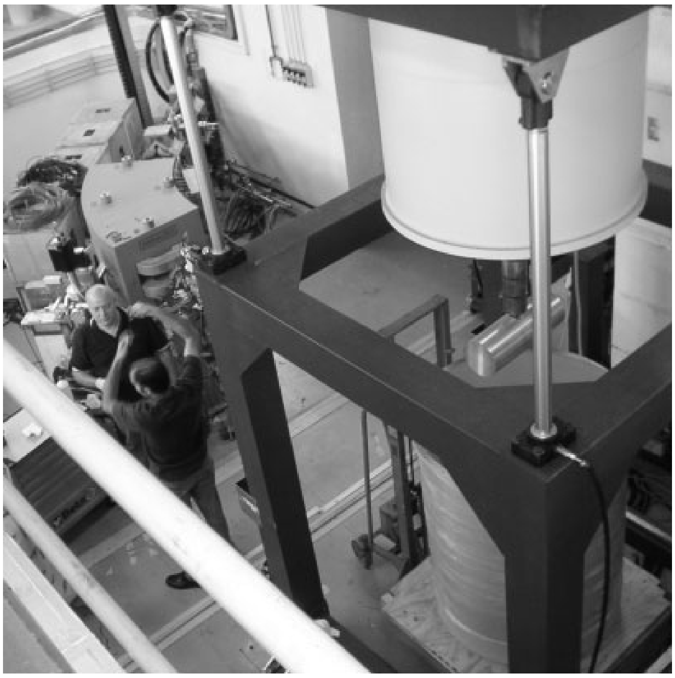

Figure 2. Picture of the mechanical structure holding the RAP apparatus, with the bar suspended inside the open cryostat, installed in the BTF experimental area.

cryostat is evacuated, and the He bath is filled with liquid He. From that point on the dilution refrigerator takes over and the final cooling stage is entered.

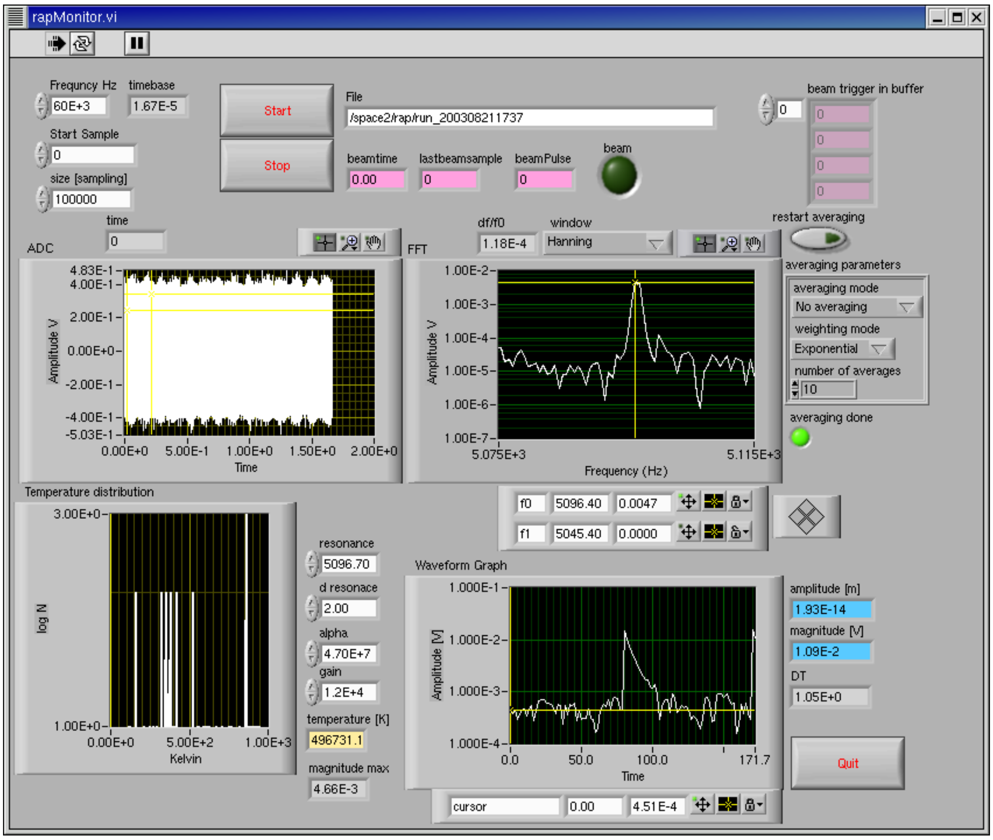

Figure 3. Online display of the bar signal amplitude (top left), fast Fourier transform of the signal at the resonant frequency (top right) and time chart of the amplitude at the resonant frequency (bottom right), showing the beam-related peak.

(This figure is in colour only in the electronic version)

The mechanical structure encloses the cryostat allowing easy positioning of the detector on the beam line and consequent removal after the expiration of the dedicated periods of data taking. A picture of the RAP apparatus installed in the BTF area is shown in figure 2.

The readout is based on a commercial piezoelectric ceramic (PZT) followed by a low-noise custom JFET pre-amplifier and a Stanford SR560 amplifier. A noise of 1 nV $\mathrm{Hz}^{-1/2}$ for the first amplifying stage at 5 kHz in the 25 kHz band has been measured, while the SR560 second stage showed a noise of $\approx$4 nV $\mathrm{Hz}^{-1/2}$ at high gain ($G = 50\,000$).

With these characteristics of the readout chain, an effective temperature of the order $T_{\mathrm{eff}} = 0.3$–0.4 K can be achieved, where kT_{eff} is the minimum signal detectable with signal to noise ratio equal to 1. The methods used for calibrating the detector are based on the use of the PZT self-calibration technique and on the use of an accelerometer.

The data acquisition system, based on a 200 ksample/s peak sensing 16 bit VME ADC (VMIC 3123) and a VME Pentium III CPU (VMIC 7740) running Linux, has been developed in the LabVIEW environment (with low-level C calls); it collects data coming from the PZT, the accelerometer, the environmental sensors and from the beam signals, originated by the upstream beam monitor detector and by the downstream electromagnetic calorimeter, measuring the residual energy of the beam products after the interaction with the detector. The overall data throughput on disk is 0.3 MB s^{-1}. An online monitor of the measured amplitude, also performing real-time fast Fourier transform analysis, has also been developed.

3. Experimental commissioning

The experiment has been installed in the experimental area for the first data taking at room temperature on the BTF electron beam. A first test-run has been performed at low intensity and at room temperature, in order to reproduce the previous experimental results, to test the whole acquisition/analysis chain, and to evaluate the background level. An example of the online monitoring of the signal is shown in figure 3, while the analysis of these first data is now under way.

The milestones of the RAP experiment are the following:

- *Phase 1*: installation and test of the full apparatus, with mechanical structure, bar, suspension, readout electronics and working DAQ. First measurement at room temperature.
- *Phase 2*: cryogenic test of full experiment. Measurement in non-superconducting state (4 K).
- *Phase 3*: installation of dilution refrigerator. Final measurement in superconducting state (100 mK).

Phase 1 was completed in September 2003. The very preliminary result accounts for an agreement of about 30% between the amplitude of the signal expected from the thermoacoustic model and the observed one with a SNR $\approx$ 35. More accurate calibration procedures are under way in order to possibly reduce the uncertainties.

The measurement at 4 K is foreseen at the beginning of 2004, and the final 100 mK measurement in the first half of 2004.

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