RAP: thermoacoustic detection at the DAΦNE beam test facility

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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...
$T = 0.14 \text{ K} \quad [8]$—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 $n$th longitudinal mode due to the specific energy loss $dW/dx$ of a particle impinging on a cylindrical bar is $[4, 9]$

$$E \propto \gamma^2 \left( \frac{dW}{dx} \right)^2 G_n^2$$

where $G_n$ is a function of the impinging track geometrical parameters, and $\gamma$ is the Gruneisen 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 DAPhiNE, 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 DAPhiNE BTF can deliver electrons or positrons in pulses made by $1\text{–}10^{10}$ 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 ($2R = 181.7 \text{ mm}, L = 500 \text{ mm}$) made of AL5056, the same aluminium alloy ($5.2\% \text{ Mg}, 0.1\% \text{ Mn}, 0.1\% \text{ Cr}$) used in NAUTILUS. The resonance frequency of the first longitudinal mode is about 5.096 kHz at $T = 300 \text{ K}$.

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 ($\approx 150 \text{ dB attenuation}$). 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 $= 3200 \text{ mm}$, diameter $= 1016 \text{ mm}$) and a $^3\text{He}\!-\!^4\text{He}$ dilution refrigerator (base temperature $= 100 \text{ mK}$, cooling power at 120 mK $= 1 \text{ mW}$). 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.
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 $1 \text{nV Hz}^{-1/2}$ 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 $\approx 4 \text{nV Hz}^{-1/2}$ at high gain ($G = 50000$).

With these characteristics of the readout chain, an effective temperature of the order $T_{\text{eff}} = 0.3-0.4 \text{ K}$ can be achieved, where $kT_{\text{eff}}$ 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 \(\text{K}\)).
- **Phase 3**: installation of dilution refrigerator. Final measurement in superconducting state (100 \(\text{mK}\)).

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 \(\text{K}\) is foreseen at the beginning of 2004, and the final 100 \(\text{mK}\) measurement in the first half of 2004.

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References