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Acoustic detection of particles in ultracryogenic resonant antenna (RAP)

P. Valente[a,*], S. Bertolucci[a], E. Coccia[b], S. D'Antonio[b], A. De Waard[c], G. Delle Monache[a], D. Di Gioacchino[a], V. Fafone[a], G. Frossati[c], C. Ligi[a], A. Marini[a], G. Mazzitelli[a], G. Modestino[a], G. Pizzella[a,b], L. Quintieri[a], G. Raffone[a], F. Ronga[a], P. Tripodi[a,d]

[a] *Laboratori Nazionali di Frascati dell'INFN, Frascati, RM 00044, Italy*
[b] *Dipartimento di Fisica dell' Universita' di Roma "Tor Vergata" and INFN, Rome 00133, Italy*
[c] *Kamerling Onnes Laboratorium, Leiden University, 2300 RA Leiden, The Netherlands*
[d] *Centro di Ricerca di Frascati dell' ENEA, Frascati, RM 00044, Italy*

Abstract

RAP is an experiment aimed to measure the effects caused by high-energy electrons impinging on bulk superconductors. The motivation is the anomalous high-energy cosmic ray rate detected by the gravitational wave antenna NAUTILUS when operated in superconducting regime.

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1. Experiment motivations

Studies [1–3] of the signals due to the interactions of cosmic rays impinging on the gravitational wave antenna NAUTILUS, have shown that in a run of the detector at thermodynamic temperature $T = 1.5$ K the results are in agreement with the thermo-acoustic model, while in a run at $T = 0.14$ K large signals are detected at a rate higher 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 a specific energy loss $\mathrm{d}W/\mathrm{d}x$ of a particle impinging on a cylindrical bar is (see for instance Ref. [4])

$$E = \frac{4k}{9\pi}\frac{\gamma^2}{\rho L v^2}\left(\frac{\mathrm{d}W}{\mathrm{d}x}\right)^2 F_n(z_0, \theta_0, l_0)$$

where k is the Boltzmann constant, ρ is the density of the bar material, L is the length of the bar, v is the speed of the sound, γ is the Grüneisen adimensional parameter of the material and F_n is

*Corresponding author. Sezione di Frascati, Via Enrico Fermi 40, Casella Postale 13, Frascati, Rome 00044, Italy. Tel.: +39-06-9403-2761; fax: +39-06-9403-2427.
E-mail address: paolo.valente@inf.infn.it (P. Valente).

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a function of the impinging track geometrical parameters.

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 experiment [5] 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 thermo-acoustic model has been recently verified by an experiment, operated only at room temperature [6], using a small suspended aluminum cylinder exposed to an electron beam.

RAP 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. Experiment 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 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 $(2R = 181.7\ \mathrm{mm}, L = 500\ \mathrm{mm})$ made of AL5056, the same aluminum alloy (5.2% Mg, 0.1% Mn, 0.1% Cr) used in NAUTILUS. The resonance frequency of the first longitudinal mode is about 4.6 kHz.

The suspension system is a cascade of 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. An attenuation of about -150 dB at the bar resonant frequency is needed. The system also provides thermal link between the bar and the dilution refrigerator.

The cryogenic and vacuum system is basically composed by 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. 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 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.

The mechanical structure encloses the cryostat allowing an easy positioning of the detector on the beam line and the consequent removal after the expiration of the dedicated periods of data taking.

The readout is based on piezoelectric ceramic (PZT) followed by a FET amplifier. Commercial PZT is used for giving a value of 0.3–0.4 for the ratio of the electrical energy in the transducer to the total energy in the resonator and a global mechanical quality factor of 10^3. At the thermodynamic temperature of 0.1 K with a FET amplifier, having a voltage noise $V_n \sim 1\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$ and a current noise $I_n \sim 10^{-15}\ \mathrm{A}/\sqrt{\mathrm{Hz}}$, a bandwidth of about 0.2 Hz and values of the order of 0.3–0.4 K for T_{eff} can be achieved, being kT_{eff} the minimum signal detectable with signal-to-noise ratio equal to 1. Methods 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 and a VME Pentium III CPU running Linux, 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 experiment is now under commissioning to be ready for the first run at room temperature on the BTF.

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