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A Vibration Decoupling System for TES Operation in the COSINUS Dry Dilution Refrigerator

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Abstract
COSINUS will be among the first underground experiments to operate Transition Edge Sensors in a dry dilution refrigerator, measuring temperature changes on the order of μK. A pulse tube cryocooler is used to cool down to 3K, trading simplified handling, by not using liquid noble gases, for an increased vibration noise level in the acoustic frequency range. As the signals measured with a TES are in the same frequency region, it is necessary to decouple the detectors from all possible noise sources. In COSINUS, a two-level passive decoupling system was developed and tested using piezo-based accelerometers. At the first level, the refrigerator is mechanically isolated from all external noise sources. For the second level an internal spring-based system was developed and tested on a mockup system. On the first level a reduction of the vibrational background up to a factor 4 below 10 Hz could be measured. On the second level a resonance frequency of 1.2 Hz with damping of higher frequencies was achieved.

Keywords Vibration isolation · Mechanical oscillator · TES · Dark matter · Dry dilution refrigerator

1 Introduction

Cryogenic detectors are a valuable class of detectors for rare event searches. Currently energy resolutions and thresholds on the order of eV are reached using Transition Edge Sensors (TES). Besides detector effects [1], one of the dominating backgrounds limiting the sensitivity and operation stability of cryogenic

Extended author information available on the last page of the article

detectors are microphonics which originate from vibrations produced by the cryogenic refrigerator itself [2] or from its surroundings.

The Cryogenic Observatory for Signatures seen in Next-generation Underground Searches (COSINUS) is searching for dark matter by using sodium iodide (NaI) and silicon beakers equipped with TES as phonon and light detectors, respectively [3, 4]. For this purpose a low-background facility is constructed in hall B of the Laboratori Nazionali del Gran Sasso (LNGS), Italy. A custom-made dry dilution refrigerator with an internal radioactivity shield is used to cool the detectors down to <10 mK.

Dry dilution refrigerators use pulse tube coolers instead of a liquid helium bath to reach temperatures around 3 K. They feature simplified handling and higher efficiency by saving liquid helium. However, moving parts of a pulse tube can introduce vibrations that are translated to temperature fluctuations in the detectors [5], or induce current noise in cables [6, 7]. It is essential to mitigate the pulse tube vibrations for a stable operation of low-temperature detectors. In the past years many refrigerators were equipped with dedicated vibration isolation systems. [2, 8–10].

The typical time scale of a COSINUS detector signal is on $\mathcal{O}(1\ \mathrm{s})$ with more than 99.7 % of its signal contribution being below 100 Hz [11]. Any noise in the same frequency range can reduce the detector's resolution. Possible sources include the pulse tube cooler and rotary valve as well as vacuum pumps and compressors external to the refrigerator. In COSINUS several systems for vibration mitigation are in place. The structure of the facility, the dedicated custom design of the refrigerator and an internal spring-based decoupling system were optimized to decouple the detectors from any vibration sources outside or inside the refrigerator.

2 The COSINUS Facility

In 2023, COSINUS finished the construction of a new cryogenic facility at LNGS. It includes a custom-made dry dilution refrigerator with a length of 3.5 m and a base temperature of <10 mK. The refrigerator has a centered dilution unit for axial symmetry and is equipped with the "Ultra-quiet technology" (UQT) patented by CryoConcept [5, 12]. It is surrounded by a water tank with a diameter and height of 7 m and accessible via two nested steel frames. During operation the refrigerator is connected to the inner frame designated for low vibrational noise. It is placed on four pillars filled with sand for further granular damping. The outer frame houses any other equipment necessary to operate the refrigerator and detectors inside, such as the rotary valve of the pulse tube cooler.

In October 2023 a measurement of the vibrational background with empty water tank was taken using an accelerometer of type PCB393b05 by PCB [13] for the inner frame and KS48C by MMF [14] for the outer frame. A drawing of the frames and the measurement positions are shown in Fig. 1.

The average power spectral density (PSD) for vertical and horizontal vibrations is shown in Fig. 2.

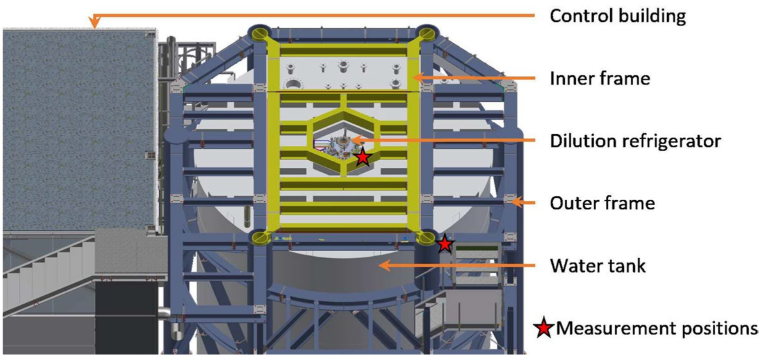


Fig. 1 Steel frames of the COSINUS facility. The low-noise inner frame is shown in yellow and the outer frame is shown in blue. The measurement positions are marked with red stars

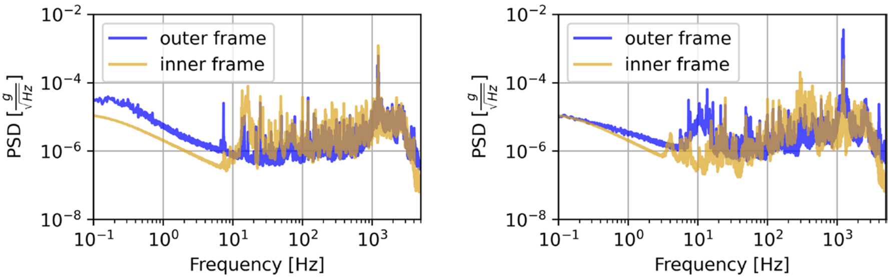


Fig. 2 Averaged PSD for vibrations in vertical direction (left) and horizontal direction (right). "inner frame" refers to the low noise zone

For frequencies smaller than 10 Hz, the vibrational background of the low-noise frame is up to a factor 4 reduced compared to the other frame. This reduction is more prominent for vertical vibrations than for horizontal vibrations.

3 Spring-based Passive Decoupling System

In addition to the efforts for vibration reduction done on the COSINUS structure and on the refrigerator design, a spring-based passive decoupling system inside the refrigerator was developed. It is based on the frequency response of a damped harmonic oscillator with base excitation, which is characterized by the resonance frequency ω_0 and a quality factor Q [15].

$$H(\omega) = \frac{1 + \frac{i}{Q}(\frac{\omega}{\omega_0})}{1 + \frac{i}{Q}(\frac{\omega}{\omega_0}) - (\frac{\omega}{\omega_0})^2} \tag{1}$$

The absolute of the transfer function for different Q is shown in Fig. 3 and characterizes the amplitude gain of the system.

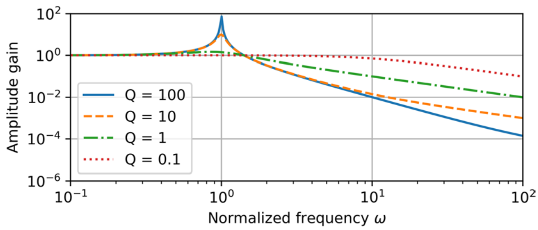


Fig. 3 Transfer function of a harmonic oscillator for different quality factors Q

For an undamped oscillator the oscillation is amplified at the natural frequency. For frequencies higher than that, the response reduces with ω^{-2}. Therefore, for a good decoupling system, the resonance at $\omega_0 = \sqrt{\frac{k}{m}}$ should be chosen as low as possible. This can be attained by choosing a low spring constant k and high inertial mass m for a spring system that decouples vertically, or choosing a long length [16] for a pendulum system that decouples horizontally. In both cases the system is ultimately limited by the available space inside the refrigerator. When introducing a linear damping term, the resonance peak reduces while also reducing the decoupling capabilities for higher frequencies to ω^{-1}. Thus, it is necessary to balance the system between decoupling capabilities and damping to suppress the resonance and stop oscillations after a short time.

The COSINUS decoupling system consists of three strings on which a box with the detectors is hung. A single string acts as a spring for vertical decoupling as well as a pendulum for horizontal decoupling. It is fixed to an internal radioactivity shield, which, due to its high mass of 190 kg, acts as a quieter base than the mixing chamber plate. Each string consists of a spring, a damping module and Kevlar wire, allowing for adjustment of the length, damping ratio and spring constant of the whole string. Furthermore, the Kevlar thermally isolates the detectors from the radiation shield. A soft copper strip between mixing chamber and detector box allows to cool the detectors to mK-temperatures. Figure 4 shows a drawing of the decoupling system as it is foreseen in the COSINUS refrigerator.

The lowest excited frequency expected in a dry dilution refrigerator is the operational frequency of the pulse tube cryocooler at 1.4 Hz. By utilizing UQT the vibrational noise at the mixing chamber is expected to decrease over the whole spectrum and only reaches critical noise levels at 10 Hz and higher [5]. This system is designed for resonance frequencies around 1 Hz to ensure a good decoupling at higher frequencies.

4 Experimental Validation

A mechanical mockup system of the refrigerator was set up at the Max-Planck Institute for Physics in Munich, Germany. It simulates the lower part of the refrigerator from the Still plate downwards, excluding the dilution unit. For the radioactivity shield, steel was used instead of copper; while, the refrigerator plates were made from aluminum. The detector box was simulated with 15 kg of lead, and hung on three decoupling springs. A photo of the mockup system is shown in Fig. 5.

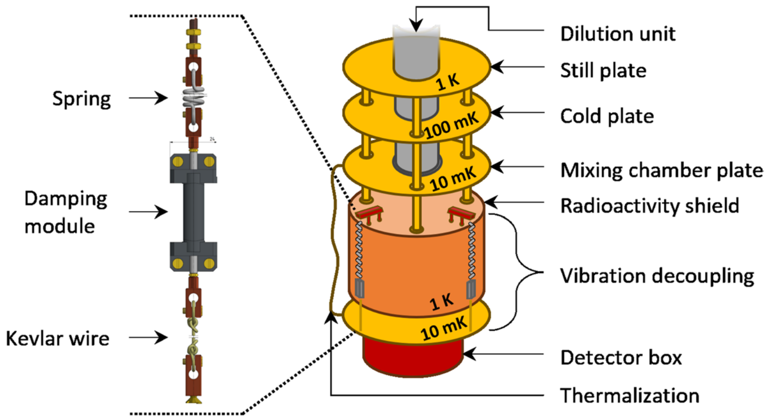
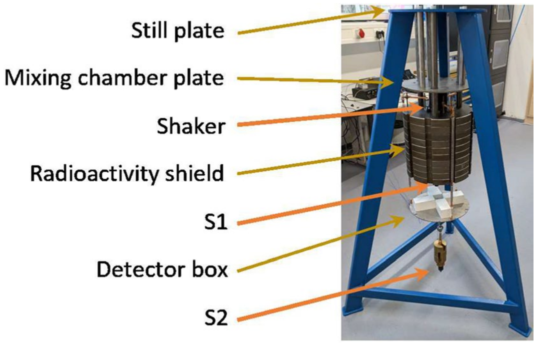


Fig. 4 Scheme of the vibration decoupling system at the mixing chamber level. Cabling will be routed, similar to the thermalization, parallel to the springs

Fig. 5 Photo of the mockup system used for transfer function measurements of the spring-based decoupling



The springs were made from spring steel 1.4310 and have a 25 N pre-tension. At a load of 50 N they reach a length of 213 mm. They are connected to a non-functional damping dummy with a length of 90 mm. Each string is connected to the detector box dummy with a 155 mm long braided Kevlar wire. All interconnections were done with 20 mm long copper pieces, leading to a total length of 550 mm.

Vertical vibrations are measured with a piezo-based accelerometer of type PCB393b05 by PCB [13] on the radioactivity shield (marked as S1) and at the detector stage (marked as S2). A shaker of type 4810 by Bruel and Kjær [17] was mounted on the Still plate. It is driven by an arbitrary signal generator connected to a pre-amplifier with a dynamic range of 10 Hz to 30 kHz. The sensor and the shaker are controlled, timed and read out with a NI-USB 6211 data acquisition system (DAQ) by National Instruments [18].

Figure 6 shows the power spectra measured with the shaker emitting logarithmic swept sine signals from 0.1 Hz to 5 kHz over 100 s to excite the system, as well as the background spectra measured with no signal emission.

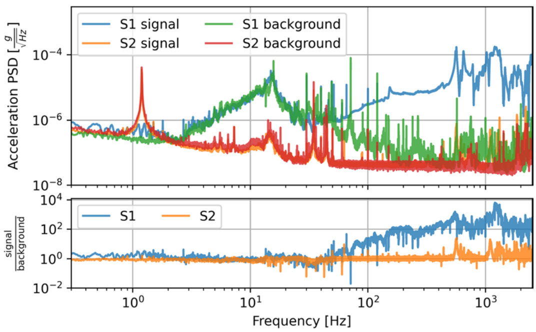


Fig. 6 Vibration PSD measured during shaker operation (blue and orange) and background PSD measured with the shaker switched off (green and red). S1 is mounted on the radioactivity shield and S2 on the detector box dummy. The bottom plot shows the ratio of signal power and background at each position

The dominating spring resonance frequency was measured to be 1.2 Hz. The shaker excitations are visible for frequencies >50 Hz and clear damping effect between the accelerometer mounted on the radioactivity shield (S1) and on the Still (S2) can be seen for these frequencies.

5 Outlook

The vibration decoupling concept of COSINUS works in two levels. On the first level, a low vibration zone for the experimental apparatus was constructed on an isolated frame with minimized vibration transfer from outside noise sources; while, the CryoConcept UQT reduces noise from the refrigerator setup. Between both frames, a reduced vibration background PSD up to a factor 4 for frequencies smaller than 10 Hz can be measured. Furthermore, an internal spring-based passive decoupling system was designed, manufactured and tested at room temperature on a refrigerator mockup. A resonance frequency of 1.2 Hz was reached and a damping effect is shown.

At this time the COSINUS setup and refrigerator is about to be completed and, in the next step, the decoupling system will be tested at low temperatures and a dedicated modal analysis will be carried out. In particular the damping capabilities of cabling and thermalization will be explored. In parallel the damping module for a controlled damping of the decoupling system is in development.

Author Contributions M.K. wrote the main text and prepared all figures. All authors reviewed the manuscript.

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Declarations

Conflict of interest The authors declare no Conflict of interest.

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