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The CUORE Pulse Tubes noise cancellation technique

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Abstract The 1-ton scale CUORE detector is made of 988 TeO_2 crystals operated as cryogenic bolometers at a working temperature of $\sim$10 mK. In order to provide the necessary cooling power at 4 K stage, a total of five Pulse Tubes refrigerators (PTs) are used. The PTs make the cryogenic system reliable and stable, but have the downside that mechanical vibrations at low frequencies (1.4 Hz and related harmonics) are injected into the experimental apparatus. An active noise cancellation technique has been developed in order to reduce such effect by taking advantage from the coherent interference of the pressure oscillations originated by the different PTs. The technique that will be presented consists in controlling the relative phases of the pressure waves running inside the CUORE PTs lines, in order to achieve the lowest detector noise. By reducing the power of PTs harmonics by a factor up to 10^4, it drastically suppresses the overall noise RMS on the CUORE detector. In the following, we demonstrate the reliability and effectiveness of the technique, showing that the optimization of the detector noise level is possible in different experimental conditions.

Keywords Pulse tube refrigerators, cryostat, noise reduction

1 The CUORE experiment

CUORE (Cryogenic Underground Observatory for Rare Events) is a 1-ton scale experiment searching for neutrinoless double beta decay in ^{130}Te at the Gran Sasso National Laboratories, in Italy. The CUORE detector consists of an array of 988 TeO_2 bolometric crystals

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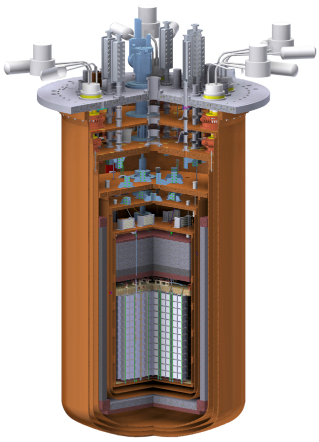

Fig. 1: A scheme of the CUORE cryostat. (Color figure online.)

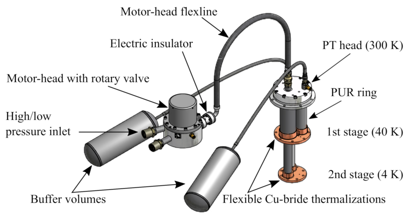

Fig. 2: Scheme of a CUORE Pulse Tube cryocooler. (Color figure online.)

arranged in 19 towers, for a total mass of 742 kg and in particular 206 kg of the ^{130}Te isotope [1]. The bolometers are solid state detectors that require cryogenic temperatures to detect the thermal variation induced by a particle depositing energy: for this reason, the CUORE bolometers are operated at a base temperature of $\sim$10 mK [2]. The CUORE data taking started in January 2017 and is currrently ongoing.

2 The CUORE cryogenic system

The CUORE base temperature is reached and maintained thanks to a cryogen-free diluition cryostat custom designed for housing the CUORE detectors (Fig. 1). A total of six copper vessels are thermalized to decreasing temperatures, namely 300 K, 40 K, 4 K, 600 mK, 50 mK and 10 mK [3]. The detector is hosted at the 10 mK stage and is protected from the cryostat radioactivity by a lateral shield of ^{210}Pb-depleted Roman lead [4] at 4 K. An additional 30 cm-thick lead shielding thermalized at 50 mK protects the detector from the top. The CUORE cryostat is designed to cool-down $\sim$1.5 ton (detectors + copper plate + vessel) at $\sim$10 mK in an extremely low radioactivity and low vibrations environment. This goal is accomplished by mean of different cooling techniques: four Pulse Tubes (PT) cryocoolers cool the cryostat down to 4 K, and the 10 mK base temperature is then reached thanks to a continuous-cycle ^{3}He-^{4}He Diluition Refrigerator. The fifth PT is kept as spare. The cryogen-free nature of the CUORE cryostat has the advantage of no need of periodical interruptions due to cryogenic liquids refills, at the cost of the introduction of mechanical vibrations into the experimental apparatus; in the following paragraphs, a technique developed to minimize the noise induced by the PTs vibrations will be described. It was applied for the first time to the CUORE system in 2017 [5], and then further tested at different detector and pulse tubes conditions: the results described in this manuscript refer to such new tests, and show that the technique is effective and reproducible in different situations.

2.1 The CUORE Pulse Tubes

In CUORE, 4 custom adapted Pulse Tubes PT415-RM by Cryomech are operated, with a cooling power of 1.2 W @ 4.2 K and 32 W @ 45 K each (Fig. 2). The Pulse Tubes cryocoolers are devices whose cooling power is provided by periodic expansions of gaseous ^{4}He. The working frequency of these pressure oscillations is provided by a motor-head, which alternatively connects the PT heads to the high and low pressure side of a compressor, thanks to a rotating valve operated at 0.7 rev/sec. Each 360° rotation of the valve completes two PT cycles, and this results in gas pulsations at 1.4 Hz and related harmonics. This mechanical vibration noise is injected into the cryostat and transmitted to the detector [5].

3 The noise cancellation techniques

Each of the four PT operating frequency is very close to 1.4 Hz, but they are 1 part per 1000 different from each other: this results in the fact that their combined action is responsible for the generation of beat frequencies into the experimental apparatus, in addition to the 1.4 Hz and harmonics. The minimization of the vibrations imparted to the CUORE cryostat is obtained by applying different methods. A passive suppression is done by using mechanical decouplers [5] that absorb and dissipate the vibration transmitted from the PT heads to the cryostat, such as special soft o-rings, a polyurethane ring (PUR) and a sandbox for the inlet high/low pressure lines exiting the compressors. A significant mitigation of the PTs noise is also obtained by replacing the Cryomech stepper motor devices driving the rotary valves with dedicated linear motors, which will be referred to as Linear Drives (LD): these are low-noise devices characterized by a micro-stepping precision control of the rotary valve position. With a precision of 1 step = $360^\circ/25600 = 0.014^\circ$, the LDs allow to obtain an accurate control of the valve rotation frequency, and therefore of the phases of the PT pressure waves. It has been previously measured [5] that the use of LDs provides a significant reduction of the intrinsic noise; moreover, it is possible to suppress the beating frequencies and further reduce the overall RMS thanks to the technique presented in the next paragraphs (Fig. 3). It has been deeply tested and is currently in use. Such technique consists in driving and stabilizing the PT relative phases at the minimum noise configuration.

3.1 The Pulse Tube Scan

Driving the PTs phases with the LDs allows to search for the configuration of the relative phases that maximizes the noise suppression, by taking advantage from the coherent interference of the PTs pressure oscillations. Since the CUORE system is complex and the PTs are asymmetrically positioned, it has to be found by scanning the configuration parameters space, testing a large number of possible configurations [5]. As mentioned above, CUORE operates with 4 Pulse Tubes: the phase shifts of three PTs are computed with respect to a fourth one, taken as reference. When the technique was tested for the first time, at 15 mK [5], the reference pulse tube was PT5, and PT2 was the spare one, while the results shown in the following have been obtained at 11 mK by taking PT1 as reference and PT5 as spare. The number of configurations spanned is obtained by setting the level of discretization of the parameters space: for example, splitting the 360° space into steps of 20°, the number of configurations that would be scanned is given by $(360^\circ/20^\circ)^3 = 5832$, where the exponent referes to the number of involved phase shifts. The PT scan starts by manually setting the

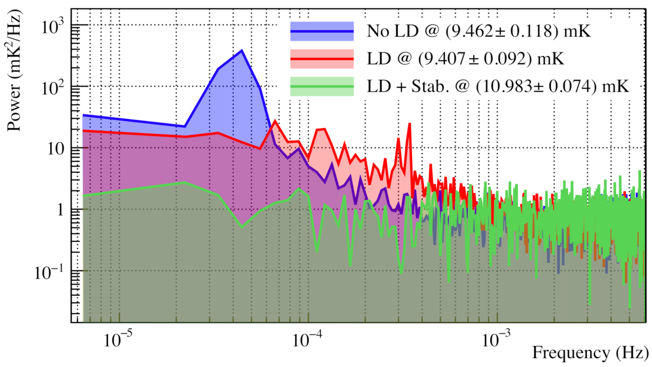

Fig. 3: Noise power spectra of the base temperature measured on the Mixing Chamber plate. Higher spectrum (blue): before replacing the Cryomech drives with the LDs, there was a strong contribution at $\sim 45\,\mu Hz$ due to a period oscillation of 6.2 h. Middle spectrum (red): after replacing the Cryomech drives with the LDs, the main peak is suppressed. Lower spectrum (green): after PT phases stabilization at the minimum noise configuration, the beating peaks and low frequencies are further attenuated [5]. (Color figure online.)

phases to an initial configuration: then, a dedicated software controls the LDs and moves the phases to the following configuration, and so on until the final one is reached. Each phase configuration is maintained to acquire 4 to 5 noise waveforms, each one 10-seconds long. These data are then analyzed to determine the one that minimizes the detector noise. When the best configuration is found after a complete 20° scan, a fine one, usually of 5° steps, is performed around that configuration, allowing a more precise identification of the minimum noise configuration. The fine scan is performed monthly in order to check that the noise level at the minimum configuration remains stable; if not, a new complete scan is done and a new minimum is found. The current minimum has been the same since March 2019.

3.2 Data analysis and phase optimization

The data analysis consists of evaluating the contribution of the first 10 harmonics of 1.4 Hz to each CUORE bolometer noise power spectrum (NPS), at each tested phase configuration [5]. This is performed by summing over the 10 NPS harmonics amplitudes and weighting by the signal power spectrum in frequency domain for each bolometer, which from now on will be referred to as channel. More than 90% of the signal power comes from frequencies below 3 Hz: in this way, the 1.4 Hz and 2.8 Hz harmonics in the NPS are strongly suppressed by the optimization algorithm with respect to the higher noise harmonics induced by the PTs. An example is shown in fig. 4: the power of the 1.4 Hz harmonic can be reduced up to a factor 10^4 varying the phase configuration. The PT noise contribution goes then through a normalization procedure in order to compare all the channels regardless of their absolute noise (Fig. 5), the latter defined for each channel as the noise distribution mediated over all the phase configurations. Finally, an optimization procedure is performed in order to get the detector's typical normalized response to a given PT phase configuration: this is obtained by computing the median over all the channels, that means collapsing the plot in Fig. 5 by channels. The minimum of the obtained distribution represents the minimum noise phase

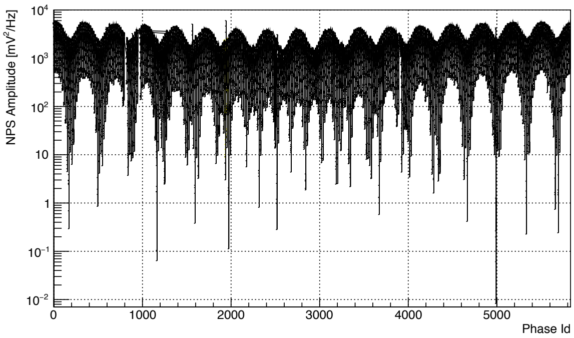

Fig. 4: Amplitude of the 1.4 Hz harmonic of one bolometer noise power spectrum, as a function of the phase configuration.

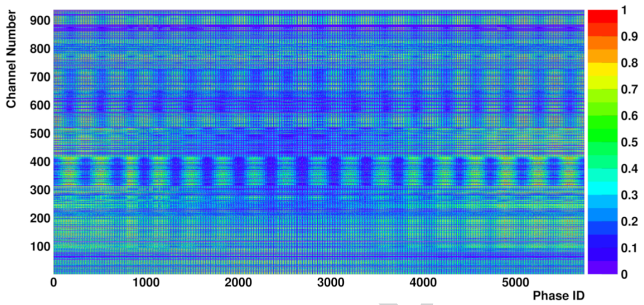

Fig. 5: Normalized median NPS of the first ten 1.4 Hz harmonics, AP weighted amplitudes. On the Y axis there is the channel number. The X axis refers to the phase configuration ID. Dark blue corresponds to low values of the normalized median noise. (Color figure online.)

configuration (Fig. 6). Before accepting the obtained minimum as the best configuration, an additional aspect has to be considered [5]. The PT vibrations do not have the same effect on all the CUORE channels: depending on their position in the detector, there are channels which NPS is strongly or weakly affected by the PT vibrational frequencies. Usually, the majority of phase configurations minimize the noise for a small amount of channels: this would result in an non-optimal configuration for the overall detector response. To avoid this, it is important to select the channels to be included in the optimization process. The minimum noise configuration is the one that minimizes the noise value for the largest possible amount of channels. To identify it, the number of channels with a low noise level is evaluated for each phase configuration (Fig. 7). An example of the noise reduction obtained after applying the phase stabilization algorithm is shown fig. 8 for few CUORE channels.

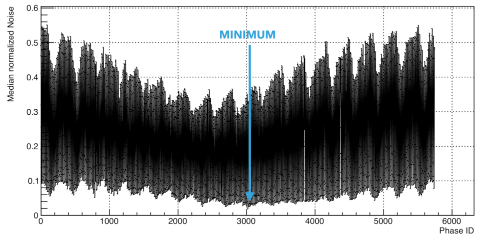

Fig. 6: Median normalized noise distribution over the configurations. The minimum of this distribution refers to the configuration that maximizes the detector's noise cancellation. (Color figure online.)

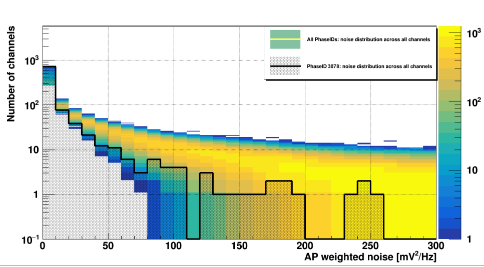

Fig. 7: A typical density histogram of the median noise across all the channels, for each phase configuration. (Color figure online.)

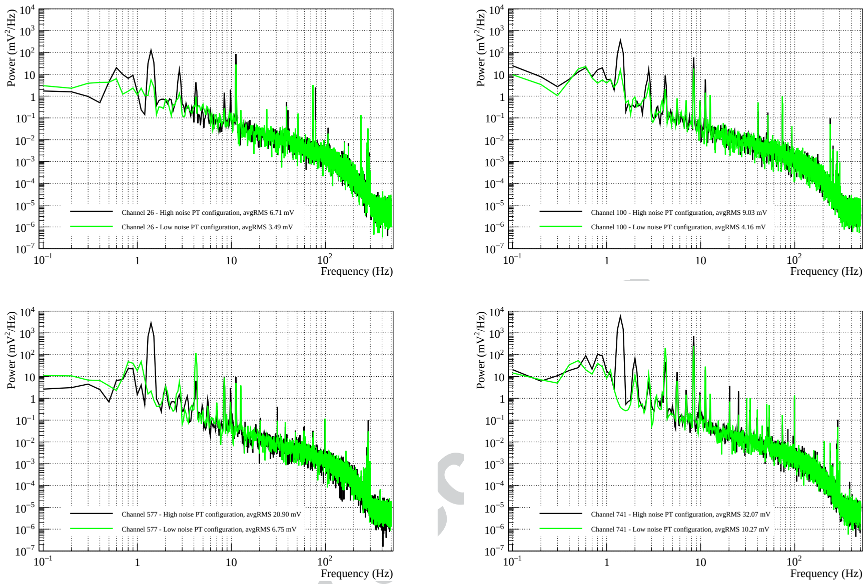

Fig. 8: Average NPS of few CUORE channels at a high (black line) and a low (green line) noise PT phase configuration. In particular, in the two top plots, the low noise configuration is the optimal one minimizing the overall detector noise, while in the bottom plots a configuration optimizing the noise of the single channel is represented. (Color figure online.)

4 Conclusions

The noise cancellation technique has been applied to the CUORE data taking since 2017, and it is currently utilized. With respect to the past [5], it has been well tested and further optimized: the new results just shown demonstrate that it is reliable in different detector conditions. This is obtained after having tested the technique in a period of almost 2 years of data, during which the conditions of the detector changed several times: we applied the technique at different temperatures, with a different reference pulse tube, after performing maintenance cryogenic activities on the CUORE system. The effectiveness of the technique has never changed in all these conditions, always providing a substantial suppression of the PT vibrational contribution to the NPS of the CUORE detectors and therefore reducing the overall RMS. The results shown in this manuscript demonstrate that it is reliable and stable in several situations, making it very flexible and easy to be applied to other cryogenic systems with pulse tubes.

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