Progress on the CUORE Cryogenic System

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Abstract. We give here an update on the CUORE cryogenic system. It consists of a large cryogen-free cryostat cooled by five pulse tubes and one high-power specially designed dilution refrigerator built by Leiden Cryogenics. The cryostat design has been completed and it is presently under construction. The site at the Gran Sasso Underground Laboratory is ready for the installation of the cryostat which is expected to begin by the end of 2009. We discuss here the preliminary results obtained on the performance of the mechanical cryorefrigerators. We also present a measurement of the residual heat leak of the copper which has been selected for the cryostat fabrication.

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1. INTRODUCTION

CUORE [1] is a second-generation neutrinoless double beta decay (0νDBD) experiment that will be installed deep underground in the Gran Sasso Underground Laboratory (LNGS, Italy). It will consist of 988, $5 \times 5 \times 5$ cm^3 TeO$_2$ bolometers operating at very low temperature ($T \leq 10$ mK). Mandatory requirements for high sensitivity are: high mass of the DBD emitter (^{130}Te, isotopic abundance = 34.5%), long exposure time (~ 10 y), extremely low radioactive background in the 0νDBD region ($Q_{\beta\beta} \simeq 2527$ keV) and very good energy resolution.

The CUORE prototype, CUORICINO [2], is the largest bolometric experiment operated up to now (40.7 kg TeO$_2$). It has been taking data at the LNGS from March 2003 to June 2008, demonstrating the feasibility of a large scale bolometric detector with good stability and energy resolution and very promising background results.

The characteristics of the experiment imposes severe requirements to the CUORE cryostat design, mainly:

- Base temperature ≤ 10 mK for optimal detectors response.
- Large cryostat dimension. At least 1000 mm high × 940 mm wide experimental space is required to accommodate the bolometers.
- High cooling power as long as the total mass to be cooled down to mK range is around 1500 kg (detectors + copper frames).
- Materials selection and shielding. Achieving an ultra-low radioactive environment requires a rigorous selection of the materials used in the cryostat, as well as surrounding the detector with proper shieldings.
- Low mechanical vibrations and high temperature stability. Mechanical vibrations result in microphonic noise and instabilities in the cryostat translate into instabilities in the detectors readout, increasing the dead time and spoiling the energy resolution.
- Cryostat reliability and high duty cycle since the data taking can be as long as 10 years.

The last two requirements strongly discourage the use of cryogens in order to increase the duty cycle and avoid instabilities due to changes in liquid levels, so for optimal performance the cryogenic apparatus must be cryogen-free. Refrigerators with the required characteristics are technically feasible as demonstrated by some cryogenic gravitational wave antennas [3, 4] but the absence of cryogens and the very low base temperature required makes the CUORE cryostat a big challenge.

2. CRYOSTAT DESIGN

Figure 1 shows a schematic view of the cryogenics apparatus. A brief description of the system is given here. For

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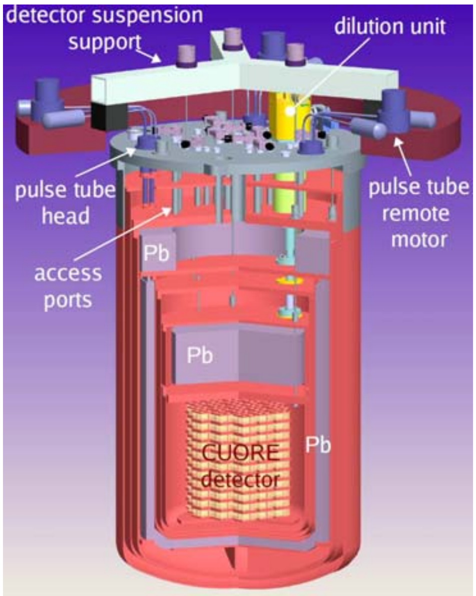

FIGURE 1. Schematic view of the CUORE cryostat

a more detailed one see refs [5] [6].

The cryostat consists of six nested vessels. Two of them are vacuum chambers: the Outer Vacuum Chamber (OVC), at room temperature, and the Inner Vacuum Chamber (IVC), at ~ 4 K. Between them there is a thermal radiation shield at $40-50$ K covered with 30 layers of Multilayer Insulation (MLI). Up to five pulse tubes (PT) mounted on the OVC top flange provide the cooling for the 40 K radiation shield (PT first stages) and the IVC (PT second stages), while the cooling to mK range is achieved by a high-power ^{3}He/^{4}He dilution unit (DU). Inside the IVC, three radiation shields are thermally linked to the DU: the Still shield ($600-900$ mK), the Cold Plate shield ($50-100$ mK), and the Mixing Chamber (MC) shield (< 10 mK) that surrounds the experimental space.

Outside the OVC a 30 cm thick lead shielding strongly reduces environmental radioactivity. Inside the cryogenic apparatus, three additional lead layers shield the bolometers from radioactive contamination in the cryostat itself: a 300 mm thick lead disk (3300 kg) thermally connected to the Cold Plate placed between the MC and the detector, a lead ring-shaped shield (1700 kg) connected to the still closing the gap between the lead disk above the detector and the external lead shielding and an additional 60 mm thick layer shielding detector's sides and bottom, around the still shield (5400 kg).

As concerns the selected materials, all vessels will be made of high purity copper OFE (Oxygen Free Electrolytic), except the components that will work at base temperature. These pieces will be made of NOSV copper (Electronic Tough Pitch), specially selected for its low hydrogen content (see section 4). Electron beam welding will be adopted for all structural components to prevent radioactive contaminants often present in conventional weldings. The components far away from the detector or well shielded by the internal lead layers will be made of austenitic stainless steel (316LN).

The detector suspension has been designed to minimize the transmission of mechanical vibrations both due to seismic noise and to the operation of cryocoolers and pumps. It is a low-frequency isolator in the vertical direction and a pendulum with natural frequency ~ 0.4 Hz in the horizontal direction. The detector suspension is kept independent from the top OVC flange by means of low-frequency isolators.

3. CRYOCOOLERS: STATUS AND PERFORMANCE

3.1. Cryogen-free dilution unit

The dilution unit (DU), that is going to be commissioned to Leiden Cryogenics, is a Joule-Thompson DRS-2000 model modified to run without cryogenic liquids. The expected cooling power are 1.5 mW @ 120 mK, 30 μW @ 20 mK and 5 μW @ 12 mK. The minimum expected temperature is lower than 6 mK with no load on the mixing chamber or the 50 mK stage, while increasing the circulation rate to get a maximum cooling power will increase the base temperature up to ~ 10 mK.

The DU is in construction at Leiden. The mixing chamber has already been produced, the gas handling is already made and a ^{3}He flow as high as ~ 2.5 mmol/s @ 0.1 mbar has been measured when circulating by means of two Adixen turbos in parallel followed by an Edwards roots pump.

3.2. Pulse tubes

The commercial PT cryocoolers that will be used are two-stage Cryomech model PT415, chosen for their high cooling power. To reduce vibrations transmitted to the cryostat the rotatory valve is detached from the cold head. The pulsed He flow is transmitted by a ~ 35 cm long tube from the valve to the cold head and by two 20 m long flexible lines to the compressor.

One of the PT has already been delivered and is being tested. Some preliminary results are given here.

The Cold head of the PT has been mounted on a vacuum chamber that lies on a stainless steel table suspended on four metal rods of adjustable high. The rotatory valve unit is placed in an independent support 20 cm

TABLE 1. Final temperature in the first (T_1) and second stage (T_2) of the PT415 in absence of heat loads as a function of the He pressure in the low and high sides of the compressor. The pressure values correspond to the steady state at cold.

P_{low}(bar)	P_{high}(bar)	T_1(K)	T_2(K)
8.3	22	34	4.15
7.2	20	32.4	3.4
5.8	16.5	30.5	2.35

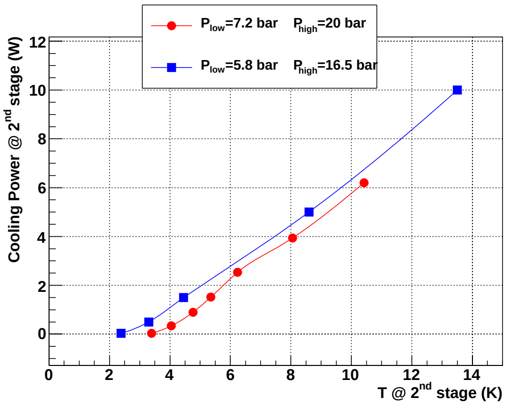

FIGURE 2. Cooling power measured at the second stage of the PT415 for two different compressor pressures.

over the top vacuum chamber flange. A 28 cm diameter aluminium plate is mounted on the first stage of the cold head. A copper radiation shield (50 cm high, 18 cm ϕ) is fixed to the plate, protecting the second stage.

In the first test the cold head reached its lowest temperature in about two hours, but the nominal second stage base temperate with no loads (2.35 K tested in USA with 60 Hz line frequency) was not achieved with the factory compressor settings. An explanation can be found in the compressor efficiency dependency on the line frequency (50 Hz in Europe). The compressor pressure was varied looking for the optimal value (see table 1) for which a temperature of 30.5 K and 2.35 K was obtained for the first and second stage respectively.

The cooling power at the second stage of the cold head was measured for two different compressor pressures. Results are displayed in figure 2. In the best configuration a cooling power of 1.4 W @ 4.2 K was obtained.

Vibration measurements have also been performed in the experimental setup described above and some preliminary results at room temperature are presented here. The sensor, a commercial accelerometer MMF model KS48, was anchored to the second stage of the cold head. Three independent measurements were carried out in the three spatial directions, the coordinate system being as follow:

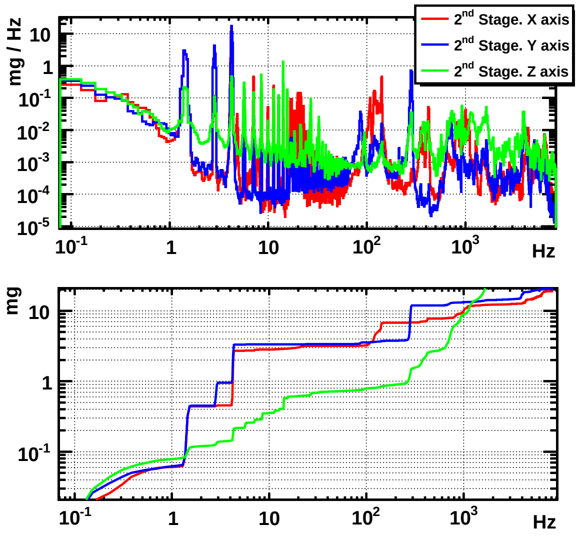

FIGURE 3. Differential (upper panel) and integral (lower panel) acceleration spectra measured at the second stage of the PT415. See text for the axis definition.

X and Y axis are contained in the plane defined by the cold head plate, X axis parallel to the tube connecting cold head and rotatory valve unit, Z axis perpendicular to the cold head plate. The accelerometer signal was preamplified (G=11) before entering the spectrum analyzer. Results in the three spatial directions in the Hz and kHz regime are summarized in figure 3. The main frequencies observed are 1.4, 2.8 and 4 Hz in the low frequency regime and 284 Hz in the medium frequency regime.

As long as the differential pressure decrease when the cold head cools down up to stabilization (for example for one of the measured configurations of the PT415 the low side varies from 6.2 to 7.6 bar and the high side from 23 to 20.4 bar) a reduction in the vibrations is expected [7]. Vibration measurements at base temperature with a piezo-electric sensor suited for low temperatures are in preparation.

4. THERMAL PERFORMANCE AND HEAT LEAK MEASUREMENTS

Table 2 summarizes the mechanical loads to be cooled in the CUORE cryostat and the estimation of the equilibrium heat loads and temperatures for the various stages. For the 40 K shield and the IVC the heat loads have been calculated from data available in the literature and three PT415 coolers are assumed. For the DU a simple numerical model has been written and pessimistic upper values are taken for the equilibrium temperatures. An ^{3}He flow rate of 2 mmols/s is considered.

TABLE 2. Mechanical loads and results of the equilibrium thermal analysis for the various stages.

	Mass (kg)	**Total Power (W)**	**Equilibrium Temp (K)**
40K	990	149.26	49.82
IVC	1920	5.07	4.74
Still	8263	2.27×10^{-3}	0.7
Cold Plate	3847	5.05×10^{-6}	0.10
MC	2016	3.04×10^{-7}	0.01

In addition to the PTs, fast cooling system is being designed to cool down the cryostat from room temperature to 4 K in approximately 15 days. Two roots pumps in cascade circulate the He gas cooled by three Gifford McMahon AL600 Cryomech cooler (600 W @ 77 K) inside the IVC vessel. Below 4 K it should take several hours to cool down CUORE to base temperature. Nevertheless, the time required strongly depends on the heat leaks which may be present in the materials (defect motion, slow relaxation of internal stresses in Pb...).

A well known problem is the heat released by hydrogen in copper due to the ortho-para conversion at very low temperatures [8]. A dedicated measurement has been performed to quantify this effect in the NOSV copper that will be used in the base temperature components.

Two NOSV copper pieces of 2.7 kg each has been tested. The pieces were suspended by 3 Kevlar fibers to the MC of a dilution ^{3}He/^{4}He refrigerator (fig 4) and thermally connected to the MC by a weak thermal link whose thermal conductivity was previously characterized in the range from 50 mK up to 500 mK (see fig 5). To check the reliability of the setup a commercial copper with not particularly low H_2 content was studied, obtaining a time-dependent heat leak of 85 pW/g after two days of cooling, that dropped to 17 pW/g after seven days.

As regards the NOSV copper, for both the pieces no differences in temperature were observed between MC and sample at $\sim$ 50 mK after 36 h of cooling within a systematic error of $\pm$5 mK, allowing to impose a limit for the heat leak of Q$<$ 3.7 pW/g, well below usual literature values for standard copper. Scaling this value to the CUORE NOSV copper mass, a limit of Q$<$ 4.7 μW can be obtained, that fulfills the CUORE requirements.

Further measurements are planned to study heat leaks in the lead, as well as the OFE copper that will be used at the Cold Plate stage.

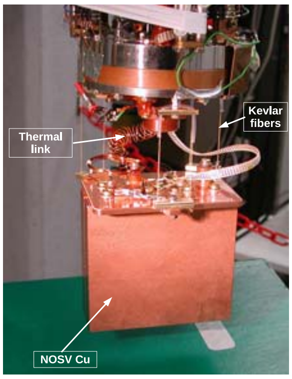

FIGURE 4: Heat leak measurement set-up. One 2.7 kg NOSV copper piece is suspended from the MC of the dilution refrigerator and thermally linked to it.

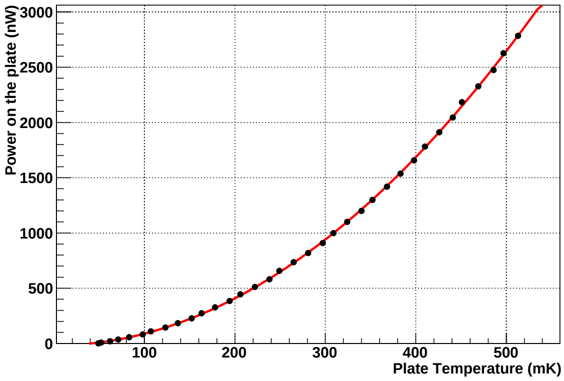

FIGURE 5. Characterization of the thermal link used in the heat leak measurements.

5. CONCLUSIONS

The CUORE Cryostat is the first attempt ever done to cool a mass as large as 1500 kg down to 10 mK. The DU is in construction at Leiden and should be delivered by the end of 2009. The characterization of the Cryomech PT415 Pulse Tubes is in progress and some preliminary results has been presented here. The Cryostat design is almost completed and its installation in the Gran Sasso Underground Laboratory is expected to begin by the end of 2009.

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