The CUORE cryostat: commissioning and performance

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The CUORE cryostat: commissioning and performance

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Abstract. The Cryogenic Underground Observatory for Rare Events (CUORE) will search for the $0\nu\beta\beta$ decay in ^{130}Te using a cryogenic array of TeO_2 bolometers, operated at a base temperature of $\sim$10 mK. CUORE will consist of a closely packed array of 19 towers each containing 52 crystals, for a total mass of 741 kg. The detector assembly is hosted in one of the largest cryostats ever constructed and will be cooled down to base temperature using a custom-built cryogen free dilution refrigerator. The CUORE cryostat along with the pulse tube based dilution refrigerator has been already commissioned at Laboratori Nazionali del Gran Sasso (LNGS) and a record base temperature, on a cubic meter scale, of $\sim$6 mK was achieved during one of the integration runs. We present the results from integration runs, characterizing the system and the cooling performance of the dilution refrigerator, effectively showcasing its stability at base temperature for the expected thermal load.

1. Introduction

Understanding the exact nature of neutrino (Dirac or Majorana) has important implications for physics beyond the standard model. Neutrinoless double beta decay ($0\nu\beta\beta$ decay), a lepton number violating process, is perhaps the only viable experiment which can help elucidate the true nature of the neutrino. An observation of this rare process would imply the definitive existence of a Majorana mass term for the neutrino and can explicate the origin of small neutrino masses[1]. The Majorana nature of the neutrino can also explain the matter-antimatter asymmetry observed in the Universe[2].

The Cryogenic Underground Observatory for Rare Events (CUORE) experiment promises to be one of the most sensitive probes for the search of the $0\nu\beta\beta$ decay in ^{130}Te. The detector constitutes a total mass of 741 kg of TeO_2, arranged in a segmented array of 988 calorimetric detectors. Each detector element is made up of 5x5x5 cm^3 single crystal of TeO_2. Since the intrinsic resolution of a calorimeter is dependent on its heat capacity and the operating temperature[3], the whole detector array will be cooled down to ~10 mK to achieve high sensitivity and good energy resolution. Cuoricino[4] and CUORE-0[5], the predecessors of CUORE, have successfully validated the detection principle for a large size bolometer crystal array.

The state-of-the-art CUORE cryostat has already been commissioned at the Laboratori Nazionali del Gran Sasso (LNGS), Italy (3600 m.w.e) and will be cooled down by a custom-built cryogen free dilution refrigerator. The dilution refrigerator has a high cooling power required to cool down ~1 tonne of detector mass together with the ~7 tonnes of the internal lead shielding. The internal lead shielding is necessary to mitigate the radioactive background arising from the materials used for the cryostat construction. The choice of a material is strictly constrained by its thermal property, mechanical strength and radio-purity.

This article gives a brief overview of the CUORE cryostat and outlines the major cryogenic milestones achieved during the commissioning and integration phase.

2. The CUORE Cryostat

Figure 1 shows the complete schematic of the CUORE cryostat. The 40 K and the 4 K plate of the cryostat are cooled by 5 two-stage pulse tube (PT) coolers (Cryomech PT415). The cooling power measured at the 4 K stage of a pulse tube cooler is ~1.5 W, which is in good agreement with the factory specifications. The choice of the PT cooler arises from the fact that, unlike the conventional cryogen based dilution refrigeration, the PT based dilution refrigeration do not require frequent interruptions for replenishing the cryogen, thus prolonging the effective live-time of the experiment. The PTs were purchased with the 'remote motor head' option to reduce the vibrations emanating from it. The motor head is connected to its respective pulse tube with a two feet long flexible stainless steel hose that dampens the vibration. Further damping is achieved at the 40 K and 4 K stage by using a flexible and soft heat link to couple the pulse tubes to the cryostat. The soft heat links are made out of bundles of copper wires and are gold plated for improved heat conduction.

The Still and the Mixing chamber (MC) plate are cooled by the high cooling power dilution unit (3 mW at 123 mK, measured on the MC). The radiation shields at 40 K, 4 K, Still, 50 mK and MC stage ensure that there is no radiation head load on the detector array. The thermal radiation shields at 40 K and 4 K are vacuum tight and constitute the outer vacuum chamber (OVC) and inner vacuum chamber (IVC), respectively. An extremely good vacuum ($< 10^{-8}$ mbar) is necessary to keep the conduction heat load from the residual gas at minimum. Moreover, the 40 K and 4 K stages of the cryostat are wrapped in multi-layer mylar insulation to further reduce the heating from thermal radiation.

The high cooling power is achieved by continuos circulation of ^{3}He/^{4}He mixture at a high flow rate. The CUORE dilution unit can sustain a flow of ~8 milli-moles/s at 120 mK. However,

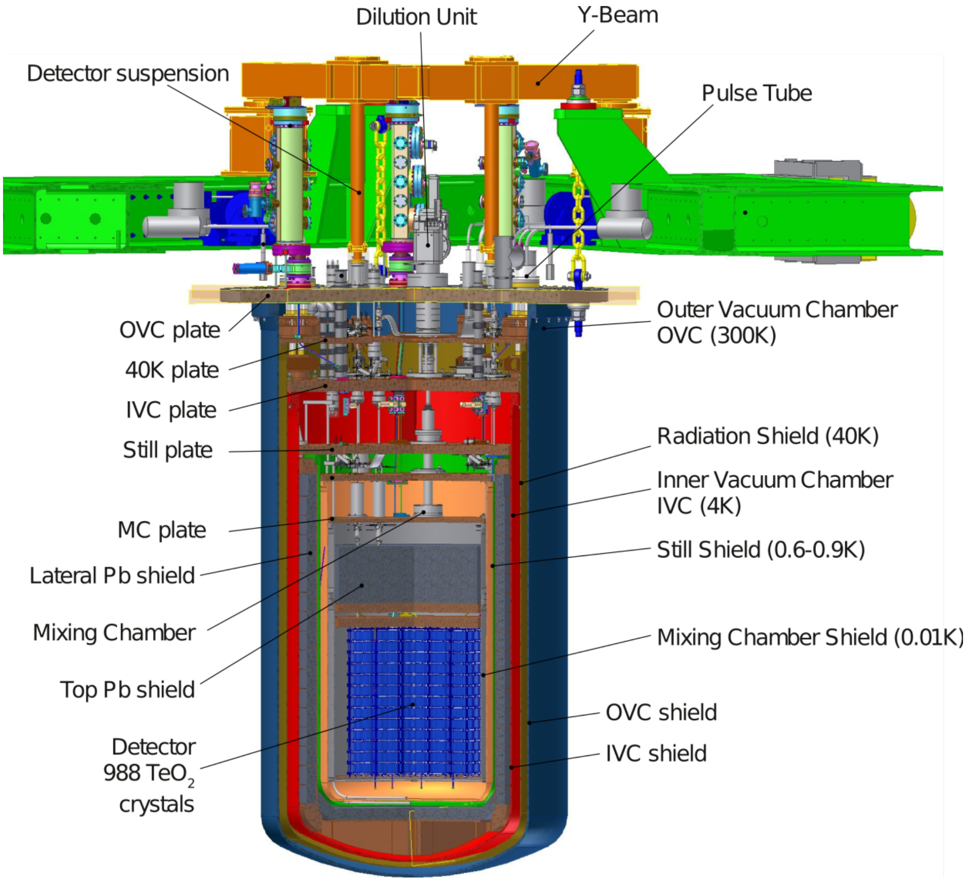

Figure 1. A complete schematic of the CUORE cryostat. (color online)

a high flow rate also results in a lot of heat load due to the incoming warm gas before it is condensed in the dilution unit. The condensing lines of the dilution are, hence, thermalized to the PT and the 4 K plate to minimize the heat load from the incoming mixture. Moreover, a Joule-Thomson stage is provided right before the Still stage to further cool down the mixture.

A part of the passive lead shielding is also housed inside the cryostat. While the top lead shield is a disc of modern lead (M = 2745 kg; h = 30 cm), the lateral lead consists of several 6 cm thick annular sections of ancient Roman lead (M = 5562 kg; ^{210}Pb$<$ 4 mBq/kg), located between the 4K and Still shields. The top lead is mechanically suspended from the 300 K plate and is thermalized to the 50 mK stage. The lateral lead load is supported on the Still suspensions, but has been thermalized to the 4 K plate since it has a higher cooling power. Together with an external lead shield (not shown in the figure), it ensures that the detector array is covered with 30 cm of lead from all sides.

2.1. Fast Cooling System

The CUORE uses an auxiliary sub system, called the fast cooling system (FCS), to aid the cool down from room temperature. Without the FCS, the pulse tubes alone would take about 5 months to cool down the 15 tonnes of mass inside the cryostat. The FCS uses a closed loop cycle to have a forced convection of cold helium gas in the IVC. The helium gas is circulated, with the help of a compressor, through a separate cryostat where the gas gives off its heat to a system of heat exchangers. The deposited heat is continuously extracted with the help of three Gifford-McMahon (GM) cryocoolers that are connected to the heat exchangers. The GM cryocoolers have a cooling power of 600 W at 77 K (each), and reaches a base temperature of ∼20 K. The cold helium gas is then injected into the IVC where it gently cools down the system. The helium flow is regulated to maintain a maximum ΔT of 40 K to avoid thermal shock to the cryostat. The use of FCS significantly reduces the cool down period to ∼3 weeks.

2.2. Detector Calibration System

The CUORE will use an intricate detector calibration system (DCS) to do an in situ calibration of the detectors with known γ-ray sources. Each source comprises a Kevlar string onto which teflon-coated copper capsules (with lengths ∼8–9 mm) are crimped, and each capsule contains a small thoriated tungsten wire. Twelve source strings, each containing 33 or 34 source capsules, would be lowered in the cryostat during the calibration. Each source string is wound on a spool that is connected to a motor on the top of the cryostat, which turns the spool to raise and lower the source string. The source strings are first cooled to 4 K by mechanical squeezing before being lowered further into the cryostat. It then passes through strategically placed guide tubes before reaching the detector region. The strings move under their own weight and the bends in the guide tube allow the sources to thermalize with the tube.

3. Results from the commissioning runs

The CUORE dilution unit was first characterized in a test cryostat. The dilution reached a base temperature of 4.95 mK and a cooling power of 9.5 μW was measured at 12 mK [6]. The dilution unit was then integrated with the CUORE cryostat (with only the copper flanges and vessels) and the system was cooled down only using the pulse tubes. A base temperature of 5.9 mK was reached, indicating a conductive heat load of about 1 μW on the 10 mK plate. The next phase was dedicated to the installation and thermalization of the wiring for the 988 detectors. The cryostat is equipped with 1300 twisted pair NbTi wires ($\phi = 100\,\mu$m) for the detector readout. Copper clamps are used at 4K, Still, 50mK and 10mK stages to thermalize the wires. The cryostat successfully reached a base temperature of ∼7 mK with the wirings installed. The run was also an opportunity to test one of the four complete DCS modules installed on the cryostat. It was shown that the source strings could be reliably lowered in the detector region, held in, and extracted successfully under operating conditions. The next phase was to integrate all the cryogenic sub system before the final detector installation. The lead shielding, both top and lateral, was installed in the cryostat prior to the run. The FCS was commissioned and used to pre cool the system. The results are extremely encouraging with the FCS hastening the cool down to 4 K within 3 weeks. The cool down from 4 K to base temperature took about 48 hrs. The system reached a base temperature of (6.3 ± 0.15) mK, and a cooling power of 3 μW at 10 mK was measured on the MC plate. In addition, all the four detector calibration modules were also integrated with the cryostat. Efforts are on to optimize the deployment speed of the source strings for the detector calibration without significantly affecting the base temperature. With the assembly and integration of all the CUORE cryogenic subsystem nearing completion, it is expected that CUORE will start detector operations in 2016.

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